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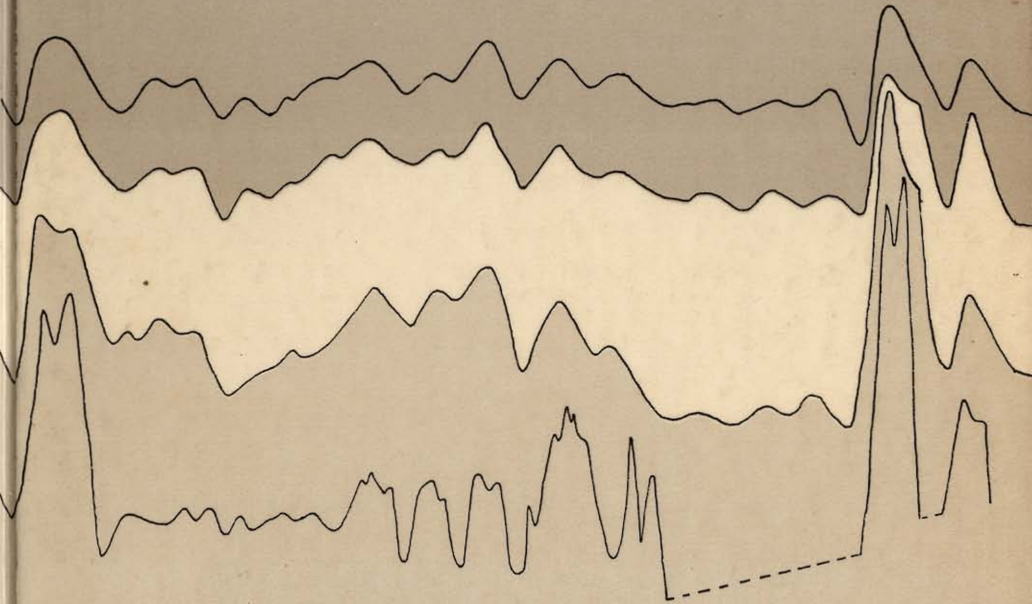

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THE GALACTIC NOVAE

by

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Dedicated
to
William Hammond Wright

PREFACE

When I undertook to write the present monograph, I did so in the belief that we know little about novae except the facts. My aim, therefore, was to summarize the known data that should form the starting point for an interpretation of the nova process.

The problem can be reduced to three questions. What is a nova outburst? How does it proceed? What causes it? The first can be answered confidently, if vaguely: the nova phenomenon is an explosion. The answer to the third is clearly multiple, and is merely touched upon in the final chapter. Most of the book is concerned with facts that bear on the second.

As work on the book progressed I was struck both with the complexity of our information and with its incompleteness, especially with the lack of quantitative spectrophotometric data. No better purpose could be served than that of calling attention to the need for obtaining such data in the future. And it would be particularly valuable, in the study of future novae, to secure spectra of expanding nebular envelopes with the slit in various orientations. The information thus obtained for V 603 Aql has opened up a new era in the study of novae.

I have become convinced that the *whole* nova phenomenon must be studied; the variations of total light and continuum, of radial velocity, and of the intensities and profiles of absorption and emission lines must be seen as connected parts of one physical phenomenon, rather than as isolated data that can be understood separately.

I have inevitably been led into active research that bears on the phenomena, and into attempts to understand the geometrical and physical factors that govern them. Few of the results have found their way into this volume, for most of them await the application of still undeveloped theory. The late spectra of novae have some similarities with those of planetary nebulae, and may be understood in terms of similar processes, but a glance at Plate I will emphasize that the parallel is not exact. And the problem of the excitation in the early stages is still more obscure. The profiles of bright lines nearly always point to some kind of axial symmetry, and their changes to some kind of directional excitation; many phenomena suggest that the latter is not purely radiative.

No apology is due for the fact that the book will be obsolete by the time it is printed. Chapters 9 and 11 had, in fact, to be largely rewritten on account of discoveries published while the book was in proof. This is a measure of the timeliness of the subject. I can ask nothing better than that this small monograph may stimulate researches that will replace estimates by facts and guesses by coherent theories. I am sure that no one will learn as much from reading it as I have learned from writing it.

CECILIA PAYNE-GAPOSCHKIN

CONTENTS

CHAPTER 1

STATISTICS OF GALACTIC NOVAE

1. Census of Novae

About a hundred and fifty galactic novae have been reported. Table 1.1 contains a list based on the compilations of Müller and Hartwig (1920), Stratton (1928, 1936), Payne-Gaposchkin and Gaposchkin (1938), Tuchenhagen (1938), Cecchini and Gratton (1941), Vorontsov-Velyaminov (1948), Kukarkin and Parenago (1948 and following years) and the current literature. Stars erroneously announced as novae are included, in parentheses, for completeness. The table gives the name of the star, the year of appearance, the position designation* (italicized for southern stars), the galactic coordinates, the Julian Day of maximum (if known), observed and extrapolated maximum brightness, minimum brightness, and explanatory notes. The page on which the star is discussed is noted in the final column. When an extrapolated maximum is tabulated, the column headed "Remarks" gives, in parentheses, the name of the nova whose light curve was judged to be similar, and was used in making the extrapolation. Recurrent novae are tabulated, but "symbiotic" novae and U Geminorum stars will be treated in Chapters 7 and 8. Supernovae are discussed in Chapter 9.

Table 1.1 provides data for preliminary studies of frequency, brightness, range and distribution. Many of the stars have been too sparsely observed to contribute much to our knowledge of the light variations of novae, and still fewer provide detailed physical information. Despite the large number of known novae, we have included only seventeen in Chapter 4 (First Class), forty-six in Chapter 5 (Second Class); the information for the remainder is fragmentary.

2. Light Curves of Galactic Novae

The observed light curves of galactic novae are collected in Fig. 1.1 to 1.7. When the scales of abscissae are compared, the stars are seen to have developed at very different rates after maximum. The rate of development provides a parameter for the classification of novae; it is found to be correlated with absolute maximal magnitude and with spectral change.

---

* Six digits denoting R. A. in hours and minutes, Dec. in degrees.

TABLE 1.1

GALACTIC NOVAE

Star	Year	Position Designation	l	b	Julian Day	Maximum Obs.	Maximum Extr.	Minimum	Remarks	Page
VY Aqr	1907	*210609*	10	—37	17790:	8.4	7.1	[16	(V 603 Aql)	190
CI Aql	1917	*184601*	0	0	—	11.0		15.5	Parenago (1931)	190
(CM Aql)	(1914)	*185803*	359	—5	—	14.4		16.4	Nova-like variable	. .
DO Aql	1925	*192606*	0	—13	24450:	8.6	8.6	16.5		156
EL Aql	1927	*185003*	358	—4	25047	6.4	6.4	19.0		157
EY Aql	1926	193014	19	—4	24762:	10.5	10.5	16.5:	(V 528 Aql)	190
V 356 Aql	1936	191201	5	—6	28378	7.0	7.0	[16.0		159
V 368 Aql	1936	192107	11	—6	28437	6.6	6.6	[15.0		161
V 500 Aql	1943	194708	15	—11	30845:	6.5	6.5	[17		162
V 528 Aql	1945	191400	4	—7	31693:	7.4		[18		163
V 603 Aql	1918	184300	1	—1	21755	—1.1	—1.1	10.8	Nova Aql No. 3	81
V 604 Aql	1905	*185604*	358	—6	17072:	8.2		[16.8	Nova Aql No. 2	165
V 606 Aql	1899	*191500*	4	—8	14754	6.7	4.4	[15.4	Nova Aql No. 1 (XX Tau)	165
V 607 Aql	1904	193000	6	—11	16650:	12.0		[16.5		191
V 841 Aql	1951	190210	12	—1	33743:	11.5		[17		165
(KY Ara)	(1937)	*180054*	307	—17	28715:	15.1		[16.2	U Gem Type ?	191
OY Ara	1910	*163352*	302	—5	18738:	6.2	5.1	17.5	(EU Sct)	166
(. . Ara)	(1862)	*173145*	313	—9	—	5.0		11.0	Rejected	. .
(W Ari)	(1855)	031428	126	—23	—	9.5		15.0	Long-period variable ?	191
(SU Ari)	(1854)	024216	127	—36	—	9.5		[14.5	Rejected	191
SV Ari	1905	031919	134	—29	17156:	12.0		[15		191
T Aur	1891	052530	145	0	12088	4.2	4.2	[15.8		89
T Boo	1860	140919	342	+68	00510:	9.7	9.7:	[17.5	(CP Lac)	191
CG CMa	1934	*065923*	203	—6	27450	13.7		[15.7		192

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum Obs.	Maximum Extr.	Minimum	Remarks	Page
η Car	1843	*104159*	255	—1	—	—0.8	—0.8	7.9	Still declining	97
RS Car	1895	*110361*	259	—1	13285:	7.2	5.0	[15.8	(GK Per)	174
MT Cen	1931	*113960*	262	+1	26472	8.5	8.2	[14.0	(DM Gem)	201
V 359 Cen	1930	*115341*	260	+20	26087 ?	13.8		[16.0		201
X Cir	1926	*143464*	282	—5	24762	6.5		[16.7		175
AI Cir	1914	*144068*	281	—9	20282	10.9	10.9	[16.4	(AR Cir)	201
AR Cir	1906	*144059*	285	—2	17260	10.6	10.6	[14.9 ?		201
(. . . Com)	(1877)	140121	345	+70	—	4.5		[10	Rejected	. .
V 394 CrA	1949	*175339*	320	+8	32999	7.5		[13.5		201
T CrB	1866	155526	9	+47	02734	2.0	2.0	10.6		104
	1946				31861					
AP Cru	1935	*122563*	268	—1	27885:	10.7	9.1	[15.0	(GK Per)	201
P Cyg	1600	201437	44	0	?	3.0	3.0	6.0		175
Q Cyg	1876	213742	58	—8	06583	3.0	3.0	14.8		175
V 404 Cyg	1938	202033	41	—3	29175	11.5	11.0	[16.5	(DK Lac)	202
V 407 Cyg	1936	205845	55	—1	—	14.0		[17.5		202
V 450 Cyg	1942	205435	47	—7	30510	7.8	7.8	[16.5		176
V 465 Cyg	1948	194836	59	+4	32700:	8:	7.3:	[17.5:		178
V 476 Cyg	1920	195553	55	+12	22561	2.0	2.0	16.15		110
(UV Eri)	(1930)	*045306*	173	—27		10.5		17.0	Long-period variable	. .
(SY Gem)	(1866)	063431	152	+12		9.2		?	Rejected	202
(VZ Gem)	(1856)	080131	159	+30		8.7		?	Rejected	202
CI Gem	1940	062322	159	+7	29632	14.7		[18.0		202
DM Gem	1903	063730	153	+13	16180	5.0	5.0	16.5		179
DN Gem	1912	064832	152	+16	19476	3.5	3.5	14.8		113

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum		Minimum	Remarks	Page
						Obs.	Extr.			
.. Gem	1892	065317	144	+11	—	7.0		?	Barnard (1906)	202
DQ Her	1934	180445	40	+26	27794	1.4	1.4	14–15		122
.. Her	1892	171224	..	..	—	7.0		?	Ashbrook (1953)	202
CP Lac	1936	221255	70	—1	28340	2.1	2.1	15.3		128
DI Lac	1910	223152	71	—5	19002	4.6	4.6	14.4		181
DK Lac	1950	224552	72	—6	33304	5.4	5.4	[13.4		132
(U Leo)	(1855)	101814	194	+54	—	9.5		[14.0	Rejected	203
RZ Leo	1918	113202	236	+59	21670:	11.5		[16.5		203
(SU Lyr)	(1905)	185036	34	+15	—	10.0		14.0	U Geminorum type?	..
(DM Lyr)	(1928)	185430	29	+11	—	13.0		17.0	U Geminorum type?	..
(HN Lyr)		191442	41	+12	—	10.8		[14.0	Long-period variable	203
HR Lyr	1919	184929	27	+11	22299	6.5	6.5:	15.3		181
BT Mon	1939	*063801*	182	+1	29515:	8.5	5:	17.6	Discovered in late decline	183
GI Mon	1918	*072106*	191	+6	21595	5.6	5.6	15.1		183
KT Mon	1942	061905	173	—2	30718	10.2	10.2	[14.0		203
IL Nor	1893	*152250*	293	+4	12638	7.0	7.0	[16.3		184
IM Nor	1920	*153251*	295	+2	22512:	9.0	9.0	16.5		203
RS Oph	1898	*174406*	348	+9	14458:	4.3	4.3	11.7	Recurrent	136
	1933				27297					
BB Oph	1897	*171824*	329	+5	14067:	11.3	11.3	[18	(V 711 Sco)	204
V 553 Oph	1940	*173624*	331	+1	29824:	11.0	10.8:	16.5	(V 528 Aql)	204
V 794 Oph	1939	*173222*	332	+3	29510:	11.7	11.7	[15.5		204
V 840 Oph	1917	*164829*	321	+7	21344:	6.5		[17.0	Nova Oph No. 5; Nova Sco 1917	204
V 841 Oph	1848	*165312*	336	+16	2396146:	5.0	2:	12.6	Nova Oph No. 2; (V 368 Aql)	184

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum Obs.	Maximum Extr.	Minimum	Remarks	Page
V 849 Oph	1919	180911	7	+12	22268	7.4	7.2	[15.0	(V 356 Aql)	185
V 906 Oph	1952	*172021*	331	+8	34241	10.5		[13	Nova-like variable ?	204
V 908 Oph	1954	*172227*	329	+1	34925	9.0		[14		205
FU Ori	1937	053909	165	+9	28700±	9.7	9.7	16:		186
GR Ori	1916	051601	169	+18	20893	11.5		[15.0		205
(... Ori)	(1677)	055220 ?	157	—1	—	6.0		[12.0	Rejected; perhaps U Ori ?	..
BD Pav	1934	*183457*	307	—22	27689:	12.4	10.5	[16.4	(V 603 Aql)	205
V Per	1887	015556	100	—4	10500±	9.4	8.8:	[16.1	(DQ Her ?)	186
SZ Per	?	034034	128	—14	—	10.5		[16.5		205
UW Per	1912	020556	101	—4	19411:	13.5		[17.0		186
GK Per	1901	032443	119	—9	15439	0.2	0.2	13–14		205
RR Pic	1925	*063462*	239	—25	24310	1.2	1.2	13.6		205
(... Psc)	(1907)	..	..	..	—	..		..	False image; see A.N., 263, 423, 1934	139 142
CP Pup	1942	*080735*	221	0	30675	0.2	0.2	[17.0		..
DY Pup	1902	*080926*	214	+5	16072	7.0	7.0	[16.0		145
T Pyx	1890	*090031*	225	+10	11516	7.9		13.6		205
	1902				15872	7.3				150
	1920				22421	6.6	6.6			
	1944				31416	7.1				
(SS Sge)	(1916)	193216	21	+3	(21090)	11.5		[15.0	Nova-like variable	..
WY Sge	1783	192817	21	+2	2372494	6:		[15.0	Nova Sge No. 1	205
WZ Sge	1913	200317	25	—9	—	7.0	7.0	16.1	Nova Sge No. 2	187
	1946				32001	7.7				
AT Sgr	1900	*175726*	332	—4	15277:	11.0	8.7:	[16.5	(V 909 Sgr)	206

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum Obs	Maximum Extr.	Minimum	Remarks	Page
BS Sgr	1917	*182027*	332	—8	21420	9.2	9.2	[16.0		206
FL Sgr	1924	*175334*	324	—7	23960	8.3		[15.0		206
FM Sgr	1926	*181123*	336	—5	24725:	8.6		16.5		206
(FN Sgr)	(1925)	*184819*	343	—10	—	8.5		[13.5 ?	Nova-like variable	206
GR Sgr	1924	*181625*	335	—7	24800::	11.4	7.5:	16.6	Dicovered in late decline	207
HS Sgr	1901	*182221*	339	—5	15280:	11.5	10.0:	[16.5		207
KY Sgr	1926	*175526*	332	—3	24666:	10.6	7.2	[16.5	(V 603 Aql)	207
LQ Sgr	1897	*182227*	334	—9	14142	13.0		[16.5		207
V 363 Sgr	1927	*190530*	335	—18	25096	8.8	7.9	[16.0	(DI Lac)	207
V 441 Sgr	1930	*181525*	335	—7	26230:	8.7	8.2	16.0		207
V 522 Sgr	1931	*184125*	336	—12	26570	12.9	12.9	[15.3	(Q Cyg)	207
V 630 Sgr	1936	*180234*	325	—8	28448	4.5	4.5	15:		151
V 726 Sgr	1936	*181326*	333	—7	28302:	10.8	10.8	[16.5		187
V 732 Sgr	1936	*174927*	330	—3	28280:	6.5	6.5	12.7		188
V 737 Sgr	1933	*180028*	330	—5	27248:	10.3	10.0	[12.5	(RR Pic)	208
V 787 Sgr	1937	*175330*	328	—4	28680:	9.4	9.0	[16.5		208
V 909 Sgr	1941	*181935*	326	—12	30172	6.8	6.8	[16.0		188
V 927 Sgr	1944	*180133*	326	—7	31197	8.0	7.3	[16.5	(CP Pup)	208
V 928 Sgr	1947	*181228*	332	—7	32316	9.5		[16.5		188
V 939 Sgr	1914	*182826*	335	—10	—	14.2		[17.0		208
V 941 Sgr	1910	*182829*	332	—11	—	11.0		[17.0		208
V 949 Sgr	1914	*183438*	334	—12	—	15.8		17.0		208
V 990 Sgr	1936	*175128*	328	—4	28424	11.1	11.1	[14.7	(DI Lac)	209
V 999 Sgr	1910	*175327*	327	—3	18680:	8.0	8.0	17.0	Nova Sgr No. 2	188
V 1012 Sgr	1914	*175931*	327	—7	20356	8.0	8.0	[17.0	Nova Sgr. No. 7 (DM Gem)	209

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum Obs.	Maximum Extr.	Minimum	Remarks	Page
V 1014 Sgr	1901	*180027*	331	—5	15520	10.3	10.3	[16.1	Nova Sgr No. 4 (DQ Her ?)	209
V 1015 Sgr	1905	*180232*	327	—8	17056	7.1	6.5	[12.0	Nova Sgr No. 6 (DM Gem ?)	209
V 1016 Sgr	1899	*181325*	335	—6	14878:	8.5	6.9	14.9	Nova Sgr No. 3 (V 368 Aql)	209
V 1017 Sgr	1901	*182529*	332	—11		10.8	7.2	14.3	Nova Sgr No. 5	189
	1919				22029	7.2				189
V 1059 Sgr	1898	*185613*	350	—10	14340:	4.9	2.0:	16.5	Nova Sgr No. 1 (CP Pup)	209
V 1148 Sgr	1943	*180226*	331	—4	30956:	8.0		[16		209
V 1149 Sgr	1945	*181228*	331	—8	—	9.0	8.8	[16	(V 356 Aql)	210
V 1150 Sgr	1948	*181224*	334	—6	—	12.0		[16		210
V 1151 Sgr	1947	*181920*	339	—6	—	10.0		[16		210
V 1172 Sgr	1951	*174420*	335	+2	33713	9.0		?		210
V 1174 Sgr	1952	*175528*	327	—4	34064:	12.0		[18		210
V 1175 Sgr	1952	*180731*	328	—8	34064:	7.0		[12		210
. . . Sgr	1928	*180923*	336	—5	—	8.9				210
. . . Sgr	1953	*175829*	329	—6	—	10.5				210
V 1274 Sgr	1954	*174317*	339	+6	34985:	9.5		[13.0		210
V 1275 Sgr	1954	*175236*	323	—8	34928	7.5		[13		
T Sco	1860	*161122*	321	+18	00552	6.7	6.7	11.0	Nova Sco No. 1, in Messier 80 (V 476 Cyg)	190
U Sco	1866	*161617*	326	+20	01646	9.1		[17.6		
	1906				17342	8.8	8.8			
	1936				28342	8.8	8.8			
KP Sco	1928	*173735*	322	—5	25419	9.4	9.4	[16.5	(EL Aql)	211
V 382 Sco	1901	*174535*	323	—6	15632:	9.4	9.4	[16.5	(DM Gem)	211
V 384 Sco	1893	*175435*	324	—8	12595:	12.3	9.2	[16.5	(V 707 Sco)	211

TABLE 1.1, continued

Star	Year	Position Designation	l	b	Julian Day	Maximum		Minimum	Remarks	Page
						Obs.	Extr.			
V 696 Sco	1944	*171635*	319	—1	31226	7.5		[16.5		211
V 697 Sco	1941	*174437*	321	—7	30060:	10.2	10.0	[16.5		190
V 707 Sco	1922	*174136*	321	—6	23249	9.9	9.6	[15.0	Nova Sco No. 3	211
V 711 Sco	1906	*174734*	324	—6	17394	9.8		[15.5	Nova Sco No. 2	211
V 719 Sco	1950	*173933*	323	—4	33482	9.8	9.8	[13.5		190
V 720 Sco	1950	*174535*	322	—5	33501	7.8	7.8	[16		190
V 721 Sco	1950	*173534*	322	—3	33528:	9.5	9.5:	[18.0		191
V 722 Sco	1952	*174134*	322	—5	34075:	9.5	9.4	[13	(Q Cyg)	211
V 723 Sco	1952	*174335*	322	—5	34236	9.8	9.0	[15		212
. . Sco	1952	*174133*	323	—4	—	11.0				212
EU Sct	1949	*185004*	357	—4	33134	8.4	8.4	17		191
FS Sct	1952	*185205*	357	—6	34188	10.1	10.1	[15		192
X Ser	1903	*161402*	339	+30	16185:	8.9	8.9	16.2		192
RT Ser	1909	*173411*	322	+29	24000:	9.0	9.0	[16.0		153
CT Ser	1948	154114	342	+ 9	32600:	8.0	5:	[16.0		193
XX Tau	1927	051316	155	+10	25154	6.0	6.0	[15.0		194
RR Tel	1946	*195656*	309	—33	33100	6.8	6.8	16.5		154
CN Vel	1905	*105853*	255	+5	17185	10.2	10.2	[16.5	(AR Cir)	194
CQ Vel	1940	*085552*	239	+4	29736	9.2	8.9	[15		212
(X Vir)	(1871)	115609	240	+69	—	8.0		11.6 ?	Constant ? Himpel (1941)	. .
SW Vul	1923	195522	29	+5	23637:	15.0		[17.5		212
CK Vul	1670	194327	31	+0	2331186:	3.0	3.0	[16.5		212

McLaughlin (1936) has discussed the light curves of well-observed novae, and demonstrated that while each star has its own individuality, the changes of brightness follow a common pattern for most of them. He recognizes nine stages in the development of a typical nova, which he relates to the characteristic spectral variations. These stages are summarized in Table 1.2; it must be admitted that in some cases they produce a rather spurious effect of uniformity, and some imagination is needed if all the stages are to be recognized for all novae. However, they form a useful summary of the main stages of the process. Stage 1 (pre-nova) represents the undisturbed star. Stages 2–4 (initial rise through final rise) cover the expansion that follows the explosion; during this initial swelling, most of the light (at least in the observable regions) comes from a pseudo-stellar continuum, and a greatly distended photosphere simulates that of a supergiant star. Stage 5 (principal maximum) marks a turning point in the history of this photosphere,

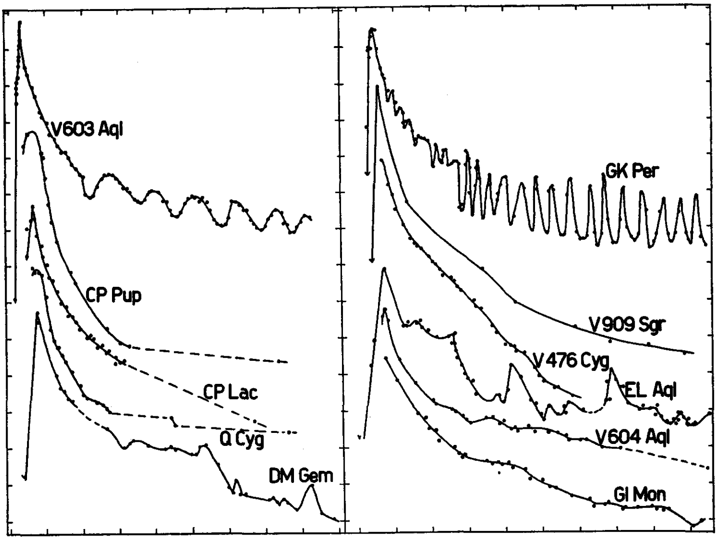

Fig. 1.1. Light curves of eleven fast novae, arranged in order of rate of fall from maximum. All are plotted on the same scale. Short vertical lines along the axis of ordinates are at intervals of one magnitude; those on the axis of abscissae are at intervals of ten days.

TABLE 1.2

STAGES IN THE NOVA LIGHT CURVE

Stage	Characteristics	Examples	Spectrum
1. Pre-nova	Constant brightness Variable brightness	RR Pic, T Pyx GK Per, V 603 Aql, DQ Her	Continuous ?; blue star (V 603 Aql)
2. Initial Rise	To within about 2m below maximum light; very rapid except for RT Serpentis stars.	V 603 Aql, 9.5 mag. in 1 day; CP Lac, 9 mag. in 1 day; DN Gem, 7 mag. in 1 day	Displaced absorption
3. Pre-maximum halt	Pause or dip in brightness	V 603 Aql, pause, 2.2 mag. below; DN Gem, abrupt slowing of rise; DQ Her, dip 1.8 mag. below	Displaced absorption; occasional strong emission (DQ Her)
4. Final rise	Much slower than initial rise	DN Gem, 1 mag. in 3 days; CP Lac, 2 mag. in 1.4 days; V 603 Aql, 2.2 mag. in 1.5 days; DQ Her, 1.8 mag. in 7 days	Displaced absorption; emissions, if present, tend to weaken
5. Principal maximum	Very brief except for very slow novae		Multiple absorptions and emissions appear in a few hours; continuum weakens
6. Early decline	To 3–4 mag. below maximum	Smooth: CP Lac, XX Tau, X Ser Oscillations: DN Gem, DQ Her	Multiple absorptions; emissions strengthen
7. Transition	Begins about 3.5 mag. below maximum	Broad, smooth minimum; DQ Her, T Aur, XX Tau Change of slope: V 476 Cyg, CP Lac Large oscillations: GK Per, V 603 Aql, DK Lac	Absorptions become more complex, finally fade; emission spectrum develops nebular character.
8. Final decline	Smooth or slightly irregular		Absorptions gone; continuum greatly weakened; nebular spectrum develops further
9. Post-nova	Constant brightness Variable	T Pyx, CP Lac GK Per, V 603 Aql, DQ Her	Usually blue star, with or without weak absorption and/or emission lines. Nebular envelope may become visible.

which must diminish rapidly in dimensions, though it probably increases in surface brightness; meanwhile the bright-line spectrum becomes conspicuous. Stage 6 (early decline) is marked by the fall in brightness of the observable continuum, the relative increase of the emission spectrum, and the arrival of multiple absorptions at the photospheric level. Stage 7 (transition), which may be marked by large oscillations of the total brightness, and even larger oscillations of the brightness of the continuum, sees even greater complexity of the absorption spectra, which now begin to weaken, and rapid changes in

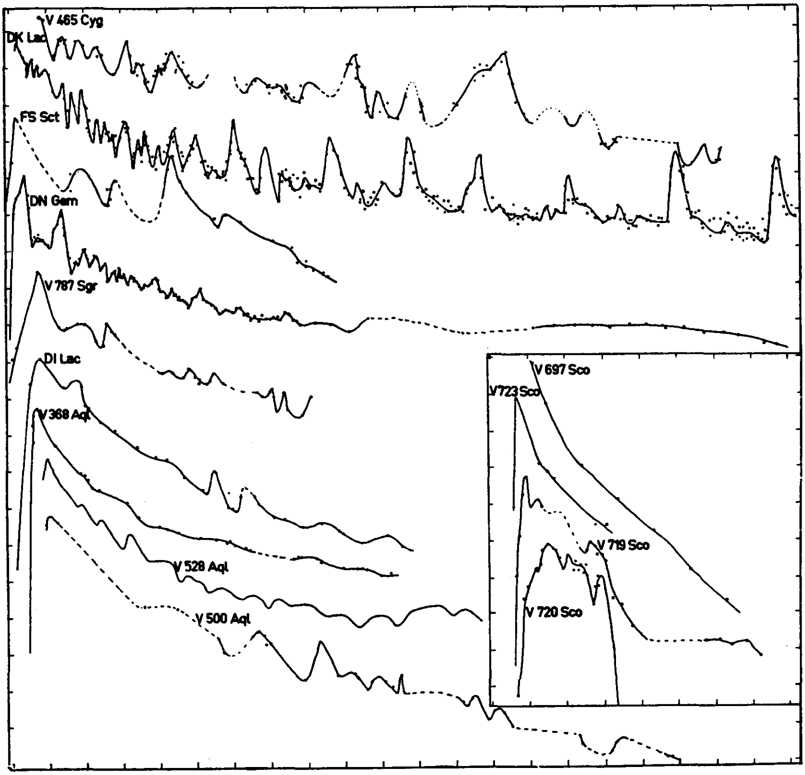

Fig. 1.2. Light curves of thirteen novae. Ordinate and abscissa are marked at intervals of one magnitude and ten days, respectively.

the bright-line spectra, which begin to develop "nebular" characteristics. Stage 8 (final decline), when the absorptions have vanished, is marked by further development of the nebular spectrum, and often gives evidence of high and rising ionization and excitation. Novae differ greatly throughout the early decline, transition, and final decline. Probably ejection through the current photospheric level continues throughout the transition; the final decline probably involves the expansion of the explosion products after ejection has ceased. Stage 9 (post-nova) sees the star gradually returning to something very like Stage 1, though the process may be a very long one, and may indeed actually terminate only in a recurrence of the explosion.

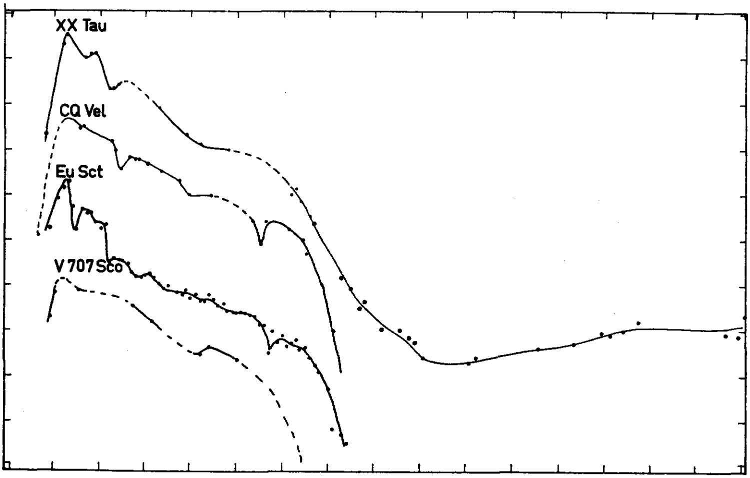

Fig. 1.3. Light curves of four similar novae. Ordinate and abscissa are marked at intervals of one magnitude and ten days, respectively.

The forms of the light curves of novae are associated with the maximal luminosities, which will now be discussed.

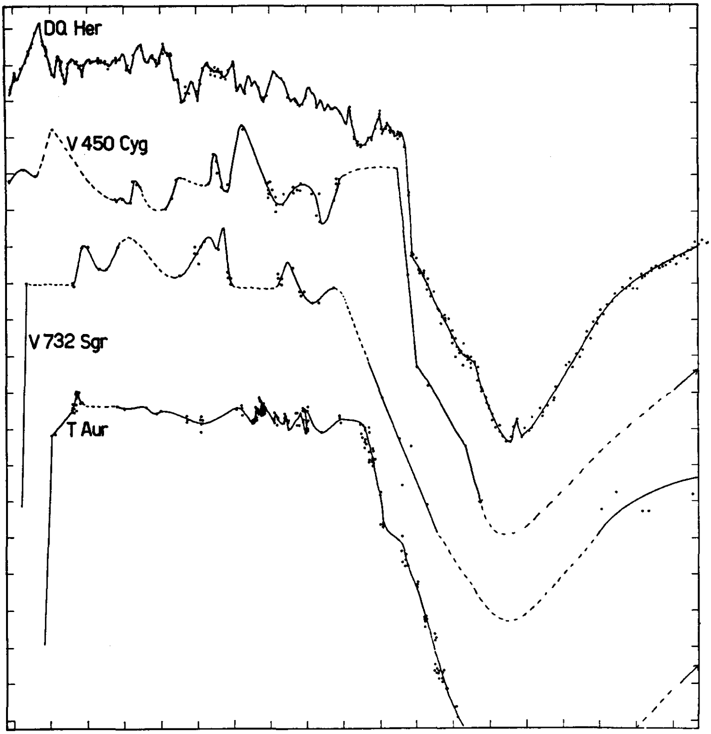

Fig. 1.4. Light curves of four novae of the "DQ Herculis type", observed through the deep minimum. Ordinate and abscissa are marked at intervals of one magnitude and ten days, respectively.

3. Luminosities of Novae

That the novae are of very high luminosity at maximum has long been recognized. Lundmark (1922, 1923) derived a value of —7.1, very near to the modern result, from the secular parallaxes of eleven novae. The high luminosity was placed beyond doubt by the discovery of many novae in Messier 31 by Hubble (1929), when the large distance of this galaxy was established by means of its Cepheids.

Five possible methods of determining the absolute magnitudes of galatic novae were critically discussed by McLaughlin (1942). They rest on: (1) direct measures of parallax, (2) secular parallaxes, (3) parallaxes from expanding nebulosity, (4) distances estimated from intensities of interstellar lines, (5) distances derived from galactic rotation.

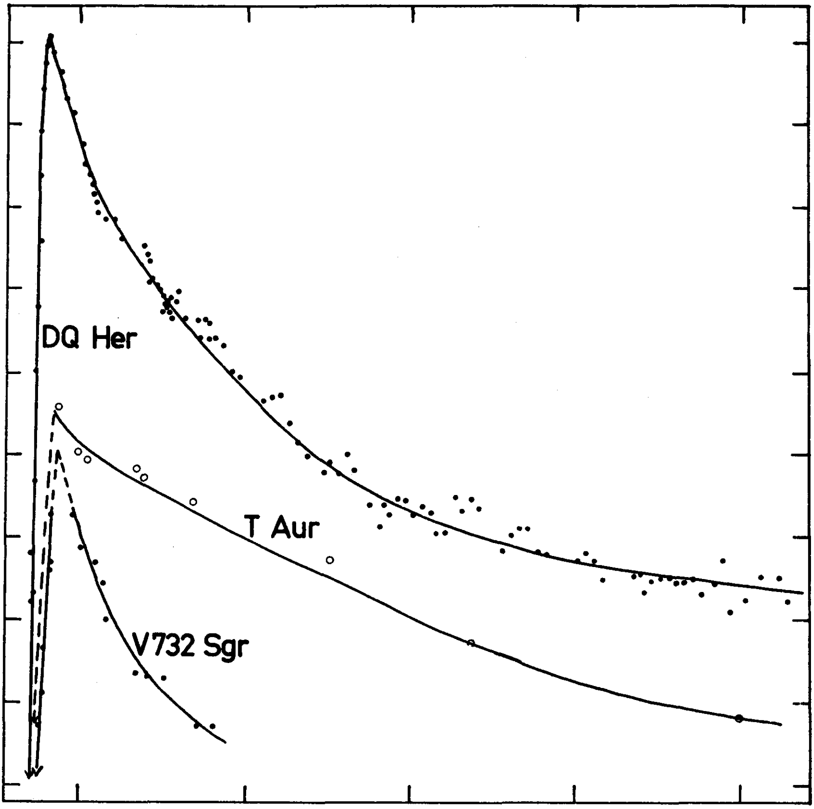

Fig. 1.5. Light curves of three novae of the "DQ Herculis type" after the deep minimum. Ordinate and abscissa are marked at intervals of one magnitude and one thousand days, respectively. The curve drawn for V 732 Sgr is the same as that for DQ Her. Note that the rise of T Aur took about the same time, but its decline was much slower.

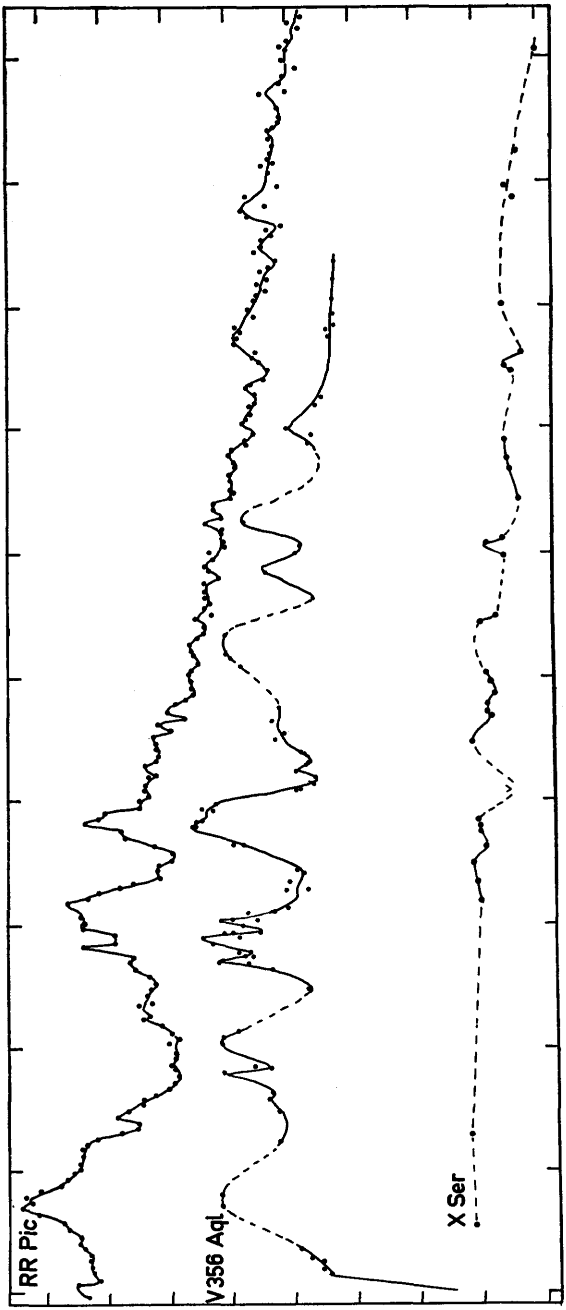

Fig. 1.6. Light curves of three slow novae. Ordinate and abscissa are marked at intervals of one magnitude and twenty days, respectively.

Trigonometric parallaxes, discussed by statistical methods that were admittedly precarious (four of the ten available parallaxes were negative) led McLaughlin to an absolute magnitude —6.7 after correction for interstellar absorption. A similar discussion by Tuchenhagen (1938) led to the value —7, but he included several types of parallax determination. This approach to the luminosities of novae can at best serve as qualitative confirmation of their great brightness. The known proper motions and parallaxes of novae, taken from the catalogue of Jenkins (1952), are given in Table 1.3.

McLaughlin was inclined to reject the method of secular parallaxes on the ground that the resulting solar motion is abnormal. He pointed out that radial velocities of most novae are indeterminate, so that solutions employing them are invalid. Lundmark's result, corrected for interstellar absorption, gave a value —7.6 for absolute visual magnitude at maximum.

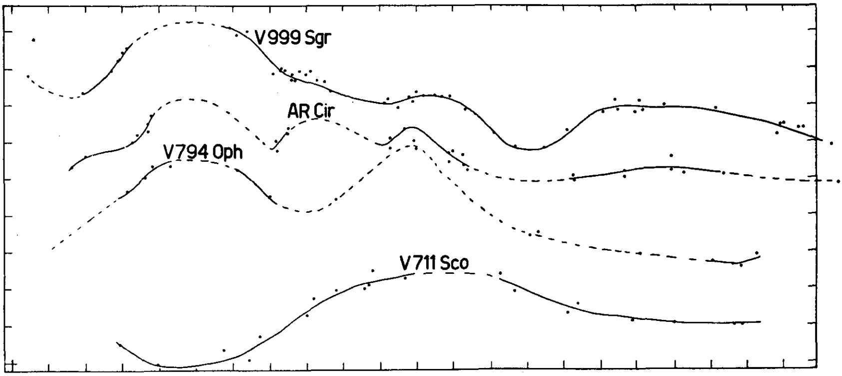

Fig. 1.7. Light curves of four very slow novae. Ordinate and abscissa are marked at intervals of one magnitude and ten days, respectively.

The most satisfactory method is the one that depends on the rate of expansion of a nebular disc, which must be identified with one of the radial velocities observed spectroscopically. Data for individual novae will be discussed later. McLaughlin deduced a mean value of —7.9 from four novae.

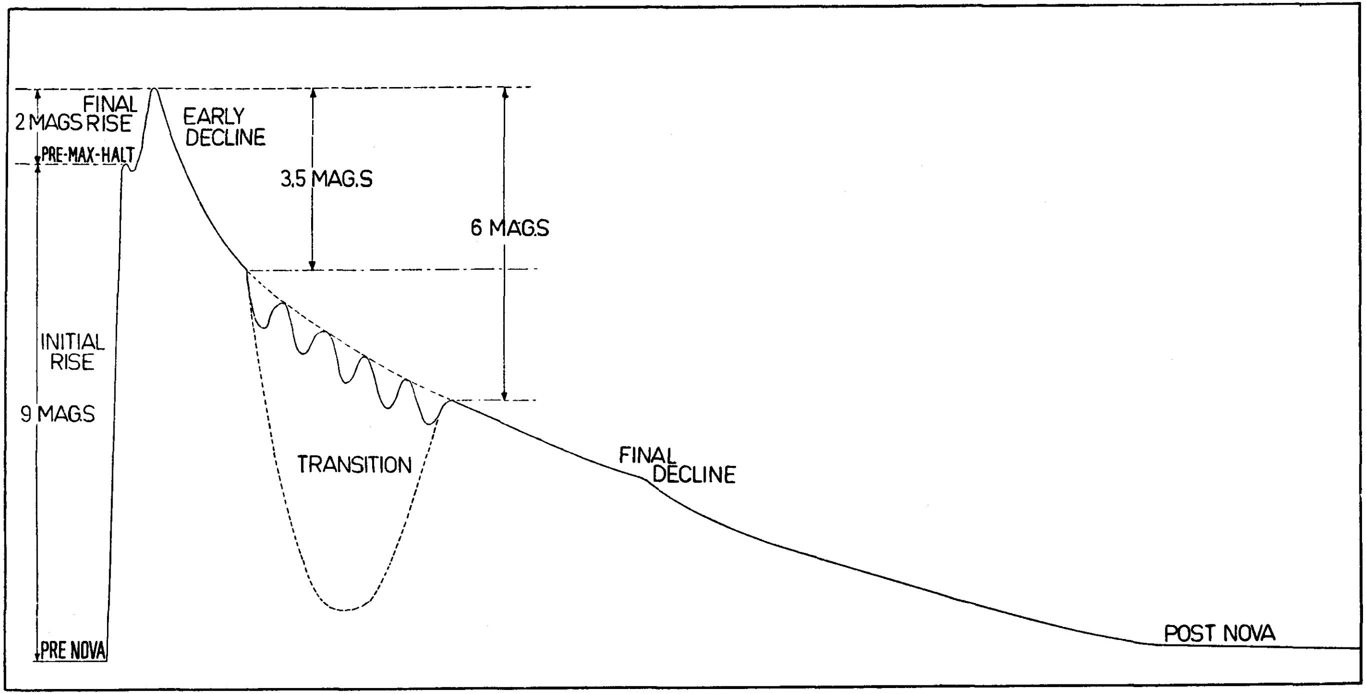

Fig. 1.8. Schematic light curve of a nova, showing typical stages. The time scale is not uniform throughout; it has been magnified in the early stages. After McLaughlin.

TABLE 1.3

PROPER MOTIONS AND PARALLAXES OF NOVAE

Star	Proper Motion		Absolute	
	μ_α	μ_δ	Parallax	
V 603 Aql	.00	—.02	—.002 ±.004	
V 476 Cyg	..	..	+.016 ±.006	
DN Gem	—.01	+.02	—.003 ±.007	
DQ Her	..	..	—.005 ±.011	
DI Lac	..	..	+.001 ±.009	
HR Lyr	..	..	+.014 ±.012	
V 849 Oph	..	..	—.006 ±.013	
GK Per	—.01	—.02	+.006 ±.004	
RR Pic	—.05	—.02	—.005 ±.008	
WZ Sge	+.08	—.02	+.011 ±.011	Recurrent nova

Distance determinations from intensities of interstellar lines have proved less satisfactory than they were first thought to be, because the distribution of the absorbing material is far from uniform. The value —7.6 was deduced by McLaughlin from seven novae; it confirms the other methods in order of magnitude. Similar qualifications must be made concerning determinations of distance from the residual velocities of interstellar lines, whose complex nature is now generally recognized. McLaughlin (1945) accordingly regards this method as less promising than it formerly appeared; in any case it gives only a lower limit for the luminosity. His earlier value, —6.5 (1942), was indeed the lowest he derived for galactic novae.

The most important source of information is the discovery of novae in stellar systems of known distance. Many novae were found in Messier 31 by Hubble (1929); nine in the Magellanic Clouds were discussed by Henize, Hoffleit and Nail (1954); a few in Messier 33 were announced by Hubble (1926, 1929), Carpenter (1929), and Bernheimer (1933); in Messier 81 by Humason (1950), Sandage (1954). Data for Messier 31 and the Magellanic Clouds were used by McLaughlin (1942) before the zero point of the period-luminosity curve had been revised; accordingly the values he obtained should be revised upward by 1.5 magnitudes or more. The discussion by Payne-Gaposchkin (1954) of the whole system of absolute magnitudes for variable stars, in which this revision was taken into account, led to —7.6 for the average maximal absolute magnitude of novae, on the basis of the material then available.

TABLE 1.4

ABSOLUTE MAGNITUDES OF NOVAE BY VARIOUS METHODS

Method	Absolute Visual Magnitude	Weight (McLaughlin)	Remarks
Trigonometric parallax	—6.7	1	
Secular parallax	—7.6	½	
Nebular expansion	—7.9	1	
Interstellar lines	—7.6	1	low weight
Galactic rotation	—6.5	½	low weight
Magellanic Clouds	—8.0	½	zero point adjusted
Messier 31	—8.2	2	zero point adjusted
Weighted mean	—7.62		
General discussion	—7.6		Payne-Gaposchkin (1954)

The studies described above are summarized in Table 1.4, which is based on McLaughlin's discussion. The mean has been taken with McLaughlin's weighting. The last entry in the table given by McLaughlin (1942), which relates to the novae in the direction of the galactic center, has been omitted. This group gave the value —6.2 in his discussion. It has been much enriched in the intervening years, and is omitted from Table 1.4, to be discussed in a later chapter. We may conclude from Table 1.4 that an absolute maximal magnitude —7.6 can be adopted with some confidence for the average nova.

Individual determinations of absolute maximal magnitude for sixteen novae are collected in Appendix I of the present Chapter, p. 35. Determinations from nebular expansion, interstellar line intensity, galactic rotation, and presence in a globular cluster are summarized there, so that the various results for each nova may be directly compared.

It is clear, however, that novae have a dispersion in absolute maximal magnitude. The best site for the exploration of these differences is certainly a distant system that is rich in novae. Conclusions drawn more indirectly from galactic novae will stand or fall to the extent that they are substantiated by such information. The recent study of the novae in Messier 31 by Arp (1956), kindly made available to the writer before publication, furnishes such material, and places the luminosities of novae on a firm footing.

One of the difficulties in all determinations of apparent (and therefore of absolute) maximal magnitude lies in the extrapolation to maximum of an incompletely observed nova light curve. If we could be confident that the light curve follows a fixed course, this difficulty would be removed; but only for Type I supernovae have we this confidence. The systematic coverage of the novae in Messier 31 by Arp removed the difficulty. His results show that the maximal luminosity is correlated both with the rate of decline (expressed as magnitudes per day for the first two magnitudes' drop in brightness), with the duration (expressed as the time in days during which the nova was brighter than the 20th apparent photographic magnitude), and with the general form of the light curve. Table 1.5 contains some of the data given by Arp for the thirty novae that he discussed. The two last columns have been added from inspection of the light curves by the present writer, for the purpose of comparing with those of galactic novae.

Nova No. 4 was found by Arp to be reddened and obscured. Both No. 10 and No. 20 have conspicuous pre-maximum rises.

The duration, as defined above, is shown by Arp to be closely related to the maximal apparent (and therefore absolute) magnitude. The rate of decline over the first two magnitudes is also related to absolute magnitude. This quantity is readily determined for well-observed galactic novae, and we may (if we assume similarity in the two galaxies) use it to estimate maximal absolute magnitude for galactic novae. This done, we can determine the duration (as defined by Arp) by the number of days that the nova spends above absolute magnitude —4.2. The assumption of identity of novae in the two systems can to some extent be tested by a comparison of the deduced durations with those found by Arp for novae with similar rates of decline, and also by examining the forms of the associated light curves. The results of the test are summarized in Table 1.6. The four first columns contain the name of the star, the observed rate of decline, the deduced absolute maximal magnitude, and the deduced duration; the next gives the observed rate of rise; two final columns describe the character of the light curve. We should note that Arp's light curves are photographic,

TABLE 1.5

NOVAE IN MESSIER 31 (ARP, 1956)

No.	$M_{\max}$* m	Duration d	Rate of Decline mag/day	Rate of Rise mag/day	Energy $\times 10^{44}$ ergs	Light Curve	
						Early Decline	Transition
1	—8.5	5.2	1.02	24	1.2	smooth	
2	—8.5	5.2	1.02	24	1.2	smooth	
3	(—8.3)	(11.2)	0.38	..	..	smooth	
4	—6.0	11.8	0.20	1	..	oscillation	
5	—8.3	16	0.17	..	4.3	oscillation	oscillation
6	—8.2	24	0.23	8	3.2	oscillation	oscillation
7	—8.3	26	0.15	..	5.8	smooth ?	
8	—8.2	29	0.23	6.7	3.7	oscillation!	oscillation!
9	(—8.2)	(33)	0.174	0.7	..	?	oscillation
10	—8.2	35	0.29	1	2.9	oscillation	oscillation
11	(—8.2)	(33:)	?	..	..	oscillation	oscillation!
12	—8.1	39	0.180	2	7.4	?	oscillation
13	—7.2	43	0.077	1	4.9	oscillation	oscillation
14	(—8.0)	(43)	0.163	..	..	smooth	oscillation
15	—7.8	43	0.126	8	..	oscillation!	oscillation!
16	—7.5	44	0.156	15	4.1	oscillation!	oscillation!
17	—7.0	49	0.069	1.4	..	oscillation	oscillation
18	—6.7	49	0.058	0.75	..	oscillation	oscillation!
19	—6.6	49	0.070	0.16	3.4	oscillation!	oscillation
20	—7.0	53	0.060	0.40	4.2	oscillation!	oscillation!
21	—6.8	65	0.075	4	4.9	oscillation!	oscillation!
22	—6.6	65	0.067	..	..	oscillation!	oscillation!
23	—6.8	72	0.046	..	..	oscillation	oscillation
24	—6.4	92	0.059	1:	..	oscillation!	oscillation!
25	—6.6	93	0.061	0.29	3.8	oscillation!	oscillation!
26	—6.2	96	0.043	0.07	4.6	oscillation!	oscillation!
27	(—6.4)	(91)	..	..	..	oscillation!	oscillation!
28	—6.4	115	0.019	0.5	7.6	oscillation!	oscillation!
29	—6.2	150	0.017	0.07	9.0	oscillation	oscillation
30	—6.1	150	0.017	0.25:	6.3	oscillation	oscillation

* Assumed $m - M = 24.2$, Baade (1954).

TABLE 1.6

GALACTIC NOVAE: OBSERVED AND DEDUCED PROPERTIES

Star	Rate of Decline observed mag/day	$M_{\max}$ deduced *m*	Duration deduced *d*	Rate of Rise observed mag/day	Light Curve	
					Early Decline	Transition
U Sco*	0.67	—8.4	8		smooth	
T CrB*	0.52	—8.4	10		smooth	
V 603 Aql	0.57	—8.35	16	9.5	smooth	oscillation
V 630 Sgr	0.50	—8.35	12:		smooth	oscillation ?
V 909 Sgr	0.50	—8.35	16		smooth	oscillation ?
CP Pup	0.40	—8.3	9		smooth	smooth
CP Lac	0.40	—8.3	23	9	smooth	smooth
Q Cyg	0.33	—8.3	23		smooth	smooth
DM Gem	0.33	—8.3	48		smooth	bump on fall
GK Per	0.33	—8.3	25		smooth	oscillation !
MT Cen	0.33	—8.3	..		smooth	
RS Oph*	0.30	—8.3	22		smooth	smooth
V 476 Cyg	0.29	—8.3	26		smooth	dip
V 723 Sco	0.29	—8.3	31		smooth	oscillation ?
V 604 Aql	0.25	—8.25	31		smooth	smooth
V 1059 Sgr	0.20	—8.25	63:			
V 1016 Sgr	0.17	—8.25	75:			
FL Sgr	0.17	—8.25			smooth	
GI Mon	0.15	—8.1	52		smooth	oscillation
DK Lac	0.14	—7.95	64		oscillation	oscillation !
FS Sct	0.14	—7.95	81			
EU Sct	0.14	—7.95	51		oscillation	abrupt fall
V 726 Sgr	0.14	—7.95	95:			
V 368 Aql	0.13	—7.8	..			
V 719 Sco	0.13	—7.8	26			
V 500 Aql	0.13	—7.8	47		smooth	oscillation
DN Gem	0.12	—7.7	46	7	oscillation	oscillation
V 787 Sgr	0.12	—7.7	64			
V 1015 Sgr	0.12	—7.7	34:			
V 528 Aql	0.12	—7.7	..			
V 720 Sco	0.118	—7.55	19			
EL Aql	0.105	—7.35	33		oscillation	oscillation
DI Lac	0.100	—7.3	39		smooth	oscillation

TABLE 1.6, continued

Star	Rate of Decline observed mag/day	$M_{\max}$ deduced *m*	Duration deduced *d*	Rate of Rise observed mag/day	Light Curve	
					Early Decline	Transition
KT Mon	0.100	—7.3	..		smooth	smooth ?
V 840 Oph	0.100	—7.3	..			
WZ Sge*	0.100	—7.3	..			
FM Sgr	0.091	—7.15	..		smooth	
KP Sco	0.091	—7.15	35			
XX Tau	0.083	—7.05	50		oscillation	dip
HR Lyr	0.064	—6.75	60:			
CQ Vel	0.054	—6.65	47		smooth	dip
V 707 Sco	0.050	—6.6	48		smooth ?	
OY Ara	0.045	—6.5	65:			
X Cir	0.040	—6.45	..			
V 1017 Sgr*	0.034	—6.4	..			
T Pyx*	0.032	—6.4	64		oscillation	oscillation
DQ Her	0.030	—6.25	66		oscillation	dip of 7 mag.
V 732 Sgr	0.027	—6.2	72		oscillation	dip of 3 mag.
RR Pic	0.025	—6.2	79		oscillation	dip
T Aur	0.025	—6.2	81		oscillation	dip of 7 mag.
V 697 Sco	0.024	—6.2	83		smooth	smooth
DY Pup	0.017	—6.05	98		smooth ?	
V 711 Sco	0.017	—6.05	95			
V 849 Oph	0.017	—6.05	..			
V 356 Aql	0.013	—6.0	57		oscillation	smooth
CN Vel	0.013	—6.0	>200		oscillation	
AR Cir	0.010	—5.95	200		oscillation	
V 999 Sgr	0.009	—5.95	250:			
DO Aql	0.007	—5.9	>250		oscillation	
BS Sgr	0.006	—5.9	200:		smooth ?	
X Ser	0.005	—5.9	370		smooth	oscillation ?
RR Tel	0.003	—5.85	525		oscillation	
RT Ser	0.002	—5.9	>1000		oscillation ?	oscillation
η Car	0.001	—5.9:	1000:		oscillation	oscillation
FU Ori	0.001	—5.6:	..		smooth	

* Known to be recurrent

and a number of the light curves of galactic novae, from which rates of decline and durations are deduced, are visual. The color indices of novae are so erratic that it has been judged impossible to improve the material by attempting to correct for this effect.

The relationships between rate of decline and duration are compared in Table 1.7. The correspondence justifies our assumption that the galactic novae are comparable to those in Messier 31.

TABLE 1.7

RELATION OF RATE OF DECLINE TO DURATION

Limits of Rate of Decline mag/day	Logarithm of Mean Duration (days) Messier 31	Galaxy
>1.00	0.715 (2)	..
0.60 to 0.69	..	0.903 (1)
0.50 to 0.59	..	1.130 (4)
0.40 to 0.49	..	1.204 (2)
0.30 to 0.39	1.040 (1)	1.470 (4)
0.20 to 0.29	1.398 (3)	1.577 (4)
0.10 to 0.19	1.544 (10)	1.714 (14)
0.01 to 0.09	1.886 (7)	1.874 (16)
0.00 to 0.009	..	2.670 (5)

Tables 1.5 and 1.6 show that both galactic and Messier 31 novae present continuous distributions of duration. There is no evidence here that the novae represent several distinct classes. McLaughlin (1945)

TABLE 1.8

CLASSIFICATION OF LIGHT CURVES

Speed Class	Definition	Rate of Decline mag/day
Very fast	Fall of 2 mag. in 10 days or less	>0.20
Fast	Fall of 2 mag. in 11 to 25 days	0.18 to 0.08
Moderately fast	Fall of 2 mag. in 26 to 80 days	0.07 to 0.025
Slow	Fall of 2 mag. in 81 to 150 days	0.024 to 0.013
Very slow	Fall of 2 mag. in 151 to 250 days	0.013 to 0.008

recognized very fast, fast, average, slow and RT Serpentis novae, but (save for the last) these classes represent convenient groupings rather than physically distinct species. For purposes of illustration we shall, however, use these terms in what follows.

The relation of light curve to speed class is summarized in Table 1.9.

TABLE 1.9

Speed Class and Character of Light Curve

Speed Class	Very Fast	Fast	Moderately Fast	Slow
Early decline:	%	%	%	%
Smooth	90	69	12	12
Oscillation	10	31	88	88
Transition:				
Smooth	38	33	0	0
Oscillation	38	42	0	67
Dip	24	25	100	33
Oscillation + dip	62	67	100	100

Clearly the very fast and fast novae tend to display a smooth early decline, and to a less extent a smooth transition, whereas the slow novae tend to oscillate during early decline, and, to an even greater extent, to oscillate and dip during transition. These tendencies are pointed out qualitatively by McLaughlin (1939). That they are also displayed by the novae of Messier 31 is testified by Table 1.5.

The relative numbers in the speed classes are shown, in percentages, in Table 1.10. A smaller proportion of moderately fast novae and slow novae in the galaxy is offset by greater numbers of fast and very fast

TABLE 1.10

Distribution of Novae Among Speed Classes

	Very Fast	Fast	Moderately Fast	Slow	Very Slow	RT Ser
Galaxy, %	24	36	17	9	5	9
Messier 31, %	6	13	43	38	..	..

novae, a difference pointed out by Arp. He notes that the effect of discovery may play some part, but probably the difference is real. Its source will be discussed in Chapter 2.

The novae whose distances have been determined from expanding nebular discs furnish an interesting comparison with the luminosities of Table 1.6. The data are given in Table 1.11.

TABLE 1.11

NOVAE WITH OBSERVED NEBULAR DISCS

Star	Absolute Maximal Magnitude Table 1.6	Absolute Maximal Magnitude Nebular Disc	Reference
V 603 Aql	—8.35	—8.9	Hubble and Duncan (1927)
		—9.3	Baade (1941)
CPPup	—8.3	—10.5*	Zwicky (1956)
		—8.5	Weaver (1955)
V 476 Cyg	—8.3	—8.9	Baade (1944)
CP Lac	—8.3	—9.2	Baade (1944)
		—8.6	McLaughlin (1945)
GK Per	—8.3	—8.4	Baade and Humason (1943)
RR Pic	—6.2	—7.3	McLaughlin (1936)
DQ Her	—6.25	—5.5	Baade (1940)
T Aur	—6.15	—5.3	Baade (1943)

* Uncorrected for absorption.

The nebular parallaxes depend on the correct selection of the radial velocity that corresponds to the motion of the expanding nebulosity. The three determinations for V 603 Aquilae and the two for CP Lacertae involve different choices for this velocity. The "nebular expansion" for RR Pic depends on the observed motion of nebulous knots, rather than of a nebulous envelope, and this star shows the largest discordance. The two similar novae DQ Her and T Aur show a discordance in the opposite sense; perhaps the rate of fall – luminosity relation is not valid for novae with this special type of light curve. The accordance for the four brightest novae, however, is very satisfactory, and both sets of absolute magnitudes show similar trends in absolute magnitude with speed class.

Two galactic novae are possibly connected with globular clusters: the very fast T Sco, and the interesting though sparsely observed V 1148 Sgr. If they are associated respectively with Messier 80 and NGC 6553, their absolute magnitudes are near —9.

TABLE 1.12

NOVAE OF KNOWN RANGE

Star	Pre-nova	Maximum		Post-nova	Notes
		Obs.	Extr.		
EL Aql	..	6.4	6.4	19.0	Wyse (1940)
V 356 Aql	16.0	7.0	7.0	..	
V 603 Aql	10.5v*	—1.1	—1.1	10.5v	
OY Ara	17.5	6.2	5.1	..	
T Aur	..	4.2	4.2	14.8v	
AR Cir	14.9	10.6	10.6	14.8	Probable companion
Q Cyg	..	3.0	3.0	14.8v	
V 450 Cyg	..	7.8	7.8	16.3	
V 465 Cyg	17.5:	8:	7.3:	..	Pre-nova, Ashbrook and Nail (1950)
V 476 Cyg	..	2.0	2.0	16.15c*	
DM Gem	..	5.0	5.0	16.5c	
DN Gem	15:	3.5	3.5	14.8v	
DQ Her	14–15v	1.4	1.4	13.8v	eclipsing star; still fading?
CP Lac	15.3	2.1	2.1	14.85	still fading?
DI Lac	14.0	4.6	4.6	14.4v	
HR Lyr	16.	6.5	6.5:	15.3	
BT Mon	..	8.5	5:	17.6:	
GI Mon	15.1c	5.6	5.6	..	
IM Nor	16.5	9.0	9.0	..	
V 841 Oph	..	5.0	2:	12.6v	
FU Ori	16:	9.7	9.7	..	still fading
GK Per	13.5v	0.2	0.2	13.v	
RR Pic	12.7c	1.2	1.2	..	
CP Pup	17	0.2	0.2	..	
GR Sgr	16.6	11.4	7.5:	16.5	
HS Sgr	16.5	11.5	10.0:	..	
V 441 Sgr	16.0	8.7	8.2	15.5c	
V 630 Sgr	15:	4.5	4.5	..	
V 999 Sgr	..	8.0	8.0	16.5v	
V 1016 Sgr	14.9	8.5	6.9	14.9c	
V 1059 Sgr	..	4.9	2.0:	16.5c	
X Ser	14.5v	8.9	8.9	15.4	
RR Tel	12.5–[14	6.8	6.8	..	still fading

* v = variable, c = constant

The relation between duration and absolute maximal magnitude that has been established by Arp in Messier 31 is very similar to the one deduced by McLaughlin (1945), which indeed it now puts on an accurate quantitative basis. It is quite distinct from the "life – luminosity relation" deduced by Zwicky (1936) and illustrated by a comparison between common novae and supernovae; this relationship associates greatest maximal luminosity and total luminosity with *longer* life, and will be mentioned in connection with the supernovae. Zwicky pointed out that the slow novae must deviate from this relation.

The minimal luminosities of novae present a more intricate problem. If we suppose that the maximal luminosities of Table 1.6 are valid, it might seem easy to deduce absolute minimal magnitudes from observed ranges. However, the data present puzzling anomalies. Table 1.12 presents our current information for novae of which we possess pre-maximum or post-maximum observations, or both.

TABLE 1.13

AVERAGE RANGES OF NOVAE (McLAUGHLIN)

	Fast Novae	Slow Novae
Average Range:		
Observed max.	10.6 (15)	9.6 (7)
Extrap. max.	10.8 (15)	9.8 (7)
Average $M_{\max}$	—8.3	—6.2
Deduced M_{min}:		
Observed max.	+2.3	+3.4
Extrap. max.	+2.5	+3.6

We thus possess information on the ranges of thirty-two novae, twenty-two seen in the pre-nova stage, twenty-two in the post-nova stage after return to "normal" brightness. Eleven were variable in the pre-nova or post-nova stage, or both; seven are recorded as sensibly constant. Table 1.12 indicates that the pre-nova and post-nova brightnesses are sensibly the same, and that detectable variations in this stage are perhaps rather commoner than constancy. Similar conclusions have been reached by McLaughlin (1939, 1941) and by Bertaud (1948). The extrapolated magnitudes of Table 1.12 are taken from Table 1.1. Recurrent novae have been excluded, and also peculiar stars such as η Carinae (probably still fading) and P Cygni.

Discussion of the observed ranges of novae by McLaughlin (1939) led to the results of Table 1.13. The final lines are added in accordance with the maximal magnitudes deduced earlier.

Some doubt is cast on the significance of these numbers by the fact, noted by McLaughlin, that the mean range of the three apparently bright slow novae T Aur, DQ Her and RR Pic is nearly twelve magnitudes. The doubt is intensified when we note that the observed range is greatest for the novae of brightest apparent maximal magnitude; in fact for stars that do not reach third magnitude it is linearly correlated with observed maximum magnitude. This relationship is clearly shown by Table 1.14, which displays the correlations between apparent maximal magnitude and range, both for the material in Table 1.12 and for the slightly different compilation of Bertaud (1948), which included η Carinae but not P Cygni.

There are three possible interpretations. These novae may all have sensibly the same *apparent* magnitude at minimum; or we are dealing with a selection effect; or the ranges of faint novae have been underestimated. The first is quite implausible; the second is made improbable by the *absence* of small ranges for apparently bright novae (P Cygni excluded); the third seems the most likely. McLaughlin (1939) indeed

TABLE 1.14

APPARENT MAXIMAL MAGNITUDE AND AMPLITUDE FOR GALACTIC NOVAE

Apparent Maximal Magnitude	Mean Amplitude		Amplitude	Mean Apparent Maximal Magnitude	
	Our Data	Bertaud Data		Our Data	Bertaud Data
-1.9 to -1.	11.9 (1)	11.25 (2)	5.0 to 5.9	..	10.0 (2)
0.0 to 0.9	15.05 (2)	12.8 (1)	6.0 to 6.9	8.85 (4)	9.0 (1)
1.0 to 1.9	12.40 (2)	12.3 (2)	7.0 to 7.9	8.60 (2)	8.0 (2)
2.0 to 2.9	13.09 (4)	13.4 (2)	8.0 to 8.9	7.42 (4)	6.89 (7)
3.0 to 3.9	11.55 (2)	11.45 (2)	9.0 to 9.9	6.05 (4)	5.7 (1)
4.0 to 4.9	10.23 (3)	10.50 (6)	10.0 to 10.9	4.50 (4)	2.95 (4)
5.0 to 5.9	11.50 (3)	10.45 (2)	11.0 to 11.9	2.32 (6)	3.39 (8)
6.0 to 6.9	9.31 (4)	10.83 (3)	12.0 to 12.9	5.05 (3)	3.3 (2)
7.0 to 7.9	9.15 (4)	8.05 (4)	13.0 to 13.9	2.52 (4)	1.83 (3)
8.0 to 8.9	7.52 (2)	7.27 (3)	14.0 to 14.9	2.00 (2)	..
9.0 to 9.9	6.9 (2)	6.75 (2)	15.0 to 15.9	..	..
10.0 to 10.9	6.5 (1)	..	16.0 to 16.9	..	..
11.0 to 11.9	..	5.0 (1)	17.0 to 17.9	0.2 (1)	..

invoked it for AR Circini when he surmised an unresolved companion.

If misidentification at minimum has falsified some of the ranges, we can obtain a better idea by studying only the novae that can be definitely located at minimum. These are the post-novae whose spectra have been identified and studied by Humason (1938), Brück (1932) and McLaughlin (1953), sixteen stars in all, of which eleven fall in the present category, five being recurrent. These stars are given in Table 1.15.

TABLE 1.15

Galactic Novae with Observed Minimal Spectrum

Star	Maximum (Obs. or Extr.) *m*	Post-nova *m*	Range *m*	Remarks
V 603 Aql	—1.1	10.8 var.	11.9	Humason (1938), Brück (1932), McLaughlin (1953): blue star, bright lines, nebula
T Aur	4.2	14.8 const.	10.6	Humason (1938), McLaughlin (1953): blue star, weak bright lines, nebula
Q Cyg	3.0	14.8 var.	11.8	Humason (1938), McLaughlin (1953): blue star, very weak bright lines
V 476 Cyg	2.0	15.5 const.	13.5	Humason (1938), McLaughlin (1953): nebula
DM Gem	5.0	16.5 const.	11.5	Humason (1938), McLaughlin (1953): no absorption or emission seen; less blue than usual post-nova
DN Gem	3.5	14.8 var.	11.3	Humason (1938), McLaughlin (1953): blue star, weak emission
DI Lac	4.6	14.4 const.	9.8	Humason (1938), McLaughlin (1953): very weak emission
HR Lyr	6.5:	15.3	8.8	Humason (1938), McLaughlin (1953): very blue star
V 841 Oph	2.0:	12.6 var.	10.6:	Humason (1938)
GK Per	0.2	13.5 var.	13.3	Humason (1938), McLaughlin (1953): blue star, emission lines, nebula
V 1059 Sgr	2.0:	16.5 const.	14.5:	Humason (1938), McLaughlin (1953)
		Mean Range	11.60	

Although the material of Table 1.15 is necessarily limited by minimal apparent magnitude, and might therefore be expected to *minimize* the deduced ranges, it gives an average range of 11.6. Several stars are surrounded by nebulae, which might be expected to reduce the ranges, but the brightest nebula is probably the one about GK Persei, a nova which has a range above the average. Indeed the mean range for novae with observable nebulae is 12.3 mag., and that for novae without observable nebulae is smaller, 11.2 mag.

The minimal absolute magnitudes for this group of novae are deduced in Table 1.16. The stars are arranged in order of absolute maximal magnitude (Table 1.6); four bright recent novae, whose ranges are known with confidence, are added to the list.

TABLE 1.16

Maximal and Minimal Absolute Magnitudes, Well-observed Novae

Star	$M_{\max}$ *m*	Speed Class	Range *m*	$M_{\min}$ *m*
V 603 Aql	—8.35	VF	11.9 var.	+3.55
CP Lac	—8.3	VF	13.2	+4.9
Q Cyg	—8.3	VF	11.8 var.	+3.5
GK Per	—8.3	VF	13.3 var.	+5.0
V 476 Cyg	—8.3	VF	13.5	+5.2
DM Gem	—8.3	VF	11.5	+3.2
DN Gem	—8.25	F	11.3 var.	+3.05
V 1059 Sgr	—8.2	F	14.5:	+6.3:
EL Aql	—7.35	F	13.5	+6.15
DI Lac	—7.3	F	9.8 var.	+2.5
HR Lyr	—6.75	S	8.8	+2.1
T Aur	—6.2	S	10.6	+4.4
RR Pic	—6.25	S	11.5	+5.3
DQ Her	—6.25	S	13.1 var.	+6.85

Average values for the different speed classes are given in Table 1.17. The selection of novae of observed minimal spectrum has led to fainter minimal magnitudes, as will be seen by comparison with the entries taken from Table 1.13. The fast and very fast novae appear to have larger ranges, and (for the mean of all) to be somewhat brighter at minimum than the slow novae. This trend would not be changed by the inclusion of CP Pup* among the very fast novae; its range of about

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* We use the nebular parallax, and have applied no correction for, absorption; the minimal absolute magnitude may thus be brighter.

seventeen magnitudes would give an absolute minimal magnitude +5.8, and would change the mean for very fast novae to +4.45. The correlations illustrated by Bertaud (1948) show differences in a similar sense, but the numerical values are not the same, since Bertaud used all available ranges rather than a critical selection, included recurrent novae, and employed inhomogeneous absolute maximal magnitudes.

TABLE 1.17

SPEED CLASS, RANGE AND ABSOLUTE MINIMAL MAGNITUDE

Speed Class		Mean Range	Mean Absolute Minimal Magnitude	Table 1.13
		m	*m*	*m*
Very fast		12.54	+4.14	+2.5
Fast		12.25	+3.90	
Slow	All	11.00	+4.66	+3.6
	HR Lyr, RR Pic	10.25	+3.70	
	DQ Her, T Aur	11.85	+5.45 +6.45*	

* adopting "nebular" parallax

There is, however, another possibility. The stars of DQ Herculis type may not follow the relation between rate of decline and absolute maximal magnitude; if for these we adopt the "nebular parallaxes", we find them much fainter at minimum, while the other slow novae differ inappreciably from the fast and very fast novae.

Two possible RT Serpentis stars, FU Orionis and RR Telescopii, are given in Table 1.12. If we extrapolate Arp's relation and assign them absolute maximal magnitude —5.9, their observed range of 6.5 magnitudes leads to an absolute minimal magnitude +0.7. Wachmann (1954) doubts whether the former star is a nova; but the spectrum of RR Telescopii leaves no doubt for that star. However, the large pre-outburst fluctuations of RR Telescopii make it possible that when first observed it was executing a protracted pre-maximum rise, so that the deduced absolute minimal magnitude is an upper limit; a parallel is furnished by the (very rapid) T CrB, which began to show signs of disturbance several years before the maximum of 1946. We accordingly consider the minimal absolute magnitudes of RT Serpentis stars as uncertainly known.

Five recurrent novae have been observed at minimum. If their maximal absolute magnitudes follow Arp's relation, we obtain the results of Table 1.18.

TABLE 1.18

ABSOLUTE MAGNITUDE AND RANGE, RECURRENT NOVAE

Star	Maximal Absolute Magnitude (deduced)	Range	Minimal Absolute Magnitude	Speed Class
T CrB	—8.4	8.6	+0.2	VF
RS Oph	—8.3	7.5	—0.8	VF
WZ Sge	—7.3	9.1	+1.8	MF
T Pyx	—6.4	7.2	+0.8	S
V 1017 Sgr	—6.4	7.1	+0.7	S

The recurrent novae thus seem much brighter at minimum than the other novae, with the luminosities of giant stars. The minimal brightness does not seem to be related to the length of the cycle; but there seems to be a tendency to faster development, and thus perhaps to greater maximal luminosity, for stars of longer cycle: T CrB, U Sco and RS Oph (very fast novae) had cycles of 80,33 and about 35 years; WZ Sge, 33 years; and the slow novae T Pyx and V 1017 Sgr have cycles of under 20 years. Recurrence is emphatically not confined to the very rapid novae; in fact the "symbiotic novae" may well be included among the recurrent novae, and their development, while erratic, is fairly slow.

A new light is thrown on the amplitudes of novae by the discovery of Walker (1954) that DQ Her displays at the present time the light curve of an eclipsing star of very short period. We shall not here discuss the physical and evolutionary implications of this discovery, but we may point out that if the tendency is general, the persistent minimal variability of at least some novae may furnish evidence of it. The observed ranges of novae would then be lower limits. All the non-recurrent novae of known minimal spectrum are faint blue stars at minimum, usually with weak bright lines; novae thus probably originate from blue subdwarfs. If we take this view, the novae of observed minimal spectrum, even if they are double stars, have ranges nearly equal to the true range of the blue subdwarf that dominates the minimal spectrum. Perhaps some of the smaller observed ranges are not based on misidentifications (as suggested earlier), but are results of a brighter companion, but this must remain a speculation in the absence of observations. The recurrent novae, some of which have minimal spectra of M giant stars, are of particular interest in this connection, as are the symbiotic variables such as Z And and R Aqr. These stars will be discussed in a later chapter; certainly the "nova component" of T CrB is now, and was for several years before the outburst of 1946, comparable in brightness with the giant M "companion"; but it may for some of the time be much fainter.

Our survey of the light curves of novae is rich in detail, but the details, and indeed the broad outlines, are still far from being understood. The main facts, which a satisfactory theory must meet, are summarized in Table 1.19.

TABLE 1.19

SUMMARY OF FACTS CONCERNING THE NOVA LIGHT CURVE

1. The outburst is sudden and the rise rapid.
2. The novae that fade most rapidly are brightest at maximum.
3. The novae that fade most rapidly have the smoothest development; slow novae tend to oscillate in brightness.
4. The absorption lines, and therefore the ejection through the photosphere, are observable, at most, through the transition, and usually become invisible when the brightness has fallen through about four magnitudes; activity at the surface of the original star is therefore brief.
5. Pre-novae are blue subdwarfs of absolute photographic magnitude about + 4; recurrent novae may be brighter at minimum, but this is not conclusively proved; DQ Herculis stars may be fainter.
6. The total energy emitted is greater for the slow novae, in spite of their lower maximal luminosities, because of the long duration of the light curve; it is of the order of 10^{44} to 10^{45} ergs.

The interpretation of these facts must also meet the more stringent and intricate requirements of the spectral phenomena, which will be discussed in general in Chapter 3, and described in detail in Chapters 4, 5 and 6.

APPENDIX 1

Absolute Maximal Magnitudes by Various Methods

Star	log t_3	Nebular Expansion	Ref.	Interstellar Lines	Ref.	Galactic Rotation	Ref.	Presence in Globular Cluster	Ref.
V 356 Aql	2.21	..		..		—6.7	McLaughlin (1942)	..	
V 603 Aql	0.90	—9.3 —8.9 —8.5	Table 1.11	—8.1	Popper, see Wyse (1939) Weaver (1955)	..		..	
T Aur	2.00	—5.3	Table 1.11	..		..		..	
V 450 Cyg	2.00:	..		—3.5	Sanford (1943)	—5.5	Sanford (1943)	..	
V 476 Cyg	1.21	—8.9	Table 1.11	—7.9	Wilson (1936)	..		..	
DN Gem	1.57	..		—6.4	McLaughlin (1942)	..		..	
DQ Her	2.00	—5.5	Table 1.11	—7.3	Williams (1935)	..		..	
CP Lac	0.95	—8.6	Table 1.11	—7.9	Merrill and Wilson (1936), Beals (1937)	..		..	
BT Mon	1.56:	..		..		—7.1	McLaughlin (1942)	..	
V 849 Oph	2.21:	..		..		—5.7	McLaughlin (1942)		
GK Per	1.11	—8.4	Table 1.11	..		..		..	
RR Pic	2.21	—7.3	McLaughlin (1941), Note 1	..		..		..	
CP Pup	0.85	—10.5	Zwicky (1956).	—8:	McLaughlin (1941)	—11:	Humason and Sanford (1942)	..	
V 1148 Sgr	..	..		..		..		—8.8	Note 2
T Sco	1.34	..		..		..		—9.05	Note 3
EU Sct	1.60	..		—8.5	Heard (1953)	—10.2	Heard (1953)	..	

NOTES

1. Van den Bos, quoted by Spencer Jones (1931) doubts whether the observed nebulous knots are analogous to expanding nebular discs shown by other novae.
2. M. W. Mayall (1949) places near a globular cluster, identified from its position as NGC 6553. Modulus of cluster taken from Lohmann (1952) as 16.8.
3. In Messier 80 = NGC 6093. Modulus of cluster taken from Lohmann (1952) as 16.05.

APPENDIX 2

THE "PRE-TYCHONIC" NOVAE (LUNDMARK, 1921, 1932)

Date	*l*	*b*	Williams (1871)	Biot (1846)	Appraisal by:			Remarks
					Lundmark (1921)	Zinner (1919)	Humbolt (1844)	
BC								
134 July	319	20	No. 31	p. 61	0	0	*	
77 Oct	103	56	38	61	1			
76 May	101	—36	39		1			
48 May	337	—2	47	61	*			
AD								
64 May 3	267	58		62	2			visible 2½ months
66 Jan 31	..	..		62	1			
70 Dec	184	54		62	2			visible 1.8 months
101 Dec	191	49		62	2			2nd–3rd mag.
107 Sep 13	210	6		63	1			
* 123 Dec	3	23		63	2*		*	Lundmark (1954)
130	..	..			0		*	
* 185 Dec 7	282	0	76	63	3*		*	visible 8 months
222 Nov 4	248	61	88	64	0	0		
290 May	..	..	115		1	0?		
300 Apr	..	..	117		1	0?		Meteor (Williams)
304	148	—21	122	64	1	0?		
* 369 Mar	85:	—2:	132		3*	*	*	visible 6 months: —3$^{\mathrm{m}}$
* 386 Apr	336	—9	134	64	3*	*	*	visible 3 months
389	15	—11			0		*	
* 393 Mar	315	1	136	64	3*	*	*	
561 Oct 8	240	37	164	64	1	0?		
568 Jun 28	309	37		64	1			
684 Sep 12	..	..	187		0			Meteor (Lundmark)
* 827	335:	—30:			3*	*	*	—10?; visible 4 months
829 Nov	184	12	203	65	2	0?		
837 Apr 29	163	11	206, 208	65	1	*		
837 May 3	232	67	207, 209	65	1			
837 Jun 26	333	—8	210	65	1			Comet (Lundmark)
900 Feb.	0	28		p. 66	2			
911 Jun	2	26		66	2			
945	86	2			0	0?	*	
962 Jan 28	356	10		66	2			
*1006	309	—2			3*	*		
1006 Apr 3	..	..		67	1			Comet?
1011 Feb 8	336	—13		67	2		*	
*1054 Jul 4	152	—4		67	2*			Crab Nebula (supernova)

APPENDIX 2, continued

Date	*l*	*b*	Williams (1871)	Biot (1846)	Appraisal by:			Remarks
					Lundmark (1921)	Zinner (1919)	Humbolt (1844)	
1070 Dec 25	122	—30		67	1			
1138 Jun	112	—39		68	1			
1139 Jun	302	53		68	1			
*1203 Jul 28	315	1		68	3*		*	Bright as Saturn
*1230 Dec 15	14	16		45	2	*	*	General amnesty in Japan
1264	86	2			1?	0?	*	
1388 Mar 29	47	28	348		1	0?		
1430 Sep 9	17	13	349		2	possible		visible 1 month
1431 Jan 3	173	—2	351		2	possible		visible ½ month; 3rd mag.
1461 Jun 29	357	—13	354	58	2	comet?		visible 1 month
1578 Feb	..	..	366	59	0		*	meteor (Lundmark)
1584 Jul 1	317	19	367	59	1	0?	*	
*1604 Sep 30	319	2	368	59	2*		*	—4; visible 6 months (supernova)
1609	..	..	369	59	0		*	
1612	..	..			0	0		
1618	..	..	371		1			
1621 May 12	..	..	371		1	0?		
1667 Apr 17	155	—3			2			Hevelius; see Table 1
1691 May 6	333	—13			2			6th mag; Baily-Flamsteed 2441
1696 Jan 22	123	13			2			5.5 mag; Baily-Flamsteed 756
1793 Jul 10	345	—19			2			Lal 36910 8th mag
1824 Jun 28	328	23			2			Bessel zones 253 9th mag.
1828 Aug 18	24	16			2			Bessel zones 433 9th mag.

The above list contains dates and *approximate* positions for possible novae before 1572, and a few later ones. The appraisals of Lundmark, Zinner and von Humboldt are indicated: zeros denote rejection, asterisks acceptance; Lundmark (1921) also indicated grades of acceptability from 3 to 0. An asterisk before the date indicates that a nova can probably be assumed. For a rediscussion of the Oriental data, see Hsi Tze-tsung (1955).

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CHAPTER 2

DISTRIBUTION OF GALACTIC NOVAE

The absolute magnitudes derived in Chapter 1 provide a basis for study of the distribution of novae within our galaxy. Before the space coordinates can be calculated, the magnitudes must be corrected for interstellar absorption, and for novae this can only be done approximately. The problem of correcting apparent distributions of variable stars has been discussed by the writer (1954). For novae the difficulty is maximal: they are bright and therefore very distant; color excesses are inapplicable because the normal colors are unknown; and many apparent maximal magnitudes require uncertain extrapolations to true maximum. Therefore the deduced distances are necessarily uncertain, and must be confined to the novae with light curves well enough observed for their absolute magnitudes to be derived.

Table 2.1 summarizes the distances deduced for eighty novae obtained on the following assumptions: that the extrapolated magnitude at maximum (Table 1.1) can be converted to modulus $(m - M)$ by means of the relationship between rate of decline and absolute magnitude; and that the correction for obscuration is $0^m.85$/kpc within a layer ± 500 pc from the galactic plane and zero outside it. The factor $0^m.85$/kpc is admittedly maximal; it was deduced by Joy (1939) from the motions of galactic Cepheids, but as these stars are more luminous and accordingly more distant than was supposed in 1939, the average absorption per kiloparsec should be smaller, perhaps more nearly $0^m.7$. The distances of Table 2.1 are therefore minimal.

A second column of distances in the table gives the values deduced by McLaughlin (1945), who used somewhat different maximal magnitudes and employed a variety of corrections for obscuration in different galactic longitudes. The two last columns are based on the writer's estimates of distance; however, the overall picture would not be greatly altered by the use of McLaughlin's data.

Fig. 2.1 shows the apparent distribution of all the novae of Table 2.1, and of the acceptable entries in Appendix 2 to Chapter 1.

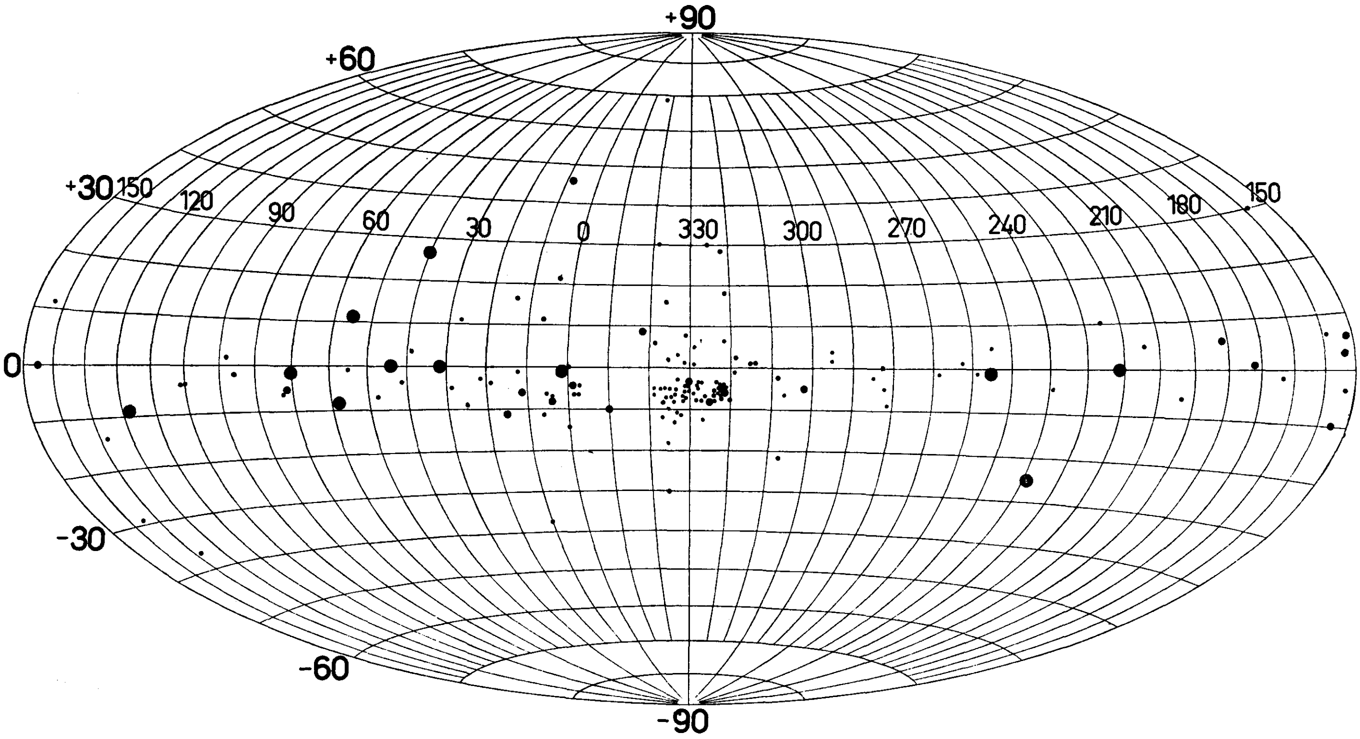

Fig. 2.1. Apparent galactic distribution of novae. Large, medium and small dots denote maxima brighter than third magnitude, third to sixth magnitude, and fainter than sixth magnitude, respectively.

TABLE 2.1

Distribution of Well-observed Novae

Star	*l*	*b*	Apparent Modulus *m*	Distance CPG	(kps) McL	*r* sin *b* kps	*r* cos *b* kps
DO Aql	0	—13	14.5	3.1	4.15	—0.70	3.0
EL Aql	358	—4	13.75	2.3	1.73	—0.16	2.3
V 356 Aql	5	—6	13.0	1.9	1.56	—0.19	1.9
V 368 Aql	11	—6	14.4	2.7	2.00	—0.38	2.7
V 500 Aql	15	—11	14.3	2.7	2.6	—0.49	2.5
V 528 Aql	4	—7	15.1	3.1	. .	—0.38	3.1
V 603 Aql	1	—1	7.25	0.2	0.22	—0.01	0.2
V 604 Aql	358	—6	16.45	4.0	3.45	—0.41	4.0
V 606 Aql	4	—8	11.45	1.2	1.90	—0.17	1.2
V 841 Aql	12	—1	17.3:	4.6	. .	—0.08	4.6
OY Ara	302	—5	11.6	1.3	2.00	—0.11	1.3
T Aur	145	0	10.4	0.8	0.50	0.00	0.8
RS Car	259	—1	13.3	2.1	1.80	—0.04	2.1
η Car	255	—1	5.1	0.2	. .	0.00	0.2
MT Cen	262	+1	16.5	4.1	3.45	+0.07	4.1
X Cir	282	—5	12.95	1.9	1.35	—0.16	1.9
AR Cir	285	—2	11.55	4.1	2.90	—0.14	4.1
T CrB	9	+47	10.2	0.8	. .	+0.56	0.6
Q Cyg	58	—8	11.3	1.2	1.09	—0.17	1.2
V 450 Cyg	47	—7	14.2	2.5	2.00	—0.30	2.5
V 476 Cyg	55	+12	10.3	0.8	0.78	+0.17	0.8
DM Gem	153	+13	13.3	2.1	1.65	+0.47	2.0
DN Gem	152	+16	11.2	1.1	1.05	+0.31	1.0
DQ Her	40	+26	7.65	0.3	0.21	+0.13	0.3
CP Lac	70	—1	10.4	0.8	0.73	—0.02	0.8
DI Lac	71	—5	11.9	1.4	1.51	—0.12	1.4
DK Lac	72	—6	13.35	2.1	. .	—0.21	2.1
HR Lyr	27	+11	13.25	2.1	2.40	+0.40	2.0
BT Mon	182	+1	10.8:	1.0	1.20	+0.02	1.0
GI Mon	191	+6	13.7	2.3	2.06	+0.24	2.3
KT Mon	173	—2	17.5	4.7	. .	—0.17	4.7
IL Nor	295	+4	14.2	2.5	1.50	+0.17	2.5
IM Nor	295	+12	14.8	2.9	2.66	+0.10	2.9
RS Oph	348	+9	12.6	1.7	. .	+0.26	1.7
V 794 Oph	332	+3	18.7	5.6	4.5	+0.32	5.6
V 840 Oph	321	+7	13.8	2.4	1.91	+0.30	2.4
V 841 Oph	336	+16	10.8:	1.0:	0.86	+0.28:	1.0:
V 849 Oph	7	+12	13.25	2.0	2.28	+0.42	1.9
FU Ori	165	+9	15.3	3.3	. .	+0.52	3.3
GR Ori	169	—18	19.7	44.	39.5	—13.6	41.7

TABLE 2.1, continued

Star	*l*	*b*	Apparent Modulus *m*	Distance CPG	(kps) McL	*r* sin *b* kps	*r* cos *b* kps
GK Per	119	—9	8.5	0.4	0.38	—0.06	0.4
RR Pic	239	—25	7.4	0.2	0.19	—0.08	0.2
CP Pup	221	0	8.5	0.4	0.42	0.00	0.4
DY Pup	214	+5	13.05	2.0	2.18	+0.17	2.0
T Pyx	225	+10	13.0	1.9	. .	+0.32	1.9
WZ Sge	25	—9	14.3	2.7	. .	—0.42	2.7
AT Sgr	332	—4	19.0	5.8	4.55	—0.41	5.8
BS Sgr	332	—8	15.1	3.1	2.00	—0.36	3.1
FL Sgr	324	—7	16.55	4.1	5.50	—0.50	4.1
FM Sgr	336	—5	15.75	3.6	4.00	—0.31	3.6
GR Sgr	335	—7	15.1	3.1	3.80	—0.38	3.1
HS Sgr	339	—5	15.8	3.6	4.80	—0.31	3.6
KY Sgr	332	—3	15.55	3.4	3.60	—0.18	3.4
LQ Sgr	334	—9	17.7:	9.2	11.4	—1.43	9.1
V 363 Sgr	335	—18	15.2	6.2	8.30	—1.93	5.9
V 441 Sgr	335	—7	15.4	3.3	3.66	—0.40	3.3
V 522 Sgr	336	—12	21.2:	40.	66.	—8.30	39.
V 630 Sgr	325	—8	12.85	1.8	1.8	—0.25	1.8
V 726 Sgr	333	—7	18.75	5.8	7.30	—0.71	5.8
V 732 Sgr	330	—3	12.7	1.8	1.20	—0.09	1.8
V 737 Sgr	300	—5	16.2	3.8	3.62	—0.33	3.8
V 787 Sgr	328	—4	16.7	4.2	2.89	—0.30	4.2
V 909 Sgr	326	—12	15.15	3.2	3.78	—0.67	3.1
V 927 Sgr	326	—7	15.6	3.4	. .	—0.42	3.4
V 939 Sgr	335	—10	20.0	32.	20.7	—5.55	32.
V 949 Sgr	332	—11	16.8	8.0	. .	—2.39	7.8
V 999 Sgr	327	—3	13.95	2.4	1.82	—0.13	2.4
V 1012 Sgr	327	—7	17.0	4.4	4.60	—0.53	4.4
V 1014 Sgr	331	—5	16.55	4.1	3.84	—0.35	4.1
V 1015 Sgr	327	—8	14.2	2.6	3.33	—0.36	2.6
V 1016 Sgr	335	—6	15.15	3.2	3.00	—0.34	3.2
V 1017 Sgr	332	—11	13.6	2.3	. .	—0.12	2.3
V 1059 Sgr	350	—10	10.25	0.8	1.37	—0.14	0.8
T Sco	321	+19	15.3	7.0	7.20	+2.16	6.6
U Sco	326	+20	17.2	13.6	. .	+4.65	12.8
KP Sco	322	—5	17.55	4.8	5.85	—0.42	4.8
V 382 Sco	323	—6	17.7	4.9	6.30	—0.51	4.9
V 384 Sco	324	—8	15.8	3.6	36.9	—0.50	3.5
V 696 Sco	319	—1	14.9	3.0	. .	—0.06	3.0
V 697 Sco	321	—7	16.2	3.8	. .	—0.46	3.8
V 707 Sco	321	—6	16.2	3.8	7.20	—0.40	3.8

TABLE 2.1, continued

Star	*l*	*b*	Apparent Modulus *m*	Distance CPG	(kps) McL	*r* sin *b* kps	*r* cos *b* kps
V 711 Sco	324	—6	16.7	4.2	4.96	—0.44	4.2
V 719 Sco	323	—4	17.6	4.8	..	—0.34	4.8
V 720 Sco	322	—5	15.35	3.3	..	—0.29	3.3
V 723 Sco	322	—5	17.3	4.6	..	—0.53	4.6
EU Sct	357	—4	16.35	4.0	..	—0.28	4.0
FS Sct	357	—6	18.05	5.1	..	—0.53	5.1
X Ser	339	+30	14.8	6.8	6.00	+3.40	5.9
RT Ser	322	+29	14.9	7.1	3.30	+3.44	6.2
CT Ser	342	+9	13.0:	1.9:	..	+0.29:	1.9:
XX Tau	155	—10	13.05	2.0	2.38	—0.35	2.0
RR Tel	309	—33	12.65	1.7	..	—0.90	1.4
CN Vel	255	+5	16.2	3.8	3.63	+0.33	3.8
CQ Vel	239	+4	15.55	3.4	..	+0.23	3.4
CK Vul	31	+0	9.6	0.6	0.38	+0.00	0.6

The apparent distribution of the novae has been discussed elsewhere by the writer (1954, p. 84). It shows a notable concentration in galactic longitude: 63% of known novae lie in the quadrant that contains the galactic center, 44% between galactic longitudes 320° and 340°.

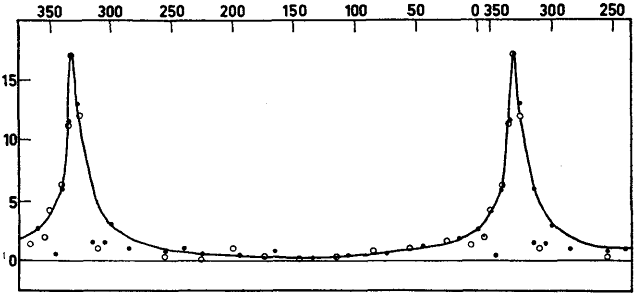

Fig. 2.2. Comparison of distribution of novae (dots) and planetary nebulae in galactic longitude. Ordinate and abscissa are number of objects and galactic longitude, respectively. See text for discussion.

The recorded novae, between galactic latitudes +10° and —10°, expressed as the number per hundred square degrees, are shown in

Fig. 2.2. The distribution is very similar to that illustrated by Minkowski (1950) for the planetary nebulae. The numbers of planetaries per hundred square degrees, read from Minkowski's diagrams and divided by 3, are inserted in the figure, as well as his curve, which "represents roughly the densities to be expected in the absence of obscuration", the ordinates also divided by 3. The correspondence is very close, except that at galactic longitude 345° the density of novae is below the density of planetaries, but even for the planetaries the density at this longitude is cut down by obscuration. The novae do not show the extremely sharp peak at 327° that is shown by the planetaries.

The clear inference from the comparison is that the galactic distribution is similar for the two types of object. If Minkowski's conclusion from the distribution of the planetary nebulae, that they belong to Population II, is valid, a similar conclusion for the novae is equally so. The support given to this identification by the large velocity dispersion of planetary nebulae is lacking for the novae, because of the difficulty of determining their true radial velocities, but there are evidences that some novae, at least, are high-velocity objects.

It would be premature to go further, and conclude that novae and planetary nebulae belong to the same astrophysical species. Minkowski (1948) has pointed out that "although the ejection of a planetary nebula and the outburst of a nova are distinctly different phenomena, they belong, nevertheless, in the same class of events... But... no direct relationship seems to exist".

The concentration of novae toward the longitude of the galactic center, though high, does not match the high peak shown by Minkowski's curve at galactic longitude 327°. The proportion of 3 : 1 for planetaries to novae per hundred square degrees would lead us to expect about seventeen novae per hundred square degrees at this longitude, whereas the maximum observed number is only twelve. We must therefore examine the relative completeness of the nova survey in this direction.

In his study of the luminosities of novae, McLaughlin (1942) used sixteen well-observed novae in the direction of the galactic center with average apparent magnitude 8.6 at maximum. He assumed that they are concentrated in the same volume of space as the numerous RR Lyrae stars, of average mean apparent magnitude 14.8, in the same direction, and thus arrived at an absolute magnitude —6.2 for the novae. It is now possible to apply this method more critically. The true clustering of RR Lyrae stars about the galactic center occurs at a much fainter apparent magnitude than McLaughlin supposed; the maximum frequency of RR Lyrae stars is placed by Baade (1950) at apparent magnitude 17.5. Moreover, McLaughlin eliminated "foreground objects" in a rather arbritrary manner, and thus depressed the mean maximal magnitude of the novae. From Table 2.1 we select the novae that lie between 317° and 327° galactic longitude, and in galactic latitude ±10°. Their distribution in apparent modulus and corrected *r* cos *b* is shown in Table 2.2.

TABLE 2.2

NOVAE WITHIN 10 DEGREES OF GALACTIC CENTER

Apparent Modulus *m* *m*	No. of Novae	Corrected *r* cos *b* kps	No. of Novae
12.0 to 12.95	2	1.0 to 1.9	2
13.0 to 13.95	1	2.0 to 2.9	2
14.0 to 14.95	2	3.0 to 3.9	12
15.0 to 15.95	9	4.0 to 4.9	9
16.0 to 16.95	6	5.0 to 5.9	2
17.0 to 17.95	6	6.0 to 6.9	0
18.0 to 18.95	1	7.0 to 7.9	0
19.0 to 19.95	1	8.0 to 8.9	0
20.0 to 20.95	1	9.0 to 9.9	1
Total	29	>10.0	29

The median apparent modulus for the material of Table 2.2 is 16.1, and the median corrected distance is 4.1 kiloparsecs. Both these values fall far short of those associated with the galactic center, and we may therefore conclude that the sample of 29 relatively well-observed novae is not centered on the nucleus of our system.

The selection of relatively well-observed novae evidently excludes some distant ones. Table 2.3 summarizes the maximal magnitudes of *all* accepted novae within galactic longitudes 317° to 337° and galactic latitudes ±10°. The material is not uniform: extrapolated maximal magnitudes, when determined, are taken from Table 1.1; otherwise, observed maximum is used; the deduced median must therefore be somewhat too faint. We obtain a value of $9^m.5$ for the median apparent magnitude at maximum from the 52 novae.

TABLE 2.3

APPARENT MAXIMAL MAGNITUDE, NOVAE WITHIN 10 DEGREES OF GALACTIC CENTER

Apparent Maximal Magnitude	Number of Novae	Apparent Maximal Magnitude	Number of Novae
4.0 to 4.9	1	10.0 to 10.9	8
6.0 to 6.9	4	11.0 to 11.9	5
7.0 to 7.9	6	12.0 to 12.9	2
8.0 to 8.9	9	13.0 to 13.9	1
9.0 to 9.9	15	14.0 to 14.9	1

If we were to assume that this group of novae is centered on the galactic nucleus, and therefore has an apparent modulus 17.5, we should deduce an average absolute maximal magnitude of —8.0; the true value should, for the reason mentioned above, be a few tenths of a magnitude brighter. In other words, if these 52 novae are centered on the galactic nucleus, they have *on the average* the luminosities of fast novae. However, they are by no means all fast novae. The sixteen within the adopted area that are well enough observed to be entered in Table 1.6 have an average absolute maximal magnitude —7.25, about a magnitude fainter than the value just deduced. Thus, either we have underestimated the luminosities, or the distribution of luminosities is not the same in the sample of sixteen as in the sample of 52, or we are not dealing with a volume centered on the galactic nucleus. There is little doubt that the third alternative is the correct one. The deficiency of novae per hundred square degrees, as compared with the planetary nebulae, points in the same direction—our nova survey is incomplete in depth. The use of the group of novae observed in the direction of the galactic center for the determination of absolute maximal magnitudes is therefore invalid.

A systematic search for novae fainter than the tenth magnitude at maximum in the immediate neighborhood of the galactic center would be most profitable; the recent discoveries by Haro of a number of such novae are an example of what may be expected. The rather exiguous material at present available suggests that slow novae may actually be relatively commoner toward the galactic nucleus, and very fast novae relatively commoner farther out. This may be one of the reasons for the general, but erroneous, notion that fast novae are the rule, slow novae the exception: the latter tend to occur at greater distances from us. If this is so, the maximum frequency toward the galactic center might lie at the tenth or eleventh apparent magnitude. It is noteworthy that the material obtained by Arp (1956) in Messier 31 includes a greater proportion of relatively slow novae than the material contained in Table 1.6. The solar neighborhood, on which our galactic sample is centered, lies toward the periphery of our galaxy, relatively further from the nucleus than the district of Messier 31 surveyed by Arp. The extremely slow RT Serpentis stars would not have been detected in a survey such as Arp's, which extended over only a few years.

The RT Serpentis stars seem to be of particularly low absolute maximal magnitude. Seven possible RT Serpentis novae are given in Table 2.1: DO Aql, SU Ari, FU Ori, BS Sgr, V 939 Sgr, V 941 Sgr, and RT Ser. The four last lie in the direction of the galactic center; DO Aql has been thought by Vorontsov-Velyaminov (1940) to be very like RR Pic, and is certainly not an RT Serpentis star; SU Ari is of practically unknown properties; and FU Ori is regarded by Wellmann (1954) as not a nova at all. Perhaps this extremely slow type of nova is characteristic of the galactic center.

The acceptable RT Serpentis stars comprise about 3% of known novae, but even this small number is too large to make the RT Serpentis stars a plausible source for planetary nebulae. Whipple (1938) calculated a mean age of 15,000 years for twenty-four planetary nebulae, from the radial velocities of Campbell and Moore (1918) and the distances deduced by Berman (1937). The average life should be twice this interval, or 30,000 years, a figure also given by Minkowski (1948). Velocities of expansion determined by Wilson (1950) are larger, on the average, by a factor of 1.5, which would point to a smaller mean age, and a lifetime nearer to 20,000 years. If we make the rough assumption that there are 500 planetary nebulae in our galaxy, a mean life of 20,000 years requires the birth of one planetary every forty years. The difference from Whipple's estimate of 200 years results from the larger expansion velocities of Wilson and the greater number of planetaries now known. Ordinary novae are more frequent than this by several orders of magnitude; even RT Serpentis stars probably appear at least at ten times this rate within a comparable volume of space. Therefore, a nova-like source for planetary nebulae would be even rarer than the RT Serpentis stars as now defined.

Fig. 2.3 shows the distribution of the well-observed novae projected on the galactic plane (r cos b). The three stars GR Ori, V 522 Sgr and V 939 Sgr fall outside the figure, and the calculated values of r cos b place all three outside the probable limits of our galaxy. McLaughlin's list (1945) assigns equally great distances to SV Ari (54.5 kpc), V 359 Cen (115 kpc), V 949 Sgr (240 kpc) and V 384 Sco (36.6 pkc). We have regarded SV Ari, V 359 Cen and V 949 Sgr as inadequately observed; our smaller distance for V 384 Sco is a result of assigning to it an absolute magnitude like that of DQ Her.

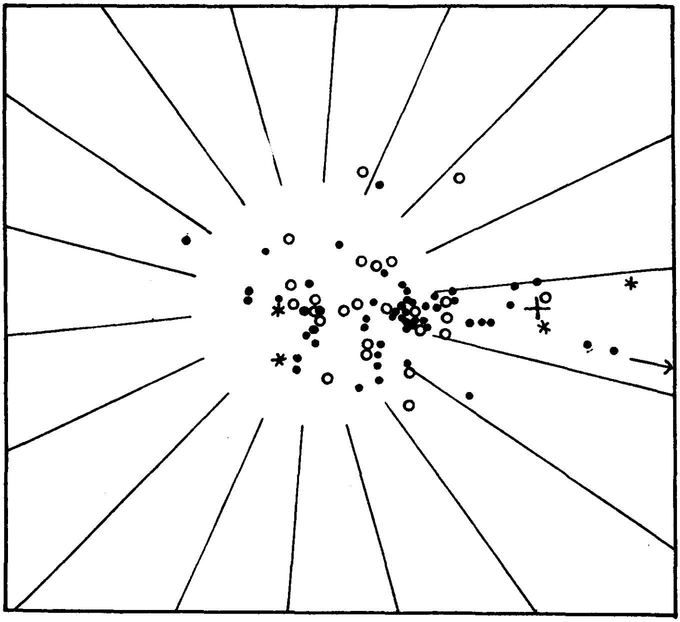

Fig. 2.3. Projection of position of novae on the galactic plane. Dots, circles and stars denote fast, slow and very slow novae. Galactic longitudes are shown at the margin. The cross denotes the position of the galactic center.

McLaughlin mentions three possible causes for the great apparent distances of a few novae: the obscuration is in excess of that adopted; the star is a "dwarf" nova; or the star is an extragalactic supernova.

For V 522 Sgr and V 939 Sgr, which lie very close to the edge of the "zone of avoidance", obscuration could be responsible, as McLaughlin recognized. The most difficult case is GR Ori: the very exiguous observations do not suggest the light curve of a supernova. More probably it is a true "dwarf nova"—a U Geminorum star of very long cycle.

The distribution of $r \sin b$ is summarized in Table 2.4.

TABLE 2.4

DISTRIBUTION OF r SIN b FOR WELL-OBSERVED NOVAE

$r \sin b$	Fast Novae		Slow Novae		RT Ser Stars		All Novae	
	No.	%	No.	%	No.	%	No.	%
.00 to .09	7	14	4	15	..	..	11	14
.10 to .19	5	10	9	35	..	..	14	17
.20 to .29	8	16	4	15	..	..	12	15
.30 to .39	11	21	3	11	1	25	15	18
.40 to .49	9	17	2	8	..	..	11	14
.50 to .59	1	2	1	4	..	..	2	2
.60 to .69	3	6	..	..	..	..	3	4
.70 to .79	1	2	..	..	..	..	1	1
.80 to .89	..	..	..	..	..	..	..	..
.90 to .99	..	..	1	4	..	..	1	1
1.00 and over	6	12	2	8	3	75	11	14

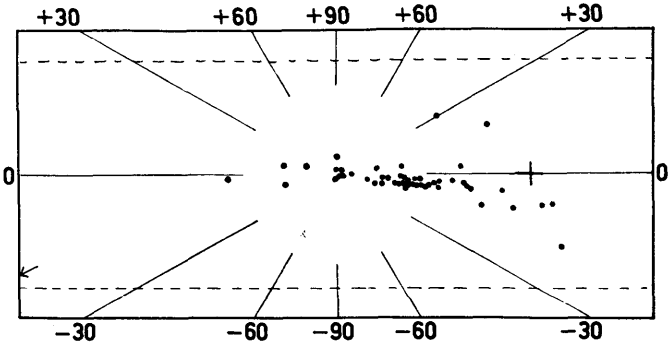

Fig. 2.4. Vertical distribution of novae in the cross-section of the galaxy from the galactic center (cross) to anticenter. The dotted lines are separated by 5 kiloparsecs. Galactic latitudes are indicated at the margin.

87% of all novae lie within 500 pc of the galactic plane: 78% of fast novae, 84% of slow novae, and only 25% of RT Serpentis stars. The distribution of $r \sin b$ toward galactic center and anticenter is shown in Fig. 2.4. The novae are distributed in a thin layer toward the anticenter; toward the center the layer is thicker, as we should expect it to be from the general density-profile of Population II in our galaxy. The distribution is in fact that of an "intermediate" subsystem.

Four novae in our table are over 5 kpc from the plane: GR Ori (—13.6 kpc), V 522 Sgr (—8.30 kpc), V 939 Sgr (—5.55 kpc) and RT Ser (+5.81 kpc). The three last are probably more obscured than we have supposed; GR Ori stands out as before, and our previous remarks apply with added force.

McLaughlin's table (1945) contains several other novae with Z coordinate ($r \sin b$) greater than 5 kpc: VY Aqr, SV Ari, V 359 Cen, V 949 Sgr, and U Sco. We have regarded the four first as inadequately observed, and shall discuss U Sco with the recurrent novae.

Recent discussion by Kopylov (1955a, 1955b) of the distribution of novae and related objects within our galaxy, necessarily based on the same material as the data of the present chapter, is summarized in Table 2.5; R, z and β denote respectively horizontal distance from the galactic center, vertical distance from the galactic plane, and degree of galactic concentration.

TABLE 2.5

HORIZONTAL AND VERTICAL DISTRIBUTION OF NOVAE AND RELATED OBJECTS

Subsystem	$\partial \log D/\partial R$	$\partial \log D/\partial z$	β ps
Supernovae	—0.15	—5.2	83
Nuclei of Planetaries	—0.21	—2.20	197
Typical Novae	—0.22	—2.39	182
White Dwarfs	—0.23	—2.7	160
Recurrent Novae	—0.25	—0.9	480
Nova-like U Geminorum Stars	—0.27	(—0.17)	2600

His conclusion that the novae belong to an intermediate subsystem is certainly justified; his table verifies the close association in distribution between novae and the nuclei of planetaries, and strongly suggest a similar association with white dwarfs. The material for supernovae and recurrent novae is too slender for accurate conclusions, but there seems little doubt that the trends suggested by the table are real: the supernovae are probably associated with flat subsystems, and the recurrent novae have, on the average, higher values of z than the normal novae. The trend in the figures from novae through recurrent novae toward U Geminorum stars is also highly plausible, but the intrinsic faintness of the latter makes quantitative conclusions very uncertain, as Kopylov himself indicates.

Further discussion of the distribution of novae within our galaxy would be unfruitful. The corrections for absorption are too critical and too uncertain, and inclusion of the less well-observed novae would merely increase the material without improving it, because both their corrected maximal magnitudes and their absolute magnitudes are uncertain.

The only galaxy besides our own in which there are enough published novae for a study of distribution is Messier 31. The novae found by Hubble (1929) in this system are concentrated toward its center, as illustrated by the writer (1954, p. 111).

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CHAPTER 3

THE SPECTRA OF NOVAE

1. The Geometry of the Nova Spectrum

The spectral development of all novae is complex, and the observations are very difficult to interpret. At maximum a nova shows an absorption spectrum, which may or may not reveal weak bright lines. The radial velocity deduced from the wavelengths of the absorption lines is usually negative (see, however, RT Serpentis). As the star declines in brightness after maximum, bright lines appear, or increase in intensity relative to the continuous spectrum. The radial velocity deduced from the absorption spectrum may change, and after a short time there is usually evidence of several absorption spectra at once, each associated with a different radial velocity. Many absorption spectra have been recorded for some novae, such as RR Pictoris, DQ Herculis, and V 476 Cygni, and all adequately observed novae have several. The associated radial velocities may remain constant for an interval, or may change systematically or erratically.

The observed brightness of a nova after maximum is the sum of the integrated brightness of the continuous spectrum (in the region of wavelength covered) and of the bright lines. The latter may be supposed to originate in an envelope that surrounds the star, part of the envelope being occulted by the volume occupied by the source of the continuous spectrum. Occasionally, as with DQ Her, strong bright lines occur *before* maximum as well as after, but even in this case, they became weak, absolutely as well as relative to the continuous spectrum, at the time of maximum (see Fig. 4.10).

The continuous spectrum usually decreases in total luminosity more rapidly than does the source of the bright lines, which accordingly appear to *increase* in intensity as judged by their contrast with the background. In fact the bright lines, too, usually decrease systematically in absolute intensity, often with large fluctuations.

A time is reached when the continuum can no longer be recorded, and absorption spectra are therefore no longer detectable. Records of absorption velocities accordingly cease at this point. A faint continuous spectrum is always present, since in normal novae the central star always survives. The bright-line spectrum continues to be detectable for an interval that differs for various novae. After some years or decades the bright-line spectrum itself becomes very weak, or more rarely disappears, and if at the final stage the star is bright enough to be observed spectroscopically, a continuous spectrum suggesting high temperature, usually with weak bright lines, or absorption lines, or both, can be detected.

The conversion of measured wavelengths in the absorption spectrum into radial velocities depends on correct identification of the lines concerned and accurate knowledge of their normal wavelengths. As Wright (1921, p. 32) pointed out long ago "the method of analysis has obvious limitations and calls for the exercise of the observer's judgment." Although often *expressed* as radial velocities, the quantities actually used are values of $d\lambda/\lambda$.

That the observed $d\lambda/\lambda$ is the result of a Doppler shift is generally accepted. But that the velocity of expansion of the material that produces the absorption lines is correctly given by the measured wavelengths, though usually assumed, is less certain. An obvious source of falsification is to be found in the effect of a strong neighboring bright line (usually toward the red); the effect may be partly photographic, but is also a product of the interaction of the absorption and emission profiles.

An example was pointed out by Wright (1921): the values of $d\lambda/\lambda$ for the Balmer lines of DN Gem on a given date are not the same, but decrease arithmetically from Hβ to H 10. Similar effects may be found in the data published for DQ Her, and are in fact the rule rather than the exception. Nor is the phenomenon confined to novae; it is shown by P Cygni and stars of similar spectral character, which are generally thought to possess expanding envelopes. Typical data are shown in Table 3.1.

Another example of the same phenomenon—the interaction of an absorption profile with an emission line to the red—is to be found in the spurious "red-shift" displayed by spectroscopic binaries that consist of a W star and an absorption B or O star. The spectrophotometric analysis by Keeping (1947) of the binary V 444 Cygni has shown that correct velocities are obtained, and the red-shift removed, by a correct allowance for the mutual effect of the two lines.

An examination of Table 3.1 shows that the largest negative velocities seem to be associated with the earliest members of the Balmer series, which have the strongest bright lines. Evidently the underlying emission has caused a spurious violet shift. Beals (1951) has published equivalent widths for a large number of bright lines in P Cygni, and the violet shift is found to be closely correlated with the equivalent width (relative to the continuum) of the associated bright line. For absorption lines with weak bright components, the radial velocity approaches a limiting value of about —125 km/sec, which is presumably the "true" radial velocity of the atoms concerned. Radial velocities in the spectra of novae are almost always derived from absorption lines that are associated with some emission, and the interpretation of the directly measured velocities is thus rendered more difficult than it would otherwise be.

TABLE 3.1

DEDUCED RADIAL VELOCITIES (KM/SEC) FROM BALMER LINES

Line	DQ Herculis (Stratton, 1936)				DN Geminorum (Wright, 1921)	P Cygni	
						Beals (1951)	Struve and Roach (1939)
Hα	—1984	—1082	..	..	..	—280	..
Hβ	—1179	—747	—549	—477	—1512	—216	—201
Hγ	—1023	—671	—507	—438	—1452	—207	—194
H∂	—746	—640	..	—325:	—1452	—189	—183
Hε	—929	..	..	..	—1425	—144	—146
H 8	—903	..	..	..	—1434	—184	..
H 9	..	..	..	..	—1440	..	—133
H 10	..	..	..	..	—1425	..	—116
H 11	..	..	..	..	..	..	—125
H 12	..	..	..	..	..	..	—119
H 13 to H 22	..	..	..	..	..	..	—128

The problem of measuring the wavelengths involves the form of the whole profile of the measured line, and the manner in which the setting is made in determining the shift. The interpretation of the measured wavelengths goes back to the more subtle question of the manner in which the complex line is formed, the resulting distribution of energy in the emission and absorption lines, and the way in which these combine to form the observed line or lines. Ideally one should follow a procedure like that used by Keeping; but although the systematic errors caused by the complex profiles can thus be eliminated, the correct understanding of the resulting information is still beset by difficulties, both geometrical and physical. The former will be our

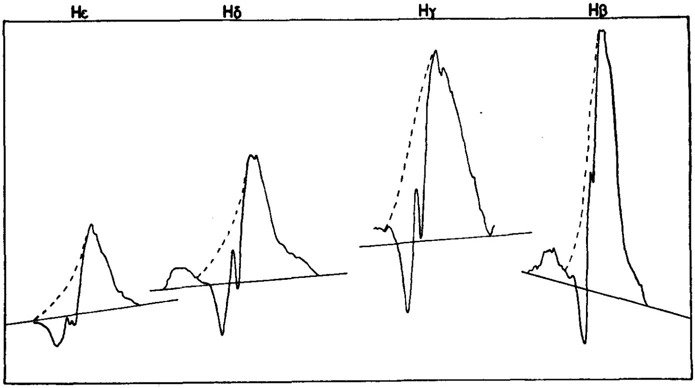

Fig. 3.1. Typical profiles of hydrogen lines: unreduced microphotometric tracing of four Balmer lines of RR Pictoris from a Harvard objective prism plate, X 14792, 1925 September 28, JD 24422. On the same date, the absorption velocities (means) are given as follows by Spencer Jones:

Main absorption: —385.9 km/sec
Weak absorption: —238.9 km/sec
Strong absorption: —685.8 km/sec (red edge),
—1102.6 km/sec (violet edge)

All these features can be traced in the profiles. Note that H. Hε appear separately in the main absorption.

Straight lines represent the probable course of the continuous background. Broken lines indicate approximate reflection of the red side of the bright-line profiles. Note that the main absorption is seen projected on the bright-line profile, and does not reach the continuum for Hβ or Hγ; the weak absorption in no case reaches the continuum. The possible effect of the bright lines in falsifying the absorption velocities may be estimated. The difficulty of measuring the intensities of the absorption lines is manifest; after the curves had been reduced to intensities, the course of the effective continuum for each absorption line would have to be guessed.

concern in the present section, but they cannot properly be understood except together. For example, we can discuss the geometrical interpretation of two simultaneously observed absorption systems with different velocities, but the real problem of how two such systems can in fact coexist is a physical one.

The distribution of intensity within a bright line is governed by the distribution and velocity of the atoms involved. A uniform spherical shell, expanding with constant velocity, and in the absence of absorption and occultation, gives a square, flat-topped profile that is symmetrical about the wavelength associated with the radial velocity of the center of the shell relative to the observer. A central star will occult part of the redward profile. The corresponding absorption line (if the transition can produce one) will appear at the violet edge of the bright-line profile, with width and intensity distribution that depend on the velocity, the angular diameter of the central star, and the depth and density-distribution of the emitting envelope.

That an optically thin spherical shell, expanding uniformly with constant velocity, will produce a flat-topped emission profile was shown by Beals (1929) in connection with the spectra of W stars; see also Rosseland (1930). A narrow bright line in an expanding transparent shell has a profile whose intensity is constant over the range of wavelength corresponding to $v_0 \pm v$, where v_0 is the radial velocity of the center of expansion relative to the observer, and v is the velocity of expansion. The central star is here regarded as of negligible dimensions, and if the expansion velocity is constant, the distribution of velocities precludes reabsorption within the shell.

If the dimensions of the central star are not negligible in comparison to the dimensions of the expanding shell, the cylinder between observer and star produces an absorption line against the continuous spectrum of the star. This line falls at the extreme violet edge of the bright-line profile, and has an overall width that corresponds to a velocity

$$v\left(1 - \frac{R^2 - r^2}{R^2}\right),$$

where r and R are the radii of the stellar photosphere and the shell respectively. It will thus be sharply bounded on the violet edge. If the stellar photosphere were a uniform disc, the intensity produced by an initially narrow absorption line would change uniformly with frequency. However, the disc of a star with an expanding envelope is darkened toward the limb, and the intensity will increase more rapidly from the minimum at the violet edge toward zero absorption at a smaller frequency, as illustrated by Menzel and Payne (1933).

The star occults a similar cylinder on its far side, and the redward edge of the bright profile is cut down. Both the width of the violet absorption line and the distortion of the redward wing of the bright line decrease as r/R decreases.

Hitherto we have spoken in terms of a thin, detached shell. Although it is usual to speak of the spectra of novae in terms of such shells, they certainly do not correspond to the reality. The profiles of absorption lines, though distorted, are not sharply bounded at the violet. Nor do their intensities diminish uniformly with time, as they would do as the radius R of a thin shell increased relative to r. We must regard the sources of emission and absorption lines as thick shells, continually replenished from below, or in other words as continuous envelopes.

An envelope can be considered to be built up of a series of shells. If the outward velocity throughout the envelope is constant and uniform, the bright-line profiles will be similar in form to those produced by a thin shell, except for the occultation effect, which now varies with depth in the shell. Rosseland (1936, p. 294) discusses bright-line

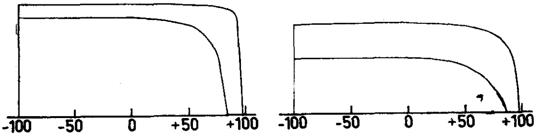

Fig. 3.2. Effect of occultation on bright line profiles. Left, profile calculated from the formula

$$I_v = \text{const.}\ (R^3—a^3/\sin^3\theta),$$

where R is the radius of the expanding envelope, velocity 100 km/sec, and a is the radius of the central star. Above, $R = 10$, $a = 2$; below, $R = 10$, $a = 5$. Right, profile calculated with emissivity proportional to mass density for the same two cases. Ordinates are in arbitrary units; abscissae are velocities in km/sec.

profiles for two cases: uniform emissivity in an expanding envelope, and emissivity proportional to mass-density. The resulting geometrical effects are illustrated in Fig. 3.2.

The absorption profiles, also, will be built up from a series of shells, each with a different value of R. A continuous envelope will produce an absorption line of overall width v, and with intensity distribution and profile that depend on the density distribution in the envelope. Such a line should still, however, be sharply bounded at the violet edge.

Truly flat-topped emission profiles have rarely been observed astrophysically; for novae the profiles tend to be unsymmetrical or saddle-shaped (with a central dip), and to change with time. Beals (1925, 1926) discussed the role played by a dispersion in the velocities of ejection, which can round off the flat tops but cannot produce a central depression. The effects of dispersion of velocities are symmetrical if the stellar radius is negligible compared to that of the envelope, so that sensible occultation effects are excluded.

A more general treatment by Chandrasekhar (1934) considers the forms of the profiles of bright lines produced by accelerated and decelerated expanding envelopes, the emissivity being a function of R, and v another function of R. The profiles associated with acceleration tend to be peaked for the conditions adopted; those from decelerated envelopes approach more nearly the flat-topped form, an obvious result of the adopted law of emissivity, which throws the major part of the intensity into wavelengths corresponding to the higher velocities. Chandrasekhar's profiles show the depression of the redward wing by the shadow cylinder of the star. They represent, in fact, the sum of a number of flat-topped profiles that correspond to a series of concentric shells with different velocities, each one suffering a different depression of the redward profile in accordance with the appropriate value of r/R. This is brought out by the slightly different treatment of Bappu and Menzel (1954), who illustrate the profile built up by a decelerated envelope with a velocity range from v_2 to v_1, and obtain a steep-sided profile with constant intensity over a range of wavelength that corresponds to $\pm v_1$. The slope of the sides depends on the adopted relation between the emissivity and R.

It seems unlikely that the atoms in the envelopes of novae are either accelerated or decelerated in the interval that immediately follows their ejection. The outburst of a nova may be regarded, to a first approximation, as made up of a series of successive ejections with different speeds. For most novae the velocities associated with any one absorption system tend to increase with time, and successive absorption systems tend to display higher and higher velocities. But this inferred increase in the speed of ejection should not be regarded as an acceleration. The currently ejected material, which must be the major contributor to an observed absorption system, is traveling outward faster than the previously ejected atoms. This produces the effect of a radial *deceleration,* since the atoms first sent out, and therefore in the outer part of the envelope, have the lowest speeds.

An optically thin shell or envelope that expands with uniform velocity cannot produce reabsorption within itself. A dispersion in the macroscopic velocities can produce reabsorption; and if the line considered has an appreciable intrinsic width, reabsorption can occur even with constant velocity of expansion. In both cases the sharp violet edge of the absorption line will be rounded off.

Another possible source of reabsorption may occur in the spectra of novae. Rosseland (1936, p. 332) enquires into the possibility of reabsorption in uniformly accelerated and decelerated envelopes, and shows that for geometrical reasons it cannot occur in the former, but can in the latter. Although we have not considered that actual deceleration is possible in a nova envelope, the increase in velocity of a given absorption system, and from one absorption system to the next, can produce an effect like that of a deceleration; in fact the two cases are indistinguishable for a single observation. Reabsorption can occur under these circumstances. We shall consider possible observations of such an effect later.

The processes mentioned hitherto have involved spherically symmetrical expansion with uniform velocity. They give scope for a large variety of bright-line profiles and absorption features on purely geometrical grounds. The picture is manifestly incomplete until the problem is treated in physical terms as well. A beginning has been made in this direction by Rottenberg (1952), who was concerned with reproducing the profiles of P Cygni stars, which have much in common with those of novae. His treatment is still geometrically simple, and he uses the model of a shell that is thin geometrically and thick optically; in this way he produces positively-displaced absorption lines, formed by the front of the shell on the background of the rear. This question will be further considered later. The profiles predicted by Rottenberg include saddle-shaped specimens, but the central dip is produced by absorption. The central depressions in the profiles of the bright lines of novae cannot be an absorption phenomenon, because they are shown (often most conspicuously of all) by the forbidden lines.

If the bright-line profiles of novae are to be interpreted in terms of Doppler effect, the observations suggest that we explore the possibility that there are departures from spherical symmetry in the emissivity. Such departures might stem from differences of mass-density in different parts of the envelope, as pictured by Menzel and Payne (1933), or from directional differences of excitation, as suggested by Grotrian (1937). Both these causes will in fact be found to be at work, but their discussion involves physical as well as geometrical considerations, and will be taken up later. Another alternative, differential mass-motion, while perhaps operative in W stars, probably plays a minor role in novae; the ejection velocities are so large that the return of any considerable part of the ejecta to the star seems improbable, and the expanding nebulae observed around several novae also rule it out as a major factor.

A rotating equatorial ring of emitting atoms was shown by Struve (1931) to produce an extreme saddle-shaped form of bright-line profile. In this case the wavelengths of the outer edges measure the component of rotational velocity in the line of sight. The exact form of the profile depends on the thickness of the ring, its extent in latitude, its distance from the star, and (because of occultation effect, which in this case cuts down the *central* portion of the profile) the radius of the star. Conceived in connection with the very different problem of the spectra of rapidly rotating Be stars, this model offers suggestions for the study of novae. In our case, rotation can play little if any part; material ejected radially at high velocity from the surface of a rotating star would rapidly lose its rotational component by the conservation of angular momentum. But the idea of a *ring* takes us from spherical to axial symmetry, more realistic in making a picture for the novae.

The case of a ring that is both rotating and expanding is discussed by Sobolev (1947), again in connection with Be stars; the resulting bright- and dark-line contours are given for several cases, in all of which, however, the rotational velocity is much greater than that of expansion.

Closer to the actual case for novae are the profiles discussed by Bappu and Menzel (1954) for emissivity concentrated toward the poles and the equator of a decelerated expanding envelope. For emission concentrated toward the poles, the bright-line profile is saddle-shaped for pole-on viewing. The opposite condition is produced for an envelope whose emissivity is concentrated toward the equator (case of an equatorial ring): saddle-shaped profiles are observed from the equatorial aspect, peaked profiles from the polar aspect.

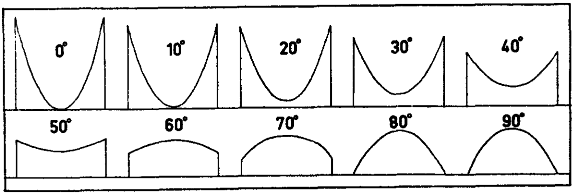

Fig. 3.3. Profiles of a bright line represented by the equation $E^1 l dl = \frac{\pi c r^3 \; c s,^2}{v} \left\{ (3 \cos r \; \theta° — 1) \frac{l^2 c^2}{v^2} + \sin^2 \theta° \right\} dl$ where θ is the angle between the axis and the observer's line of sight, for the indicated values of θ. These are essentially the profiles given by a luminous ring in various orientations, from equatorial to pole-on viewing.

Many novae, perhaps the majority, display saddle-shaped profiles during early decline. If uniform expansion (though not spherically symmetrical) with constant velocity is involved, this observation is compatible with emitting volumes that are like dumbbells viewed endwise or like doughnuts viewed from the side. This schematic picture admits of considerable elaboration, but does not fulfil all the requirements of observation. Actual bright-line profiles (cf. V 603 Aql, CP Pup) tend to display a variable, castellated structure, as thought several saddleshaped profiles with different velocity ranges were superimposed. A representation that fits the facts might involve, for instance, several conical distributions of ejected material, with the apices of the cones directed toward the central star, and their axes coincident. Such an arrangement is shown by Weaver's reconstruction of the envelope of V 603 Aql.

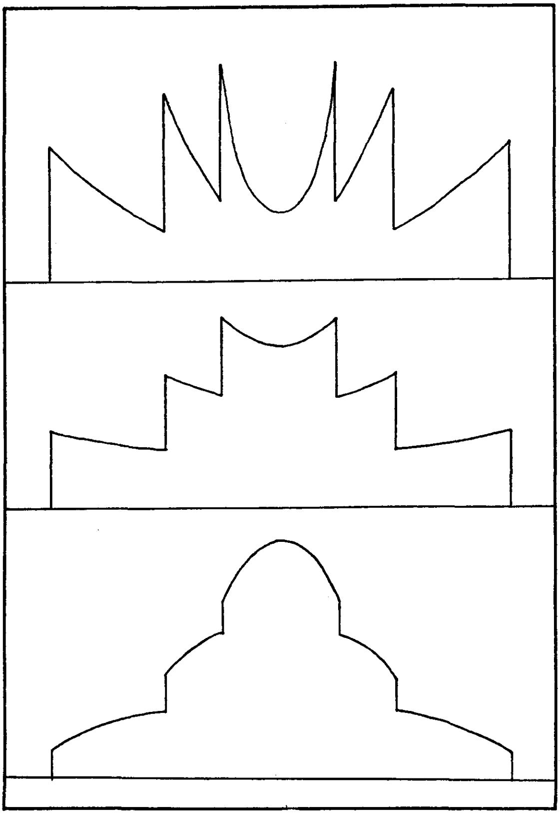

Fig. 3.4. Profiles compounded from three arbitrarily spaced pairs of axially symmetrical rings, viewed respectively at $\theta = 30°$, $50°$ and $70°$ (see Fig. 3.3).

2. Geometrical Reconstruction of a Nova Outburst

The geometry of a nova outburst near maximum may be pictured as follows. A central star becomes greatly distended, and ejects material through a photosphere whose position is defined by the optical depth at which the continuous spectrum is formed. Absorption lines are produced by the atoms that are above this photosphere, atoms that have in most cases passed outward through it recently. The level at which the continuous spectrum is formed, and therefore the size and brightness of the distended star, changes from moment to moment. Grotrian (1937) suggested that the characteristic photospheric level may be defined jointly by the velocity of ejection and the number of atoms ejected per square centimeter per second through the surface (the rate of ejection). Until the time of maximum we may regard the photosphere as having expanded spherically; it is roughly comparable to the photospere of a supergiant star, with which it is observed to have many properties in common. The atoms that have already passed outward through the photosphere surround the nova with an expanding envelope that produces wide bright lines.

Grotrian suggests that the radius r_{p} of the photosphere is defined by the expression:

$$r_{\mathrm{p}} = r_0 \sqrt{n_0/v\, n_{\mathrm{p}}}$$

where r_0 represents roughly the pre-nova radius, n_0 the number of atoms ejected per square centimeter per second *through this surface*, v, the velocity of ejection, and n_{p} the number of atoms corresponding to a characteristic photospheric density. Before maximum, the ratio n_0/v must then increase because the continuous spectrum is observed to brighten; after maximum it must decrease.

A typical nova with a range of twelve magnitudes must, on this assumption, increase its value of n_0/v by a factor of more than a million. As v can hardly decline to this extent, the burden must be borne by an increase in n_0. That v may, nevertheless, decline before maximum is attested by the measured fall in velocity in the pre-maximum spectrum of DQ Her, from about —1000 km/sec on JD 27785 to about —180 km/sec on JD 27790; the ejection velocity must have risen (perhaps gradually) from a small or zero value to a maximum from which it declined (probably fast).

The great width and strength of the bright lines observed in DQ Her on JD 27785 (ten days before maximum, with the star nearly two magnitudes below maximum brightness) present an interesting problem. The data given by Stratton (1936) lead to a difference of —1130 km/sec between the centers of absorption and emission lines of hydrogen; the widths of the bright lines give a velocity of ±750 km/sec. If the true velocity of the material that produces the bright lines is 1130 km/sec, and the width of the bright lines is reduced by occultation, the depth of the envelope that produces them is given by the equation:

$$v_2 = v_1/\left(1 - \frac{r_1^2}{r_2^2}\right)$$

where v_1 is the outward velocity, v_2 the velocity deduced from the widths of the bright lines, r_1 the radius of the "photosphere", r_2 the radius of the envelope. With the given data, the depth of the envelope is about one third of the radius of the photosphere, which at this stage is near 100 solar radii. Thus the expanding material, if the bright lines are produced in the manner suggested, has outrun the expanding "photosphere", and this can only be the case if the main burden of the photosphere has been borne by an increase in n_0. The ratio n_0/v must have increased, and as v can hardly have been very great to start with, yet has risen to 1130 km/sec, it must have risen to a maximum and then declined. The ejection may have been going on for some time, but the rapid brightening dated from the fall in velocity.

We should bear in mind, however, that the disc of an expanding "photosphere" is likely to be greatly darkened toward the limb, and that our crude geometrical allowance for occultation may have to be considerably modified; an expanding photosphere has a larger effective radius in eclipsing than in radiating, and the effect would be to broaden the bright lines more toward the violet than toward the red.

Two possible alternatives for the production of pre-maximum bright lines should be mentioned: differential mass-motion and Zeeman effect. The former is not likely to be important, for reasons already stated. Bruce (1949) has suggested that a Zeeman effect would be in harmony with the observed correlation of the widths of the bright lines with their wavelengths. It would help to account for their great breadth but would not elucidate their occurrence. Electromagnetic effects offer an interesting and unexplored field in the understanding of the nova phenomenon, to which we can do no more than make a reference.

After maximum light, when the radius of the "photosphere" begins to decrease, the velocity v usually increases, and this, coupled with the ultimate decrease in n_0, may be regarded as the cause of the fall in brightness of the continuous spectrum that always takes place sooner or later. For rapid novae the rate of ejection falls and the velocity rises; for slow novae such as DQ Her and RR Pic, both change slowly and the decline in brightness is also slow. For the novae that fluctuate in the post-maximum decline (like DN Gem) or in the transition stage (like V 603 Aql), the changes in the brightness of the continuous spectrum are related to the changes in the rate and velocity of ejection. In all these cases the changes in rate and velocity of ejection do not *follow* the change of brightness, as is sometimes stated; they *cause* them.

The fall in brightness, however, is not simply occasioned by a steady decrease in rate of ejection accompanied by a steady increase in ejection velocity. All adequately observed novae have shown several successive absorption systems, which appear abruptly and often are visible simultaneously. Let us elide, for the moment, the fundamental question as to how several absorption systems can physically coexist. We shall continue to think in terms of spherical symmetry, although the facts show that this simple picture is untenable.

As the spectral development proceeds, we envisage changes in the opacity of the envelope that expose successively deeper layers to observation; the photospheric level falls, the "star" becomes smaller and fainter. The highest layer that provides the appropriate conditions is responsible for the continuous spectrum at any given time. Usually (but not necessarily always) this is the region associated with the most-displaced absorption visible. We should not assume that the various absorption systems originate at the time when they are first seen; they are simply laid bare as the opacity of the overlying layers falls, and their origin is the central star. They must be the sequelae of the original wave.

Many of the observations suggest that there are departures from spherical symmetry; we must envisage axially symmetrical ejection, or localized motions, loosely described as "jets". Some absorption systems persist for a long time with occasional fadeouts, which may be ascribed to temporary increases and decreases in the opacity of the overlying layers, leading to temporary expansions and contractions of the underlying photosphere. The disappearance of a given absorption system may also be ascribed to collision with another system, leading to destruction of the one with less energy, or to coalescence; but in many cases the disappearing system recurs later. Such observations make it seem unlikely that the ejected material is arranged in spherically symmetrical "shells" that can destroy one another. We shall return later to this problem.

Striking illustrations are furnished by V 603 Aql during its transitional fluctuations. At each minimum (marked by a drop in the continuum) the velocity of the "Orion" absorption spectrum increased sharply, and the absorption lines faded and disappeared, i.e., v increased and n_0 increased (in Grotrian's conception). In DN Gem during the post-maximum fluctuations, the principal factor was the reduction of ejection rate at the minima, velocity changing only slightly, i.e., n_0 decreased. For this nova we find a linear correlation between the radius of the photosphere, deduced from the apparent magnitude of the continuum, and the radius calculated from Grotrian's formula with the aid of the observed velocities and equivalent widths (the zero being arbitrary because of our ignorance of r_0, the initial radius).

As the brightness of the nova falls and the spectrum grows in complexity, a new factor affects the absorption lines. Each absorption system usually has a higher velocity than its predecessors, and the velocity of any one absorption system tends to increase with time. Hitherto we have spoken of the absorption spectrum or spectra as formed by the atoms that have just passed through the current photospheric level, which is fixed jointly by the rate and velocity of ejection. That the velocity of the system that currently defines the photosphere might change with time is understandable; but if we think of earlier absorption systems in terms of detached "shells" that have already reached higher levels, changes in their velocities are less easy to visualize. Accelerations in the outer layers can hardly be produced by the selective absorption of radiation, as the changes of velocity involve groups of spectroscopically unrelated lines; and the violent disturbances of the Orion spectrum are not reflected in the velocities of the principal or diffuse enhanced spectra. We must refine the picture by considering that the fall of the photospheric level is caused by a fall in general opacity, but that line-opacity may produce a sort of pseudo-photosphere at higher levels.

Suppose that a high-velocity absorption system has newly appeared; the dark lines are accompanied at their redward edges by bright lines of the appropriate width, wider than those associated with previous systems. Let us confine our thought to the atoms of hydrogen, which contribute to nearly all the observed absorption systems. The absorptions that correspond to the new velocity of ejection now appear at the violet edge of the newly produced bright lines, but in addition the original hydrogen absorption spectrum usually persists for a time. The new bright line acts as a pseudo-continuum for the slower-moving atoms ejected earlier. In many novae the phenomenon recurs several times, and several components of the hydrogen lines may be seen, all but the most recently-ejected being projected against the wide bright lines produced by the current and previous ejections. Other lines, associated with atoms that appear for the first time, and seen against the true continuum, may at first appear without bright components, as the lines of helium did in Nova Pictoris.

The absorption lines of the outer, slower-moving atoms of hydrogen, that absorb the light of the pseudo-continuum produced by the underlying wider bright lines of hydrogen, reproduce some of the conditions for reabsorption by a decelerated envelope. The wavelength absorbed by such an atom is that appropriate to the relative velocity of that atom and the more rapidly moving atoms of the same kind at the lower levels of the envelope. Only in a decelerated envelope (or its equivalent) can the line-of-sight velocity be the same for observable points in the envelope. The observed radial velocity of the outer atom will now not be its true radial velocity relative to the center of expansion. If v_1 is the true velocity of the earlier ejection and $v_2 > v_1$ that of the later ejection, v', the observed radial velocity, is related to v_1 and v_2 by the expression:

$$v'^2 = (v_1^2\, t_1^2 - v_2^2\, t_2^2) \,/\, (t_1^2 - t_2^2) = (r_1^2 - r_2^2) \,/\, (t_1^2 - t_2^2),$$

where t_1, t_2 are the intervals since the ejection of the first and second groups of atoms through the photosphere, and r_1, r_2 the radii of the "shells" in which they are currently to be found. The radius of the photosphere is here neglected; it will be important only if t_2 is very small. The equation has two roots, which correspond to v' respectively greater and less then zero. The negative root corresponds to absorption of the light of the inner, faster "shell" by atoms in the outer; the positive root represents the absorption of the light of the outer, slower shell by atoms of the inner shell in the rear of the star.

The reabsorption in a decelerated shell, discussed by Rosseland (1936, p. 333) differs from the simple case of two discrete velocities, and represents an integration for a range of velocities from v_2 to v_0, the velocity at infinity given by the adopted law of deceleration. The result is what would be expected from the above: "an inner core of the line, the width of which is twice the velocity at infinity, will remain unaffected. Outside this core reabsorption will take place right out to the border of the line." Both the effects of the two discrete velocities, and those of continously decelerated envelopes, must be sought in the spectra of novae. A rather similar case, which leads to the production of lines very little displaced, was discussed by Stratton (1936) for DQ Her.

Observations of positively-displaced absorption lines in the spectra of novae are not numerous, nor would they be expected to be. The phenomenon would be most likely to occur for a slow nova that ejected continuously for some time. The most striking case is the series of lines observed by Morgan (1936) in DQ Her with a velocity of +1190 km/sec (which recalls the ejection velocity of —1130 km/sec on the first day of observation). An absorption system with a velocity of +230 km/sec was recorded for the slow nova V 465 Cyg by Bloch (1950). Perhaps the small number of such observations has been occasioned by a tendency to interpret in terms of expectation.

The picture thus roughly sketched, of the geometrical development of a nova, involves the ejection of material (actually small in amount) from a star, probably always a subdwarf. The star itself is unobservable during most of the process, and in a sense all the recorded phenomena are those of the envelope with which it surrounds itself. Finally this envelope, or part of it, becomes visible as a nebula around the star. It is not easy to describe the continuous process correctly, and drawing a sharp distinction between the star and the nebula at any one stage does not conduce to clarity. Properly speaking, the *whole* object is the nova; or alternatively, we may regard *all* the observed spectral phenomena as due to the nebula.

Undeniably, however, the nova that has become a nebula of observable size and structure can provide information that is less equivocal than that deduced from the earlier changes of spectrum, brightness, and velocity. First, the nebulae around novae show that at least some of the material involved in the outburst has actually been ejected. Second, the distribution of the ejected material shows that GK Per, for example, did not throw off a spherically symmetrical mass, but ejected primarily over one hemisphere. Third, the radial velocity and linear expansion of the nebulosity furnish the only reliable source of parallaxes and luminosities of novae. Fourth, the spectra of central star and nebulosity can be seen separately, and the object can be treated astrophysically as a planetary nebula. Fifth, the spatial distribution of the ejecta can be studied. Baade, as described by Van de Hulst (1951) has reconstructed V 603 Aql as a series of axially symmetrical rings, expanding away from the star. Weaver (1955) has re-examined the data, and deduced the elaborate system of cones and jets that seems to give a full account of the spectral peculiarities.

However, the geometrical picture is incomplete. Physical problems complicate the situation. The spectra and discussion published by

Wyse (1939) show that although the velocities of V 603 Aql did not change between 1919 and 1922, the distribution of light received from the nebulous structures was not uniform, that it differed also from one atomic source to another, and that the difference changed with time. Similar phenomena are shown by the nebulous shell of DQ Her.

Enough has been said to stress the importance of three contributors to the observed nova spectrum: the continuous spectrum, the absorption lines, and the bright lines. Our discussion has hitherto been geometrical. We pass now to the more difficult problem of the physical problems presented by the expanding shells of novae.

3. Physical Problems of the Nova Spectrum

The difficult theoretical problems encountered in the spectra of novae are largely untouched.

The initial rise in brightness cannot be understood without a physical theory of the opacity of the expanding envelope. What, for example, determines the effective temperature just before maximum, probably lower than that of the pre-nova, but comparable to that of a late B or early A star? Would an expanding nova display a greatly darkened disc, perhaps bright at the limb, or would it have an absorption spectrum at the center and bright lines at the limb? Some relevant data could be secured by a careful spectrophotometric study of the pre-nova continuum, and a comparison with the predictions of the theory of Kosirev (1934) and Chandrasekhar (1934). Such a study, made for DQ Her by Whipple and Payne-Gaposchkin (1936b), indicated that the expected conditions for an expanding envelope were present. Certainly the rising nova cannot be expected to radiate like a black body. Other novae, notably CP Lac, have been shown to display during their rise the characteristic ultraviolet excess, which becomes even more pronounced after maximum.

The absorption line spectrum of a nova before maximum is difficult to treat by the existing methods, developed for an atmosphere in equilibrium. Aller (1954) describes applications of a curve of growth to estimate the amount of matter in the early envelope of DQ Her. He used the curve of growth of α Per for comparison, but even this relatively quiescent supergiant displays anomalies that may, according to Greenstein and Hiltner (1948) stem from large-scale turbulence, rotation, or an extended atmosphere. Equivalent widths of the Balmer lines, such as those published by Whipple and Payne-Gaposchkin

(1936a) for DQ Her, can be translated into numbers of atoms only by the methods developed for optically thin, quiescent atmospheres, which are patently inapplicable. Turbulence would be expected in the nova spectrum at all times; Zeeman effect must be considered; and a proper allowance for Stark broadening requires more knowledge than we possess at present.

The post-maximum spectrum presents further difficulties. The changing level at which the continuum is formed cannot be discussed merely in geometrical terms, and the bright lines, which can produce pseudo-continua, further complicate the picture. Here again careful spectrophotometric study of the continuum of future novae is an important problem, much more difficult than for a nova before maximum because of the difficulty of evading the emissions, and almost an impossibility for such stars as CP Lac and V 630 Sgr with their very wide bright lines.

The problems of the absorption lines, too, are more complicated in the post-maximum stage. Components from different systems may be hard to separate for measurement; the course of the underlying continuum can at best be surmised; and the unknown effect of such factors as turbulence makes quantitative conclusions impossible. To what extent are the fainter lines obliterated by the line width produced by the outward velocities of the atoms? McLaughlin (1942) believes that the diffuse enhanced spectrum is particularly affected by turbulence, "since hydrogen and metallic lines are broadened by like amounts. The hypothesis... is supported by the relative strengths of the lines," the weaker lines being "proportionately much too weak." It would be interesting to see the suggestion tested quantitatively. McLaughlin makes the same suggestion for the Orion spectrum.

The effects of dilution may also be sought in the absorption spectrum. Struve (1939, 1942) discusses the problem in some detail. Certainly the rapid decline of 4481 Mg II in the nova spectrum can be ascribed to this cause. The abnormal weakening of the lines in some multiplets of Mg I and Ca I that are depopulated by ordinary transitions, whereas their neighbors which terminate in metastable levels do not weaken, is another manifestation of dilution that should be studied quantitatively in suitable novae. Our present information is confined to eye-estimates, and is little more than suggestive.

Most of the discussions of the absorption spectra of novae have been made differentially, by a comparison with a star that is nearly similar. Such stars are usually themselves exceptional; for example, Wellmann (1951) compared the line spectrum of FU Ori with those of γ Cyg, α Per, α CMi and ϱ Cas; apparently it lies between the first and last of these—both supergiants, and the latter extremely abnormal. The absorption spectrum of a nova is an exaggerated case of the problem of the extended stellar atmosphere, which is itself still far from solution.

The bright lines present a new series of problems. At first the spectrum is dominated by permitted lines; later a number of forbidden lines appear. The absorption spectra present some uniformity (when differences of temperature are taken into account; e.g., V 603 Aql was of spectrum *A* at maximum, RR Pic of spectrum F5), though abnormal intensities, such as exceptionally strong lines of O I and C I, do occur. The bright-line spectra present far more variety. Some novae in their later stages, such as V 630 Aql, show strong [O III] and relatively weak [Ne III], others, like GK Per and V 630 Sgr show very strong [Ne III] and relatively weaker [O III]. In the spectrum of GK Per the lines of [Ne IV] and [Ne V] were also abnormally strong. Slow novae, such as DQ Her and especially RR Pic, tend to display the forbidden lines of successive spectra of iron up to [Fe VII]. A few novae, notably recurrent ones but also CP Pup and CP Lac, have shown the "coronal lines" of [Fe X] and [Fe XIV], and CP Pup, exceptionally for a fast nova, showed [Fe II].

It would be tempting to associate these striking differences with differences in composition, but the quantitative data necessary for such an analysis are still incomplete. Bowen and Swings (1947) have pointed out that the chief factor in the production of the coronal lines is probably density: the ratio [Fe VII]/coronal lines should decrease with increasing density.

That apparent anomalies in atomic abundances may arise from the method of excitation is also pointed out by Bowen and Swings. About 99% of all the atoms in the envelope are hydrogen and helium (mainly H I and He II), whose continuous absorption cuts down radiation to the shortward of 912 A and 228 A respectively. Atoms with ionization potentials slightly greater than those of H and He II, screened by these strong continua, will not be so readily ionized as atoms whose limits fall in other spectral regions. They will therefore be present in (relatively) abnormal abundance. Their permitted and low-excitation forbidden lines, whether excited by radiation or by collision, should thus be "abnormally" strong.

The high-excitation permitted lines are normally formed by recombination, and should therefore be relatively strenghtened for the next lower stage of ionization. Table 3.2 illustrates the principle.

The mechanism is most effective when the optical thickness of the underlying layers is greatest. The Balmer decrement furnished some indication; it was shown by Baker and Menzel (1937) to be less steep for a nebula transparent to Lyman radiation than for a thick nebula, and rather insensitive to temperature. Quantitative measures of the Balmer decrement for novae require absolute spectro-photometry and are difficult to obtain. But changes can be detected with certainty. For V 603 Aquilae, e.g., Wyse (1939, p. 117) noted that "the Balmer decrement increases in the order, Absorptions I, II, III." Measures of changes in the relative intensities of the bright hydrogen lines of CP Lac and CP Pup by the writer show that the Balmer decrement increased sharply up to the time when the absorption lines disappeared, and then fell abruptly to a nearly constant value. These observations are consistent with an increase in optical thickness up to the disappearance of the absorptions and a drop thereafter. The mechanism just described should be most effective in the interval before the absorption lines disappear, though at later dates it may still operate, for there is no reason to suppose that the nebula becomes completely transparent to Lyman radiation.

The selective mechanism described by Bowen and Swings is of significance in providing for the occurrence of several stages of an atom at the same time. In RS Oph, for example, where C III, N III, [O III], [Ne III] and [Fe II] were all "abnormally strong", it refers the condition to a "relatively thick layer of gas". Their further suggestion, that strong Lyman emission lines of H and He II may increase the population of an atom of appropriate absorption limit, would lead, for example, to an enhancement of the Fe IV over the Fe III population.

The strengthenings predicted of Table 3.2 include a number of lines that are prominent in some novae, but not in all. For instance, no lines of any stage of carbon were noted in V 603 Aql. Moreover, some lines, such as those of C I, noted as exceptionally strong in certain novae, do not fall within its compass.

Finally, the prediction is of *abnormal* strengthening, and for many of the lines we cannot safely infer the normal intensity, which depends on temperature, electron density, transition probability and collisional

TABLE 3.2

Atom	Ionization Potential	Forbidden and Low-excitation Lines		Behavior Predicted	High-excitation Lines		Behavior Predicted
		Example Wavelength	Multiplet*		Example Wavelength	Multiplet*	
H I	13.595						
He II	54.403						
C III	47.67	. .	. .		4647.40	1	Strengthened
					4650.16		
					4651.35		
					5696.0	2	Strengthened
C IV	64.22	. .	. .		5801.51	1	Unaffected
					5812.14		
N III	47.24	. .	. .		4097.31	1	Strenthened
					4103.37		
					4640.64	2	Strengthened
					4634.16		
					4641.90		
N IV	77.09	. .	. .		4057.80	3	Unaffected
O I	13.56	6300.23	1 F	Strengthened			
		6363.88					
		5577.35	3 F	Strenthened			
O II	35.00	3728.91	1 F	Unaffected	4649.138 etc.	1	Strenghtened
		3726.16					
O III	54.71	5006.84	1 F	Strengthened	5592.37	5	Unaffected
		4958.91					
		4931.8					
		4363.21	2 F	Strengthened			
Ne II	40.91				4219.76, etc.	52	Strngthened
Ne III	64:	3868.74	1 F	Strengthened	. .	. .	
		3967.51					
		3342.9	2 F	Strengthened			
Fe I	7.858	3859.913, etc.	4	Unaffected	4957.603, etc.	318	Strengthened
Fe II	16.16	4287.40, etc.	7 F	Strengthened	4233.167, etc.	27	Unaffected
Fe III	30.48	4658.1, etc.	3 F	Unaffected	4419.59, etc.	4	Strengthened
Fe IV	?	5041 ?	. .	Strengthened	. .	. .	

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* Taken from Moore (1945)

cross-section, to name what are probably the principal unknown or uncertain factors. We are not at present in a position to say how far the large differences of the intensities of bright lines in the spectra of various novae point to true differences of composition. The great strength of [Ne III] relative to [O III] in the early stages of GK Per was not maintained; after 1901 the nebular lines of these atoms seem to have had similar intensities.

The most important special mechanism for excitation in the spectrum of a nova is that first described by Bowen (1934) in connection with anomalous intensities in gaseous nebulae. It involves the absorption of bright 307.780 He II by an atom of O III, one of whose ultimate multiplets includes a line of wavelength 303.799 A. In gaseous nebulae the relative velocities are comparitively low, so that the He II radiation can rarely affect the next nearest wavelength of the O III multiplet, at 303.693 A. But in the envelopes of novae, where velocities are of the order of 1000 km/sec, all six lines of the O III multiplet are accessible to excitation, and the selectivity in the subsequently emitted O III lines, which suggested the existence of the mechanism, will not be expected.

The next step is the excitation of an N III atom by components of the O III multiplet near 374 A. Here again, because of the large differential velocities, all six of the O III lines can be absorbed by one or other of the N III transitions at 374.441 A and 374.204 A. Here again, therefore, the selectivity in the intensities of the subsequently emitted N III lines will be reduced as Bowen indicated that they should be for high relative velocities. The mechanism is important in novae because it bears on the well-know phenomenon of "nitrogen flaring", first emphasized by Wright (1921).

The first, and still the best example of nitrogen flaring is the relatively slow nova DN Gem. At times the normal, rather narrow N III group near 4640 displayed diffuse broadening to a width of over 100 A, the normal N III group and He 4686 became invisible, or what looked like a broad and shallow absorption replaced the latter.* The lines 4097, 4103 of N III tended to flare at the same time, 5680 N II displayed similar changes, and the lines of O III weakened. Such effects can be seen in the very different novae GK Per and V 603 Aql (during transitional fluctuation), TCrB and RR Pic.. The flared

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* Photometry of the spectrum casts doubt on this interpretation of the feature.

nitrogen recalls the spectrum of a WN star, seemingly underlying the rest of the nova spectrum.

Three factors are involved in nitrogen flaring: the increased intensity of N III and reduced intensity of [O III]; the great width of the N III lines (corresponding to a velocity of about 3200 km/sec); the apparent suppression or reversal of 4686 He II. Because of the large velocities, Swings and Struve (1942) consider that the O III transition must compete with photoelectric absorption by other, commoner atoms in a rapidly expanding atmosphere, and that for a large constant velocity the Bowen mechanism should be "practically absent". Their argument refers to W stars, but seems even more applicable to novae. Hence Swings and Struve (1943) conclude that the flaring, if produced by Bowen's mechanism, requires either a change in the velocity gradient, or a stratification of the radiating atoms. The great velocity of the flaring nitrogen they attribute to selective radiation pressure by N III 452, which could be effective only if the velocity gradient was large. (It seems doubtful whether the actual velocity gradient is ever large enough to produce the observed widening of the lines.) "The replacement of the emission of 4686 by an absorption feature," they suggest, "is not surprising, since this absorption requires singly ionized atoms which may be present on the outskirts..., whereas the recombination line 4686 requires He^{++} ions, which are more abundant in the deepest layers."

The interpretation covers some of the main features of nitrogen flaring, but not all. The weakening of [O III] might be ascribed to a departure from the conditions for the enhancement of [O III] (Table 3.2), which would, however, also weaken the N III lines concerned. We could remove the discrepancy, if O^{++} atoms were depleted, but not the N^{+++} atoms (the N III lines being formed by recombination), and O^{++} is much nearer the He^{+} limit than N^{+++}. This solution, however, is very artificial. The remarkable feature of nitrogen flaring is, indeed, that the widening involves nitrogen in at least two successive stages, and not the lines of other atoms. Conceivably it may involve the absorption of 303 He II by members of the N IV multiplet near 303 A, which could only take place at differential velocities of about 700 km/sec, with the He II line produced within the N IV layer, and moving outward more rapidly. The observed velocities for various absorption systems of DN Gem at the times of laring lend some support to the idea. Nitrogen flaring is probably present to some extent in most novae.

Mass motion up and down as a factor in nitrogen flaring seems unlikely, as there seems no reason to single out one atom for such motion, nor to suppose that the effect would appear and disappear at short intervals.

Stratification of the atoms that emit particular lines, as mentioned by Swings and Struve, is implied by much of what has already been said. An even more complicated picture, that seems to demand directional differences in emissivity, is forced on us by the observations. When discussing the geometrical aspects of bright lines, we referred to the frequent occurrence of saddle-chaped profiles, which are found in the spectra of most novae at some stage.

The spectra of CP Lac, V 630 Sgr and CP Pup, for instance, at first showed single Balmer lines. Soon a central depression appeared, the violet edge of the line being slightly the stronger. After the absorption lines had faded, and at the same time that the Balmer decrement diminished, the red edge of the Balmer lines became the stronger, and so it remained. However, in the spectrum of CP Pup, the lines 4686 He II, 4640 N III and 4609 N V, when they appeared, were stronger at the violet edge, and remained so as long as the spectrum was recorded, although the contrast between the two edges diminished somewhat.

Even more striking was the development of line structure in V 603 Aql. The bright lines showed a series of maxima and minima from the time of their first appearance, well illustrated by the profiles for the Balmer series published by Sayer (1935). A saddle-shaped profile soon appeared, superimposed upon this structure, the red edge considerably stronger than the violet, as may be seen from the discussions of Sayer (1935), Wyse (1939) andPearson (1936). During the transitional fluctuations of the nova, the intensity of the original band structure fluctuated, while the saddle-shaped profile remained comparatively unaffected and probably changed little, according to Wyse, in absolute intensity.* About two months after maximum, the red and violet edges were about equal in intensity, and thereafter the violet component became the stronger, as illustrated by Payne-Gaposchkin (1941). While the transitional fluctuations continued, the central structure intensified during the maxima and faded at the minima. The center-edge contrast was shown by Wyse to vary strikingly for 4686 He II, less so for the Balmer lines, 4640 N III, 5679 N II, 5875 He I, even less for 5007

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* Photometry of the spectrum shows real changes of intensity.

[O III], and least of all for 5755 [N II]. Meanwhile the ratio in total intensity of 5755 [N II] and 5007 [O III] changed with the fluctuations, being greater at maxima than at minima. We have selected only certain salient features of the emission line structure, but the related variations of velocity, absorption line intensity and excitation in the absorption spectrum were equally striking.

When the ejected nebulosity became visible, and its spectrum could be recorded in various position angles, as recorded by Wright (1919), by Moore and Shane (1919) and by Wyse (1939), it was seen that the structure that had been visible from the first in the bright lines was still present. As the nebular disc grew in size, these spectra made possible the spatial reconstruction of the ejected material, as already described in the previous section. The system of rings or cones and the two "blobs" can be identified respectively with the series of maxima observed at the outset, and the edges of the saddle-shaped profile, and show that the spatial structure emerged in the course of a few hours just after maximum, and persisted thereafter with little or no change of velocity, or, apparently, of velocity dispersion. Up-and-down mass motion, in particular, seems to be excluded.

From 1919 through 1922, the violet maximum of the saddle-shaped profile, now identified with the advancing "blob", remained the stronger.

The material for the [O III] nebular lines is the most detailed. In these lines the brightness of the rings faded more rapidly than that of the blobs, which were the only observable feature by June, 1922. The rings, while visible, were not uniform in brightness, and the distribution of their light strongly suggests obscuration by the advancing blob; the equatorial ring seems least affected. The changes of intensity of the [N II] lines at 6548, 6584 A that flank Hα, reproduced by Wyse, show a strong contrast with those of the nebular lines. The equatorial ring did not fade relative to the blobs, and in 1922 its intensity in [N II] was nearly as great as that of the approaching blob, greater than that of the receding blob. Thus, by 1922 the [O III] nebular radiation was essentially confined to the blobs, whereas in [N II] light, the blobs and the equatorial ring were both well defined. Possibly the narrow central maximum of 4686 He II noted by McLaughlin (1947) in July 1918 stemmed from the equatorial ring, but apparently this radiation had weakened too much to be recorded in the spectrum of the expanding nebula.

The structure of the bright lines of CP Pup resembled that for V 603 Aql in many ways, although, in the absence of transitional variations of brightness, no relative fluctuations of central structure and saddle-shaped profile were observed. The lines of hydrogen, at first structureless, developed saddle-shaped form after a few days; the component of greater intensity changed from the violet to the red as the spectrum developed. The central detail, described by Sanford (1945, 1947) became more prominent as time went on. Lines of He II, N III and N V always had a stronger violet component, as shown by Weaver (1944), and they, too, developed central detail that grew more definite with time.

Although the spectrum of the expanding nebula could not be studied in spatial detail, there is little doubt that the distribution of the emissions followed a pattern similar to that for V 603 Aql; Sanford's published spectra show essential similarity in the structure of Hβ and the [O III] nebular lines in 1943, and his velocities derived from maxima within the bright lines are compatible with an equatorial ring, four rings on each side of it (two quite weak) and two polar blobs. By analogy with V 630 Aql we can hardly invoke up-and-down mass motions to account for the difference in structure of the lines of hydrogen and He II. The only plausible alternative seems to be directional excitation.

The spectrum of the nebulosity about DQ Her suggests a similar conclusion. The difference in the distribution of light from the [O III] nebular lines and the [N II] lines at 6548, 6584, demonstrated by Baade (1942) is of the same nature, though it points to a structure less complex. Baade photographed an ellipsoidal shell in the [O III] nebular lines, and showed that there were strong condensations in the light of these lines that were aligned along the major axis of the nebula, and could be identified with the components seen visually by Kuiper (1941), Strong [N II] emissions lay along the minor axis and weaker ones along the major axis, and the intensity distribution changed with time. The velocity structure observed by Humason (1940, in Hβ and the [O III] nebular lines conforms to this picture.

The data could be amplified by reference to other novae, but the three cases mentioned are the best documented. In all of them we note a certain axial symmetry; but this was (perhaps exceptionally) absent for GK Per.

In every instance, the facts seem to require directional excitation.

This suggestion was made, with singular foresight, by Grotrian (1937), who saw in the supposed duplicity of DQ Her a directionally excited nebula, and touched on the possibility of a rapidly-rotating star, radiating differently at equator and pole. The recent discovery by Walker (1954) that DQ Her is an eclipsing star of very short period provides a pair of rapidly-rotating stars within the nebula, and shows that we view them equatorially. It does not tell us which axis of the nebula corresponds to the stellar poles; if the polar radiation (as Grotrian surmised) is more intense, the poles must point in the direction of the major axis of the nebula.

The physical problem raised by the simultaneous occurrence of several absorption systems, associated with different velocities, remains to be mentioned. If we think in terms of a spherically symmetrical model, we must imagine that the continuous spectrum is produced at a certain level determined by the opacity of the envelope, and that all the absorption spectra are produced by atoms above the level. This seems only to be possible if all except the lowest-lying are essentially located in detached shells. If this is the case, three results would follow: each spectrum except the last to appear should diminish in intensity as the shell expands; dilution effects and shell characteristics should appear and grow progressively more prominent; and the rapidly-moving shells should overtake and destroy (or be destroyed by) the outer, slower shells, and this destruction should be permanent.

There is no very convincing evidence that any of the three results is achieved in practice. The relatively slowly-moving principal spectrum often lasts for a long time—as long, indeed, as most of the subsequent absorption systems—and does not fall off in intensity as rapidly as would be expected if it constituted a thin shell. In fact, it is difficult to see how the source of the principal spectrum, at least, can fail to be a significant contributor to the continuous spectrum, and thus to obliterate the absorption lines of atoms nearer the central star. Second, none of the absorption systems ever has the typical character of a shell spectrum; V 603 Aql at maximum showed the Balmer series only as far as H 18, and in DQ Her it can be traced no farther than H 19. Nor is there any evidence of such intensification of 3888 He I as is shown, for example, by γ Cassiopeiae. The rapid fall in intensity of 4481 Mg II, mentioned earlier, is the only well-attested affect that may be ascribed to dilution. Moreover, the lines of the principal absorption tend to be strong and broad, and the diffuse character of those of the "diffuse enhanced" and "Orion" spectra has already been commented upon. The mutual destruction of shells has been suggested by McLaughlin and others, usually with the idea that the principal spectrum, by virtue of its greater mass, tends to be the survivor; however, in his discussion of DQ Her, McLaughlin (1954) recognized the difficulty presented by the recrudescence of a spectrum that seems to have disappeared.

These difficulties suggest a somewhat different picture, which can only be presented as a tentative suggestion. The pre-maximum spectrum represents a more or less spherical expansion; the principal spectrum, which appears near maximum, may also be the product of a more or less spherical expansion, the result of an ejection process that lasts for a considerable time, the rate of ejection (in Grotrian's sense) falling off rapidly in fast novae, more slowly in stars like DQ Her and RR Pic; the source of the principal spectrum is responsible for the major part of the true continuous spectrum. The other absorption systems represent *localized* ejection from the central star, perhaps in jets or zones, and become visible as the atoms concerned penetrate the level of the envelope formed by the principal spectrum where the current photosphere is located. Thus the principal spectrum is to be thought of as gradually torn to pieces by localized jets that pass through it. This picture provides a cause for the "turbulent" character of the "diffuse enhanced" and "Orion" spectra, permits the principal spectrum to survive until its own ejection ceases, and makes possible the repeated appearence and disappearance of the other absorption systems. This picture is still, of course, purely geometrical, and does not provide a mechanism for the production of the jets.

An empirical observation that lends some color to this idea may be mentioned here. The pre-maximum and principal spectra, and in some cases even the diffuse enhanced spectra, can be roughly classified on the same system as the spectra of more normal stars (see Chapter 10). There is an evident correlation between the spectral class and the associated radial velocity for the pre-maximum and principal spectra, and if the *difference* of velocity between principal and diffuse enhanced spectra is used, the latter, too, conform to the correlation. Table 3.3 summarizes the data.

If we make the rough guess that the temperatures are the same as those of giant stars of the same spectral class, the temperature is seen to be proportional to the square of the velocity. As we are very likely here to be dealing with shock fronts, it seems plausible to consider that the velocity *determines* the spectrum that is observed. No temperatures are assigned for the N III and N V absorption, but evidently they extend the correlation.

TABLE 3.3

Spectral Class	Average Radial Velocity km/sec	Number of Stars
F8	—142	2
F5	—168	2
F0 to F2	—268	4
A5	—618	4
A2	—560	3
A0	—600	2
B9	—600	2
B5	—1000	1
B1	—1216	1
(NIII)	—1378	7
(NV)	—1950	3

It would be premature to discuss the relationship further, but it suggests one more comment. We should expect that if each absorption system constituted a spherical shock front, each would be opaque enough to obliterate all absorption systems that lay below it. This is simply a restatement of the problem of the coexistence of several absorbing shells in a more cogent form, and emphasizes the probability that the ejections associated with high-velocity absorption systems are localized.

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CHAPTER 4

GALACTIC NOVAE, FIRST CLASS DATA

The three chapters that follow will present the salient data concerning the known galactic novae. Recurrent novae are included, but supernovae, symbiotic novae and dwarf novae or U Geminorum stars will be found respectively in Chapters 9, 7, and 8.

The present chapter covers seventeen bright novae—those for which our information is so detailed that they furnish the real basis for physical study of the nova problem. They range from very rapid novae (such as V 603 Aql and CP Pup) through slower novae (DN Gem, RR Pic) to very slow novae (RT Ser, η Car). Space forbids detailed description or complete bibliography for every star, but an attempt is made to mention significant information and to refer to the principal published sources. A few stars are described in especial detail as examples of their class: V 603 Aql, DN Gem, DQ Her, RR Pic, T CrB, and η Car.

The stars are arranged by constellations; position designation, and date and magnitude of maximum, are given for each. The symbols dt and dm are used to refer to the interval since maximum, in days, and the decline from maximum, in magnitudes.

V 603 AQUILAE 184300 JD 21755 (1918) —1.1

The light curve of V 603 Aql was distinguished by a sharp maximum, and a steep fall was followed by striking post-maximum fluctuations. Fig. 4.1 shows the changes of visual brightness during the interval when absorption spectra were recorded, taken from the compilation by Campbell (1919). It also includes the light curve of the continuum, freed from the contribution of the bright lines, as deduced spectrophotometrically by Payne-Gaposchkin and Gaposchkin (1942). The continuum fluctuated with a greater amplitude than the integrated visual or photographic brightness, as it has done for other novae.

The most complete discussion of the spectral changes was made by Wyse (1940). The three velocity systems recognized by Wyse are shown

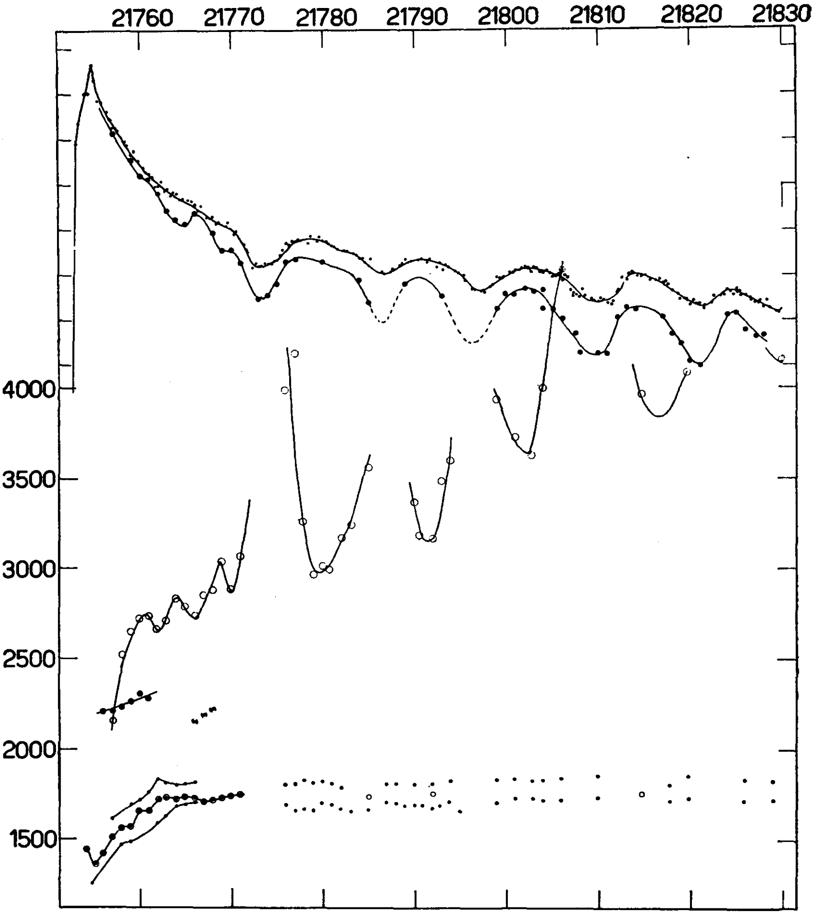


Fig. 4.1. V 603 Aquilae. Abscissae are Julian Days.
Upper curves: small dots, visual light curve; large dots, magnitude of photographic continuum. Ordinates are magnitudes.
Below: velocities (ordinates in km/sec) for the various absorption systems.
Note: a. the relation between the Orion velocities and the magnitude of the continuum
b. the disapparence of absorption spectra at minima of the continuum

in the figure, which is supplemented by a few velocities published by

Cortie (1919), Harper (1920), Lunt (1920), Newall (1919), and Pearson (1936).

Absorption I represents the pre-maximum spectrum. It developed from early Ap to an "*a* Cygni" class. Initially it showed lines of H and neutral and ionized metals (Ca I, Ca II, Cr I, Cr II, Fe I, Fe II, Mg II, Sc II, Sr II and Ti II). The Fe II spectrum persisted until JD 21766 (dt = 11); H and Ca II were seen until JD 21770 (dt = 15). At first broad, the lines of Absorption I were seen doubled between JD 21757 and 21764; on JD 21766, when the continuum seems to have had its first subsidiary maximum, they were again single. Like the other absorption spectra, Absorption I was invisible during the minima of the subsidiary fluctuations, and reappeared, usually doubled and with progressively diminishing intensity, at four successive brightenings. At each recurrence, the lines were strongest at maximum brightness.

Absorption II, with sensibly constant velocity, was strong and of short duration. It showed lines of H, Ca II, strong Fe II, Ca I 4226, and the D lines of Na I.

Absorption III, which showed large velocity variations that reflected the changes of brightness of the continuum, displayed lines of H, He I, O II, N II, N III and N V. Lines of He I and N II were present from its first appearance on JD 21756, until JD 21791 and 21764, respectively. Lines of O II were seen from JD 21757 to 21779; N III, from JD 21758 to 21792; N V, from JD 21775 to 21819, when all absorptions disappeared. Lines of H were recorded by Wyse in this absorption system from JD 21775 to 21791.

Wyse noted that Absorptions I, II and III display progressively rising ionization; the Balmer decrement also increases from Absorption I to III. Absorption III itself displayed progressively rising ionization: N II was present from dt 1 to 9, N III, from dt 3 to 37; N V from dt 20 to 64. Absorption lines were often seen superimposed upon bright lines, and Wyse stated that some of them "appear strong enough to indicate that a part of the emission radiation of one element is actually absorbed by the atoms of another". No emissions corresponded to Absorption III.

The emission lines of V 603 Aql were broad, and many of them overlapped. Wyse identified C II ?, Ca II ?, Fe II, H, He I, He II, N II, [N II], N III, N V, Na I, O I, [O I], O II, O III, [O III], O IV and perhaps O VI, Si II, [S III]. The nebular pair of [Ne III], prominent in many novae (see GK Per), was absent or very faint.

A very striking feature of the spectrum was the changing form of the bright-line profiles during the post-maximum oscillations of brightness. At the minimum of light, the profiles tended to be saddle-shaped, the violet maximum always stronger than the red. At the maximum, a central, rounded profile seemed to rise and fill in the

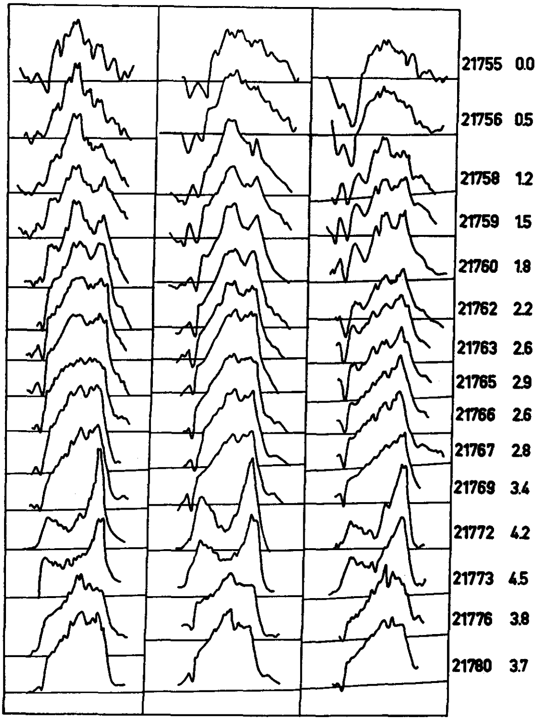


Fig. 4.2. Profiles of three bright hydrogen lines in V 603 Aquilae (after Sayer). All are expressed in terms of the intensity of the neighboring continuum, and absolute intensities are therefore not comparable. Violet is to the left.

Julian Day and magnitude of continuum are indicated on the right.

Compare Fig. 4.1 and also Fig. 3.3 and 3.4.

central dip, and this central profile had itself a double maximum. Typical profiles are illustrated in Fig. 4.2; their complex form can be analyzed into the superimposition of several saddle-shaped profiles of differing width, all symmetrical about a single wavelength, or nearly so. The significance of these profiles can be understood in the light of the structure of the expanding nebulosity, as will be seen later. The half-widths of the emissions were shown by Wyse (1940) to correspond to the velocity of Absorption I, save that Absorption II was accompanied by emissions during its brief lifetime. Both Absorption I and II appeared about two days before the corresponding emissions became visible. The relationship between the brightness of the continuum, the velocity of Absorption III, the intensity of the complex bright lines, and the ratio of intensity between its two principal red and violet maxima is illustrated by Payne-Gaposchkin (1939) from data obtained in a joint investigation with Menzel.

Total intensities of the bright lines are difficult to separate on account of the great widths of the lines and the consequent overlapping. The structure of the 4640–4686 complex, for example, is illustrated in Fig. 4.3 (compare Fig. 4.19 which shows the same region for CP Pup, where the velocities were smaller). The intensities can, however, be shown to be affected by the secondary oscillations of brightness, and to follow the latter with a lag of a day or two; it is this lag that erases the rhythmic fluctuations shown by the continuum, and makes the integrated light of continuum and bright lines appear to have ceased fluctuating before the continuum has actually done so (see Fig. 4.1). The forbidden lines do not seem to reflect the oscillations as closely as the permitted lines, and, according to Wyse (1940) their profiles also vary less. Wyse also noted that [N II] 5755 strengthens at the maxima (at least relatively), whereas the lines of [O III] weaken. Moreover, N II 5678 and [N II] 5755 vary in opposite sense, the former following He I 5875 in behavior.

We might expect the intensities to be strictly comparable when the continuum has a given brightness, as seems to be the case for DK Lac, but this is not the case of V 603 Aql. For continua of equal brightness, permitted lines are relatively strongest at minima, forbidden lines at maxima. Especially notable is the behavior of N V 4604, first seen at the minimum of JD 21795, and recorded at the minima until JD 21892, but seen only once as a bright line at secondary

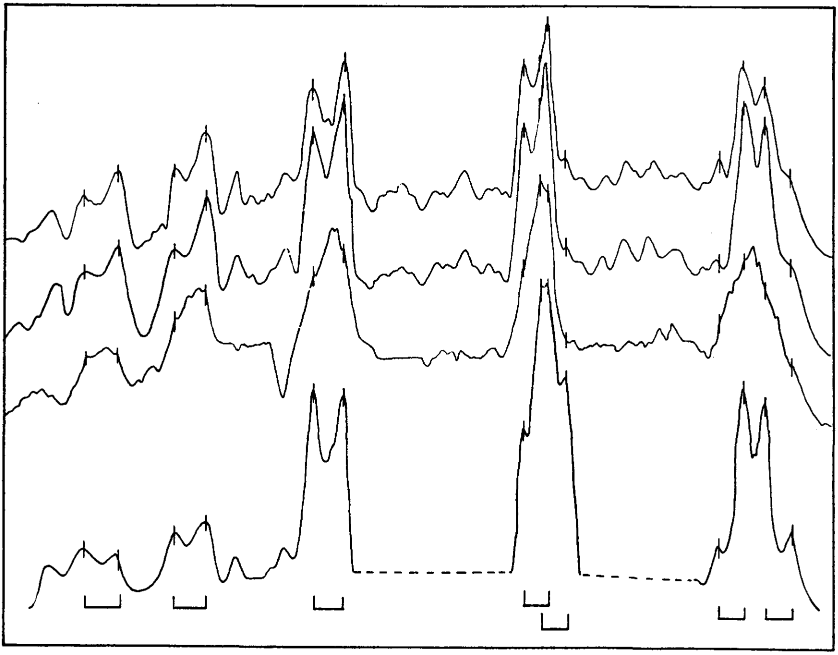
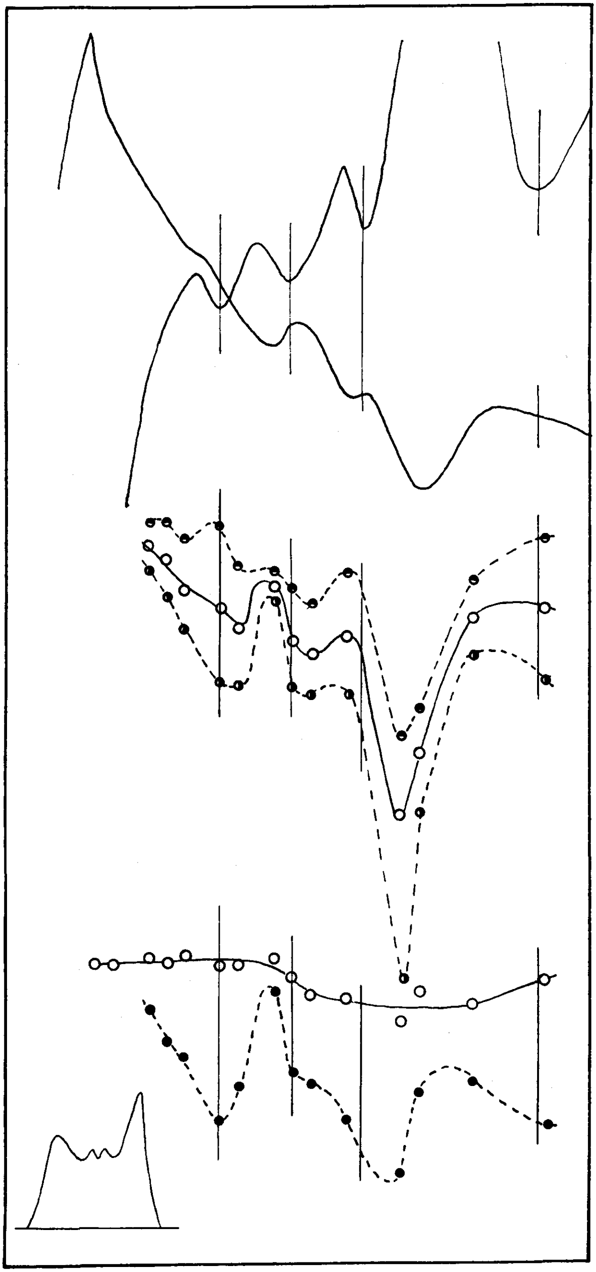


Fig. 4.3. Photometric tracings of part of the spectrum of V 603 Aql on four days (indicated, with the apparent magnitude of the continuum, at the left). Vertical lines mark the red and violet maxima of eight prominent lines. Note:
a. the interplay of H 4340 and O III 4363
b. the interplay of N V 4607, N III 4640 and He II 4686
c. the intense absorption of N III 4097, 4103 on JD 21777; this pair makes a considerable contribution to the bright-line profile on the other days.
The tracings are all reduced to *intensities* on the same scale, and are shifted vertically for conveniende of comparison. Compare Fig. 4.2; the present figure is derived from Harvard plates with a provisional standardization.

maximum, when the brightness of the continuum had fallen to $5^m.3$.

The fading nova was found by Barnard (1919) to be surrounded by a small nebula, which has continued to expand at a uniform rate (the brightness of the continuum being taken into account). References to the observations of the nebula by Aitken, Hubble and Duncan, Wyse, and Wright are collected by Wyse (1940); the observations extend from 1918 to 1933. An observation by Baade in 1936 is recorded



by Humason (1938); the image was then stronger in yellow than in blue light. The diameter of the nebula is found to be expanding at the rate of 1″.9 or (more probably) 2″.0 a year.

For several years the spectrum of the fading nova showed also the spectrum of the expanding nebulosity, which was last recorded, according to Wyse, on a Mount Wilson plate of 1926. Direct observations of the spectrum of the expanding disc, and spectra photographed at the Lick and Mount Wilson observatories with the slit in various position angles, reveal complex structure, which differs from one atom to another and suffers changes in intensity with time. Some of the Lick spectra are shown by Wyse (1940). The intensity distribution is evidently very different for the [O III] lines 5007, 4958, the [N II] lines 6548, 6584 and Hα 6563.

These spectra can be used, in conjunction with the observed expansion of the nebula, to determine the distribution of the material from which the light of these atoms emanates. Van de Hulst (1951) described an unpublished investigation by Baade, in which "an unambiguous spatial image could be constructed. It was not a system of jets, but a system of rings, around a common axis... There was one

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Fig. 4.4. Relation of intensities and profiles of Hγ in V 603 Aquilae to the light and velocity curves.
Above: light curve and velocity of Absorption III (see Fig. 4.1); ordinates are magnitudes (left margin) and velocities in km/sec (right margin); abscissae are Julian Days. The points in the line profile that have been measured are indicated in the small figure at the bottom left; violet is to the left.
Three central curves: highest: log M_1—log M_3; lowest: log M_2—log M_4; the middle curve is the average.
Two lowest curves: above: log M_1—M_2; below: log M_3—log M_4.
The values of M are peak intensities in terms of the local continuum.
Short vertical lines are drawn at the approximate positions of minima of the velocity curve.

Note:
a. The three central curves fall toward minima soon after minima of the velocity curve, and rise to maxima soon after maxima of the velocity curves. The effect is greatest for the redward components.
b. The lowest curve (difference between two redward components) has minima near minima of the velocity curve. The difference between the two violetward components changes little if at all with the velocity curve; its average level falls somewhat during the first strong minimum of the light curve (velocity rises to a maximum and absorption spectra disappear).

equatorial ring, two pairs of rings on either side of the equator, symmetrically placed, and two polar blobs... The common axis, which presumably is the axis of rotation of the star, is inclined by 16° to the line of sight... The rings are all expanding in a direction from the star. They are lying between two concentric spheres". The ejection of the material concerned must have taken place in a very brief interval, since the corresponding features can already be traced in the structure of the bright lines given by the integrated light of the nova on JD 21755, the date when Absorption II emerged.

A similar analysis, recently carried out by Weaver (1955), leads to a somewhat different spatial reconstruction, in which the "rings" are represented by cones of emitting material, and the "blobs" by two jets, nearly but not quite in the axis of symmetry of the cones; the material is distributed between concentric spheroids. Each cone of material contributes one saddle-shaped profile. The integrated spectrum of the nova in its early bright-line stages shows a "battlemented" structure in each bright line (see Fig. 4.2), which can now be interpreted as the superimposition of several saddle-shaped profiles, (one from each cone), whose changes of relative intensity are responsible for the remarkable changes in the profiles during the star's secondary fluctuations.

Weaver identifies the features of the spatial distribution thus determined with the rate of expansion of the observed nebulosity, and derives an absolute maximal magnitude —8.5 for V 603 Aql, a result in harmony with the data discussed in Chapter 1, and additional assurance of the correctness of the analysis.

The basic structure is similar for the lines for which data have been published, but the relative intensities differ; for example, the jets are relatively more prominent in the [O III] lines than in the [N II] lines. Wyse (1940) comments that the other [N II] line 5755 never shows a saddle-shaped profile. Excitation conditions evidently depend on a directional factor, actual directional segregation of the atoms being most implausible. Data for other novae point to similar conclusions: the He II line 4686 has a different intensity distribution from that of N III 4640 in CP Puppis; and the observed structure of the nebulosity about DQ Her is different in [O III] and in [N II], Hα light.

No other nova has hitherto been observed* so that the spatial detail

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* Unpublished material exists for DQ Her.

of the nebulosity can be directly studied, but there is no doubt that many have similar structure. The saddle-shaped profiles of CP Pup, with their intricate detail, suggest an even more complicated arrangement than that of V 603 Aql; and the very common occurrence of saddle-shaped profiles in the spectra of novae suggests that they, too, ejected material in cones.

The spectrum of V 603 Aql was studied in 1938 by Humason (1938), who found a strong continuum, extending well into the violet, and weak emissions of H and He II. He noted that the nebula was sensibly circular, concentric with the star, and gradually growing fainter. The spectrum between 1919 and 1950 has been discussed by McLaughlin (1953a). The line He II 4686 has gradually weakened, and the Balmer lines, invisible at the beginning of the interval, were about as strong as 4686 at the end of it. Lines of He I were occasionally seen faintly, and C III 4650, at first invisible, strengthened and later weakened somewhat. On the whole the excitation of the spectrum fell as the star declined from seventh to eleventh magnitude.

A number of pre-maximum spectra were taken at Harvard. The description by Cannon (1920) has sometimes been misinterpreted: "The spectrum appears to be nearly continuous... Several narrow dark lines are, however, barely seen, which appear to belong to the hydrogen series. In the distribution of light, the spectrum resembles those of classes B or A. While the spectrum cannot be classified, it is safe to say that it was not of Class G or K, but was near Class A". A microphotometer tracing of one of these spectra is reproduced by Gaposchkin (1939).

T AURIGAE 052530 JD 12088 (1892) 4.2

The first well-observed nova of modern times was of the relatively uncommon type to which V 450 Cyg, DQ Her and V 732 Sgr also belong. Fig. 1.4, p. 13, shows the photographic light curve published by Leavitt (1920).

Many of the spectroscopic observations were visual, but photographic studies were made at Lick Observatory by Campbell (1892, 1894, 1896), by Belopolsky (1892) at Pulkowa and by Cannon (1916) at Harvard.

The spectrum shows a close agreement, almost from day to day, with that of DQ Her. Recorded appearance and great minimum for T Aur occurred at JD 12077 and 12166, with an interval of 89 days;

Julian Days	Principal Absorption km/sec	Diffuse Enchanced km/sec	Orion km/sec	Emission Velocities km/sec
12137 to 12143	—399	—804, —940	..	+521, +794
12170±	—559	—1100	—1193	+460

Julian Day	Reference	5890 5896 Na I	5317 Fe II	5169 Fe II	4924 Fe II	4861 $H\beta$	4584 Fe II	4340 $H\gamma$	4102 $H\delta$	Rem.
12131*	Huggins (1892)	p				p		p		1
12132	Cannon (1916)					p		p	p	2
12132	Sidgreaves (1892)	p	p	p	p	p	p	p	p	
12133*	Espin (1892)	p			?	p	?	p	p	
12134	Cannon (1916)					p		p	p	3
12135	Young (1892)	p		p	p	p		p		
12136	Lockyer (1892)					p	p	p	p	4
12137–8	Campbell (1893)	p	p	p	p	p	p	p		5
12138	Cannon (1916)					p	p	p	p	
12139	von Gothard (1892)		p	p	p	p		p		
12141	Young (1892)	p		p	p	p		p		
12144	Young (1892)		p	p		p				
12151*	Campbell (1892)	p		p		p	p			
12151	Maunder (1892)				p	p	p	p	p	6
12152*	Fowler (1892)	p	p	p	p	p				7
12153*	Fowler (1892)		p	p	p	p				
12157*	Campbell (1892)	p	p	p	p	p		p		8
12158	Vogel (1892)							p		9

NOTES

1. Dark components on violet edges; relative velocity bright and dark lines 880 km/sec.
2. Wide dark lines to violet of wide bright bands.
3. H and K lines show double absorptions.
4. Many more Fe II lines recorded.
5. Many more bright lines recorded, including $H\alpha$ and Fe II lines; also the first record of 6300, 6363 [O I], and probably 5577 [O I].
6. Dark hydrogen, Ca II and Fe II components; relative velocity, bright and dark lines, 1312 km/sec.
7. Records $H\alpha$, 6300 and 5577 [O I].
8. Records many lines, including $H\alpha$, 6363, 6300, 5577 [O I] and numerous lines of Fe II.
9. Velocity of dark lines, —650 km/sec.

Julian Day	Reference	Remarks
12171*	Campbell (1892)	Lines of H, 5755 [N II], 6363, 6300, 5577 [O I], Fe II.
12164	Campbell (1892)	Lines of H, C II, N II, O II, Fe II. Perhaps lines recorded at 4355, 4246 are [Fe II]; last detailed photograph.
12174–74	Cannon (1916)	Continuum has grown fainter; Hγ strong, possisible 4363 [O III]?
12178	von Konkoly (1892)	Hβ, Fe II.
12179	Cannon (1916)	Continuum faint; only H lines seen; Hβ = Hγ.
12187	Pickering (1892)	Last photograph obtained. As the star fainted, the bright lines faded in the order: Ca II 3933; Ca II 3970; Hα; Hβ; Fe II; Hγ, the latter line becoming much the brightest when the star was faint.

corresponding dates for DQ Her were JD 27785 and 27895, an interval of 110 days. The actual maxima were at JD 12084 and 27794 respectively, and intervals from maximum to great minimum were accordingly 82 days for T Aur, 101 days for DQ Her. For V 450 Cyg the intervals from discovery and from maximum to great minimum were 106 and 94 days; thus T Aur developed slightly faster and V 450 Cyg was intermediate. However the difference is very small, and McLaughlin (1941) finds that T Aur on JD 12138 (54 days after maximum) exactly matched DQ Her on JD 27843 (49 days after maximum).

The absorption spectra and associated radial velocities have been given by McLaughlin (1941) from a rediscussion of the Lick plates. He finds three absorption systems: a principal absorption with lines of H, Fe II, Ti II and a few of Cr II, Sc II and Mg II; a diffuse enhanced spectrum with H, Fe II, Ti II, Cr II, in which the lines of H and Fe II are relatively stronger; and an Orion spectrum with lines of He I, N II, O II.

The velocities, their changes, and the doubling of the diffuse enhanced spectrum have close parallels in DQ Her.

The emission spectra from various sources have been discussed by Hoffleit (1937), who again finds a close parallel with DQ Her. The first spectrum was obtained about fifty days after maximum, and accordingly there is no record of the early post-maximum stages.

Julian Day	Reference	5755 [NII]	5007 [OIII]	4959 [OIII]	4861 Hβ	4686 HeII	4640 NIII	4606 NV	4363 [OIII]	4340 Hγ	4101 Hδ	3968 [NeIII]	3869 [NeIII]	Rem
12329, 30	Campbell (1892)		p	p	p									1
12331	Campbell (1892)	p	p	p	p	p			p*		p	p		
12344	Cannon (1916)		p						p					2
12350, 1	Campbell (1894)	1	10	3	1		0.8			0.1				
12362	Cannon (1916)		p							p				3
12400	von Gothard (1893)	p	p				p			p		p	p	4
12431	von Gothard (1893)	p	p				p			p		p	p	4
12556, 72	Cannon (1916)		very strong							trace				
12810, 24	Cannon (1916)		only line seen											
12957	Campbell (1894)	0.4	10	3	1		0.8			0.1				
13079	Campbell (1894)	0.4	10	3	1		0.2			0.1				
13161	Campbell (1894)	0.3	10	3	1		0.1			0.1				
13787*	Campbell (1896)	0.1	10	3	1									
13839*	Campbell (1896)	0.1	10	3	1									
15640	Palmer (1902)		p		p					p	p			
16356	Perrine (1903)		absent		p					p	p			
20210–14	Adams and Pease (1914)		absent		2	2	1			3	2			5
27396 28547 28603	Humason (1938)					very weak				very weak				6

* strongest line.

NOTES

1. Very weak continuum.
2. 4363 > 5007.
3. 5007 > 4363.
4. [Ne III] 3968, 3869 and [O II] 3737 also recorded.
5. Continuum (relatively) very strong.
6. Continuum extends well into violet; He II 4686 slightly stronger than H∂.

A summary of the principal observations during the diffuse enhanced stage is given in the next tabulation. The letter p denotes that a line was present; an asterisk after the Julian Day denotes that the observation was made visually. Only the most prominent lines are listed.

The spectrum now entered the Orion stage, as indicated by the appearance of the corresponding absorption spectrum. Unfortunately as the star grew fainter before the great minimum, observations became sparser and there were fewer photographic ones.

This rather sparse table of observations shows the fading of the continuum; the emergence of the [O III] line at 4363, which was certainly the strongest line noted by Pickering on JD 12187; and possibly the emergence of the [Fe II] lines. The latter were a conspicuous feature of DQ Her just before the great minimum, but, as pointed out privately by McLaughlin, they are not visible on the Harvard spectra of T Aur. The long series of observations by Vogel, which extends to JD 12174, were unfortunately discussed by that author (1893) only for the structure of the lines of hydrogen. His table of wavelengths of bright lines, which refers to the whole interval, JD 12143 to 12174, suggests the presence of several [Fe II] lines, such as the one at 4288, but the ascription is uncertain. Except for this point, the correspondence with the behavior of DQ Her in the descent to the great minimum is close.

On emergence from the great minimum, the spectrum continued to run true to type, as will be seen from the table on p. 96.

These descriptions and qualitative estimates correspond closely to the data for DQ Her. The nova returned to the pre-nova stage after about forty years.

Like several other novae, T Aur is now surrounded by a nebular envelope; Adams (1943) reports that Baade photographed an elliptical nebula, 12″ in diameter, in 1943.

η CARINAE *104159* 1843 —0.8

Certainly not a conventional nova, η Car is the best-observed representative of a small group of ejection variables that attain very high luminosity, perhaps intermediate between those of novae and supernovae. The most closely comparable galactic stars are RT Serpentis and RR Telescopii; parallels may perhaps be seen in the Magellanic Clouds and in some of the nearest galaxies, as noted below.

The variations of brightness can be traced for 350 years. The early observations are discussed by Müller and Hartwig (1918) and the light curve between 1836 and 1900 was compiled and illustrated by Innes (1903). In 1603 the star was probably not as bright as fifth magnitude. The first reliable observation is the one made by Halley, at fourth magnitude, in 1677. The brightness seems to have risen to second magnitude, where it remained from perhaps 1729 to 1752; in 1782 the star was again recorded as of the fourth magnitude; it seems to have been somewhat brighter in 1801, of the fourth magnitude again in 1811–15, and after a possible drop to sixth magnitude soon after 1820, it rose to first magnitude in 1827, perhaps fell slightly in 1834–37, and reached its highest maximum, at —1, in 1843. Since that time it has declined, with fluctuations, and now displays small but definite variations near the seventh (visual) magnitude. Maxima and minima, recorded since the coverage was fairly continuous, are suggested as follows by the available data.

Maximum	*m*	Minimum	*m*
1827	1:	1826:	6
1843	—1	1838	1½:
1856	0.3	1854	1:
1871	6.6	1869	7.0
1889	6.7	1886	7.6
1952	6.5	1901	7.8

The early observations indicate that in addition to the great maximum, the star fluctuated irregularly in a cycle of between 15 and 16 years. Since 1900 it had been relatively quiescent, but in 1952 it was shown by de Vaucouleurs and Eggen (1952) to have brightened again to magnitude 6.5 (vis), and the brightening was verified by photographic observations, which showed that the magnitude was 8.5 from 1935 to 1941, fluctuated between 7.4 and 8.0 from 1941 to 1949, and rose to about 7.3 in 1951. Their observations revealed more rapid, small variations also. Clearly the activities of the star are not over, and a very considerable brightening in the future is far from improbable.* The changes are not like those of a typical nova, even apart from their extreme slowness; the star had been well above its present brightness for more than two centuries before the high maximum of 1843.

* O'Connell (1956), in his detailed discussion of the recent brightening, makes the same suggestion.

The interpretation of the brightness is complicated by the presence of the expanding nebulous halo discussed by Gaviola (1949) and Thackeray (1950). The contribution of the halo to the total brightness was shown by Thackeray (1953b) to be about 1.5 magnitudes visually, and he draws the conclusion that the most recent brightening, at least, stems principally from the halo.

The spectrum, as first observed by Le Sueur (1870) showed bright lines that can be identified as those of H, He I and Fe II.*

The next observation of the spectrum, made visually by Miss Clerke (1888) in 1888, revealed no bright lines, but with characteristic acuity she surmised that η Carinae might later undergo important changes. Photographs of the spectrum in 1892 and 1893, discussed by Cannon (1916), Bok (1930) and Whitney (1952) showed a supergiant F5 spectrum with weak bright lines of H, Fe II and [Fe II]; during this time the star was fading from the maximum of 1888. By 1902, the observed spectrum consisted of bright lines of H, Fe II, [Fe II], Ti II and Cr II and the continuum was comparatively weak; the relative intensities of the bright lines appear to have changed little since then. At first unidentified, many of the prominent bright lines were first shown by Merrill (1928) to be those of [Fe II]; extensions of the identification of this and other atoms were made by Spencer Jones (1931b) and Hoffleit (1933).

The most extensive studies of the current spectrum of η Car are those of Thackeray (1951, 1953a) and Gaviola (1953). Each measures the wavelengths and estimates the intensities of many hundred bright lines; Thackeray reduces the wavelengths in accordance with the radial velocity +25 km/sec found for the star by Moore and Sanford (1913); when Gaviola's wavelengths are similarly reduced, the agreement for all but the weakest lines (not recorded by both observers) is close. The two lists constitute the richest existing material on a stellar bright-line spectrum. Space forbids more than a summary description of the results. The identifications of bright lines embrace H, He I, He II ?, [N II], N III ?, O I ?, Ne III, Na I, Mg I ?, Mg II ?, Si II, [P II], S II], [S III], Sc II, Ti II, V II, Cr II, [Cr II], [Fe I] ?, Fe II, [Fe II], Fe III, [Fe III], Co II, Ni II, [Ni II], [Cu II], Zn II. Both Gaviola and Thackeray recognize that many of the strongest bright lines show complex structure, notably those of H, [Fe II], Fe II ?, and [Fe III].

* I am indebted to Dr. W. P. Bidelman for this reference.

Thackeray's table of double emission components may be summarized as follows. The radial velocities of the fainter components are relative to the brighter component.

Element	Radial Velocity Fainter Component	Intensity Ratio Brighter/Fainter
H	—216 to —128	2 : 1
[Fe II]	—258	5 : 1
Fe II	—255	15 : 1
[Fe III]	—282	2 : 1

Gaviola considers that Hα has sixteen emission components, of which the two brightest yield a velocity difference —234 km/sec; the difference falls off in much the same sense as found by Thackeray; some of his velocities for fainter components of early Balmer lines are greater than 1000 km/sec, both positive and negative.

Even more striking is the detection of a faint continuum and numerous absorption lines. Faint absorption components of Balmer lines had been announced in 1926 by Perrine (1926). Both Gaviola and Thackeray were able to record the continuum and to measure and identify a number of additional absorption lines; their lists supplement one another, the Cordoba results extending farther to the ultraviolet. Although the two authors do not always concur on identification, the presence of lines H, He I, Na I, Ca I, Ca II, and Fe II seems well established, and absorptions in the ultraviolet recorded by Gaviola may well be ascribed to Ti II, Cr II and Mn II. Thackeray's identification of [Fe II] is discussed later. Velocities deduced by the two authors (corrected for the velocity of the star itself) are summarized below.

Element	Mean Velocity		Number of Lines	
	Thackeray	Gaviola	Thackeray	
H	—465:	—455 to —325	3	Gaviola: Hα to H 17
He I	—376	..	2	
Na I	—370	—407	1	
Ca I	..	—462	..	
Ca II	—475	—424	2	
Fe II	—432	..	4	
[Fe II]	—471	..	12	See below

Gaviola adds Fe I, with corrected velocity —328 km/sec, but the absence of some of the strongest lines of this ion makes the identification uncertain.

The absorption spectra photographed in 1952, when compared with that of 1893, as discussed by Whitney (1952), reveal a basic similarity. However, the radial velocity deduced by Whitney for the absorptions relative to the emission lines then visible was —200 km/sec for lines other than those of Fe I, and —130 km/sec for Fe I, a difference in the same sense as found by Gaviola, so the effect may be real.

We can infer that in 1952, the ejection velocity of the material responsible for the absorption lines was about 450 km/sec; in 1893 it seems to have been significantly smaller. We cannot, however, speak of an *acceleration* in connection with the change, for in both cases we are merely dealing with the current speed of ejection from the surface, and the same atoms were certainly not involved on these two occasions, nearly sixty years apart. Both the 1952 spectrum and that of 1893 were obtained during a subsidiary rise in the star's brightness. Gaviola noted an increase in the relative intensity of the continuum to the emission spectrum between 1944 and 1948, when, as we have seen, the nova was brightening. The plates from which Gaviola determined velocities were taken from 1944 to 1951; he noted changes of intensity, but did not mention changes of wavelength.

The complexities of the bright-line spectrum undoubtedly arise in part from the surrounding nebulosities, presumably ejected mainly at the maximum of 1843. The structure and motion of the nebulosities, and their relation to earlier measures, have been discussed by Gaviola (1949) and by Thackeray (1950b).

The embedded star is now of the eighth magnitude, and is the main source of the absorption spectrum recently observed by Gaviola and by Thackeray. If the maximal absolute magnitude was about —11 (see below), η Carinae is now (1956) of about absolute magnitude —4, comparable to a supergiant such as α Persei in luminosity and dimensions. Two points about its spectrum may be remarked. The Balmer lines are visible on Gaviola's spectra (which extend well into the ultraviolet) as far as H 17. The absorption lines, which are rather broad and hazy, cover a large range of excitation, He I, H, Fe II, Ca II, Ca I, Na I. The absorption lines identified by Thackeray as [Fe II] are only slightly weaker than those of Fe II. Although the occurrence of [Fe II] in absorption is definitely not an impossibility, such lines should be weaker than those of Fe II by a factor of between 100 and 1000 on account of their transition probabilities. Even though the *bright* lines of Fe II and [Fe II] are of comparable intensity (as they are in the current spectrum) the [Fe II] *absorption* lines can hardly be of comparable intensity with those of Fe II. It is true that absorption lines of [O I] have been observed in the solar spectrum, and reported for DN Gem and for V 465 Cygni. However, these lines have very different transition probabilities from those of [Fe II], as shown by the tabulation given by Bowen and Swings (1947). Data on the occurrence of the corresponding forbidden lines in *emission* are collected in several columns. It should be noted that, except for the corona, the numbers given are estimates, not necessarily on a uniform scale. The letter P denotes presence (not always simultaneously).

TRANSITION PROBABILITIES FOR FORBIDDEN LINES IN NOVAE

Atom	Wave-length	A_m $\sec^{-1}$	CP Lac	CP Pup	T Pyx	RS Oph	T Cr B	RR Pic	η Car	Corona
Ca XIII	4086.3	319	..	..	..	2	?	..	..	1.0
Ni XII	4231.4	237	..	..	..	4	?	..	..	2.6
Fe XIV	5302.86	60	P	P	2	6	P	..	..	100
Fe XI	3986.9	9.5	..	..	..	4	?	..	..	0.7
Fe X	6374.51	69	P	P	..	20	P	..	..	8.1
Fe VII	6087.6	.49	..	..	5	3	P	P	..	..
	5722.6	0.30	..	..	masked	..	..	P	..	..
	5163.2	0.21	..	..	2	0	..	P	..	..
	3758.9	0.37	..	..	2	4	..	P	..	..
Fe VI		<1*	..	..	..	..	..	P	..	..
Fe V		unknown	..	..	..	..	..	P	..	..
Fe III		unknown	..	..	..	..	..	P	P	..
Fe II		9–100*	P	..	..	..	P	P	P	..
O III	5006.84	0.016	P	P	40	3	..	P	..	..
	4958.91	0.0056	P	P	20	1	..	P	..	..
	4363.21	2.8	P	P	50	35	P	P	..	..
O I**	6363.75	0.0026	P	P	..	..	..	P	?	..
	6300.32	0.0078	P	P			..	P	..	..
	5577.35	2.2	P	P			..	P	..	..

* Bowen and Swings (1947)

** Transition probabilities from Bowen (1948)

From the relationship given by Bowen for N, the number of atoms in the lower state corresponding to an equivalent width, W:

$$N = \frac{W\, mc^2}{f\pi^2 e^2 \lambda^2} = \frac{(2J' + 1)\, 8\pi\, cW}{(2J + 1)\, A\lambda^4},$$

we see that the equivalent widths of permitted and forbidden Fe II absorption lines cannot be comparable; the former must in all cases be much larger. We note that the difference of excitation for the permitted and forbidden lines of Fe II is much smaller than for the permitted and forbidden O I lines discussed by Bowen (1948), which differed by about 9 volts. The Boltzmann factor for Fe II is accordingly much smaller, introducing a ratio of about 100 for the two types of transition. We therefore conclude that the occurrence of [Fe II] in absorption in the spectrum of η Car is improbable.

From the relationship between the rate of expansion of the nebulosities and the associated radial velocity, Thackeray (1953) concluded that the distance of η Car is about 1200 parsecs, not far from the determination by Bok (1930). The absolute magnitude at maximum must thus have been brighter than —11. Here we have another striking difference between η Car and the normal novae. The high luminosity seems well substantiated; we could escape from it by the supposition that the nebulosity now visible was ejected much later than 1843. Although *some* of the visible nebulosity may have emerged at subsidiary maxima, it is difficult to imagine that the very bright maximum was not its main source. If we suppose that the even earlier brightening also contributed something to the nebulosity, we are forced to adopt an even larger distance and a correspondingly brighter maximal absolute magnitude.

We may recall the behavior of another star that is sometimes classed with the novae: P Cygni, now of absolute magnitude —8, brightened in 1600 to the third magnitude, and thus was of absolute maximal magnitude —11. The stars are, of course, very different in many ways, but we may regard both as supergiants that threw off extensive shells. Perhaps a closer parallel with η Car is furnished by HD 34664; the resemblance is pointed out by Smith (1955), who states that the strongest [Fe II] lines are about half as strong as the permitted lines of the same ion. The absolute magnitude of HD 34664, which is in the Large Magellanic Cloud, is —7.5 photographic.

We recall that the brightest variable stars in Messier 31 and Messier 33, as described by Hubble and Sandage (1953), have the spectra of supergiant F stars; their current absolute magnitudes are in the neighborhood of —8. Their rather slow and erratic variations may find a parallel in the behavior of η Car between the years 1700 and 1830, when its absolute visual magnitude fluctuated between about —4 and —9 (if the distance of 1200 parsecs is adopted). The spectrum of HD 34664, on the other hand, suggests the post-maximum stage of η Car.

T CORONAE BOREALIS 155626 JD 02734 (1866), 31861 (1946) 2.0, 2.0

The maxima of 1866 and 1946 are the only recorded ones, but the observed outbursts have been so brief that others may have been missed.

The maximum of 1946 is well observed; McLaughlin (1946) considers that the outburst of 1866 was, on the available evidence, almost precisely similar. Many observations of the recent maximum have

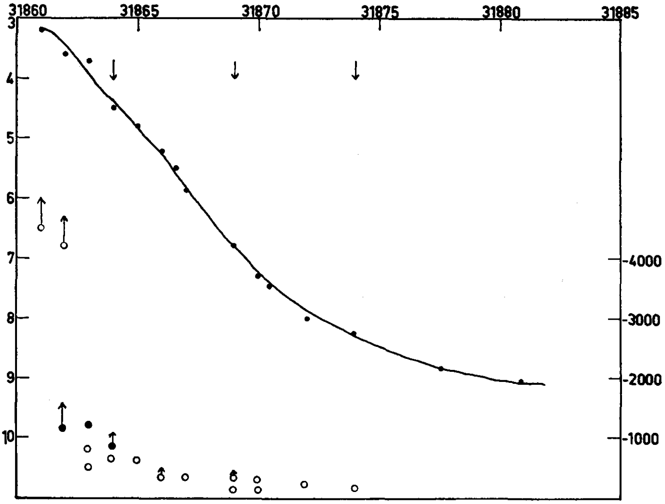


Fig. 4.5. Light curve and radial velocities for T Coronae Borealis. Abscissae are Julian Days. Ordinates are magnitudes (upper part) and radial velocities in km/sec (lower part). The dots and circles denote velocities measured at the centers of the lines; arrows extend to the velocity determined from the violet edge. Dates of appearance of prominent bright lines are shown by arrows, above: OI, NI; [FeX]; Fe [XIV].

been published; the figure embodies the visual measures published by Ashbrook (1946), Morgan and Deutsch (1947) and Pettit (1946).

Observations of radial velocity cover the first few days only; the absorptions faded early (see Fig. 4.5).

The enormous initial velocity is notable. The small later velocities, sometimes doubled, are ascribed by McLaughlin to a "shell spectrum," especially strong in lines such as He I 3888, 3965. He has recently (1957) withdrawn his suggestion of decleration.

Julian Day	Vis. Mag.	Radial Velocity km/sec	Reference
31861	3.2	—4500 (—5000)*	Morgan and Deutsch (1947)
31862	3.6	—1350	
31862	3.6	—4360 (—4700)	Herbig and Neubauer (1946)
31862,	3.6,	—4000	McLaughlin (1946)
31863	3.7	—1200	
		—800	
		—500	
31862	3.6	—1100 (—1580)	Herbig and Neubauer (1946)
31862	3.6	—1150	Sanford (1946)
31864	4.5	—855 (—1065)	Herbig and Neubauer (1946)
31864	4.5	—640	Sanford (1946)
31865	4.8	—620:	Sanford (1946)
31866	5.2	—420:	Sanford (1946)
31866	5.2	—370 (—455)	Herbig and Neubauer (1946)
31867,	6.0	—350	McLaughlin (1946)
31869	6.8		
31869	6.8	—320 (—450)	Herbig and Neubauer (1946)
31869	6.8	—300	Sanford (1946)
		—120	
31870	7.3	—300	Sanford (1946)
		—120	
31872	8.0	—210	Sanford (1946)
31874	8.1	—190	Sanford (1946)
31864 to 31872		—320	Bloch *et al.* (1946)

* Parentheses refer to the violet edge.

The development of the bright-line spectra is well summarized by Sanford (1946) in the table that follows.

T CORONAE BOREALIS: BRIGHT-LINE SPECTRA (SANFORD)

J.D. Vis. Mag.	31862 3.7	31864 4.5	31865 4.8	31866 5.2	31869 6.8	31870 7.3	31872 8.0	31874 8.1
H	*	*	*	*	*	*	*	*
He I	*	*	*	*	*	*	*	*
He II	*	*	*	*	*	*	*	*
N II					*	*	*	*
N III					*	*	*	*
N IV			*	*				
[O III]		*	*	*	*	*		
Na I	*							
Mg II		*	*	*	*	*	*	*
Si II				*		*	*	*
Ca I					*	*	*	*
Ca II	*	*	*	*	*	*	*	*
Sc II				*	*	*	*	*
Ti II					*	*	*	*
Cr I					*	*	*	*
Cr II					*	*	*	*
Fe I					*	*	*	*
Fe II	*	*	*	*	*	*	*	*
[Fe X]					*	*	*	*
[Fe XIV]								*

The emission spectra developed rapidly. On JD 31861, when only hydrogen and 4471 He I were visible in absorption, wide bright lines of H, He I and Fe II were observed by Morgan and Deutsch (1947). On JD 31862, emission lines of H, He I, He II, C II, C III, N II, N III, N V, O III, Mg II, Si II, Na I ?, Ti II were noted by Herbig and Neubauer (1946), who suggested that the N III, O III were excited by the Bowen mechanism. Similar identifications were made on three following dates by Salanave (1946), and by Bloch *et al.* (1946). On JD 31864 Deutsch (1948) detected the Paschen series, 8446 (with P 18) O I, the strongest line, 7774 O I, half as strong, and 8680 N I as bright lines. Over this interval the bright lines narrowed in a striking manner; Sanford (1946) measured a width corresponding to 2000 km/sec on JD 31862, 500 km/sec two days later, and a diminution to 190 km/sec by JD 21874.

The most striking feature of the early days of T CrB was the emergence of the "coronal Lines": 6374 [Fe X] is recorded by Sanford (1946) on JD 31869; Bloch *et al.* (1946) detected it faintly on JD 31864 and classed it as one of the strongest lines on JD 31867 to 31868; according to Sanford it was gone by JD 31885. The green coronal line 5303 [Fe XIV] was recorded by Sanford on JD 31874; Bloch *et al.* saw it ten days earlier, recorded it strong on JD 31867, fainter by JD 31872; it was recorded by Brahde (1946) on JD 31869. The intensities of these two, the most conspicuous coronal lines, are illustrated by Bloch and Tcheng (1953) in relation to Hβ. Fainter coronal lines identified by Bloch *et al.* (1946) are 3601 [Ni XVI] (JD 31866 to 31868), 4231 [Ni XII] ?, and 3986 [Fe XI] ?. If present, 4086 [Ca XIII] was very weak. The lower-excitation line 6086 [Fe VII] was not found.

Lines of [Fe II] appeared about JD 31874, and were noted to have strengthened on JD 31891 by Morgan and Deutsch (1947); Bloch *et al.* (1946) described them as strengthened by JD 31898, really strong by JD 31920.

The lines of [O III] appeared late in the spectral development; 4363 was first noted on JD 31874 by Bloch *et al.* (1946), who detected 5007 between JD 31894 and 31898. They were not strong for another month; [Ne III] strengthened at the same time.

Between JD 31970 and 31981 the star, which had faded to 9.7, brightened to 8.2; in this interval Herbig (1946) noted that the bright lines of He I, He II, N III faded until nearly invisible, especially 4686 He II; the Balmer lines also weakened. Bloch and Tcheng (1953) discussed the fall of the bright lines of H, He II, N III, [O III] and [Ne III] relative to the continuum. The coronal lines did not at first reappear, but according to Sanford (1947) 6374 [Fe X] was visible again about JD 32080 and remained so until about JD 32190. It was accompanied by 6086 [Fe VII] but not by 5303 [Fe XIV]. The lines of [O III], [Ne III], N III were recorded continuously by Sanford during this interval, except for a period of invisibility near JD 31983.

The spectrum of T CrB at minimum is that of an M star. At actual maximum the M spectrum was not seen, but Deutsch (1948) observed it on JD 31871 (7.7), and Sanford (1949) on JD 31872. A low color temperature was observed by Bloch and her associates (1946, 1953) during and after the maximum.

Similar observations, based on the color of the star as the brightness fell, have been made by Pettit (1946), who assigned the characteristic color of an M star from JD 31876 onward.

Julian Day or Year	Color Temp. °K	Vis. Mag.
31864	8300	4.5
31865	7500	4.8
31866	6500	5.2
31867	6400	5.9
31868	6300	6.4
1947	4300	
1948–1952	3900	

The velocity of the post-maximum M spectrum was shown by Sanford (1947, 1949) to vary with a regular period of 230.^{d}5 and a semi-amplitude of 21 km/sec. The systemic velocity is —29 km/sec, which agrees closely with the (constant) mean velocity from the bright lines, —28.8 km/sec. Sanford considers that the constancy of the velocity derived for the bright lines renders implausible an interpretation in terms of orbital motion of two bodies associated respectively with the M spectrum and the bright lines; compare, however, Fig. 4.6 and the discussion in the legend.

The numerous observations of the spectrum of T CrB before the great brightening of 1946 were discussed, in conjunction with the changes of brightness and color, by Payne-Gaposchkin and Wright (1946). Without making any assumption concerning possible duplicity, we separate the brightness of the "red" and "blue" components of the continuum; the spectral changes are seen to be correlated with the magnitudes of the "blue continuum," deduced from the paper cited.

No magnitude is available for JD 30753, when Swings and Struve (1943b) noted bright lines of H, He II, [O II], O III, [O III], N III, [N III], Fe II, [Fe II] ?, [Ne V] and [Fe VII]; probably the star was then brighter than magnitude 10. Absorption (shell) spectra are associated with the bright "blue continuum," as on JD 29056–29117, JD 29671–29744, and probably JD 30753.

Pettit (1946) suspected rapid variations of small range, and these are confirmed photoelectrically by Walker (1954a). Deutsch (1955) has deduced, from simultaneous photoelectric and spectroscopic observations, that the changes in brightness "cannot be attributed to

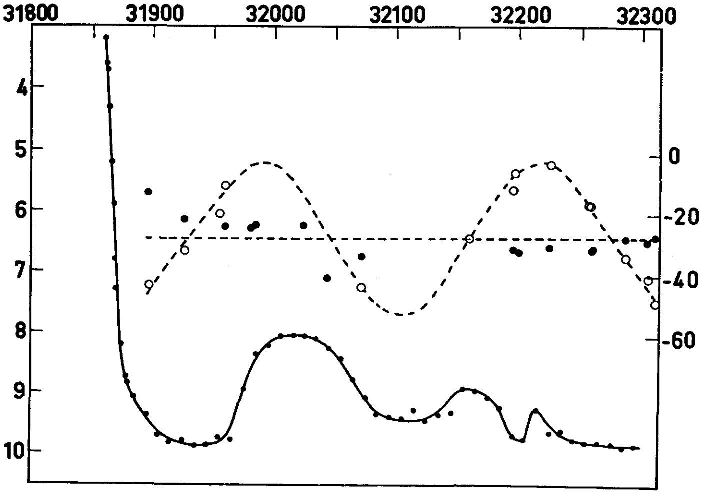


Fig. 4.6. Light curve of T Coronae Borealis and velocity curve of M star. Small dots and line: visual light curve, after Pettit and the observations of the American Association of Variable Star Observers; ordinates (left margin) are visual magnitudes; abscissae are Julian Days.

Circles and broken curve: radial velocity of the M star (Sanford); ordinates (right margin) are radial velocities, km/sec. The systemic velocity is shown by a broken line.

Large dots: velocities from bright lines in the Nova spectrum (Sanford).

Note:

a. The velocity variation is unrelated to the change of brightness.

b. The bright lines of the nova do not share the velocity variation; however, as they stem from a localized explosion, this fact does not rule out orbital motion as an interpretation of the velocity curve of the M star. They do, indeed, show traces of of the orbital trend during the first hundred days.

c. If the velocity curve is regarded as due to orbital motion, the radius of the orbit of the M star about the center of gravity of the system is about 8 × 10^7 km. If this star is an M giant of absolute magnitude zero, its radius is about 4.9 × 10^7 km; and it should produce eclipse effects on the nova itself (though only the receding portion of the nova envelope) during perhaps one quarter of the period.

changes in the strength of the Balmer emission lines and continuum". We may conclude that T CrB is the seat of continuous intrinsic variations.

Magnitude Blue Cont.	Julian Day	Description	Reference
9.8:	29056–29117	H, He I, He II, Ca II, [O III], [Ne III]	Joy (1938)
10.0	29995–30026	Increased excitation	Swings and Struve (1941)
10.0–10.1	29671–29744	H, He I, He II, Ca II, [O II], [O III], [Ne III], O III, N III	Swings, Struve and Elvey (1940)
10.3	29620–30630	H, Fe II	Swings and Struve (1941)
10.3	29417	Continua, 3000°, 16,000, about equal photographically	Wellmann (1939)
10.6	30783	Shell spectrum H, He I, Ca II, Class B8	Minkowski (1943)
10.8	29102	H, He II, N III, [O II]	Hachenberg and Wellmann (1939)
11.2	30504	M spectrum, bright H, He II	Minkowski (1943)
<13	26700	gM3, little or no emission	Berman (1932)

The interplay of "blue" and "red" spectra, particularly near maximum, led Deutsch (1948) to doubt whether T CrB can properly be regarded as binary. Bowen and Swings (1947) have indicated a type of interpretation that might make a binary hypothesis unnecessary. The balance of evidence seems, however, to be in favor of the binary nature of this nova.

V 476 CYGNI 195553 JD 22561 (1920) 2.0

The relatively smooth light curve of V 476 Cyg was associated with a complex series of absorption spectra. The figure, with the light curve taken from the discussion by Campbell (1932), shows the velocity systems, which ceased to be visible soon after the drop in brightness steepened at about JD 22602. The most complete series of spectra, obtained at Michigan, was discussed by Baldwin (1940). The data included in Fig. 4.7 are grouped in accordance with his analysis, and embody the more fragmentary data published by Wright (1920), Stratton, (1921), Adams and Joy (1920a), Frost (1920), Hnatek (1920), Wolf (1920) and Burson (1920). The velocity curves differ considerably

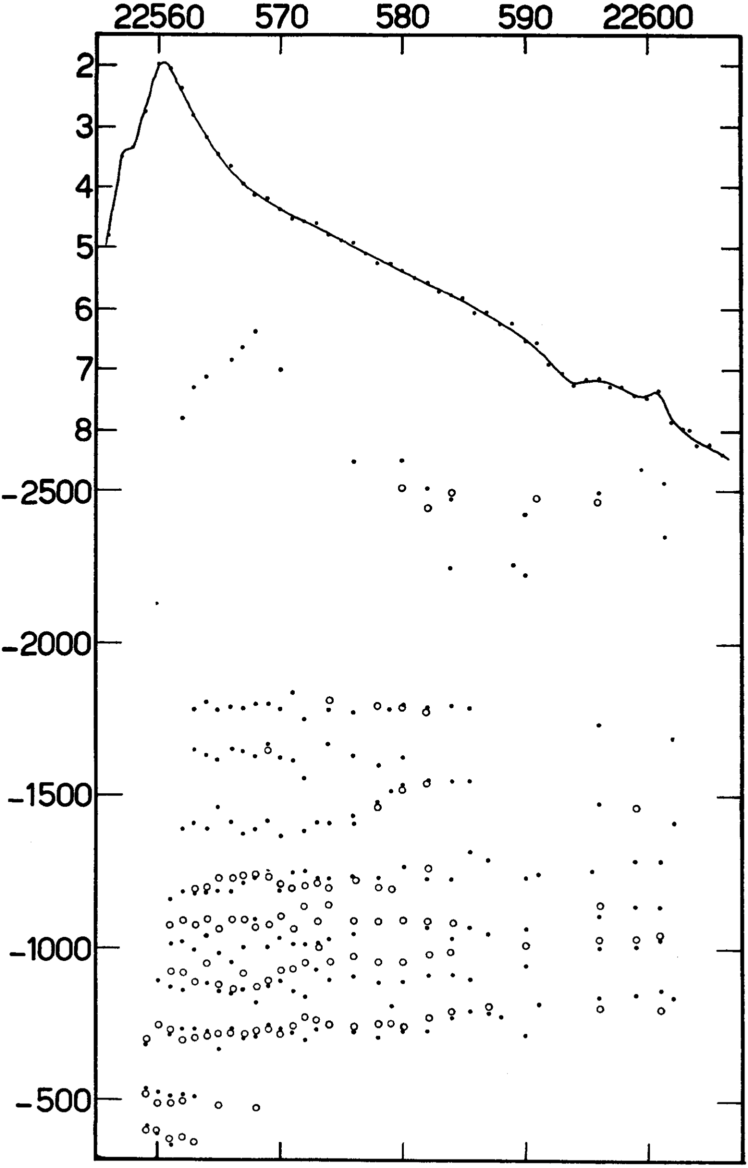


Fig. 4.7. Light curve and radial velocities for V 476 Cygni. Circles refer to lines of hydrogen.

from those published by Bertaud (1945), who did not use Baldwin's material, and was not able to differentiate the many absorption systems present on early dates, on account of the scattered material that he combined.

Baldwin distinguishes twelve absorption systems. Two (0 and I) are premaximum, of spectral class A0 and gA8–F0 respectively. The former has unusually strong lines of C I, the latter shows C I, N II, O I, O II was well as the usual ionized metals. The principal spectrum (II) is of class gA8–F2, with prominent lines of C I and O I. Absorptions III, IV, and V are similar to one another and probably associated. Absorption VI is the diffuse enhanced spectrum; it seems associated with Absorption VIII. Absorptions IX, X, XI have very large displacements and may again be associated; X and XI show the characteristic Orion lines, notably N III. Lines of N V, observed by Baldwin and by Wright, seem to be affiliated with Absorption IX.

The nova ran its course rapidly, and the emissions that went with the various absorption systems were not readily differentiated. Both Emissions I and II showed lines of H and ionized metals; emission I displayed also lines of C I, O I, [O I], N II and [N II], but no helium. The list of bright lines in the visual region given by Harper (1921) for JD 22570 (before Absorption X and XI had appeared) can be identified as those of H, [O I], N II, Fe II and Fe III.

The nebular lines of [O III] appeared after a drop of about five magnitudes in brightness, just before the absorption spectra disappeared. The auroral line 4363 was first visible about JD 22599 (visual magnitude 7.40) and the nebular pair at about the same time, according to the estimate of Payne-Gaposchkin and Gaposchkin (1942). These lines were weak at first, but on a Lick plate of JD 22913, they were the strongest in the spectrum; next in order comes [O III] 4363, then the Balmer lines, He II 4686, [Ne III] 3968 and N III 4640.

Later spectra of V 476 Cyg were discussed by Humason (1938). In the interval from JD 23547 to 29045, while the star fell in brightness from magnitude 10.9 to about 15.5, the [O III] lines declined, from being the dominant lines, into invisibility on the latter date. The line He II 4686 rose to a maximum on JD 27687 and was equal to the Balmer lines on the date of the last observation. The Balmer lines increased in relative strength at JD 27687, 28337, and then grew weaker. The continuum rose from moderate to strong intensity, relative to the bright lines, during the same interval.

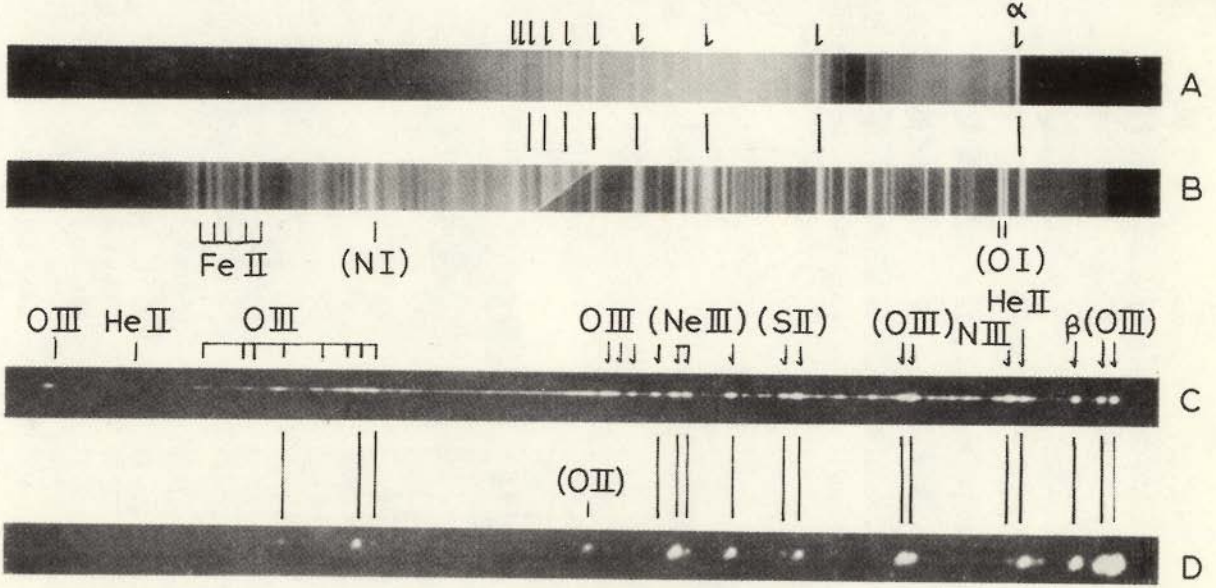


Plate I. Three stages in the spectrum of DQ Herculis (Lick Observatory).

A. 1934 December 15 (pre-maximum). The positions of the Balmer lines, from Hα onward, are marked with half arrows.

B. 1935 April 10 (beginning of great minimum), same scale as (A), Balmer lines marked. Lines of Fe II, [N I], and [O I] are marked below the spectrum.

C. 1935 June 4 (unwidened). Counting from the right, the marked lines are: [O III] 5007, 4959, Hβ, He II 4686, N III 4640, [O III] 4363, Hγ, Hδ, [S II] 4068, Hϵ, H8, [Ne III] 3869, H 9, H 10, H 11, O III 3760, O III, Multiplets 15 and 3, He II 3203, O III 3132.

D. Slitless spectrum of the planetary nebula NGC 7027, for comparison (same scale as C). The lines of [O II], only weakly present in DQ Her, are marked. The first and second O III lines from the left are reinforced by [Ne V]. Note the relatively incomplete representation of O III as compared with DQ Her. The Bowen fluorescent mechanism is more important in the spectrum of NGC 7027 than of the nova.

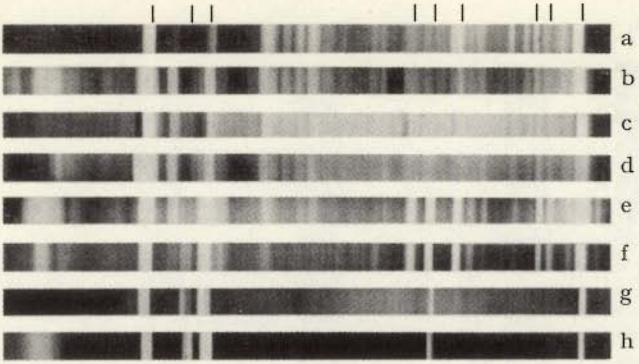


Plate II. Spectra of DN Gem (widened), Lick Observatory. Vertical lines mark the position of (left to right) Hβ, N_2, N_1, 5680, 5755, 5889–96, 6300, 6363, Hα.
(a) 1912 March 18, (b) March 20, (c) March 23, (d) March 31, (e) April 2, (f) May 9, (g) Aug. 6, (h) Nov. 18.
From Wright, Publ. Lick Obs., Vol. 14, Part II, 34.

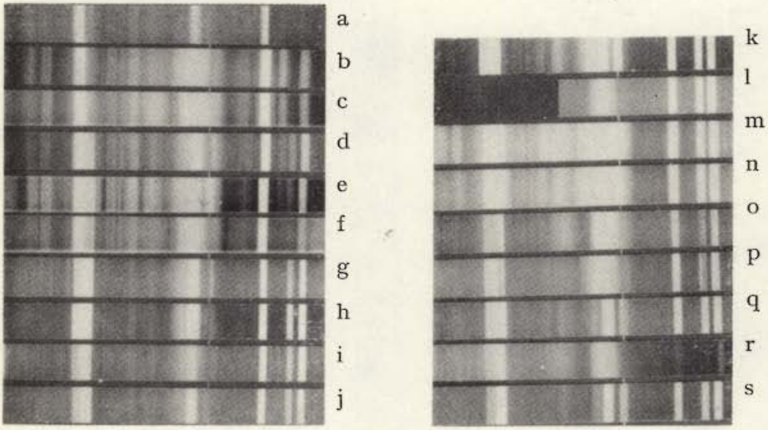


Plate III. Spectra of DN Gem (widened), Lick Observatory; region between Hβ and Hγ, to show nitrogen flaring.
(a) 1912 April 15, (b) 1912 April 16, (c) 1912 May 2, (d) 1912 May 5, (e) 1912 May 12, (f) 1912 May 27, (g) 1912 Aug. 8, (h) 1912 Aug. 18, (i) 1912 Sept. 4, (j) 1912 Sept. 11, (k) 1912 Nov. 16, (l) 1912 Nov. 18, (m) 1912 Sept. 21, (n) 1912 Nov. 26, (o) 1912 Dec. 8, (p) 1912 Dec. 9, (q) 1912 Dec. 13, (r) 1913 Febr. 4, (s) 1913 Febr. 10.
From Wright, Publ. Lick Obs., Vol. 14, Part II, 84.

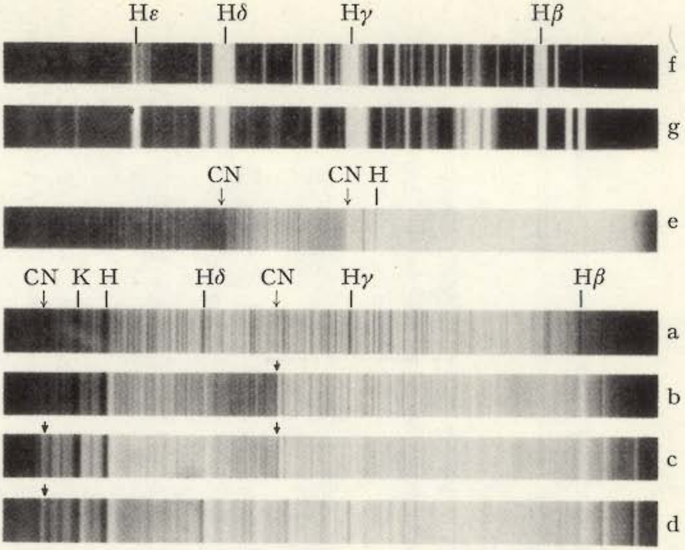


Plate IV. Spectra of DQ Herculis (widened), Lick Observatory. (a) 1934 Dec. 23, (b) 1934 Dec. 25, (c) 1934 Dec. 26, (d) 1935 Jan. 7; vertical lines mark the Balmer lines and the H and K lines of Ca II; arrows mark the heads of the CN bands. (e) 1934 Dec. 24; a vertical line marks the H line; arrows mark the heads of CN bands; (f) 1935 April 9; (g) 1935 May 24. At (f) the star is in the η Carinae stage and has entered the deep minimum; at (g) it is rising from the minimum and has entered the nebular stage.

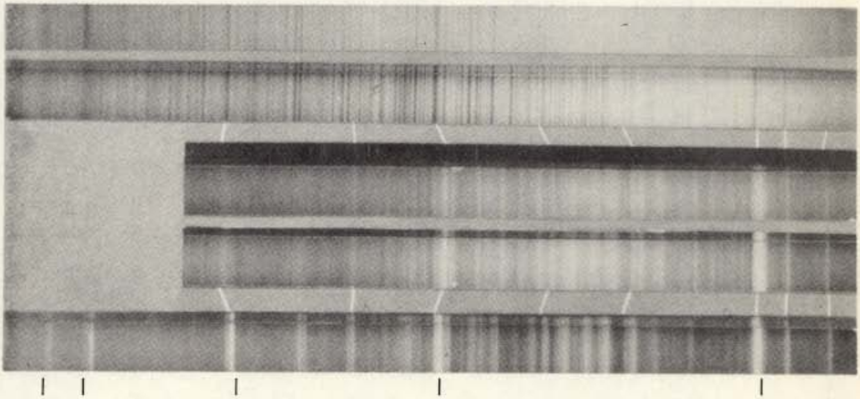


Plate V. Spectrum of Nova Pictoris.

(a) 1925 May 31, (b) June 7, (c) June 17, (d) June 17, (e) June 27; (a), (b) and (e) were taken with a single prism, and (c) and (d) with two prisms. The dispersion is different for the two sets and guide lines are provided to aid the eye in correlating the spectra. Vertical lines, right to left, mark Hβ, Hγ, Hδ, Hε, K. From Wright, P.A.S.P. Vol. 37, No. 219, 1925, 235.

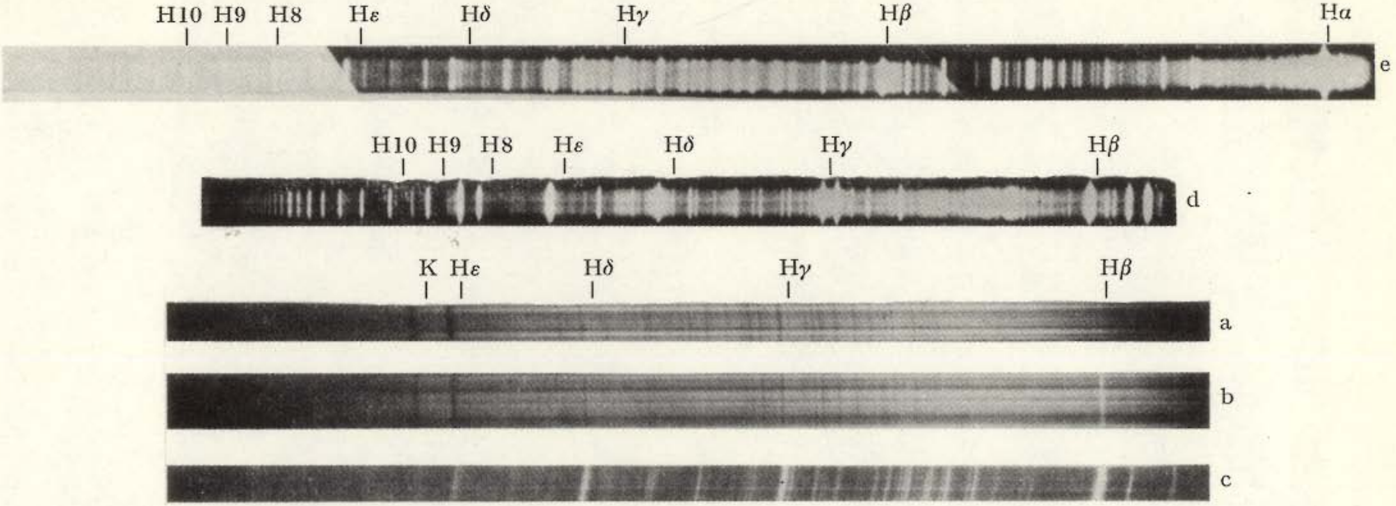


Plate VI. Spectra of RR Telescopii.

(a) JD 33101; (b) JD 33125; (c) JD 33199; objective prism spectra, Boyden Station, Harvard Observatory. (d) June 1953; slit spectrum taken by Henry Smith at the Boyden Station; (e) slit spectrum of η Carinae, for comparison, taken by Henry Smith.

A nebular disc around V 476 Cyg was discovered by Baade (1944); it had then a diameter of 4″.3; McLaughlin (1953a) associates the disc with a velocity of 650 km/sec and derives an absolute minimal magnitude of +4.1. This approach to absolute magnitude, as noted in Chapter 1, is likely to give more reliable results than the intensities of interstellar lines, as used by Wilson (1936).

Noteworthy features of V 476 Cyg are the complexity of the absorption systems; the strength of neutral carbon and oxygen in the early spectrum; and the well-observed sequence of nitrogen spectra. Although Baldwin noted the absence of N I, the lines of N II, N III, N IV (the unassigned line at 4058 noted by Baldwin in Absorption X probably has this origin) and N V appeared successively in absorption, and N II, [N II] and N III in emission.

DN GEMINORUM 064832 JD 19476 (1912) 3.5

The first really well-observed nova of modern times, DN Gem presents such a wealth of data that only a brief epitome is possible. The visual light curve, derived from the compilation by Campbell (1915), shows the typical post-maximum fluctuations of a moderately slow nova, and also the slow rise to maximum after the initial sharp brightening. The latter feature permitted pre-maximum observation of a nova spectrum, almost for the first time.

Spectroscopic observations were discussed in detail by Stratton (1920) and by Wright (1925); the former included with the Cambridge plates those taken at the Allegheney Observatory and at Bonn; the latter used the Lick plates and the Mount Wilson material more briefly discussed by Adams and Kohlschütter (1912). Additional data are contained in the papers of Belopolsky (1912), Furuhjelm (1913) and Curtiss (1923). Thus the spectrum has been studied in detail, for which the original papers should be consulted.

The spectral history falls into three sections: the interval during which absorption spectra were visible (JD 19475 to 19529), covered by almost daily observations; the interval from JD 19529 to 20186, when the Lick and Cambridge records terminate; and the spectrum taken long after maximum, between 1914 and 1933.

The first section of the spectral history will be compactly tabulated, and is also illustrated in the Figure; the occurrence of several absorption systems with different displacements and physical characters

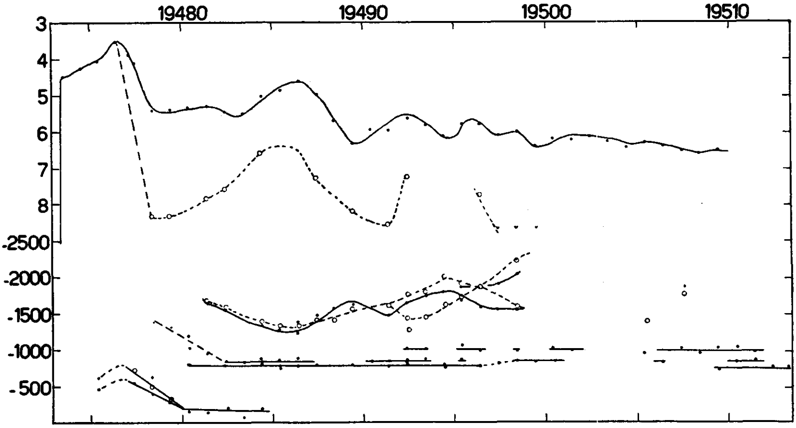


Fig. 4.8. Visual light curve, light curve of the continuum (circles) and radial velocities for DN Geminorum.

was first recognized in DN Gem, and later novae have been found to conform to the general pattern first outlined in Stratton's memoir.

Three absorption systems, designated I, II, III have been recognized. They are separately tabulated; the radial velocity is given under the first atom included in a group, the others being indicated by asterisks. The letters S and W denote observations by Stratton (1920) and

Absorption I

Julian Day	Ref.	Vis. Mag.	H	CaII	ScII	TiII	CrII	FeII	SrII	Remarks
19475	S	4.08	—450	—600						
19477	S	4.15	—570γ	*	*	*	*	*	*	Maximum, 3.50, occurred JD 19476
19478	S	5.30	—450δ	*	*	*		*	*	Absorption II appears
	W		—415							
19479	S	5.40				—330		*		
19480	S	5.40	—150					*		Fe II weak
19481	S	5.28	—150							Absorption III appears
19482	S	5.47	—210			*		*		
19483	S	5.50	—90β, δ							
19484	S	5.15	—210					.		
19491	S	5.80	+180?			*		*		

DN GEMINORUM, ABSORPTION II

			Absorption IIa (km/sec)							Absorption IIb (km/sec)							
Julian Day	Ref.	Vis. Mag.	H	He I	N II O II	Ca II	Cr II	Ti II	Fe II	H	He I	N II O II	Ca II	Ti II	Sr II	Fe II	Rem.
19478	S	5.30								—1380							1
19479	S	5.40								—1320				(*)	*		
19480	S	5.40									(—1200)				*		2
	W		—780					—750	*	—1110							
19481	S	5.28	—960	(*)				*	*								
19482	S	5.50	—900					*	*								
	W		—846			*		—810	*								
19483	S	5.50	—840	(*)				*									
19484	S	5.15	—840	(*)		*	*	*	*								
	W		—828			*		*	*								
19485	S	4.90	—810			—780		*	*								
	W		—810			—888	—768	*	*								3
19486	S	4.60	—840														
	W		—840						—786								4
19487	S	4.90	—810	(*)		—870		—810	*								
19488	S	5.70	—780			*		—750	*								
19489	S	6.30	—750						*								
19490	S	6.13	—840														
19491	S	5.80	—810					*	*								
	W		—873						—780								
19492	S	5.55	—840							—1050			—930	*	*		
	W		—831			—825			—825	—1002			—1036				5
19493	S	5.70							—750	—1070				*	*		
	S									—930							
	W		—810						—870	—990							
19494	S	6.12	—780						—750								
	W		—771						—777								
19495	S	5.92								—930					—900		6
	W		—870							—1050							
19496	S	5.74					—810	*	*	—960							
	W		—870							—1090							

DN GEMINORUM, ABSORPTION II, continued

Julian Day	Ref.	Vis. Mag.	Absorption IIa (km/sec)							Absorption IIb (km/sc)							
			H	He I	N II O II	Ca II	Cr II	Ti II	Fe II	H	He I	N II O II	Ca II	Ti II	Fe II	Sr II	Rem.
19497	S	6.25	—810					(*)	*								
19498	S	5.85					—840	*	*	—930							
	W									—969							
19499	S	6.50	—840														
19500	S	6.30								—1020							
19501	S	6.15								—990	*	*	*	*			
19503	S	6.20	—840					*	*								
19505	S	6.30								—930				*	*	*	7
19506	S	6.35	—810					(*)	*								
19507	S	6.50								—1020	*	*			*		
19508	S	6.60								—930				*	*		
19509	S	6.60	—720	*	*					—1020				*	*		
19510	S	6.45	—840		*					—1020				(*)			
19511	S	6.40	—840	*	*					—960				*	*	*	
19512	S	6.40	—750														
19514	S	6.70		—840													
	W							—750	*		—1080	*					8
19515	S	6.80								—1050	*	*		*			
19516	S	6.70								—930		(*)		(*)	(*)		
19517	S	6.80								—930	(*)	(*)		*			
19522	S	6.90								—990	(*)	(*)					

NOTES

1. Wright questions the reality of absorption on this date.
2. We assign Stratton's absorptions for this and the preceding date to Absorption IIb.
3. Wright includes Na I in the velocity for Ca II.
4. Wright notes Sc II, —780 km/sec, possible Ca I, —570 km/sec.
5. Wright notes Na I, —960 km/sec, Si III, —1110 km/sec, [O I], —960 km/sec.
6. Stratton's velocity for Fe II includes Cr II; Wright's velocities are from H γ.
7. Stratton includes Sc II in Absorption IIb.
8. Wright includes [O I] in Absorption IIb.

DN GEMINORUM, ABSORPTION III

Julian Day	Ref.	Vis. Mag.	Absorption IIIa (km/sec)						Absorption IIIb (km/sce)						
			H	He I	N II	O II	Ca II	Fe II	H	He I	N II	O II	N III	Si III	Rem.
19481	S	5.28	—1680	*	(*)	(*)									
19482	S	5.50	—1680	*	*	*									
	W		—1590	*	*	*	*								
19483	S	5.50	—1620	*	(*)	(*)									
19484	S	5.15	—1500												
	W		—1467	—1323	—1380	—1380	—1380								1
19485	S	4.90			—1350	*									
	W		—1383	—1254	—1281	*	—1290	—1410							2
19486	S	4.60	—1440												
	W		—1389					—1380							3
19487	S	4.90	—1440	*	*	*	*	*							
19488	S	5.70		—1560	*	*		*							
19489	S	5.70	—1560	(—1650)	(*)	(*)									
19490	S	6.13	—1590	*	*	*									
19491	S	5.80	—1620												
	W		—1680	—1985											4
19492	S	5.55	—1440						—1800	—1650	*	*			
	W		—1449				—1500		—1734	—1650	*	*			
19493	S	5.70	—1340						—1770	*	*	*			
	W		—1485							—1760	*	*			
19494	S	6.12							—1680	—1920	*	*			
	W								—1710	—1680:					
19495	S	5.94							—1680	*					
	W								—1740:						
	W								—1860	*	*	*			

DN GEMINORUM, ABSORPTION III, continued

Julian Day	Ref.	Vis. Mag.	Absorption IIIa (km/sec)						Absorption IIIb (km/sec)						
			H	He I	N II	O II	Ca II	Fe II	H	He I	N II	O II	N III	Si III	Rem.
19496	S	5.74							—1830	*	*	*			
19497	S	6.25		—1530					—1890		*	*			
19498	S	5.85	—1530						—2130						
	W		—1590						—2250		—2040				
19505	S	6.50	—1350	*					—1860	*	*	*			
19507	S	6.50							—1710	(—1800)	(*)	(*)			
19514	W	6.70							—2220	*					
19415	S	6.80							—1710	(*)	(*)	(*)			5
19525	W	7.00							—2160		*	*	*		
19526	W	7.00							—2460:						

NOTES

1. Wright notes C II for the only time; notes another Ca II line ?, —2325 km/sec.
2. Wright includes Si III with N II.
3. Wright includes Mg II, —1380 km/sec; Si III, —1230 km/sec.
4. Stratton calls attention to the rapid change, from —1620 to —1670 km/sec, during the night.
5. Wright notes a pair of lines, which can be identified as those of N V, on this date and on JD 19521, 19525.

Wright (1925a) respectively. Greek letters under the H column indicate the Balmer lines used, where these are specified. Remarks amplify each table.

Noteworthy points about Absorption I are: the rapid disappearance of the lines of Cr II, Sc II and Sr II, last seen at the date when Absorption II appears, JD 19478; the intermittent appearance of Ti II, perhaps weaker at maxima of light; and the possible appearance of absorption lines shifted to the red, as the star is rising to its third maximum, JD 19491.

Absorption IIb appears at the bottom of the first large drop in brightness, disappears as brightness rises and Absorption III appears, JD 19481, and reappears after another drop in brightness. It tends to fade at minima of light. Metallic lines are most persistent in this absorption; He I appears with the reappearence of Absorption II after an intermission, at JD 19501. Absorption IIa appears just after the second rise in brightness, and shows no sensible fluctuations of velocity. It shows lines of Ca II up to and through the first subsequent maximum and Sc II is seen at the brightest point of that maximum. Wright suspects absorption at red edges of hydrogen lines at JD 19480. Cr II appears after Ca II has disappeared, and persists though several fluctuations of light. Wright notes [O I] in absorption on two dates, the first being the date of the doubling of absorptions, JD 19492, the second that of a re-emergence of Absorption III, JD 19504.

Absorption III and IIIa show Ca II up to the time of the second maximum; at this date Fe II is greatly strengthened, and Mg II, Si III are seen. Ca II is also seen at the subsidiary maximum, JD 19492. Absorption IIIb shows lines of N III and N V just before the disappearance of all absorptions after JD 19526. Absorption IIIa shows no N II or O II, He I, N II and O II are present in Absorption IIIb.

These facts point to a complex interplay of excitation conditions; within each absorption spectrum the intensities seem to be functions of the apparent magnitude, and the excitation in each rises as the brightness of the nova diminishes.

The emission spectra are more difficult to analyze and present, owing to the intermingling of the emissions associated with the various absorptions. The next tabulation summarizes the appearances of the more important emission spectra.

Appearance of Emissions

Atom	Line	Ionization Potential of Previous stage ev	Upper Excitation Potential ev	Date of Appearance	m	Last Date Not Seen	Remarks
H	Balmer	..	12.04, etc.	19475	4.08	..	
Ca II	3933	6.09	3.14	19475	4.08	..	Last seen, 19505.
Na I	5889	..	2.10	19477*	4.15	..	
Fe II	5018	7.86	5.34	19478	5.30	..	Weakened by 19507.
[O I]	6300	..	1.96	19480*	5.40	..	
He I	5876	..	22.97	19480*	5.40	..	
[N II]	5755	14.49	4.04	19480*	5.40	..	
N II	5680	14.49	20.58	19480*	5.40	..	
He I	4471	..	23.63	19485	4.90	19484	
N III	4640	14.49, 29.49	32.99	19490 ?	6.13		
O II	4417	13.56	26.11	19494	6.12	19492	
C II	4267	11.20	20.86	19497	5.85		
He II	4686	24.48	50.80	19508	6.60		
N II	3995	14.49	21.51	19509	6.60	19498	
[O III]	4363	13.56, 35.00	5.33	19515	6.80	19509	
N IV	4058	14.49, 29.40, 47.24	52.98	19525	7.00		Perhaps on JD 19502.
[O III]	4959, 5007	13.56, 35.00	2.50	19526	7.0		
He II	4200	24.48	53.51	19533	7.3		
N V	4603	14.49, 29.49, 47.24, 77.09	58.99	19885*	8.7		

* May have appeared earlier

The permitted lines show increasing excitation as the brightness of the nova falls; other conditions, of course, govern the appearance of the forbidden lines. That the excitation continued to increase is shown by McLaughlin's probable indentification (1953) of [Fe X] on plates made between JD 19492 and 19532.

The most interesting of the emission phenomena, first seen in DN Gem, but later found in other novae, is the "nitrogen flaring" noted by Wright (1921, 1925). The N III group at 4640 develops broad wings, sometimes 100 A wide or more; this widening is shared by other N III lines such as those at 4097, 4103, and those near 4515, as well as by the N II lines at 5680; the He II line at 4686 seems to be suppressed during the flaring, and to be represented by a wide absorption. Wright noted also that at a period of flaring, the [N II] line 5755 was represented only by its redward maximum, while the violetward maxima of N_1 and N_2 of [O III] were the stronger.

Another important phenomenon, just mentioned, is the "saddle-shaped" form of the emission bands, which sometimes showed stronger violet maxima, sometimes equality, sometimes stronger red maxima. In the early stages the intensities tended to alternate; from JD 19493 to 19621 the red maximum was stronger, a period of near equality followed, and from JD 19682 to 20078 the violet maximum tended to be the stronger one.

A final note on this phase of the development relates to the continuum. As Wright pointed out, the subsidiary maxima and minima are always associated with strengthening and weakening of the continuum, rather than the bright lines. The date when the absorptions II and III doubled for the first time, JD 19492, was accompanied by a strengthening of the continuum and a brightening of the star from visual magnitude 5.80 to 5.55.

In the second stage of the development, after the disappearance of the absorption spectra, the principal points of interest were the changing intensities of the various bright lines. The published data do not lend themselves to numerical summary.

The next tabulation summarizes the changes of the bright lines from JD 19535 (vis. mag. 7.3) to 27396 (vis. mag. 14.5). Where dates are mentioned, visual magnitudes follow in parentheses. The basic data are furnished by Stratton (1920), Wright (1925a), Humason (1938) and McLaughlin (1953a).

CHANGES OF BRIGHT LINES BETWEEN JD 19523 AND 19700

Magnitude Change from 7.0 to 8.0

Greatly strengthened: [O III] 4363, 4959, 5007.
Strengthened: [N II] 5755.
Weakened: He I, N II.
Greatly weakened: [O I] 6300, 6363; 5577 has already disappeared.

The excitation seems to reach a peak at about JD 20186 (11.3); thereafter, as McLaughlin points out (1953a), it decreases.

DN GEMINORUM: CHANGES OF BRIGHT LINES

Atom	Line	Behavior	Strongest	Last Seen	Next Record
H	Balmer	Weakens, always present	19535 (7.1)	..	..
He I	4471	Moderate, weakens	..	19833 (8.4)	19854
He II	4686	Strengthens*	20186 (11.3)	..	..
	Pickering	Weak, weakens		21312 (11.8)	27396
C II	4267	Moderate, weakens	..	19833 (8.4)	19854
N III	4640	Strong; flares 19858, 198550, 19650	19650 (7.7)	20186 (11.3)	20273
	4515	Seen 19803–21312; not N III?	20186 (11.3)	21312 (11.8)	27396
N IV	4059	Seen at nitrogen flare	19525 (7.0)	19525 (7.0)	19526
N V	4605	Seen 19657 (7.8)	20186 (11.3)	20906 (12.0)	21312
O II	4416	Weak, weakens	..	19671 (7.8)	19694
[O III]	4363	Strong, strongest line at max.	20078	20186 (11.3)	20273
	4959	Strong	19854	20273 (11:)	20541
	5007	Strongest line at max.	19854	20273 (11:)	20541

* Suppressed at times of nitrogen flaring

At the last observation, 21 years after the outburst, only H and He II are visible in the spectrum.

The velocities of the edges of the bright bands have been measured by McLaughlin (1953b) in a search for evidence of the presence of [Fe X] within the bright line near 6363. The two other lines measured give radial velocities for the violet and red edges as follows: 5755 [N II], —762, +887; 6300 [O I], —646, +774. If the centers of these two forbidden lines can be taken to reflect the true radial velocity of the star, we obtain respectively +62.6 and +64 km/sec.

DQ HERCULIS 180445 JD 27794 (1934) 1.4

Nova Herculis is perhaps the best observed of all novae, and a brief treatment cannot do justice to the rich materal.

The light curve given in the figure is based on discussions of the very numerous observations from many sources, by Kukarkin and Gitz (1937) and by Grouiller (1935). It shows characteristic fluctuations about a slow fall from maximum, about two magnitudes in a hundred days, an abrupt drop of about nine magnitudes, a slow recovery by about six magnitudes in about a hundred days, and a very gradual decline. Several other novae, notably T Aur, have shown precisely similar behavior.

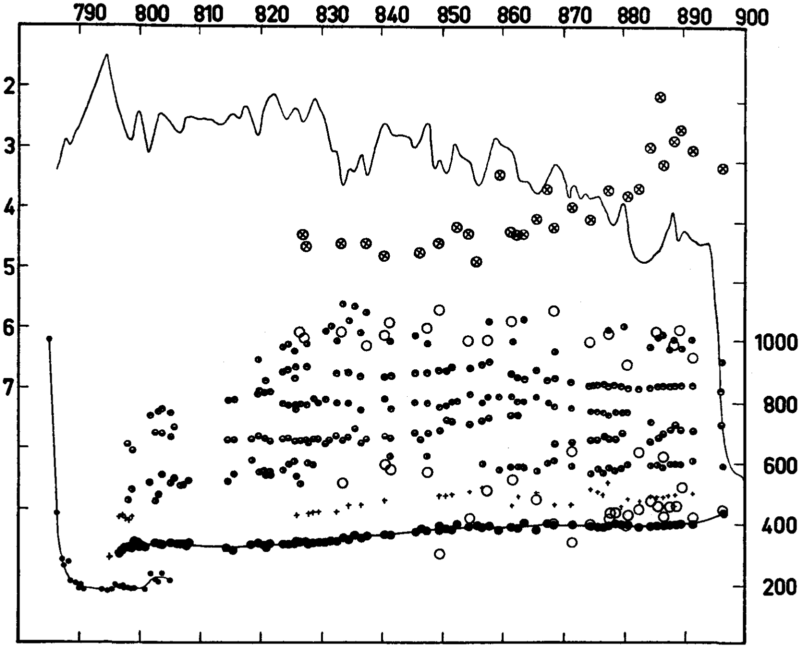


Fig. 4.9. Light curve and absorption systems for DQ Herculis up to the deep minimum. Abscissae are Julian Days; ordinates for the light curve are at the left margin.
Below are shown the velocities of the absorption systems, taken from McLaughlin (1954). Ordinates (velocities in km/sec) are on the right. The various velocity systems are labelled in accordance with McLaughlin's notation. Small dots, Absorption I; large dots, Absorption II. Absorption III is shown by half-filled dots (five systems). Absorption IV (Orion spectrum) is shown by large circles. The displaced hydrogen absorption V) is shown by circled crosses. Blended lines, and a few isolated groups of lines, are omitted for the sake of clarity.

The complex spectral development has been treated monographically by Stratton (1936b) and by McLaughlin (1937). It has also been beautifully illustrated by the Atlas of Stratton and Manning (1939), which reproduces almost daily spectra, and furnishes a model for the future discussion of novae. The absorption spectra, extensively observed, have been discussed exhaustively by McLaughlin (1937) (1953) on the basis of observations made by Merrill (1935), Bobrovnikoff (1935), Grotrian and Rambauske (1935), Adams, Joy, Christie, Sanford, and Wilson (1935), Bertaud (1945) and himself. The velocity systems, labelled in accordance with McLaughlin's analysis, are embodied in the figure.

The pre-maximum spectrum (I) was decribed by Adams and his collaborators (1935) as resembling that of α Cygni; the principal spectrum (II) was likened to that of ε Aurigae. In Absorption I McLaughlin (1937) recognized lines of H, C I, O I, Na I, Mg I, Mg II, Al II, Si II, Ca II, Sc II, Ti II, V II, Cr II, V II, Cr II, Fe II, Co I, Ni I, Ni II, Sr II, Y II, of which H, O I, Mg II, Si II, Ca II, Ti II and Fe II are conspicuous. He also suspected the presence of He I, C II, N I, N II, O II, A II, Cr I, Co II and a few others. Ca I, however, was definitely absent. In Absorption II he identified H, He I, C I, N I? O I, Na I, Mg II, Al I, Si II, Ca I, Ca II, Sc II, Ti I, Ti II, V I?, V II, Cr I, Cr II, Mn I, Fe I, Fe II, Co I, Co II?, Ni I, Ni II, Sr II, Y II, Zr II, Ba II, La II, Ce II. In addition to the line spectra, the band absorption of cyanogen was noted on JD 27796 by Wilson and Merrill (1935) at wavelength 3883, and by Dufay and Bloch (1935) on the following day. At the same time Sanford (1935) observed cyanogen bands in the red; the velocity was the same as that given by the atomic lines, —330 km/sec according to Sanford. The bands were conspicuous until JD 27800, and could be seen, according to Barbier and Chalonge (1940) until JD 27805. Stoy and Wyse (1936) pointed out that the cyanogen bands appeared at the same time as the [O I] lines.

The very rapid decrease of the velocity of Absorption I is notable. On JD 27785, the day before maximum, the velocities published by Stratton (1936b) were derived from Greenwich objective prism plates and were therefore referred to the emission maxima; Stratton estimated that they might be 25% too high "on account of halation". Even when appropriately reduced they are still very high. Stratton's table, which relates the measured velocity to the width of the emission, shows a strong correlation for each plate. The effect is probably not purely photographic; the apparent centers of the dark lines are displaced as a result of the steep gradient of the bright line, which constitutes a pseudo-continuum. Nonetheless, a real decrease of velocity is certainly shown by Absorption I. However, it should not be interpreted as a deceleration, but rather as a change in the velocity of ejection through the effective photosphere, whose level is probably determined jointly by the velocity and the density of the ejected material, as pointed out by Grotrian (1937). The changes of intensity of the various absorption systems have been well illustrated by McLaughlin (1953c), who emphasized the importance of the concept of continuous ejection in the interpretation of the absorption spectra. Spectrophotometric measures of the continuum and of equivalent widths of the Balmer lines were used by Whipple and Payne-Gaposchkin (1936) to substantiate the occurrence of continuous ejection during the first three months of the development of DQ Her.

The bright Balmer lines were very conspicuous in the pre-maximum spectrum, but faded almost to invisibility as maximum was approached. The intensities of the bright lines of H, Ca II, Fe II and [O I] were measured during the first three months by Whipple and Payne-Gaposchkin (1937). The lines of H, He I ?, C I, N I ?, N I, O I ?, [O I], Na I, Si II, Ca II, Sc II, Ti II, Cr II, Fe II and Ba II were recorded in the early emission spectrum by McLaughlin (1937). About JD 27868 the lines of [Fe II] were first recorded. Adams and Joy (1936) recorded them as weak on JD 27887, very strong on JD 27908, strong on JD 27943; meanwhile the lines of Fe II had become much weaker.

The star had gradually grown fainter with marked fluctuations. On JD 27894 the brightness dropped abruptly, the continuum faded to invisibility and the absorption spectra disappeared. The bright lines, especially the forbidden lines, had been saddle-shaped for some time. Although they persisted during the drop in brightness, they all decreased greatly in intensity, and their redward maxima all but disappeared. During the decline the nova became very red, and this was certainly a result of the great intensity of Hα, 6300, 6363 [O I] and 6583, 6548 [N II], since the bright lines contributed virtually all the light at this time. The lines of [O III] were the first nebular lines to appear, according to Wyse (1936), shortly followed by [O II] and then by [Ne III].

When the nova rose to its secondary maximum, the spectrum had changed to the characteristic nebular type. A very complete discussion of this phase has been published by Beer (1936). The intensities of the bright lines, shown in the figure, were measured by Payne-Gaposchkin and Whipple (1939). Between JD 27962 and 28084, Adams and Joy

(1936) recorded weakening of 4068 [S II], 5575, 6300, 6363 [O I], strengthening of 5755 [N II] and considerable strengthening of 4363, 5007, 4959 [O III] and 3869 [Ne III]. The excitation therefore increased steadily.

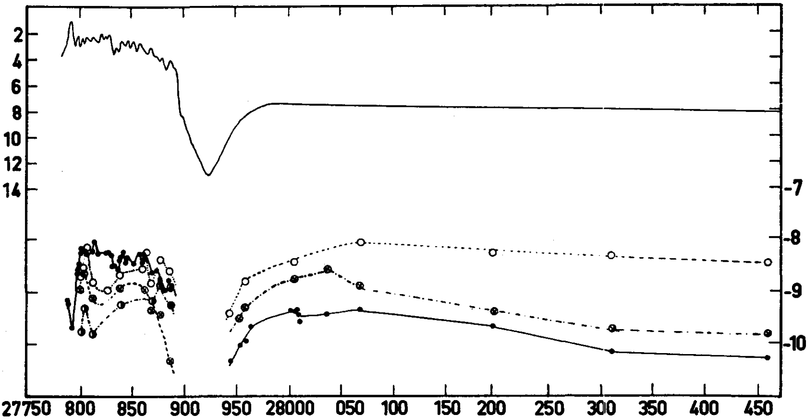


Fig. 4.10. Light curve of DQ Herculis and intensities of bright lines. Abscissae are Julian Days. Ordinates (left) are magnitudes for the light curve. Below are intensities of selected bright lines, expressed as logarithms of energy received at the earth (ergs cm^{-2} sec^{-1}). Dots: mean of the Balmer lines Hβ, Hγ, Hδ. Circles: sum of nebular pair of [O I] (left of deep minimum), [O III] (right of deep minimum). Circled crosses, auroral line of [O I] (left of deep minimum), [O III] (right of deep minimum). Half-filled circles: auroral line of [N II]. Notice that, as pointed out by Whipple and Payne-Gaposchkin (1939) the dilution increases progressively after the deep minimum, but the excitation does not.

On JD 28206, Adams and Joy (1936) recorded 6087 [Fe VII] as a prominent line. At about the same time, Popper (1936) identified other lines of [Fe VII] and a line of [Fe VI].

The later development of the bright-line spectrum has been described by Swings and Jose (1949, 1952). Intensities for a few representative lines are reproduced from their table. A blank indicates that the region was not satisfactorily covered by the plate.

Swings and Jose conclude from these intensities that the exciting star does not radiate in the ultraviolet like a black body. The excitatation seems to have reached a peak in 1940 or 1942. In 1940, Swings and Struve (1940) noted, besides atoms mentioned above, the presence

INTENSITIES OF BRIGHT LINES

Year	1940	1942	1947	1949	1950
4340 Hγ	6	8	9	10	10
4471 He I	2	1–0	1	3	
4686 He II	5	7	8	12	12
4267 C II	3	2–3	4	5	2
4650 C III	2	2	2	5	
5801 C IV	1		1		
4607 N II	2	1–0	?	1	
5755 [N II]	6		1–2	0–1	absent
4640 N III	6	10	10	11	8
3726 [O II]	6	5	8	15	20
3444 O III	3	1–0	0–1		
4363 [O III]	4	4	4	6	1
5007 [O III]	25	30	15	6	2
3869 [Ne III]	6	1–2	1	0–1	absent
3426 [Ne V]	3	0–1	0?		absent
3587 [Fe VII]	1	0	0		absent
6086 [Fe VII]	1			absent	absent

of [Fe III], [Fe VI] and [N I].

Spectrophotometric studies of the temperature of the continuum, by Whipple and Payne-Gaposchkin (1936), Beileke and Hachenberg (1935), Oehler (1935) and Petrie (1935), when compared with the light curve, show that the color temperature rises as the brightness decreases.

The apparent duplicity of DQ Her announced by Kuiper (1937, 1941) relates, not to the separation of two stellar objects, but to the development of structure in an expanding nebulous envelope. Baade (1940) photographed a fairly uniform elliptical disc; the position angle of its longer axis was the same as that recorded for the apparent double object, and the star was detected at the center of the ellipse. Light of the [N II] lines showed a different distribution from that of the [O III] lines. Both ends of the nebula were found by Swings and Struve (1940) to give similar velocity distributions. In 1942 the distribution of brightness within the nebular images was observed by Baade (1942) to have become smooth. On JD 29909, Baade found lines of [O III] strong, [Ne III] weak, and all were "saddle-shaped". The central star was of photovisual magnitude 13.35, and was described as bluish.

Although the supposed duplicity observed by Kuiper was in fact structure in the nebulous envelope, DQ Her seems to be a double star. The light curve observed by Walker (1954b) is interpreted in terms of an eclipsing system with a period of 0.194 days. The system has a suggestive similarity to the well known subdwarf system of UX UMa.

The analysis of the light curve by Walker (1955, 1956) leads to very remarkable photometric elements. The deduced radii of both stars are about one tenth of the sun's, and the masses about 0.006 suns. He adds that "it is possible that... the secondary star... is actually a normal Mitype dwarf. However, unless the system is so abnormal that the photometric elements have no meaning, the mass of the nova component must be very much less than the usually assumed value of 1.5" suns. We may recall the minimum masses of the U Geminorum stars SS Cygni (0.2 suns) and AE Aquarii (about one solar mass) deduced by Joy, as described in Chapter 8.

CP LACERTAE 221255 JD 28396 (1936) 2.1

The light curve of the bright nova CP Lacertae is taken from the compilation by Bertaud (1945), which agrees closely with a series of visual estimates by S. Gaposchkin. The various velocity systems illustrated in the figure are taken from the work of Adams, Sanford and Wilson (1936), Bobrovnikoff and Hynek (1936), Harper, Pearce, Beals, Petrie and McKellar (1937), Heard (1937), McLaughlin (1936), and Wyse (1937). Differences of ascription to the various systems by different investigators have been occasioned by the rapid development of the nova, which, as Wyse points out, had an exceptionally high final velocity. In tracing the systems, the general scheme outlined by McLaughlin has been followed, and the system of smaller velocity which he did not report has been regarded as the pre-maximum spectrum. Absorption III, which McLaughlin assigns to the "diffuse enhanced" spectrum, and "Absorption II", was noted by Wyse to be double on JD 28352, with the component of smaller velocity the stronger; Heard measured the two components from JD 28349 to 28353, and the other investigators in this interval probably measured primarily the stronger component. The Orion spectrum (Absorptions IV and V, characterized by the lines 4097, 4103 N III from JD 28352 on) underwent large fluctuations, as noted by Wyse and McLaughlin.

The development, as described by McLaughlin, was rapid; similar to that of V 603 Aql, three times as fast as V 476 Cyg, four times as

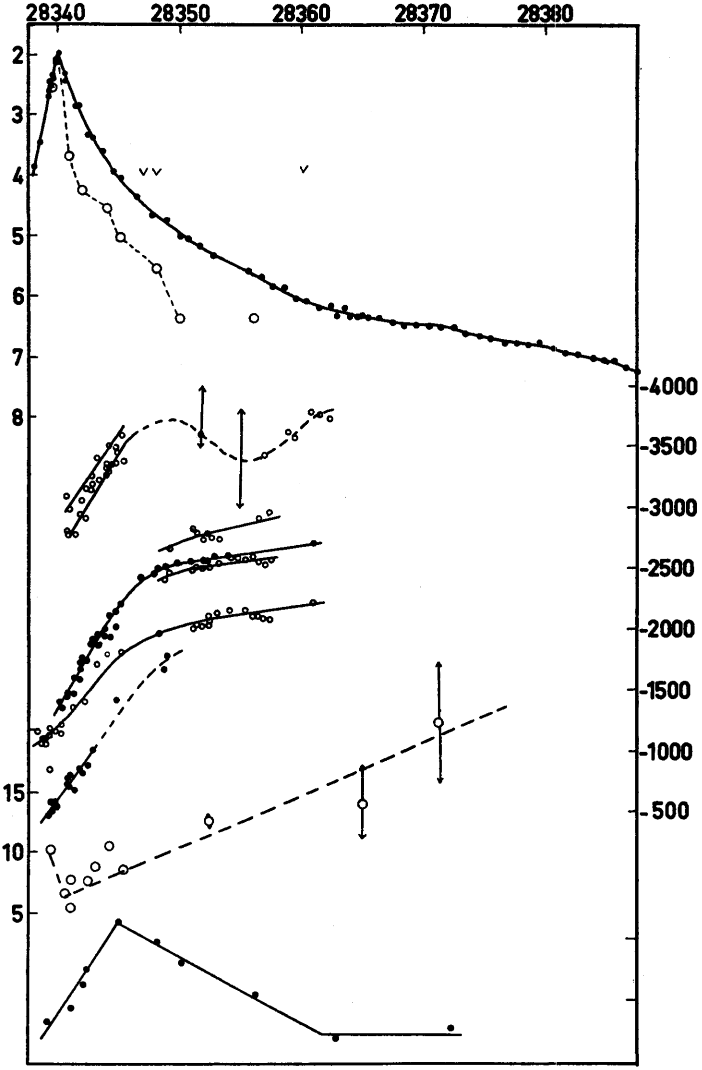
Figure	McLaughlin	Description
Abs. I	. .	
Abs. II	Abs. I	Principal spectrum: on JD 28339.3 of spectral class B9, with lines of C II, N II, O II; on JD 28340.3, class cA2, with lines of O I; on JD 2834./13, yielding to Absorption III (II), and gone by JD 28361.
Abs. III	Abs. II	Diffuse enhanced spectrum; appears JD 28340.3; JD 28341.3, class cF2; lines of H conspicuous until JD 28356, disappear about JD 28361.
Abs. IVa	Abs. III	Appeared JD 28341.3; diffuse lines of H, Ca II, Orion lines.
Abs. IVb	Abs. IV	Developed and faded with previous spectrum. H, some Fe II; lines of Na I, O I, Si II may have belonged to either or both.
Abs. V	Abs. V	4097, 4103 N III.

fast of DN Gem, Harper and his collaborators, however, regarded it as slower than V 603 Aql.
The emission lines were very wide, in conformity with the large radial velocities.

First appearances of prominent emissions were noted as follows:

Julian Day	Visual Magnitude	Line	Atom	Remarks
28340	2.0	D lines	Na I	Wyse
28340	2.0	6150, 6240	?	Wyse
28345	4.05	5314, 6000	?	Wyse
28347	4.48	6300, 6363	[O I]	Wyse; conspicuous by JD 28352
28348	4.65	5755	[N II]	Wyse; conspicuous by JD 28362
28352	5.25	4640	N III	McLaughlin
28360	6.00	5007	[O III]	Wyse; McLaughlin reports on JD 28361; strong by JD 28392.
28360	6.00	5876	He I	Wyse; strong by JD 28362.

The color temperature of CP Lac was measured by Petrie (1936), by Harper, Pearce, Beals, Petrie and McKellar (1937), by Behr (1937) and by Cecchini and Gratton (1936). The tabulation shows that it fell to a minimum near maximum brightness and rose thereafter.


28340
28350
28360
28370
28380
2
3
4
5
6
7
8
15
10
5
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500

Julian Day	Vis. Mag.	Color Temperature Harper *et al.*	Behr	Cecchini and Gratton
28339.45	2.4	10,250 ± 125		
28340.46	2.4	6,650 ± 50		
.97	2.6		8,500	
28341.05	2.7			5,400
.45	2.8	7,800 ± 200		
28342.50	3.25	7,700 ± 425		
28343.01	3.45			8,900
.98	3.75		14,000	
28344.42	3.9	10,500 ± 450		
.98	4.05		16,200	
28345.40	4.15	8,400 ± 175		
28347.95	4.65		15,800	
28352.45	5.3	12,500 ± 500		
28365.45	6.35	14,000 ± 3000		
28371.44	6.6	20,500 ± 5000		
28385.46	7.25	34,000 ± 30,000		

The bright lines showed complex structure, with two maxima and a saddle-shaped profile. Their intensities have been discussed by Popper (1940).

Fig. 4.11. Light curve, absorption velocities, temperature and Balmer decrement for CP Lacertae. Abscissae are Julian Days.
Top: curves: photographic light curve (dots) and light curve of continuum for CP Lacertae; ordinates are photographic magnitudes (left margin).
Center: velocity systems in descending order: V, IV, III (including doubled components), II, I.
Below: circles and broken line, color temperatures (see text); ordinates are temperatures (left margin).
Bottom: Logarithm of the ratio $H\beta/H\gamma$, derived from Harvard plates; ordinates on right margin, counting from bottom of figure, 0.0, 0.1, 0.2.

DK LACERTAE 224552 JD 33304 (1950) 5.4

Although it was only of fifth magnitude at maximum, DK Lac is one of the most significantly studied novae. The light curve shown in the figure is based on the critical compilation by Larsson-Leander (1954a), supplemented by the visual observations of Beyer (1952). The violent fluctuations were of unusual amplitude, and persisted over a drop of nearly seven magnitudes in the average brightness.

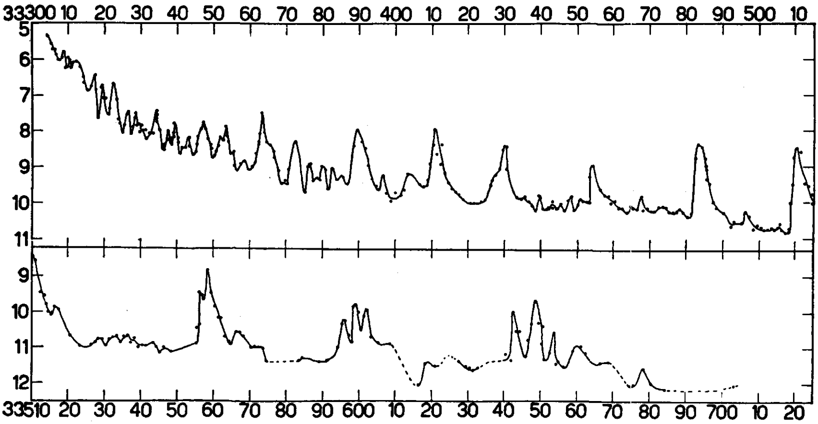


Fig. 4.12. Light curve of DK Lacertae.

The absorption spectra, observed by McLaughlin (1950), Barbière, Ribelaygue, Courtès and Fehrenbach (1950), Wellmann (1951) and Larsson-Leander (1953, 1954b), were complex, and recall those of DN Gem in general behavior. The investigators differ somewhat in their ascription of lines to the various absorption systems. Fig. 4.13 shows a section of the light curve, beginning shortly after the maximum and the absorption systems and spectral changes associated with it. The velocities are marked according to McLaughlin's notation, and all available data are included.

The velocity systems have been exhaustively discussed in the papers cited. Their relationship to the light curve is well defined. The appearance of a new absorption system usually followed a decline in brightness. Perhaps II_1 and II_2 were associated with the minimum at JD 33307.5; III_1, III_2, III_3 and III_4 appeared at or soon after the minima at JD 33309, 33311, 33315.5, and 33321.5, respectively. The

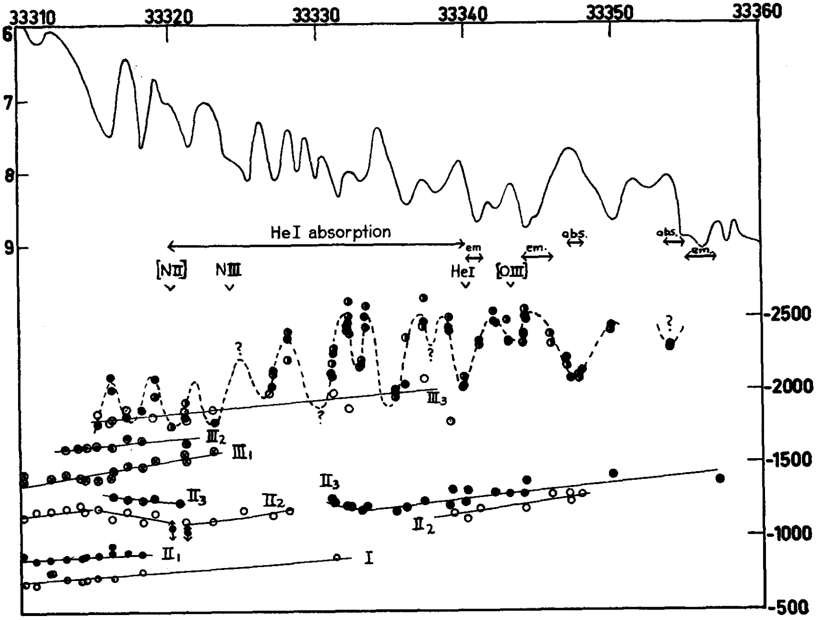


Fig. 4.13. Part of the light curve of DK Lacertae and the velocity systems for the same interval (notation of Larsson-Leander). Different systems are shown by distinctive symbols, and are arbitrarily joined by lines for clarity. Compare Fig. 4.12. Abscissa and ordinate are Julian Days and magnitudes (left margin), km/sec (right margin). The alternation of He I absorption and emission, and the first appearance for bright lines of [N II], N III, He I and [O III] are indicated.

Note:

a. The relationship of the Orion, N III spectra (broken curve) to the light curve: conspicuous minima of the light curve tend to be associated with maxima of the velocities and vice versa.

b. The "flashes" occur near minima of the light curve.

c. He I absorption gives way to He I emission at minima of the light curve below about $8^m.7$, and recurs at maxima.

d. Absorption II_1 and II_2 appear to coalesce near JD 33320.

e. Absorption III_3 does not share the fluctuations of the Orion and N III spectra, though the velocities overlap.

f. The absorption spectra do not disappear at minima of the light curve, such as those at JD 33344, 33350; contrast the behavior of V 603 Aquilae.

Orion absorption spectrum and the N III absorption allied with it appeared immediately after JD 33321.5.

The changes of velocity from day to day that were shown by the Orion and N III systems were closely related to the light curve. Minima of velocity always went with high maxima of the light curve, and the N III spectrum continued to show this tendency as long as it was observed. However, some low maxima were not matched by minima of velocity. The correlation between the Orion and N III velocities and the magnitude of the nova, pointed out by Wellmann and Larsson-Leander, is another way of illustrating the relation between the velocity curves and the light curve. The very similar pattern for V 603 Aql is recalled. None of the other absorption systems, excepting III_4, reflects the fluctuations of the light curve; here, again, we recall V 603 Aql, but in that nova the earlier absorption systems were less complex.

The emission features also tend to appear after minima of the light curve. The [O I], [N II], N III, He I, and [O III] "flashes" followed respectively the minima at JD 33309, 33332, 33324, 33341, and 33344. The alternation of absorption and emission for the He I spectrum, described by Barbière and collaborators, followed the light curve: emission appeared with the star fell below about magnitude 8.7, absorption when it was brighter.

Both Wellmann and Larsson-Leander demonstrated that the spectrum of DK Lac was almost uniquely correlated with the brightness of the nova. As the star dropped from seventh magnitude, the O II, N II and He I absorptions first increased to a maximum of intensity near magnitude 7.8, they declined to invisibility near magnitude 8.5. The N III absorptions reached maximum near magnitude 8.2, and disappeared a little below ninth magnitude. The bright lines behaved similarly: maximum was reached at a fainter magnitude than for the corresponding absorption lines. The Balmer decrement also decreased as the brightness fell.

The relation between type of spectrum and magnitude is summarized by Larsson-Leander in the accompanying table. The striking feature of the relationship lies in the recrudescence of earlier spectral types during the late flarings of the nova by a magnitude or more. Although the N III absorption spectrum was stated by Larsson-Leander to have disappeared after about JD 33360, it was observed again by Wellmann at the bright flarings of JD 33412, 33429, 33485, and 33558, when the star rose briefly above the ninth magnitude.

Spectral Type	Description	Magnitude Intervals
Q0	Pre-outburst	Not observed
Q1	Pre-maximum	Not observed
Q2	Post-maximum, principal absorption and emission	to 6.0
Q2–3		6.0 to 6.1
Q3	Diffuse enhanced stage	6.1 to 7.3
Q3–4		7.3 to 7.5
Q4	Orion absorption stage	7.5 to 7.9
Q4–5w		7.9 to 8.1
Q5w	4640 stage	8.1 to 8.5
Q6w	Transition stage with notrogen and nebular spectra	8.5 to 9.5
Q7	Fully developed nebular stage	9.5 to –
Q8	Wolf-Rayet stage	Not observed
Q9	Final stage, identical with Q0 ?	Not observed

The emissions consistently showed a castellated structure with a central maximum. The form of the lines suggests the superimposition of two saddle-shaped profiles and a central peak, each of the saddle-shaped profiles having the red edge much the stronger, at least for the Balmer lines. The structure near 4640 is naturally more complex, but appears to be different; possibly, as with CP Pup, the profile of He II 4686 has the violet edge stronger than the red. At certain of the minima, the structure of 4640 suggests nitrogen "flaring" like that shown by DN Gem.

The redward emission edges of the bright lines correspond in velocity to the Orion spectrum and the principal spectrum. The central maximum has a width of about ±400 km/sec.

The clear-cut results that have been obtained for DK Lac make it a star high importance for the study of novae. In many ways it bears out the findings for V 603 Aql. However, its light curve is unique, and so is the close relationship between its spectral behavior and its brightness.

RS OPHIUCHI 174406 JD 14458: (1898), 27297 (1933) 4.3

Of the two maxima, in 1898 and 1933, the second is by far the best observed. The photographic observations published by Prager (1940) show that the star rose about 3½ magnitudes a day just before maximum on JD 27297. Prager considered that the forms of the two maxima were probably similar, if the poorly-observed rise of 1898 took place on JD 14458. The light curve of 1933 is taken from the compilation of Bertaud (1947). The drop in brightness was at first very steep and seems to have been smooth.

The first spectra were obtained on JD 27301, four days after maximum. Adams and Joy (1933a) derived a velocity of —60 km/sec from lines of hydrogen on this date. Apparently the absorption faded rapidly; it was much fainter on JD 27303. Between JD 27303 and 27314, Westgate (1933) noted rapid fading of Fe II, He I nearly constant, and the appearance of He II on JD 27314.

The bright-line spectrum developed rapidly. Adams and Joy (1933a) noted bright lines of H, He I and Fe II on JD 27301; strong Hα gave the star a red color. On JD 27301 to 27305, Wright and Neubauer (1933) noted also 5755 [N II] and bright lines that may be 6300, 6363 [O I].

On JD 27303, Adams and Joy (1933a) observed 4363 [O III] as a sharp, narrow bright line. By JD 27316, the lines 3689, 3968 [Ne III], 4363, 5007, 4959 [O III] were all visible as sharp, narrow lines. By JD 27314, 4639 N III and 4686 He II were prominent; during the following days, 4686 He II varied in intensity, being weakened as lines of He I strengthened. This effect is shown also by the measures of intensities of bright lines by Sayer (1937). By JD 27318, the line 4686 He II was at its strongest. During this interval the bright lines grew narrower and sharper.

Striking changes had taken place by JD 27348, when the star had declined by about five magnitudes. Adams and Joy (1933b) observed the coronal lines 6374 [Fe X] and 5303 [Fe XIV]; the former may have already have been present on JD 27324, but not the latter. They recorded the appearance of the other coronal lines soon afterwards. A complete discussion of the identification of the bright lines for the interval JD 27318 to 27387 by Joy and Swings (1945) records the presence of lines of H, He I, He II, C III, [N II], N III, [O I], O III, [O III], [Ne III], [Ne IV], Na I, Si I:, Si II, Si III, Si IV, [S II], [S III], [A V], [A XI], [K IV], [Ca V], [Ca VI], [Ca VII], [Ca XIII], [Sc VIII], Fe II, [Fe II], [Fe IV], [Fe V], [Fe VI], [Fe VII], [Fe X], [Fe XIV], [Ni XII], [Kr III]. The excitation was thus extremely high, though not so high as in the solar corona. A line of [K XI] was added to the identifications by Bowen and Swings (1947).

By about JD 27540, Adams and Joy (1934) noted the disappearance of the coronal lines; the bright lines of hydrogen were the most prominent; He I was moderately strong; 4630, 4640 N III and 4650 C III were well marked, and 4686 He II was stronger than in pre-maximum spectra, which are otherwise very similar. The star had fallen to about twelfth magnitude.

Spectrophotometric measures of color temperature by Sayer (1947) indicated a decline from 7800° to 5800° between JD 27301 and 27315, and a rise from 5500° to 6200° between JD 27325 and 27327. On JD 27315, Wilson and Williams (1934) obtained the lower color temperature 4000°.

Brightness at minimum is variable, and the spectrum also undergoes changes. On JD 23621, when the magnitude was 11.5, Adams, Humason and Joy (1927) observed weak bright lines of hydrogen and Fe II; they suggested a basic spectrum of Class G. Humason (1938), while reiterating that absorption lines are present, does not confirm this spectral class, which refers primarily to the apparent distribution of energy in the continuum. On JD 28397 (three years after the maximum of 1933) he observes bright lines of hydrogen, 5007 and 4959 [O III], and no absorptions.

Later observations of the minimal spectrum have been made by Swings and Struve (1941, 1943a). On about JD 30115 they identified bright lines of H, He I, He II, O III, [O III], N III, [Ne III]. No lines of [O II] were found; the lines of [Ne III] and [O III] were of about equal intensity. On JD 30560, 30570, 30573, they observed lines of H, He I, He II, C II, C III, N II, N III, [O III], [Ne III], Mg II, Si II, [S II], Ca II, Ti II, Cr II, Ti II, Fe II, [Fe II], [Fe X]. Lines of [O III] were now stronger than those of [Ne III]. These changes seem to have followed a minor brightening of the star, with a peak of about JD 30475.

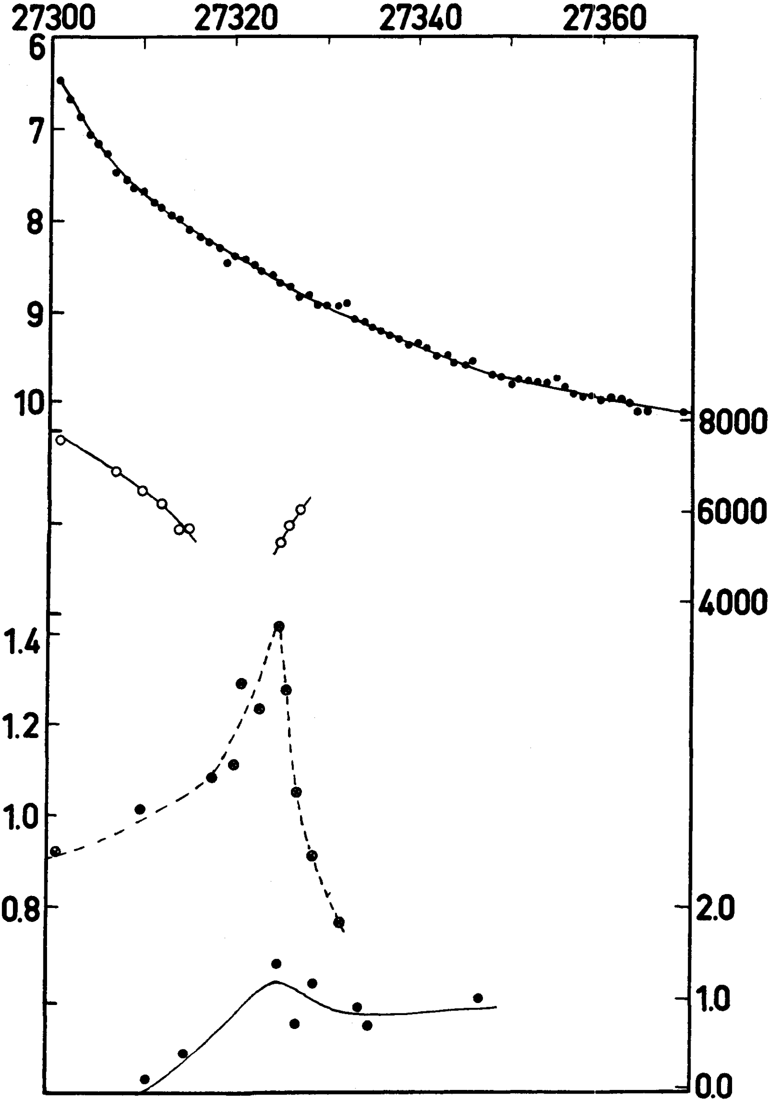


Fig. 4.14. For legend, see p. 139

GK PERSEI 032443 JD 15439 (1901) 0.2

The first bright nova of the twentieth century has many points of interest. Its light curve underwent large semiperiodic fluctuations during the transition stage, more rapid than those shown by most stars that show this feature. The light curve shown in the diagram is derived by a selective rediscussion of the visual observations compiled by Campbell (1903).

A monographic discussion of the spectral changes by McLaughlin (1949) embodies the studies of Adams (1901), Cannon (1912), Campbell and Wright (1901), Hale (1901), Belopolsky (1903), Stratton (1936a), Vogel (1901) and others.

The pre-maximum spectrum on JD 15438 was that of a peculiar B star with broad absorption lines of H, He I, C II, N II, O II, Si II, Si III, S II, Mg II. The Balmer lines and 4481 Mg II were strong and showed weak emissions to the red.

On JD 15439, at maximum, the lines characteristic of a B Star had faded, and the spectral class was about A0. On JD 15440 it was about A 5, and absorption lines of Fe II, Ti II were visible.

McLaughlin (1949) has compiled or derived velocities for three absorption systems: Absorption I (pre-maximum), Absorption II

Fig. 4.14. Light curve, temperature and line intensities for RS Ophiuchi. Abscissae are Julian Days.
Top curve: Photographic light curve at the maximum of 1933; ordinates (left) are magnitudes.
Next curve: color temperature, after Sayer; ordinates are temperatures (right).
Third curve: logarithm of the ratio Hα/Hβ, after Sayer; ordinates on the left.
Fourth curve: logarithm of the ratio 4686 He II/4471 He I, after Sayer; ordinates on the right.
Note that at or near JD 27320 the color temperature falls to a minimum, the Balmer decrement reaches an abrupt (and very high) maximum, and the ratio He II/He I goes through a maximum. Part of the intensity of Hα may come from the pair of [N II] lines that flank it, but there can be no doubt that the Balmer decrement is very large at the maximum, and changes greatly before and after it.

(principal spectrum, A5p), Absorption III (diffuse enhanced), and a system of Orion lines, including He I, N II, O II, N III, which were perhaps to be associated with Absorption III. During the transitional oscillations, the absorption spectra tended to disappear at the minima.

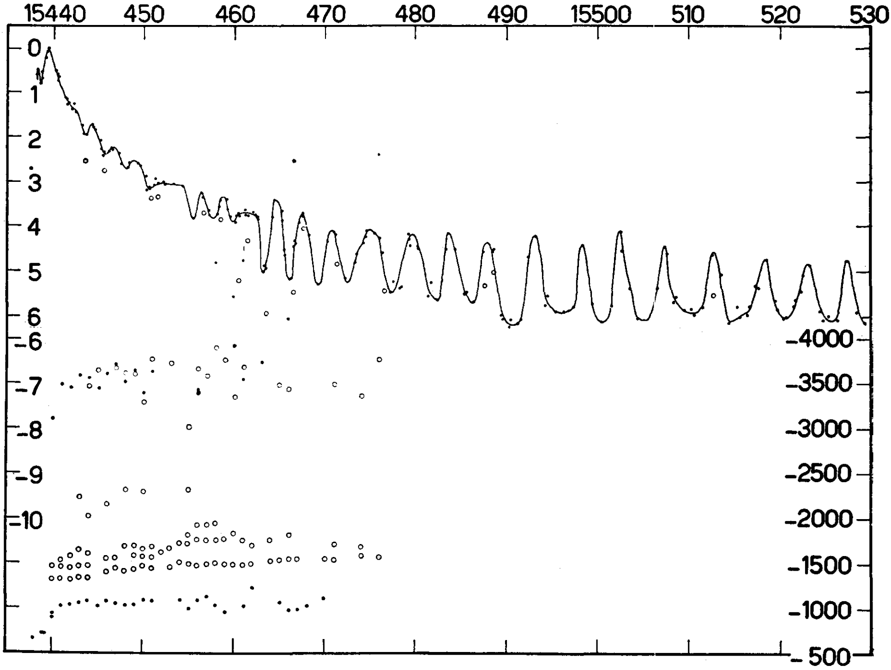


Fig. 4.15. Light curve of GK Persei and velocities of absorption systems.

The emissions present in the pre-maximum spectrum had disappeared at maximum on the following day. Thereafter the bright Balmer lines and lines of Fe II appeared as the star faded. The lines of O I were observed by JD 15441, and 4471 He I on JD 15445. Hazy Orion emissions (N II, N III) were visible, at 4640 for instance, by JD 15451; they disappeared at the first deep fluctuation on JD 15461, reappearing and vanishing at subsequent maxima and minima. When the broad band at 4640 disappeared at the minima, well-marked narrower 4640 N III and 4686 He II emerged, also 4725 [Ne IV] ? after JD 15467.

The lines of [O III], which had appeared when the fluctuations began (4363 on JD 15464 and 5007 four days later) were intensified at the minima and extinguished at the maxima. The fluctuations of brightness, pronounced enough in the visual light curve, are seen to be even larger when the continuum is isolated.

The structure of the bright lines early became complex, and underwent some changes of intensity and velocity, not uniquely related to the fluctuations of light, although McLaughlin (1949) noted that the greatest redward asymmetry tended to be associated with the maxima.

One of the striking features of the nebular spectrum of GK Per was the great prominence of the lines of neon. The lines 3869, 3968 [Ne III] were the strongest lines in the photographic spectrum during most of 1901. The line 4725 [Ne IV] ? was unusually strong during the year, and Perrine (1903) noted two strong lines in September-October 1901 which McLaughlin (1949) identifies as probably 3342 [Ne III], 3346 [Ne V] and 3426 [Ne V]. That this observation does not necessarily point to unusual abundance of neon is shown by their disappearance, noted by Hartmann (1908), late in the year. In the three following years the [Ne III] and [O III] lines seem to have had very similar intensities. By 1905 the only observable lines were 4686 He II and Hβ. Between the years 1913 and 1939, McLaughlin (1949) gives intensities for the Balmer lines (strongest on the last date), 4471 and 4026 He I, 4686 He II (strongest on the last date), 4640 N III.

An expanding nebular shell surrounds GK Persei. The spectrum shows velocity-distribution over the nebular image that points to the presence of an incomplete expanding spheroidal shell. In 1934 the lines 3869, 3968 [Ne III] were much stronger than 5007, 4959 [O III] in the nebular spectrum photographed by Humason (1935).

The illumination of the nebulosity seen near GK Per late in 1901 has been the subject of many speculations. Couderc (1939) has analyzed the observations and concludes that the illuminated nebula is a roughly plane sheet between the observer and the nova and about 46 light years from the latter.

If the analysis of Couderc is correct, the argument of Oort (1951) that the expanding shell has recently reached the interstellar material responsible for the light-echo, must be abandoned. If the ejected material is now interacting with the interstellar nebulosity, the latter must be nearer to the nova than 46 light years.

RR PICTORIS *063462* JD 24310 (1925) 1.2

The light curve of RR Pictoris is remarkable for the long pre-maximum rise; the spectrum at the time of first observation makes clear that the observed maximum was the first one. The diagram of the light curve is made on the basis of the compilation of magnitudes by Spencer Jones (1931a); the magnitudes of the continuum are taken from the spectrophotometric study by Payne-Gaposchkin and Menzel (1938). The velocity systems shown in the diagram are taken from the study by Spencer Jones (1931).

The seven absorption systems are characterized by Spencer Jones as follows:

Absorption	Description	Remarks
I	Ca II, H, Fe II, Ti II, Sr II, Sc II; absorption broad and diffuse, many with narrow, weak emissions to the red. Spectral class cF5.	Pre-maximum spectrum
II	Fe I, Mn I, Cr I more prominent than in Absorption I. Spectrum cF8.	Principal spectrum
III	Relic of Absorption I, Sr II has disappeared.	
IV	H and 4923, 5018, 5169 Fe II; very weak at first, broad and strong by JD 24322, faded by JD 24329.	
V	Weak and diffuse JD 24330, strengthened thereafter. Very sharp; strong H, Ca II; Ti II stronger than in Absorption I; Mg II, Sr II weak. Faded until only H visible.	
VI	H, Ca II, weak Fe II, Ti II, Cr II, Sc II; finally merges with Absorption V.	
VII	H, He I, latter unaccompanied by emission. Large fluctuations of velocity and intensity.	Orion spectrum

The fluctuations of velocity of Absorption VII, perhaps also of VI and IV, are associated with the variations of the continuum; as with other novae, minima of velocity go with maximum of the continuum. None of the prominent forbidden bright lines appear during these early stages, except the line 4068 of [S II].

Discussion of the early spectrum were made by Wright (1925b, 1926) and by Payne-Gaposchkin and Menzel, as well as the extensive monograph of Spencer Jones.

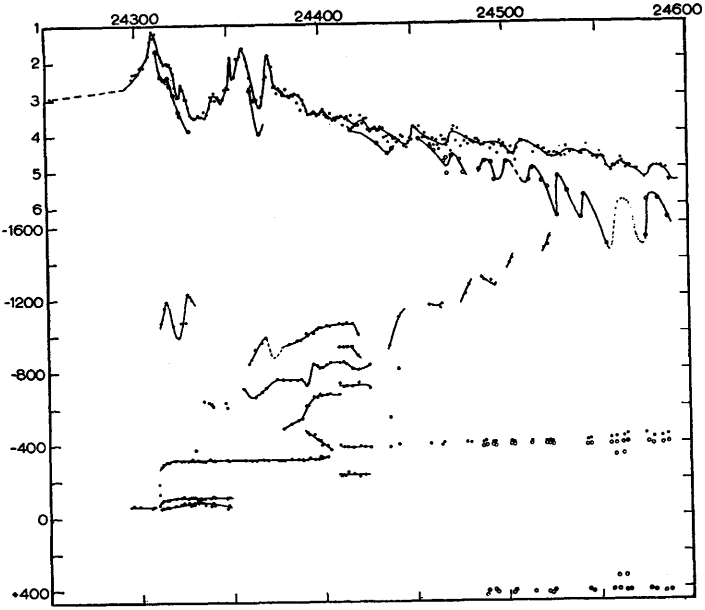


Fig. 4. 16. Light curve and velocity systems of RR Pictoris.
Above, visual light curve (dots) and light curve of continuum (circles).
Below, radial velocities from absorption lines (after Spencer Jones), dots. Radial velocities of edges of emission lines, circles.
Ordinates are Julian Days; abscissae are magnitudes (above) and radial velocities (below).

The table contains intensities of selected bright lines, deduced by means of the quantitative measures of Payne-Gaposchkin and Menzel, and the estimated intensities of Spencer Jones (1931, 1932, 1933, 1934); the first six columns give the logarithms of intensity (ergs cm^{-2} sec^{-1}), the next two, the numerical estimates, and the next two, the descriptions, of Spencer Jones. The last two columns display the negative results of Thackeray (1949) and Henize and McLaughlin (1950); the former described a continuum with no observable bright lines, the latter, a continuum with weak Hα.

A striking feature of RR Pic was the prominence of the lines of iron from the first. The successive display of the forbidden lines up to those of [Fe VII] is shown by the table. Between 1931 and 1934 the [Fe VII] lines dominated the spectrum, but they had disappeared by 1948.

EMISSION SPECTRUM OF RR PICTORIS (SELECTED LINES)

Julian Day		24328	24448	24500	24575	24728	25400	26500	26700	27200	27600	32700	33400
Vis. Mag.		3.0	3.8	4.0	5.3	5.6	7.1	8.3	8.5	8.7	8.8	11.1	11.1
H	4861	—7.6	—7.8	—7.9	—7.7	—7.7	—8.8	15	15	mod.	str.	. .	Hα only ?
	4340	—7.8	—8.2	—8.2	—8.0	—8.3	—8.9	12	12	str.	str.	. .	. .
	4101	—7.7	—8.2	—8.3	—8.3	—8.3	—9.0	5	5	mod.	str.	. .	. .
He I	4471	. .	. .	. .	—8.4	—8.6	—9.7	. .	. .	. .	. .	. .	. .
	4026	. .	. .	. .	—8.8	—9.1	—9.8	. .	. .	. .	. .	. .	. .
He II	4686	. .	. .	. .	. .	—8.4	—8.7	40	40	str.	str.	. .	. .
N III	4640	. .	. .	. .	. .	—9.3	—9.9	. .	. .	. .	. .	. .	. .
[O III]	4363	. .	. .	. .	—8.6	—8.6	—9.2	1	1	v. wk.	v. wk.	. .	. .
	4959	. .	. .	. .	—8.9	—9.3	—8.8	. .	. .	. .	. .	. .	. .
	5007	. .	. .	. .	—7.8	—8.2	—8.7	. .	. .	. .	?	. .	. .
[Ne III]	3968	. .	. .	. .	—8.4	—8.2	—8.8		2	wk	mod	. .	. .
	3869	. .	. .	. .	—8.8	—7.6	—8.0				wk	. .	. .
[S II]	4068	—8.4	—8.7	—9.2	—9.0	—9.5:	. .	. .	. .	. .	. .	. .	. .
Ca II	3933	—7.6	—8.6	—8.7	. .	. .	. .	. .	. .	. .	. .	. .	. .
Ti II	4289	—8.3	—8.7	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
Fe I	4202	—8.3	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
Fe II	4924	—7.8	—8.1	—8.2	. .	. .	. .	. .	. .	. .	. .	. .	. .
	4178	—8.2	—8.6	—8.9	. .	. .	. .	. .	. .	. .	. .	. .	. .
[Fe II]	4413	. .	—8.6	—8.9	—8.9	—9.8	—9.8	. .	. .	. .	. .	. .	. .
	4243	. .	—8.6	—8.8	—8.9	—9.5	—9.6:	. .	. .	. .	. .	. .	. .
[Fe III]	4658	. .	. .	. .	—8.8	—9.5	—9.9	. .	. .	. .	. .	. .	. .
	4813	. .	. .	. .	—8.9	—9.7	—9.8	. .	. .	. .	. .	. .	. .
[Fe V]	4178	. .	. .	. .	. .	—9.5	—9.7	. .	. .	. .	. .	. .	. .
	4072	. .	. .	. .	. .	—9.4	—9.6	. .	. .	. .	v. wk.	. .	. .
[Fe VI]	5271	. .	. .	. .	. .	—9.6	—9.8	8	8	wk.	p	. .	. .
	5172	. .	. .	. .	. .	—9.5	—9.5	5	5	wk.	p	. .	. .
[Fe VII]	5720	. .	. .	. .	. .	—9.4	—8.6	30	30	str.	str.	. .	. .
	6087	. .	. .	. .	. .	—9.6	—9.1	75	75	str.	str.	. .	. .

Wright (1926) commented on the relatively small part played by the spectra of nitrogen in the development of RR Pic.

The observation of nebulous knots in the neighborhood of the nova was discussed by Spencer Jones, and Wright (1926) suspected the presence of nebulosity on spectroscopic grounds.

The very extensive material that has been obtained on the spectral development of RR Pic cannot be condensed into a short space, and the original papers, especially the monograph of Spencer Jones (1931) should be consulted.

CP PUPPIS *080735* JD 30675 (1942) 0.2

One of the bright novae of the century, in absolute as well as apparent magnitude, CP Pup rose from fainter than seventeenth magnitude, and thus had the largest range recorded for a nova. As Weaver (1944) pointed out, the range indeed suggests a supernova, but the spectrum does not. The light curve in the figure was determined photographically by Gaposchkin (1942, 1946). The fall in brightness was very rapid, three magnitudes in 6½ days, almost as fast as that of T CrB, faster than those of V 603 Aql and CP Lac. The absorption lines on the first few days were wide and diffuse, but the radial velocities were not exceptionally great.

Absorption spectra were recorded for only fifteen days. The velocities shown in the figure were determined by Sanford (1945), McLaughlin (1943) and Weaver (1944). Most of the observations appear to relate to the principal spectrum, first measured by Sanford on JD 30675 with a velocity (hydrogen lines)of —1010 km/sec. The velocity of this absorption system increased to about —1300 km/sec before its disappearance after JD 30690. On JD 30679, McLaughlin noted a weak "diffuse enhanced" spectrum, velocity —1600 km/sec, and (from 5680 N II) an "Orion spectrum" with velocity —2000 km/sec. On J. D. 30676, at maximum light, McLaughlin classified the very diffuse principal spectrum as about A 5; he noted that 6155 O I was conspicuous in absorption and emission, but rapidly weakened. The D lines, on the other hand, were absent, but were strong three days later, on JD 30679.

Sanford noted that the bright lines had doubled by JD 30679, and were very complex by JD 30690; he listed eleven intensity maxima for the interval JD 30820 to 31020, with a velocity range from —454 km/sec to +570 km/sec.

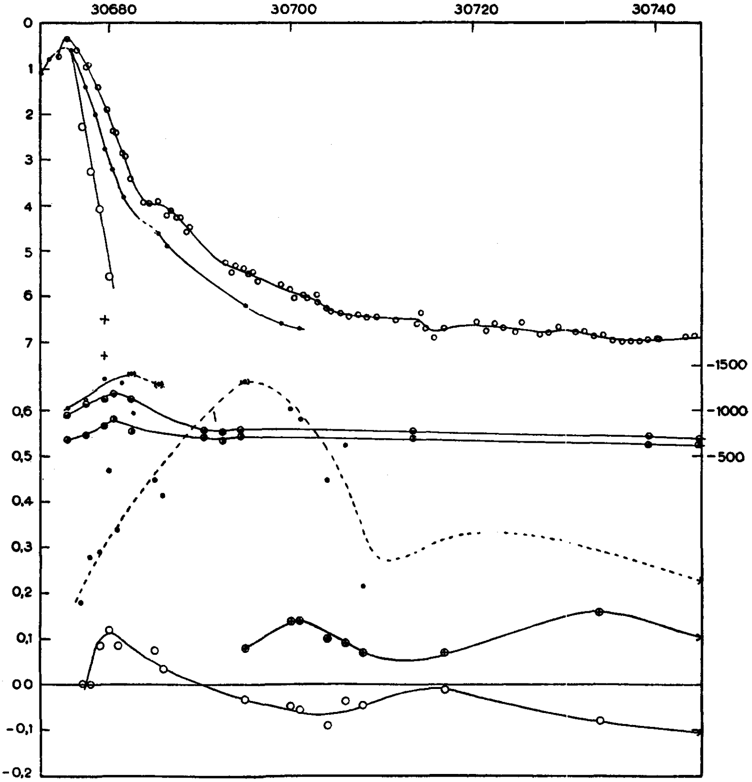


Fig. 4. 17. Above, light curves of CP Puppis: small dots, photographic (Gaposchkin); small circles, visual (Pettit, Gaposchkin); large circles, continuum. Ordinates and abscissae are magnitudes and Julian Days. Note that visual and photographic curves cross just before maximum, and their later divergence points to progressive reddening of the star's light.

The next three curves show the radial velocities (Sanford). Top curve (dots), velocities from absorption lines. Next curve (half-filled circles), velocities of red edge of bright lines *with reversed signs;* next curve (half-filled circles) velocities of violet edge of bright lines. Two crosses, above, denote the velocities of two other systems measured by McLaughlin. Ordinates are shown on the right.

The next three curves refer to the intensities of the bright lines. Ordinates are shown on the left. First curve (dots and broken line), logarithm of intensity ratio Hβ/Hδ, a measure of the Balmer decrement. Note that the ratio at first rises sharply; soon after the disappearance of the absorptions and the narrowing of the bright lines it falls even more abruptly, beginning at about the date of appearance of He II 4686. The arrow at the right margin denotes the averages approached at later dates.

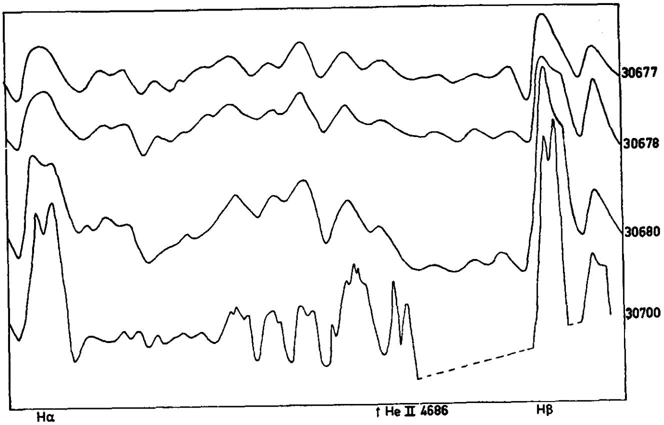


Fig. 4.18. Microphotometer curve of a section of the spectrum of CP Puppis, reduced to intensities and plotted on equal but shifted scales for four dates.

Note the changing profiles of Hβ and Hγ and the extreme width of the associated absorption on the first three dates. On the fourth date, note the contrasting profiles of hydrogen and 4686 He II. Compare Fig. 4.17.

For the interval JD 30675 to 31423 Sanford (1945) identified bright lines of H (Balmer and Paschen series) He I, He II, C II, N I, N II, N III, N IV (JD 30682), N V, O I, [O I], [O III], O VI, [Ne III], Na I, Ca II, [Ca VII] ?, Si II, [Cr III], [Mn VI], Fe II, [Fe II], [Fe VII], [Fe X] and 7891 [Fe XI] ?. Even on these early dates the excitation was exceptionally high. McLaughlin (1953) confirmed the presence of [Fe X] on six Mount Wilson spectra between JD 30694 and 30803,

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Second curve (circled crosses), logarithm of the ratio V/R for the line He II 4686. Third curve (dots), logarithm of the ratio V/R for the Balmer lines. Note that the intensities are equal at first for the Balmer lines; the violet edge grows stronger, the ratio reaches a maximum at the times when the widths of the bright lines have their maximum, then declines. The edges are about equal when the Balmer decrement is at its maximum and the line He II 4686 appears; thereafter the red edge becomes stronger, and remains so with a slow fluctuation. The curve of the He II line shows changes in the opposite sense to those of the Balmer lines; the ratio has a maximum when that for the Balmer lines is near minimum, and vice versa, but the violet edge is always the stronger. The three lowest curves are deduced from measures of Harvard plates.

during which interval 6374 [Fe X] increased in intensity by a factor of two.

Weaver's study (1944) shows that the excitation of the absorption spectrum on JD 30677 and 30678 was lower than that of α Cygni. He noted, in addition to atoms already mentioned, the presence of bright lines of C I ? and [N II] on JD 30687–30690, and first observed 4686 He II on JD 30689, a saddle-shaped line with the violet edge the stronger; this structure was shared by He I, perhaps by [O I], but not by Ca II. Between JD 30716 and 30726 the intensity of [O I], [N II] and [S II] increased, and O III, N III, [Ne III] and [Fe II] appeared, as well as the Pickering series. Lines of [O III] had appeared before JD 30716, and those of N V, between JD 30690 and 30716. The appearance of [Fe II] is of interest in so rapid a nova; no lines of [Fe III] were found.

During 1943, Weaver noted progression toward the nebular stage: [O III] and [Ne III] were strong, 4605 N V increased in intensity, and [Ne V] ? appeared near JD 30750; meanwhile the lines of [Fe II] remained unaltered. On JD 30855, the lines of [O III] were stronger than those of [Ne III]. On JD 30990, Gratton (1953) estimated the lines of [O III] the strongest in the spectrum, followed by the Balmer lines, [Ne III], He II, 4640 N III, 3426 [Ne V], 3760 [Fe VII].

In 1944–45, Gratton (1953) reports [O III] still the strongest, but relatively fainter, [Ne V] very strong and [Fe VII] stronger than before. In 1945–46 he notes relative strengthening of the continuum. On JD 31895 in 1946, Sanford (1947) identifies lines of H, [O III] still the strongest lines, [O I], [N II], He I, He II, [Fe VII], [Fe X] and [Fe XIV] The emission lines still had complex structure; their overall width corresponded to 1200 km/sec on JD 32195, as against 2000 km/sec on JD 30834.

CP Pup is a noteworthy star on account of its large range, rapid development, high terminal excitation, and the presence of [Fe II] in a rapid nova that displayed unusually high excitation at the same time. It forms an interesting parallel with CT Ser.

An expanding nebular disc, of 2″.78 radius, has been observed by Zwickly (1956). If 1600 km/sec is adopted as the corresponding radial velocity, the maximal absolute magnitude, uncorrected for absorption, is —10.5 (visual). This luminosity, which is in accordance with that deduced by Humason and Sandford (1942) from galactic rotation (p. 35), is higher than what would be deduced from Arp's relation

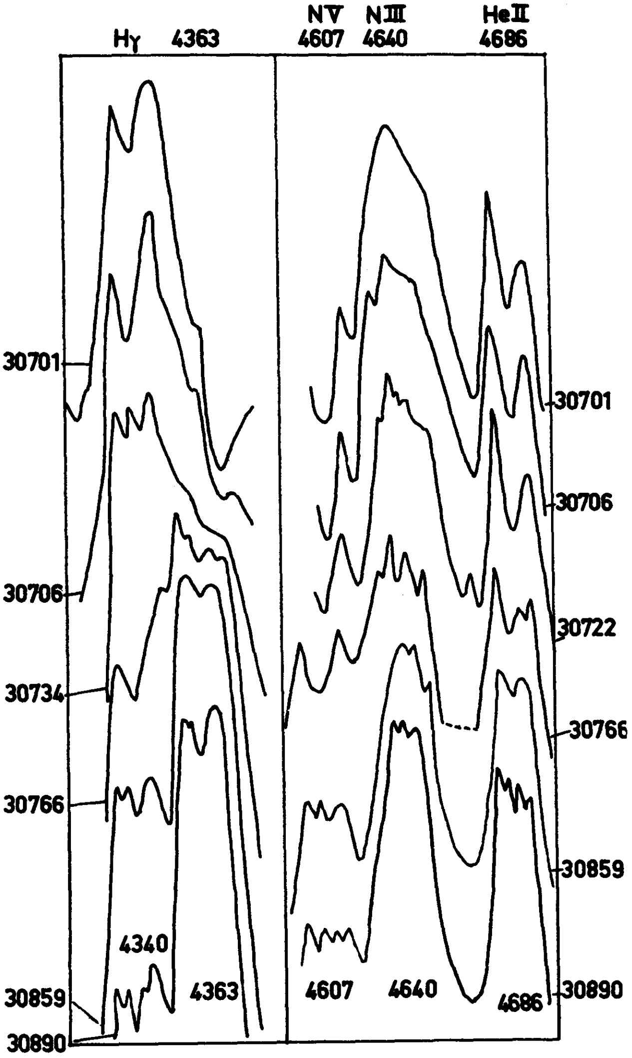

Fig. 4.19. Microphotometer curves for two sections of the spectrum of CP Puppis, reduced to intensities and plotted on equal but shifted scales for six dates.

Left: note the interplay of Hγ and 4363 [O III].
Right: note the interplay of 4607 N V, 4634, 4660 N III and 4686 He II.

between maximal luminosity and rate of decline. We must conclude that CP Pup is anomalous in this respect also, and does not fit the luminosity-light curve pattern of the majority of novae. Whether the anomalies point to membership in the group of Type II supernovae is discussed on p. 280.

T PYXIDIS *090031* **JD 11516 (1890), 15872 (1902), 22421 (1920),**
31416 (1944) 6.6

Four maxima, in the years 1890, 1902, 1920 and 1944 have been observed for T Pyx. The three earliest are discussed by Leavitt (1920); brightest magnitude was recorded on JD 11516 (7.9?), 15872 (7.25, 7.40) and 22421 (6.60, 6.65). Magnitudes for the fourth have not been published in detail; Campbell (1945) records magnitude 7.1 on JD 31416.

Examination of the published magnitudes shows that at each maximum there were considerable fluctuations, and that the decline was comparable to that of a slow nova. Campbell (1945) considers that

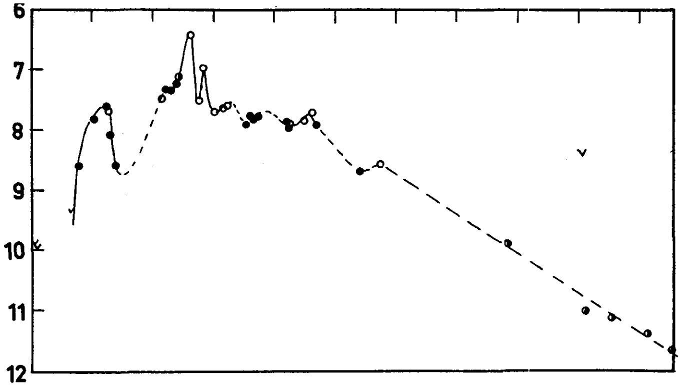

Fig. 4.20. Composite light curve of T Pyxidis from three maxima. Dots, circles and half-filled dots refer to the maxima of 1902, 1920 and 1944 respectively. The two first can be confidently aligned by means of the unobserved pre-maximum points; one point of overlap only is available for the 1944 maximum. Ordinates are photographic magnitudes; the scale of abscissae is marked at intervals of 20 days. The date of Joy's spectroscopic observation (see text) is marked with an arrowhead.

all the maxima showed similar courses, but on account of the early fluctuations of each well-observed maximum, this statement is true only for the later stages of the decline. The slow fall of brightness indicates that at least one recurrent nova—and the one that has had most recurrences—did not show the "flash" type of curve displayed by T CrB and RS Oph.

No spectra were recorded at the maxima of 1890 and 1902. In 1920 the star was first photographed on JD 22394 at magnitude 7.7; it reached maximum recorded magnitude, 6.6, on JD 22421. The spectrum on JD 22426, 22442 and 22445 was obtained by Adams and Joy (1920b). On JD 22426 it showed bright Balmer lines, 25 A wide, fainter lines of Fe II and perhaps O II, N II. Dark components yielded a radial velocity of —1700 km/sec. On JD 22442, 22445, complex dark lines (hydrogen, N II, O II, and others) gave velocities of —2100 km/sec, —1600 km/sec, —1100 km/sec, and (faint) —540 km/sec. The magnitude on these dates is not recorded, but probably had passed through a minimum since JD 22426 and was about 1½ magnitudes fainter than maximum.

The brightening of 1944 was noted by Joy (1945) on JD 31549, but the star was then over a hundred and thirty days past its maximum and had faded to the eleventh magnitude.

The spectrum at this late stage was very different from the maximal spectrum of 1920. On JD 31549 to 31564, Joy (1945) noted bright lines of H, He I, He II, N I?, N II, N II, N III, [O I], [O II], O III, [O III], [Ne III], [Ne IV], [S II], [Fe V], [Fe VI], [Fe VII], [Fe X] and [Fe XIV]. On JD 31559, 31560, Herbig (1945) recorded the strongest of these lines. The lines of H and [O III] were especially prominent. Joy estimated the expansion velocity from the half widths of the lines as about 1700 km/sec; Herbig gave the value 1660 km/sec, and noted that permitted and forbidden lines showed no difference. These velocities are of the same order as those deduced from the absorption lines at the maximum of 1920.

The minimal spectrum on JD 27509 was described by Humason (1938) as having a fairly strong continuum with bright lines: strong 4686 He II, moderate hydrogen, weak 5007 [O III]. Elvey and Babcock (1943) observed a faint continuum with no strong lines. It is not possible to determine the color of the star from the spectroscopic observations.

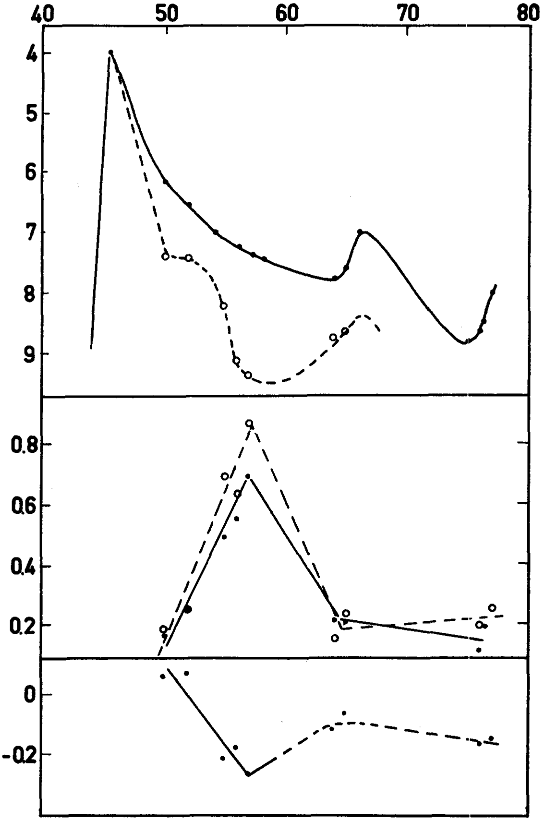

Fig. 4.21. Light curve and line profiles for V 630 Sagittarii.

Top curve: photographic light curve (dots) and curve of continuum; ordinates are magnitudes (left margin). The light curve depends on few estimates. The first secondary maximum is fixed by a visual estimate by Joy (private communication).

Middle curve: logarithm of the ratio Hβ/Hγ; dots denote the red edge, circles the violet edge.

Lower curve: logarithm of the ratio V/R for Hγ; ordinates on the left. Note that the maximum in the Balmer decrement, and the minimum in in the ratio V/R, seem to follow the abrupt drop of the continuum to a minimum.

V 630 SAGITTARII 180234 JD 28448 (1936) 4.5

The star dropped in brightness with unusual rapidity, two magnitudes in 4 days, 3 magnitudes in 9 days. The light curve has been determined by Gaposchkin (1955). Only few spectra were secured. They were distinguished by very large absorption line velocities and emission line widths.

On JD 28449, very broad Balmer lines and 4471 He I were observed in emission by Joy, Adams and Dunham (1936); they were saddle-shaped, with the violet edge stronger than the red, and the violet maximum had a radial velocity of —1580 km/sec. Wide, hazy absorption lines were assigned to two systems: Hβ, Hγ and 4471 He I with a velocity of —3590 km/sec, and Hβ, Hγ with a velocity of —2130 km/sec. On JD 28459 they noted that the absorption lines were weakened, the bright band near 4600 strengthened, and a possible bright line at 5007 [O III]. The bright lines were 60 A wide, thus corresponding in velocity to the second absorption system.

On JD 28748 the spectrum was observed by Wyse (1937). He noted the lines 5007, 4959 [O III]; 3869, 3968 [Ne III]; 3426 [Ne V]; possibly 4686 He II, but no lines of hydrogen. He commented on the strength of the lines of [Ne III], 3869 being stronger than both the lines of [O III]. The absence of lines of hydrogen is notable.

RT SERPENTIS 173411 JD 24000: (1909) 9.0

The light curve of this exceedingly slow nova is taken from the compilation by Gaposchkin (1941), which also indicated the essential nova character of the spectral development. The star brightened at about JD 18700; it rose gradually to a little brighter than ninth magnitude

Julian Day	Radial Velocity km/sec	Remarks
22060	+82.9	Hβ, Hγ narrow absorption; also Mg III, Fe II
22069	+80.0	
22090	+43.7	
22144	+64.0	
22540	+49.7	Hβ a weak emission; H absorption; enhanced lines more prominent?
22541	+47.8	
22851	+69.4	Hβ stronger in emission; H invisible, Hγ strong absorption.

by about JD 24000, and then fell, with fluctuations, to about the eleventh magnitude by JD 28000.

The spectrum during the rise in brightness was studied by Adams and Joy (1928).

It is noteworthy that all the absorption velocities are positive.

One spectrum described by Adams and Joy (1928) and two by Joy (1931), after maximum had been passed, showed a striking change and consisted primarily of bright lines.

If the velocity of +92.3 km/sec, derived by Joy for the bright lines, represents the true velocity of the nova, the absorption spectrum points to velocities between —10 and —40 km/sec, and RT Ser is a high-velocity star. No other nova has shown only positive absorption velocities.

Julian Day	Radial Velocity km/sec	Remarks
25424	+72.3	Continuum barely visible; spectrum perhaps A8p. Bright lines of H, Fe II, [Fe II].
26516,	+92.3*	Bright lines of H, He I, Fe II (much weakened), [Fe II], [Fe III], 4363, 5007 [O III]. Weak 4686 He II and 4649 C III ?

* Velocity from bright lines

Still later spectral development is shown by the work of Swings and Struve (1940, 1942b). On JD 29753, when the star had declined to the fourteenth magnitude, they observed lines of H, He I, He II, [N II], [O I], [O III], [Ne III], [Ne IV], [Ne V], [S II], [S III], [A IV], [Fe III], [Fe V] and [Fe VI]. On JD 30567 the spectrum showed bright lines of H, He I, He II, [O I], [O III], [Ne III], [Ne IV], [Ne V], [Ca V], [Fe III], [Fe V], [Fe VI] and [Fe VII]. The excitation thus appears to have increased steadily.

RR TELESCOPII 195656 JD 33100: (1949) 6.85

The only nova that was known as a periodic variable star before its rise to maximum, RR Tel was shown by Gaposchkin (1945) to vary with a period of 387 days and a range between photographic magnitudes 12.5 and [15. Soon after 1930, the range increased to about three magnitudes, while the star continued to vary with the same period; minimal magnitude at this time was between 16 and 17. In 1944 the star brightened to about the seventh magnitude, where it remained for about six years. A light curve from 1889 to 1948 has been published by Mayall (1949). Small fluctuations with a period near 387 days have persisted, even through maximum. Greatest brightness ($6^m.85$) was reached about JD 33100, by JD 33836 the star had fallen below eighth magnitude, and it continues to decline. The light curve is very like that of RT Ser, as illustrated by Payne-Gaposchkin and Gaposchkin (1938); RT Ser occupied about 5000 days in rising to its highest maximum, with slow fluctuations, after the abrupt rise, and RR Tel rose in about 1600 days.

The spectrum was not observed until 1949; observations have been discussed by Thackeray (1950a, 1953a, 1954), by Henize and McLaughlin (1951), and by Payne-Gaposchkin (1955). Although the first observations were made five years after the abrupt rise in brightness, several of them preceded actual maximum. The maximal spectrum resembled that of an F5 supergiant, with weak bright edges to the red of the Balmer lines. The bright components were weakest near the time of maximum brightness, as in DQ Her, for instance.

The Fe II spectrum was extremely rich by the end of the interval covered by the table; [Fe II] began shortly to appear and strengthen. By JD 33427 the lines of [S II] and the strongest lines of [Fe III] could be detected on the Harvard plates. On JD 33531, Henize and McLaughlin identified bright lines of H, He I, N II, [N II], O I, [O I], [O III], Fe II and [Fe II] between Hα and Hβ, and noted the great strength and asymmetry of Hα.

By 1951, Thackeray observed a marked increase of excitation; the ions now present were those of H, He I, He II, C II, C III, N II, [N II], N III, N IV, O I, [O I], [O II], [O III], [Ne III], Mg I, Mg II, Si II, [S II], [S III], [A III], Ca II, Ti II?, Fe II, [Fe II], [Fe III], [Fe IV], [Ni II]. The continued rise in excitation is illustrated by the lines that were strengthened between 1951 and 1952: those of He I, He II, C III and [A III]; greatly strengthened were those of [Ne III], [O III] and N III. The trend continued into 1953 with the further strengthening of [A III] and the appearance of [A IV] and [Cl III]?; [Fe II] was fading, [Fe III] and probable [Fe IV] prominent. No nebulous envelope was visible; both this and the appearance of the forbidden lines of more highly-ionized iron may be looked for in the coming years. Henry Smith (1955) noted the appearance of N V and

EARLY OBSERVATIONS OF THE SPECTRUM OF RR TELESCOPII

Julian Day	Pg. Mag.		Observer
33043	7.3	Absorption: strong H, Ca II, Ti II, weaker Fe II, weak bright Hβ.	Payne–Gaposchkin
33087,88	7.1	Absorption: H, Ca II, Ti II; supergiant F	Thackeray
33101	6.85	Absorption: H, Ca II, Ti II, Sr II, Fe II; weak bright Hβ; magnitude near maximum.	Payne–Gaposchkin
33120	6.95	Absorption: H, Ca II, Ti II, Fe II, weak bright Hβ.	Payne–Gaposchkin
33124–26	7.0	Similar, bright H stronger, Fe II emission begins.	Payne–Gaposchkin
33137	7.1	H ?, Fe II emission; Ca II, Ti II absorption.	Thackeray
33139–48	7.1	Very strong, broad, bright Hα; bright Hβ stronger	Payne–Gaposchkin
33172	7.3	Primarily an emission spectrum: H, Fe II, Ca II; Ti II in absorption.	Thackeray, Payne–Gaposchkin
33199– — 33255	7.— 7.6	Similar, emissions strengthening relative to continuum.	Thackeray, Payne–Gaposchkin

C IV in 1953 and their persistence into 1954, and remarked that the spectrum of a WN5+ star appeared to underlie the narrow bright-line spectrum.

Absorption lines of He I were observed in 1951 and 1952 by Thackeray; their wavelengths yielded radial velocities of —685 km/sec for 1951 and —865 km/sec for 1952.

An obvious parallel for RR Tel is η Car, which, however, developed far more slowly; in ten years RR Tel has outstripped the progress made by η Car in 110 years. In his comparison of the two spectra as they appeared in 1952, Thackeray noted the higher ionization and excitation, and the smaller Balmer decrement, of RR Tel. The most striking difference, however, was the relatively great strength of the spectra of O I, O II, and O III in RR Tel, and their absence from η Car. Other bright lines, such as those of [N II], [S II] and [Fe II] are so similar in the spectra of the two novae that a real difference in oxygen abundance may well be indicated. The absorption spectrum of He I observed for RR Tel recalls the absorptions in η Car, which also seem to have shown increasing radial velocity between 1893 and 1954.

Other parallels for RR Tel have been suggested by Henize and McLaughlin, who liken it to DO Aql in 1926, and to RT Ser in 1928, as we have already done. They note, however, that RT Ser showed no [O III] lines at the time, though it developed them later. The parallel between η Car and RT Ser is fairly close also, and RR Tel has developed more rapidly than either.

Henize and McLaughlin suspect a further parallel with the symbiotic novae, and suggest that RR Tel was a long-period variable, presumably of Class M, during its early fluctuations near the thirteenth magnitude. There is no observational basis for this suspicion; Gaposchkin made it clear that he did not consider the star an ordinary long-period variable; in fact the quality of its photographic images suggests that it was by no means a red star at the time.

Henize and McLaughlin also consider the increase in the amplitude of the periodic variation before the main outburst as possible evidence that a single star is involved. We recall that the fluctuations of T CrB just before the maximum of 1946 showed the same properties, even including the decline of the minimal photographic magnitude just before the main outburst. For this star, the spectroscopic observations during the disturbed pre-outburst interval leave little doubt that the "blue component" was responsible for the increasing amplitude of the fluctuations; see Payne-Gaposchkin and Wright (1946). The evidence for T CrB strongly favors the idea of duplicity, and the same may indeed be true of RR Tel. Observations over several decades will reveal whether the spectrum of a late-type companion will appear as the nova outburst dies away, and if so, whether the persistent 387-day period is associated with it. The photographic light curve of RR Tel published by Mayall shows that the minimal magnitude (from which the periodic rises of brightness took place) declined from near 13 in 1890, was about 14 from 1900 to 1909, and fell from about 15 to fainter than 16 between 1926 and 1939. The photographic light curve of T CrB between JD 29000 and 32000 was very similar. If RR Tel is indeed a double star, the range of the nova outburst was over ten magnitudes.

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CHAPTER 5

GALACTIC NOVAE: SECOND CLASS DATA

The novae included in the present chapter are less completely observed than those of Chapter 4. They still furnish valuable astrophysical information, though often it covers only a part of the variation. The arrangement is the same as those of the preceding and following chapters.

DO AQUILAE 192606 JD 24450 (1925) 8.6

A typical very slow nova, with a protracted "flat-topped" stage in the light curve, DO Aquilae was discovered by Wolf (1925). The visual light curve, based on observations by Vogt (1928), Beyer (1929), Steavenson (1926, 1927) and Peek (1928) is shown in Fig. 5.1. Spectra were observed as noted in the figure. During the flat-topped interval, the spectrum displayed no bright lines; those secured at Harvard and described by Cannon (1925) show very little, but the H and K lines may be present in absorption.

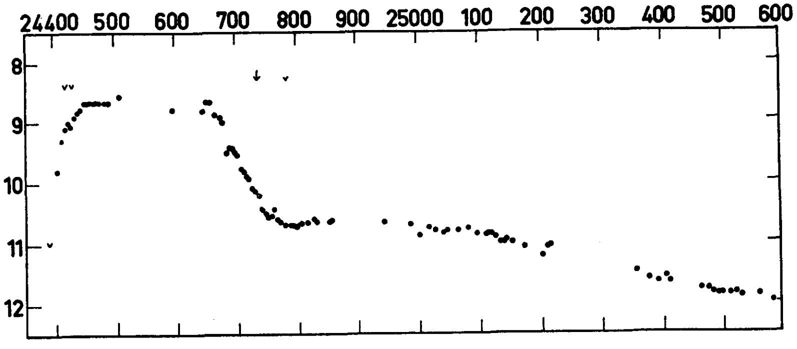

Fig. 5.1. Light curve of DO Aquilae. Ordinates and abscissae are visual magnitudes and Julian Days. Arrows mark absorption spectra, Merrill's spectral observation, and nebular spectra.

After the drop in brightness, spectra with bright lines were obtained by Merrill (1926), Tikhoff (1926) and (visually) by Beyer (1929) and Peek (1928). Tikhoff and Beyer mention characteristic bright lines; Merrill publishes his spectrum without analysis.

The light curve and the spectrum published by Merrill are discussed by Vorontsov-Velyaminov (1940). He identifies lines of H, Fe II, [Fe II], [Fe III] and [O III], and notes similarities with the spectrum of RR Pic. His conclusion, that DO Aql may have had a sharp maximum during the unobserved interval between JD 24500 and 24590 seems improbable to the writer. The subsequent fluctuations of DO Aql were inconspicuous, unlike those of RR Pic. An analogy with RR Tel and FU Ori seems more likely. The former star showed an absorption spectrum with strong H and K lines during its flat maximum, and a bright-line spectrum appeared as the light declined. The latter star is still at its protracted maximum and shows an absorption spectrum.

EL AQUILAE 185003 JD 25047 (1927) 6.4

Photographic and visual light curves, the former based on observations by Cannon (1927) and Harwood (1927), to which the observations of Voûte (1927) have been reduced empirically; the latter on the light curve of Beyer (1929) and a few observations of Barabascheff and Straschny (1928) are shown in Fig. 5.2. The curve is much like that of DN Gem.

The time of the most significant spectral observations, those of Humason (1927), Wyse (1940) and Schajn and Nikonoff (1928), are shown in the figure. Visual observations of the spectrum, such as those made by Guthnick and Prager (1927) and Bohlin (1927) add little to the photographic records. Unfortunately, the early spectral changes were not recorded.

The plates taken at Lick Observatory on JD 25109, 25111, as discussed by Wyse (1940) showed essentially similar spectra. Two absorption systems could be detected:

System	Displacement Factor	Radial Velocity km/sec	Remarks
Absorption I	—28.7	— 861	Remains of supergiant A. spectrum.
Absorption II	—69.2	—2076	Spectrum B1p, "perhaps the most fully developed Class B spectrum on record for a temporary star".

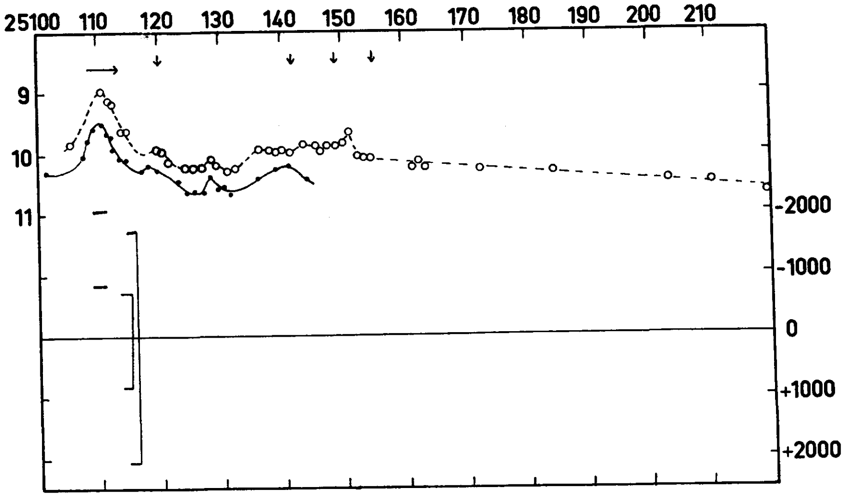

Fig. 5.2. Part of light curve and spectroscopic observations for EL Aquilae. Abscissae are Julian Days. For the whole light curve, see Fig. 1.1. Circles and broken line, visual light curve; dots and continuous line, photographic light curve. Ordinates (left margin) are magnitudes. The horizontal arrow denotes the duration of the absorption spectra. The short lines (I, III) denote the radial velocities observed by Wyse (ordinates, km/sec, on the right). The ranges indicated to their right show, in km/sec, the separations of the edges of the main emission features.

Above the light curve, arrows denote the appearance of [O III] and the occurrence of nitrogen flaring (N), deduced from the paper of Shajn and Nikonoff. Notice that this stage immediately precedes the transition to a slow, steady fall of brightness.

Wyse considered that Absorption II was comparable to the system called Absorption III for DN Gem and V 603 Aql. We may regard Absorption I as the principal spectrum, Absorption II as the Orion spectrum. A plate taken by Humason on JD 25111 showed similar features.

Both absorption systems had disappeared by JD 25114, when Humason's next spectrum was taken, and apparently they were not observed again. Their disappearance coincided with the cessation of the marked fluctuations of brightness.

Later spectra showed broad bright lines of H, He I, He II, C II, N II, [N II], N III, [O III] and perhaps [S II]. Wyse's tabulation of the displacement factors for the inner and outer emission edges of bright hydrogen lines suggests a central region with displacement factors —24 and +27 (—720 and +810 km/sec) and a wider, weaker outer region with displacement factors of —58 and +69 (—1740 to +2070 km/sec), probably to be associated with Absorptions I and II, respectively.

The diagrammatic representation of the bright line intensities by Schajn and Nikonoff (1928) suggested broader bright lines than those inferred by Wyse (probably, as he noted, on account of the very low dispersion used). One significant feature of their diagram is the evidence it displays for a marked "nitrogen flaring" at JD 25155, another feature that recalls DN Gem.

Although rather faint at maximum, EL Aql is one of the few that have been reliably observed at minimum. Wyse records it as of photographic magnitude 19.0 on JD 29786, thirteen years after the outburst, and presumably back to normal brightness. The range was therefore 12.6 magnitudes.

V 356 AQUILAE 191201 JD 28378 (1936) 7.0

The large post-maximum oscillations shown in Fig. 5.3 are characteristic of a slow nova. The star was not discovered until sixty days after the first rise, and the consequent incompleteness of the record has led us to place it with the second-class novae, although the later velocities are observed in considerable detail. The early part of the light curve rests on photographic observations. It has been compiled from the data of Overhage and Zwicky (1936), Harwood (1936), and Hoffmeister and Morgenroth (1936). Visual observations by Beyer (1936, 1939) have also been used.

The very complete summary of the velocities by McLaughlin (1955) has been the basis of the lower part of Fig. 5.3, but the light curve is that derived from the writer's discussion. The duration of the oscillations fell abruptly at first and then more slowly, from about 26 to about 8 days. After JD 28520, soon after the absorptions disappeared, there seems to have been a steady decline in brightness.

In addition to the data given by McLaughlin, the tabulation shows a few observations that are worthy of note.

McLaughlin tabulates velocities of the emission edges in the nebular stage as shown in the next table.

Julian Day	Magnitude and Light Curve m		Spectrum	Reference
28371, 28372	9	Rising	Continuum, no emission or absorption seen, maximum intensity in red	Stein and Zirwes (1936)
28433	8.3	Minimum	Typical maximal spectrum, strong, broad H emission; absorption lines —1011 km/sec	Hinderer (1936) Note 1
			Strong continuum, strong emissions of H, N III	Strohmeier (1936)
			a Cygni spectrum, —400 km/sec H spectrum, —900 km/sec	Wyse (1936)
			Orion spectrum, —1100 km/sec	Note 2
28434	8.8	Minimum	As on JD 28433	Wyse (1936)
28435,6	8.7	Minimum	Bright H, violet absorptions; Note 3	Wachmann (1936)
28439	8.0	Rising	Strong, double H and K lines	Wyse (1936)
28458	8.5	Minimum	Atypical; continuum strong, absorption weak, emission suspected	Bohlin (1936)
28508	8.6	Maximum	Post-maximum spectrum	Popper (1937)
28590	10.0:	Falling	Emission bands 1200 km/sec wide; maxima 700 km/sec apart; [O III] 4363 the strongest line; N_1, N_2, [Ne III] weaker than in DQ Her	Popper (1937)

NOTES

1. H visible as far as H 8; emission and absorption of Fe II, He I, O II, N III N II ?; Ca II in absorption only. H and N III 4640 give anomalously large velocities because of great breadth of bright lines.
2. *a* Cygni spectrum very faint, H and ionized metals. H lines of second and third spectra blended, strong. Third spectrum shows absorption lines of N II, N III, O II, He I, C II, others ?. Bright lines: H, strongest lines of Fe II, He I, O II, N III 4634–4640.
3. Intensities of bright lines (arbitrary scale): $H\gamma$, 10; $H\delta$, 8; $H\varepsilon$, 3; $H\zeta$, 1; [$H\eta$, 1.

Two observations are worthy of note. The absorption spectra were observed to persist through at least one of the deep minima of the light curve, at JD 28433, by Wyse, Hinderer, and McLaughlin. An emission feature near wavelength 4660 (attributed to N II and O II

Julian Day	All Lines km/sec		Weaker Lines km/sec		Spectrum
28586	—684 (9)	748 (8)	—622 (4)	404 (4)	Lick
28668	—673 (12)	712 (12)	—560 (4)	544 (4)	Lick
28702	—559 (9)	674 (9)	—521 (4)	659 4()	Mount Wilson

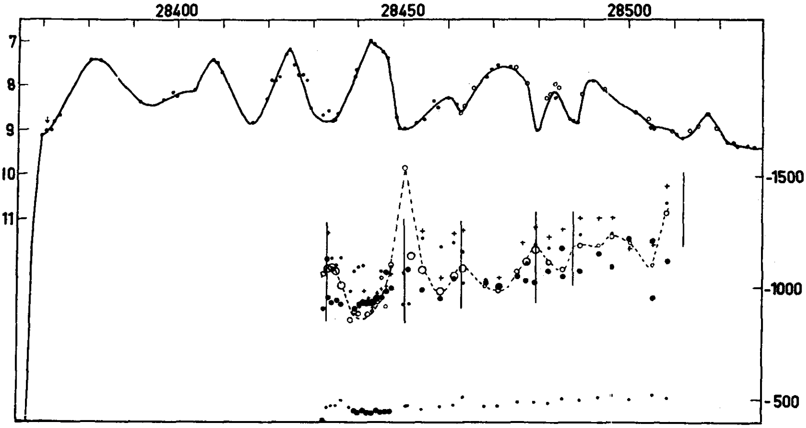

Fig. 5.3. Light curve of V 356 Aquilae (see text) and velocity systems, after McLaughlin.
Above: ordinates and abscissae are magnitudes and Julian Days. The circles denote supplementary means from observations by the American Association of Variable Star Observers. Dots are taken from the sources mentioned in the text. After JD 28520 a steady decline of brightness begins, without fluctuations.
Below: daily means of radial velocities. McLaughlin's principal and diffuse enhanced systems are shown by dots, the Orion system, by circles, and Mg II velocities, by crosses. Large, medium and small dots and circles denote relative intensities, deduced from McLaughlin's diagram. The scale of ordinates (km/sec) is on the right.
Short vertical lines mark minima of the light curve; note that the Orion system has maxima of velocity at or near these dates. The "diffuse enhanced" component of lower velocity is almost always the more intense of the two.
An arrow marks the pre-maximum spectrum of Stein and Zirwes.

rather than to N III) was noted by McLaughlin to fluctuate in intensity with the star's brightness, being conspicuous near minima of the light curve (JD 28433, 28450, 28458, 28486, 28510) and absent or faint near the maxima (JD 28445, 28456, 28462, 28468). The first of these observations contrasts strongly with the disappearance of all absorptions, for example, at the minima of the light fluctuations of V 603 Aql. The second is similar to what is observed in the spectra of most fluctuating novae.

The pre-maximum spectrum obtained by Stein and Zirwes (1936) is one of the few recorded for a nova so far below maximum. It presents a strong contrast to the early pre-maximum spectrum of DQ Her, which showed very strong bright lines.

V 368 AQUILAE 192107 JD 28437 (1936) 6.6

The light curve, compiled from observations published by Beyer (1936), Lacchini (1936), Hoffmeister (1936) and Hinderer (1936) is that of a typical fast nova. Maximum was at about JD 28437. Beyer (1939) records rapid irregular variations after the fall to twelfth magnitude, about two hundred days after maximum.

Observations of the spectrum have been made by Wyse (1936), McKellar (1936), Krumpholtz (1936), and McLaughlin (1939, 1953). On JD 28462 (about 25 days after maximum), Wyse observed two absorption systems: an *α* Cyg spectrum showing H, Ca II, Fe II ? and He II 4686; and a spectrum of higher velocity that included lines of N III and He I, but no hydrogen, although broad emission wings of corresponding width were noted for the Balmer lines. Wyse noted the absence of hydrogen absorption at this stage as anomalous. McLaughlin (1939) suspected the hydrogen absorption to be present six days later, and also noted the emission edge. The $_i$O III^c line at 5007 was noted by Wyse with the same width as the broad hydrogen wings.

On JD 28463, Krumpholtz (1936) observed a strong continuum and strong emission lines. Wyse (1936) observed strong N III 4634, 4640; also He I 4471; Fe II, 4923, and unidentified lines at 4528, 4783.

McLaughlin (1953) examined plates taken on JD 28479 in a search for the line of [Fe X] 6374, whose presence in this nova he judged to be doubtful. He observed [O I] 6364, 6300 as bright lines with half widths corresponding to 1250 km/sec and 1085 km/sec, respectively. The bright-line spectrum had no unusual features; by JD 28515 the line [O III] 5007 equalled Hβ in intensity, about eighty days after the outburst.

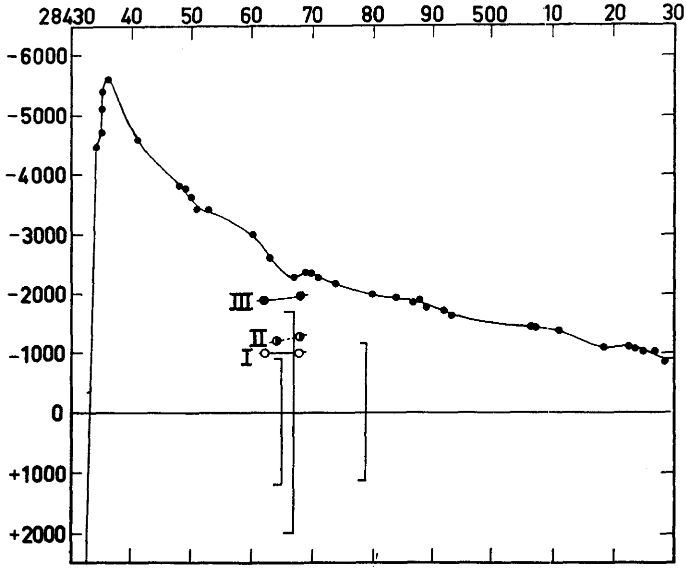

Fig. 5.4. Light curve and velocities for V 368 Aquilae. Abscissae are Julian Days; ordinates (left) are magnitudes, (right), velocities in km/sec.
Absorption systems designated I, II, III in the text are shown respectively by circles, half-filled circles, and dots. The vertical lines denote the range of radial velocities between the red and violet components of bright lines, which correspond respectively to Absorption I and III. The vertical line to the right represents the mean of the velocity ranges of the nebular pair of [O I].

The velocities are summarized as follows:

	Wyse			McKellar	McLaughlin	McLaughlin
	28462 to 28468			28464	28468	28479
Spectrum JD	Absorption	Emission		Absorption	Absorption	Emission
		Red edge	Violet			half width
	km/sec	km/sec	km/sec	km/sec	km/sec	km/sec
I Hydrogen	—1000	— 900	+1200	..	—1000	..
II Weak hydrogen ..		..	..	—1200	—1300	..
III N III, He I	—1900	—1700	+2000	..	—2000	..
[O I] 6363	..	..	..	..	..	±1250
6300	..	..	.	.	..	±1085

V 500 AQUILAE 194708 JD 30845: (1943) 6.5

The light curve given by Gaposchkin (1943) suggests a rapid fall, with marked fluctuations after about fifty days. The coverage is rather incomplete, the early unobserved interval is thirteen days, and maximal brightness cannot be accurately estimated. At minimum the nova was fainter than $17^m.5$.

The spectrum described by Sanford (1943) was taken about 170 days after maximum. It showed lines of H, He II, N II, [N II], N III, [O I], O II, [O III], [Ne III], and [Fe VII], [Ca V], and no visible continuum; the excitation was thus rather high. Sanford noted saddle-shaped profiles, especially striking for [N II] 5755, which seems to be divided into two equal components. The mean overall width of the bright lines was 40 A at Hγ, corresponding to a spread of ±2760 km/sec. The mean radial velocity for the centers of the bright lines is —75 km/sec, which probably represents roughly the true speed of the star.

V 528 AQUILAE 191400 JD 31693: (1945) 7.4

The light curve has been compiled by Bertaud (1951). The fluctuations are probably real, as revealed by comparison with the observations of Hagopian and Sawyer (1946).

Observations of the spectrum are given by Neubauer and Herbig (1945) and by Sanford (1945). Two absorption systems are recorded; Absorption I showed lines of hydrogen, ionized metals, perhaps He I; Absorption II, H, Ca II, Mg II, Fe II. Between JD 31699 and 31706, the associated bright lines were present with width corresponding to a velocity of 2500 km/sec. Cyanogen absorption at 3550 A was noted by Neubauer and Herbig.

On JD 31753 Sanford noted that [N II] 5755 emission was conspicuous; it had been absent on JD 31715.

The absorption velocities are summarized below. Absorption I was seen doubled on and after JD 31711; both its components were sharper than those of Absorption II. The (variable) component of shorter wavelength was noted by Sanford as the stronger of the two.

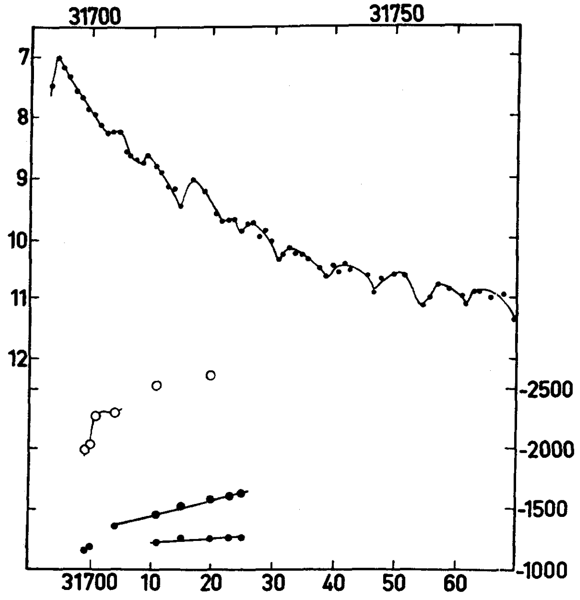

Fig. 5.5. Light curve and velocities for V 528 Aquilae. Abscissae are Julian Days. Ordinates (left) are photographic magnitudes; (right), velocities in km/sec. Absorptions II and I are denoted by circles and dots; larger dots denote the stronger component. Notice that Absorption II was not observed at the minimum of the light curve, JD 31715. Compare V 603 Aquilae.

Julian Day	Absorption I km/sec		Absorption II km/sec	Reference
31699	—1150		—1980	Sanford
31700	—1180		—2040	Sanford
31701	. .		—2270	Sanford
31700 to 31703	—1200		—2100	Neubauer, Herbig
31704	—1350		—2280	Sanford
31711	—1230	—1460	—2520	Sanford
31715	—1270	—1530	. .	Sanford
31720	—1250	—1570	—2610	Sanford
31723	—1260	—1600	. .	Sanford
31725	—1260	—1630	. .	Sanford

V 604 AQUILAE 185604 JD 17072: (1905) 8.2

The light curve published by Walker (1923) probably nearly covers maximum; the unobserved interval is seven days. Two spectra are described by Cannon (1916); they are immediately post maximum and in the transition stage, respectively. Intensities are on a arbitrary scale.

Julian Day	Hβ	He I 4471	N III ? 4646	? 4600	Hγ	Hδ	Remarks
17076	30	tr	tr	..	10	5	Violet absorptions
17110	p	..	..	p	p	p	

V 606 AQUILAE 191500 JD 14754 (1899) 6.7 (4.4)

The early part of the light curve observed by Leavitt (1920) was not covered by the material, and maximum can hardly be estimated. The light curve is rather unusual; perhaps the closest parallel is with OY Ara. We may guess that maximum was near JD 14754, but the nearest previous observation was 184 days earlier than this date.

Three spectra are described by Cannon (1916):

Julian Day	Hβ 4861	Hδ 4101	Hε 3970	Hζ 3889	[O III] 4363	[O III] 5007	He II, N III 4653	Magnitude
14839	2	3	1	0.5	10	1	3	11.4
14905					p	p		11.6
14955		1			p	p		

We note the progressive increase of [O III] 5007 relative to 4363. All the observed spectra fall within the "nebular stage" of the spectrum.

V 841 AQUILAE 190210 JD 33743: (1951) 11.5

The light curve shows considerable fluctuations, as illustrated by Hoffleit (1952). The earliest observation, JD 33753 ($12^m.1$), may be much later than actual maximum. Zwicky (1951) observed magnitude 11.5 on JD 33801; post-maximum fluctuations were certainly going on at this time. The star was probably fainter than seventeenth magnitude at minimum. The spectrum obtained by Zwicky on JD 33801 was characteristic of a stage long past maximum.

Julian Day	Hα 6563	Hβ 4861	Hγ 4340	Hδ 4101	He II 4686	N III 4640	[O III] 5007 4957	[O III] 4363	Reference
33801	very strong	weak	weak	..	..	..	medium	..	Zwicky (1951)
33839	..	p	p	..	mod. strong	fairly strong	very strong	stronger than Hβ	Minkowski (1951)

On JD 33801 the continuum was present, but weak. On JD 33839 the spectrum was in the nebular stage; an expansion velocity of 750 km/sec was deduced from the widths of the bright lines.

OY ARAE *163325* JD 18738: (1910) 6.2 (5.1)

The light curve published by Walker (1923) may nearly reach the true maximum; the unobserved interval was 16 days and the decline was slow. Fluctuations are suggested about 65 days after maximum, when the brightness had falled through about three magnitudes.

Four spectra, described by Cannon (1916) all fall in the early nebular stage, when the magnitude was between 10.3 and 10.8. Taken on JD 18858, 18878, 18883, 18887, they are essentially similar. The lines recorded, and their intensities on an arbitrary scale, are: Hβ, 1; Hδ, 1; N III 4640, 2; [O III] 5007, 1, [O III] 4363 + Hγ, 10.

RS CARINAE *110361* JD 13285: (1895) 7.2 (5.0)

The light curve published by Walker (1923) probably almost reaches maximum. The large post-maximum fluctuations recall DN Gem, but the coverage is rather fragmentary.

Julian Day	Hβ 4861	Hδ 4101	Hε 3970	N III ? 4650	[O III], Hγ 4363	Remarks
13298	1	5	1	..	10	All lines have violet absorptions
13360	..	..	..	present	present	[O III] 5007 absent

Two spectra are described by Cannon (1916); the first is of typical post-maximum character, though the great intensity recorded for Hγ suggest an unusually early appearence of [O III] 4363. The second is a transitional spectrum; [O III] 5007 has not yet appeared.

X CIRCINI **143464** JD **24762 (1926)** **6.5**

The light curve published by Cannon is too fragmentary for deduction of maximal magnitude. The one spectral observation by Becker (1929) was made on JD 25002 during an interval not covered by the observed light curve. The spectrum was then in the early nebular stage.

Julian	Hβ 4861	Hδ 4101	Hε 3970	Hζ 3889	He II 4686	[O III] 5007 4958	[O III], Hγ 4363
25002	1	4	1	0.5	3	2	10

P CYGNI **201437** **1600** **3?**

This well-known and much studied supergiant B star is often included in lists of novae, but is not an ordinary nova. Rather it should be regarded as a bright star that underwent something akin to shell activity when it brightened to third magnitude in 1600. If it is now of absolute magnitude —8, its maximal absolute magnitude was about —11, comparable to that of the equally atypical, but dissimilar, star η Car. Perhaps a closer parallel is with AG Peg. There is no record of duplicity in connection with P Cyg, but a giant M companion would of course be undetectable beside so luminous a star.

Q CYGNI **213742** JD **06583 (1876)** **3.0**

Although photographic data are lacking for the bright nova of 1876, the summary of deductions from visual observations by Lockyer (1891) provides valuable information, and reveals a surprising grasp of the main phenomena of a nova outburst.

The spectral development may be divided into three intervals: the initial rapid stage (JD 06591 to 06603); the transitional stage (JD 06621 to 06664); and the nebular stage (JD 06866 to 06918).

Julian Day:	06591 to 06603	06621 to 06664	06866 to 06918	Remarks
Stage:	Initial	Transitional	Nebular	
Magnitude:	5 to 7	7.3 to 7.6	10:	
Hydrogen	decreasing	decreasing	..	Hα gone after JD 06653
He I 5876	decreasing	strong	..	
He II 4686	decreasing	increasing	..	Appeared JD 06595
N III 4640	strong	..	..	JD 06597 only
[O I] 6300	weak	..	..	
[O III] 5007	..	increasing	strong	
[N II] 5755	increasing	decreasing	..	Appeared JD 06594
Fe II 5167, 5018	weak	..	..	

The development is that of a fast nova.

The light at minimum continues to vary; Steavenson places it at 14.8 visually, with a range of $0^m.8$, in 1948. Turner (1921) believed the variations to be periodic.

Humason (1938) observed the spectrum sixty years after the outburst and showed it to be that of a faint blue star with a strong continuum that extends far into the violet. No absorption lines are noted, but very faint emissions are suspected at Hβ, Hγ, and Hδ on JD 28385 and 28397.

V 450 CYGNI 205635 JD 30510 (1942) 7.8

The light curve is complied from the pre-discovery observations of Ashbrook and Nail (1942), the magnitude reported by Sanford (1942, 1943) and by Harwood (1943). The light curve is definitely of DQ Her type, but the fluctuations at maximum are larger. The drop from magnitude 9 to less than 16.5 is also larger than that recorded for DQ Her, and seems to have taken place in about ten days.

The spectral development also was parallel to that of DQ Her; on JD 30617, about 100 days after the first rise, Sanford (1942) reported a spectrum similar to that of DQ Her fifty days after its maximum. Sanford noted the weakening of the continuum and the concurrent strengthening of the bright lines of Fe II, [Fe II], especially the latter, exactly as in DQ Her just before the great minimum. The nebular spectrum during the recovery of light in 1943 was again similar.

Multiple absorptions of the hydrogen lines were observed, as tabulated below, by Sanford (1942) and by Swings and Bidelman (1942). Sanford noted that the centers of the bright metallic lines had an apparent velocity of —340 km/esc. Swings and Bidelmann observed the Balmer continuum in absorption. They also measured a width corresponding to 1500 km/sec for bright lines of Fe II and Ti II, and, like Sanford, noted a violet shift of the centers. Ti II absorption was noted in the ultraviolet, with the same velocity as the main Balmer component.

Absorption	Sanford JD 30617 km/sec	Sanford 30617–25 km/sec	Width km/sec	Swings and Bidelman 30621 km/sec	Width km/sec	Intensity	Remarks
I	..	—250	..	—237	..	..	1
II	—510	—500	rather sharp	—507	135	3	2
III	..	—800 ?		—706	..	1	3
IV	..			—887	200	3	4
V	—1200	—1200 to 400		—1262	444	20	5
VI	..	..		—1454	..	4	6

NOTES

1. Short-lived (Sanford); K line only, faint (Swings and Bidelman).
2. Persistent, velocity constant (Sanford); fairly strong (Swings and Bidelman)
3. Very weak.
4. Short-lived.
5. Sometimes multiple (Sanford); Swings and Bidelman refer to main component.
6. Faint.

The post-minimum spectrum, observed by Sanford (1943) on JD 30864, showed bright lines of H, He I, He II, C II, N III, [O II]? [O III], [Ne III], [S II], and [Fe V]?. Intensity ratios were recorded as follows: [Ne III] 3867/$H\zeta = 4$; [O III] 4363/$H\gamma = 6$; [O III]/$H\beta = 3$. We again note a strong resemblance to DQ Her after the rise from minimum.

V 465 CYGNI 194836 JD 32700: (1948) 8 (7.3)

The light curve, with conspicuous fluctuations about a rather slow decline, from tenth to twelfth magnitude in about two hundred days, is compiled from the observations of Soloviev (1949) and of Ashbrook and Nail (1950). The latter authors suggest that actual maximal magnitude may have been as bright as 7.3, and point out that the prenova was of about $17^m.5$.

Studies of the spectrum, by Joy (1948), Yoss (1949) and Bloch (1950) point to three absorption systems:

Julian Day	Absorption I km/sec	Absorption II km/sec	Absorption III km/sec	Notes
32707–32789	—1240	—620	+230	1
32709	—1200	..	..	2
32714–32729	—1270	—560	..	3
32826	—1500	..	..	4

NOTES

1. Bloch (1950): emission maxima correspond to velocities of —800 km/sec, —60 km/sec, + 420 km/sec.
2. Yoss (1949): diffuse enhanced stage. Faint continuum; Balmer lines 20 A wide; emissions at Hβ, Hγ, Hδ, Fe II.
3. Joy (1948): spectrum, JD 32714, typically post-maximum; Hγ, [O I] 6300, [O I] 6363, [O I] 5577 the outstanding bright lines; H, He I, Ca II, Fe II, Ti II, Sc II in absorption and emission.
4. Yoss (1949): little change except for appearance of N III 4640 in emission.

The changes of intensity of the dark and bright lines are well shown by Bloch's discussion of 23 spectra, distributed between JD 32707 and 32789.

Noteworthy are the prominence of the lines of oxygen, while neon is not detected, and the occurrence of the positively-displaced Absorption III. The table above includes unblended lines only; in addition, Bloch identifies Na I, Ti II, Si II and [S II]; she also suggests that [O I] 5577, 6300, and 6363 are represented by absorption components. We recall the suggested occurrence of [Fe II] in absorption in η Car, and note that [O I] lines have been observed as weak absorptions in the spectrum of the sun.

	Absorption Spectra			Emission Spectra Change JD 32707–32786		
Atom	JD 32707–32721	32724–32752	32754–32786	I	II	III
	Av. Pg. Mag. 10	10.6	11.1	—800 km/sec	—60 km/sec	+420 km/sec
Absorption I:						
H	very strong	very-strong	very strong	+	++	+
He I	weak-medium	weak-medium	weak-strong	0	+	0
C II	..	..	..	0	—	?
N I	absent-very weak	very weak-weak	very weak-medium	0	+	—?
N II	absent-medium	very weak-medium	weak-strong	+	+	+
[N II]	..	..	..	0	+	0
N III	..	..	..	0	0	++
O I	weak	strong	strong	0	+	0
[O I]	..	..	..	0	++	0
O II	weak	strong	strong	0	+	+
[O III]	..	..	..	0	++	++
Ca II	very strong	very strong	very strong	..	..	..
Mg II	strong	absent	absent	..	..	..
Fe II	medium-strong	very weak-weak	absent-very weak	0	—	0
Absorption II:						
H	strong	strong	strong			
Ca II	strong	strong	strong			
Absorption III:						
H	strong	weak	weak-absent			

Spectrophotometric comparison with α Coronae Borealis lead Bloch to a color temperature of 5200° between JD 32707 and of 4400° between JD 32734 and 32789; these are much lower than the color temperatures determined for CP Lacertae, for instance, but V 465 Cyg is a slow nova, more nearly comparable with DQ Her.

DM GEMINORUM 063730 JD 16180 (1903) 5.0

The well-observed light curve published by Leavitt (1920) probably nearly reaches maximum; it shows a sharp drop, a well-marked transitional stage, and a decline, perhaps marked by fluctuations.

The spectral development was typical and rapid; the table is compiled from the observations published by Cannon (1916), Hale (1903), Perrine (1903), Curtis (1904) and Perrine (1904). Even at the time of the first spectrum obtained, the 4640 stage had been reached, and [O III] 4363 was evidently strong. The nebular stage had appeared by JD 16344.

Atom	JD 16199	16202	16203–	16207–	16211	16344–	16355–
			16205	16213		16345	16360
	Cannon	Hale	Cannon	Perrine	Curtis	Curtis	Perrine
Hβ 4861	5	strong	5	strong	present	rather faint	very faint
Hδ 4101	8		8	very strong			weak
Hε 3970	2		2	medium			
Hζ 3889	1		1	faint			
[N II] 5755		present					
N III 4640	12	broad	12	broad, very strong			
[O III] 4363	10	present	10	very strong			strongest line
[O III] 5007		faint			present	medium	strong

The wavelengths published by Reese and Curtiss (1903) suggest that at least three absorption systems were present:

Julian Day	Absorption I km/sec	Absorption II km/sec	Absorption III km/sec
16207	—189	—570	—1365
16210	—219	—700	—1420

Another possible system, with velocity —1100 km/sec, may have been present on JD 16210, 16227. The widths of the bright lines given by Hale for JD 16202 would correspond roughly to a velocity of 2200 km/sec.

Humason (1938) observed the spectrum on JD 27367, thirty years after maximum, as showing neither absorption nor emission lines, and having a less pronounced violet extension than is usual for old novae.

DI LACERTAE 223152 JD 19002 (1910) 4.6

The light curve, by Leavitt (1920) is well determined, and shows a smooth fall, probably followed by fluctuations about 3.5 magnitudes below maximum. Observations of the spectrum began about forty days after maximum, when the star had reached the 4640 stage. No radial velocities were measured.

The longest series of spectra was made at Harvard, and described by Cannon (1916). The Balmer lines faded steadily from JD 19041 ($7^{m}.7$) to 19096 ($9^{m}.4$); N III 4640 was strong on JD 19041, faded temporarily at a minimum of the light curve on JD 19054, strengthened again and finally faded. Lines of Fe II were recorded from JD 19054 to 19065. The line [O III] 5007 appeared on JD 19086 ($9^{m}.4$); as [O III] 4363 was never separated from Hγ, its presence at an early date (perhaps JD 19065) must be inferred from the intensities of all the Balmer lines. After JD 19065 it certainly strengthened. The brightline spectrum was thus entirely normal. In the following year, on JD 19240, only [O III] 5007 and a trace of Hγ (probably [O III] 4363) were recorded; the nova was then below tenth magnitude.

The bright lines were noted at Harvard as double, i.e., saddle-shaped, from JD 19049 onward. Genard (1931) noted similar structure at Hγ on a Paris spectrogram of JD 19066, but he was probably mistaken in supposing that the line was uncontaminated by 4363 at this date.

On JD 28372, twenty-six years after maximum, Humason (1938) found the star very blue, with a strong continuum extending well into the violet, and no visible lines. McLaughlin (1953) estimates the intensities of emission lines on several post-maximum spectra. Between JD 19982 and 20071, the lines of hydrogen, He II 4686, C III 4650 increased in intensity, as did the nebular lines of [O III]. Between JD 20745 and 30204 they all diminished to traces or zero. The minimal magnitude seems to be constant at 14.4.

HR LYRAE 184929 JD 22299 (1919) 6.5

Maximum brightness of HR Lyr was almost certainly observed on JD 22299; the star was fainter than 16.5 two days earlier, according to Bailey (1920). The light seems to have fluctuated until about JD 22370; later visual observations by Nijland (1925) showed a steady fall from 9.55 on JD 22302 to 13.8 on JD 23018.

The data on the spectra are rather fragmentary. Observations by Adams and Joy (1920) and Wright (1920) are brought together by Wyse (1940a). The earliest spectra discussed were taken sixty days after maximum.

Wyse gives data for two absorption systems; Absorption I displayed the Balmer lines; Absorption II showed lines of H, He I, N II, N III, O II, Mg II, Si III and Si IV, and (on JD 22403) N V.

JD	22360 km/sec	22389 km/sec	22403 km/sec
Absorption I	—1009	..	..
Absorption II	—1863	—2100	—2520

The emission spectra followed a normal course; observations began on JD 22360.

Julian Day	Atoms represented
22360	H (strongest line), He I 4471, C II 4267, N II 3995, N III 4640, O II 4415? [O III] 5007, Fe II 4924.
22368	H, N III 4640 (strongest line), He II 4686.
22369	N III (strongest line); [O III] 4363 appears?, O II 4415 definite.
22389	He II 4200 appears?, [O III] 4363 strengthens, N IV 4057 appears.
22397	[O III] 4959 appears.
22549	[O III] 5007 strongest line; H weaker than any of the [O III] lines.

A plate in the visual region, JD 22373, shows N II 6482, $_i$N II^c 5755.

Structural detail within the bright lines, JD 22396, 22414 showed two maxima, displacements equivalent to —780 km/sec and +690 km/sec, with four minor minima between them; violet and red edges of the bright lines extended to —900 and +846 km/sec.

Post-maximum spectra were obtained by Humason (1938) on JD 28339, 28340, when the star was of magnitude 15.3. An extremely strong continuum, extending far into the violet, marked HR Lyrae as one of the bluest of the old novae. No absorption or emission was visible. The brightness continued to decline, and the photographic magnitude was given by Wyse (1940c) on JD 29786 as 15.4; the star had thus not returned to pre-maximum brightness, less than 16.5, in over twenty years.

BT MONOCEROTIS 063801 JD 29515 (1939) 8.5

The light curve published by Whipple (1940) shows BT Monocerotis fainter than eighth magnitude at the time of discovery, but he points out that it may even have been a naked-eye star at maximum. It rose from below the seventeenth magnitude.

Four spectra have been described. On JD 29558 ($8^m.5$) H and N III 4640 were seen in emission, an indication that maximum was long past. On JD 29586, the nebular [O III] lines and He II 4686 were visible and the continuum was weak. After these two Harvard spectra, the next (JD 29624) was obtained by Sanford (1940), who recorded bright lines of H, He I, He II, C II, C III, N III, O II, [O III], and noted that H, [O III] and N III were strong. On JD 29946, when the brightness has fallen to $11^m.3$, Swings and Struve (1941) found Hα the only strong Balmer line; almost all the light in the visual region came from [O III] and H + ([N II]?). Weak lines of [N II] 5755, He II 4686, N III 4634–4640 and [S II] 4076 were recorded.

On JD 29558, 29586, Whipple estimated that the width of the bright lines corresponded to 1500 km/sec; on JD 29624, Sanford estimated 2100 km/sec; and on JD 29946, Swings and Struve deduced 1730 km/sec.

GI MONOCEROTIS 072106 JD 21595 (1918) 5.6

The light curve, published by Leavitt (1920) is well covered for nearly a hundred days, and maximum cannot have been missed by more than a few tenths of a magnitude. The fall was rapid and smooth, with an inflection about three magnitudes below maximum.

No radial velocities are recorded. The course of the spectral development may be traced from the description by Cannon (1918) of spectra between JD 21646 and 21690, by Adams and Joy (1918) for JD 21653, 21654, 21676. Lines of H, N III 4640 and [O III] 5007 were visible; the great strength recorded for Hγ shows that [O III] 4363 was already strong. Thereafter the H and N III weakened, while [O III] strengthened steadily. On JD 21690 ($10^m.5$) only [O III] and very weak N III were visible on a Harvard plate.

Attention was called by Paddock (1918) to the saddle-shaped profiles of the bright lines, the violet edge being the stronger.

IL NORMAE *152250* JD 12638 (1893) 7.0

The early stages of the light curve, published by Walker (1923) are poorly covered, though maximum at JD 12638 ($7^m.05$) was probably recorded. There is little to indicate the early course of the curve; fluctuations seem to have continued from JD 12875 to 13000, as the brightness fell from about magnitude 10.5 to 11.5.

On JD 12655, as described by Cannon (1916), the spectrum seems to have been that of a slow nova soon after maximum. By JD 12888 it had entered the nebular stage; [O III] 4363 was by far the strongest line, and Hβ, Hγ, [O III] 5007 and N III 4640 were present. The spectrum was essentially similar on JD 12947, 12979.

V 841 OPHIUCHI 165312 JD 2396146 (1848) 5 (2)

The nova of 1848 is important because it is the earliest for which we have data concerning the post-nova. Its curve and maximal magnitude are therefore of importance. The observations of Hind (1848), Petersen (1848), Schumacher (1848) and others are difficult to reduce to a consistent curve. On JD 2396146, Hind described it as like ν Serpentis (visual magnitude 4.35); on JD 2396149 he likened it to 20 Ophiuchi (4.73), and he gave it as fainter than ninth magnitude on JD 2396123, twenty-three days before he discovered it. The observations by Argelander, published by Pickering (1900) show a slow decline from fifth magnitude on JD 2396155 to seventh on JD 2396244.

From these data it seems unjustifiable to conclude that the star was at maximum when Hind discovered it; indeed if it had a light curve like that of V 476 Cyg, it could have been at least three magnitudes brighter than his first estimate during the three weeks before discovery. If the star were a slow nova, greater fluctuations might have been expected to occur during the first days of observation. Moreover several observers, notably Hind, Petersen and Schumacher, commented on the star's redness when first discovered, which suggests that it was already well advanced into the emission stage. We cannot, therefore, draw any definite conclusions as to the range.

The star continues to vary slightly between twelfth and thirteenth magnitude. The spectrum, as observed by Humason (1938) on JD 28388, almost ninety years after the maximum, showed a strong continuum, extending into the violet, without either absorption or emission lines.

V 849 OPHIUCHI 180911 JD 22268 (1919) 7.4 (7.2)

The available observations, summarized by Wright (1920) show the large postmaximum fluctuations of a slow nova, similar to V 356 Aql or V 794 Oph. The spectrum was described by Cannon (1920), Adams and Burwell (1920), Adams and Joy (1920) and particularly by Wright (1920). No spectra were obtained until about seventy days after the first recorded appearance (JD 22191); the observed features throughout the subsidiary maximum at JD 22268 were characteristic of the early nova stage. A similar situation is found for RR Pic, for example.

The one absorption system observed showed lines of H, Ca II, Fe II, Ti II, Mg I, Ca I, Sc II and Sr II, all of which were noted by Wright to strengthen during the subsidiary rise, from JD 22262 to 22268, or (like Sr II) to be present at the maximum only. At the same the bright lines diminished in relative intensity; they comprised H, Ca II, Fe II, Ti II and Mg II. Here we clearly have to do with a strengthening of the continuum, as observed for example at the subsidiary maxima of DN Gem.

The recorded displacements of the absorption spectrum increased slightly:

Julian Day	Vis. Mag.	Velocity km/sec	Remarks	Reference
22264, 22265	7.85	—330		Adams and Burwell
22265	7.70	—336	Fe II, Ti II	Wright
22268	7.20	—396	Fe II, Ti II	Wright

During the nebular stage the intensities of the bright lines changed: between JD 22449 and 24548, the lines of H, He I 4471, He II 4686, N III 4640, O II 4416, [Ne III] 3869 and [S II] 4068 weakened; C II 4267 and N II 3995 disappeared, and [O III] strengthened slightly. The lines of [Ne III] and [O III] seem equally intense.

Wright noted that on JD 22265 the Balmer lines were about 8 A wide, the Fe II lines about 11 A wide; on JD 22276 the Balmer and Fe II lines had widths of 12 A and 13 A respectively, and maxima had developed near their edges (saddle-shaped profiles). On JD 22264, 22265, Adams and Joy assigned a width of 8.5 A to Hγ.

FU ORIONIS 053909 JD 28700 (1937) 9.7

If it is indeed a nova, FU Ori is the slowest known. It rose by six magnitudes within ninety days in 1937, and is still bright after seventeen years. It remained constant near tenth photographic magnitude until 1948, and fell slowly to $10^m.5$ between 1948 and 1954, according to the observations of Wachmann (1954). At minimum it was shown by Hoffleit (1939) to have been variable with a small amplitude. It is relatively red, as pointed out by Wellmann and Hachenberg (1939), and the visual observations of Ashbrook (1953), which showed it to be of visual magnitude 8.96 in February, 1953, confirm the redness and the protracted maximum.

The behavior of the star is summarized by Wellmann (1951): FU Ori is within a nebula which also brightened, and is part of the dark nebula B 35. Struve (1939) showed that the nebula shines by reflected starlight, and has in addition weak emissions that are apparently not excited by the star.

The spectrum was first described as of Class A8, but was perhaps a little later. It has changed gradually from cF5 to F8–G0 Ia, then to G3 Ia. Wellmann (1951) compares it with the spectra of several F stars, and finds that it falls roughly between ϱ Cassiopeiae and γ Cygni, but that hydrogen and metallic spectrum cannot be matched at the same time. If we consider the comparison a criterion of luminosity, FU Ori at maximum would have an absolute magnitude near —6; from the observed color excess, Wachmann considers the value to be nearer to —4.

The presence of the nebula and the absence hitherto of a characteristic nova spectrum have led Wachmann to suggest that FU Ori is actually an extrinsic nebular variable. We incline it to liken it to RR Telescopii, whose maximum was similar though not so protracted, and whose spectrum shows supergiant F character. Later development of the spectrum will decide the matter.

V PERSEI 015556 JD 10500: (1887) 9.4 (8.8:)

The nova was discovered long after maximum and was then fainter than ninth magnitude, according to the light curve published by Leavitt (1920). McLaughlin (1946) surmises that it may have been as bright as fourth magnitude, and at maximum five or six months earlier.

The slight spectroscopic information, derived mainly from a Harvard objective prism plate of JD 10579, has been rediscussed by McLaughlin. The bright Balmer lines were very faint, [O III] 4363 faint, and [Ne III] 3869, 3968 the strongest lines in the spectrum. The non-observation of Hβ and [O III] 5007 are ascribed to poor focus. V Per may thus be one of the novae in whose spectrum the lines of [Ne III] are unusually conspicuous.

WZ SAGITTAE 200317 JD 20094 (1913), 32001 (1946) 7.0, 7.7

The star was shown to be a recurrent nova by Mayall (1946), who recorded maxima in 1913 and 1946. In 1913 the maximal magnitude was 7.0; brightness fell by three magnitudes in 24 days. In 1946, the maximum was at 7.7, and brightness fell three magnitudes in 21 days; there was a sharp increase is slope later, not paralleled in 1913.

No spectrum was observed at either maximum. At minimum (JD 27630, 27654, magnitude 15) Humason (1938) recorded a fairly strong continuum extending into the violet, but no absorptions or emissions. These observations are important in establishing the small range of about eight magnitudes.

WZ Sge has been regarded as a "faint nova" because of its parallax and proper motion. Jenkins (1952) gives an absolute parallax of 0″.11 ±0″.11, and an annual proper motion of 0″.08. The undisplaced broad absorption lines described by Mc Laughlin have a suggestive resemblance to those of SS Cyg and SW UMa.

V 726 SAGITTARII *181326* JD 28302 (193) 10.8

The light curve published by Mayall (1938) shows a fairly steady and slow decline from magnitude 10.8 on JD 28302 to about 13 on JD 20370, and a more rapid drop in brightness thereafter. The unobserved interval is thirteen days, and at maximum the star could have been two or three magnitudes brighter.

On JD 28318 the bright lines, in order of intensity, were: Hγ + [O III] 4363; Hδ; Hζ + [Ne III] 3869; Hε + [Ne III] 3968. The lines were about 40 A wide, corresponding to an expansion velocity of about 1500 km/sec; both the rapidly-advancing spectral stage and the high velocity point to a fast nova. On JD 28342 the line Hζ + [Ne III] 3869 was the strongest in the photographed spectrum, placing V 726 Sgr with the novae that show [Ne III] with unusual prominence.

V 732 SAGITTARII *174927* JD 28280: (1936) 6.5

Discovered at Mount Wilson from its bright-line spectrum, as reported by Burwell (1937), the nova is inseparable from a nearby K star of magnitude about 11.6. A light curve was published by Jones (1938), and the star was re-examined by Swope (1940), who corrected for the brightness of the companion, and pointed out that the nova is of DQ Herculis type.

The spectral observations confirm this ascription; the development of the spectrum was slow, and [O III] 4363 only appeared after the "great minumum" on JD 28631, becoming the strongest line in the spectrum by JD 28672. The star showed typical, well-marked fluctuations during the eighty-day protracted maximum, and the maximal magnitude of about 6.5 can be adopted with confidence. Miss Swope called attention to irregular bright nebulosity seen during the first long maximum.

V 909 SAGITTARII *181935* JD 30172 (1941) 6.8

The light curve published by Mayall (1946) probably reaches maximum at $6^m.8$ on JD 30172; the star was invisible two days earlier. The drop in brightness was very rapid: 3, 5, and 7 magnitudes in 7, 27 and 62 days, respectively. There were no conspicuous fluctuations.

On a Harvard plate of JD 30194, when the star had declined nearly five magnitudes, broad bright Balmer lines and very strong lines of [Ne III] were visible.

V 928 SAGITTARII *181228* JD 32316 (1947) 9.5

The spectrum of JD 32320, recorded by Merrill, Burwell and Miller (1947), was evidently shortly after maximum; the star was at ninth magnitude. Bright Balmer lines, Fe II 4924, 5018, 5169, and perhaps the D lines of Na I, were present. On JD 32330 the bright lines of H and Fe II had half-width velocities of 1060 and 1040 km/sec, respectively. Apparently the change of spectrum during the next fifteen days was not rapid. Little can be inferred about the type of light variation.

A radial velocity of +190 km/sec (corrected to the sun) for the bright lines suggests that V 928 Sgr is a high-velocity star.

V 999 SAGITTARII *175327* JD 18680 (1910) 8.0

The light curve published by Walker (1923) shows peculair slow fluctuations that recall RR Pic. The first observation, at magnitude 10.3, was followed by an unobserved interval of more than 150 days.

A rise from 9.9 to 8.1 then occupied about fifty days; whether the latter observation represents the principal maximum is uncertain.

The spectrum seems to have developed slowly. Eighty days after the brightest observed maximum, Harvard spectra showed primarily the bright Balmer lines. Five months after the observed maximum, Wright (1910) recorded bright lines of H, a broad band from 4607 to 4700, He I 4471, and the D lines; the nebular spectrum had not appeared.

No absorption velocities have been recorded. From the rather uncertain widths of the bright lines, McLaughlin (1940) deduced an expansion velocity of about 700 km/sec, which he associated with a "diffuse enhanced spectrum".

V 1017 SAGITTARII *182529* JD 15641 (1901), 22029 (1919) 10.8, 7.2

The observations of McLaughlin (1946) show that V 1017 Sgr, announced by Woods (1919), is probably recurrent. The maximum of 1919 rose to maximum 7.2, and had the typical rapid decline of a fast nova. The maximum of 1901, on the other hand, had a slow rise to magnitude 10.8. No satisfactory observations of the spectrum were made at maximum.

Spectra at minimum have been obtained by Humason (1938) and in 1927 by Brück (1935). The former recorded only a strong continuum extending well into the violet, and noted the absence of absorptions and emissions. The latter suggested a spectral class G5.

V 1059 SAGITTARII *185613* JD 14340 (1898) 4.9 (2.0:)

The light curve published by Walker (1923) shows a rapid early decline from probable maximum on JD 14347 at about magnitude 4.9. A halt or dip at about magnitude 8.5, from JD 14383 to 14409, was followed by a steady fall.

Spectra were described by Pickering (1899) for JD 14399, 14401; they show bright lines of H, N III 4640 and several fainter lines. The spectrum seems typical of the 4640 stage, with wide bright Balmer lines and very broad 4640.

A description of the minimal spectrum by Humason (1938) states that no lines are seen, but that it gives the impression that the star is blue.

T SCORPII *161121* JD 00552 (1866) 6.7

Great interest attaches to T Sco because of its possible association with the globular cluster NGC 6093, Messier 80. The maximum of 1860, JD 00552, and the subsequent decline, have been thoroughly discussed by Sawyer (1938). The drop in brightness seems to have been fairly rapid, three magnitudes in 21 days.

U SCORPII *161617* JD 01646 (1866), 17342 (1906), 28342 (1936)
9.1, 8.8, 8.8

Three maxima of this recurrent nova have been recorded: JD 01646 (m^{vis} 9.1) by Pogson (1908), on JD 17342 (m_{pg} 8.8) by Thomas (1940), and on JD 28342 (m_{pg} 8.8) by Thomas (1940). Photographic minimum brightness is fainter than 17.6.

The rate of decline was very rapid; a mean for the maxima of 1863 and 1936 is three magnitudes in 6.7 days, five magnitudes in 10.6 days. The maxima are so brief that several may well have been missed. The star deserves continuous watch. No spectra have been recorded, and spectroscopic observations would be of great importance.

V 697 SCORPII *174434* JD 30060 (1941) 10.2 (10.0)

The light curve published by Mayall (1946) shows a steady decline from JD 30063 ($10^m.2$) to 30600 ($16^m.6$). Maximum was probably much earlier, as Harvard plates taken between JD 30120 and 30200 show well-developed [O III] 5007, 4959, and the great strength recorded for Hγ shows that [O III] 4363 was also strong at the time.

V 719 SCORPII *173933* JD 33482 (1950) 9.8

The observations of Herzog and Zwicky (1951) cover the rapid rise to maximum ($9^m.0$) on JD 33482, and a decline, probably with fluctuations, to 13^m 9 on JD 33510; thereafter the fall in brightness became much slower, and the star reached $14^m.7$ on JD 33545.

The spectrum was not atypical for such a light curve; Henize and McLaughlin (1951) observed the not unusual feature of narrowing of the emission lines. On JD 33488 two absorption systems were identified by McLaughlin (1951), with velocities about —1100 km/sec and —2200 km/sec, and complex structure was noted in the bright lines.

V 720 SCORPII *174535* JD 33501 (1950) 7.8

The light curve, deduced from observations by Haro (1950), Herzog and Zwicky (1952), and O'Connell (1954) shows a well-observed slow rise to maximum, from magnitude 9.3 on JD 33493 to about 7.8 on JD 33501. Thereafter the brightness fell by about two magnitudes, with fluctuations, until JD 33514, and dropped suddenly below twelfth magnitude by JD 33518.

The spectrum described by McLaughlin (1951), Henize and McLaughlin (1951) and Sahade and Dessy (1952) showed weak bright Balmer lines before maximum, virtually no absorption or emission at maximum, and bright lines of hydrogen and ionized metals, with a steadily weakening continuum, during the slow decline McLaughlin noted the appearance of [O I] 5577 between JD 33506 and 33510. He observed a velocity of —1100 km/sec for the absorptions relative to the centers of the bright lines, and noted that the widths of the Fe II emissions corresponded to a velocity range of ±900 km/sec The star resembles a very rapid DQ Her, but no bright [Fe II] lines were reported, and a secondary rise was not detected.

V 721 SCORPII *173534* JD 33528 (1950) 9.5

The observations of Haro (1950) and of Herzog and Zwicky (1951) show a rapid fall from magnitude 9.5 on JD 33528. Actual maximum was probably a good deal brighter. Observations by McLaughlin (1951) and Henize and McLaughlin (1951) showed strong bright Hα from JD 33532 to 33541, and a spectrum not unlike that of V 720 Sco.

EU SCUTI *185004* JD 33134 (1949) 8.4

The light curve has been compiled by Bertaud (1953); maximum visual magnitudes on JD 33133, 33134 were given as 7.59, 7.43; photographic magnitudes on the same days were 8.41, 8.45. Ashbrook (1950) and Wellmann (1951) placed maximum a day later, at visual magnitudes 8 and 7.7 respectively. The decline was slow at first, about four magnitudes in fifty days, and then more rapid.

The maximal spectrum was observed on JD 33133 by Kourganoff, Canavaggia and Münch (1949) to resemble that of an F supergiant without any emissions. Their reproductions of the spectrum on JD 33133, 33135, 33137 show the development of bright lines, notably those of hydrogen. There is a close resemblance to DQ Her, also pointed out by Wellmann (1951). Absorption lines of H, Ti II (relatively strong than in DQ Her), Ca I (stronger), Fe II (weaker), and O I, Sc II (much weaker) were noted by Wellmann. Kourganoff, Canavaggia and Münch observed lines of C I with unusual strength. Similar findings were published by Colacevich (1950), who observed, on an infra-red plate of

JD 33139, bright lines of H, He I, N I, O I, Na I, Si II, Ca II, Ti II and Fe II, and absorptions of H, C I, Si II, Ca II and Ti II.

Radial velocities at maximum were measured by Wellmann (1951) between JD 33132 and 33142; one absorption system increased steadily in velocity from —307 km/sec to —400 km/sec; weaker absorptions corresponded to —750 km/sec and —1600 km/sec. The series of observations by Heard (1953) covers the interval JD 33142 to 33176. Three absorption systems are identified: the principal absorption coincides with Wellmann's velocity for his least displaced component; the diffuse enhanced absorption appears on JD 33164 at about —570 km/sec, and fades, with perhaps a small reduction in velocity, until JD 33176. The Orion absorptions are recorded from JD 33164 to 33176 with a velocity about —1100 km/sec. The velocities and the spectral development recall those of DQ Her.

FS SCUTI *185205* JD 34188 (1952) 10.1

As reported by Whitney (1952), the nova rose to a sharp maximum ($10^m.1$) on JD 34188, having brightened from magnitude 12.4 on JD 34185. Then followed a rather slow drop, with large fluctuations in a cycle of about 12 days, as shown by the observations of Gaposchkin (1952), Hunaerts (1953), Bertaud (1952), Tempesti (1952) and others, which are bnt, however, on accordant magnitude scales.

The spectrum on JD 34220, described and illustrated by Hunaerts (1953) shows very broad bright Balmer lines, lines of Fe II, and broad bright 4640. It is doubtful whether FS Sct had reached the nebular stage, as suggested by Hunaerts, at this early date. The bright lines seem unusually wide for a nova whose brightness declined so slowly.

X SERPENTIS 161402 JD 16185 (1903) 8.9

The light curve published by Walker (1923) had a protracted maximum from at least JD 16170 to about 16350, during which interval the star fell from ninth to tenth magnitude. The subsequent fall seems to have been marked by fluctuations. By JD 22375, the magnitude had fallen below the fifteenth.

An analysis of the minimal brightness by Boyce (1942) showed variations from magnitude 14.3 to 16.2 with a period of 275 days. This behavior recalls the pre-outburst variations of RR Tel. If the star observed by Boyce is actually the nova, the range was not much over six magnitudes; X Ser is probably not a normal nova, and possibly belongs in the "symbiotic" class.

CT SERPENTIS 154114 JD 32600 (1948) 8.0 (5:)

When discovered by Bartay (1948), CT Ser was well past maximum. Davis (1950) estimates that it must have reached fifth magnitude. The early observations of brightness have been compiled by Lohmann (1949). At the time of discovery, JD 32615, the magnitude was 8.0, and fell through about three magnitudes, with rapid minor fluctuations, by JD 32838. A slow decline with small fluctuations was later noted by Ashbrook (1953) from 13.1 to 13.3 between JD 33386 and 34540. During the whole observed interval the overall changes of brightness were very slow.

The spectrum showed unusually high excitation, and it is especially regrettable that its early stages were not recorded. Wellmann (1948) described the spectral behavior from JD 32786 to 32790. He observed bright lines of H, He I, C IV, N II, [N II], N III, N V, [O I], [O III], [Fe VII], [Fe X], and [Mn VI], with widths corresponding to expansion with a velocity of 400 km/sec. He remarked on the similarity to the spectrum of CP Pup, with [Fe VII] fainter and [Fe X] stronger.

A series of spectra between JD 32702 and 32766 was discussed by Bloch (1950); she confirmed the ascriptions of Wellmann, and noted no sensible changes during this interval. Her identifications of bright lines comprised H, He I, He II, C II, C III, C IV, N II, N III, N V, O II, O III, O IV, O V, O VI, [N II], [O I], [O III], [Ne III], [S II], [Ca V], [Ca VII], [Mn V] ?, [Mn VI] ?, [Fe II], [Fe III], [Fe V], [Fe VI], [Fe VII], [Fe X], [Fe XI]. The ions whose lines were noted as very intense were, H, He I, He II, N III, N V, [O III], [Ne III] (less intense than [O III]).

The bright lines showed two maxima, with displacements corresponding to velocities of —275 km/sec and +185 km/sec. No absorption lines were observed, and had presumably faded at the time of discovery. Bloch determined an electron temperature of 7780° from the measured intensities of the nebular and auroral lines of [O III].

Other spectral observations relate to the photographic region. On JD 32709, McLaughlin (1948) observed strong [O III], and also noted H, He II, N III visually. Bidelman (1948) observed a "normal nebular spectrum" on JD 32712. Wilson (1948) recorded H, He I, He II, C II, N III, [O III], and S [II], and derived a radial velocity of 34.8 +15.6 km/sec from the bright lines, whose width corresponded to an expansion velocity of about 700 km/sec. These observations are not incompatible with those of Wellmann and Bloch, as all the high-excitation features are in the visual region.

McLaughlin (1948) suggested that the star was of DQ Her type, first observed at the secondary brightening. If so, it must have developed more rapidly, as Gossner (1948) reported that it had not yet brightened on JD 32438, only 150 days before the discovery. The considerable fluctuations, as great as a magnitude, that were recorded by Gossner between JD 32580 and 32660 also speak against ascription to DQ Her type, for the secondary maxima of such stars usually have variations that are smooth and continuous.

XX TAURI **051316** **JD 25154 (1927)** **6.0**

The light curve is well defined by the photographic observations of Cannon (1928), which cover the pre-maximum rise, and of Wachmann (1929), and the visual observations of Beyer (1929). The brightness fell but about 3½ magnitudes in the first fifty days; a long, sinuous rise of about a magnitude in eighty days ensued, after which the brightness declined gradually. The light curve is very like that of EU Sct, even to the small post-maximum fluctuations, but EU Sct is not recorded to have brightened after its steep fall.

The spectrum, as decribed by Schwassmann and Wachmann (1928) showed bright Balmer lines and N III 4640 on JD 25203, two magnitudes below maximum and fifty days after it. Between JD 25203 and 25231 the Balmer lines strengthened relative to the continuum; N III 4640 strengthened until JD 25207 (the time when the drop in brightness grew more rapid), then weakened.

CN VELORUM ***105853*** **JD 17185 (1905)** **10.2**

The rather fragmentary light curve published by Walker (1923) shows a very slow decline, with fluctuations, from the first observation on JD 17185 ($10^m.2$). The star did not reach the twelfth magnitude for about 500 days.

The spectrum was not observed until about 550 days after discovery. On JD 17733, when the star was between twelfth and thirteenth magnitude, it showed bright lines of [O III], H, N III 4640 and He II 4686, [O III] 4363 being the strongest.

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CHAPTER 6

GALACTIC NOVAE, FRAGMENTARY DATA

Notes on the galactic novae that have not been included in Chapters 4 and 5 are here collected. For the most part the observations relate only to the light curves. Arrangement is by constellations.

VY AQUARII *210609* JD 17790: (1907) 8.4 (7.1)

The star was discovered by Ross (1925). The only other observations are those by Woods (1925) which show a fall from magnitude 8.4 to 12.6 between JD 17796 and 17815; Ross' observation falls in this interval. On JD 17777, Woods found that the nova was invisible, fainter than magnitude 12. McLaughlin (1936) gave 8 as the extrapolated maximum magnitude, but the star may have been much brighter in the unobserved interval of 19 days; if it was a very fast nova, as the smooth, rapid fall of brightness suggests, it may even have reached the sixth magnitude at maximum. Maximum luminosity and distance are indeterminate. No spectra are recorded.

CI AQUILAE *184601* JD 21395 (1917) 11

Only four positive observations are recorded:

JD	18529	$14^m.8$	Parenago (1931)
	21395.5	11	Reinmuth (1925)
	21782.5	15.0	Reinmuth (1925)
	24702	15.1	Parenago (1931)

Parenago regards the star as a possible nova.

EY AQUILAE 193014 JD 24762: (1926) 10.5

Only the light curve is known; the observations of Albitsky (1929) are confirmed by Hoffleit (1932). The brightest observed magnitude was 11.2, but there is an unobserved interval of more than twenty days, and the true maximal magnitude cannot be safely estimated.

V 607 AQUILAE 193000 JD 16650: (1904) 11.0

Two positive observations show that maximum was on or before JD 16653.

JD	16653	$11.^m$	Ross (1927)
	16668	11.5	Wolf (1905)

KY ARAE *180054* JD 28715 (1937) 15.1

The star, which may be a nova or a U Geminorum star, was of magnitude 15.1 between JD 28715 and 28721, as recorded by Shapley, Boyce and Boyd (1939).

W ARIETIS 031428 1855? 9.5

There is no decisive information. The data are discussed by Prager (1936), who considers it uncertain whether the star was a nova.

SU ARIETIS 024216 1854? 9.5

Twice recorded in 1854 as of magnitude 9.5 (JD 2398466, 2398519), the star may have been a nova, but neither maximal magnitude nor type can be estimated. The data are summarized by Müller and Hartwig (1920).

SV ARIETIS 031919 JD 17156: (1905) 12.0

The star was observed by Wolf and Wolf (1905); on JD 17156 (two plates) it was given as a little brighter than twelfth magnitude, and on JD 17171, as about of magnitude 13.5; on a plate of JD 17151 it was not visible. It may be a nova or a U Geminorum star; no further positive information exists.

T BOOTIS 140919 JD 00510: (1860) 9.7

The observations of Baxendell (1861) show that the star declined from magnitude 9¾ on JD 2400510 to 12.8 on JD 2400523; it was not seen again. On JD 33715, 33718, nearly a century later, Ashbrook (1953) found that it was fainter than seventeenth photographic magnitude. Maximum brightness cannot be inferred, but T Boo was no doubt a very fast nova.

CG CANIS MAJORIS *065923* JD 27450 (1934) 13.7

The light curve published by van Hoof (1948) must nearly cover the maximum; the unobserved interval is only four days, and the star can scarcely have become brighter than the thirteenth magnitude. If actually a galactic nova, it is among the faintest well-authenticated examples. The apparent modulus, about 20, places it at an improbable distance for a galactic star in the direction of the anticenter.

MT CENTAURI *113960* JD 26472 (1931) 8.5 (8.2)

The light curve published by Uitterdijk (1934) shows an extremely rapid rise (at the rate of six magnitudes a day on JD 24671) and a rapid fall. Maximum may have been between magnitudes 7 and 8 on JD 24672, when no observations were made.

V 359 CENTAURI *115341* JD 26087: (1930) 13.8

As recorded by Opolski (1935), the star fell from $13^m.8$ to $15^m.0$ between JD 26087 and 26094. Maximum brightness in the unobserved interval of 22 days cannot be fixed. If the star is a nova and not a U Geminorum star, it was rather faint at maximum.

AI CIRCINI *144068* JD 20282 (1914) 10.9

The fragmentary light curve published by Swope (1931) probably represents post-maximum fluctuations of a slow nova.

AR CIRCINI *144059* JD 17260 (1906) 10.6

The spectrum published by Walker (1923) recalls that of RR Pic, but the star may have been executing transitional oscillations like those of V 603 Aql. The unusually small range led McLaughlin (1939) to the plausible suggestion that the fourteenth magnitude minimum may refer to a close companion. No spectra are recorded.

V 394 CORONAE AUSTRINAE *175339* JD 32999 (1949) 7.5

The star was discovered by Erro (1949) as of the seventh magnitude on JD 32999; on the previous night it was fainter than magnitude 12.5. On JD 33028, when the magnitude was about 9.5, Erro noted bright Balmer lines and strong 4640 N III. By JD 33037, the magnitude 11.5 was recorded by Paraskevopoulos (1949). The rapid fall and the spectral development point to a fast nova.

AP CRUCIS *122563* JD 27885: (1935) 10.8 (9.1)

The light curve published by O'Connell (1948) shows a very rapid decline from magnitude 10.8 on JD 27885, and an abrupt change in slope near JD 27892, which probably marks the beginning of the transitional stage. Although the unobserved interval is only seven days, the very steep fall does not preclude a much brighter magnitude at maximum, perhaps even ninth.

V 404 CYGNI 202033 JD 29175 (1938) 11.5 (11.0)

The observations of Wachmann (1948) show very rapid fluctuations, probably associated with the transitional stage. Maximum may have occurred in the unobserved interval of sixteen days, and been considerably brighter than twelfth magnitude.

V 407 CYGNI 205845 1936 14.0

Hoffmeister (1940) assigns the star to RT Serpentis type. It was invisible in 1935 from May to October (less than 16th magnitude); at fourteenth magnitude from 1936 March to November; about $15^m.5$ in 1937; less than $16^m.5$ in the summer of 1938; and $17^m.5$ to 18^m in 1939 August.

SY GEMINORUM 063431 1866 ? 9.2

The star, recorded in the B.D. as of magnitude 9.2, is regarded by Parenago (1933) as probably a nova. Others, however, as noted by Prager (1936) have thought it a U Geminorum star. We have rejected it from our list of novae.

VZ GEMINORUM 080131 1856 ? 8.7

Two observations made for the B.D., on JD 2399040 ($8^m.7$) and JD 2399042 ($9^m.5$) comprise the positive evidence. Parenago (1933) considers that the star was undoubtedly a nova, perhaps brighter than $8^m.7$ at maximum. We have not, however, included it in our accepted lists.

CI GEMINORUM 062322 JD 29632 (1940) 14.7

Hoffmeister (1943) found the star only on thirteen photographs in January, 1940, and described it as nova-like. Kukarkin and Parenago (1946) consider it as probably a U Geminorum star, and we have treated it as such.

NOVA GEMINORUM 1892 065317 1892 ? 7.

The description by Barnard (1906, 1907) of a seventh magnitude object observed visually strongly suggests a nova, but no further information is available.

NOVA HERCULIS 1892 171224 JD 12288 (1892) 6.3

Observed as a star of magnitude 6.3 on a plate made at the Paris Observatory on JD 12288 for the Astrographic Catalogue, this object has never been seen again. The plate bears three images, which are described by Baillaud and de Grandchamp (1927) as perfectly normal. Ashbrook (1953) considers that there is a strong presumption that the star was a nova.

U LEONIS 101814 1855? 9.5

The BD star +14°2239 (9.5) may have been a nova, but no conclusion can be drawn concerning maximal magnitude or type. The faint star its position that has been studied may or may not be the same object. We have not retained U Leonis in our accepted list.

RZ LEONIS 113202 JD 21670: (1918) 11.5

Discovered by Wolf (1919) to have been of magnitude 10–11 on JD 21666, the star was recorded on JD 21665 by Beljawski (1923) at magnitude 11.5. It was very likely a nova, but its maximal magnitude cannot be deduced, as no other positive observations were made. Rügemer (1932) found no star as bright as thirteenth magnitude at the position in 1929–1932.

HN LYRAE 191442

Although announced as a recurrent nova on Harvard Announcement Card 711, the star is found by Chernova (1949) to be a long-period variable of spectrum M4e and period 406.3 days.

KT MONOCEROTIS 061905 JD 30718 (1942) 10.2

The nova was discovered by Vyssotsky on a spectrum plate of JD 30727, which showed broad bright lines of hydrogen, He II 4686 and N III 4640. The light curve, obtained by Gaposchkin (1954) displays greatest observed brightness, $10^m.30$, on JD 30724.7, but a reconstruction with the aid of a negative observation (fainter than $13^m.35$) on JD 30710.8 suggests that the star may have been at maximum, about $9^m.8$, on about JD 30718, nine days before Vyssotsky's observation. The spectrum and the rapid decline, to below fourteenth magnitude by JD 30783, place KT Mon among the fact novae. A possible pre-maximum observation at magnitude 13.6: on JD 30700 is noted by Gaposchkin.

IM NORMAE *153251* JD 22512: (1920) 9.0

On JD 22510 the star was fainter than 12.5; on JD 22513 it had risen to ninth magnitude, where it remained until JD 22546. Bailey (1920) announced the discovery.

BB OPHIUCHI *171824* JD 14067: (1897) 11.3

From the slight information published by Woods (1926) it can be inferred that BB Oph was a slow nova, and probably underwent typical fluctuations during early decline; maximum magnitude cannot be deduced.

V 553 OPHIUCHI *173624* JD 29824: (1940) 11.2 (10.8)

The observations published by Burwell and Swope (1941) suggest a relatively rapid development. The star may have reached maximum near JD 29822, and could have attained the eleventh, or even the tenth magnitude. The observation that the spectrum on JD 29845, 29865 showed bright Hα and other possible emissions is not incompatible with this conclusion.

V 794 OPHIUCHI *173222* JD 29510 (1939) 11.7

The light curve given by Burwell and Hoffleit (1943) shows the star to be a nova of slow type with large post-maximum fluctuation. The brightest observed peak falls at least eighty days after maximum, and recalls V 356 Aql, which was, however, more completely observed. There are large gaps in the observed light curve of V 794 Oph, and other bright peaks may have been missed. Two spectral observations, JD 29460, 29482, record bright Hα and no visible continuum; they suggest a considerable interval since the rise, perhaps also a considerable fall of brightness. A bright maximum might indeed have occurred between JD 29410 and 29429. A rapid fall during the first few days, however, would have been anomalous for a slow nova, which the later course of V 794 Oph showed it to be.

V 840 OPHIUCHI *164829* JD 21344: (1917) 6.5

The observations described by Bailey (1920) show that V 840 Oph was observed near its maximum, at magnitude 6.5, and that it displayed large fluctuations thereafter. It was probably a slow nova, but a definite ascription cannot be made; no spectra were recorded.

V 906 OPHIUCHI *172021* JD 34340: (1952) 9.3

The star seems to have declined steadily from magnitude 9.2 on JD 34240, falling through three magnitudes in 25 days.

The spectrum, photographed by Hiltner (1954) on six dates from JD 34251 to 34265, showed very broad bright and dark lines. On the earliest date it resembled that of GK Per when two magnitudes below maximum. The maximal magnitude may therefore have been as bright as 7.

V 908 OPHIUCHI *172227* JD 34925: (1954) 9.0

Blanco (1954) announced the magnitude as 9 on JD 34926. The infrared spectrum showed bright lines at 7773, 8446 O I, and was like that of FS Sct, about seven days after its maximum. At its brightest, V 908 Oph may have been of eighth or even seventh magnitude.

GR ORIONIS 051601 JD 20883 (1916) 11.5

The star was recorded by Thiele (1916) on JD 20883 ($11^{m}.5$) and on JD 20902 (13); on JD 20881 it was fainter than fifteenth magnitude. So faint a nova, with maximum hardly brighter than 11.5, in the direction of the galactic anticenter is most unusual. We may well consider the possibility that GR Ori is a U Geminorum star, with rare maxima that have been missed on the rather few occasions when the star has been looked for.

BD PAVONIS *183457* JD 27689: (1934) 12.4 (10.5)

The star was invisible on JD 27684; of magnitude 12.4 on JD 27688; 12.85 on JD 27694; and invisible, fainter than 15.5, on JD 27708. These observations, published by Shapley, Boyce and Boyd (1939) suggest a faint nova that did not rise above twelfth magnitude.

SZ PERSEI 034034 10.5

This missing BD star is surmised by Himpel (1941) to have been a nova, perhaps with irregular brightenings at minimum.

UW PERSEI 020556 JD 19411: (1912) 13.5

Zinner (1952) concludes that the star is of U Geminorum type. A maximal magnitude of 13.5 is rather improbable for a galactic nova.

DY PUPPIS *080926* JD 16072 (1902) 7.0

The observations published by Shapley (1921) show that the nova was a slow one; it fluctuated at about seventh magnitude between JD 16072 and 16089. Its subsequent fall in brightness carried it through three magnitudes in about 160 days, and through five magnitudes in a little over 300 days.

WY SAGITTAE 192817 JD 2372494 (1783) 6:

The star was at its recorded maximum, of the sixth magnitude, between 1783 July 26, July 27, and July 29.

Weaver (1951) has identified it as an irregularly variable blue star of photographic magnitude 18.9. Its range was therefore about thirteen magnitudes.

AT SAGITTARII *175726* JD 15277: (1900) 11.0 (8.7:)

The observations of Swope (1940) establish that the nova was a fast one, but no conclusion can be drawn as to maximal magnitude; i) the first observation, JD 15283, preceded maximum, the star may have been considerably brighter than eleventh magnitude.

BS SAGITTARII *182027* JD 21427 (1917) 9.2

The star seems to have an exceedingly slow nova, which took nearly a year to rise to observed maximum. Magnitudes are summarized by Cannon (1923) as follows:

JD 21062	$12^m.1$	JD 21431	$10^m.1$
21156	10.5	21850:	11.5
21427	9.2	22580:	12.8

Kukarkin and Parenago (1948) consider the star a "nova-like variable".

FL SAGITTARII *175334* JD 23960 (1924) 8.3

The observations by Gill (1927) show a magnitude 8.3 on JD 13960, after an unobserved interval of thirty days; the star fell rapidly in brightness, with a sudden steepening at JD 13992, and by JD 14075 was fainter than thirteenth magnitude. It may have been considerably above eighth magnitude at maximum.

FM SAGITTARII *181123* JD 24725: (1926) 8.6

The observations published by Cannon (1927) show magnitude 8.6 on JD 24727, after an unobserved interval of fourteen days. Thereafter the brightness declined rapidly, and the star was clearly a fast nova. At maximum the magnitude may have been well above eighth.

FN SAGITTARII *184819* JD 21880: (1925) 8.5

The star, normally of about the fourteenth magnitude, was observed to have brightened in about 1925 by Beljawsky (1927) and by Payne (1928). The light curve shows the typical fluctuations of a slow nova;

the range seems very small, but perhaps the initial rise took place before the first observation, JD 21880.

The spectrum, observed by Herbig (1950) between JD 31994 and 33478, when the magnitude was about 13 and variable, was described as "not atypical for an old nova". It showed a weak continuum, and bright lines (in decreasing order of intensity): Hβ, Hγ = He II 4686, [O III] 4363, [O III] 4958 = He I 4922 = He I 4471 = Hε, He I 5015 = He I 4388 = He I 4026, [Ne III] 3967.

GR SAGITTARII *181625* **JD 23906: (1924) 11.4**

The observations by Woods (1927) show very slow fading from the first bright observation, $11^m.4$ on JD 23906. The unobserved interval was about 225 days, before which the magnitude (perhaps that of an unresolved neighbor) was recorded as 16.6. Magnitude at maximum cannot be inferred, but maximum was evidently long past by JD 23906.

HS SAGITTARII *182221* **JD 15280: (1901) 11.6**

The observed variations, published by Woods (1927) are very peculiar: first seen at magnitude 12.55 on JD 15264, the star was next observed on JD 15526 at magnitude 11.6; thereafter it faded, first rapidly and later very slowly. Nothing can be determined as to type or maximal magnitude.

KY SAGITTARII *175526* **JD 24666: (1926) 10.6 (7.2)**

The observations by Woods (1927) showed the star declining from JD 24678 to 24686. The observation by Swope (1940) probably caught the star on the rise, and places the maximal magnitude near 9.

LQ SAGITTARII *182227* **JD 14142: (1897) 13.0**

The three observations published by Woods (1927) show that the star was a nova, but convey little information about the light curve; maximum may have been a great deal brighter than the thirteenth magnitude recorded on JD 14189.

V 363 SAGITTARII *190530* **JD 25096: (1927) 8.8 (7.9)**

The light curve given by Walton (1930) shows an unobserved interval of over thirty days before the first observation at magnitude 8.8; the actual maximum may have been much brighter.

V 441 SAGITTARII *181525* **JD 26230: (1930) 8.7 (8.0)**

The observations published by Hoffleit (1932) show a fairly slow fall, with probable fluctuations, from magnitude 8.7. on JD 26232 to 15.5 on JD 26615. During the unobserved interval of fifteen days the nova may have risen to about 8.0.

V 522 SAGITTARII *184125* JD 26570 (1931) 12.9 (12.8)

The observations of van Gent, discussed by Ferwerda (1935) show the star recorded only in the immediate vicinity of maximum, which probably fell on JD 26570.7, and reached about $12^m.8$. The pre-maximum rise was at the rate of at least 3.5 magnitudes a day.

V 737 SAGITTARII *180028* JD 27248: (1933) 10.3 (10.0)

The light curve give by O'Leary (1937) shows a pro-maximum rise and halt, at about JD 27245, followed by a faster rise. After an unobserved interval of 19 days, the brightness fell with rapid fluctuations like those of GK Per. It is possible that the actual maximum was missed, and fell near JD 27253, in which case it could have been much brighter than tenth magnitude, and may even have reached the seventh.

V 787 SAGITTARII *175330* JD 28680 (1937) 9.4

The light curve published by Swope (1940) and the observations obtained by O'Connell (1954) show that the nova had some resemblance to V 603 Aql, with a rapid rise, followed by a decline with rhythmic fluctuations, perhaps at intervals of about eight days. O'Connell surmises that maximum may have fallen in JD 28680 and been as bright as ninth magnitude; indeed it could have been even brighter

V 927 SAGITTARII *180133* JD 31197: (1944) 8.0 (7.3)

Observations by M. W. Mayall, reported by Campbell (1947) show a rapid drop of five and a half magnitude between JD 31197 and 32222. Maximum was probably not much brighter than the eighth magnitude in the unobserved interval of eleven days.

V 939 SAGITTARII *182826* JD 20337: (1914) 14.2

The only observations are those of Innes (1917). The star rose from below sixteenth magnitude on JD 19592 to 15.0 on JD 19597; it seems to have brightened gradually to magnitude 14.2 on JD 20337, 20339; on JD 20716 it was of seventeenth magnitude, and was not seen after JD 20748. McLaughlin (1945) places it with the RT Serpentis stars. We note that the magnitude scale used by Innes is probably not the International Scale.

V 941 SAGITTARII *182829* JD 19575: (1910) 11.0

The observations by Innes (1917) indicate a rise to $13^m.5$ between JD 18882 and 18916; an eleventh magnitude maximum on JD 19575, and a decline, with fluctuations, to invisibility on JD 21064. McLaughlin (1945) places the star in the RT Serpentis class.

V 949 SAGITTARII *183428* JD 20337: (1914) 15.8

Innes (1917) found the star fainter than seventeenth magnitude on JD 19982; of magnitude 16.5 on JD 20330; 15.9 on JD 20337; and 15.7 on JD 20339. On JD 20713 it was fainter than seventeenth magnitude. No conclusions can be drawn as to maximal magnitude or type of light curve.

V 990 SAGITTARII *175128* JD 28424 (1936) 11.1

The light curve derived from the observations of Plaut (1948) shows that maximum, at about eleventh magnitude, occurred at or just before JD 28424. The brightness fell through three magnitudes in 24 days, and apparently more slowly thereafter. No spectra were recorded.

V 1012 SAGITTARII *175931* JD 20356 (1914) 8.0

The light curve, as described by Bailey (1920), showed a rapid drop, from the eighth magnitude maximum on JD 20356, 20357, to twelfth magnitude on JD 20406. The actual maximum was recorded; on JD 20352 the star was fainter than $11^m.2$, on JD 20354 it was $9^m.5$. The star rose from below seventeenth magnitude.

V 1014 SAGITTARII *180027* JD 15520 (1901) 10.3

The observations by Walker (1923) show the typical fluctuations of a slow nova. They are insufficient to show whether the star resembled DQ Her of RR Pic. It was of about eleventh magnitude between JD 15526 and 15575.

V 1015 SAGITTARII *180232* JD 17051: (1905) 7.1 (6.5)

The star rose from below the twelfth magnitude $8^m.8$ on JD 17051; on JD 17080 it had fallen to $10^m.0$. This behavior, as described by Bailey (1920) is that of a typical fast nova.

V 1016 SAGITTARII *181325* JD 14878: (1899) 8.6 (6.9)

The light curve published by Walker (1923) records the rise, from below $11^m.5$ on JD 14876, to $8^m.6$ on JD 14877, but not the actual maximum. In the interval between JD 14877 and JD 14890, when the magnitude was 8.55, the star may have been as much as two magnitudes brighter.

V 1148 SAGITTARII *180325* JD 30956 (1943) 8.0

The star, discovered by Mayall (1949) was of eighth magnitude at maximum, which was covered by the observations. It lies near the globular cluster NGC 6553, with which it may perhaps be associated. It is unique in having shown an absorption spectrum of Class K at maximum, after which it developed a typical bright-line spectrum. There are too few observations for a definition of the type of light curve.

V 1149 SAGITTARII *181228* 1945 9.0 (8.8)

The nova, which had a maximum brighter than ninth magnitude in 1945, was discovered by Mayall (1949).

V 1150 SAGITTARII *181224* 1946 12.

The star was discovered at twelfth magnitude; maximum was in 1946, according to Mayall. No details of the light curve can be determined.

V 1151 SAGITTARII *181920* 1947 10.0

A tenth magnitude observed maximum in 1947 was recoded by Mayall (1949); no details of the light curve are available.

V 1172 SAGITTARII *174420* JD 33713 (1951) 9.0

The star was discovered at maximum by Haro (1951) on JD 33713, at ninth magnitude. Bright Balmer lines and a strong continuum in the red were recorded on this data. On JD 33717, Page (1951) noted bright lines of hydrogen and helium with half widths corresponding to a velocity of 2000 to 3000 km/sec.

V 1174 SAGITTARII *175528* JD 33918: (1951) 12.0

The star was discovered on JD 33918 by Zwicky (1951), at magnitude fainter than 12; the spectrum showed a strong red continuum. On JD 33919 the red continuum was present, and Hα was a strong bright line. Maximum probably was not brighter than twelfth magnitude.

V 1175 SAGITTARII *180731* JD 34064 (1952) 7.0

The star was discovered at seventh magnitude by Haro (1952). Maximum was perhaps on JD 34064; on JD 34065 Haro noted bright Balmer lines, [O III] 4363 and Fe II, which suggests that maximum may actually have been some time past. By JD 34101 the magnitude had fallen to 10.5.

NOVA SAGITTARII (1928) *180923* 1928 8.9

The light curve, published by Dishong and Hoffleit (1955) is that of a moderately fast nova, perhaps comparable with DI Lac.

NOVA SAGITTARII (1953) *175829* 1953 10.5

The nova was discovered at magnitude 10.5 by Haro (1953).

V 1274 SAGITTARII *174317* JD 34985: (1954) 9.5

The nova was discovered by Wild (1954) at magnitude 10.5.

V 1275 SAGITTARII *175235* JD 34928: (1954) 7.5

The magnitude of this nova was reported by Haro (1954) to be 7.5 at maximum.

KP SCORPII *173735* JD 25419 (1928) 9.4

The observations published by Swope (1929) cover maximum, at magnitude 9.4, on JD 25419. The brightness seems to have fallen steadily to fifteenth magnitude on JD 25498.

V 384 SCORPII *174525* JD 12595: (1893) 12.3 (9.3)

Three observations by Swope (1936) show that the nova rose to maximum about JD 12585; probably it declined rather fast. Maximum brightness may have reached the tenth magnitude.

V 382 SCORPII *175435* JD 15632: (1901) 9.4

Observations by Swope (1936) show the star declining in brightness. The first observation, JD 15631, showed the star of photographic magnitude 9.4; the decline at first was rather slow, and probably the star did not rise much above ninth magnitude in the unobserved interval of twelve days.

V 696 SCORPII *171635* JD 31226 (1944) 7.5

The observations by Mayall (1947) show a probable maximum of magnitude 7.5, on JD 31226, and a decline to magnitude 13.4 by JD 31309.

V 707 SCORPII *174136* JD 2349 (1922) 9.9 (9.6)

The photographic observations published by Shapley (1922) cover the rise in brightness; maximum may have been on JD 23249, and can scarcely have been brighter than magnitude 9.5. The decline was rather slow, about two magnitudes in 50 days.

At maximum the spectrum showed no bright lines, but they appeared soon afterwards, and by JD 23269 ($10^m.6$) it was of characteristic nova type.

V 711 SCORPII *174734* JD 17394 (1906) 9.7

The light curve published by Walker (1923) shows a very unusual slow rise from twelfth magnitude on about JD 17330 to maximum ($9^m.7$) on JD 17394. A somewhat slower fall to magnitude 11.4 occupied about a hundred days, and two hundred days later the star was no longer visible.

V 722 SCORPII *174134* JD 34075 (1952) 9.5 (9.4)

The visual light curve published by Taboada (1953) covers maximum ($9^m.4$) on JD 34075, and shows a steady fall of three magnitudes in the next 18 days. The star therefore qualifies as a fast nova.

V 723 SCORPII *174335* JD 34236 (1952) 9.8

The star seems to have been at maximum, of ninth magnitude, on JD 34236 when discovered by Soloviev (1952); one day earlier it was of the twelfth magnitude. The observations obtained at the Cape Observatory (1952) show the very rapid decline of three magnitudes in 17 days.

NOVA SCORPII (1952) *174133* JD 34121 (1952) 11.

The magnitude announced by Haro (1952) at discovery, on JD 34121, was 11; there was an unobserved interval of nine days. The star does not seem to be identical with V 722 Scorpii, though close to its position.

CQ VELORUM *085552* JD 29736 (1940) 9.2 (8.9)

The photographic light curve published by Hoffleit (1950) covers maximum, a little brighter than ninth magnitude. There is a slow decline of about 3.5 magnitudes in fifty days, then a more abrupt drop, apparently a slow rise to about fourteenth magnitude on or before JD 30925, and a steady decline, reaching sixteenth magnitude about JD 31160.

The resemblance to XX Tauri is very close, including the rise after the abrupt drop in brightness.

SW VULPECULAE 195522 JD 23637: (1923) 15.0

The star has been regarded as a possible nova. However, Zagar (1947) noted the occurrence of several brief maxima, two of them brighter than fifteenth magnitude. His brightest observation, on JD 25915, reached $14^m.3$. He is undoubtedly right in assigning the star to the U Geminorum class.

CK VULPECULAE 194327 JD 2331186: (1670) 3.0

The nova of 1670 seems to have been of the slow type. An unpublished discussion, by Ashbrook (1954), of the observations suggests that maxima, between second and third magnitude, occurred near JD 2331200 and 2331500.

Humason (1938) attempted unsuccessfully to locate the star; he rejected three stars near the position of the nova on the basis of their spectra.

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Opolski, A., 1935, Lwow Contr. No. 4.	V 359 Cen
Page, T., 1951, Harv. Ann. Card 1119.	V 1172 Sgr
Paraskevopoulos, J. S., 1949, I. A. U. Circ. 1211.	V 394 CrA
Parenago, P. P., 1931, N. N. V. S., *3*, 120.	CI Aql
Parenago, P. P., 1933, N. N. V. S., *4*, 228.	SY Gem
Parenago, P. P., 1933, N. N. V. S., *4*, 229.	VZ Gem
Payne, C. H., 1928, Harv. Obs. Bul. 861.	FN Sgr
Plaut, L., 1948, Leiden Ann., *20*, No. 1.	V 990 Sgr
Prager, R., 1936, G. u. L., II, *1*, p. 94.	W Ari
Prager, R., 1936, G. u. L., II, *2*, 108.	SY Gem
Reinmuth, K., 1925, A. N., *225*, 385.	CI Aql
Ross, F. E., 1925, A. J., *36*, 123.	VY Aqr
Ross, F. E., 1927, A. J., *37*, 156.	V 607 Aql
Rügemer, H., 1932, A. N., *248*, 73.	RZ Leo
Shapley, H., 1921, Harv. Obs. Bul. 760, 761.	DY Pup
Shapley, H., 1922, Harv. Obs. Bul. 773, 775.	V 707 Sco
Shapley, H., Boyce, E. F., and Boyd, C. D., 1939, H. A., *90*, 244.	KY Ara
Shapley, H., Boyce, E. F., and Boyd, C. D., 1939, H. A., *90*, 250.	BD Pav
Soloviev, N., 1952, Harv. Ann. Card 1184.	V 723 Sco
Swope, H. H., 1929, Harv. Obs. Bul. 870.	KP Sco
Swope, H. H., 1931, Harv. Obs. Bul. 883.	AI Cir
Swope, H. H., 1936, Harv. Obs. Bul. 902.	V 382 Sco
Swope, H. H., 1936, Harv. Obs. Bul. 902.	V 384 Sco
Swope, H. H., 1940, Harv. Obs. Bul. 913.	AT Sgr
Swope, H. H., 1940, Harv. Obs. Bul. 913	KY Sgr, V 787 Sgr
Taboada, D., 1952, Bol. Tonan, y Tac., No. 5.	V 722 Sco
Thiele, H., 1916, A. N., *202*, 13.	GR Ori
Uitterdijk, J., 1934, B. A. N., *7*, 176.	MT Cen
Wachmann, A. A., 1948, Beob. Zirk., *20*, 59.	V 404 Cyg
Walton, M. L., 1930, Harv. Obs. Bul. 878.	V 363 Sgr
Walker, A. D., 1923, H. A., *84*, 197.	AR Cir, V 1014 Sgr, V 1016 Sgr, V 711, Sco
Weaver, H. F., 1951, Ap. J., *113*, 320.	WY Sge
Wild, P., 1954, Harv. Ann. Card 1270, 1271.	V 1274 Sgr
Wolf, M., 1905, A. N., *167*, 342.	V 607 Aql

Wolf, M., and Wolf, G., 1905, A. N., *169*, 415.	SV Ari
Wolf, M., 1919, A. N., *209*, 91.	RZ Leo
Woods, I. E., 1925, Harv. Obs. Bul. 836.	VY Aqr
Woods, I. E., 1926, Harv. Obs. Bul. 835.	BB Oph
Woods, I. E., 1927, Harv. Obs. Bul. 851.	GR Sgr
Woods, I. E., 1927, Harv. Obs. Bul. 851.	HS Sgr
Woods, I. E., 1927, Harv. Obs. Bul. 681.	KY Sgr
Woods, I. E., 1927, Harv. Obs. Bul. 859.	LQ Sgr
Zagar, F., 1947, Asiago Contr. No. 6.	SW Vul
Zinner, E., 1952, G. u. L., II, *3*, 73.	UW Per
Zwicky, F., 1951, Harv. Ann. Card 1150.	V 1174 Sgr

CHAPTER 7

THE SYMBIOTIC NOVAE

1. Introductory

The stars now to be discussed present many enigmatic features. Merrill (1932) called attention to the group of stars with spectra that combine the characteristic features of relatively late spectral type and a high-excitation bright-line spectrum; later (1940) he specifically raised the question as to whether they are double stars or single objects. He called attention to the known duplicity of VV Cephei and *o* Ceti, and pronounced the evidence for the duplicity of R Aquarii as "almost conclusive". He has applied the happy term "symbiotic stars" to these objects, and they are commonly said to have "combination spectra".

Since 1940 the number of known combination spectra has increased to about thirty, but there is no consensus concerning their possible duplicity. Several of the stars concerned have shown variations and spectral changes that are nova-like in character, and a discussion of novae can scarcely avoid them.

A complete list of combination spectra and related objects would overlap with the very extensive list of composite spectra, and some of the stars that display the latter are certainly related to those now considered. We have virtually restricted ourselves to combination spectra with one component of Class M; all the objects in our list are certainly giants or supergiants. A parallel list, with the red component a dwarf or subwarf, is furnished by the U Geminorum stars of the following chapter. The restriction to combination spectra with M characteristics is justified by the fact that, so far as is known, only stars with such spectra display nova-like characteristics, but by no means all of them have been observed to do this.

Table 7.1 brings together the objects with composite spectra that will be discussed in the present chapter.

The italicized spectrum is the stronger under normal conditions. Remarks on individual stars will follow.

TABLE 7.1

Stars with Combination Spectra and Related Binaries

Star		Des.	Range	Spectrum		Remarks
Z	And	232848	8.0 –12.4	M 0	*Be*	Cycle of variation 694 days
R	Aqr	*233815*	6.7 –11.6	M7e	O	Long-period variable, period 387 days
ε	Aur	045443	3.7 – 4.5	(I)	FSI	Eclipsing star, period 9883 days
KN	Cas	000462	10.5 –11.1	M1ep	B	Irregular variable; red star, luminosity Ib
W	Cep	223257	8.8 – 9.8	Mep	B ?	Irregular variable
VV	Cep	215362	6.22– 4.42	M2ep	B	Eclipsing star, period 7430 days
o	Cet	*021403*	2.0 –10.1	Mbe	Bep	Long-period variable, period 331 d.
BF	Cyg	191929	9.3 –13.4	gM4	Bep	Cycle of variation 754 days
CI	Cyg	194635	10.7 –13	gM4e	B	Cycle of variation 855: days
V 407	Cyg	205845	13.2 –16.5	Mep	?	Considered a slow nova; combination spectrum
WY	Gem	060523	9.5 – 9.7	M2ep	B	Red star, luminosity Iab
YY	Her	181020	11.1 –13.2	M2ep	?	Combination spectrum; variable velocity
RW	Hya	*132824*	9.7 –10.9	gMep	?	Combination spectrum
17	Lep	*060016*	(5.0)	M2	Beq	
AX	Mon	062505	6.6 – 6.8	gM2	Beq	Known binary, period 235 days? Irregularities
BX	Mon	072003	10.0 –13.0	Mep	?	Combination spectrum
SY	Mus	*112764*	11.3 –12.3	Mep	?	Combination spectrum
AR	Pav	*181066*	10.2 –12.7	M	*Beq*	Eclipsing system, period 605 days; variable between eclipses
AG	Peg	214612	6.4 – 8.2	M	*Bep*	Spectroscopic cycle about 800 days
AX	Per	012953	10.8 –12.5	gM3e	?	Cycle of variation, 675 days
RX	Pup	081041	11.1 –14.1	?	Bep	Like CI Cygni?
CL	Sco	*164830*	11.2 –13.9	?	Be	Resembles AX Persei in light curve; cycle about 600 days
HK	Sco	*164830*	13.1 –15.8	?	Be	May be composite spectrum; light curve like that of AX Persei; cycle about 700 days
V 455	Sco	*170033*	12.9 –16.5	?	?	Very strong $H\alpha$; probably a combination spectrum. Variation irregular
BL	Tel	*185851*	7.0 –10.4	M	F8I	Eclipsing star, period 777 days
WY	Vel	*191852*	8.8 –10.2	Mep	?	Combination spectrum? Nova-like variable?
HR	2902			M2ep	B	Swings and Struve (1940, 1941a)
HR	8164			M1ep	B	Swings and Struve (1940)

TABLE 7.1, *continued*

Star	Des.	Range	Spectrum	Remarks
F6–7	*175920*	(11)	M ?	Combination spectrum, Merrill and Burwell (1950)
+67° 922	160167		K1 ? Be	Variable velocity, Roman (1953)
	194119	(11)	?	Hα very strong; combination spectrum. Merrill and Burwell (1950)
	193768		M Be ?	Combination spectrum, Thackeray (1954)

Several facts emerge from a cursory study of the table. It contains three eclipsing stars (ε Aurigae, VV Cephei and BL Telescopii); in addition three stars (YY Herculis, AX Monocerotis and +67°922) show variable radial velocities, and thus are probably binaries; Merrill (1940) considered the binary nature of R Aquarii "almost conclusive", and *o* Ceti is a visual binary; that T Coronae Borealis is a binary is also virtually certain. Thus almost a third of the entries in the table may be considered to be double objects. That all of them are binary may be used as a working hypothesis to be tested by exploring its implications.

The behavior of individuals will now be very briefly summarized. Many of the stars have been relatively quiescent during the observed interval. Nova-like outbursts are represented as follows:

M star normally much brighter than B star: R Aqr, *o* Cet, V 407 Cyg, YY Her
M star normally brighter than B star: AX Per
M star normally fainter than B star: Z And, BF Cyg, AR Pav, AG Peg

Most of the stars are variable; those not known to be so would be profitable subjects. All however, are potentially subject to brightening, and all will therefore be briefly noted, with especial stress on those of largest range.

2. Description of Individual Stars

Z ANDROMEDAE 232848

The nova-like outbursts of this thoroughly-studied star appear to be associated with the cycle of 690 days shown most conspicuously by the blue component. The analysis of the variations of brightness into "red" and "blue" components by Payne-Gaposchkin (1946) suggested that the "red" component varies with the same cycle, but much less—perhaps by a magnitude. The range of the "blue" component is about six magnitudes at its largest outbursts, but a large outburst tends to be followed by smaller ones of progressively diminishing amplitude; high maxima have recurred at irregular intervals of from 5000 to 8000 days.

Information can be pieced together from the many spectroscopic studies, particularly that of Plaskett (1928) and the series of papers by Merrill (1927, 1944, 1947, 1948, 1950, 1953) and by Swings and Struve (1940, 1941a, 1941b, 1942a, 1942b, 1943a, 1943b, 1945) and Struve (1944) and Aller (1954). The rise to maximum is characterized by the appearance of a B-type shell spectrum, whose continuum dominates the photographic light and drowns out the M spectrum. As the brightness declines, the shell spectrum weakens; bright-line spectra of progressively increasing excitation appear; forbidden lines develop. The lines of highest excitation that have been recorded in the late decline are those of [Fe VII], and the spectrum presents a superficial parallel with that of RR Pictoris. There is, however, no evidence of *multiple* absorptions: one shell only is involved, and an actual "shell spectrum" is rather rarely seen.

The cycles of 650–750 days, observed in the radial velocities of the bright lines by Merrill (1947, 1948) recall the cycle of about 690 days in the variations of brightness.

R AQUARII *233815*

A long-period variable of period 383 days is here evidently related to a high-temperature source, which has gone through a disturbed interval since 1921. The brightness of "blue" and "red" components, as analyzed by Payne-Gaposchkin and Boyd (1946), closely parallels the brightening of the blue continuum observed in the spectrum by Merrill (1935, 1940, p. 84). A striking feature of the variation was the apparent suppression of the brightness of the long-period variable, whose maximal brightness fell by more than two magnitudes when the blue component was brightest, and recovered after about two periods.

The shell spectrum recorded by Merrill looked like that of an Of star; as it weakened and the intensity of the blue continuum diminished, lines of [Fe II], [Fe III] and [S II] appeared. The lines observed after the decline include those of [O II], [O III] and [Ne III], the latter representing the highest excitation attained.

The existence of an outer lenticular nebulosity, which is observed to be expanding, strongly suggests that a much more violent outburst took place in the remote past. The expansion of the nebulosity, first noted by Hubble, was confirmed by Baade (Mount Wilson Annual Report, 1942–43). The following year the expansion was shown at Mount Wilson to be compatible with a nova-like outburst about six hundred years ago. The radial velocity is stated to represent an expansion at between 80 and 100 km/sec, and the distance deduced from angular velocity and radial expansion leads to the plausible absolute visual magnitude —0.4 for the long-period variable at maximum.

The relative intensities of the [Ne III] lines and the [O III] lines (not then identified) were surmised by Wright (1919) to show the effects of occultation by Ca II and Ti O respectively. A similar observation was made between JD 29520 and 29610, (when the blue continuum had greatly weakened) by Swings and Struve (1940) for the lines of [O III]. It is tempting to regard this as evidence of an atmospheric eclipse in a binary system. Unfortunately the existing data give no information as to a possible cycle, except that it cannot be longer than twenty years.

For R Aquarii, as for Z Andromedae, the evidence points to a single shell.

ε AURIGAE **045443**

This well-known eclipsing system is included for comparison, because it is generally thought to possess an extremely diffuse, low-temperature component. The supergiant F star is cyclically variable at maximum, and according to Struve and Elvey (1934) evinces the high "turbulent" velocity of 20 km/sec, which may be expressed in terms of a kinetic temperature of over a million degrees. Wright and van Dien (1949) found that the high turbulent velocity is associated with low-excitation lines; lines of higher excitation give a lower value, and effects of stratification are suggested. Sharp circumstellar Ca II lines were noted by Struve (1951), and Kraft (1954) associates the shell spectrum with the supposed infra-red component. The high "turbulent" velocity is exceeded by that recorded for 17 Leporis.

KN CASSIOPEIAE 000462

Bidelman (1951) describes the spectrum as like that of HR 2902 (see below). The highest observed excitation is that of hydrogen, and bright Fe II also is noted. The variations recorded by Efremov (1949) are small and irregular.

W CEPHEI 223257

The combination spectrum shows bright lines of H and [Fe II] on the background of an M star. Swings and Struve (1940) suggest: "It is possible that the spectrum of a bright late-type star is combined with that of a relatively faint star of very early type." The observed variations are small and irregular.

VV CEPHEI 215362

Another well-known eclipsing system VV Cephei provides a rather close parallel to the stars whose combination spectra display only low excitation. Lines of [Fe II] and [Ni II], noted by Struve (1944) and by Swings and Struve (1945), are to be associated with the Be component. Struve (1944) notes that the shell must envelop the whole system. The Be component is not known to be variable in brightness.

o CETI *021403*

Mira Ceti, the one long-period variable with a separately observable Be companion, has been extensively studied. Data relevant to our present purpose have been summarized by Joy (1954).

The Be companion is spectroscopically variable, probably in a long cycle. It shows bright lines of H, Ca II and Fe II; the Balmer lines have been observed with strong P Cygni components.

The brightness of the Be component is variable by at least two magnitudes; there seems to be a long cycle of 12 to 15 years, but sudden changes also seem to occur. The long cycle is, suggestively, near to the orbital period of 14 years deduced by Parenago (1950). As the average apparent visiual magnitude of the companion is about 11, its absolute magnitude must be about 9, a great deal fainter than the blue components of most symbiotic variables, and perhaps not far from the minimal brightness of the hypothetical blue component of R Aquarii, which, however, evinces higher exciting power.

BF CYGNI **191929**

The variations of brightness were found by Jacchia (1941) to be fairly regular in a cycle of 754 days. The star is bluest when brightest. Most of the variations seem to come from the blue component, but probably the red star varies also.

Studies by Merrill (1943, 1950), Aller (1954) and Tcheng and Bloch (1954) reveal a typical combination spectrum; the gM4 component is usually masked by the spectrum of the Be star. The motions and intensities seem to vary rapidly and often erratically. The highest observed excitation is that of the [O III] and [Ne III] lines.

Aller (1954) has constructed a hypothetical mode which involves an M giant and a Be star embedded in an extended nebula. This idea will be discussed later in connection with the whole group of stars.

CI CYGNI **194635**

The red component varies with a period of about 850 days. One small "outburst" of nearly 1½ magnitudes was observed by Mrs. Greenstein (1937), but the B component seems to be quiescent for long intervals.

The bright-line spectrum, as shown by Swings and Struve (1940), Merrill (1944, 1950), Aller (1954) and Tcheng and Bloch (1954) is of very high excitation; in addition to [O III] and [Ne III] it shows [Fe VII] and [Ne V] strongly, and [Fe X] weakly, thus recalling T Pyxidis and RS Ophiuchi in their early decline. The hot component, which seems to be erratically variable, is found by Aller (1954) to have a temperature "well in excess of 60,000°. The gM4 spectrum is relatively much stronger than in Z Andromedae or BF Cygni; the hot star is therefore relatively fainter than in these sysrems, and could vary considerably while affecting the integrated brightness very little. No spectroscopic observations have yet been made during a bright outburst such as occurred in 1911.

V 407 CYGNI **205845**

An outburst was observed by Hoffmeister (1940), who classified the star as a slow nova, with range 14.0–17.5. Merrill and Burwell (1950) note that Hα was strong when the star was of magnitude 11.5, and that Minkowski has observed a combination spectrum. Bidelman (1954) records an observation by Herbig (October 10, 1952) of strong TiO and bright H. Similarity with Z Andromedae is strongly suggested.

WY GEMINORUM **060523**

The observed variations are small and irregular. Besides the M2 Iab spectrum, bright lines of H, [Fe II], [Ni II], [Cr II] are noted by Redman (1931), Swings and Struve (1940) and Swings (1943, 1944).

YY HERCULIS **181020**

Herbig (1950) notes moderately strong TiO and a bright-line spectrum which shows H, He II, [O III] 4363 and faint He I. He also notes variable radial velocity.

RW HYDRAE **132824**

The brightness was shown by Yamamoto (1924) to vary in a period of 370 days with a range little more than a magnitude.

Studies of the spectrum by Merrill and Humason (1932), Merrill (1933, 1940, 1944, 1950) and Swings and Struve (1941b, 1942b) show that a gM2 spectrum underlies a bright-line spectrum that displays H, He I, He II, [O III], [Ne III], [Fe V] and [Fe VII]. Merrill (1950) finds a cycle of 376 days in the radial velocities, very near to the photometric period deduced by Yamamoto.

17 LEPORIS ***060016***

An analogy with ε Aurigae leads to the inclusion of 17 Leporis in our list. The faint TiO spectrum was observed by Slettebak (1950). The B component, which has been extensively studied, is notable for the high "turbulent" velocity of 67 km/sec, equivalent to a kinetic temperature of about nineteen million degrees (Struve and Elvey, 1934). The star is not known to be variable, but variability would be expected.

AX MONOCEROTIS 062505

Bidelman (1954) includes AX Monocerotis among the known combination spectra. The variations of brightness are small and erratic.

Plaskett (1926) observed changes of radial velocity with a period of about 235 days and an amplitude near 120 km/sec, so the star is a binary. He noted a transitory "α Cygni" stage in the spectrum, normally of Class B3, and Struve (1943) showed AX Monocerotis to be a shell star. The variations of brightness are more rapid than the 235-day cycle, and certainly stem from the shell activity.

BX MONOCEROTIS 072003

The star is described by Mayall and Cannon (1940) as the long-period variable of longest known period, about 1380 days. The photographic range, from 10.0 to 13.0, is rather small. Bidelman (1954) records strong bright Balmer lines near minimum, on an absorption spectrum of class M4. A blue companion like that of R Aquarii is perhaps responsible.

SY MUSCAE *112764*

The observation by Henize (1952) of bright lines of H, He I, He II, N III and [O III] 4363, together with TiO absorption, places SY Muscae with the symbiotic stars.

AR PAVONIS *181066*

Shown to be an eclipsing star with a period of 605 days by Mayall (1937) AR Pavonis has large erratic variations at maximum. Thackeray (1954) describes the system as an example of "multiple symbiosis". He finds: the continuum and absorption spectrum of a supergiant F star; a high-excitation bright-line spectrum of H, He I, He II, C III, N III, [O III] and [Ne III]; a low-excitation emission spectrum of Fe II, [Fe II]; and TiO absorption and perhaps Fe I during minimum.

A[illegible] PEGASI 214612

Perhaps the most remarkable of symbiotic stars, AG Pegasi seems according to Lundmark (1921) to have brightened from ninth to sixth magnitude. Continued study of its variations would be important.

The spectrum has been studied in great detail, notably by Merrill (1942, 1944, 1951a, 1951b), Swings and Struve (1940), Joy and Wilson (1949), Tcheng (1950) and Tcheng and Bloch (1952).

The extremely complicated variations of the shell spectrum are classical. A period near 800 days has been detected by Merrill in the radial velocities. The bright-line spectrum varies; sometimes no forbidden lines are seen; on other occasions bright lines of [N II], [Fe III], [O III] and [Ne III] appear; permitted lines up to and including C IV, N IV and Si IV are recorded. The excitation is thus not particularly high. The TiO spectrum is less conspicuous than in Z Andromedae.

AX PERSEI 012953

The variations strongly recall those of Z Andromedae, but observations of the spectrum, such as those of Swings and Struve (1940, 1941b, 1942a 1943b) and Tcheng and Bloch (1954) show that the excitation is much higher, comparable to that of CI Cygni. A weak line of [Fe X] is recorded by Swings and Struve.

RX PUPPIS *081041*

The variations of brightness have been rather slow, with a range of about three magnitudes. Swings and Struve (1941b) find bright lines of H, He I, He II, [Fe VII], [Ne V], [Fe VI] and [Ca VII] and infer a similarity to CI Cygni. They find no unequivocal evidence of the presence of a red companion.

CL SCORPII *164830*

The star is included because the light-curve published by Swope (1940) is very like those of Z Andromedae and AX Persei. The cycle is near 600 days. Elvey and Babcock (1943) observed a continuum with strong emission lines of H, He I, and He II when the star was not far from a minimum.

HK SCORPII *164830*

The light curve published by Swope (1940) recalls those of Z Andromedae and AX Persei. The cycle is near 700 days. Elvey (1941) observed the spectrum near minimum with bright lines of H, He II, and a continuum faint in the photographic region, strong in the visual. The evidence for a combination spectrum seems convincing.

V 455 SCORPII *170033*

The variations are described as irregular with a range over three magnitudes. Merrill and Burwell (1950) note very strong Hα, and state that the star probably has a combination spectrum.

BL TELESCOPII *185851*

The star recalls AR Pavonis and ε Aurigae. Cousins and Feast (1954) derive a period of 777 days; the brighter star is an F8 supergiant, the light is variable at maximum, and during eclipse a weak TiO spectrum is visible.

WY VELORUM *191852*

The observations of the spectrum by Cannon (1923) suggest that the star is a symbiotic variable.

The other stars in the list are not known to be variable. Representative references are given in Table 7.1.

3. **Discussion**

Other stars, clearly like those just mentioned, were omitted because no late-type companion has been observed. Z Canis Majoris has a behavior not unlike that of AX Monocerotis. The spectrum is discussed, for example, by Swings and Struve (1940); the excitation is not greater than that required for Fe II. P Cygni has had a photometric history that recalls AX Monocerotis also, and many other P Cygni and shell stars are known to be more or less variable, witness the behavior of γ Cassiopeiae and Pleione (BU Tauri).

A survey of our list suggests, in fact, that the group of stars considered are nearly all rather active shell stars, with luminosities not much below the normal for luminosity class V. Nova outbursts are, in a sense, shell phenomena, but they emanate from stars that have very different physical properties, and lie well below the Main Sequence.

The spectroscopic parallel with the novae is superficial. A true nova outburst seems always to be multiple, and this is probably an index of its deep-seated nature—the star itself is profoundly affected and the ejection phenomenon involves a sequence of events. The ejection of a shell is a more transient episode, and does not affect the whole star.

The schematic picture of BF Cygni suggested by Aller (1954), shown in Fig. 7.1, is probably representative of most members of the group. Neither the length of the cycle not the photometric amplitude is obviously related to the highest observed excitation, which ranges from [Fe X] for AX Persei and CI Cygni to bright H and Fe II for stars like W Cephei and WY Geminorum. We may conclude that the blue components of the systems, regarded as binaries, have a rather wide variety of exciting powers, which we may, if we choose, interpret as a variety of temperatures.

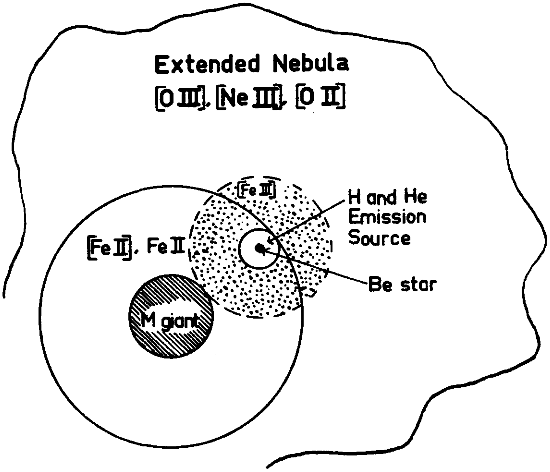

Fig. 7.1. Possible schematic model for BF Cygni, after Aller (1954).

The conclusion reached by Swings and Struve (1940) is strengthened by the foregoing summary.

"We suggest that some mechanism other than axial rotation is responsible for P Cygni type emission. It is probable that high luminosity favors this process... But there are also normal main sequence stars with strong P Cygni characteristics. We infer that luminosity is not alone to blame. Some of these stars... are known binaries. It is at least probable that the binary nature of a star favors the origin of a shell. This hypothesis is supported by the peculiar class of composite spectra... Some of the objects have B-type spectra which are perfectly normal in all respects and which have no excessive rotation and no supergiant characteristics. Yet, when these normal stars are associated with an M-type star, as a binary, they give rise to strong emission spectra of Fe II... or to emission spectra of high excitation and ionization... The fact that a few related stars... are apparently not composite does not mean that they are not binaries... There is all reason to believe that the binary nature of a star stimulates the process of shell formation".

Swings and Struve (1941b), after a discussion of Z Andromedae, AX Persei, RW Hydrae, T Coronae Borealis (before the 1946 outburst) and RS Ophiuchi, concluded further: "In all the five cases considered here the line-emission spectrum behaves in the same way as in novae in their nebular stages. On the whole, the density decreases in the shell, and the excitation increases; but the fluctuations of the novae also produce nebular variations, and in some cases the phenomena are recurrent. The similarity of the five peculiar binaries to novae is well established. But the ejection processes are in all cases slower than in single novae."

"... Whenever an otherwise normal stellar spectrum of advanced type, which is not expected to show emission lines, is complicated by permitted and forbidden emissions of excitation far beyond those normally associated with the types of these stars, we either find more or less conclusive evidence of... binary nature..., or, in a few cases, we find at least no obstacles to the assumption that a faint, hot companion to a late-type star excites the emission lines in a gas of very low density, which (in the case of α Sco) is distributed in the form of a small nebulosity around the system but which in other cases may well be concentrated in the outermost layer of the late-type component."

"The outbursts of Z Andromedae, RS Ophiuchi and T Coronae Borealis show that binaries of the type considered are subject to recurrent nova outbursts on a relatively small scale. But even though the similarity of the spectroscopic history of these binaries with typical large-scale novae is very striking, there is, as yet, no evidence that the physical causes of the outbursts are similar."

The general conception is very like the one embodied in Fig. 7.1. As far as T Coronae Borealis is concerned, the conclusions must be modified in the light of the subsequent 1946 outburst, which was associated with the largest initial radial velocity ever recorded for a nova, and was certainly nova-like in scale. It seems probable that the star went through a protracted stage of "premaximum rise", but the normal magnitude of the blue component is very difficult to determine. Certainly the blue components of the symbiotic stars are far from the domain of the Hertzsprung-Russell diagram from which the normal novae arise, well below the Main Sequence. Possibly T Coronae Borealis, too, originated from this area, and represents a transitional stage between the symbiotic stars and the novae proper.

The companions of *o* Ceti and R Aquarii are much fainter than the other blue components shown in Table 7.1, and these stars may be more closely allied to the blue component of T Coronae Borealis than the others. The present outward velocity of the R Aquarii nebulosity is small, but in the nova range, and we note that after a couple of days, T Coronae Borealis at its 1946 outburst no longer showed a very high expansion velocity, and its bright lines grew relatively narrow.

The conception that the symbiotic stars are binaries does not solve the difficult astrophysical problems presented by the spectral changes of the long-period variable stars, with the intricate interplay of absorption and emission spectra, as described by Merrill (1940). Here we may indeed be able to picture all the phenomena as originating in the distended and disturbed envelope of a single star, on the lines suggested by Sobolev (1947).

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CHAPTER 8

THE U GEMINORUM AND Z CAMELOPARDALIS STARS

1. Census of U Gem and Z Cam Stars

The group of frequently-recurrent variable stars considered in the present chapter has often been likened to the novae. Points of similarity are the suddeness and form of the outburst, and a superficial spectroscopic likeness, with an absorption spectrum at maximum, which is usually replaced at minimum by bright lines. The points of contrast are more striking; the luminosities are comparatively very low; the spectra are very unlike when examined in detail, and in particular, never display forbidden lines. The frequent recurrences furnish a possible link with the recurrent novae, with which these stars have more in common than with the ordinary novae. For this reason, and because important theoretical conclusions can be drawn if a fundamental similarity is established, we devote the present chapter to the U Geminorum and Z Camelopardalis stars.

Table 8.1 gives a list that includes 125 stars, of which five have been discredited for the reasons noted. However, as with the novae, our detailed knowledge rests on about a dozen stars, which will be described later.

The table gives ranges, average cycles, and durations of maximum, when known. The magnitude scales are far from uniform; most of the fainter objects have been studied photographically, but for our thorough knowledge of a few bright ones we are greatly indebted to the amateur observers, notably the members of the American Association of Variable Star Observers, whose complete light curves are an important contribution to knowledge of these stars.

The Z Camelopardalis stars are distinguished from the U Geminorum stars by more frequent outbursts, smaller observed ranges, and in many cases protracted hesitations at an intermediate brightness. However, the ranges show a continuous distribution, and there is probably no clear-cut physical distinction between the two groups of stars. Frequent outbursts and small ranges are probably cause and effects, or, more strictly, both depend on the same conditions.

TABLE 8.1

U Geminorum and Z Camelopardalis Stars

Star	Des.	Range	Cycle Days	Duration of Maximum Days	Reference
RX And	005840	10.3–13.6v	14	..	See following §
VZ Aqr	*212503*	11.8–15	..	..	P. P. Parenago, N. N. V. S. 43
AE Aqr	*203401*	9.7–11.7	..	..	See following §
CV Aqr	*211614*	12.4–[16.6	..	..	H. Shapley and E. M. Hughes, 1934, H. A., *90*, 169
UU Aql	*195109*	11.0–16.8	30–80	5, 12	O'Connel, H. B., 890
(FH Aql)	*185705*	13.4–[16	..	..	Probably RW Aurigae type
FO Aql	191100	13.8–[17.5	28.7	..	E. Ahnert Rohlfs, W. Gotz, 1952, M. V. S. 156
KX Aql	192914	13.1–[16.3	..	..	D. Hoffleit, 1932, H. B., 887
V 725 Aql	195110	13.7–16.2	..	..	E. Rohlfs, 1949, V. S. S. *1* No.3
V 800 Aql	185100	14 –[16	..	..	C. Hoffmeister, 1949, Erg. A N., *12*, A16
AT Ara	*172346*	13.0–16.8	70:	20:	H. Shapley and H. H. Swope 1934, H. A., *90*, 182
BF Ara	*173047*	13.8–[16.0	..	..	H. Shapley and H. H. Swope, 1934, H. A., *90*, 182
FV Ara	*172562*	13.0–[16.5	..	..	H. H. Swope, 1935, H. A., *90*, 209
KY Ara ?	*180054*	15.1	..	..	See Chapter 6
SS Aur	060547	10.5–14.5v	54.1	..	See following §
TT Boo ?	145441	12.7–[15.6	..	..	A. Brun, M. Petit, 1952, B. A. F. No. 1
UZ Boo	143922	13.2–[16.1	..	..	C. M. Hanley and H. Shapley, 1940, H. B., 913
AF Cam	032458	13.4–[17.1	15:	..	H. E. Kurochkin, 1953, Var. Stars, *9*, 405
Z Cam	081473	10.2–13.4v	23	..	See following §
(RV Cnc)	080319	13.0–	..	..	Probably constant
SY Cnc	085518	10.9–13.8	..	..	See following §
SV C Mi	072506	13.0–16.3	..	..	C. Hoffmeister, 1930, A. N., *238*, 37
EP Car	*102458*	13.0–[16.0	..	10:	Hertzsprung, 1925, 1928, B. A. N., *2*, 209; *4*, 172
DK Cas	001256	15.4–[17.4	..	7–13	P. Ahnert, C. Hoffmeister, 1943, K. V. B. B., *28*, 74
FI Cas	000055	15.0–[17.2	31.2	..	P. Ahnert, C. Hoffmeister, 1943, K. V. B. B., *28*, 61

TABLE 8.1, continued

Star	Des.	Range	Cycle Days	Duration of Maximum Days	Reference
GX Cas	004356	13.9–[17.5	..	..	C. Hoffmeister, MS
HT Cas	010359	13.5–16.4	..	..	C. Hoffmeister, MS
KP Cas	003260	14 –16.5	long	..	C. Hoffmeister, 1949, Erg. A. N., *12*, A8
KU Cas	012457	13 –[17.6	60:	..	C. Hoffmeister, 1949, Erg. A. N., *12*, A8
KZ Cas	230355	14.5–[17	short:	..	C. Hoffmeister, 1949, Erg. A. N., *12*, A20
LM Cas	230586	15 –[17	long	..	C. Hoffmeister, 1949, Arg. A. N., *12*, A20
BV Cen	*132554*	10.5–14.0	..	..	D. Hoffleit, 1930, H. B., 874
MU Cen	*120743*	12.4–15.0	40:	..	E. Rybka, 1934, Lwow Contr., *2*, p. 13
NN Cen	*130760*	13.2–[16.5	..	..	H. Shapley and H. H. Swope, 1934, H. A., *90*, 178
V 359 Cen ?	*115341*	13.8	..	..	See Chapter 6
V 373 Cen	*122045*	13.3–15.8	..	..	A. Opolski, 1935, Lwow Contr. *4*, p. 14
V 436 Cen	*110937*	11.9–15.4	..	30	L. E. Erro, 1940, H. B., 913
V 442 Cen	*111935*	12.1–[16.5	..	20	W. J. Luyten, 1933, A. N., *249*, 395; L. E. Erro, 1940, H. B., 913
V 485 Cen	125132	13.0–[16.3	10 ?	4	M. Huruhata, 1940, H. B., 913
V 591 Cen	123633	14.0–16.0	..	..	M. Huruhata, 1940, H. B., 913
BS Cep	222564	14.0–16.0	40:	..	P. Ahnert, H. van Schewick, C. Hoffmeister, 1941, K. V. B. B., *24*, 115
CG Cep	230666	14.5–17.2	20	..	P. Ahnert, H. van Schewick, C. Hoffmeister, 1941, K. V. V. B., *24*, 115
BP Cr A	213843	8.2–12.1	13.5:	..	B. P. Gerasimovich, 1933, Pulk. Circ. No. 9, p. 32
SS Cyg	213843	8.2–12.1v	50.4	..	See following §
EY Cyg	195032	11.4–15.7	..	..	Jacchia, B. Z., *12*, 64; *13*, 2
(FO Cyg)	192718	13.8–16.2	..	..	Long Period Variable
HN Cyg	192928	13.8–15.9	..	..	?
V 337 Cyg	195638	14.4–[16.5	..	..	W. Baade, 1933, A. N., *249*, 271
V 503 Cyg	202343	14.4–16.7	..	..	
V 550 Cyg	200132	15 –[18	..	..	C. Hoffmeister, 1949, Erg. A. N., *12*, A7

TABLE 8.1, continued

Star	Des.	Range	Cycle Days	Duration of Maximum Days	Reference
V 630 Cyg	213140	14 –[17	. .	. .	C. Hoffmeister, 1949, Erg. A. N., *12*, A19
V 632 Cyg	213139	13 –16.5	. .	. .	C. Hoffmeister, 1949, Erg. A. N., *12*, A19
AB Dra	195277	12.0–15.8	12:	. .	See following §
XZ Eri	*040615*	14.6–[16.5	. .	. .	H. Shapley and E. M. Hughes, 1934, H. A., *90*, 170
AH Eri	*041813*	13.5–[16.5	. .	. .	H. Shapley and E. M. Hughes, 1934, H. A., *90*, 170
AQ Eri	*050104*	12.5–16.5	78/n	. .	J. Hoppe, 1935, A. N., *254*, 369
U Gem	074922	8.8–13.8v	102.96	. .	See following §
SY Gem ?	063431	9.2	. .	. .	See Chapter 6
UV Gem	063218	14.7–[17.2	58	. .	C. Hoffmeister, MS
(AU Gem)	073931	12.3–[15.1	. .	. .	Long-period variable
AW Gem	071628	13.0–[17	. .	. .	
C I Gem	062322	14.7	. .	. .	See Chapter 6
AH Her	164025	10.9–14.7	19.6	. .	L. Jacchia, 1941, H. B., 915
CH Her	183024	13.5–17:	. .	. .	P. Ahnert, H. van Schewick, C. Hoffmeister, 1941, K. V. B. B., *24*, 36
KW Her	183612	13.8–16.5	long	. .	P. Ahnert, C. Hoffmeister, 1943, K. V. B. B., *28*, 36
PR Her	180438	14.0–[17.5	. .	. .	C. Hoffmeister, 1950, M. V. S., 115
PU Her	180631	15.8–[17.6	. .	. .	C. Hoffmeister, 1950, M. V. S., 115
RU Hor	*024364*	14.0–[16.3	. .	7–10	E. H. Boyce, 1943, H. B., 917
AG Hya	*094523*	14.3–[16.0	15	10	E. H. Boyce, 1936, H. B., 903
CT Hya	084503	14.5–[16.5	. .	. .	C. Hoffmeister, 1936, A. N., *259*, 39
EX Hya	*124728*	11.5–13.3	. .	<26d	M. Huruhata, 1940, H. B., 913
VW Hyi	*040971*	8.5–13.4	27	8–10	E. H. Boyce, 1943, H. B., 917
AY Lac	221849	15 –[17	. .	. .	K. Himpel, 1943, B. Z., *25*, 101
EG Lac	224654	15.5–[17.5	. .	. .	C. Hoffmeister, 1949, Erg. A. N., *12*, A20
X Leo	094512	12.0–15.1v	22	. .	See following §
TU Leo	092421	11.7–14.9	. .	. .	P. P. Parenago, 1934, Var. Stars, *4*, 279
BR Lup	*152940*	13.5–[16.0	24:	. .	H. H. Swope and I. Caldwell, 1930, H. B., 879

TABLE 8.1, continued

Star	Des.	Range	Cycle Days	Duration of Maximum Days	Reference
SU Lyr	185036	12 –[16	. .	. .	C. Hoffmeister, MS
AY Lyr	184137	12.6–16.0	23	. .	L. Jacchia, B. Z., *12*, 88, 102; *13*, 16, 31, 35, 58
CY Lyr	184826	13.3–16.8	17:	. .	
DM Lyr	185430	13.7–17.0:	long	. .	P. Ahnert, H. van Schewick, C. Hoffmeister, 1941, K. V. B. B., *24*, 56
LL Lyr	183138	12.8–17.1	. .	. .	C. Hoffmeister, 1950, M. V. S., 116
CW Mon	063100	12.5–16.0	. .	. .	P. Ahnert, 1944, M. V. S., 66
EQ Mon	065209	13.4–16.0	13.9	. .	P. Ahnert, 1945, M. V. S., 105
IQ Mon	063509	15.3–16.6	. .	. .	C. Hoffmeister, 1952, M. V. S., 154
AB Nor	*154242*	13.9–[16.0	. .	. .	H. H. Swope and I. Caldwell, 1930, H. B., 879
HP Nor	*161254*	12.9–15.3	17.3	. .	W. E. Kruytbosch, 1935, B. A. N., *7*, 253
IK Nor	*161755*	13.0–[15	. .	5–10	W. E. Kruytbosch–E. Hertzsprung, 1942, B. A. N., *9*, 275
TU Oph	*162022*	13.6–[16	. .	. .	K. Himpel, 1944, B. Z., *26*, 25
(AO Oph)	*172903*	12.5–[14.5	. .	. .	Long-period variable
V 699 Oph	*161904*	13.8–[16.0	. .	5—30	E. H. Boyce, 1942, H. A., *109* 12
V 810 Oph	173507	14.8–15.8	. .	15:	E. H. Boyce and M. Huruhata, 1942, H. A., *109*, 21
BI Ori	051800	13.2–[16	24.6	. .	C. Hoffmeister, 1923, A. N., *218*, 316
CN Ori	*054705*	11.8–14.7v	19.2	. .	See following §
CZ Ori	061015	11.8–16.2	38	. .	L. Rosino, 1941, Bologna Publ., 4, No. 2
GR Ori ?	051601	11.5	. .	. .	See Chapter 6
V 344 Ori	060915	14 –[16	long	. .	C. Hoffmeister, 1949, Erg. A. N., *12*, A9
V 350 Ori	*053509*	10.9–12.6	. .	. .	
AS Pav	*180359*	13.0–[16	short	10	H. Shapley, E. M. Boyce, C. D. Boyd, 1939, H. A., *90*, 244
RU Peg	220912	10.0–13.1v	70	. .	See following §
TZ Per	020657	12.3–15.2v	17	. .	See following §
UV Per	020356	12.0–17.5	300	. .	

TABLE 8.1, continued

Star	Des.	Range	Cycle Days	Duration of Maximum Days	Reference
UW Per	020556	13.5	..	..	See Chapter 6
FO Per	040150	13.8–16.2	11.3	..	A. van de Vorde, MS
TY Psc	012031	12.5–[15.0	..	..	P. P. Parenago, 1949, Var. Stars, *7*, 155
BV Pup	*074423*	13.1–15.1	15–23	..	W. H. Dirks, 1941, B. A. N., *9*, 197
BX Pup	*075024*	13.8–15.8	15–20	..	W. H. Dirks, 1941, B. A. N., *9*, 197
WW Sgr	*181627*	12.2–[16.5	..	..	K. Himpel, 1943, B. Z., *25*,105
V 551 Sgr	*175434*	13.7–[16.5	..	..	
V 735 Sgr	175329	13.5–16.5	20–30	..	H. H. Swope, 1940, H. A., *109* 4
V 1089 Sgr	*190217*	13.8–16.6	..	5:	J. Uitterdijk, 1949, Leiden Ann., *20*, 59
FQ Sco	*170132*	12.0–[16.5	24	..	H. H. Swope, 1939, H. A., *90*, 235
MM Sco	172342	13.0–[16.5	..	..	H. Shapley and H. H. Swope, 1934, H. A., *90*, 182
V 478 Sco	*171935*	14.0–[16.5	..	..	H. H. Swope, 1939, H. A., *90*, 236
V 598 Sco	*165634*	14.8–[16.5	..	..	H. H. Swope, 1943, H. A., *109*, 32
V 601 Sco	*165736*	15.0–[16.5	..	..	H. H. Swope, 1943, H. A., *109*, 32
UZ Ser	*180514*	12.2–16.6	40:	..	
WW Tel	*181555*	14.6–[17.4	..	..	H. Shapley, E. H. Boyce and C. D. Boyd, 1939, H. A., *90*, 246
YY Tel	*182554*	14.4–[17.4	..	..	H. Shapley, E. H. Boyce and C. D. Boyd, 1939, H. A., *90*, 247
AK Tel	*183555*	14.6–15.8	..	..	H. Shapley, E. H. Boyce and C. D. Boyd, 1939, H. A., *90*, 247
VW Tuc	*001574*	15.4–[16.5	..	..	H. Shapley and E. M. Hughes, 1932, H. A., *90*, 172
SU U Ma	080362	11.1–14.5v	16	..	See following §
SW U Ma	082953	10.8–[14.9	459	..	See following §

TABLE 8.1, continued

Star		Des.	Range	Cycle Days	Duration of Maximum Days	Reference
BB	Vel	*083347*	13.3–15.2	..	..	J. de Kort, 1937, B. A. N., *8*, 173
CU	Vel	*085441*	12 –[13.5	..	..	C. Hoffmeister, 1949, Erg. A. N., *12*, A24
TW	Vir	*114003*	11‘8–16	25	..	See following §

The most thoroughly studied star of the group is SS Cygni. Scarcely a maximum has been missed since 1896. Over forty thousand observations were discussed by Campbell (1934), who classified the maxima according to steepness of rise and to duration. A statistical study of this material by Sterne and Campbell (1934) led to a number of significant conclusions, summarized in Table 8.2.

TABLE 8.2

STATISTICAL PROPERTIES OF LIGHT CURVE OF SS CYGNI (STERNE AND CAMPBELL)

Frequency distribution of cycles follows normal law of errors

A steep maximum tends:	to be a high one
	to be followed by a steep rise
A bright maximum tends:	to be a wide one
	to be followed by a long cycle
	to be followed by a faint maximum
A wide maximum tends:	to be followed by a long cycle
	to be followed by a wide minimum
	to be followed by a narrow maximum
A wide minimum tends:	to be followed by a steep rise
	to be followed by a bright maximum
	to be followed by a wide maximum
A long cycle tends:	to be followed by a steep rise
	to be followed by a bright maximum
	to be followed by a long cycle

Correlations		Correlation Coefficient	Standard Error
Length of cycle with:	height of following maximum	+0.415	±0.051
	length of following cycle	+0.280	0.056
Height of maximum with:	length of following cycle	+0.485	0.047
	height of following maximum	+0.505	0.046
Width of maximum with:	length of following cycle	+0.486	0.047
	width of following maximum	—0.475	0.048
	height of same maximum	+0.391	0.052

The associations and correlations of Table 8.2 are seen all to be significant; however, the correlation coefficients are not so high as to encourage the hope that the data from any one cycle can be used to draw conclusions concerning the physical process involved. The variation must be determined jointly by a number of successive cycles, or alternatively, the instantaneous condition of the star must affect a number of successive outbursts.

The frequencies of width of maximum show a significant division into "wide" and "narrow" for SS Cygni, as for many other stars of the class. Sterne and Campbell determine the mean (visual) range as $3^{m}.34$ with a standard deviation $0^{m}.36$. Similarly they derive $8^{m}.55$, with a standard deviation of $0^{m}.27$, for maximal apparent (visual) magnitude. The extreme observed range given in Table 8.1 is greater, and the maximal magnitude brighter. General discussions of range should properly repose on such means, but only a few stars are well enough observed to justify the procedure.

A similar study has been made for U Geminorum, with considerably less material, by Greep (1942), who treats wide and narrow maxima separately. Table 8.3 displays some of his results.

TABLE 8.3

CORRELATIONS FOR U GEMINORUM (GREEP)

		Broad Maxima		Narrow Maxima	
Length of cycle with:	height of following maximum	+0.34	±0.20	+0.70	±0.11
	width of following maximum	+0.40	0.19	+0.68	0.12
	radiation of following max.	+0.49	0.17	+0.71	0.12
	*length of following cycle		0.00	±0.23	
Height of maximum with:	*length of following cycle	—0.06	0.22	+0.15	023.
Radiation of maximum with:	*length of following cycle	+0.13	0.24	+0.00	0.24
Width of maximum with:	*length of following cycle	+0.26	0.21	+0.13	0.23

The correlations marked with asterisks are not significant, but reference to Table 8.2 shows that they were significant for SS Cygni. The mean cycle of U Geminorum is about twice that for SS Cygni. In comparing Tables 8.2 and 8.3 it should be remembered that the former rests on a discussion of more than 250 cycles, the latter, of less than twenty.

Greep finds, for broad and narrow maxima respectively, average (visual) amplitudes if $3^m.45$ and $3^m.30$, not significantly greater then the mean amplitude of SS Cygni.

Typical light curves for U Geminorum stars are shown in Fig. 8.1.

A relationship between the mean cycle and the amplitude of U Geminorum and Z Camelopardalis stars has often been discussed. Before dealing with this subject, and with the implied relationship with the recurrent novae, it will be well to examine the few stars of the U Geminorum class that have been intensively observed.

2. Individual U Geminorum Stars

RX ANDROMEDAE 005840

The light curves show the same peculiarities as those of Z Camelopardalis. The spectrum was first described by Joy (1940) as continuous, with faint Balmer emission lines not more than 10 A in width, at an unspecified phase of the light curve. Joy and Wilson (1949) included it in their list of stars whose spectra show bright H and K lines, noting the intensity as 6 (the stars of this class with the strongest bright H and K lines are assigned a value 50) and variable. Elvey and Babcock (1943) observed it during one of its typical hesitations of brightness, between maximum and minimum. Their description on various dates, when the magnitude was between 11.5 and 12.5 (the limits of the variation being 10.3 to 13.6) record bright lines of hydrogen, but no helium. At magnitude 12.5 a faint emission was seen at the K line. The lines were strongest, and most numerous, when the star was faintest. The color was noted as similar to that of a late A-type star.

AE AQUARII *203401*

The variations of brightness are very complex. Zinner (1938) observed outbursts of about 2 magnitudes' amplitude, and suggested ascription to the U Geminorum type; three of these outbursts occurred at intervals of about 371 days. They are superimposed on semiregular fluctuations of perhaps half a magnitude amplitude. In addition, the light suffers very rapid fluctuations of extremely short cycle; Lenouvel and Daguillon (1954) recorded 80 outbursts in 68 hours of photoelectric observing, about one every fifty minutes. See also Lenouvel (1952) and Lenouvel and Golay (1953).

The bright outbursts are evidently rare, and none has yet been observed spectroscopically. Induced to study the spectrum by Vyssotsky's discovery of bright H and K lines, Joy (1943) observed it to "show the characteristic features of the SS Cygni stars at minimum light". Bright lines of H, He I and Ca II were about 20 A wide, the He I very faint, the Ca II very strong. Even more striking was the discovery that a prominent dG8 spectrum underlies the emission spectrum, and that the radial velocity is variable. Joy drew the conclusion that AE Aquarii is a binary system.

More recently, Joy (1954) has shown AE Aquarii to be a double-lined spectroscopic binary with a period of 0.701024 days; one component is a dK0 star, the other the source of the bright-line spectrum. "Strong emission lines of H, He, and Ca II, 20 A in width, are present, accompanied by a continuum which indicates a high-temperature source. ...The velocity range is more than 300 km/sec for the red star... and the masses are nearly equal... The absolute magnitude of the red star is 6.0. The hot star somewhat fainter." Crawford and Kraft classify it as a subgiant (K 5 IV–V).

Although AE Aquarii is photometrically far from being a typical U Geminorum star, it is clearly a member of the physical group to which they belong, and Joy's results are of the greatest general significance, especially as he notes that SS Cygni and RU Pegasi probably constitute similar systems. The hot component of AE Aquarii is estimated by Joy as being visually about a magnitude fainter than the red companion or about +7. If, as will appear likely, most U Geminorum stars are members of similar binary systems, the observed amplitudes are minimized by their companions. A similar problem was envisaged for the novae in Chapter 1.

UU AQUILAE *195109*

The study by O'Connell (1932) verified the ascription to the U Geminorum class, and estabished the (photographic) range as nearly six magnitudes, and the cycle as rather long. The spectrum at minimum was observed by Elvey and Babcock (1943) to display moderately strong, bright Hα, and to have an underlying continuum of intensity distribution similar to that of a G star.

SS AURIGAE 060547

The variations, which have been thoroughly observed visually, are very like those of SS Cygni; the cycle is of about the same length, and the extreme (visual) range about four magnitudes.

Elvey and Babcock (1943) observed the spectrum near maximum to be nearly continuous, with a faint trace of Hα in emission, and the color of an early A or B star.

Z CAMELOPARDALIS 081473

The short cycles, small range and protracted hesitations at intermediate magnitude have been chosen to define the subclass that bears the star's name. The variations are well observed; the extreme (visual) range is 3.2 mag., and the average cycle about 23 days.

The minimal spectrum, as observed by Elvey and Babcock (1943) had the continuum of a dG5 star, though no absorption lines were seen; several fairly strong Balmer lines, a few weak He I lines, and a slightly stronger K line were noted, all the bright lines being very wide. As the star brightens, the emission lines weaken and are then replaced by broad, shallow absorption lines of hydrogen. With declining light, the spectrum appears nearly continuous, probably because of the emergence of the emisson lines which for a time obliterate the absorption spectrum, and finally reappear themselves as minimum is approached. The process is the same as that to be described in more detail for SS Cygni.

Joy (1940) described the spectrum of Z Camelopardalis as similar to that of RX Andromedae.

SY CANCRI 085518

The light variations, described by Gaposchkin (1950) has a (photographic) range over 2.5 mag. and a mean cycle 51.3 days. The variations are continuous, as in RX Andromedae, despite the length of the cycle, and the star was at first suspected of being of RV Tauri type. Joy (private communication) pointed out that the spectrum places SY Cancri with the U Geminorum stars; two plates at maximum show a practically continuous spectrum with a bare trace of bright Balmer lines. The star deserves further study. Herbig (1950) describes the maximal spectrum with typical broad absorptions, succeeded at minimum by the characteristic broad emission lines.

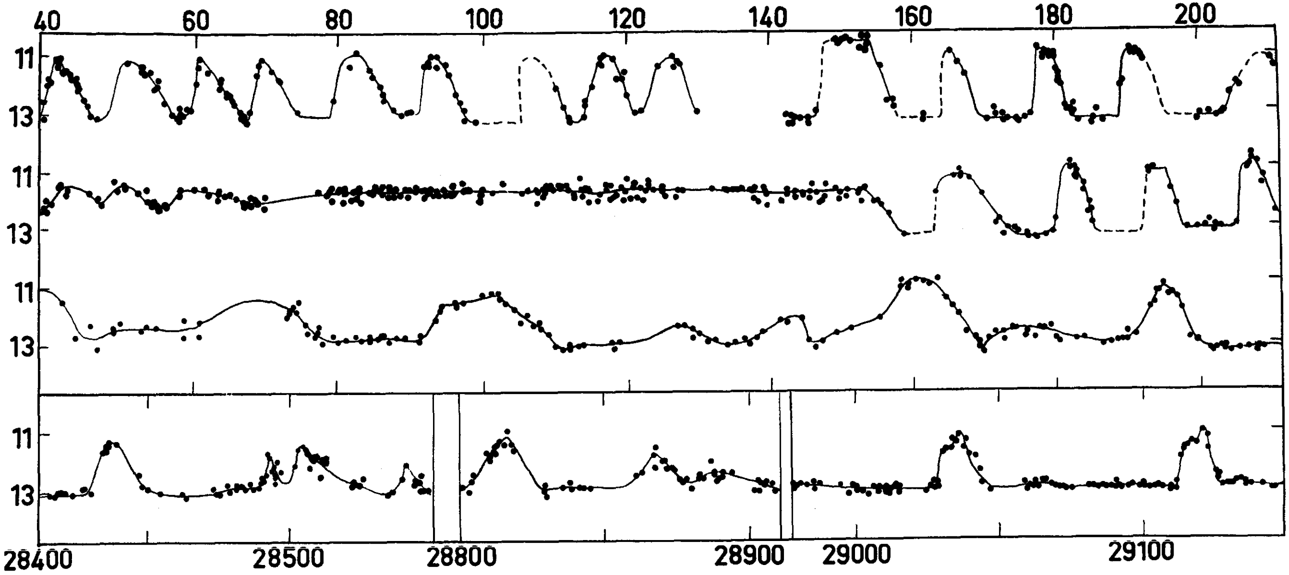

Fig. 8.1. Portions of the light curves of RX Andromedae (above) and RU Pegasi (visual observations by Jacchia). Ordinates are visual magnitudes.

Abscissae for RX Andromedae: Julian days with the following additive constants: upper row, 27300; middle row, 27600; bottom row, 28700.

Abscissae for RU Pegasi (below): Julian Days.

SS CYGNI 213843

The characteristics of the light variation have already been described, and a typical section of the curves is shown in Fig. 8.2.

Joy (1943, 1956) has shown that the star is a spectroscopic binary with a period of 0.276244 days. The components, as seen at light minimum, are dG5 and sdBe stars.

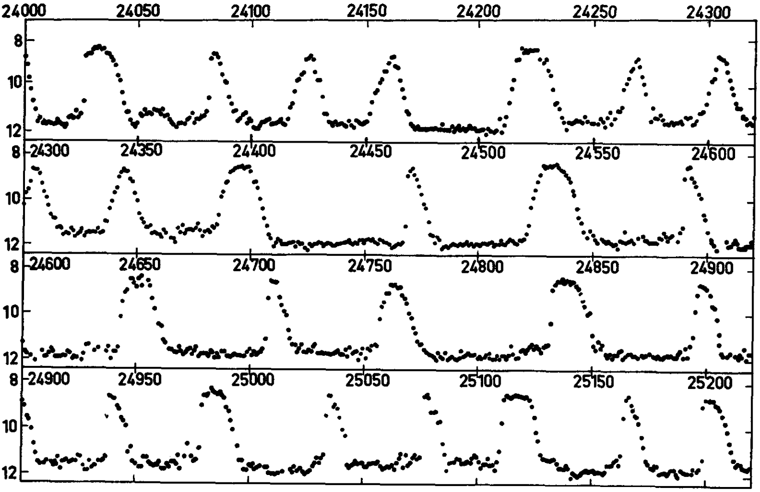

Fig. 8.2. Variations of SS Cygni, from observations by the American Association of Variable Stars Observers, as compiled by Campbell (1934). Ordinates are visual magnitudes; abscissae are Julian Days. Vertical lines are drawn at 50-day intervals, and the four strips begin respectively at J.D. 24000, 24300, 24600, 24900. There is a 20-day overlap between successive stips.

The spectrum at maximum was described by Fleming (1912) as displaying broad, shallow absorption lines of hydrogen. Adams and Joy (1922) confirmed the Balmer lines at maximum and noted faint helium; at minimum they observed bright lines. More detailed study was made by Elvey and Babcock (1943), who found at minimum a continum with the intensity distribution of a dG5 star, but saw no absorptions save possibly the D lines of Na I. In addition, they noted the strongest emission that had been observed for a star of the class: Balmer lines were seen to H 10, and continuous Balmer emission to the violet; bright lines of He I and Ca II were also noted. Similar observations had been made by Wachmann (1935).

The spectrum near maximum seemed nearly continuous with very weak hydrogen emissions "which appear as if they were only the tips of former emissions, which were visible at minimum". This description is precisely borne out by the study of Hinderer soon to be described. As the brightness declined, Elvey and Babcock noted a progressive change from maximal to minimal spectrum; the continuous spectrum, which has the energy distribution of an early B star at maximum, reverts to that of a G star as minimum is approached. The accompanying change of color had long before been noted by Gerasimovich and Payne (1932).

A later spectrophotometric study of SS Cygni by Hinderer (1949) amplified and confirms what had been observed already. His description of the minimal spectrum included a continuum with the energy distribution of a G star, and the broad bright lines, to which he added He II 4686.

With rising brightness, Hinderer noted the strengthening of the underlying continuous spectrum, and the violetward shift of its maximum intensity. The emission lines weaken and vanish; He II 4686 fades more slowly, and may even increase for a time, but vanishes at maximum light. Hydrogen absorption lines develop under the emission lines, and as their wide wings increase in strength they produce successively the impression of weak absorption wings, a double absorption line, an absorption line with narrow central reversal, and a broad, shallow absorption line appears at maximum itself.

Maximal spectrum differs somewhat for different types of maximum. For an average maximum the spectrum is of Class AO-Al during the "flat-topped" interval; the absorption spectrum is displayed more briefly during the shorter, peaked maxima. The Balmer lines are 50 to 100 A wide and very shallow; a weak K line appears, but He II 4686 does not.

As the light declines, the same profiles appear in reversed order: weak central emission is followed by the appearance of duplicity, by emission with wide absorption wings, and finally by the minimal spectrum with wide emission lines. As the Balmer emissions appear, He II 4686 becomes a strong bright line (possibly within an absorption line), which increases as the magnitude falls but is always weaker than the strongest Balmer lines.

Hinderer measures width, central intensities and equivalent widths for the bright and dark Balmer lines; his values for maximal spectrum are shown in Table 8.4.

TABLE 8.4

MAXIMAL SPECTRUM OF SS CYGNI (HINDERER)

	Hγ	Hδ	Hε	Hζ
Width at 5%	100	81	60	54
Half width (km/sec)	1250	1050	900	870
Line depth (mag.)	0.24	0.31	0.27	0.33
Equivalent width (*m*A)	8600	8400	6000	6400

Hinderer's study of spectrophotometric gradients leads to a color temperature of about 12,000° at maximum, and about 4900° at minimum. In view of Joy's discovery of the duplicity of SS Cygni, this may be interpreted in the sense that the continuum of the blue star is dominant at maximum, that of the G companion at minimum; the strong ultraviolet excess shown at minimum is partly due to the bright Balmer continuum, but also stem from the true continuum of the blue star. We may infer that the G star is somewhat brighter at minimum than the blue star, as with AE Aquarii; but as the relative intensity of the bright K line at minimum is recorded by Joy and Wilson (1949) as 50, the same value as they give for AE Aquarii, the difference of visual magnitude at minimum is probably about the same in the two systems. Thus the true visual range of SS Cygni should have an average value of about 4.3 mag. Joy notes that the absorption spectrum of the G star is more easily seen at some minima of SS Cygni than at others, which may point to inconstancy of the minimal magnitude of the blue star.

The presence of rapid, irregular fluctuations of brightness in SS Cygni has recently been observed by Grant (1955). They have amplitudes of the order of 0.2 mag., and often last less than ten minutes. At times a wave of period 2–3 hours, superimposed on these fluctuations, and of similar amplitude, was observed, and flare-like increases of amplitude 0.3 to 0.4 magnitude occurred at times. These fluctuations persist (with the same absolute amplitudes) throughout the rise to maximum.

Grant suggests that these rapid fluctuations may be attributed to intensity fluctuations of the emissions lines. It will be recalled that Joy (1954) suggested for AE Aqr that "the increases of light due to [the irregular variation of about $\frac{1}{2}$ mag. in a cycle of several hours] may result in the intensification of the emission continuum and the broad bright lines".

The variations of the type observed by Grant may very well be responsible for the apparent inconstancy of the minimal magnitude of the SS Cygni system which can be seen in Fig. 8.1; although the visual magnitudes there presented are of low individual precision, the star is so heavily observed that we can scarcely doubt that the differences of brightness at minimum are real in many cases.

The phenomena in SS Cygni and AE Aquarii are evidently related. They recall, also, the rapid fluctuations of DQ Her, McRae +43°1, and other novae or potential novae. Especially relevant is the observation by Deutsch (1955) concerning T CrB: "Following Merle Walker's discovery of very rapid fluctuations in the brightness of T Coronae Borealis, low-dispersion spectra were obtained simultaneously with his photo-electric observations. These spectra indicate that the observed light variations cannot be attributed to changes in the strength of the Balmer emission lines and continuum".

This observation, the fact that the G spectrum in SS Cyg is more clearly discernible at some times than at others, and the absence of observable bright lines at the maximum of SS Cyg, inclines the writer to the opinion that the fluctuations may be intrinsic in the blue component itself.

From SS Cygni we obtain a clear picture of the typical succession of spectral changes for stars of the class. Further amplification is furnished by the spectrum of SW Ursae Majoris, to be described below.

EY CYGNI 195032

Elvey and Babcock (1943) noted a faint continuous spectrum, with the color distribution of a G star, when the star was near minimum.

AB DRACONIS 195277

Joy (1940) noted that the star shows a continuous spectrum, with faint emission lines not more than 10 A in width, similar to those of RX Andromedae and A Camelopardalis.

U GEMINORUM 074922

Neither Fleming (1912) nor Joy (1940) observed any absorption features in the maximal spectrum, which appeared continuous. Elvey and Babcock (1943) saw fairly strong Hα and very faint Hβ, but no other

Balmer lines, at maximum; He II 4686 was present. The distribution of energy in the continuous spectrum suggested Class B5.

At minimum, Balmer lines as strong as those displayed at minimum by SS Cygni were noted by Elvey and Babcock, as well as the bright Balmer continuum, the stronger lines of He I, and the K line. The underlying continuum at minimum light had the energy distribution of a late G dwarf. Joy and Wilson (1949) assign a much weaker intensity to the bright K line than for SS Cygni. We may infer that the G companion is as bright as, or a little brighter than, that of SS Cygni, relative to the blue star; the true visual range would thus be about six magnitudes.

AH HERCULIS 164025

The minimal spectrum was found by Elvey and Babcock (1943) to show bright Balmer lines and a featureless continuum like that of a G star.

X LEONIS 094512

The maximal spectrum was described by Joy (1940) as essentially continuous. Elvey and Babcock (1943) observed Hγ, Hδ and Hε as definite absorption lines at maximum, but not Hα or Hβ; the lines were wide, diffuse and faint, and the distribution of energy in the continuum was that of a late A or early F star, considerably redder than either SS Cygni or U Geminorum at maximum.

AY LYRAE 184137

The minimal spectrum, as observed by Elvey and Babcock (1943) shows, exceptionally, no bright lines, but displays as absorption spectrum that can be rougly classified as G. Possibly the blue star is relatively fainter than the G companion, perhaps by as much as two magnitudes; the true visual range would then be over five magnitudes.

CY LYRAE 184826

As observed by Elvey and Babcock (1943), the spectrum near maximum is either continuous or shows shallow, broad Balmer lines. The intensity distribution resembles that of an A star.

CN ORIONIS **054705**

The spectrum near maximum was found by Elvey and Babcock (1943) to display very wide, shallow Balmer lines or to be apparently continuous.

RU PEGASI **220912**

The variations of brightness are unusually irregular, and the range seems exceptionally small for a star of relatively long cycle. The discovery by Joy (1943) that the star has a measureable G spectrum at minimum, and is a spectroscopic binary, elucidates the small range: the blue star must be relatively faint compared to the G companion. However, bright Balmer lines, helium lines and a faint K line were noted at minimum by Elvey and Babcock, so the difference can hardly be as great as two magnitudes. The true visual range may thus be just under five magnitudes.

TZ PERSEI **020657**

Elvey and Babcock (1943) observed an apparently continuous maximal spectrum, with the color near that of an A5 star.

SU URSAE MAJORIS **080362**

Joy (1940) found the maximal spectrum essentially continuous, as did Elvey and Babcock (1943), who noted an energy distribution like that of a B5 star, and suspected bright Hα. The bright lines were seen to emerge as the magnitude declined; at minimum bright Balmer lines of medium intensity, very faint lines of He I, and a faint K line were noted; the absorption spectrum of a yellow star was also suspected. The blue star may therefore be rather more than a magnitude fainter visually than the companion, and the true visual rqnge about 4½ magnitudes.

SW URSAE MAJORIS **082953**

The cycle of this star is unusually long, probably between 400 and 500 days; the observed photographic range is about five magnitudes.

A careful survey of the brightness and a spectrophotometric study by Wellmann (1952) show that the development of the line contours follows the pattern already established for SS Cygni by Hinderer (1949). From the spectrophotometric gradient at maximum, Wellmann determines the high temperature of 60,000°. His discussion of the source of the profiles will be mentioned later.

TW VIRGINIS *114003*

At minimum, Elvey and Babcock (1943) suspected an underlying continuum (class G ?), and noted bright Balmer lines, He I, and possibly Ca II.

3. Summary of Spectroscopic Behavior

Table 8.5 summarizes our information concerning the behavior of the nineteen stars whose spectra have been observed.

TABLE 8.5

U GEMINORUM AND Z CAMELOPARDALIS STARS WITH KNOWN SPECTRA

Star	Range Observed *m*	Range Revised *m*	Cycle *d*	Maximal Spectrum	Minimal Spectrum	Remarks
RX And	3.3v	..	14	..	(Ae*)	During intermediate stages
AE Aqr	2.0v	3.0:v	?	..	dKo ep	Spectroscopic binary
UU Aql	6.0pg	..	55	..	Ge ?*	
SS Aur	4.0v	5.0v	54	A–B*	..	Weak bright Hα at maximum
Z Cam	3.2v	4.2:v	23	..	dG5e ?*	
SY Cnc	2.5pg	..	51	continuous	..	Trace of bright H at maximum
SS Cyg	3.9v	4.9:v	50	SdB	dG5	Spectroscopic binary
EY Cyg	4.3pg	..	..	..	G ?*	
U Gem	5.0v	6.0:v	103	B5 ?*	Ge ?*	
AH Her	3.8v	..	20	..	Ge ?*	
X Leo	3.1v	..	22	A–F*	..	
AY Lyr	3.4v	4v	23	..	G	No emissions at minimum
CY Lyr	3.5pg	..	17	A ?*	..	
CN Ori	2.9v	..	19	A ?*	..	Maximal spectrum continuous
RU Peg	3.1v	5:v	70	..	dG3ep	Spectroscopic binary
TZ Per	2.9v	..	17	A5 ?*	..	
SU UMa	3.4v	4.5:v	16	B5 ?*	Ge ?*	Maximal spectrum continuous
SW UMa	5pg	..	459	A5:*	..	
TW Vir	4.2pg	5: pg	25	..	G ?e*	

* Spectrum assigned from energy distribution of continuum

The data of Table 8.5, though fragmentary for many stars, concur in suggesting that the members of the group are binaries, with a G dwarf (or subdwarf ?) companion and a blue star that reaches the color of a B or A spectrum at its maxima, and develops the corresponding bright-line spectrum at minimum. Length of cycle is not obviously related to maximal color; possibly the stars of longest cycle may tend to have companions of earliest spectrum, but the material is very scanty. Only four absorption spectra are positively seen at minimum; the other minimal spectra are inferred from energy distribution. A similar, but shorter table is given by Bidelman (1954).

The revised ranges now permit an examination of the relationship between range and cycle. A range-cycle relationship was first pointed out by Kukarkin and Parenago (1943). For six U Geminorum stars (RX And, X Leo, Z Cam, SS Aur, SS Cyg and U Gem) they pointed out a close correlation between amplitude and mean cycle. They included AC And, now generally considered to be an intrinsic variable like AI Velorum. They extended the correlation to cover the recurrent novae T Pyxidis and RS Ophiuchi, and derived the relationship:

$$\bar{A} = 0.63 + 1.667 \log \bar{P}$$

where amplitude A and period (cycle) P are averaged.

Kukarkin and Parenago formed four points for SS Cygni and two for SS Aurigae by grouping the amplitudes according to the lengths of cycles preceding the maxima considered, and found that they followed the general relationship, as would be expected for the former star from the correlations noted by Sterne and Campbell (1934). Greep (1942) extended the procedure to individual cycles and maxima of U Geminorum; the correlation was poor, as would be expected from the entries of Table 8.4, and he derived the relationship:

$$A = 0.79 + 1.87 \log P,$$

similar to that of Kukarkin and Parenago, but differing significantly both in slope and in constant.

We have seen in the preceding section that many, if not all U Geminorum stars with adequately observed spectra are probably binaries, with a G or K companion of low luminosity. The fact that all the stars whose spectra have been observed at true minimum (RX Andromedae was studied at the intermediate hesitation-stage) show evidence of a G or K spectrum suggests that the yellow companion is at least as bright as the blue star at minimum. The true amplitude should therefore be at least three quarters of a magnitude greater than the observed amplitude. The corrected (visual) amplitudes given in Table 8.5 are seen to be correlated with the logarithms of the average cycles; to allow roughly for the differential color index of the yellow and blue stars, the observed photographic amplitudes of UU Aquilae and TW Virginis have been reduced by 0.6 magnitudes (Fig. 8.3). The relationship is now represented by the formula:

$$\text{corr } A = 2.00 + 1.78 \log P.$$

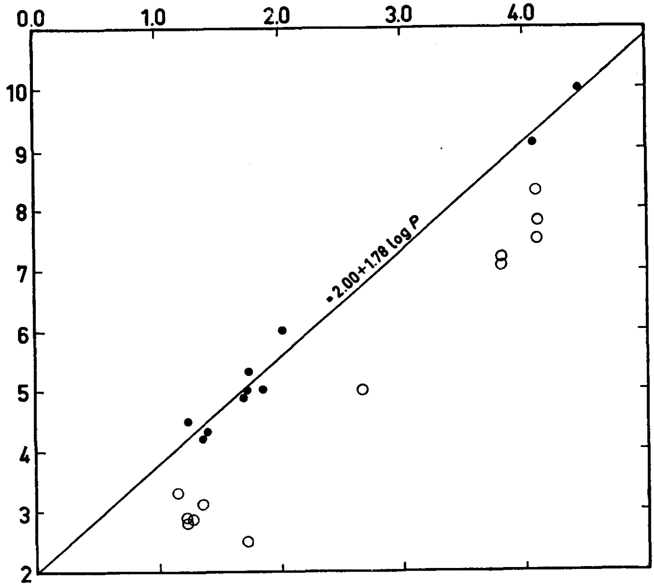

Fig. 8.3. Range and cycle for U Geminorum stars and recurrent novae. Ordinates are visual magnitudes; abscissae are logarithms of cycles in days. Dots denote revised ranges; circles, ranges for other stars. The straight line corresponds to the relation A = 2.00 + 1.78 log C.

A further test of the validity of this treatment involves the observed amplitudes of the stars whose spectra have not been studied. If some or all of them have companions, their observed amplitudes should be smaller than their true amplitudes, and all should fall below the straight line that represents the above formula. This is in fact the case.

The relationship given by Kukarkin and Parenago included two recurrent novae, and was used as an argument for the essential similarity of the two classes of star. It remains to discuss the material bearing on the recurrent novae and to compare it with the conclusions just derived.

4. The Recurrent Novae

Six recurrent novae have been described in earlier chapters. The relevant data are collected in Table 8.6.

TABLE 8.6

RECURRENT NOVAE

Star.		Des.	Range	Cycle	Remarks
				y	
T	CrB	155526	10: pg	80	Spectrum of companion gM; range taken from Payne-Gaposchkin and Wright (1946)
RS	Oph	*174406*	7.5pg	35	Spectrum G ? at minimum. Adams, Humason and Joy (1927); Humason (1938).
T	Pyx	*090031*	7.2pg	18	Continuous spectrum with bright lines at minimum; no class assignable.
WZ	Sge	200317	9.1pg	33	Minimal spectrum with strong violet continuum, star very blue, Humason (1938).
V 1017	Sgr	*182529*	7.1pg	33	Spectrum G5 ? at minimum, Brück (1935).
U	Sco	*161617*	]8.5pg	35:	No recorded spectrum.

Three of the stars have minimal spectra that at least suggest the presence of companions; the evidence is slight for V 1017 Sgr, fairly definite for RS Oph, and conclusive for T CrB. In the case of the last star, the separation of the red and blue continua by Payne-Gaposchkin and Wright (1946) allows us to deduce a photographic range of about 10 magnitudes for the nova, which is thus photographically nearly as bright at minimum as the gM3 companion, visually perhaps 1½ magnitudes fainter.

The observations of the minimal spectrum of WZ Sge by Humason (1938) suggest that the nova itself is the dominant contributor, so that the observed photographic range, 9.1 mag., is probably that of the actual outburst, or very little less.

The spectrum of T Pyxidis at minimum conveys no significant information as to the presence of a companion, and that of U Scorpii is unobserved.

We accordingly insert the ranges of T CrB and WZ Sge in Fig. 8.3, and note that they conform well to the relationship between corrected amplitude and cycle deduced for the U Geminorum stars. For both stars the cycle is based on two outbursts only, and the range of observed cycles for T Pyxidis (no less than those of SS Cygni and similar stars) emphasizes that the values used may deviate considerably from the average cycle. It is also conceivable that a maximum may have been missed, at least for T CrB. When these factors are considered, Fig. 8.3 substantiates the general conclusions of Kukarkin and Parenago, but leads to revised values for their constants. It should be noted that the ranges of the recurrent novae that probably have companions place them below the linear relationship, just as was found for the U Geminorum stars with uncorrected amplitudes.

5. Interpretation of Spectral Peculiarities

The contours of dark and bright hydrogen lines obtained by Elvey and Babcock (1943), Hinderer (1949) and Wellmann (1952) have been discussed by the latter in his study of SW UMa. The salient points are the extreme breadth and shallowness of the dark lines, the breadth, symmetry and concave wings of the bright lines, and the fact that dark and bright lines do not appear to undergo relative displacements.

Three possible sources of the absorption contours are suggested: rapid rotation, turbulence, and filling up of the centers by emission lines. Wellmann regards rotation as improbable, on account of the high velocities, about 1600 km/sec, that are required. Turbulence, he argues, would be of the order of 2000 km/sec, would require a radius for the envelope of 10 to 50 solar radii, which is inadmissably high, and would produce a very different emission spectrum. He inclines to believe that the centers of the absorption lines are filled in by emission, even at maximum. The course of the changes in line contours makes the suggestion seem probable: some stars show virtually a continuous spectrum, with a suspicion of *bright* lines, at maximum.

The fact that several U Geminorum stars are known to be spectroscopic binaries, and the strong probability that many or all have this property, suggests that rapid rotation cannot be altogether ruled out. The period of AE Aqr is 0.7 day, Joy finds that SS Cygni has a period of about 6½ hours, and analogy with DQ Herculis lends color to the idea. Rapid rotation might explain the difficulty of discerning the details of the spectra of the G companions, but this might also be interpreted in the sense that they tend to be subdwarfs, whose lines are weak and inconspicuous. Both effects are in fact suggested by Joy (1956) for SS Cygni.

Wellmann passes to the discussion of the profiles of the bright lines, which are symmetrical with wide, concave wings. He concludes that they are best represented by an envelop accelerated outward, presumably by radiation pressure.

Another possibility might also be considered: violent localized mass-motion might account for the symmetry of the bright and dark lines. The spectra of the U Geminorum stars present some of the same problems as those of the (very different) Wolf-Rayet stars, which, however, rarely show the underlying broad and undisplaced absorptions, though some examples are known. Stars of both classes are remarkable in the absence of displaced absorption lines, such as are seen in the early stages of novae toward the violet edge of the bright lines, and in the total non-occurrence of forbidden lines, which would be expected to appear in the outer parts of an expanding envelope, especially if it were accelerated.

Rapid rotation is not incompatible with violent mass-motion at the surface. Perhaps the blue components are always surrounded by a distended envelope, which occasionally increases greatly in dimensions as a result of the increased ejection that attends an outburst. The Z Camelopardalis stars in their "hesitation" stages would represent prolonged distention of this envelope. The recurrent nova T Coronae Borealis seems for the last few decades to have been in a distended state of this kind, and is now "bubbling" at a magnitude not far inferior to that of its gM3 companion; forty years age it seems to have been less disturbed and much fainter.

6. Luminosities of U Geminorum Stars

There is no doubt that the stars of the class now considered are far less luminous at maximum than the conventional novae, and even than the recurrent novae.

The well-determined parallax of SS Cygni, 0″.032 ±0.007 obtained by Strand (1947) accords well with the previous estimate, 0″.038, obtained by Parenago and Kukarkin (1934) from a study of the proper motion; it leads to an absolute magnitude +9.5 from the observed minimum, and if the blue star is a magnitude below this limit, its absolute magnitude is fainter than 10. Joy (1956), however, regards the G5 star as a subdwarf of absolute visual magnitude +5.5, and the sdB star as of similar luminosity. The absolute parallax of U Gem is given by Jenkins (1952) as $0''.010 + 0''.012$, which gives absolute minimal magnitude +8.8 visual.

Joy's study of AE Aquarii (1954) concludes that the absolute magnitude of the blue star is about +7, and the G star is about a magnitude brighter, but somewhat below the Main Sequence. The cycle of true U Geminorum outbursts for AE Aquarii is unknown, and probably long. The irregular fluctuations, with a cycle of the order of a day, may be associated in Joy's words, with "the intensification of the emission continuum and the broad bright lines"—possibly a form of the "hesitation variation" observed for RX Andromedae. The short flares, with a cycle of less than an hour may, according to Joy, occur in either star.

Luminosities for the other U Geminorum stars may be expected to resemble those just mentioned, but are difficult to assign precisely. If the G companions are actually subdwarfs they may lie one or two magnitudes below the Main Sequence, with absolute magnitudes from +6.5 to +8; the associated blue stars would range about a magnitude fainter, perhaps more. The recurrent novae, on the other hand, seem not to be fainter than +2, and are thus even brighter than the average normal nova at minimum.

Minimal radii of recurrent novae would thus be about 0.6 solar radii, and those of the blue components of U Geminorum stars would range from 0.10 to 0.02 solar radii. Minimum masses (almost equal for the two components) are near the solar mass for AEAqr (Joy, 1954), and about 1/5 solar mass for SS Cyg (Joy, 1956).

7. Theory of Recurrent Novae

The hypothesis developed by Schatzman to account for nova explosions, described in Chapter 12, leads to relationships that can be compared with the data just assembled.

Schatzman (1951), in examining the role played by ^{3}He in nova outbursts, concluded that the quantity $k = Lp/E_{obs}$ should be sensibly the same, not only for all outbursts of the same star, but also for the outbursts of stars of similar structure. E is the total energy radiated in an outburst, p the cycle in days, and L the energy radiated per day at minimum. An upper limit for k is 2.3, if 3/7 of the energy involved is released as radiation.

The data on U Geminorum stars and recurrent novae are examined by Zuckermann (1954) in the light of this prediction. The values of E are obtained from the areas of the light curves of maxima, plotted on an intensity scale. For the U Geminorum stars, averages of k_{pg}, k_{vis} and k_{bol} (deduced from visual and photographic light curves, and arbitrary correction to bolometric energies) were 0.20, 0.39, and 0.19 respectively. In the light of our previous discussion, however, this treatment overestimates L and somewhat underestimates E; the visual values should be divided by about 2.5, the photographic values by about 1.75, to allow for the true ranges of the stars. Corrected average values of k_{pg} and k_{vis} would then be 0.115 and 0.155 respectively.

The data for the recurrent novae should be restricted to WZ Sagittae and T Coronae Borealis, whose ranges are known with confidence (Table 8.6). Means of Zuckermann's values for these stars are 0.60: for k_{pg} and 3.5: for k_{vis}. The average of her values of k_{vis} for the other recurrent novae is about 5; if we make a bold application of Fig. 8.3 and conclude that these novae are, on the average, two magnitudes fainter than their companions at minimum, the corrected value of k_{vis} for them would be about 0.8.

Thus, although our rediscussion of the data leads us to reduce all the values of k derived by Zuckermann, the recurrent novae still fall appreciably above the U Geminorum stars. Zuckermann finally adopts 0.20 and 1.0 as representative values of k_{total} for U Geminorum stars and recurrent novae respectively. Our discussion reduces them to perhaps 0.1 and 0.4. The results deduced from these revised values are shown in Table 8.7.

TABLE 8.7

ENERGY SOURCES FOR U GEMINORUM STARS AND RECURRENT NOVAE

	k	Ratio of Energy: $\frac{\text{Proton-proton}}{{}^{3}\text{He}}$	Ratio of Energy: $\frac{\text{Proton-proton}}{\text{total}}$	Ratio: $\frac{{}^{3}\text{He abundance at explosion T}}{{}^{3}\text{He abundance at end of outburst}}$
U Geminorum stars	0.1	0.92	0.48	0.96
Recurrent Novae	0.4	0.70	0.41	0.84

The inferred conditions are more similar for the two types of star than was deduced by Zuckermann, but still appear to differ sensibly. The proton-proton reaction plays a more important role in the U Geminorum stars.

We may conclude that while the U Geminorum stars suggest, by their similarity of *k*, a similar structure, the recurrent novae must differ in this respect. If we are to judge from the minimal dimensions of normal novae, they are rather nearer to the U Geminorum stars than to the recurrent novae. One qualification should be recognized: it is not obviously justifiable to extrapolate the relationship of Fig. 8.3 to make an estimate of recurrence cycles for normal novae, as has been done by Kukarkin and Pårenago, Greep, and others. If ordinary novae are recurrent, their cycles are doubtless very long. But, to judge from the properties of the recurrent novae, recurrence is not confined to stars with a particular type of light curve, and some of the novae in the regular list will probably recur with cycles of decades or centuries, rather than millions of years, as predicted from the cycle-amplitude relationship.

Is recurrence associated with duplicity? Certainly this is so for the U Geminorum stars; several recurrent novae are probably members of binary systems; but DQ Herculis also is a binary, and a search for duplicity for other supposedly normal novae would be a profitable enterprise. The possibility has already been discussed in Chapter 1.

The system of AE Aqr is considered by Crawford and Kraft (1955): "Rapid evolutionary expansion may have brought it to the point of filling one lobe of the zero-velocity surface passing through the inner Lagrangian point of the system. On this hypothesis... the K star is found to eject material, some of which is collected by the blue companion... It is suggested that the accretion of mass by the blue star is related to the outbursts of 2 magnitudes found by Zinner, and a possible connection with the U Geminorum stars is pointed out". Struve (1955) relates the components of AE Aqr to the evolutionary tracks for binary stars suggested by Huang (1955); this conception provides a mechanism for differentiating the violent outbursts of U Gem stars (and novae?) from the rhythmic and controlled pulsations of RR Lyrae stars, a problem discussed by Schatzman (see Chapter 11).

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CHAPTER 9

THE SUPERNOVAE

The novae that reach exceptionally great brightness at maximum have been recognized as such for less than forty years. Curtis (1917a) considered the "island universe" theory in the light of novae that had been found in "spiral nebulae", and found it necessary to exclude S Andromedae and Z Centauri from calculations based on the properties of galactic novae. Shapley (1917) pointed out that the hypothesis requires a minimum absolute magnitude —15 for S Andromedae, and listed seven of the supernovae now recognized, although at the time not convinced of their great distance. Stratton (1928) called attention to the exceptional character of S Andromedae. When Hubble (1929) derived a period-luminosity relation for Cepheids in Messier 31 he showed that S Andromedae does indeed belong to "that mysterious class of exceptional novae which attain luminosities that are respectable fractions of the total luminosity of the system in which they appear". Curtis (1933) assigned a definite absolute magnitude —15 to S Andromedae, and the high luminosities of supernovae had by that time been generally conceded. The class of supernovae was defined and described by Baade and Zwicky (1934).

Over fifty supernovae are known at present, largely through the researches of Baade, Minkowski, Zwicky and their collaborators. Table 9.1 contains data garnered from the compilations of Baade (1938, 1941), Sawyer (1938), Bertaud (1941, 1949), Zwicky (1942), Kukarkin and Parenago (1948), Vorontsov-Velyaminov (1948), and Reaves (1953).

The first studies of supernovae established the very high luminosity, and such spectra as were secured up to 1939 proved to be enigmatic and without counterparts among those of other, less luminous stars. Later it appeared that the spectra of all supernovae are not alike, and

TABLE 9.1
Catalogue of Supernovae

System	Type	Mag.	Year	Supernova Maximum	
				Obs.	Extr.
				m	*m*
Galaxy	Sb	..	1054	—6.0*	—6.0*
			1572	—4.1*	—4.1*
			1604	—2.2*	—2.2*
NGC 224	Sb	4.5	1885	7.2*	7.2*
NGC 253	Sc	9.3	1940	14.0	..
NGC 1003	Sc	13.1	1937	13.0	12.8
NGC 1482	Sap	14.4	1937	16.5	12.2
NGC 2535	SBc	13.7	1901	14.7	14.7
NGC 2608	SBc	13.6	1920	12.9	11.0:
NGC 2672	E2	12.6	1938	15.5	..
2673	E0				
NGC 2841	Sb	10.6	1912	18	..
NGC 3177	Sb		1946	16.8	..
NGC 3184	Sc	11.8	1937	13.8	13.5
			1921	13.9	13.4:
			1921	11.1	..
NGC 3254	Sc	12.8	1941	15.1	14.2:
NGC 4038	Sp		1921		
NGC 4136	S	12.1	1941	16.8	..
NGC 4157	Sc	12.0	1937	16.2	14.4
NGC 4214	Irr	10.7	1954	9.0	9.0
NGC 4273	Sc	12.4	1936	14.4	14.4
NGC 4303	SBc	10.4	1926	14.4	12.8
NGC 4321	Sc	10.5	1901	11.9	11.9
			1914	15.7	..
NGC 4424	SBbp	12.5	1895	11.1	11.1
NGC 4486	E0p	10.1	1919	12.3	12.0
NGC 4527	Sc	11.3	1915	15.5	13.0
NGC 4545			1940	15.0	
NGC 4559	Sc	10.7	1941	13.5	
NGC 4621	E5	11.4	1939	12.1	11.8
NGC 4632	Sc	12.1			
NGC 4636	El	10.8	1939		12.6
NGC 4674	Sb	14.5	1907	13.5	..
NGC 4699	Sb	10.5		17.0	..
NGC 4725	SBb	10.8	1940	12.5	..
NGC 5195	E	11.1	1945		11.0
NGC 5236	Sc	8.8	1923	14.1	..
NGC 5253	Irr	11.0	1895	8.0	8.0

* visual

TABLE 9.1, continued

System	Type	Mag.	Year	Supernova Maximum	
				Obs. *m*	Extr. *m*
NGC 5457	Sc	8.9	1908	13.3	..
NGC 5879	Sb	12.1	1954	14.5	..
NGC 5907	Sb	11.8	1940	13.5	..
NGC 6181	Sc	12.6	1926	14.8	14.2:
NGC 6946	Sc	11.1	1917	14.6	12.9
			1939	13.3	13.2
			1948	15.3	..
IC 1099			1940	16.3	
IC 4051			1950		
IC 4182	Sc	13.5	1937	8.2	8.2
IC 4652			1934	16.5	15.0
IC 4719	Sb	13.9	1934	13.6	
Anon:					
005405	Sb	..	1939	16.0	
011815	SBc	..	1936	15.1	
023434	SBc	15.0	1938	15.4	14.5
220723	SBc	..	1937	(15.3)	..
*					

two groups of supernovae were recognized by Minkowski (1940, 1941), distinguished both by their spectra and by their light curves. Baade (1938) had derived an average absolute magnitude for all known supernovae at maximum; he now (1941) determined it separately for the two groups. These derived luminosities are affected by the revision of the zero point of the period-luminosity curve described by Baade (1952), as discussed, for instance, by Payne-Gaposchkin (1954); the earlier values must be brightened by between one and two magnitudes.

The light curves of supernovae discovered before 1939 were discussed by Baade (1941), who found that the well-observed ones displayed great uniformity, and that individuals deviated but little (less than 0.14 mag.) from the mean. The light curve, illustrated in Fig. 9.1, is characteristic of the "Type I" supernova of Minkowski.

A compilation of all known supernova light curves by Hoffleit (1939) showed, besides the form displayed by Baade, another pattern, typified

* Note added in proof: Gates (1956) reports a supernova in NGC 3992 and a suspect in NGC 3294.

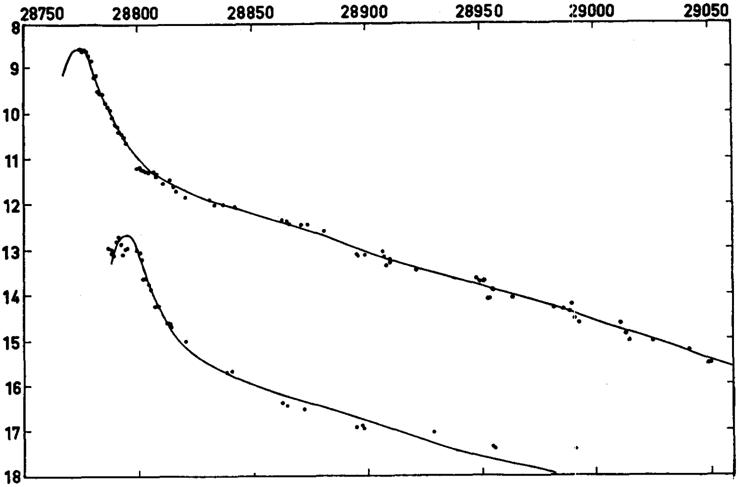

Fig. 9.1. Light curves of the supernovae in IC 4182 and NGC 1003 (Type I), after Baade and Zwicky (1938). Ordinates and abscissae are photographic magnitudes and Julian Days. The same curve has been traced (with shifted scales) for both stars.

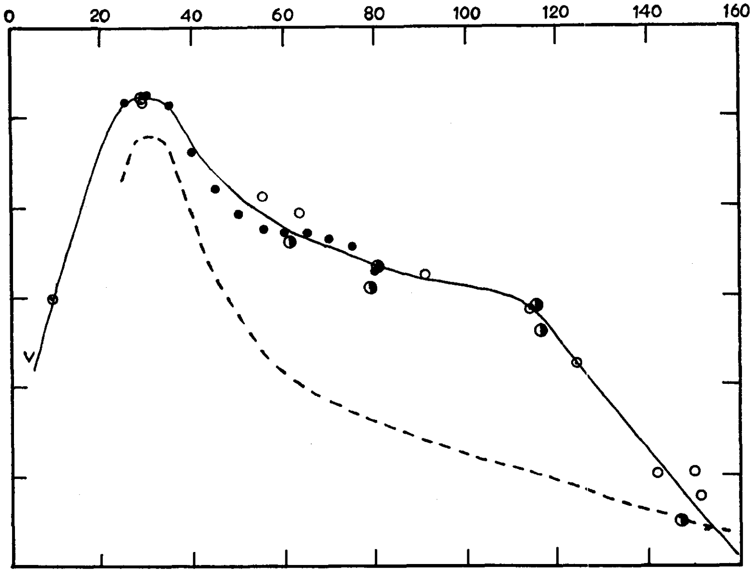

Fig. 9.2. Composite light curve for three supernovae of Type II. Ordinates and abscissae are photographic magnitudes and days. Dots, circles and half-filled circles refer respectively to the supernovae in NGC 5236, in NGC 4273 (1936) and in NGC 4157 (1937). The scales have been shifted to bring the curves into coincidence. The broken line shows the Type I curve (Fig. 9.1) for comparison.

TABLE 9.2

SUPERNOVAE IN SYSTEMS OF KNOWN DISTANCE

System	Modulus	Reference for Modulus	Apparent Maximum Magnitude	Absolute Maximum Magnitude	Notes; Type from Spectrum
NGC 224	24.25	Baade (1954)	7.2	—17.05	?
NGC 1003	28.6*	Baade and Zwicky (1938)	12.8	—15.8	Type I
NGC 3177	28.8*	Baade (1947)	]16.8	]—12	Type II
NGC 4214	..	Wellmann (1955)	9.0	—17.0	Type I ?
NGC 4273	29.2*	Baade and Minkowski (1953)	14.4	—14.8	Type II; Virgo group
NGC 4303	29.2*	Baade and Minkowski (1953)	12.8	—16.4	Type II; Virgo group
NGC 4321	29.2*	Baade and Minkowski (1953)	11.9	—17.3	Virgo group
NGC 4424	29.2*	Baade and Minkowski (1953)	11.1	—18.1	Virgo group
NGC 4486	29.2*	Baade and Minkowski (1953)	12.0	—17.2	Virgo group
NGC 4527	29.2*	Baade and Minkowski (1953)	13.0	—16.2	Virgo group
NGC 4559	27.6*	Humason and Minkowski (1941)	13.5	—14.1	Type II
NGC 5195	26.0*	Baade and Minkowski (1953)	11.0	—15.0**	Type I
NGC 5236	26.6*	Baade (1938)	14.1	—12.5	Type II
NGC 5457	26.0*	Baade and Minkowski (1953)	13.3:	—12.7:	
NGC 5907	27.4*	Humason and Minkowski (1940)	13.5	—13.9	Type II
NGC 6946.1		Baade (1938)	12.9	—14.2	Type I
.2			13.2	—13.9	Type II
.3			15.3	—11.8:	Type II
IC 4182	26.6*	Baade and Zwicky (1938)	8.2	—18.4	Type I

* Revised by —1.8 mag. ** Reddened and obscured; minimal value

by the supernova in NGC 4273, with a shoulder on the downward slope. This light curve is found to be associated with spectra of "Type II"; other supernovae that displayed it are those in NGC 4157 observed by Zwicky (1937) and in NGC 5236, by Lampland (1936).

Type I light curves seem to be so uniform that fragmentary observations can be extrapolated to determine the apparent magnitude at maximum. Those of Type II are less similar to one another, or perhaps there are more than two types of supernova. Both in spectrum and in light curve they are less similar to one another than the recognized members of Type I.

Luminosities of supernovae are determined from membership in galaxies of known distance; the greatest uncertainty almost always lies in the apparent maximal magnitude, both because of the uncertainty of the standards and of the frequent need to extrapolate the maximum observed magnitude. In the latter repect, the supernovae of Type I are less uncertain than those of Type II. The distance moduli determined earlier are subject to the upward revision mentioned above. In what follows we have made an arbitrary correction of —1.8 magnitudes. Öpik (1953) uses the larger average correction of —2.9 magnitudes, and obtains correspondingly brighter absolute magnitudes.

Mean absolute magnitudes for supernovae of Types I and II at maximum, deduced from Table 9.2, are given in Table 9.3. The second column gives the values published by Baade (1941b), and the third, these values revised by —1.8 mag.

TABLE 9.3

Absolute Magnitude of Supernovae

Type	From Table 9.2	Baade (1941)	Zero Point Revised
I	—16.1 (5)	—14.05 ±0.35	—15.85 ±0.35
II	—13.9 (7)	—11.8	—13.6

Lists of Supernovae

The spectra of supernovae, which compelled the recognition of at least two types, were first described by Minkowski (1939a, 1940), and an excellent summary of their character was given by Hubble (1941). The spectra of eighteen supernovae have now been photographed—ten of Type I, eight of Type II (Table 9.4), and we have descriptions of the visual observations of S Andromedae as well. Some of these observations are fragmentary, but are complete enough for a few stars of each type to permit a general summary such as the one given by Hubble.

When supernovae were first actively studied, they were considered to be fundamentally different from ordinary novae; at present this distinction is reserved for Type I, and the possibility that Type II may in fact be intermediate between ordinary novae and supernovae is considered, for example, by Minkowski (1940).

TABLE 9.4

SPECTRA OF SUPERNOVAE

System	Type	Year	Reference	Spectrum
NGC 253	Sc	1940	Humason and Minkowski (1941)	I
NGC 1003	Sc	1937	Minkowski (1939)	I
NGC 4136	S	1941	Humason and Minkowski (1941)	II
NGC 4214	Irr	1954	Wellmann (1955)	I
NGC 4273	Sc	1936	Humason (1936), Baade (1936)	II
NGC 4303	SBc	1926	Shane (1926), Humason (1936)	II
NGC 4559	Sc	1941	Humason and Minkowski (1941)	II
NGC 4621	E5	1939	Minkowski (1939b)	I
NGC 4636	E1	1939	Minkowski (1939b)	I
NGC 4725	SBb	1940	Humason and Minkowski (1941)	II
NGC 5195	E	1945	Humason (1945)	I
NGC 5253	Irr	1895	Payne-Gaposchkin (1936)	I
NGC 5907	Sb	1941	Humason and Minkowski (1940)	II
NGC 6946	Sc	1917	Pease and Ritchey (1927)	I
		1939	Minkowski (1940)	II
		1948	Mayall (1948)	II
IC 4182	Sc	1937	Minkowski (1939a), Popper (1937), Strohmeier (1937)	I
023434	SBc	1938	Minkowski (1939b)	I
*				

We shall summarize the published information, first for supernovae of Type I, then for those of Type II, lastly for fragmentary data and rejected novae.

The data contained in the tabulations describe the properties for two main types of supernova. Typical light curves appear in Fig. 9.1; average luminosities are described above. The spectra of Type I are exhaustively described by Minkowski (1939a). They evidently consist of extremely wide, overlapping bright lines, which are conspicuous before maximum. This feature distinguishes them from Type II, and from most ordinary novae, where bright lines before maximum are, however, not quite unknown. The atomic or molecular sources of the features in the spectra of Type I have not been identified to general satisfaction, as will be discussed below.

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* Note added in proof: Mayall (1956) has obtained spectra of the supernova in NGC 3992.

TABLE 9.5

SUPERNOVAE OF TYPE I

System	Type	Year	Reference	Remarks
NGC 253	Sc	1940	Humason and Minkowski (1941)	Spectrum of Type I; star strongly reddened and obscured.
NGC 1003	Sc	1937	Baade and Zwicky (1938) Minkowski (1939a)	Typical light curve. Typical spectrum.
NGC 4214	Irr	1954	Wellmann (1955)	Typical light curve; spectrum somewhat atypical.
NGC 4621	E5	1939	Minkowski (1939b)	Typical spectrum.
NGC 4636	E1	1939	Minkowski (1939b)	Typical spectrum.
NGC 5195	E	1945	Humason (1945)	Typical spectrum; reddened and obscured.
NGC 5253	Irr	1895	Payne-Gaposchkin (1936) Johnson (1936) Minkowski (1939)	Typical spectrum; Z Centauri.
NGC 6946	Sc	1917	Pease and Ritchey (1927) Minkowski (1939) Baade (1938)	Typical spectrum.
IC 4051		1950	Humason (1950)	Typical light curve, color.
IC 4182	Sc	1937	Baade and Zwicky (1938) Minkowski (1939a)	Typical light curve. Typical spectrum.

Spectra of Type II, which first led to the recognition of a second category of supernovae, are well described by Hubble (1941). At and directly after maximum they are essentially continuous, as noted by Humason and Minkowski (1941c) for the supernova in NGC 4559, by Minkowski (1940a) for that in NGC 4725, and by Minkowski (1940b) for that in NGC 6946, 1939. The great extension of the pre-maximum spectrum into the ultraviolet points to a surface temperature, according to Minkowski, of about 40,000°; thus the Type II supernova suggests an energy distribution that goes with a much higher color temperature than that of an ordinary nova, which usually has the color of an A or F star at maximum. This point must be borne in mind when estimating the absolute bolometric magnitudes of supernovae. Later in their development, the spectra of Type II supernovae display greatly widened bright lines, and suggest "a gigantic ordinary nova" according to Payne-Gaposchkin (1936) and Hubble (1941).

The very high luminosity of S Andromedae invites inclusion in Type I. However, the light curve, as represented by Hoffleit (1939) and

Parenago (1949) is more like Type II. Note that the circles labelled "photographic" in Parenago's light curve are actually visual means. The accounts of the (visually observed) spectrum suggest that it

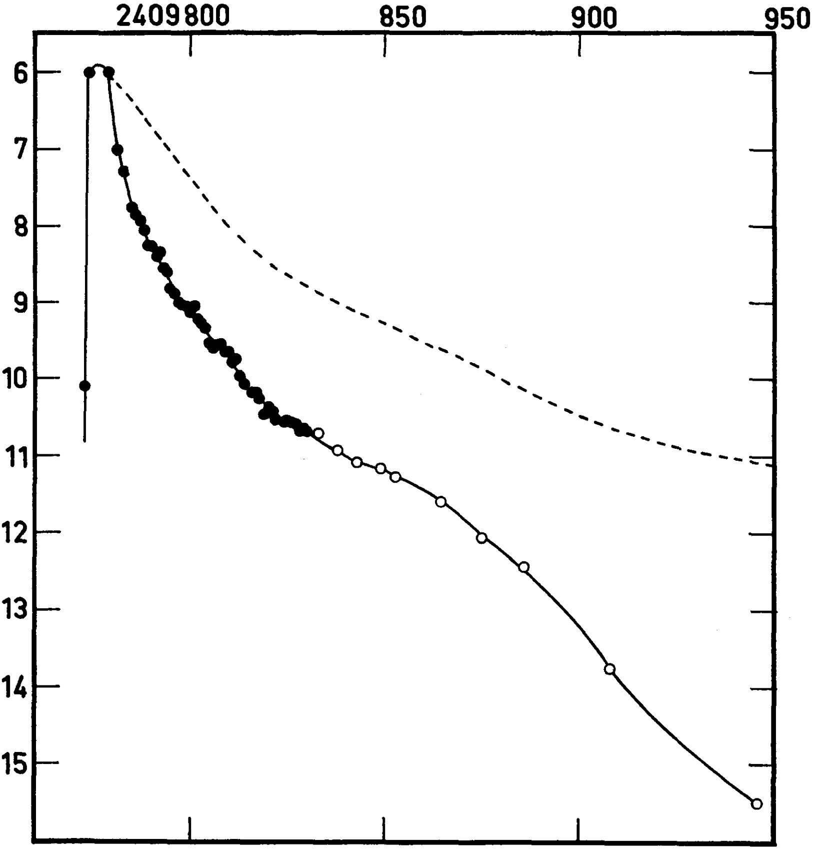

Fig. 9.3. Visual light curve of S Andromedae, from the compilation by Parenago (1949). Ordinates and abscissae are visual magnitudes and Julian days. The broken line shows, for comparison, the mean of the *visual* light curves of the Type I supernovae in IC 4182 and NGC 1003, as given by Parenago. The detailed observations on which these two light curves are based are tabulated by Parenago, but the sources are not stated.

showed bright lines from the first, thus resembling Type I, but it is difficult to identify its features with those of well-observed Type I spectra. Thus, ironically, the brightest supernova of modern times remains an enigma.

TABLE 9.6

SUPERNOVAE PROBABLY OF TYPE I

System	Type	Year	Reference	Remarks
NGC 224	Sb	1885		S Andromedae.
NGC 1482	Sa pec.	1937	Zwicky (1939a, 1942)	"Reliable extrapolation" of light curve to 12.2 mag. makes the supernova 2.2 mag. brighter than NGC 1482.
NGC 2608	SBc	1920	Wolf (1920)	Baade extrapolates maximum to 11.0; supernova thus 2.6 mag. brighter photographically than NGC 2608.
NGC 3184	Sc	1921	Shapley (1939)	About 1 mag. brighter than NGC 3184.
NGC 4424	SBb pec.	1895	Wolf (1925)	If a member of Virgo cluster with modulus 29.2, $M_{\max} = -18.1$; V W Virginis.
NGC 4486	Eo pec.	1919	Balanowsky (1929) Hubble (1923)	If a member of Virgo cluster, $M_{\max} = -17.2$.
NGC 4527	Sc	1915	Curtis (1917a)	If a member of Virgo cluster, $M_{\max} = -16.2$.
NGC 4674	Sb	1907	Luyten (1936)	1 mag. brighter than NGC 4674.

The post-maximum features of two Type II supernovae have, in fact, been plausibly identified. The supernova in NGC 4273 was studied spectroscopically by Humason (1936) and by Baade (1936). Maximum, according to Hubble and Moore (1936), took place near 1936 January 18. On February 4, probably no strong "bands" were present; by February 20, however, wide emissions were certain. During the interval the star had fallen about a magnitude in total photographic brightness. The spectrum on February 24–26 was reproduced and discussed by Humason, who adopted a wavelength correction corresponding to +2200 km/sec to compensate for the red-shift of NGC 4273. He considered the clearest features to be the violet edges of $H\gamma$ and $H\beta$; the widths of the corresponding bright lines led to a velocity of 6000 km/sec. His deduced wavelengths and descriptions are given in Table 9.11.

A close parallel was the supernova of 1948 observed in NGC 6946

TABLE 9.7

SUPERNOVAE OF TYPE II

System	Type	Year	Reference	Remarks
NGC 3177	Sb	1946	Baade (1947)	Typical light curve and spectrum.
NGC 4136	S	1941	Humason and Minkowski (1941)	Typical spectrum
NGC 4157	Sc	1937	Zwicky (1937)	Light curve like that of supernova in NGC 4273.
NGC 4273	Sc	1936	Hubble and Moore (1936)	
			Baade (1936)	
			Humason (1936)	Spectrum.
			Baade (1940)	Light curve assigns to Type II.
NGC 4303	SBc	1926	Shane (1926) Duncan and Nicholson (1926) Jones (1940) Minkowski (1940a)	Spectrum resembles that of supernova in NGC 4273; note that, if a member of the Virgo cluster, $M_{\max} = -16.4$.
NGC 4559	Sc	1941	Humason and Minkowski (1941a,b) Humason and Minkowski (1941c)	Abnormal; emission very weak. Multiple absorption, probaly H and Ca II. Perhaps a third type of supernova or an unusually bright nova.
NGC 4725	SBb	1940	Johnson (1940)	
			Minkowski (1940a) Humason and Minkowski (1941c)	Spectrum continuous, extends far to ultraviolet.
NGC 5236	Sc	1923	Lampland (1936)	
			Baade (1940)	Type II assigned from light curve.
NGC 5907	Sb	1940	Humason and Minkowski (1940)	Typical spectrum.
			Minkowski (1940b)	
NGC 6946	Sc	1939	Minkowski (1940b)	Typical spectrum.
			Zwicky (1942)	$M_{\max} = -12.1$ (old zero point).
		1948	Mayall (1948)	Typical spectrum.

by Mayall (1948). The spectrum when first observed was that of a Type II supernova several weeks past maximum. For this galaxy Mayall points out that wavelengths probably require no correction for red-shift or rotation. He tabulates wavelengths of dark (absorption line?) features, which are given with his identifications in the first

TABLE 9.8

SUPERNOVAE PROBABLY OF TYPE II

System	Type	Year	Reference	Remarks
NGC 3184	Sc	1921	Hubble and Zwicky, see Shapley (1939)	Over 1 mag. fainter than NGC 3184
		1937	Jones (1939) Zwicky (1942)	Over a mag. fainter than NGC 3184 $M_{\mathrm{max}} = —12.3$ (old zero point)
NGC 5457	Sc	1908	Wolf (1909) Hubble (1929) Baade (1938)	Peculiar light curve; considerably fainter than NGC 5457. SS Ursae Majoris.

TABLE 9.9

UNASSIGNED SUPERNOVAE

System	Type	Year	Reference	Remarks
NGC 2535	SBc	1901	Reinmuth (1923)	
NGC 2841	Sb	1912	Pease (1917)	One observation.
NGC 4038	Spec	1921	Hubble (1939)	Two plates.
NGC 4321	Sc	1901	Curtis (1917a)	One plate.
		1914	Curtis (1917a)	
NGC 4545		1940	Johnson (1940)	
NGC 5879	Sb	1954	Wild (1954)	
NGC 6181	Sc	1926	van Maanen (1941)	
IC 1099		1940	Zwicky (1940)	
IC 4652		1935	Boyd (1937)	
IC 4719	Sb	1934	Boyd (1938)	

two columns of Table 9.11. The absorptions designated I and II correspond respectively to velocities of —5700 km/sec and +360 km/sec, the former being the stronger.

The spectrum of the supernova in NGC 4303 reproduced by Humason and reduced to the scale of that in NGC 4273 for comparison, is very similar. Most strong features are common to both, and if Hβ and Hγ are matched, the supernova in NGC 4303 is seen to terminate sharply at the violet edge of Hδ, which is not visible in the other spectrum. Later development of the supernova of NGC 4273 is described by Baade (1936); after about a hundred days, when the brightness had fallen about three magnitudes, the only conspicuous emission feature,

TABLE 9.10

REJECTED SUPERNOVAE

System	Year	Reference	Remarks
NGC 224	1664	Lundmark (1920)	Brightness of nucleus of Messier 31, observed by Bullaldius, exceptional?
		Reaves (1953)	Rejected.
NGC 2403	1910	Ritchey (1917)	
		Baade (1936)	Rejected as plate defect.
NGC 3147	1904	Roberts (1914)	
		Baade (1936)	Rejected as too distant from the system.
NGC 3184	1938	Vorontsov-Velyaminov (1948)	Apparently a duplication of the 1937 supernova.
NGC 4486	1922	Sawyer (1938)	Apparently a duplication of the 1919 supernova (C. P. G.)
NGC 5236	1950	Haro (1950)	
		Hoffleit (1950)	Absolute magnitude (old scale) only about —10.
		Reaves (1953)	Rejects.
NGC 7331	1892	Roberts (1921)	
		Lundmark (1922)	A plate defect.

centered at wavelength 4640.7, is probably to be identified as N III. Its width, 203 A, leads to a velocity of 6600 km/sec. The presence of N III, and analogy with the spectra of ordinary novae, suggests that the N III pair at 4097, 4103 may have contributed at the earlier date to the bright "band" overlying Hδ and thus obliterated the dark Balmer line. The testimony of these three supernovae points to strongly displaced Balmer lines in absorption, and strong, broad bright lines of hydrogen and N III. It justifies the suggestion that supernovae of Type II are, in Hubble's words (1941), "gigantic ordinary novae". The spectrum of the one in NGC 4725, as described by the same writer, showed at first the continuous spectrum of a very hot star; bright lines developed after four or five days with widths corresponding to a velocity of 4000 km/sec.

The enigmatic spectra of supernovae of Type I present an unsolved, or at least an incompletely solved problem. Direct identification having failed, an attempt at synthesis by the combination of suitably chosen and appropriately widened bright lines was made by Payne-Gaposchkin and Whipple (1940) and by Whipple and Payne-Gaposchkin (1941).

TABLE 9.11

SPECTRA OF TWO TYPE II SUPERNOVAE

NGC 6946 (1948)		NGC 4273 (1936)	
Wavelength	Identification	Wavelenght	Description
		3787	Maximum
3859			
3901	Hε (I)	3911	violet edge
3970	Hε (II)		
4029	Hδ (+ N III ?) I		
4107	Hδ (+ N III ?) II		
		4219	red edge
4246	Hγ I	4247	violet edge Hγ
4349	Hγ II		
		4418	red edge
		4428	absorption
		4442	absorption
4481		4479	violet edge
		4723	red edge
4763	Hβ I	4767	violet edge Hβ
4868	Hβ II		
		4915	red edge
		4938	violet edge

It appears that hydrogen cannot be a major contributor to the bright line spectrum. It is possible to produce a superficial resemblance to the observed spectra and their changes but the number of parameters is limited only by the number of atomic species available, and such essays are suggestive rather than conclusive. In the intervening decade the problems of cosmic abundance have been pursued further, but are still far from solved even for objects with identifiable spectra. The writer has the impression that the spectra of Type I supernovae might perhaps be synthesized from forbidden lines in metallic spectra of moderate ionization, such as Fe II to Fe VI and Mn II to Mn VI. Progress must depend on further analyses, for example of the almost unknown spectrum of Fe IV. Baade *et al.* (1956) go back to the early suggestion that the spectra are affected by molecular bands.

Distribution and Frequency of Supernovae

That supernovae are not peculiar to any particular type of galaxy, but seem to be commonest in Sc spirals, was pointed out by Baade (1941a). Representation by galaxy type for 44 supernovae, derived by Payne-Gaposchkin (1954) is shown in Table 9.12. The data are further subdivided according to supernova type, as given in Table 9.7 to 9.10 (16 supernovae of Type I, 9 of Type II).

TABLE 9.12

Supernova Type and Galaxy Type

Type of Galaxy	% of Supernovae All (44)	 Type I (16)	 Type II (9)
I	2	12+	..
Sc, SBc	62	44	66+
Sb, SBb	23	12+	33+
Sa	2	6	..
E	11	25	..

The data are exiguous, and allowance for selection is difficult and treacherous. Information for irregular galaxies and Sa spirals is too small to be significant. But the table leaves no doubt that Type II supernovae favor the spirals, Type I, the elliptical systems.

If we are to relate the supernovae to stellar population, their place of occurrence within the galaxy in which they appear is of importance. Whipple (1939a) examined the positions of twenty supernovae then known, and concluded that their distribution tended to follow that of the main body of the system in which they were found. Ten (or fifty percent) he found to lie on a main axis, arm or condensation; the quantitative distribution in distance was similar to that found for ordinary novae in Messier 31 by Hubble (1929), and there was a slight avoidance of the nucleus, such as that also noted in Messier 31 by Hubble and by Arp (1956) for ordinary novae. Whipple's tentative conclusion was that the supernovae are produced among "average stars."

The recognition of two types of supernova refines this comparison. Reaves (1953) finds that the Type II supernovae have not the same distribution as ordinary novae, but tend to favor spiral arms (and as we have seen in Table 9.12 they have hitherto been reported only in spirals). Seven supernovae in "late" (i.e., SBc) barred spirals lie in or near the arms, none in the nucleus or bar. This suggests an affiliation with Population I for supernovae of Type II. That Type I supernovae only have been found at present in elliptical galaxies suggests that they are associated with Population II; both types have been found in the mixed Sc system NGC 6946, for instance. The three galactic supernovae (see below) are all regarded by Baade (1942, 1943, 1945) as of Type I, and Reaves (1953) points out that all lay between spiral arms. Zwicky (1948) however considers that the galactic supernova of 1054 belonged to a different class, not to Type I. The evidence is strongly to the effect that Type I supernovae belong to "Population II", Type II supernovae to "Population I." As we have argued above, ordinary novae are probably to be affiliated with Population II, so this ascription does not point to the identification of supernovae of Type II with ordinary novae of exceptional luminosity, as suggested by Baade (1941b), for instance.

The frequency of supernovae has been discussed by Zwicky (1938, 1942), who revised the result of his earlier discussion (one supernova per average galaxy per 457 years) to the figure of one supernova per average galaxy per 359 years. The well-known occurrence of more than one supernova in at least four galaxies (our own, NGC 3184, NGC 4321 and NGC 6946) points to large statistical fluctuations.

The frequencies of supernovae of Types I and II are even harder to deduce. Baade (1941b) estimates that Type II is about six times as common as Type I in "average stellar systems". If both this estimate and Zwicky's figure are taken at face value, Type I supernovae should appear less than once in 2000 years in an average galaxy. Baade and Minkowski (1953) estimate that there should be about five Type I supernovae in 1000 years in a giant stellar system like our own. That two should have appeared in our system within a generation, and that all three accepted ones should lie within a volume of 1% of that of the system, are remarkable coincidences. Öpik (1953) considers one supernova every thirty years (type unspecified) a "fair estimate" for our galaxy; Hsi Tze-tsung (1955) deduces one in 150 years.

The Galactic Supernovae

The three supernovae definitely known to have appeared in our galaxy were observed respectively in the years 1054, 1572, and 1604. All are regarded by Baade as of Type I although Zwicky (1948) questions this for the supernova of 1054.

SUPERNOVA OF 1572 (TYCHO'S NOVA, B CASSIOPEIAE)

The light curve, derived by Baade (1945) from original sources, is of Type I, with apparent maximal magnitude —4.0. The star has thus declined by more than 22 magnitudes, as it cannot now be identified, and this feature was used by Baade (1938) to classify the star as a supernova. If (as is generally believed, at least for Type I) the outburst involved a radical change in the star, and ejection of most of the original mass, pre-maximum rise may have been much less than post-maximum fall. But it can hardly have been less than ten magnitudes, even if the star was originally a supergiant like υ Sagittarii. Color as well as light curve seem to have been characteristic of Type I.

No stellar remnants of Tycho's nova have been found, but Minkowski (1956) has found faint nebulosity close by. Possible stellar survivors were suggested by Lundmark and Humason (1922) and by Baade and Humason (1937), but Humason (1938) later concluded that neither is the post-nova. If the modulus is the same as that of the Crab Nebula, and if the ejecta are expanding at the same rate (1000 km/sec, assumed constant), Baade (1945) points out that Tycho's nova should now have a nebulous shell 2′ in diameter. Baade inferred a stellar remnant of absolute bolometric magnitude less than +5, a surface temperature near 100,000°, and a condition near to that of a white dwarf. As pointed out by Baade and Minkowski (1953), the nova is heavily obscured in comparison with the Crab Nebula, and thus observationally at a disadvantage. A radio source near the supernova has been observed by Hanbury Brown and Hazard (1952).

SUPERNOVA OF 1604 (KEPLER'S NOVA)

The well-observed light curve, discussed by Baade (1943) was of Type I, with maximum at —2.2. A nebulous remnant is present, heavily obscured and greatly reddened, about four magnitude fainter, than the Crab Nebula. There is no known stellar survivor, and no associated radio source has yet been recorded.

The spectrum of the nebulous remnant, observed by Minkowski (1943), shows bright lines of [O I], [O III], [N II], [S II] and Hα. The intensity ratio of hydrogen to nitrogen is similar to that shown by the spectrum of the Crab Nebula; both spectra suggest poverty in hydrogen. The relative spectral intensities are affected by interstellar reddening, and Minkowski estimates a color excess of 2.1 mag. The observed radial velocity of the nebulous fleck, —200 km/sec, affected by an unknown projection factor, is not incompatible with expansion like that of the Crab Nebula. The bright-line spectrum is not unlike that of the Crab Nebula, but is without the strong continuum of the latter.

Supernovae of 1054 (Crab Nebula)

The first of the three well-attested galactic supernovae is the one that has left the most conspicuous remnant, the Crab Nebula. The supernova itself is documented from contemporary records by Oort and Mayall (1942), Duyvendak (1942) and Baade (1942).

The nebulous part of the remnant is unique. Its delicate and varied structure is described by Baade (1942), its spectrum by Mayall (1937) and by Minkowski (1942). The outer filamentary structure (about 4′.0 by 6′.0) has a bright-line spectrum, and the main mass (3′.2 by 5′.9) a continuous spectrum which comprises 80% of the observed light of the system. The bright-line spectrum, which gives evidence of expansion, displays lines of H, [N II], [O II], [O III], [Ne III], and [S II], and the intensities point to hydrogen poverty.

The Crab Nebula coincides with a powerful continuous radio source, first definitely identified by Bolton, Stanley and Slee (1949). The radio source is shown by Baldwin (1954) to be about twice the size of the amorphous light source. Baade and Minkowski (1953) pointed out that the radio emission may come from the filaments, or the central mass, or both. Minkowski (1942) suggested that the south preceding of the two central stars of the nebula is the stellar remnant, but Greenstein and Minkowski (1953) contemplated the possibility that no stellar remnant survived. Later observations, however, have made its existence virtually certain.

In his earlier discusion, Minkowski (1942) ascribed the spectrum of the inner amorphous mass to free-free emissions from an ionized gas at a temperature of about 500,000°. After the discovery and identification of the "Taurus A" radio source, Greenstein and Minkowski

(1953) rediscussed the optical spectrum of the Crab Nebula, and established among other things that since the observed radio flux is at least ninety the thermal emission, the two cannot be reconciled with purely thermal emission at any temperature. If the visual continuum is of thermal origin, the radio emission is non-thermal. Greenstein and Minkowski considered that at the high deduced electron temperature of 20,000,000° (corresponding to a nebular mass of 36 suns), energy might be converted from mass motion by shocks, turbulence and viscosity, and the observed radiation from the central mass could be maintained, even if the original star had disappeared as such. An earlier estimate of the nebular mass by Minkowski (1942) was 15 suns, and Struve (1954) has made a lower estimate of about 2 suns for supernovae in general. Recent studies of the Crab Nebula, however, have radically changed our ideas, and have reduced the estimated masses.

Two new observations of the greatest importance have been made for the Crab Nebula. Moving wisps and knots, with velocities of the order of a tenth of that of light, have been observed within the nebula by Baade (1954); such phenomena had indeed been noted by Lampland (1921) over thirty years ago. This observation points to the continued existence and activity of a central star (probably the south preceding of the pair of stars within the nebula, which has not, however, been observed to be variable).

Even more striking is the discovery that the light of the Crab Nebula is highly polarized. The polarization, predicted by Shklovsky, was first observed by Vashakidse (1954) and confirmed by Dombrowski (1954). It has been studied by Martel (1956), and in detail by Oort and Walraven (1956) and by Baade (1956). The mean polarization in the central region is 17.2%, and much higher values, even perhaps complete polarization, are found locally. The maximum electrical amplitude tends to be aligned in position angle about 160°.

The difficulties encountered by an interpretation of the continuum of the Crab Nebula in terms of free-free emission are discussed by Oort and Walraven (1956); see also Oort (1956). The amorphous nebula shows no emissions comparable to those of the solar corona; and improbably great mass is required for the expanding material, which should, moreover, have remained of naked-eye brilliance for over a century, contrary to observation. The theory also fails to account for the intense radio emission, for the high polarization, and the rapidly-moving nebular features.

The difficulties are removed by the interpretation given by Shklovsky (1953), which goes back to the suggestion by Alfvén and Herlofson (1950) that electrons with energies in the cosmic ray region, trapped in magnetic fields, might give rise to the observed radio stars. Shklovsky's suggestion that the optical radiation of the Crab Nebula may be this type of synchrotron radiation seems to offer a satisfactory interpretation of the observations, and to avoid the difficulties mentioned above.

The observation of Baade (1956) that the filamentary structure of the nebula conforms to a direction perpendicular to the electric vector points to a magnetic field directed along the filaments. The main nebula is envisaged as a shell of filaments expanding with a velocity of about 1100 km/sec. Its total mass may be 0.01 suns according to Shklovsky; Oort and Walraven consider that it may be ten times as great, but still far less than the masses required in the theory of free-free emission. The shell, which may be excited by the central star or by the far ultra-violet radiation of the amorphous part of the nebula, radiates like a planetary nebula, but seems for poorer in hydrogen. The mass of the fast particles in the amorphous part of the nebula may be about 10^{-8} suns, negligible in comparison with that of the whole nebula.

The underlying magnetic field may be interstellar, but be increased by small-scale turbulence within the mass to values from 10^{-4} to 10^{-3} gauss. The electrons that are responsible for the optical radiation will have energies of 10^{12} ev or even higher. Energies of 10^{9} ev would be adequate to account for the total radio emission, about 7×10^{32} ergs/sec.

The fact that energy is still being injected into the nebula suggests continued activity of the central star, possibly, according to Oort (1956) by a mechanism like that of solar flares. We note that in this case nothing need be implied about the color of the exciting star, earlier interpretations suggested that this star should be extremely blue, and therefore cast doubt on the object with which it is now identified.

If the mechanism just described is accepted for supernovae in general, these stars can account for about 10% of the observed cosmic radiation.

Other Galactic Supernovae

The occurrence of other galactic supernovae has often been the subject of speculation. Lundmark (1921, 1932) offers a number of possible candidates in his list of "pre-Tychonic novae" (see p. 36). Among these, the supernova of A. D. 369 is stated by Shklovsky and Parenago (1952) to be close to a strong radio source in Cassiopeia. Zwicky (1940) identifies the Veil Nebula in Cygnus with a possible supernova outburst over 10,000 years ago; here again we note that no central star has ever been found. That the great Hα ring in Orion is of similar origin is suggested by Öpik (1953), who likens it to the similar structure described by Lindsay (1953) in the Large Magellanic Cloud, "which," Öpik says, "can hardly be interpreted as anything but a remnant of an old supernova explosion." In his "Catalogue of Ancient Novae", published too late to be incorporated in Appendix II, Hsi Tze-tsung (1955) considers that the stars observed in AD 185, 396, 437, 827, 1006, 1054, 1181, 1203, 1230, 1572 and 1604 were supernovae. He withdraws the identification of the object of AD 369 with Cas A, as maintained by Shklovsky (1953) and Shklovsky and Parenago (1952), on account of a revised position.

We have quoted the estimate of Baade and Minkowski (1954) that about one Type I supernova in 200 years should be expected in a galaxy like ours. If (and it is a multiple assumption) there are six Type II supernovae to each Type I supernova in our neighborhood, we might expect at least one Type II supernova every forty years (a figure that brings Öpik's estimate, one supernova every thirty years, to mind). The estimate of six to one must, of course, be qualified. Baade (1941b) made it for the "average stellar system." If, as we have concluded above, Type I supernovae favor Population II, and Type II, Population I, a numerical estimate must relate to a galaxy not only of specified stellar content, but also of specified population makeup. If by "average stellar system" we understand the commonest galaxy type, the small elliptical, which Population II dominates if it does not monopolize, the frequency of supernovae of Type II in our own system might even be expected to exceed one in forty years, and to reach perhaps one in a decade.

Are there records of galactic Type II supernovae? One-third of all Type II supernovae have been observed in Sb spirals (Table 9.12), so our system is not an unsuitable habitat.

Five criteria for Type II supernovae might be suggested: (1) high luminosity at maximum, (2) large range, (3) high ejection velocity, (4) early premaximum spectrum, (5) form of light curve. These criteria are arranged in decreasing order of validity.

(1) Very high liminosity has been ascribed to CP Puppis, but the actual value is uncertain. Several suggestions of very high luminosity have been made for η Carinae, but its distance is somewhat uncertain, and in a direction where we survey a deep and relatively unobscured vista, Gaviola's (1955) suggestion that this star is part of the Carina O-Association must remain not proven. Neither of these stars had the spectrum of a Type II supernova, in particular the high expansion velocity; that for η Carinae was notoriously very low, and the observed velocities for CP Puppis were by no means high in comparison, for example, with V 603 Aquilae.

(2) The outstanding range (Table 1.9) is that of CP Puppis, over 17 magnitudes, which seems to cut it off from other novae.

(3) The highest pre-maximum radial velocity recorded is that for T Coronae Borealis, certainly not a supernova. High velocities (over 3000 km/sec) for later absorption systems are found (see Table 8.7) for V 603 Aquilae, CP Lacertae and GK Persei, all known from expansion parallaxes to have been common novae. I do not recall the spectrum of any galactic nova that displays bright lines quite as wide and formless as those shown by the supernovae of Type II in NGC 4273, 4303, and 6946.

(4) The earliest pre-maximum spectral classes recorded are those for DQ Herculis, CP Lacertae and GK Persei, none a supernova.

(5) Several Type II supernovae, though not all, have had similar light curves—a rather slow decline, a marked "shoulder" and a steeper fall (Fig. 9.1). Four galactic novae have had such light curves: CQ Velorum, XX Tauri, EU Scuti and V 707 Scorpii. For the first of these no spectrum has been observed; the second and third had spectra typical of common novae, and that of the fourth, though unusual, was not like those of Type II supernovae that have been published.

A sixth possible criterion is not available; we do not know what remnants are left by Type II supernovae. We can, however, make some guesses. Their spectra, though suggestive of extreme velocity, are relatively normal; in particular they show a strong continuum in the early stages, and some continuum is present during the initial development. This suggests that, unlike the Type I supernovae which seem to be without continuum after the first few days, the Type II supernovae are not radically modified during the outburst, and may end as a subdwarf, intermediate, or white dwarf. We have no direct information about their ranges, and therefore the use of range to identify them is to some extent irrelevant. However, their ranges are likely to be large rather than otherwise. The pre-maximum and post-maximum range of a Type I supernova may very likely differ a good deal; but this may not be so for a Type II supernova, any more than it is for a common nova.

It will be noticed that most of the novae that fulfil one of the suggested criteria are known to be common novae, and that CP Puppis is the only one that fulfils more than one. I have a strong impression that if V 603 Aquilae is a common nova, so is CP Puppis, which is like it in many ways, though perhaps it is unique among fast, bright novae in its display of [Fe II] lines and in high luminosity.

The failure to identify any galactic Type II supernovae lends a certain plausibility to the idea that these supernovae are simply common novae of extreme properties; but the testimony of the common novae of extreme properties that were mentioned does not convict them as supernovae. Moreover the common novae in Messier 31, as studied by Arp (1956), have maximal luminosities that are correlated with the forms of their light curves, and seem to have an upper limit at M_{max} of about —9. If novae of higher maximal luminosity exist, Arp's series of light curves seems to suggest that they belong to a different type; the rather slow decline of brightness of the Type II supernova does not follow naturally on the extreme speed of development of the brightest common novae in Messier 31. Farther, as already mentioned, Type II supernovae seem related to Population I, while common novae have a distribution (both in our galaxy and in Messier 31) that associates them a spheroidal population, verging toward Population II: The balance of evidence, in fact, tends to divorce the Type II supernovae from the common novae.

Finally, the number of Type II supernovae that we might expect to have observed is very small. If its absolute maximal magnitude is —14, a Type II supernova that appears between us and the galactic center (apparent modulus about 17), will be of the third magnitude or brighter. At the rate of one in forty years, we have about a fifty-fifty chance of having observed one since the beginning of the century, a good chance of observing one before its end. Very likely no Type I supernova has appeared in our galaxy since 1604, and we may hope for another in the not distant future. Type II supernovae, besides being intrinsically fainter, are at the additional disadvantage of probably lying near the galactic plane, behind obscuring material.

In considering the speculative question of the probable number of observable supernovae, we have neglected another factor: Schwarzschild and Spitzer (1953) have suggested that the frequency of the supernovae that give rise to white dwarfs is greatest in the early stages of a galaxy. Perhaps this is another aspect of the need to specify population makeup when stating the frequency of supernovae; the tendency is clearly borne out by Table 9.12, especially if we adopt the view suggested earlier, that the Type II supernovae are the generators of white dwarfs, and assign to those of Type I the more creative role envisaged by Öpik (1954).

The more general evolutionary aspects of supernovae, and some associated theoretical problems, will be touched upon in a later chapter.

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CHAPTER 10

COMPARATIVE STUDY OF SPECTRAL DEVELOPMENT

An important step in the study of novae is the recognition of a common pattern of development, as described by McLaughlin (1942, 1944). Table 10.1 is taken from his discussion.

TABLE 10.1

RELATION OF SPECTRA CHANGES OF LIGHT CURVE

Absorption System	Emission System	Duration (Magnitudes from Max.)	Light Curve
1. Pre-maximum	Pre-maximum	(through maximum)	Rise (decline)
2. Principal	Principal	0.6 to 4.1	Early decline
3. Diffuse enhanced	Diffuse enhanced	1.2 to 3.0	Early decline
4. Orion	Orion (hazy bands)	2.1 to 3.3	Early decline
5. Nitrogen (Orion)	4640 (Orion)	3 to 4.5	Transition
6. ..	Nebular (Principal)	4 to 11	Transition-final decline
7. ..	Post-nova (narrow stellar emissions)	8 to minimum	Final decline-post-nova.

The four absorption systems, pre-maximum, principal, diffuse enhanced and Orion, are shown by almost all adequately observed novae. Sometimes one or more are weak; often one or more are multiple. Occasionally a coincidence or near-coincidence of wavelength makes recognition difficult. The successive stages will be discussed in order. References to particular novae may be found in the Chapters 4 to 6 under the star concerned.

1. The Pre-maximum spectrum

The few novae for which the spectrum has been observed shortly before maximum have usually shown only one absorption system at that time; the lines have nearly always been broad, diffuse and negatively displaced. The spectrum of V 356 Aql, photographed on the

TABLE 10.2

PRE-MAXIMUM SPECTRA OF NOVAE

Star	Type*	First Observation				Maximum				Post-maximum			
		J.D.	Mag.	Spectrum	V(km/sec)	J.D.	Mag.	Spectrum	V(km/sec)	J.D.	Mag.	Spectrum	V(km/sec)
V 356 Aql	S	28371	9.0	Cont.	..	28381	7.4	..	..				
V 603 Aql	VF	21753	0.6	AO	..	21754	—0.6	A5	—1250	21755	0.0	A5	—1300
T CrB	VF, R	..	..	..	..	31861	3.2	B8 ?	—4500	31862	3.5	A ?	—4360
V 476 Cyg	F	22559	2.2	AO	—400	22560	2.0	A2	—380	22561	2.3	A5:	—360
DN Gem	F	19475	4.2	A5	—450	19476	3.5	FO:	—500	19477	3.7	F5	—550
DQ Her	S	27785	3.	B5	—1000	27794	1.7	FO	—180	27796	2.0	F5	—176
CP Lac	VF	28339	2.7	B9	—500	28340	1.8	A2	—600	28341	2.7	A5 ?	—750
GK Per	VF	15438	0.5	B9	—700	15439	0.0	AO	—800	15440	0.6	A2:	—1000
RR Pic	S	24296	2.3	F2	—72	24309	1.2	F8	—64	24314	2.1	F8	—79
Average:	VF			B 9.3	—600			A 2.3	—880			A 4	—1020
	F			A 2.5	—425			A 6	—440			FO	—460
	S		RR Pic	F 2	—72			F 4	—120			F 6.5	—230
			DQ Her	B5	—1000								

rise, was reported as continuous, without observable absorptions or emissions. The very slow nova RT Ser always showed positively displaced absorptions, but this is probably to be ascribed to high space velocity.

A spectral class can always be assigned to the immediately pre-maximum absorption spectrum, which may nevertheless display marked peculiarities. The spectrum often displays bright lines to the red of some of the absorptions.

The data on Table 10.2 cover the observed pre-maximum spectra. There is some variety of spectral class: if V 1148 Sgr had been included we should note that one nova has displayed a pre-maximum spectrum of Class K, but the light curve of this nova is very fragmentary, and we cannot be sure that the spectrum was actually pre-maximum.

Very strong, wide bright lines were observed for DQ Her on JD 27785; they faded nearly to invisibility at maximum. Rather strong bright lines were present for RR Pic from discovery to maximum. The first observations of T CrB seem to have been exactly at maximum; the bright lines were very strong and broad, and may have strengthened slightly during the first few hours of observation. It may be significant that the two novae whose pre-maximum velocity greatly exceeded that of the principal spectrum were those that showed strong bright lines at or before maximum. Very weak, wide bright lines are discernible on the first Harvard spectra of GK Per (JD 15438, the day before maximum). If bright lines were present in the first pre-maximum spectra secured of V 603 Aql, V 476 Cyg, DN Gem and CP Lac, they were very weak.

For the three novae V 603 Aql, DQ Her and RR Pic we have records of the spectrum during the last magnitude of the rise: one is a fast nova, the others are differing slow ones. The largest change is shown by DQ Her, with a drop in velocity by a factor of more than 5, and a spectral change from B5 (the earliest pre-maximum spectrum on record) to F0. The changes for V 603 Aql and RR Pic, over nearly the same magnitude range, were much smaller.

All the observed changes are in the direction of later spectral class. Note, however, that the "ejection" velocity increased from discovery to maximum for DN Gem, CP Lac and GK Per, and decreased for V 476 Cyg, DQ Her and perhaps RR Pic.

There is a tendency for the absorption lines to become sharper, and perhaps stronger, as maximum is approached, especially notable for DQ Her, DN Gem, V 603 Aql and RR Pic.

During the rise to maximum (except for DQ Her) the brightness of the nova came almost entirely from the continuum, at least in the regions observed.

The pre-maximum spectrum survives for a short time after maximum, but it weakens rapidly and is soon superseded by the principal spectrum, whose "emergence" coincides with maximum. Changes of spectrum and velocity for the pre-maximum absorption after maximum are shown in Table 10.2. Spectral class continues to grow later. Changes in the observed velocities are usually in the same direction as before. The very early maximal spectrum of T CrB is notable, in conjuction with the very large radial velocity.

There is a rough correlation between the spectrum at discovery and the associated radial velocity: high velocities tend to go with "early" spectra. Spectrum at maximum follows a similar trend; but one would give much to know what spectrum T CrB displayed two magnitudes pre-maximum. The radial velocity of V 603 Aql on the day of discovery is likewise unknown; it probably exceeded all those tabulated except for T CrB.

The few observations of pre-maximum continua indicate that the effective temperature fell during the final rise, and roughly paralleled the spectral changes.

A satisfactory theory of the pre-maximum phenomena should predict the absolute brightness and its changes as functions of radial velocity, rate of ejection, surface brightness and spectral class (i.e., state of ionization and excitation) and should also account for the widths, profiles and intensities of bright lines.

2. The Principal Spectrum

The emergence of the principal spectrum coincides with maximum light. Always with a larger negative velocity than its predecessor, the principal spectrum soon surpasses it in intensity, and after a short time the pre-maximum spectrum is no longer discernible. At maximum the complex interplay of bright and dark lines has not gone so far as to make spectral classification impossible, but the exact significance

TABLE 10.3

PRINCIPAL SPECTRA OF NOVAE

Star	Type	Maximum or Earliest Observation				Intermediate Dates						Last Record		
		J.D.	Mag.	Spectrum	V km/sec	J.D.	Mag.	V km/sec	J.D.	Mag.	V km/sec	J.D.	Mag.	V km/sec
EL Aql	F	25047	6.4	(A)		25109	8.9	—860						
V 356 Aql	S			(A2)		28433	8.8	—960						
V 528 Aql	F	31694	7.0	(F)		31699	7.6	—1200						
V 603 Aql	VF	21754	—0.6	F5	—1450	21765	2.4	—1720	21790	3.7	—1810	21834	4.6	—1850
											—1680			—1730
T Cr B	VF, R	31861	3.2	B9 ?	—1350	31862	3.6	—1580						
V 450 Cyg	S					30617		—500						
V 465 Cyg						32707		—620						
V 476 Cyg	F	22560	2.0	FO:	—700	22575	4.9	—740	22587	6.1	—800	22602	7.9	—840
DM Gem	F	16180	4.9	. .	—190	16207	8.5	—190	16210	8.5	—220			
DN Gem	F	19476	3.5	A5:	—800	19490	6.3	—800	19496	6.5	—800	19513	6.7	—750
											—1000			—1080
DQ Her	S	27794	1.8	F5	—315	27833	3.5	—340	27863	4.0	—380	27888	4.6	—395
CP Lac	VF	28340	1.8	A2	—1300	28350	5.0	—1800	28355	5.6	—2150	28361	6.1	—2200
DK Lac	F	(33332)	8.1	A	—1200	33342	8.5	—1280	33357	8.9	—1370	33369	9.4	—1450
HR Lyr	F	22300	?	(A ?)		22360	8.9:	—1010						
V 849 Oph	S	?		(F ?)		22264	7.8	—330	22268	7.2	—400			
RS Oph	VF, R	27297	4.3	. .				—60:						
GK Per	VF	15439	0.0	A5	—1270	15455	3.6	—1500	15465	3.5	—1540	15476	4.3	—1560
RR Pic	S	24309	1.2	F8	—285	24380	2.9	—320	24450	4.0	—400	24572	3.6	—440
CP Pup	VF	30675		A5	—1010							30690		—1300
T Pyx	S, R	(22426)	6.6	B9–A ?	—1100									
V 630 Sgr	VF	28449		B9 ?	—2130									
V 719 Sco	S	33482	9.8	. .	. .	33488	10.6	—1100						
V 720 Sco	S*	33500	7.7	. .	. .	33506	8.3	—1100						
EU Sct	F	33132		F	—310	33142		—400						
Average:	VF			A 4.2	—1420			—1650						—1870
	F			A 7.5	—640			—810						—1120
	S			A 8.5	—570			—660						

of the assigned spectral classes is debatable. Data concerning principal spectrum are given in Table 10.3.

As McLaughlin (1944) has pointed out, the principal spectrum at maximum has much in common with that of a supergiant of Class A or F; in addition it tends to display strong lines of CI and O I, though neither was noted for RR Pic. Lines of Sr II may be intensified at maximum and quickly lose prominence, as in V 849 Oph and RR Tel. The rapid fading of 4481 Mg II and other lines of similar origin is readily explained by Struve (1939) by the effect of dilution cn lines whose lower levels are not metastable. The lines that do persist tend to become sharper, probably as a result of weakened wings. Spectrophotometric studies of profiles and equivalent widths at this stage would be observationally less difficult than when the emission lines are more pronounced, and would give important information.

Lines of neutral helium may appear after a time in the principal absorption spectrum, an indication of increased excitation. In the spectra of V 603 Aql and DN Gem the principal absorption, at first single, later appeared intermittently double.

The duration of the principal absorption differs considerably from star to star. Table 10.4 summarizes approximate lifetimes and associated magnitude changes for six novae; we note that the more significant change in the magnitude of the continuum is considerable greater than the drop in the integrated spectrum, and may well be more similar from one nova to another. If we make the crude assumption that the nova at maximum has 100 solar radii, and that the pre-maximum spectrum is destroyed when the principal spectrum catches up with it, we find that Absorptions I and II, if they travelled with constant velocity, must have started out at an interval of about one day. However, if we take the velocities of Tables 10.2 and 10.3 at face value, the principal spectrum never overtook the pre-maximum spectrum of T CrB or DQ Her.

Emission lines appear immediately after maximum; they are terminated to the violet by the corresponding absorptions and (if the latter are taken into account) seem to be symmetrical about the undisplaced wavelength. The Balmer lines are usually the most conspicuous; in CP Pup the day after maximum they were not stronger than those of Fe II, but they soon grew relatively more intense. Strong bright lines

TABLE 10.4

DURATION OF PRINCIPAL SPECTRUM

Star	Type	Interval in Days	Interval in Magnitudes	Average Velocity km/sec
V 603 Aql	VF	80	5.2	—1700
V 476 Cyg	F	42	5.9	—750
DN Gem	F	37	3.2	—800
DQ Her	S	94	2.8	—350
CP Lac	VF	21	4.3	—1800
GK Per	VF	37	4.3	—1400
RR Pic	S	263	3.4	—350
CP Pup	VF	15:	4.9	—1200
Average:	VF	32	4.7	—1525
	F	40	4.6	—775
	S	184	3.1	—350

of Ca II and Fe II are always present. A day or two after maximum the nebular lines of 6300, 6363 of [O I] appear, shortly followed by 5755 [N II]. The auroral line 5577 [O I] has rarely appeared in any strength, and the nebular pair 6538, 6584 [N II], if present, are lost in the great intensity of Hα at this stage. The line 5876 He II and other neutral helium lines appear soon afterwards, and the [O III] lines a little later. All these bright lines appear to be similar in width and structure.

The structure of the bright lines appears to follow a general pattern. For most novae they are featureless at first, but an early suggestion of asymmetry, with greater intensity to the violet, may soon develop, as in CP Lac and CP Pup. After a few days the profile may then become saddle-shaped with the violet edge the stronger. From now on, the emissions associated with the various absorption systems begin to overlie one another, and are far more difficult to separate and analyze than the latter. However, there seems to be no doubt that even the principal emission (to use McLaughlin's terminology) may display the significant saddle-shaped profile.

3. The Diffuse Enhanced Spectrum

The third recognizable system, which usually appears after the integrated brightness has declined by about a magnitude and a half, has

TABLE 10.5

Diffuse Enhanced Spectra of Novae

Star	Type	Maximum		First Observation			Later Observation			Last Record		
		J.D.	Mag.	J.D	Mag.	V(km/sec)	J.D.	Mag.	V(km/sec)	J.D.	Mag.	V(km/sec)
V 356 Aql	S	?	?	28433	8.8	—1080						
V 368 Aql	F	28437	?	28462*		—1200 ?				28468		. .
V 528 Aql	F	31694	7.0	31699	7.6	—2100				31706 ?	8.6	. .
V 603 Aql	VF	21754	—0.6	21756	0.3	—2200	21759	1.3	—2270	21761	1.8	—2280
V 476 Cyg	F	22560	2.0	22562	2.4	—1370	22580	5.4	—1540	22599	7.4	—1420
DM Gem	F	16180	4.9	16207*	8.5	—570	16210	8.5	—700			
DN Gem	F	19476	3.5	19478	4.7	—1370				19498	5.9	—2000
DQ Her	S	27794	1.8	27799	2.3	—780	27833	3.5	—870	27888	4.6	—860
CP Lac	VF	28340	1.8	28340	1.8	—1400	28355	5.6	—2600	28361	6.1	—2700
DK Lac	F	33304	5.4	33311	6.0	—1150				33332	7.9	—1500
GK Per	VF	15439	0.0	15440	0.3	—3100	15451	3.2	—3620	15463	4.7	—3750
RR Pic	S	24309	1.2	24335	3.5	—640	24380	2.9	—680	24425	3.6	—860
CP Pup	VF	30675	0.6	30679	2.5	—1600						
V 630 Sgr	VF	28446	4.5	28449*	6.6	—3590						
V 719 Sco	S	33487 ?	9 ?	33488	9.5 ?	—2200						

* Probably not first appearance.

generally a much larger displacement and more diffuse lines than its predecessors. The spectrum by this time defies conventional classification. Data on diffuse enhanced spectra are assembled in Table 10.5. The lifetimes of the diffuse enhanced spectra of well-observed novae are summarized in Table 10.6.

TABLE 10.6

APPEARANCE AND DURATION OF DIFFUSE ENHANCED SPECTRUM

		Appearance		Average	Disappearance		Duration	
Star	Type	Interval in Days*	Interval in Mag.*	V (km/sec)	Interval in Days	Interval in Mag.	Interval in Days	Interval in Mag.
V 528 Aql	F	5	0.6	—2100	12	1.6	7	1.0
V 603 Aql	VF	2	0.9	—2200	6	2.4	4	1.5
V 476 Cyg	F	2	0.4	—1370	39	5.4	27	5.0
DN Gem	F	2	1.2	—1370	22	2.4	20	1.2
DQ Her	S	5	2.3	—780	94	2.8	89	0.5
CP Lac	VF	0	0.0	—1400	21	4.3	21	4.3
DK Lac	F	7	0.6	—1300	28	2.5	21	1.9
GK Per	VF	1	0.3	—3100	24	4.7	23	4.4
RR Pic	S	26	2.3	—640	116	2.4	90	0.1
Average:	VF	1.0	0.4	—2230	17.0	3.8	16.0	3.4
	F	4.0	0.7	—1620	25.2	3.0	21.2	2.3
	S	15.5	2.3	—710	105.0	2.6	89.5	0.3

* From Maximum

The strength and diffuseness of the lines of the diffuse enhanced spectrum are ascribed by McLaughlin to the effects of turbulence on the curve of growth. Quantitative measures would be very useful in establishing this point. Usually the Balmer lines are the most conspicuous features of the diffuse enhanced spectrum.

The diffuse enhanced absorptions are accompanied by an emission spectrum with lines of corresponding width. These bright lines underlie the emissions associated with the principal spectrum, but are proportionately wider.

Unlike the pre-maximum and principal spectra, whose changes of velocity, if any, are steady, the diffuse enhanced spectrum may display oscillations of observed velocity. McLaughlin (1943) called attention to early real oscillations for DN Gem, DQ Her and RR Pic. For novae in which the diffuse enhanced spectrum later becomes multiple (as it

TABLE 10.7

ORION ABSORPTION SPECTRA OF NOVAE

Star	Type	Maximum		Orien Spectrum Appearance			Last Record			N III Appearance			Last Record		
		J.D.	Mag.	J.D.	Mag.	V (km/sec)	J.D.	Mag.	V (km/sec)	J.D.	Mag.	V (km/sec)	J.D.	Mag.	V (km/sec)
EL Aql	F	25047	6.4	25109	9.2	—2076									
V 356 Aql	S	28382	7.4	28433	8.8	—1100	28445	7.1	..						
V 368 Aql	F	28436	5.4							28462*	8.3	—1900	28468	8.6	—2000
V 603 Aql	VF	21754	—0.6	21756	0.3	—2160	21778	3.2	—2970	21758	1.0	—2640	21792	3.7	—3450
T Aur	S	12084	4.2	12170*	7.7	—1193									
V 450 Cyg	S	30531	7.9	30617*	9.0	—1200	30621*	9.9	—1260						
V 476 Cyg	F	22560	2.0	22576	4.9	—2600	22601	7.7	—2530						
DM Gem	F	16180	4.9	16210.	8.5	—1100?	16227*	8.9	—1100?						
DN Gem	F	19476	3.5	19481	5.3	—1680	19525	7.0	—2160	19492	5.6	—1850	19525	7.0	—2160
DQ Her	S	27794	1.8	27833	3.5	—500	27896	7.3	—440						
				27826	2.5	—1030:	27891	4.5	—940						
CP Lac	VF	28340	1.8	28341	2.2	—3050	28361	6.1	—3800	28343	3.5	—3200	28362	6.2	—3700
DK Lac	F	33304	5.4	33324	7.1	—2100	33337	8.3	—2390	33332	7.9	—2500	33429	8.5	—2950
HR Lyr	F	22300	6.5	22360*	9.0?	—1860	22403	9.7	—2520	22360*	9.0?	—1860	22403	9.7	—2520
GK Per	VF	15439	0.0	15445	2.0	—3600:	15474	4.4	—3080	15444	1.8	—3460	15494	4.9	—3820
RR Pic	S	24309	1.2	24436	4.1	—930	24545	4.6	—1610	24503:	4.6	—1450			
CP Pup	VF	30675	0.6	30679	2.5	—2000									
EU Sct	F	33132	8.4	33164	11.0	—1100	33176	11.9	—1100						
					dm			dm			dm			dm	
Average:	VF				1.30	—2700		4.17	—3280		1.70	—3100		4.53	—3660
	F				2.56	—1900		3.80	—2140		2.50	—1840		3.33	—2150
	S				1.92	—1090		2.42	—1270		3.4	—1450			

* First record; probably not first appearance.

did for DN Gem, DQ Her, V 356 Aql and RR Pic), apparent oscillations may be associated with changes in the intensities of the components.

4. The Orion Spectrum

The fourth absorption system that can usually be identified is the so-called Orion spectrum, characterized by lines of He I, O II, N II, and C II; it may lack the Balmer lines. It tends to be of higher velocity displacement than previous systems, and may compete in intensity with the diffuse enhanced spectrum. Occasionally, as for DN Gem, it may coincide in wavelength with the diffuse enhanced spectrum; one system, identified in Nova Herculis as an Orion spectrum, lay between the principal and diffuse enhanced spectra in velocity, but another Orion system of greater wavelength was also found.

An important feature of the late stages of the Orion spectrum is the N III pair at 4097, 4103. The great persistence of these lines is no doubt due to the fact that they are seen within the wide bright Balmer line Hδ. The lines 4603, 4620 N V, observed in the late Orion spectra of a few novae, probably persist because they lie in the wing of 4640 N III. Occasionally the Orion absorption spectrum is well enough defined to be classified; that of D Q Her (smaller velocity) was described by McLaughlin (1944) as B 1; the same class was assigned by Wyse (1940) to the Orion spectrum of EL Aql.

Data on observed Orion spectra are given in Table 10.7, and lifetimes of the various contributors are summarized in Table 10.8.

The Orion absorption spectrum is the one that may show the largest variations of velocity, which are especially well shown by the lines 4097, 4103 N III. These velocity variations are shown by V 603 Aql, DN Gem, V 356 Aql, DK Lac and DQ Her to be correlated with fluctuations of brightness, of which they are no doubt the principal cause. Greatest velocity is associated with minima of the light curve, and may be accompanied by weakening of the lines concerned. In V 603 Aql, all absorptions disappeared temporarily at the secondary minima, but in V 356 Aql the absorption spectra persisted through at least one of the deepest minima.

The fluctuations of several novae are further marked by changes in the relative intensities of the absorption systems. At the secondary minima of V 603 Aql the diffuse enhanced spectrum weakened relative to the Orion spectrum; the opposite effect appeared at the secondary maxima.

TABLE 10.8

Duration of Orion Absorption Spectrum

Star	Type	Orion Spectrum					N III Spectrum					N V Spectrum					Orion	N III	N V
		First		Last		V	First		Last		V	First		Last		V	Duration in Days		
		dt*	dm*	dt	dm	(km/sec)	dt	dm	dt	dm	(km/sec)	dt	dm	dt	dm	(km/sec)			
V 356 Aql	S	51	1.4	63	-0.3	—1100											12		
V 368 Aql	F						(26)	2.9	32	3.2	—1950							(6)	
V 603 Aql	VF	2	0.9	24	3.8	—2500	4	1.6	38	4.3	—3050	21	4.2	63	4.8	—4010	22	34	42
T Aur	S	(86)	3.5)			—1200													
V 450 Cyg	S	(86)	(1.1)	(90)	(2.0)	—1230													
V 476 Cyg	F	16	2.9	41	5.7	—2570						20	3.4	36	5.1	—2480	25		16
DṀ Gem	F	(30)	(3.6)	(47)	4.0	—1100													
DN Gem	F	5	1.8	49	3.5	—1920	16	2.1	49	3.5	—2000	39	3.5	49	3.5	. .	44	V33V	10
DQ Her	S	39	1.7	102	5.5	—470											63		
		32	0.7	97	2.7	—980											65		
CP Lac	VF	1	0.4	21	4.3	—3400	3	1.7	22	4.4	—3450						20	19	
DK Lac	F	20	1.7	33	2.9	—2240	28	2.5	125	3.1	—2720						13	97	
HR Lyr	F	(60)	(2.5)	(103)	(3.2)	—2190						(103)	(3.2)	. .		—2520			
GK Per	VF	6	2.0	35	4.4	—3340	5	1.8	55	4.9	—3640						29	50	
RR Pic	S	127	2.9	236	3.4	—1270	194:	3.4			—1450						109		
CP Pup	VF	4	1.9	. .	. .	—2000											. .		
EU Sct	F	32		44													12		
Average:	VF	3	1.3	27	4.2	—2810	4	1.7	38	4.5	—3350	21	4.2	63	4.8	—4010	14	34	42
	F	14	2.1	41	4.0	—1850	22	2.3	69	3.3	—2220	30	3.4	42	4.3	—2520	27	47	12
	S	70	1.7	132	1.9	—1156					—1450						62		

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* From maximum.

The system of bright lines associated with the Orion spectrum is distinctive. They are always wide and diffuse, and their presence and character are best seen at secondary minima of the light curve. Most prominent of all is the so-called "4640 emission", produced by the N III multiplet near that wavelength, but the characteristic Orion emission also includes 4995, 5680 and 5950 N II, 4097, 4103 N III, 3484 and perhaps 4058 N IV. These lines are all involved in the "nitrogen flaring" shown by many novae, notably by DN Gem, DK Lac and EL Aql. These very broad nitrogen lines can also be seen, underlying the narrower emissions, in late spectra of T CrB, RR Pic and RR Tel; in the last of these stars there is a suggestion of a WN spectrum underlying the high-excitation bright-line metallic spectrum. For stars like DN Gem and V 603 Aql, which oscillate in brightness, the broad flaring bands tend to dominate the maxima and the narrower bright lines appear at the minima.

The so-called "4640 stage" of the bright line spectrum persists after the absorptions have disappeared, and overlaps the nebular stage, in which forbidden lines develop and finally become dominant.

TABLE 10.9

APPEARANCE OF CHARACTERISTIC BRIGHT LINES

Type	VF, R		VF		F		S	
Lines	dt*	dm*	dt	dm	dt	dm	dt	dm
[O I] neb.	3	1.3	6	2.0	4	1.9	59	2.6
[O III] aur.	5	1.8	22	4.2	29	2.9		
[O III] neb.	10	2.1	31	4.8	44	3.4	124	3.7
[N II] aur.	3	1.3	12	2.9	16	2.2	76	2.9
He I	2	0.8	10	2.7	4	1.9		
He II	8	1.6	14	3.4	32	3.0	113	3.4
[Ne III]	44	4.7	32	5.5			266	3.9
[Ne IV]			80	5.3				
[Ne V]			315	8.2				
Fe II	(13	5.0)					110	2.3
[Fe III]							266	3.9
[Fe V]							419	6.8
[Fe VI]							419	6.8
[Fe VII]			(219	4.4)			419	6.8
[Fe X]	50	4.6	(8	3.6)	(16	2.5)		
[Fe XIV]	50	4.6	(13	5.0)				

* From maximum

As shown by Table 10.8, the Orion stage begins between 1 and 2 magnitudes below maximum light, and ceases about three magnitudes below maximum for fast novae, about one magnitude for slow novae. Near the time of disappearance of the Orion stage the Helium II flash, the [O III] auroral flash and the [O III] nebular flash occur almost simultaneously or in quick succession. The principal absorption lines vanish very soon afterwards. In fact this stage is a turning-point in the history of the spectral development, marking the time when ejection through the photospheric layers virtually ceases, and the size of the effective photosphere contracts sharply so that no readily observable continuum is seen. At the same time the excitation rises, presumably because the falling opacity of the outer layers leads to greater transparency to short-wave radiation, and at the same time the diminishing density and increasing dilution permit the appearence of the forbidden lines, and usher in the nebular stage. At this point the Balmer decrement, which has tended to increase since maximum, falls noticeably and thereafter remains essentially constant, probably with the "nebular" values appropriate to the current conditions in the envelope.

The lines 4097, 4103 N III and 4603, 4620 N V may persist after the main absorption systems have died away, no doubt as a result of the pseudo-photospheres provided respectively by Hδ and 4640 N III.

5. The Nebular Stage

After the forbidden lines have appeared, the spectra of novae display their greatest diversity. The auroral line 4363 [O III] at first attains greater intensity than the nebular pair of the same atoms, but the latter increases in intensity and ultimately dominates the photographic part of the spectrum. For some novae the [O III] lines are very strong, but for others, such as T CrB, they may be weak; in that star 4363 appeared late in development, and the nebular pair was not observed at all. The very similar nebular pair 3869, 3968 [Ne III] appears in the spectra of most novae; sometimes it is weak, as in V 603 Aql, sometimes, as in GK Per, it is stronger than the corresponding [O III] pair.

Even greater diversity is displayed by the successive forbidden spectra of iron. The lines of [Fe II] appeared in the early nebular stages of DQ Her, T Aur and RR Pic, and in course of time their intensity exceeded that of Fe II. This was even more striking in the late spectrum of RR Tel, where five years after the outburst the [Fe II] lines recalled those of the extremely slow, abnormal nova η Carinae. But [Fe II] lines are not confined to slow novae; they were conspicuous in the early spectrum of the very fast, bright CP Pup. Lines of [Fe III] appeared after an interval in the spectra of RR Pic and DQ Her, but not CP Pup. Still later, the lines of [Fe V], [Fe VI] and [Fe VII] were found in RR Pic and DQ Her, appearing nearly simultaneously. Weak lines of [Fe VII] were shown also by the fast recurrent nova RS Oph and the slow recurrent nova T Pyx. Finally, the line 6374 [Fe X] was very strong in the spectrum of RS Oph, present but weaker in T CrB and T Pyx, and was observed in the early spectra of CP Pup and (much weaker) in those of CP Lac and V 603 Aql; it has been suspected in some other fast novae. The line 3987 [Fe XI] is recorded for RS Oph, and 5303 [Fe XIV] for RS Ophiuchi, T CrB and T Pyx, but much weaker than [Fe X]. We note that the [Fe XIV] line is much stronger in the solar corona than the [Fe X] line, and the [Fe VII] lines are not seen; at present the absolute intensities of the coronal lines in the sun and these various novae have not been critically compared. No conclusions concerning actual abundances of these or other atoms that give forbidden lines in the nebular stages of novae can be drawn until we know more about the relevant atomic constants than we do at present.

The widths of the lines in the nebular stage are such as to associate them (on the assumption of unchanged velocities) with the principal spectrum; they may, however, have weak wings that associate them with the Orion spectrum.

Although the nebular stage is usually associated with a fairly steady fall in the total brightness of the nova, there are doubtless some fluctuations of the continuum still going on; DK Lacertae, for example, experienced several sharp rises of brightness, accompanied by changes of the relative intensities of bright lines and flaring of N III long after the observed absorptions had faded away. During such temporary widening of the N III lines, the nebular [O III] lines and also 4686 He II tend to fall in intensity, and to increase again as the flaring ceases. Such changes were shown by V 603 Aql and GK Per.

After the forbidden lines have come to dominate the spectrum, they too in time decrease in intensity; the auroral lines weaken first, and later the nebular lines; these changes can be watched most easily for the atoms [N II] and [O III].

TABLE 10.10
Lines in Spectra of Old Novae

Star	Years since Maximum		H 4101	H 4340	[C III] 4363	He I 4471	4517	N III 4610	N III 4640	He II 4686	H 4861	[O III] 4967	[O III] 5007	Continuum	Ref.
V 841 Oph	F	112	..	..	..	..	..	..	..	..	..	..	..	str. violet	1
Q Cyg	F	58	tr ?	tr ?	..	..	..	..	..	..	tr ?	..	..		1
T Aur	S	45	tr ?	..	..	..	..	..	..	tr ?	..	..	..		1
V 1059 Sgr	F	38	..	..	..	..	..	..	..	..	..	..	..	str. violet	1
GK Per	VF	36	5	6	..	1	..	..	..	6	4	..	..		1
V 603 Aql	VF	32	3	4	..	1	..	..	(1)	(2+)	(2+)	..	..		2
DI Lac	F	31	tr ?	..	..	..	..	..	..	tr ?	..	..	..		2
DM Gem	F	30	..	..	..	..	..	..	..	..	..	..	..		2
DI Lac	F	26	..	..	..	..	..	..	..	..	..	..	..	str. violet	1
T Aur	S	22	2	3	..	..	..	tr	1	2	2	..	..		3
DN Gem	F	21	1—	1—	..	..	..	..	..	1—	1—	..	..		2
WZ Sge	F, R	21	..	..	..	..	..	..	..	..	..	..	..	str. voilet	1
V 476 Cyg	VF	18	2	2	..	..	..	..	..	2	2	..	..		4
V 1017 Sgr	F, R	17	..	..	..	..	..	..	..	..	..	..	..	str. violet	1
HR Lyr	F	17	..	..	..	..	..	..	..	..	..	..	..	str. violet	1
T Pyx	S, R	16	2	2	..	..	..	..	..	10	3	..	1		1
GK Per	VF	12	2	3	..	..	tr ?	tr	1	5	2	..	..		3
V 603 Aql	VF	8	tr ?	tr ?	..	..	tr ?	..	tr	tr	tr	..	..		4
V 476 Cyg	F	7	tr	tr	tr	..	..	..	tr	tr	tr	vs	vs		4

1. Humason, 1938, Ap. J., *88*, 228.
2. McLaughlin, 1953, Ap. J., *117*, 279.
3. Adams and Pease, 1914, Ap. J., *40*, 294.
4. Humason, 1927 P.A.S.P., *39*, 369.

During the nebular stage a few novae have been seen to display visible discs of expanding nebulosity, and as the latter expands and weakens in intensity, the central star can be studied. Observations of the nebular shells have been discussed in Chapter 4.

6. The Post-nova Stage

The spectra of a number of novae have been studied after their return to pre-maximum brightness. Details have been collected under individual novae in Chapters 3 and 4. In table 10.10 the data are arranged in order of interval since maximum, the latest available date being chosen for such stars as GK Per and V 476 Cyg. The intensities are as published, and therefore not all on the same scale.

For the longest intervals, on the whole, the emissions tend to be the weakest; the large intensities observed for GK Per after 36 years and V 603 Aql after 32 years may stem partly from the surrounding nebulosity, though for the former star they are given separately by Humason for star and nebula. The two slow novae seem to lag behind the others, but the intervals, to be on the same scale as for fast novae, should be divided by a factor of about 5.

The lines of hydrogen and ionized helium are the most persistent; the very early disappearance of the forbidden lines is noteworthy. We recall for comparison, that V 603 Aql had a pre-maximum spectrum that was blue and showed no observable emission or absorption lines. Apparently after a century or so the average nova reverts to the same stage, but HR Lyr had already seemingly reached it after only seventeen years. It is not easy to decide whether some of the observed bright lines come from unobserved nebular discs or from the "star itself." However, the great width of the stellar bright lines of Nova Persei, for instance, and their persistent changes of intensity (coupled with the equally persistent changes of brightness) suggest that some sort of surface activity is still going on. This is also suggested for the old novae for which Walker (1954) observes rapid fluctuations of brightness, such as T CrB and DQ Her (in addition to the eclipsing variations of the latter). Whether even this surface activity ultimately dies away is not definitely indicated, but it seems possible. The earliest observations of the spectrum of T CrB did not indicate the high-excitation peculiarities that later heralded the outburst in 1946, as described in Chapter 3, but this star has no exact counterpart, and general conclusions should not be based on its behavior.

7. Summary

The foregoing brief description of the course of the nova spectrum is summarized in Table 10.11. The time and magnitude intervals have been compiled separately for the very fast, recurrent novae, the very fast, the fast and the slow novae.

TABLE 10.11

CHARACTERISTIC NOVA STAGES

Type	VF, R		VF		F		S		McLaughlin	
Stage	dt	dm	dt	dm	dt	dm	dt	dm	dt	dm
Maximum	0	.0	0	.0	0	.0	0	.0	0	.0
Diffuse Enhanced Spectrum Appears			1.0	0.4	4.0	0.7	15.5	2.3	0.16*	1.2
Orion Spectrum Appears			3.2	1.3	14	2.1	70	1.7	0.46	2.1
0 I flash	3	1.3	6	2.0	4	1.9	59	2.6	0.7	2.6
N III Absorption Appears			4	1.7	22	2.3	193	3.4	0.8	2.7
Diffuse Enhanced Spectrum Disappears			17	3.8	25	3.0	105	2.6	1.0	3.0
N II flash	3	1.3	12	2.9	16	2.2	76	2.9	1.25	3.3
N V Absorption Appears			21	4.2	30	3.4			..	..
Orion Absorption Disappears			27	4.2	41	4.0	132	1.9	1.25	3.3
He II flash	8	1.6	14	3.4	32	3.0	113	3.4	1.5	3.6
O III flash (aur)	5	1.8	22	4.3	29	2.9			1.6	3.7
O III flash (neb)	10	2.1	31	4.8	44	3.4	124	3.7		
Principal Absorption Disappears			32	4.7	40	4.6	184	3.1	2.2	4.1
N III Absorption Disappears			38	4.5	69	3.3	236	3.6	2.7	4.4
N V Absorption Disappears			63	4.8	42	4.3				

* Normalized

The table is arranged much like the one given by McLaughlin (1944), but omits some of his categories and includes some others. The intervals dt and dm in all but the two last columns are reckoned from maximum in days and magnitudes respectively. The two last columns contain the corresponding entries, averaged for well-observed novae, from McLaughlin's table; his value of dt is normalized to allow for relative speed of development. On the whole, the order of the entries and the average value of dm agree with his values, but more novae, for which the data are less complete, have been used for our table, so exact correspondence would not be expected.

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CHAPTER 11

EVOLUTIONARY AND THEORETICAL PROBLEMS

"It is only with the greatest reluctance," to quote ter Haar (1950) "that the present author writes about this subject," "At the most," in Kipling's words, "one can but thrust an impertinent pen into matters only properly understood by specialists."

The subject matter of the preceding chapters is, or ought to be, the basis for theories of novae. But acceptable theories must also blend into the current fabric of astrophysics and cosmogony, and not a few spring from the latter, rather than from the known facts about the novae themselves. This final chapter cannot present more than a superficial survey; complete and critical treatment would transcend our limits. Even so it would not be final, for the problems are unsolved, the conclusions tentative if not speculative.

Theoretical problems of novae may be considered in three groups, not quite mutually exclusive. First (best understood, though far from simple) comes the theory of the physical processes that go on in a stellar envelope in rapid expansion. Second come the problems of the "cause" of the outburst. Third, we consider the closely allied questions: what conditions brought this cause into play, how did the star come to be the site of such conditions, what role do they play in the stellar lifetime, and what are their sequelae? This third group of problems is so closely attuned to the current trends of cosmogony that it is in some danger of becoming their victim.

The physical processes in the stellar envelope have been discussed in Chapter 3, and only the second and third group of problems will now concern us. Each covers the field of explosive variables, from Type I supernovae to SS Cygni stars. As a necessary preliminary, let us survey what seem to be the relevant facts concerning these stars. We shall then present the salient information basic to assessment of their cosmic status, and a summary of the ideas of stellar development into which they must be fitted. Only then shall we be ready to summarize theories of the nova process, and of the past and future of the stars that undergo it.

PROPERTIES OF EXPLOSIVE VARIABLE STARS

The penetrating analysis by Zwicky (1940) defines the "integral properties," P_z, of novae: $L_{\max}$, the maximal luminosity; E_{vis}, the total visual energy radiated in the outburst; M_g, the material mass ejected; $\bar{v}$, the average expansion velocity; and a suitably defined lifetime, ζ, and frequency, ν. In addition we must specify the mass, luminosity, radius, and spectral properties of the pre-nova and post-nova. In Table 11.1 we collect such of these properties as can be regarded as known at present. We have added the interval N between outbursts for such as are recurrent.

TABLE 11.1

INTEGRAL PROPERTIES OF EXPLOSIVE VARIABLE STARS

Property	Supernova Type I	Supernova Type II	Common Nova	Recurrent Nova	Symbiotic Nova	U Gem Star
$L_{\max}$ (M_{pg})	—16.1	—13.9	—7.8	(—7.8)	—7	+5.5
E_{vis} (ergs)	10^{49}	10^{47}	6×10^{44}	10^{44}		6×10^{38}
M^g (solar masses)	10^{-1}	..	10^{-3}	5×10^{-6}		10^{-9}
v (km/sec)	10,000 ?	6,600	1000	600	100	
ζ (days above $m_{\max} + 2$)	30	70	2 to 400	3 to 60	400:	2 to 10
(total decline in years)	?	?	10 to 50	3 to 10	3:	0.1:
ν (per year, our galaxy)	1/200	1/40:	50	..	..	..
(total in our galaxy)	2×10^7 ?	10^8 ?	2×10^6 ?	10^4 ?	10^5 ? ?	10^5
N (years)	$\propto$	..	10^7 to 10^3 ?	20	3.5	0.2
Pre-nova: M (suns)	20:	..	0.2 to 2.0	?	?	?
L (M_{pg})	—4:	..	3 to 4	0	0	+9.5
(M_{bol})	? ?	..	0:	0:	—2:	+7.5:
R (suns)	? ?	..	0.2	6	60	0.03
Post-nova M (suns)	?	..	0.2 to 2.0	?	?	?
L (M_{pg})	[+6	..	3 to 4	0	0	9.5
R (suns)	? ?	..	0.2	6	60	0.03
Spectrum	?	?	O — B	F:	M:	B — A

Many of the data of Table 11.1 are quite uncertain. The values of $L_{\max}$ are documented in previous chapters. Those of E_{vis} are based on Whipple (1939) for supernovae, and on Gaposchkin (1939) for common novae and U Geminorum stars; similar values are given by Arp (1956) for novae in Messier 31. The ejected mass for supernovae of Type I is the estimate of Oort and Walraven (1956); higher masses were previously given by Minkowski (1942) and by struve (1954), and a lower mass by Schklovsky (1954). Ejected masses for common novae, all of the same order, were given by Ambarzumian and Kosirev (1933), Whipple and Payne-Gaposchkin (1936), Gordeladse (1937), Payne-Gaposchkin and Gaposchkin (1942) and Aller (1954), on general principles, from spectrophotometry of bright lines, and from absorption lines. The much higher masses derived by Mustel (1947) are omitted. The value for recurrent novae is the determination for RS Ophiuchi by Sayer (1948). That for U Geminorum stars is based upon Gordeladse (1938) and Greep (1942). Mean velocities, frequencies and lifetimes are taken or deduced from the data of earlier chapters. The properties of the pre-novae and the post-novae are taken from the discussion of Chapter 1. For the masses of these stars we refer to the very plausible arguments of Strömgren (1939); as the pre-novae can be supposed not to be degenerate, their masses may be estimated within close limits by the mass-luminosity relation for suitable mean molecular weight. Probably these arguments are at least correct in making the masses of common novae neither very large nor very small; we regard such huge masses as 1000 suns, determined by Mustel (1948a) for DN Geminorum 1912, as unreal and improbable. The initial data for Type I supernovae imply a radical transformation of a massive star; if the pre-supernova was a white dwarf, they would have much lower values.

The integral parameters are important in themselves, and also in their relationships; discontinuous correlations, for example, would furnish a basis for subdivision into several groups. For instance, the "life-luminosity relation" was pointed out by Zwicky (1936); the more luminous the nova, the greater its "life," defined by the width of the light curve a certain number of magnitudes below maximum. However, within the group of the common novae, as Arp (1956) has shown, the shortest "life" (thus defined) goes with the greatest luminosity—an indication, in the writer's opinion, that strengthens our conviction that supernovae of both types, common novae and U Geminorum stars are separate groups and do not grade into one another.

To examine the table a little more closely: the maximal luminosity, emitted energy, ejected mass and average ejection velocity are all correlated, probably because they are all governed by the same phenomenon, whatever it is, that "causes" the outburst and determines its scale and intensity (as reflected by energy output, mass ejected, and velocity). However, the properties of pre- and post-novae are not all so correlated; minimal absolute magnitude is not correlated with the scale and intensity of the outburst, and minimal spectrum, for example, is not correlated with the scale and intensity phenomena or with the lifetime or cycle of the outburst.

Of particular interest is the relationship between the average cycle of a recurrently explosive star and the light amplitude and energy emitted in one outburst. For two recurrent novae (RS Ophiuchi and T Pyxidis) and the U Geminorum and Z Camelopardalis stars, the empirical formula:

$$\bar{A} = 2.00 + 1.78 \log \bar{P},$$

where A is amplitude in magnitude and P the period in days, was established in Chapter 8 (see page 251). The formula does not, however, represent the amplitudes and cycles of the "symbiotic novae."

The energy emitted in one outburst is a better index of the process than the amplitude (considered without relation to the duration of the maximum). Schatzman (1951c) obtained theoretically, on grounds to be mentioned later, the relationship:

$$P = k\,E/L,$$

where P is the average interval between outbursts, E the energy of one outburst in the observable region, and L, the minimal energy output per day; k is a constant whose theoretical upper limiting valued is 2.3. Correlations of this type were established by Greep (1942) for U Geminorum, and by Zuckermann (1954) for U Geminorum stars and novae, and although the data leave much to be desired, they appear to substantiate Schatzman's premise concerning the source of the outburst, and its essential similarity for U Geminorum stars and recurrent novae, as already adumbrated empirically by Kukarkin and Parenago.

These facts permit us to surmise that the explosive phenomenon that reveals the several types of nova can arise in stars of different kinds, probably in a variety of ways, very likely at different stages of a stellar life history. The next step in the enquiry involves placing the novae on the background of the whole stellar community.

COSMOGONIC PARAMETERS OF EXPLOSIVE VARIABLES

The important cosmogonic parameters include: (1) position of the pre-nova and post-nova in the Hertzsprung-Russell diagram; (2) distribution and (3) motion within the stellar system; (4) frequency relative to each other and to other types of stars. Information to be deduced from these data, and necessary to an understanding of the nova process, is (5) internal constitution and composition; and (6) population affiliation.

The information of Table 11.1 has all been presented in one or another of the preceding chapters.

TABLE 11.2

PRE-NOVA AND POST-NOVA IN RELATION TO HR DIAGRAM

Type	Pre-nova	Post-nova
Supernova Type I	Massive star?	White dwarf
Supernova Type II	Unknown	Unknown
Common Nova	Blue subdwarf	Blue subdwarf
Recurrent Nova	Yellow subdwarf? Blue subdwarf?	Yellow subdwarf? Blue subdwarf?
Symbiotic Nova	Red giant	Red giant
U Geminorum star	Blue subdwarf or Intermediate	Blue subdwarf or Intermediate

TABLE 11.3

DISTRIBUTION, MOTION, POPULATION AFFILIATION AND FREQUENCY

Type	Distribution	Motion	Population	Frequency* one in:
Supernova Type I	Spheroidal?	?	II	2×10^8
Supernova Type II	Flat?	?	I	10
Common Nova	Spheroidal	High vel?	II	2×10^4
Recurrent Nova	Spheroidal??	High vel??	II	10^7?
Symbiotic Nova	Flat?	?	I??	10^4?
U Geminorum	?	?	?	10^4 to 10^6

* Calculated from Table 11.1 on the assumption that our galaxy contains 10^{11} stars of Population II and 10^9 stars of Population I.

If Table 11.3 gives a just estimate, our galaxy contains more stars that have been supernovae than have been common novae; and the other types of explosive variables are still rarer. This apparently implausible result springs from the implicit assumption that all novae except supernovae of Type I are recurrent. If, as will appear later, the Type II supernovae are to be regarded as the source of the white dwarfs, the high estimate for the frequency of the former fits in with the requirements for stellar deaths pointed out by Schwarzschild and Spitzer (1953). We should also mention that (with the exception of the supernovae) the classes are not mutually exclusive; a star may, as Vorontsov-Velyaminov (1947) suggests, be successively a common nova, a recurrent nova and a U Geminorum star, the relative frequencies giving an idea of the rate at which the star develops. These questions cannot profitably be discussed at the present stage.

Conclusions concerning constitution and composition are more difficult to assess. Type I supernovae are generally conceded to be hydrogen-poor; their spectra, as discussed in Chapter 9, give no evidence of hydrogen, and the Crab Nebula, supposed to be the nebular remnant of a Type I supernova, also suggests poverty in hydrogen. Their richness in heavy elements suggests a constitution appropriate to very high internal temperature. The spectra of Type II supernovae seem to contain as much hydrogen as those of common novae.

The constitution of common novae, as discussed by Strömgren, (1939) points, despite their considerable density (about 100 times that of the sun) to non-degeneracy, and his calculations indicate that the physical properties of the pre-nova are compatible with the "Russell mixture." Evidence from the spectra of common novae is not conclusive on the hydrogen content of the whole star, since we see material that presumably comes only from superficial layers which may not be representative, and Öpik's (1954a) dictum should be kept in mind: "There is little mixing on the stars; on their surface, light elements acquired by accretion are floating. About the inside nothing is known." The same strictures do not apply to the spectra of supernovae, if the current idea, that the major part of the star blows off, is correct.

Definite statements on hydrogen content and constitution of the U Geminorum and Z Camelopardalis stars cannot be made either on the basis of their spectra. If they represent progress through the intermediate stage toward the hydrogenless white dwarf described by Öpik (1954b), we might expect that they are poorer in hydrogen than common novae; but this is inference, not observation. Even the U Geminorum stars do not fall as low as the white dwarf sequence described by Luyten (1952) as parallel to the main sequence and 8 to 9 magnitudes below it; but they are approaching it.

STELLAR STRUCTURE AND EVOLUTIONARY PATTERNS

Our current picture of stellar evolution is based on the structure of the Hertzsprung-Russell diagram and the relative frequencies of the component stars, as embodied in the Hess diagram (see, for example, Payne-Gaposchkin, 1951a). The changing pattern of both diagrams as we pass from extreme Population I (typified by the limiting galactic cluster) to the globular cluster pattern of Population II provides the background for theories of stellar structure which in turn fix the course of stellar evolution.

We may pass quickly over the early stages of stellar development, since they do not seem to involve the explosive variables. These stages are typified by the galactic clusters, which display some part of the main sequence and often include red stars of giant dimensions. The members of the double cluster in Perseus include a section of the main sequence that extends upward to about absolute photographic magnitude —6, and also a group of equally luminous red supergiants, first pointed out by Bidelman (1943). Very young stars, still contracting homologously, are considered by Schatzman (1954c) to spend between 10^5 and 10^6 years in moving from the right of the HR diagram toward the main sequence. A similar evolutionary track, occupying about the same time, is illustrated by Struve (1955) from the unpublished work of Henyey. Such stars are found by Walker (1956) in NGC 2264.

The red giant stars displayed by galactic clusters such as the Hyades probably represent, as suggested by Miczaika (1954), stars that have begun to move away from the main sequence. Accurate photometric studies of a number of such galactic clusters by Johnson (1954) arranges them in a series terminating in Messier 67, whose HR diagram shows an "advanced" pattern for a system assigned to Population I.

The theoretical basis for these evolutionary tracks involves the whole problem of stellar structure and stellar energy sources, whose discussion would be out of place here. The thermonuclear reactions in the first rapid contractional stage are such as can proceed at moderate internal temperatures, described, for example, by Salpeter (1954); see also Fowler (1954). While on the main sequence, the star subsists on the carbon cycle and/or the proton-proton reaction. But when the star leaves the main sequence and moves again to the right, homogeneous models based on these reactions can no longer represent it. Nonhomogeneous models, first suggested by Opik (1938), have been partially successful in representing the giant stars; see, for example, Hoyle and Lyttleton (1942, 1949), Gamow and Keller (1945), Li Hen and Schwarzschild (1949), and Sandage and Schwarzschild (1952). These models, built around an isothermal, hydrogen-exhausted core, become increasingly distended; the hydrogen-rich envelope expands, the star becomes over-luminous, the temperature at the surface declines, and the core contracts. The isothermal core, however, cannot include more than 12% of the mass of the star, as shown by Schoenberg and Chandrasekhar (1942). As the core continues to contract its temperature rises, and at 10^8 degrees begins to liberate energy from the reaction, described by Öpik (1951) and Salpeter (1952), in which three alpha particles combine to form a nucleus of C^{12}. The evolutionary track turns sharply upward at this point, and the resulting HR diagram is shown by Sandage (1954) to simulate very well the lower main sequence and red giant branch of the color-magnitude array of a globular cluster such as Messier 3. Theory has up to now carried the accurate prediction of the evolutionary tracks no further, but Sandage is able to construct them empirically from the remainder of the color-magnitude array of the cluster. They turn again sharply toward the blue with little change of luminosity and pass through the pulsating (RR Lyrae) stage. The further course of development is at present only guesswork, but we may picture it turning downward along the subdwarf sequence, and finally reaching the degenerate white dwarf stage.

Probably all the pre-novae fall somewhere on this conjectural section of the curve (with the possible exception of the Type I supernovae). The abrupt explosion must be related to instability that arises from internal changes of structure and temperature. The nova process carries the star, probably by successive steps, to eventual degeneracy. If the mass is low, the history can be that of a recurrent nova of shortening cycle and diminishing violence. But, as shown by Schoenberg and Chandrasekhar (1942) a star of mass greater then about 1½ suns cannot become degenerate unless it loses the excess mass; possibly in its final stages, as Chandrasekhar (1951) suggests, such a star becomes a supernova.

The evolutionary theories and conjectures just outlined are those with which acceptable theories of explosive variables must harmonize. Evidently stellar explosions are now regarded as belonging to the final stages of a stellar career (always remembering that the "age" of a star is not to be reckoned by years but by progress along its evolutionary track—faster, *ceteris paribus,* for massive stars). The ultimate stage, the white dwarf, is probably the end of many, if not all novae. But we cannot be sure that all white dwarfs have had an explosive past; as Schwarzschild and Spitzer (1953) point out, the number of galactic white dwarfs requires a larger "stellar death rate" by explosion than appears currently to be taking place.

THEORIES OF NOVAE

A phenomenon so spectacular could not fail to inspire a succession of theories. We shall pass over those of merely historical interest, involving, for example, collisions of stars with nebulae and meteor swarms, and begin our brief survey with the time when the theory of novae was first related to stellar constitution.

Allusion has already been made to the discussion of the physical condition of the pre-novae by Strömgren (1939), which he prefaced to the first account of the theory later published by Biermann (1939). The pre-nova is regarded as a hydrogen-poor subdwarf with contraction the main source of energy. The outburst is attributed to the liberation of the energy of ionization in a zone of instability; 10% of the star's mass is ejected, the radiated energy is about 10^{44} ergs, and it comes from a region in which the temperature is about 10% of the star's central temperature. The theory is physically consistent, but the essential requirement of hydrogen-poverty is probably not fulfilled, and the ejected mass seems excessive.

A totally different theory advanced by Hoyle and Lyttleton (1943) linked the nova process to their binary picture of Cepheid variation as modified by accretion: rotational instability was supposed to follow the consequent separation of the components, and to result in the violent expulsion of material. This theory, as ter Haar (1950) points out, derives novae from stars to the right of and above the main sequence, instead of to the left and below it, where the pre-novae certainly lie. The double star theory of Cepheid variability has moreover not been generally accepted. As mentioned in an earlier chapter (p. 128), at least one nova is now a component of a binary, and it is not impossible that all novae may now be members of binaries, rather than that binaries turn into novae. In his discussion of evolutionary processes in close double stars, Struve (1950, p. 234) remarks: "There is no reason why the process [of development of W Ursae Majoris stars, close binaries] should become explosive in character... We cannot definitely exclude [this] evolutionary path, but we consider it highly improbable."

Rotational instability of a single star is further explored by Hoyle (1946, 1947), who regards the P Cygni stars, W stars, common novae and supernovae as a continuous sequence. A collapsing stage is reached by stars that have exhausted their available hydrogen supply; supernovae are stars of small angular momentum which must collapse greatly before rotational instability sets in; the larger the angular momentum, the sooner is instability reached, and a continuous series of exploding stars is thus envisaged. The undoubted distinction between supernovae and common novae makes this concept seem too simple, but it represents a step in the direction of the picture now accepted, and harmonizes with the current evolutionary pattern. Probably, as we shall see, it gives the best account of Type II supernovae.

So far the theories described have, like Biermann's, not required thermonuclear reactions at all, or have not specified particular ones. Even though the stellar life-history has not yet been followed theoretically throughout the whole HR plane, it is already evident that when a star begins to tap a new energy source, the direction of the evolutionary path will alter, perhaps abruptly. This idea is as old as, if not older than, the conceptions of "giant stuff" and "dwarf stuff" suggested by Russell, Dugan and Stewart (1927) in an attempt to account for the "reversed 7" of the HR diagram at a time before the thermonuclear processes in stellar interiors had been identified.

The fact that pre-novae (except Type I supernovae) seem to be confined to the part of the HR plane below the main sequence but above the white dwarfs encourages an attempt to find the "cause" of the nova outburst in the structural properties and thermonuclear processes that are, or may be, characteristic of this domain. Massewitsch (1954), see also Massewitsch, Matveev and Tulenkova (1951), considering only the carbon cycle and proton-proton reaction as energy sources, estimated that "essential perturbations" of a stellar model with a radiative envelope and convective core might result in nova outbursts at intervals of about 10^5 years for a star with a mass of 10 suns. We regard one solar mass as a more likely value, in which case the interval between outbursts would be of the order of 10^9 years, and the recurrent stage of novae could not be represented. Gurevich and Lebedinsky (1947) have worked out a theory for a star with a spherical carbon-cycle core and an outer layer in which low-temperature thermonuclear reactions are going on. Such a model requires the nova process to take place early in the star's history, and as it stands is therefore inacceptable. If adapted to reactions at higher temperatures, it might represent the conditions for a nova outburst.

The most satisfactory discussion of the nova process is that due to Schatzman. His analysis of the stars close to the white dwarf area of the HR diagram (1947a, 1947b, 1951a) developed methods of determining the hydrogen content and energy generation for such stars, among or near which the pre-novae are to be found. Schatzman (1948c, 1949b) next developed the hypothesis that a shock wave, propagated within the star, is responsible for the ejection of energy from a nova. He calculated that 0.220 grams of hydrogen per gram of ejected material must be converted into helium. This conception, that the nova explosion is essentially a hydrogen bomb, was carried further by Schatzman (1950, 1951b, 1951d), who showed that the He^3 atom could act as detonater, most probably by means of the reaction:

$$He^3 + He^3 \rightarrow He^4 + H^1 + H^1.$$

Sufficient He^3 can accumulate, according to Schatzman (1951d) by means of the reactions:

$$H^1 + H^1 \rightarrow D^2 \text{ and } D^2 + H^1 \rightarrow He^3.$$

He estimates that 10^{-2} grams of He^3 per gram of matter, at density 1000, will start a shock wave with a velocity of 700 km/sec and a temperature of 10^8 degrees.

Schatzman (1951c, 1951d, 1953a, 1953b, 1954a, 1954b) has since considered the vibrational instability due to the processes just described, and obtained a theoretical expression that relates the interval between recurrences of novae, the total energy liberated in one explosion, and the rate of energy output between explosions. This prediction has been verified for recurrent novae and U Geminorum stars by Zuckermann (1954), incidentally pointing to a similar process for all these objects. An interesting sidelight is the suggestion by Schatzman (1953c, 1954b) that "pulsating" and explosive variables may have an underlying similarity: "The parallel that exists between the structures of SS Cygni stars, novae and periodic variables may be closer than appears at first sight... In both cases the oscillations are excited because the star is vibrationally unstable; but in the first case no mechanism intervenes to limit the amplitude of the pulsations... Novae and SS Cygni stars... only appear at a late evolutionary stage." For white dwarfs, on the other hand, Schatzman (1951d) considers that vibrational stability will be unaffected, because the He^3 will be very short-lived.

Besides operating in the required domain of the HR diagram, and employing thermonuclear reactions that are known and probable, the theories described by Schatzman (1951d, 1951e) furnish a link with the processes observed in the nova envelope. He points out that the liberation of 10^{40} ergs at the center of the sun would produce a shock wave that would transfer almost all the energy to the surface, since the transport of energy by a compressional wave is very efficient. Although these conditions cannot be realized within the sun, the corresponding theory has applications to novae. Schatzman (1951d) relates the energy carried by the wave, the Mach number, and the velocity of the shock; for instance, with an outburst energy of 10^{45} ergs, a velocity of 2000 km/sec, and the plausible value 16 for the Mach number, the temperature of the shell before ejection would be about ten million degrees, and the ejected mass, about 10^{-5} solar masses. There is an obvious field for application of the observed range of ejection velocities within the scope of this theory, which has not yet been published in detail.

The theory of shock waves will be a fertile approach to the nova phenomenon, as already suggested by Rosseland (1946). Calculations by Kopal and Lin (1951) and Carrus, Fox, Lin and Kopal (1951) have made a beginning in this direction; Witham (1953) has treated the spherical shock waves necessary to the nova application.

A purely qualitative idea of the behavior of a spherical shock wave reflected from the boundary of a spherical star can be obtained by analogy with the multiple reflection of a spherical sound wave from the interior of a spherical reflector, discussed by Wood (1898). The case where the origin of the wave is halfway between the center and periphery of the reflector, illustrated by Wood, shows elaborate cusping of the wave front after only a few reflections. The stellar case would correspond to the acoustical case with velocity that varied with distance from the center of the relector, and would be still more complex and involve more cusps. We can see, however, that waves originating at or near center of the reflector would not be cusped, and that the cusping would become more complicated, the nearer was the wave origin to the outside. If the analogy is applied to a nova, we are tempted to associate elaborate ring structures, such as those shown by V 603 Aquilae and CP Puppis, with highly cusped wave fronts, i.e., with disturbances that originated near the surface, and more symmetrical ejecta, such as that of DQ Herculis, with disturbances originating deeper within the star. Under the conditions of high density temperature that probably exist within the pre-nova, the velocities would be so high that a number of reflections would take place within a few hours. We recall the statement of Baade, quoted by Payne-Gaposchkin (1951b) that the whole "ring structure" for V 603 Aquila was ejected within six hours. Perhaps it is significant that the novae that show the most pronounced structure in their ejecta (V 603 Aquilae, CP Puppis) seem also to have had the brightest maximal magnitudes, perhaps associated with shallower origin of the outburst than for less luminous novae such as DQ Herculis and RR Pictoris, which also had smaller ejection velocities and later (i.e., lower-temperature) pre-maximum spectra.

Although much work remains to be done, it seems that we are approaching a reasonably clear idea of the origin and course of the nova process, and of the stage of the stellar life history at which it can occur.

THEORIES OF SUPERNOVAE

More spectacular than common novae, supernovae have proved even more attractive to the theorist. Here we have the complication of at least two types of supernova, probably demanding different interpretations.

Just as for common novae, external agencies have been invoked to account for supernovae. Whipple (1939a, 1939b) discussed the frequency and distribution of supernovae, and concluded that collisions between stars were a promising, if not a proven hypothesis. However, Zwicky (1940) argued convincingly against the collision hypothesis: that it requires the frequency of supernovae to be a monotonously decreasing function of maximal luminosity, in conflict with observation; that the numbers of supernovae should increase rapidly toward the centers of galaxies, which apparently they do not; that their light curves are too uniform to be produced by stellar collisions; and that the similarity of their spectra is also an adverse fact.

Baade and Zwicky (1934a, 1934b, 1934c) see also Zwicky (1936, 1939), had already advanced a theory of supernovae that involved the sudden collapse of a star to a neutron core, and Gamow (1939) and Gamow and Schoenberg (1951) advocated collapse theories involving liberation of neutrinos, as did Bouvier (1952). These theories associate supernova outbursts with cosmic rays, which will be mentioned in the next §, devoted to the observable ejecta of supernovae.

Very different ideas of the origin of supernovae were advanced by Unsöld (1948) and by von Weiszäcker (1947), who associated the outbursts with the birth of double stars; Struve (1950, p. 245) mentions, however, that the latter no longer considers the idea valid; von Weizsäcker had already criticized the idea of collapse to a neutron star on grounds of the necessary change of angular momentum. The neutron core theory was also criticized by Johnson (1946), on the grounds that the process was not specified, and that a successful treatment must consider both the reaction velocity and the transport velocity; both objections are met by the theory of Schatzman mentioned below.

The suggestion that a supernova may originate from the rotational instability of a massive hydrogen-exhausted O or B star, also made by von Weizsäcker (1947) and by Hoyle (1946, 1947) has more plausibility. Such a star, if above the Schoenberg-Chandrasekhar limit, may, as Chandrasekhar (1951) suggests, become a supernova, and rotational instability provides the mechanism. Probably, as ter Haar (1950) and Mestel (1952) remark, this theory is appropriate to the supernovae of Type II, which are very likely associated, as we have seen, with Population I, and show apparently normal atomic abundances in their spectra.

Schatzman (1946, 1948a, 1948b) advanced the thermal blowup of a white dwarf as the origin of the Type I supernova, and Mestel (1952) has discussed the same process, but the conditions and detailed process are very different in the two theories. The blowup of a star with an exhausted isothermal core is likewise described by Öpik (1953, 1955); a white dwarf, in his picturesque phrase, remains as a "stellar stump."

Supernova outbursts of Type I, however, are more probably to be associated with thermonuclear reactions. Zwicky (1940) considered that the very close similarity of the declining light curves of such supernovae points to an association with a nuclear reaction of appropriate half-life. Such a reaction was seen by Borst (1950, 1952) in the decay of ^{7}Be, which might be produced at a central temperature of 2 or 3×10^9 degrees. Greenstein and Minkowski (1953), however, remark that this argument loses force if much of the beryllium is ionized, as it may well be.

The closely similar exponential declines of the light curves of several supernovae (such as that in IC 4182, B Cas, and Kepler's nova) had been shown by Baade (1945) to correspond to 0.0137 mag/day, corresponding to a half-life of 55 ± 1 days, compatible with the decay of Be^7. But, as was pointed out by Baade, Burbidge, Hoyle, Burbidge, Christy and Fowler (1956), it would also be compatible with the decay of Sr^{89} and of Cf^{254}. Whereas the beryllium and strontium reactions, which involve capture or emission of an electron, release from 0.1 to 1 Mev, the californium reaction is a spontaneous fission, which would liberate about 200 Mev, and the fission of only 10^{29} grams of Cf^{254} would release 10^{47} ergs. The total energy of the supernova outburst is estimated at from 10^{49} to 10^{50} ergs, but during the exponential decay the output is about 10^{47} ergs.

Baade and his collaborators envisage the formation of californium as a consequence of a large neutron flux, the element being mainly built up from the Fe abundance peak by successive neutron captures. *Implosion* of the inner regions of the star is supposed to raise the temperature in the outer interior of the star to about 10^8 degrees; the capture of protons by light nuclei in the hydrogen-deficient interior would account for the liberation of about 10^{17} ergs/gram, enough radiation to account for the total emission. The californium nucleus is the only one of appropriate half-life known that decays by fission, rather than by relatively low-energy alpha-emission.

The supernovae of Type II are regarded as not being hydrogen deficient, at least not to nearly the same extent as Type I supernovae; in this case Cf^{254} would not be built up, but the capture of protons with the release of gamma rays would be intense enough to provide the necessary high temperature, and to confer a velocity of the order of 5000 km/sec.

Apparently the visible radiation of the Type I supernovae is not of thermal origin. The only identified radiation in their spectra, according to Minkowski (1939) is relatively narrow bright [O I]; an early suggestion is revived, that the enigmatic Type I spectra are affected by strong molecular bands arising from compounds of carbon, nitrogen and oxygen, which, with neon, are regarded as present in about equal abundance with protons and alpha particles in the interiors of pre-supernovae.

As with the common novae, we thus appear to have the makings of plausible theories for both types of supernova. It will be seen that there is no *prima facie* reason why all Type II supernovae should be fainter than all Type I supernovae, and the apparent occurrence of a few rather bright ones among the former does not present a serious difficulty, as it would do if both types were to be associated with the same process.

The ejecta and sequelae of supernovae form so large and special a subject that they will be described in a separate §.

SEQUELAE AND EJECTA OF SUPERNOVAE

The masses of the known ejecta of supernovae have already been discussed. Because the material ejected from supernovae plays an important part in theories of the origin of stars, some further discussion is called for.

The possibility that the great "Cygnus loop" may be the remnant of a supernova was discussed by Zwicky (1940). He pointed out that the gaseous shells, initially of much greater speed, may have shared their kinetic energy with interstellar material and thus been slowed down. The mass of this interstellar material might, as he pointed out, considerably exceed that of the original ejected material. For example, the present volume of the Cygnus loop may be taken as 5×10^{56} cm^3; if the density is 10^{-25} g m/cm^3, its mass is 5×10^{31} g. At its present velocity it would have taken 160,000 years to expand to present dimensions, but allowance for the deceleration makes the probable interval since the outburst less than 10,000 years. Zwicky believes that the original velocity may have been between 15,000 and 100,000 km/sec; the deceleration of the charged gaseous masses and the electric potential could have produced cosmic rays. Many other discussions of the possible production of cosmic rays by supernovae have been made, for example, by Cernuschi (1939), Hoyle (1946), ter Haar (1949), Wolfe, Routly, Wightman and Spitzer (1950), Saha (1951), Shklovsky (1953), Ginsburg (1953) and by Baade, Burbidge, Hoyle, Burbidge, Christy and Fowler (1956).

Oort (1946, 1951) has discussed the expansion of the Crab Nebula and the possible deceleration by interstellar material. He concludes that in twenty to thirty thousand years it will resemble the Cygnus loop, and considers it "tempting to imagine" that the nebula still has the temperature of the interior of the exploded star.

The idea that the ejecta of supernovae may sweep up large amounts of interstellar material, even many thousands of solar masses, has been developed by Öpik (1954b, 1955). He suggests that a supernova explosion may lead to the formation of an expanding galactic cluster such as that described by Blaauw (1953), and even conceivably (in the far past) of the globular clusters. He points out that sheets of interstellar dust could be swept up, thus providing the necessary centers of nucleation. The dust-gas ratio required for star formation is discussed by Strömgren (1955); Schatzman (1949a) has shown that the density of the dust component should be approximately equal to that of the gas. The ideas developed by Öpik, though still in the qualitative stage, appear to complement the requirements of Ambarzumian (1954) for the very properties of the pre-stellar matter required for the origin of stars.

The second aspect of the post-supernova material is its chemical composition. The fact that it is relatively rich in heavy elements (which may account for the relative hydrogen-poverty of the "young" Population I stars) is attributed to the thermonuclear reactions that have gone on in the highly condensed pre-supernovae (presumably those of Type I). Gold (1954) considers this composition as favorable to the supernova theory of the generation of the elements. This theory was first discussed by Hoyle (1946); Shklovsky (1952) advanced arguments in its favor, apparently in connection with the theory of supernovae advanced by Mustel (1952) which, as it seems to involve implausibly large masses, we have not discussed. A summary of the bearing of the theory on the origin of the elements is given by ter Haar (1949) and by Podolanski and ter Haar (1954).

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