8. THE EXTREMELY RAPID LIGHT-VARIATIONS OF OLD NOVAE AND RELATED OBJECTS

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It has been recognized in recent years that extremely rapid light-variations occur in certain stars. Flares lasting only a few minutes have been observed in a number of dMe stars [1]. Flaring has also been observed in the W Ursae Majoris star U Pegasi [2]. Rapid variations in light have been found in some T Tauri stars [3], in the U Geminorum variable AE Aquarii [4, 5], and in the short-period eclipsing binary UX Ursae Majoris [6, 7, 8]. Observations during the past two years at the Mount Wilson Observatory have shown that extremely rapid and apparently continuous variations in light occur also in many of the old novae and in a number of related stars.

The investigation of these stars was undertaken following the discovery of rapid light-variations in MacRae $+43°$ 1 [9], whose spectrum resembles that of an old nova [10]. The light-variations of MacRae $+43°$ 1 appear to be completely random and have cycle lengths ranging from 1 to 30 min. The star has been observed to vary in ultra-violet light by as much as 0·4 magnitude in 5 min. The range of the fluctuations varies with wave-length, the amplitude in the yellow and blue being 0·7 and 0·8, respectively, of the amplitude in the ultra-violet.

To date, thirteen old novae, three possible novae, five nova-like variables, four U Geminorum stars, two binary Mira-type variables, and one white dwarf have been examined for rapid variations in light. Some traces of short-period variability similar to that of MacRae $+43°$ 1 were found in all of the novae, the possible novae, the U Geminorum stars, and the Mira-type variables. Little or no variation was found in four of the nova-like variables or in the white dwarf. The details of the observations are given in Table 1. Since the present programme was of an exploratory nature, not enough observational material has been obtained for most of the stars to permit a complete analysis of the light-variations. Consequently, the activity of the stars has been described in Table 1 merely by giving for each object the maximum variation in light during the period of observation, the dispersion of points measured at equal time intervals

https://doi.org/10.1017/S007418090001860X Published online by Cambridge University Press

along the light-curve about the level of mean light during the observations, and the average time interval between maxima.

Table 1 indicates that the most active of the old novae is T Coronae Borealis. Sections of Brown Recorder sheets showing the light-variations of this star in the ultra-violet on 30 May and 1 June 1954 are reproduced in Figs. 1 and 2, respectively. Near ultra-violet spectra having a dispersion of 83 Å/mm. were obtained by A. J. Deutsch during several of the photo-electric runs on T Coronae. These spectrograms would have shown any pronounced changes in the line spectrum that might have accompanied the variations in light. Since no changes in the appearance of the spectrum were found, the light-variations cannot be attributed to fluctuations in the strength of emission lines or in the continuous Balmer emission. The light-variations must result from fluctuations, presumably of a thermal nature, in the strength of the continuous spectrum. During the spring of 1954, the brightness of the nova component was such that it dominated the blue and violet regions of the spectrum. It was found that even though the amplitude of light-variation was very large in the blue and ultra-violet, there was practically no trace of activity in yellow light. This, together with the spectroscopic results, is consistent with the hypothesis that (*a*) the system is composed of two distinct stars, and (*b*) only the nova component is responsible for the rapid variations in light.

The other old novae that were observed show varying amounts of activity. Two of them, Nova (T) Aurigae 1891 and Nova (WZ) Sagittae 1913, 1946, do not appear to show the extremely rapid fluctuations having periods of only a few minutes that were found in the others. These two stars, while they are definitely variable, behave in a much more leisurely fashion, exhibiting maxima only every 40 or 50 min. The degree of variability of the old novae does not appear to be correlated with the type of nova or the time elapsed since the outburst. There is also no correlation with the appearance of the spectrum, as given by M. L. Humason [11]. However, the spectra may have changed since his observations were made; to be certain whether or not such a correlation exists, spectra would have to be obtained concurrently with the photometric observations. There may be a correlation between the degree of short-period activity and the presence of long-period variations in light. The stars with the greatest amounts of short-period activity tend to be the ones which have been found to be variable from visual observations. It must be remembered that at present we know nothing about the 'secular' occurrence of these short-period variations. It may be that the differences in activity found in the different stars result primarily from long-term changes in the degree of activity of all the stars.

Table 1. *Observations of Old Novae and Related Stars*

Type	Star	Date (U.T.)	V (mag.)	B–V (mag.)	U–B (mag.)	Maximum variation during observation (mag.)	Dispersion (mag.)	Average interval between maxima (min.)	Interval observed (min.)	Notes
Novae	Nova (GK) Per 1901	1953 Oct. 28	12·96	+0·69	−0·56	0·20	—	(4·2)	21	1
		29	12·96	+0·74	−0·60	0·15	0·035	5·0	52	—
	Nova (T) Aur 1891	1954 Feb. 24	14·92	+0·28	−0·64	0·14*	0·039*	(50·)	50	2
	Nova (DN) Gem 1912	1953 Oct. 29	15·56	+0·20	−0·95	0·08	—	—	—	1
		Nov. 2	—	—	—	0·06	—	(5·)	25	1
		30	—	—	—	0·05	—	—	—	1
	Nova (V481) Oph 1848	1954 Feb. 25	13·47	+0·39	−0·57	0·03	—	—	14	1
		May 31	13·52	+0·36	−0·64	—	—	—	—	3
	Nova (DQ) Her 1934†	1954 Aug. 29	14·17	0·00	−0·88	—	—	—	—	4
	Nova (V603) Aql 1918	1954 April 2	—	—	—	0·26	0·066	3·2	66	—
		May 31	11·58	−0·09	−0·81	—	—	—	—	3
		July 8	11·50	−0·04	−0·82	—	—	—	—	3
	Nova (HR) Lyr 1919	1954 July 8	15·71	+0·08	−0·86	0·11*	0·034*	(10·)	36	—
	Nova (V476) Cyg 1920	1954 July 9	17·09	+0·15	−0·94	—	—	—	—	3
	Nova (Q) Cyg 1876	1953 Oct. 31	14·93	+0·33	−0·65	0·30	0·078	10·2	50	—
		1954 Aug. 30	—	—	—	0·28	0·096	11·2	40	—
	Nova (DI) Lac 1910	1953 Oct. 30	14·57	+0·24	−0·64	0·05	—	—	48	1
Recurrent novae	T CrB†	1954 May 29	—	—	—	0·49	0·106	3·5	106	5
		June 1	—	—	—	0·28	0·072	4·0	100	—
	RS Oph	1954 May 29	—	—	—	0·13	0·034	(3·)	12	—
		31	11·28	+1·14	−0·04	—	—	—	—	3
		July 8	10·74	+1·07	−0·06	—	—	—	—	3
	Nova (WZ) Sge	1954 July 8	15·21	+0·09	−0·71	0·24*	0·065*	(40·)	41	—
Possible novae	V426 Oph	1954 May 30	—	—	—	0·30	0·082	3·4	31	—
		July 8	12·64	+0·50	−0·74	—	—	—	—	3
	MacRae +43° 1†	1953 Aug. 7	—	—	—	0·44	0·102	3·2	55	—
		9	13·38	−0·13	−1·05	—	—	—	—	—
		9	13·67	−0·08	−0·98	—	—	—	—	—
	EM Cyg	1954 May 31	12·90	+0·17	−0·72	0·24	0·048	6·3	19	—
		June 1	—	—	—	0·18	0·069	7·2	43	—

Nova-like	V Sge	1954 May 30	—	—	—	0·08	0·022	(11·)	22	—
		July 8	12·24	+0·03	−0·87	—	—	—	—	3
	BF Cyg	1954 July 30	—	—	—	—	—	—	19	5, 6
	CI Cyg	1954 July 30	—	—	—	—	—	—	8	5, 7
	P Cyg	1953 Nov. 12	—	—	—	—	—	—	20	8
	Z And	1954 Aug. 29	—	—	—	0·02	0·006	(13·)	26	5
U Gem	RX And	1954 July 31	—	—	—	0·15	0·032	2·1	41	—
	AE Aqr†	1954 July 30	—	—	—	1·51	0·371	5·7	103	—
	SS Cyg†	1954 July 9	11·90	+0·62	−0·62	0·22	0·057	3·3	22	—
		31	—	—	—	0·12	0·033	2·7	19	—
	RU Peg	1954 July 30	—	—	—	0·06	0·018	6·4	19	—
Mira	*o* Cet†	1955 Aug. 11	—	—	—	0·10	0·031	(10·)	19	5, 9
	R Aqr	1954 July 30	—	—	—	0·04	0·012	(10·)	20	5, 10
White dwarf	40 Eri B	1953 Nov. 12	—	—	—	—	—	—	16	7

* Observations made in blue light; others are in the ultra-violet. † Additional observations are available.

1. Few observations.
2. Observations poor.
3. Magnitude and colour measurement only.
4. Nova (DQ) Her 1934. Eclipsing binary. Intrinsic variations occur throughout the 4-hour cycle of the star with periods from 1 to 40 min. and amplitudes up to 0·15 magnitude in the ultra-violet. Between phases 0·110P (the end of eclipse) and 0·325P, there occur extremely rapid variations of a periodic nature in the light. The range of these variations is 0·07 magnitude in the ultra-violet, and their period is 1·180 minutes. Dispersions and average intervals between maxima have not been computed for DQ Her since, owing to the unique character of this system, the source of the variations may be entirely different from that producing the variations in the other old novae.
5. Composite spectrum.
6. Possible ultra-violet variation of 0·01 magnitude.
7. No ultra-violet variation ⩾ 0·01 magnitude.
8. No ultra-violet variation ⩾ 0·005 magnitude.
9. *o* Cet. This star was observed when the red component was near minimum light (phase = 0·57P). According to A. J. Deutsch (private communication), the blue star dominated in the blue and ultra-violet regions of the spectrum at the time of this observation. The observed activity thus refers to the blue component.
10. R Aqr. Observed somewhat after minimum light (phase = 0·68P). The small amplitude found in the ultra-violet may thus result from dilution of the ultra-violet light of the blue star by light from the red component.

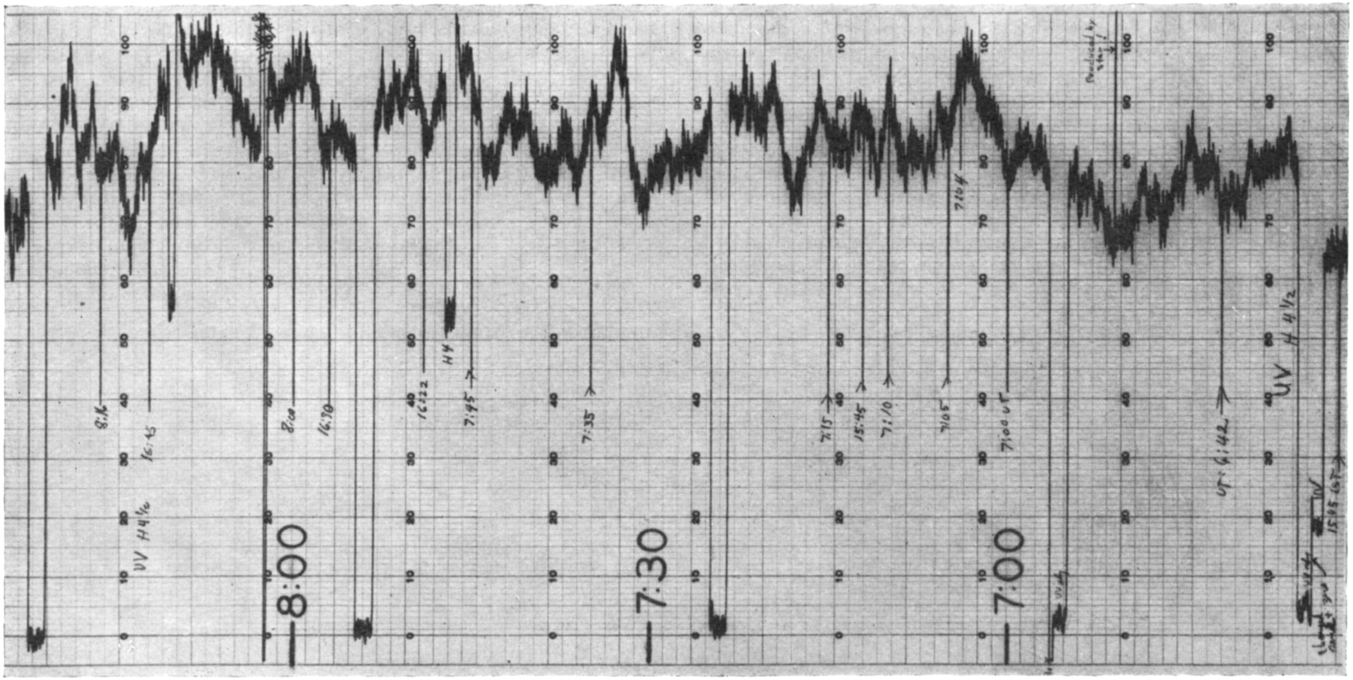

Fig. 1. The light-curve of T Coronae Borealis on 30 May 1954 (U.T.). A section of the Brown Recorder sheet showing the continuous variations of the star in ultra-violet light. Universal Time is marked at intervals of 30 min.

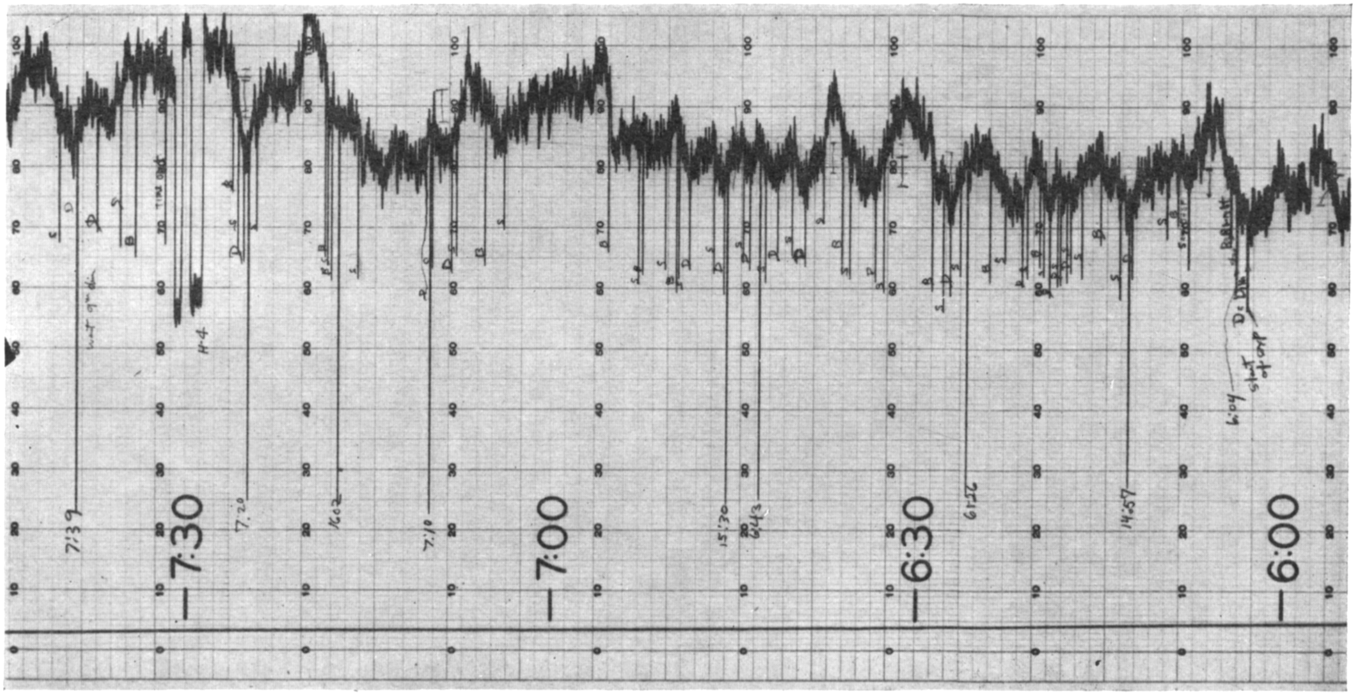

Fig. 2. The light-curve of T Coronae Borealis on 1 June 1954 (U.T.). A section of the Brown Recorder sheet showing the continuous variations of the star in ultra-violet light. Universal time is marked at intervals of 30 minutes. The level of the sky intensity is indicated by the heavy line at the bottom of the figure. In this and the preceding figure, the vertical lines depending from the light-curve are timing marks, and were not produced by the star.

One of the most important results of these observations of old novae was the discovery that Nova (DQ) Herculis 1934 is an eclipsing binary having the shortest known period, $4^h\,39^m$. In addition to the eclipse, rapid intrinsic variability similar to that found in the other old novae also occurs in DQ Herculis. Periods from 1 to 40 minutes and ultra-violet ranges of as much as 0·15 magnitude have been observed. In addition, periodic variations occur between phases $0{\cdot}110P$ and $0{\cdot}325P$ in the eclipse cycle. These fluctuations have a period of 1·180 min. and a range in the ultra-violet of 0·07 magnitude. This is the only star in which rapid variations of a periodic nature have been observed. While no explanation of these variations has been found, the fact that they occur only during a certain phase interval indicates that they probably result in some manner from the binary nature of the system. The observations of this system have been discussed in detail elsewhere [12].

The detection of rapid light-variations in the old novae led to a search for variability of this kind among a number of related stars. One of the first experiments undertaken was the investigation of two stars that had been suspected of being old novae from the appearance of their spectra. EM Cygni was found by E. M. and G. R. Burbidge [13] to have a spectrum similar to that of an old nova, while a similar result was obtained by G. H. Herbig [14] for V426 Ophiuchi. Rapid light-variations were detected in both of these stars, strengthening the supposition that they are old novae.

Rapid variations in light have also been found in four U Geminorum stars. These stars were included in the programme because of their supposed relationship to the novae and since the observations of K. Henize [4] and F. Lenouvel and J. Daguillon [5] had already shown that rapid variations occur in one of them, AE Aquarii. In the other three, RX Andromedae, SS Cygni, and RU Pegasi, the light-variations are similar to those found in the old novae. However, both the work of Lenouvel and Daguillon [5] and the present observations indicate that the light variations of AE Aquarii consist primarily of large outbursts having amplitudes up to 1·5 magnitude, upon which are superimposed fluctuations of lesser amplitude. Between these outbursts the star is relatively quiescent.

Four out of the five nova-like variables observed showed little or no variation. Three of these four, BF Cygni, CI Cygni, and Z Andromedae, have composite spectra. Consequently, the failure to detect variability in these stars may have resulted from the faintness of the blue star relative to the red component at the time of observation. Such an explanation will not suffice for the fourth star, P Cygni. Further work will be required to determine whether rapid light-variations are absent in all P Cygni stars, or whether the absence of activity in P Cygni is related to the long time interval which has elapsed since the outburst of this star. The elapsed time since the explosion of P Cygni is much longer than for any of the old novae examined in this programme.*

The observations of the two Mira-type variables were made near the light-minima of their red components. In *o* Ceti, the spectrum of the blue star was dominant in the blue and ultra-violet at the time of the photo-electric measurements, according to spectroscopic observations by A. J. Deutsch. R Aquarii was observed somewhat further from minimum light than was *o* Ceti, and it is therefore possible that the small amplitude found in this star may have resulted from the effect of ultra-violet light from the red component.

While no detectable light-variation was found in the white dwarf 40 Eridani B, this result is not completely conclusive since the star was observed for only a short time on a single night.

Magnitudes and colours for most of the stars have been obtained on the U, B, V system of Johnson and Morgan [15]. These result mainly from single observations or means of only a few observations obtained while the stars were being monitored for rapid variations in light, and the results may differ very appreciably from the true mean values. For some of the more active stars, even these 'instantaneous' colour measurements may be in error by several hundredths of a magnitude owing to changes in the brightness of the star during the colour observations.

The U–B and B–V colours of the old novae are plotted in Fig. 3. It will be seen that these stars deviate markedly from the relationship between the two colour indices found for normal main sequence stars, which is indicated by the curved line. Such a departure could result from interstellar reddening, abnormal brightness of the star in the ultra-violet, or a composite spectrum. The last possibility may be ruled out on the basis of the spectroscopic observations of these stars. One possible exception might be RS Ophiuchi, which was reported to have had in 1923 an absorption spectrum corresponding to a spectral class of about G5 [16]. The two diagonal lines in Fig. 3 represent reddening paths, and the fact that the old novae fall roughly along a sequence parallel to these lines might suggest that their abnormal colours result from interstellar reddening. The amount of reddening of a few of the old novae can be checked roughly since they occur in fields where the absorption has been derived from star counts. Thus, Nova (GK) Persei 1901 is reddened by at least 0·2 magnitude [17]. The amount of reddening is probably larger than this since observations of the 'light echo' seen after the 1901 maximum indicate that the star must be

* Note by the Editor: The detection of small variations in the light of P Cygni was reported by Kharadze at the Symposium: see p. 87.

https://doi.org/10.1017/S007418090001860X Published online by Cambridge University Press

situated in or near a dark cloud. On the other hand, Nova (T) Aurigae 1891 is located in a region of very light obscuration [18]. It would appear likely that the location of the stars in the two-colour diagram results from a combination of reddening and abnormal ultra-violet intensity. Additional work on this problem is needed.

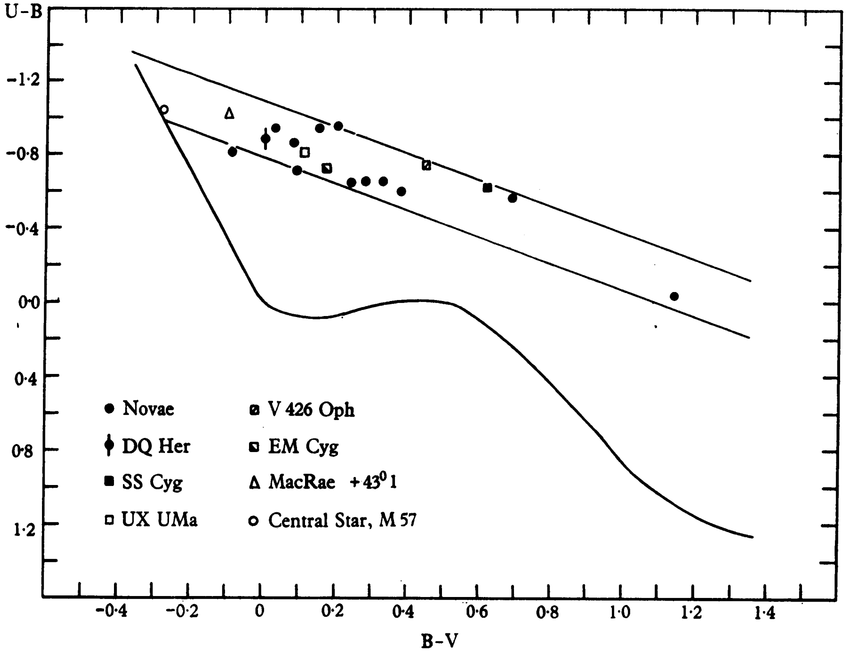

Fig. 3. Two-colour diagram of old novae and related stars. The relationship between the colours for un-reddened main sequence stars is shown by the heavy curved line. The two diagonal lines represent reddening paths.

The colours of the central star of the planetary nebula M 57 have been plotted in Fig. 3 for comparison with the colours of the old novae. Unlike the novae, the colours of this star appear to be normal. If the observed colours of the novae represent an intrinsic abnormality in the energy distributions of these objects, then the differences in the colours may indicate that the novae are quite different from the nuclei of planetary nebulae. However, if the colours of the old novae are intrinsically normal and their position in Fig. 3 is the result of interstellar reddening, then the colours and temperatures of the old novae must be very similar to those of the central star of M 57.

It is to be noted that the colours of the three stars suspected of being novae from their spectra, V426 Ophiuchi, MacRae +43° 1, and EM Cygni, agree quite well with those of the known novae.

Much additional work will be needed to determine the cause and nature of the rapid light-variations. However, certain conclusions may be drawn from the present material. As we have pointed out, the dependence of the amplitude of the light-variations upon wave-length and the fact that in T Coronae there are no changes in the line spectrum accompanying the variations in light indicate that the fluctuations are produced by variations in the temperature of some portion of the surface of the star. The observations also suggest that the disturbances producing the variations involve a large portion of the surface of the star. For example, the temperature of MacRae $+43^\circ$ 1 corresponding to the B–V colour is about 13,000° K. The largest observed short-period variation in ultra-violet light was 0·44 magnitude. If this light-variation were produced by a spot or 'flare' on the surface of the star, then if the temperature of the spot were 100,000°, the radius of the spot would have to be 0·11 that of the star, while if the temperature of the spot were 1,000,000°, the radius of the spot would still have to be 0·03 the radius of the star. If the intrinsic colours of MacRae $+43^\circ$ 1 and of the old novae are normal and their observed colours the result of interstellar reddening, then the situation becomes even worse. If the temperature of the star is actually 25,000°, then if the temperature of the spot is 100,000°, its radius must be 0·27 that of the star, while if its temperature is 1,000,000°, the radius will have to be 0·07 of the radius of the star. On the other hand, if the observed colours of the old novae are not affected by reddening, the spot can be somewhat smaller. If the temperature of the star is actually 8,000° and the temperature of the spot is 100,000°, its radius would be 0·026 that of the star, while if the spot temperature were 10,000°, its radius would be 0·082 that of the star.

Perhaps we might suppose as a working hypothesis that the rapid light-variations are caused by the alternate heating of the atmosphere of the star by shock waves and its subsequent cooling by radiation. If this is the case, then the rapidity of the light-variations would suggest that the quantity of material which is being heated and cooled is relatively small, and consequently, if the entire surface of the star is involved, that the star itself is small.

What is the origin of the observed instability of these stars? The fact that different classes of stars display this same type of rapid light-variation suggests that there may be some sort of relationship between them. It is interesting to note that a large number of these stars are known to be binaries: Nova (DQ) Herculis has been shown to be an eclipsing binary. AE Aquarii has been shown by A. H. Joy[19, 20] to be a spectroscopic binary, and Joy[19] has also found that SS Cygni and RU Pegasi have variable radial velocities and may thus be binaries. *o* Ceti is a visual double, while th e duplicity of T Coronae, Z Andromedae, and R Aquarii is indicated by the composite spectra of these objects. In addition, rapid light-variations occur in the short-period eclipsing binary UX Ursae Majoris. Thus, it is possible that all of the novae and related stars are binaries and that both the short-period fluctuations and the more violent explosions of these objects result in some way from their binary nature. Additional observations will be required to determine whether or not this is actually the case. Even if all of these stars are binaries, it is probable that binary nature *per se* is not both a necessary and sufficient condition for the occurrence of novae or nova-like phenomena. This is shown by the fact that all of the novae fall in a restricted area of the Hertzsprung-Russell diagram.

In conclusion, it should be noted that recent theoretical investigations[21, 22] indicate that white dwarf stars will be unstable if sources of nuclear energy are present in them. Consequently, we might expect that white dwarfs would show no fluctuations in light, in accord with the observations of 40 Eridani B. On the other hand, if it is true that the novae represent stars which are approaching the white dwarf stage, it might be that the rapid variations, and perhaps the more violent outbursts, indicate that the star is in a stage where it is becoming unstable with respect to the processes of nuclear energy generation, but in which these processes have not yet become entirely exhausted.

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