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UBVRI PHOTOMETRY OF THE RECURRENT NOVA T CORONAE BOREALIS

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ABSTRACT

Differential *UBVRI* photometry of this bright recurrent nova at three different observatories in 1981, 1982, and 1983 reveals variability on three different timescales. By Fourier analysis we determine the amplitude of the ellipticity effect at *UBVRI* and use it to find the prolateness coefficient $z = 0.14 \pm 0.01$. Times of minimum light equated with times of conjunction and combined with previously published times yield $227^d67 \pm 0^d02$ for a refined orbital period. Continuous photometry on one night confirms short-term variability reported earlier. Residuals from the Fourier fits reveal an additional variability with a period (probably not constant) of ~ 55 days and an amplitude (definitely not constant) that in 1983 was 0.35 mag in V, 0.5 mag in B, and 0.8 mag in U. We conclude that the gM3 primary is probably a semiregular (pulsating) red variable.

I. INTRODUCTION

T CrB is a recurrent nova which underwent major outbursts, each followed by a secondary outburst four months later, in 1866 and 1946. At quiescence it is around $V = 10$ mag; during the major outbursts it rose to $V = 2$ or 3 mag; at the secondary outbursts it rose to about $V = 8$ mag. Its long orbital period (227^d5) and its giant primary (gM3) make it unique among the known cataclysmic variables. The hot secondary is visible in the spectrum only by its emission lines and it is significant in the continuum only at very short wavelengths. Although the binary system is not known to be eclipsing and hence the orbital inclination is unknown, the $\mathcal{M} \sin^3 i$ value for the hot secondary makes it too massive to be a white dwarf. More specifics about the T CrB system can be found in two recent papers: Kenyon and Garcia (1986) and Webbink *et al.* (1987).

At the suggestion of J. O. Patterson, we began long-term photoelectric photometry of T CrB, hoping to follow it photometrically throughout its entire 227.5 day orbital period. Analysis of 1960–1971 visual estimates and 1891–1917 photographic estimates by Bailey (1975) resulted in discovery of the ellipticity effect in both spectral regions. In a more recent paper by Peel (1985), careful reduction of 1872–1904 visual and 1892–1911 photographic brightness estimates revealed long-term photometric variability attributable to the ellipticity effect and possibly also to various other photometric peculiarities. Earlier photoelectric photometry, the most recent being the 1985 *UBV* photometry by Raikova and Antov (1986), demonstrated the existence of variability on a short (~ 10 min) timescale. Until the 1981–1983 *UBVRI* photometry discussed in this present paper, however, there still had not been photoelectric coverage of T CrB throughout its orbital cycle.

II. OBSERVATIONS

Observations were made at three sites. T. McFaul observed in *VRI* on ten nights in 1981 and 11 nights in 1982 at this observatory in Hopewell Junction, New York, using a 14 in. Celestron telescope equipped with an Optec solid-state photometer, and on four nights in 1983, using the same photometer attached to a 22 in. Maksutov telescope at Stamford Observatory in Stamford, Connecticut. R. and H. Lines observed in *BV* on eight nights in 1982 and in *UBV* on 50 nights in 1983 at Lines Observatory in Mayer, Arizona, using a 20 in. Cassegrain telescope equipped with a 1P21 PMT photometer.

All observations were made differentially with respect to BD $+26°2761$, a comparison star used in previous photometric studies of T CrB, for example, by Peel (1985). The *UBV* observations are corrected for differential extinction and transformed to the standard system. The *r* and *i* observations are instrumental, as transformation coefficients (to the Johnson *RI*) have not been determined for McFaul's instrumentation in these bandpasses.

The differential photometry for all three telescopes, in all five bandpasses, and for all three observing seasons is given in Tables I and II. Each value is a nightly mean of generally three comparisons between T CrB and BD $+26°$ 2761, in the sense variable minus comparison.

TABLE I. Differential photometry of T CrB by McFaul.

JD(Hel.) 2440000 +	ΔV (mag)	Δr (mag)	Δi (mag)
4715.797	0.313	−0.475	−1.463
4727.734	0.365	−0.476	−1.464
4747.740	0.187	−0.517	−1.526
4756.673	0.166		
4763.623	0.138		
4784.724	0.393		
4833.554	0.085		
4840.602	0.116		
4859.581	−0.067		
4876.531	0.284		
5075.699	0.081	−0.624	−1.615
5084.800	0.130	−0.562	−1.575
5092.624	0.063	−0.581	−1.498
5105.665	0.228	−0.500	−1.445
5111.589	0.280	−0.370	−1.449
5132.675	0.320	−0.315	−1.439
5180.665	0.198	−0.570	−1.531
5222.561	0.276	−0.473	−1.481
5230.525	0.196	−0.370	−1.416
5232.542	0.292		
5245.500	0.355	−0.352	−1.357
5423.729	−0.015	−0.742	
5426.899	0.039	−0.623	
5448.727	0.218	−0.569	−1.462
5461.744	0.183	−0.452	

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TABLE II. Differential photometry of T CrB by Lines.

JD(hel.) 2440000 +	ΔV (mag)	ΔB (mag)	ΔU (mag)
5141.711	0.456	0.663	
5145.784	0.494	0.803	
5146.810	0.450	0.804	
5156.811	0.360	0.542	
5160.697	0.326	0.531	
5161.682	0.314	0.550	
5162.706	0.296	0.516	
5176.676	0.180	0.452	
5382.987	0.261	0.380	
5439.820	0.113	0.380	
5440.802	0.123	0.387	
5441.827	0.141	0.428	
5458.864	0.231	0.246	
5460.844	0.205	0.155	
5462.862	0.250	0.140	
5463.836	0.300	0.275	− 0.856
5466.806	0.368	0.393	− 0.731
5467.812	0.365	0.419	− 0.637
5468.878	0.324	0.352	− 0.850
5473.862	0.409	0.494	− 0.622
5474.910	0.423	0.537	− 0.506
5488.721	0.377	0.585	− 0.261
5489.729	0.424	0.644	− 0.159
5490.738	0.434	0.663	− 0.183
5491.774	0.429	0.629	− 0.209
5493.720	0.442	0.672	− 0.080
5495.733	0.373	0.589	− 0.049
5496.718	0.314	0.474	− 0.288
5500.701	0.216	0.393	− 0.454
5501.695	0.151	0.279	− 0.551
5502.723	0.228	0.439	− 0.274
5504.702	0.189	0.367	− 0.505
5505.729	0.055	0.119	− 0.887
5506.733	0.107	0.178	− 0.890
5507.706	0.100	0.177	− 0.932
5511.698	0.074	0.192	− 0.676
5514.728	0.021	0.138	− 0.708
5516.723	− 0.022	0.070	− 0.937
5518.691	− 0.098	− 0.080	− 1.200
5520.689	− 0.057	0.003	− 1.013
5531.688	0.033	0.166	− 0.799
5532.697	0.060	0.204	− 0.687
5534.689	− 0.006	0.147	− 0.828
5545.693	0.179	0.371	− 0.384
5549.709	0.260	0.561	+ 0.025
5558.660	+ 0.222	+ 0.402	− 0.207
5559.671	+ 0.219	+ 0.463	− 0.171
5581.643	+ 0.392	+ 0.518	− 0.345
5582.647	+ 0.353	+ 0.462	− 0.520
5583.646	+ 0.280	+ 0.320	− 0.632
5585.647	+ 0.404	+ 0.569	− 0.266
5586.641	+ 0.317	+ 0.424	− 0.466
5587.642	+ 0.251	+ 0.255	− 0.783
5595.630	+ 0.379	+ 0.556	− 0.266
5593.628	+ 0.360		
5596.633	+ 0.306	+ 0.359	− 0.732
5599.632	+ 0.395	+ 0.589	− 0.122
5602.641	+ 0.297	+ 0.308	− 0.630

Differential measures of our comparison star BD + 26°2761 with respect to our check star BD + 26°2763 were made on three nights in 1982 and three nights in 1983. Though not large in number, these differences were sufficiently constant ($\sigma_1 = \pm 0.015$ mag) to indicate that our comparison star was not responsible for the much larger variations (tenths of a magnitude) discussed later in this paper.

Differential photometry of BD + 26°2761 with respect to HD 143291, for which *UBV* magnitudes have been determined by Roman (1955) and by Eggen (1964), yielded the following magnitudes and color indices: $V = 9.83$ mag, $B - V = 1.05$ mag, and $U - B = 0.83$ mag, each uncertain by approximately ± 0.01 mag.

III. FOURIER ANALYSIS OF THE PHOTOMETRY

First we examined our *UBVRI* light curves, plotted versus phase computed with the preliminary ephemeris

$$\mathrm{JD(hel.)} = 2{,}435{,}690.0 + 227\overset{d}{.}5\,E, \qquad (1)$$

where the initial epoch is a time of conjunction with the gM3 primary behind and the period is the orbital period, both determined by reanalysis (Paczynski 1965) of existing radial-velocity measures of both the hot and the cool components. Inspection showed that, indeed, as Bailey and Peel had found, there was evidence of an ellipticity effect having a full amplitude of some tenths of a magnitude in all five bandpasses. On top of the ellipticity effect, which is "normal" for a binary, there was also evidence of photometric abnormalities: asymmetry, more scatter than expected for our photoelectric photometry, and nonrepetition from one season to the next at corresponding phases.

At this point we had no clear understanding of the overall photometric behavior so, as a first step, we dealt with the ellipticity effect alone. To this end, we used least squares to fit all six light curves (McFaul in *VRI*, Lines in *UBV*) separately to a cos 2θ curve. Such a curve, which has maximum brightness at times of the two quadratures and minimum brightness at times of the two conjunctions, is the customary description of the so-called ellipticity effect caused by mutual tidal deformation of the shapes of the two stellar components. Table III shows the results. Here n is the number of nightly means, Δm is the full amplitude of the cos 2θ variation in magnitude units, A_2 is the corresponding semiamplitude in light units relative to unity at mean brightness, and JD(min.) is a time of minimum, which the ellipticity effect requires to coincide with one of the two conjunctions.

IV. REFINING THE ORBITAL PERIOD

Our six times of minimum along with the six of Peel and two times of conjunction from Paczynski (one from absorption lines of the gM3 star and one from emission lines of the blue companion) give us a baseline more than 80 yr long with which to improve the orbital period, estimated by Sanford (1949) to be 230ᵈ5, by Kraft (1958) to be 227ᵈ6, Pac-

TABLE III. Results from Fourier analysis.

Observer	λ	year	n	Δm (mag)	A_2	JD(min.)
McFaul	V	1981–83	24	0.30 ± 0.05	− 0.138 ± 0.024	2445138.9 ± 3.7
McFaul	R	1981–83	16	0.30 ± 0.05	− 0.137 ± 0.023	2445137.9 ± 3.8
McFaul	I	1981–83	13	0.17 ± 0.03	− 0.080 ± 0.014	2445134.8 ± 3.8
Lines	U	1982–83	42	0.39 ± 0.14	− 0.178 ± 0.064	2445358.4 ± 6.5
Lines	B	1982–83	57	0.32 ± 0.07	− 0.148 ± 0.032	2445364.6 ± 3.7
Lines	V	1982–83	57	0.38 ± 0.03	− 0.173 ± 0.015	2445362.9 ± 1.5

zynski (1965) to be $227^{\rm d}5 \pm 0^{\rm d}15$, by Bailey (1975) to be $227^{\rm d}64 \pm 0^{\rm d}1$, by Peel (1985) to be $227^{\rm d}52 \pm 0^{\rm d}05$, and by Kenyon and Garcia (1986) to be $227^{\rm d}53 \pm 0^{\rm d}02$.

There was no problem determining the proper cycle count of all 14 times. The initial epoch in the preliminary ephemeris in Eq. (1) was, as we said, conjunction with the gM3 star behind. Our six times turned out to be times of the other conjunction (the blue companion star behind) so we assigned them half-integer cycle numbers. Similarly, the times of minimum Peel had labeled "Type I" were given half-integers and his "Type II" minima were given integers. All of this is summarized in Table IV, where residuals computed with the preliminary ephemeris in Eq. (1) are given as $\mathrm{O} - \mathrm{C}_1$.

A linear fit by least squares to the 14 times in Table IV, with each one given equal weight, yielded the refined ephemeris

$$\mathrm{JD(hel.)} = \underset{\pm 1.3}{2{,}435{,}687.6} + \underset{\pm 0.02}{227^{\rm d}67}\ E, \tag{2}$$

where the initial epoch is a time of conjunction with the gM3 star behind. The residuals from this fit are given in Table IV as $\mathrm{O} - \mathrm{C}_2$.

The corresponding ephemeris derived by Kenyon and Garcia (1986) from analysis of all available old and recent radial-velocity determinations is

$$\mathrm{JD(hel.)} = \underset{\pm 0.13}{2{,}431{,}933.83} + \underset{\pm 0.02}{227^{\rm d}53}\ E. \tag{3}$$

If this epoch is moved forward by 16.5 cycles, it agrees with our epoch in Eq. (2) within $0^{\rm d}5$, consistent with our uncertainty of $\pm 1^{\rm d}3$. It is puzzling that our periods differ by more than the combination of the respective uncertainties. Times of conjunction derived from Fourier analysis of the photometric-ellipticity effect should be directly comparable to times of conjunction derived from radial-velocity curves.

V. DETERMINATION OF *Z*

The amplitudes in Table III can be used to determine the prolateness coefficient z, which is a measure of tidal deformation.

The light of the system is dominated by the gM3 primary because its blue companion, a main-sequence star, should be several magnitudes fainter than the giant. Therefore, the ellipticity effect should be produced almost entirely by the distortion of the gM3 star, which Kraft and others have argued probably fills its Roche lobe.

Although the radius of the gM3 star can be expected to be independent of wavelength, the amplitude of the ellipticity effect is determined additionally by the so-called "photometric enhancement factor." In their approximate treatment of this effect, Russell and Merrill (1952) called this factor N and presented the equations

$$Nz = \frac{-4(A_2 - C_2)}{(A_0 - C_0) - (A_2 - C_2)} \tag{4}$$

and

$$N = \frac{(15+x)(1+y)}{5(3-x)}, \tag{5}$$

where x is the limb-darkening coefficient, y is the gravity-darkening coefficient, A_2 was defined in Sec. III, A_0 is approximately unity, and C_0 and C_2 are terms that describe the reflection effect.

If the gM3 primary is the dominant source of luminosity in the system, then the much fainter secondary should produce a negligible reflection effect on it (although Peel (1985) suspected a possible reflection effect in his mean light curve of turn-of-the-century photographic and visual estimates). If we neglect C_0 and C_2, which go to zero in the case of negligible reflection, then Eq. (4) reduces to $Nz = -4A_2$. Taking values of x and y appropriate for the temperature of a gM3 star and the wavelengths of the U, B, V, R, and I bandpasses, we computed N with Eq. (5) so that we could plot our A_2 coefficients in Table III versus N. This is shown in Fig. 1, where the straight line is the best fit made to pass through the origin. Thus the slope in Fig. 1 provides a determination of the prolateness coefficient z, in this case $z = 0.14 \pm 0.01$.

VI. ADDITIONAL VARIABILITY WITH AN ~55 DAY PERIOD

To try to understand the variability not fully accounted for by the ellipticity effect, we plotted (versus Julian date) the *residuals* from the cos 2θ Fourier fits. For the 1983 observing season these are shown in Fig. 2. It is immediately obvious that T CrB is varying additionally with a period around 55 days and an amplitude of a few tenths of a magnitude.

TABLE IV. Times of conjunction.

JD(conj.)	E	$\mathrm{O}-\mathrm{C}_1$ (days)	$\mathrm{O}-\mathrm{C}_2$ (days)	Reference
2414858	− 91.5	− 15.8	+ 2.4	Peel (1985)
2414970	− 91.0	− 17.5	+ 0.6	"
2417591	− 79.5	− 12.8	+ 3.3	"
2417820	− 78.5	− 11.3	+ 4.6	"
2418838	− 74.0	− 17.0	− 1.8	"
2418942	− 73.5	− 26.8	− 11.7	"
2435687 ± 2	0.0	− 3.0	− 0.6	Paczynski (1965)
2435693 ± 3	0.0	+ 3.0	+ 5.4	"
2445138.9 ± 3.7	+ 41.5	+ 7.6	+ 2.8	Table III
2445137.9 ± 3.8	+ 41.5	+ 6.6	+ 1.7	"
2445134.8 ± 3.8	+ 41.5	+ 3.5	− 1.3	"
2445358.4 ± 6.5	+ 42.5	− 0.4	− 5.4	"
2445364.6 ± 3.7	+ 42.5	+ 5.9	+ 0.9	"
2445362.9 ± 1.5	+ 42.5	+ 2.7	− 0.9	"

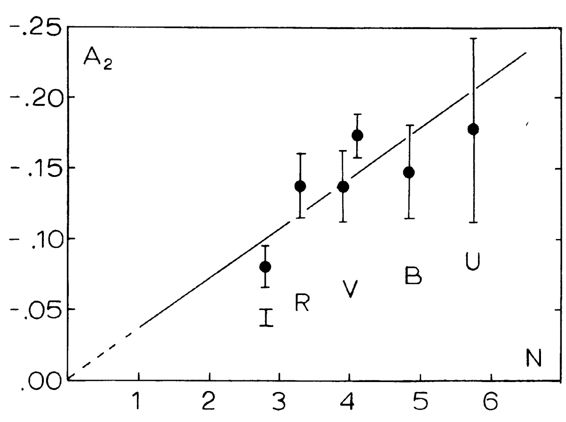

FIG. 1. Observed ellipticity coefficient A_2 versus the wavelength-dependent photometric enhancement factor N. The slope of this line, entered in Eq. (4), yields the prolateness coefficient $z = 0.14 \pm 0.01$.

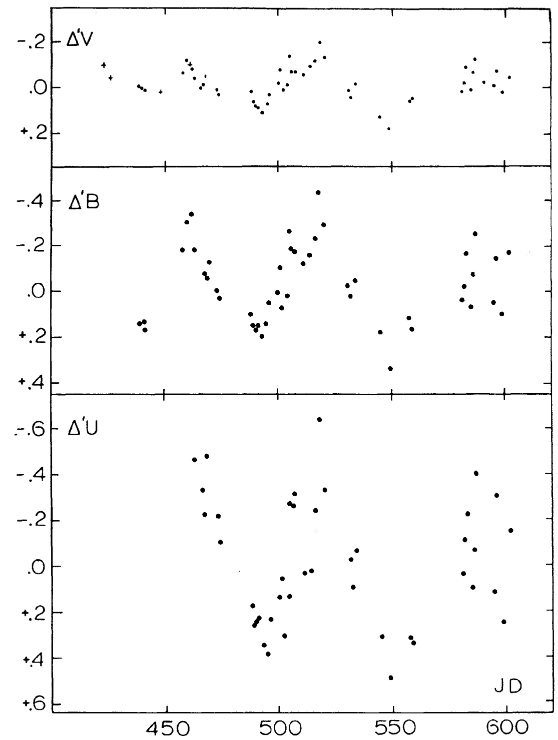

FIG. 2. Each point is a residual from the cos 2θ Fourier fits, coefficients for which are given in Table III. The variation apparent in all three bandpasses, with a period on the order of 55 days, occurs over and above the ellipticity effect and results presumably from pulsation of the gM3 primary, which can be considered a semiregular red variable. Only the 1983 photometry is shown here. Dots are Lines and pluses are McFaul. The abscissa, plus 2445000, is Julian date.

Figure 2 shows that the amplitude is quite different in the three bandpasses: ~0.35 mag in *V*, ~0.5 mag in *B*, ~0.8 mag in *U*. This additional variation shows up also in the 1982 and 1981 photometry, but the amplitudes are generally less (~0.15 mag in *V* in 1982, ~0.25 mag in *V* in 1981). Because of the sparser coverage and smaller amplitudes in 1981 and 1982, we could not use all three years to determine an accurate period for this additional variation. There was some indication, moreover, that this variation is not strictly periodic.

The fragmentary *ubv* (not transformed to the *UBV* system?) photometry of Oskanian (1983) was partly coincident with our 1982 photometry. Because both of us used the same comparison star, a direct comparison was possible. The two data sets outlined consistent photometric behavior. Specifically, we both saw the same drop to a deep minimum at $\Delta V \sim +0.5$ mag in mid-June 1982.

We used the 12 nights of photometry by Raikova and Antov (1986) to examine the photometric behavior in 1985. Residuals from our cos 2θ Fourier fit showed similar variations: a range of a few tenths of a magnitude and a suggestion of a period (or quasiperiod) around a couple of months.

The visual and photographic photometry presented by Bailey (1975) and by Peel (1985) was not useful in this regard because their light curves were plotted modulo the orbital period and thus smoothed out any variability with a different periodicity.

It is interesting to compare our ~55 day periodicity with the perhaps similar ~41 day periodicity present just before the 1946 major outburst (Webbink 1976).

VII. SHORT-TERM VARIABILITY

Although each value in Tables I and II is a nightly mean, we had noticed during observing an obvious (~0.1 mag) relatively rapid (~10 min) variability in our measures. Apparently, we were witnessing the same rapid photometric variations found in T CrB earlier by Walker (1954), Walker (1977), Oskanian (1983), and most recently by Raikova and Antov (1986). These oscillations may be similar in nature to the flickering observed in many cataclysmic variables. This probably could account for the scattered appearance of the light curve in Fig. 2. Whereas our differential photometry of a star around $V = 10$ mag should yield nightly means reliable to ± 0.01 or ± 0.02 mag, residuals from smooth curves drawn in Fig. 2 would be as large as $+0.05$ mag.

On one night we observed T CrB in *V* and *B* almost continuously for 2 hr. The results, shown in Fig. 3, illustrate this short-term variability quite clearly. The full amplitude was 0.09 mag in *V* and 0.18 mag in *B*.

VIII. DISCUSSION

Our refinement of the orbital period should be meaningful. Use of individual times of minimum light, however, would have been misleading, because of the 55 day variation, but Fourier analysis modulo the 227^{d}5 orbital period circumvented this problem. Somewhat similarly, Peel's six dates of minimum light, though not corrected for any quasiperiodic variation that may have been present, can be treated as times of conjunction. Each one is based on a mean light curve embracing such a large interval of time (several years) that the effect of a secondary variation, similar to the ~55 day variation and not commensurate with 227^{d}5, would have been averaged out.

There is little more we can say about the 55 day variability itself, until there is additional photometry long enough in duration and continuous enough in coverage to define several consecutive cycles. Our guess would be that the gM3 star

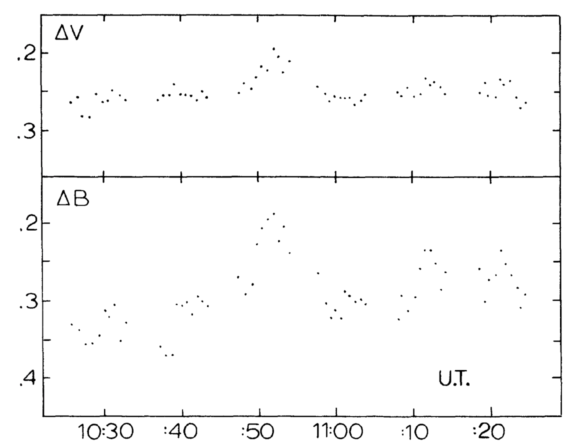

FIG. 3. Light curve in *V* and *B* for 2 hr of continuous photometry on the night of JD 2446585.5. Brief gaps appear when the comparison star was observed. This is the short-term variability discussed in Sec. VII.

could be considered a semiregular red variable. Its amplitude, quasiperiod, and spectral type are all consistent with such a classification.

It would, however, be interesting to see the valuable long series of both visual and photographic brightness estimates, such as those discussed by Bailey (1975) and by Peel (1985), analyzed more closely. Specifically, would *residuals* from the cos 2θ variation modulo $227^{d}5$ show that an additional quasiperiodic variation was present also at earlier epochs?

The value $z = 0.14$ we found for the prolateness coefficient or, alternatively, our values of the A_2 coefficients themselves, should be useful in an attempt to estimate the orbital inclination and thereby the true masses of the two stellar components. Relatively reliable estimates of $\mathscr{M}_1 \sin^3 i$ and $\mathscr{M}_2 \sin^3 i$ are known, for example, those in Webbink *et al.* (1987, Table 1), but the inclination is still a largely unknown parameter.

A search for possible eclipses, though important, will be exceptionally difficult in T CrB. If the small hot component indeed is 5 mag fainter than the gM3 primary, as Kraft (1958) claims, then a primary eclipse should be on the order of 0.01 mag deep if total and even less deep if partial. The irregular short-term variation and the semiregular ~ 55 day variability would conspire to make detection of eclipses virtually impossible. If, on the other hand, the small component ever brightens again, during a minor or a major outburst, a search for possible eclipses might be more promising.

If, as we are suggesting, the gM3 star is a semiregular red variable and has a variable radius as a result of pulsation, then it cannot be exactly filling its Roche lobe at all times, as has been presumed by several authors. On the other hand, it is exciting to contemplate that Roche lobe overflow at epochs of maximum radius extent might be the trigger for (occasional) mass transfer on a dynamic timescale and consequent (occasional) eruptions due to the liberation of accretion energy.

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