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OPTICAL OBSERVATIONS OF THE X-RAY BINARY V1727 CYGNI (=4U 2129+47) DURING A LOW STATE: SOME UNEXPECTED RESULTS[1]

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ABSTRACT

We report on observations of the X-ray binary V1727 Cygni = 4U 2129+47, which ordinarily displays a pronounced X-ray heating light curve on a 5.2 hr period, taken when the object was in an X-ray and optical low state. Extensive CCD photometry obtained at McGraw-Hill Observatory shows *no* photometric modulation; at the binary period, the 99% confidence limit on the amplitude of a sinusoidal modulation is only 0.012 mag in the V band. No eclipse is detected, despite extensive coverage at the expected phase in both the V and B photometric bands. We measure $V = 17.88 \pm 0.03$ and $B-V = 0.93 \pm 0.05$. A spectrum taken with the Kitt Peak 4 m telescope and cryogenic camera resembles a late F type, with Balmer and (possibly interstellar) Na D absorption lines; another taken with the Isaac Newton Telescope shows no emission lines.

We attempt to reconcile these observations with previous models of this supposedly well-characterized system, which predict that the low state should exhibit strong ellipsoidal variations or eclipses or both, and which predict a much redder color and later spectrum at minimum light. No entirely satisfactory model is found, although a very low metallicity system with a somewhat underfilled Roche lobe may be consistent with the observations. Another possibility is that the X-ray star has actually faded below visibility and we are observing another star along the line of sight. The probability of an *unrelated* interloper is found to be small (10^{-3}), but the system might more plausibly be triple.

Subject headings: stars: individual (V1727 Cygni) — X-rays: binaries

I. INTRODUCTION

The optical counterpart of the X-ray object 4U 2129+47 was discovered by Thorstensen *et al.* (1979) to be a star, later named V1727 Cygni, with a pronounced photometric variation on a period of 5.24 hr. The modulation was similar in form to that in Hercules X-1 and the color was bluest at maximum light, which showed that the modulated light arose at the X-ray heated face of the normal star in the system. Within this framework, Thorstensen *et al.* described the system and derived a rough distance. McClintock, Remillard, and Margon (1981; hereafter MRM81) obtained more accurate light curves and refined the ephemeris and models. A radial velocity study by Thorstensen and Charles (1982) indicated a rather low mass for the system. More recently, Horne, Verbunt, and Schneider (1986) published superior high-state spectroscopic data which indicated a low mass (about 0.7 $M_{\odot}$) for the compact object.

The observed X-ray flux from this system is quite weak for a Galactic X-ray binary. McClintock *et al.* (1982; hereafter MLBG82) observed *partial* X-ray eclipses at the phase expected from the optical ephemeris; they interpreted this as partial obscuration of an accretion-disk corona (ADC) source. In their model, the system is nearly edge-on to us, the compact X-ray source itself is hidden from us by the accretion disk, and we observe only those X-rays Compton scattered toward us by a hot atmosphere (or corona) above the accretion disk. Recently, Garcia and Grindlay (1987) found an X-ray burst in archival *Einstein Observatory* observations; this showed conclusively that the accreting object is a neutron star, rather than a degenerate dwarf as the indications of a low mass (Thorstensen and Charles 1982; Horne, Verbunt, and Schneider 1986) had suggested. The burst's properties also supported the ADC model.

The high-state observations suggested a model with a

1 Based partly on observations obtained at the McGraw-Hill Observatory, which is operated jointly by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology.

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normal star of roughly 0.6 $M_\odot$ (derived from the orbital period) orbiting a neutron star (Thorstensen *et al.* 1979; MRM81). The inclination of the orbit was known to be close to edge-on because of the X-ray eclipses and pronounced optical modulation. All told, the V1727 Cyg/4U 2129+47 system was felt to be relatively well-understood among the low-mass X-ray binaries (see e.g., Bradt and McClintock 1983).

Recently, Pietsch *et al.* (1986) announced that the source had gone into a low state. No X-ray flux was detectable with *EXOSAT*, and the source had faded from a mean V magnitude of 17.0 to 18.0, some 0.6 mag fainter than minimum light in the high state. Observations with a conventional photoelectric photometer showed that the optical modulation was considerably weaker than in the high state (which shows $\Delta B = 1.5$ mag; MDM81), with upper limits of about 0.2 mag in B and $B-V$.

We undertook photometric observations of the source in the low state in the expectation of discovering ellipsoidal variations, and spectroscopic observations to study the normal star in the system without the interfering veil of light from the X-ray heating. We did not find what we expected.

II. OBSERVATIONS

a) Photometry

We obtained CCD photometry of this source from McGraw-Hill Observatory on several different observing runs.

MIT Data.—Two of us (R. A. R. and J. E. M.) used the McGraw-Hill Observatory 1.3 m telescope with the MASCOT CCD camera (Ricker *et al.* 1981) in its direct mode in July and December of 1983. Stellar magnitudes were extracted from the images using procedures described by McClintock *et al.* (1983). The December data were of significantly better quality than the July data, so we confine our remarks to the December data; the July data were consistent with these. The passband extended from 4000 to 6400 Å; 2.9 hr and 2.8 hr of data were obtained on 1983 December 8 and 10 UT, respectively, covering about 60% of the binary phase. Integrations were 15 minutes long and the sky transparency was good. All observations were normalized to three bright (but unsaturated) stars in the field to remove any transparency variations. Much to our surprise, there was *no* significant variation in V1727 Cyg, with an upper limit (derived from the scatter of comparison stars of comparable brightness) of about 0.03 mag.

Dartmouth Data.—More extensive data were obtained (by J. R. T., D. E. M., and the Off-Campus Program Students) on 24 nights in 1985 September, 1986 August/September, and 1986 November/December, using the McGraw-Hill 1.3 m telescope and an RCA CCD chip. These data were reduced using the aperture-photometry program described by Thorstensen (1987); all data were normalized to a bright star in the field (marked as star 2 by Pietsch *et al.* 1986). For all the relative photometry, a 3″.7 diameter synthetic aperture was used, effectively eliminating the crowding star described by Pietsch *et al.* The sky background varied across the field because of the presence of a bright star off the south edge of the frame; to minimize any effect of this, we measured the sky close to each object. The most accurate observations were in a V passband; the 1986 observations matched the V passband accurately, but for the 1985 observations a pseudo V filter which suffered a substantial red leak was used. The magnitude differences from 1985 were consistent with those from 1986 save for an offset of 0.023 mag, which was applied to the data in subsequent analysis. In 1986 many integrations were taken in a B filter as well. Integration times for all observations were either 8 or 10 minutes. Some frames were taken in cloudy weather; to preserve the quality of the data, frames were discarded if the comparison star was more than 1 magnitude fainter than its mean level. A journal of observations is given in Table 1.

In Figure 1, the Dartmouth photometric data are shown folded with the ephemeris of MLBG82. Once again, there is no evidence at all of variation. In the V band, the 99% confidence upper limit on the amplitude of a sinusoidal modulation at the orbital period is only 0.012 mag; at half the orbital period (the expected dominant frequency in ellipsoidal variation), the 99% confidence upper limit is 0.015 mag. Furthermore, comparison of the scatter of the measurements of V1727 Cyg with the scatter of the stars around it shows no evidence for variability in V1727 Cyg within the limits of our measurement accuracy; the standard deviation of any irregular variations in V1727 Cyg can be no more than 0.026 mag. In the B band, the limits are much less stringent, but again consistent with no variation at all. The phase in Figure 1 is arranged so that an eclipse would occur near the middle of the plot (the period from the high state is quoted to high precision [MLBG82], so the extrapolation of the ephemeris should introduce little uncertainty). There is no evidence for any eclipse, even in the blue, where one might expect any residual accretion disk to contribute the most flux.

On four nights in 1986, we established an absolute photometric calibration in this field, using observations of standard stars from the list of Landolt (1983). The four measurements were very consistent; the main comparison star used (star 2 of

TABLE 1

PHOTOMETRIC OBSERVATIONS OF V1727 CYGNI

JD Start (1)	JD Stop (2)	Passband[a] (3)	n (4)	Observers[b] (5)
5676.604.........	.723	bb	10	RAR, JEM
5678.581.........	.698	bb	10	RAR, JEM
6313.909.........	...	(V)	1	JRT
6317.748.........	.918	(V)	11	JRT
6318.906.........	.958	(V)	7	JRT
6319.896.........	...	(V)	1	JRT
6669.876.........	.956	V	12	JRT
6670.789.........	.958	V	16	JRT
6672.916.........	.948	V	5	JRT
6675.871.........	.948	B	8	JRT
6675.920.........	.927	V	2	JRT
6676.650.........	.734	B	11	JRT
6676.854.........	.976	V	14	JRT
6677.836.........	.974	B	14	DEM, JRT
6678.878.........	.941	B	8	DEM, OC
6680.853.........	.947	B	12	DEM, OC
6682.838.........	.855	B	3	DEM, OC
6683.734.........	.873	B	7	DEM, OC
6684.813.........	.938	B	16	DEM, OC
6685.814.........	.936	B	14	DEM, OC
6686.882.........	.930	B	15	DEM, OC
6687.819.........	.930	B	15	DEM, OC
6688.828.........	.928	B	13	DEM, OC
6690.819.........	.920	B	13	DEM, OC
6691.795.........	.912	B	8	DEM, OC
6764.609.........	.618	V	2	JRT
6765.605.........	.708	V	18	JRT

NOTE.—Col. (1) is JD − 2,440,000. Col. (2) is JD − 2,440,000 minus the first four digits of col. (1).

[a] Passbands are: bb = broad band λλ 4000–6500, (V) = pseudo V + red leak, V = accurate V, B = accurate B.

[b] The Off-Campus Program Students are designated "OC."

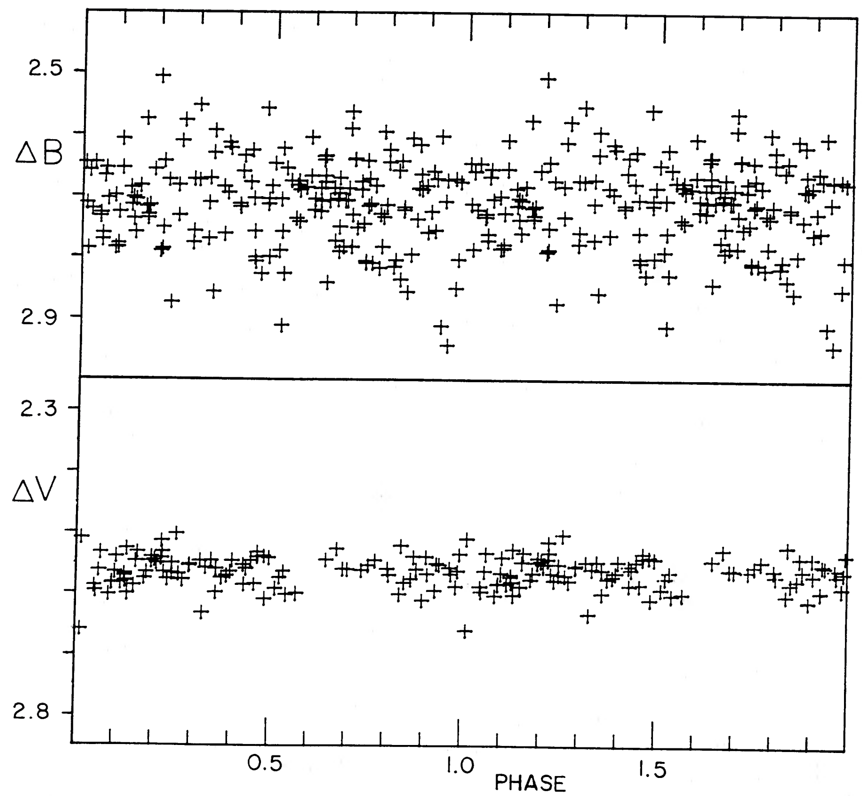

FIG. 1.—Light curves of V1727 Cyg folded according to the ephemeris of MLBG82. All magnitudes are relative to the comparison star, and two cycles are shown with all data plotted twice for continuity. The data in the top panel were taken with the B filter and those in the bottom with the V.

Pietsch *et al.* 1986) was found to have $V = 15.35 \pm 0.03$, $B-V = 0.77 \pm 0.05$, where the errors are estimates of the total external error. Using the very well-determined mean magnitude differences between V1727 Cyg and the comparison star, we find that V1727 Cyg has $V = 17.88 \pm 0.03$ and $B-V = 0.93 \pm 0.05$, where the errors are again estimates of the external errors. Our V magnitude for V1727 Cyg is identical to that given by Pietsch *et al.* (1986) but our $B-V$ color is some 0.18 mag redder than theirs. For comparison, in the bright state the sharp minima typically had $V = 17.42 \pm 0.03$ and $B-V = 0.82 \pm 0.04$ (MRM81).

b) Astrometry

As we shall see in § III, the lack of any residual modulation in the quiescent object is unexpected and puzzling, so we have considered some unusual explanations. For example, the object seen in the low state might be a nearly coincident (but unrelated) field star, and V1727 Cyg itself might become faint enough to be lost in this star's light. To estimate the probability of this, we set limits on any positional offset between the low- and high-state objects. Using the Grant measuring engine at Kitt Peak National Observatory, we measured archival plates taken (by J. R. T.) with the Crossley reflector at Lick Observatory when the object was bright. We compared these measurements to the star positions from our later CCD data and found no significant offset. The 99% confidence error radius derived from the transformation between the data sets was 0″26. To assess the *a priori* likeliness of this agreement, we counted stars on an archival Crossley plate of the field taken in the red-yellow spectral region (Kodak 098-04 emulsion + Schott GG495 filter) to a limit rather fainter than the faint-state object, and established a star density in the region. The probability of a chance superposition of this precision was found to be 1×10^{-3}, assuming that the low-state object is not physically associated with the X-ray object. Thus a coincidence is quite unlikely.

c) Spectroscopy

Isaac Newton Telescope.—We obtained one spectrum of the object covering the wavelength range from 5000 to 10000 Å with the faint object spectrograph and the 2.5 m Isaac Newton Telescope in 1984 July. No features were visible in emission or absorption (save for the telluric A band), though the continuum was clearly detected. The signal-to-noise ratio was poor, however, so the upper limit on the equivalent widths of lines is only about 20 Å.

Kitt Peak 4 m.—A 1000 s exposure of the object was obtained (by D. C. K.) using the Kitt Peak 4 m telescope and cryogenic camera (DeVeny 1985) starting at 1984 November 22.140. The grating used gave a resolution of 15 Å FWHM and covered the wavelength region from 4500 to 7000 Å with good focus. The data were reduced using the IRAF system at Space Telescope Science Institute; reduction steps included subtraction of the bias level, flat fielding, sky subtraction, and wavelength calibration. The stellar spectrum was extracted from the two-dimensional frame using a routine written by F. Valdes, and a (relative) flux calibration was applied. The spectrum, shown in Figure 2, shows absorption at Hα, Hβ, and the Na D lines (blended at this resolution). Possible traces of Mg I and Fe I features near λλ5175 and 5280 are also visible. The equivalent width of the Hα feature is 4 ± 1 Å; that of Hβ is 6.2 ± 1 Å; and the Na D blend is 2.6 ± 0.5 Å, where the errors are all eye

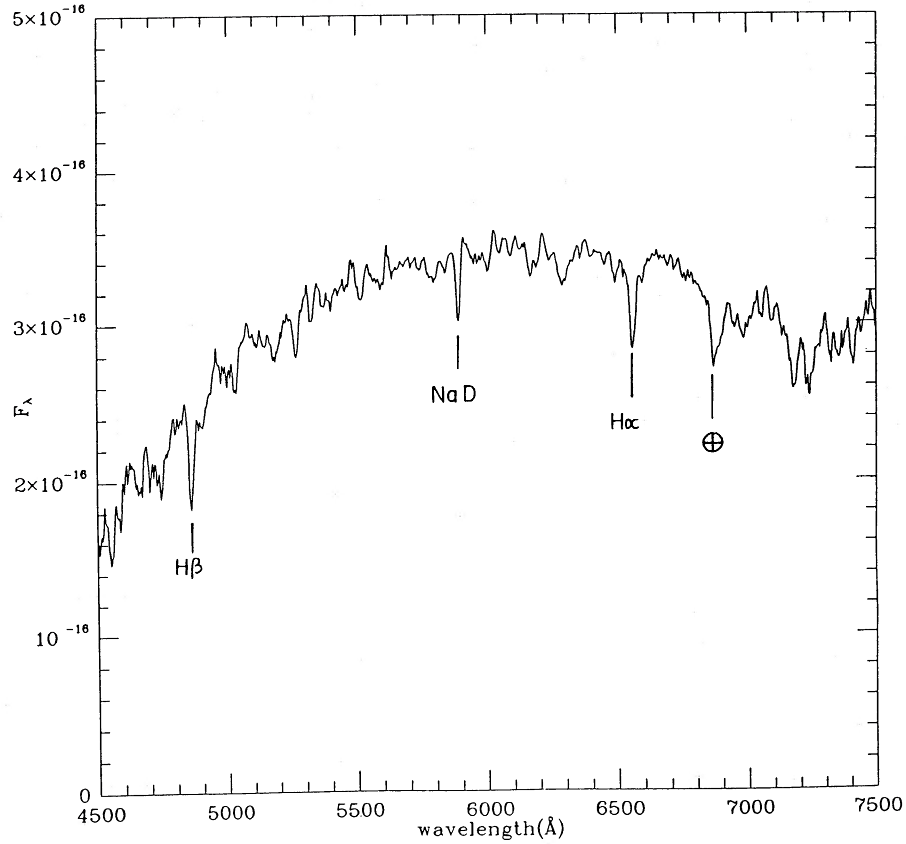

FIG. 2.—Spectrum of V1727 Cyg taken with the KPNO 4 m telescope and Cryocam spectrograph. The flux scale is relative only, as the night was partly cloudy. Note the Balmer absorption at Hα (λ6563) and Hβ (λ4861), the Na D blend at λ5893, and the absence of significant emission lines. The telluric B band is marked with an Earth symbol.

estimates. The Balmer lines appear somewhat broader than the Na I lines; a very rough estimation of the broadening gives 600 km s^{-1} FWHM. This may indicate that the NaD line is interstellar, while the Balmer lines are stellar. The spectrum, when compared with examples in the spectral atlas of Jacoby, Hunter, and Christian (1984) generally resembles that of a late F star.

III. DISCUSSION

The most striking aspect of our data is the complete absence of residual photometric modulation in the low state. This presents a severe challenge to previous models of the system, which predict an ellipsoidal variation far larger than our upper limit. To see the extent of the surprise, consider the model proposed by MRM81 and elaborated by MLBG82. They invoke a 1.3 $M_{\odot}$ compact object with a 0.65 $M_{\odot}$ normal star (though this estimate is rather uncertain; see below). The normal star is presumed to fill its Roche lobe, and the binary inclination is 70°–80°. Bochkarev, Karitskaya, and Shakura (1979; hereafter BKS) computed light curves for tidally distorted stars over a wide range of parameters. From their tables, we find that the ellipsoidal variation of a normal star with these parameters which fills its Roche critical surface should be over 0.1 mag peak-to-peak, even ignoring limb-darkening and gravity-darkening, both of which would make the amplitude still larger.

The object also appears unexpectedly hot (blue and spectrally early) in its low state. MRM81 and Thorstensen *et al.* (1979) estimate, on the basis of the normal star's expected mass, that it should have a late K or early M spectral type, and hence a color $(B-V)_0$ near 1.3. This is already redder than our *observed* value of 0.93 ± 0.05. If the distance to V1727 Cyg is of order 1 kpc or greater, it should suffer at least a few tenths of a magnitude of reddening (Thorstensen *et al.* 1979), which exacerbates the discrepancy. The spectrum (Fig. 2) is also not consistent with a type as late as K or M.

There are several ways in which we might alleviate these two problems, which we will call the *modulation problem* and the *temperature problem*; we discuss them in turn.

Light from an Accretion Disk?—The bulk of the light from the system might arise in a residual accretion disk around the X-ray star, in which case the ellipsoidal variation could be diluted and the intrinsic color made much bluer. This is unlikely for several reasons. First, we see no hint of an eclipse. At least a partial eclipse would be expected based on previous estimates of the inclination of the system (MLBG82), which in turn are based on studies of the X-ray eclipse; Horne, Verbunt, and Schneider (1986) also see evidence for an eclipse of the disk's He II λ4686 line at maximum light. Second, the spectrum does not exhibit the strong, highly broadened emission lines almost always seen in cataclysmic variable stars at minimum light (Williams 1983), in which most of the light does come from an accretion disk (Patterson 1984). Although cataclysmics in outburst can show Balmer absorption lines, these are generally broader than the ones we observe and they usually have emission cores, which we do not observe (Warner 1976).

A Low-Mass Neutron Star?—The expected ellipsoidal variation is dependent on the mass ratio of the binary system. Spectroscopic studies (Horne, Verbunt, and Schneider 1986; Thorstensen and Charles 1982) have indicated that the compact object's mass is likely to be rather lower than the nominal 1.3 $M_\odot$ taken from above. However, the tables of BKS show that changing the mass ratio M_X/M_N (where M_X is the X-ray star mass and M_N is the mass of the normal star in solar masses) from 3.2 to 1.0 reduces the expected ellipsoidal variation only by about 30%. Thus, while a low-mass neutron star might help the modulation problem slightly, it cannot solve it.

A Low Metallicity System?—MRM81 suggested this in view of the $U-B$ color at (high-state) minimum light. A low metallicity might help the modulation problem slightly by changing the calculated mass of the normal star in the system. More importantly, the larger mass of the secondary would make it hotter and bluer, and the lack of line blanketing might make it bluer still, helping solve the temperature problem.

The standard estimates for the mass of the secondary (e.g., MRM81) are based on the condition that the normal star fit within its critical Roche surface. As long as the neutron star is somewhat more massive than the normal star, expressions given by Paczyński (1971) can be adapted to show that the volume-averaged Roche lobe radius in solar radii is given by

$$R_R = 0.705 {M_N}^{1/3}$$

for the binary period of this system. The mass of a Roche-lobe–filling secondary star can then be found by assuming a mass-radius relationship and solving for M_N. However, as Patterson (1984) points out for cataclysmic variable systems, there is considerable question as to the proper mass-radius relation to use for the lower main sequence, even without considering metallicity. Thus we have reexamined the secondary star's characteristics using a variety of different assumptions about the mass-radius relationship. If we assume the semiempirical mass-radius relationship advocated by Patterson (1984), we find $M_N = 0.53\ M_\odot$. Theoretical models by VandenBerg (1985), with $Z = 0.0169$ (solar), $Y = 0.25$, and an age of 10^{10} yr, extrapolated slightly, give $M_N = 0.66\ M_\odot$. Rather surprisingly, lower metal-abundance models from VandenBerg and Bell (1985) do not result in substantially different masses, though other parameters are strongly affected. If the normal star fills its Roche lobe and is on the main sequence, all models lie in the range $0.53 \leq M_N \leq 0.72$. This is essentially the same as the nominal value, and hence the ellipsoidal variation is unaffected.

However, a low metallicity has an important effect on the temperature problem. The nominal normal metallicity, 0.6 $M_\odot$ main-sequence secondary would have $(B-V)_0 = 1.3$; this is substantially *redder* than our observed $B-V$ of 0.93 ± 0.05, and hence impossible. However, the VandenBerg and Bell (1985) models for $Z = 0.0001$ (or [Fe/H] = -2.2), interpolated to $M_N = 0.65$ and $Y = 0.25$, predict $B-V = 0.55$. This implies a reddening within the range estimated for the field by Thorstensen *et al.* (1979). The spectroscopic evidence in hand also does not rule out a rather low metallicity; indeed, the spectrum appears consistent with a star of this color. If we are seeing light from such a companion, it should have M_V of very roughly 5–6 (VandenBerg and Bell 1985). Our measured apparent magnitude, combined with the implied $E(B-V)$ of 0.4, them implies a distance of order 10^3 pc, which appears plausible.

An Underfilled Roche Lobe?—As the filled fraction of the Roche lobe decreases, the expected ellipsoidal variation decreases quickly. The tables of BKS show a decrease of nearly a factor of 2 in amplitude when the filling fraction decreases from unity to 0.9, which makes underfilling of the Roche lobe an attractive solution to the modulation problem. However, it has long been thought that mass transfer in low-mass X-ray binaries is driven by Roche lobe overflow (Bradt and McClintock 1983, and references therein; White and Mason 1985). There are perhaps two ways in which an underfilled Roche lobe might be made compatible with the mass transfer that does occur in the high state.

First, the Roche lobe may be filled during the high state, but the normal star may shrink substantially during the low state. While it seems likely that the normal star does detach slightly from the Roche lobe enough to stop mass transfer, the shrinkage needed to nullify the ellipsoidal variation is quite large, around 10%–30% in radius. This seems unphysical. Unless the envelope were extremely tenuous, a large amount of gravitational binding energy would have to be radiated away in a time scale of a year or so, while the Kelvin-Helmholtz time of the envelope is much longer than this.[4]

Another possibility is that the mass transfer proceeds through some other mechanism than pure Roche lobe overflow. Davidson and Ostriker (1973; see also London, McCray, and Auer 1981) proposed a "self-excited wind" model for these sources, in which X-ray heating of the normal star creates an enhanced stellar wind which feeds the X-ray source. If the star fills a sizable fraction of its Roche lobe, the gravitational potential barrier which material must surmount to be transferred is much smaller than that faced by a wind from a single star's surface, so a fairly strong flow might be maintained.

If the normal star is substantially below its main-sequence radius, the estimates given above for its mass must be revised downward. If $R_N = 0.8\ R_R$, for instance, then the lowest metallicity models predict $M_N = 0.50\ M_\odot$. These models predict $(B-V)_0$ near 0.85, which is only just consistent with our observed color. This effectively sets a limit on how much the Roche lobe may be underfilled.

Binary Evolution of the Secondary?—For completeness, we mention the possibility that some effect of binary stellar evolution might somehow lead to a relatively hot "normal" companion of below main-sequence radius. Given how artificial more conventional models seem, theoretical scenarios leading to this result might be sought.

A Third Star?—As mentioned above, it is unlikely *a priori* that an unrelated field star lies at the position of the X-ray source. However, the system could always be triple, and the light could arise from the third star, giving a trivial solution to the problem. This would be rather disappointing, in that the current puzzle seems an opportunity to learn more about binary stellar evolution.

IV. CONCLUSION

Our extensive observations of this system at minimum light only make sense if the standard models are modified considerably, and even then only marginal consistency is obtained. It should be studied further.

[4] A crude but conservative estimate using a solar interior model given by Allen (1973) shows that this is at least 10^2 yr.

Note added in manuscript.—J. Kałużny (1988) also observes a flat light curve for this object. His measured magnitude and color agree with our values. He attributes much of the light to a residual accretion disk, which we feel is doubtful for the reasons given above.

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