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EVIDENCE FOR NONPOLAR EMISSION REGIONS IN A NEW AM HERCULIS CANDIDATE

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ABSTRACT

We present *UBVRI* and long-term plate photometry of the faint and highly erratic cataclysmic variable discovered by Hawkins from a sequence of UK Schmidt measurements. Observations of the $V \approx 18$ star using the ANU 2.3 m telescope over two consecutive nights in 1986 September show pronounced and repeatable modulation at a binary period of 108.6 minutes. Dramatic color differences are evident in the folded *UBVRI* light curves: in the *U* band, a single sinusoidal peak is present, while at longer wavelengths, a second red peak is dominant at a phase separation of $\Delta\phi \approx 0.5$. This behavior is strongly suggestive of cyclotron emission from two magnetic accretion funnels in an AM Herculis binary system. The binary period and the long time scale two-state activity of the source also support this classification. We conclude therefore that the object (designated Grus V1) is almost certainly a new AM Herculis variable and develop a model in which the blue and red components originate from two *nondiametric* (and probably *nonpolar*) cyclotron regions that are characterized by differing electron temperatures and opacities. Predictions are made regarding the linear and circular polarization properties of the system.

Subject headings: stars: binaries — stars: individual (Grus V1) — stars: magnetic — stars: white dwarfs

I. INTRODUCTION

As part of a survey aimed at detecting faint and variable objects, Hawkins (1981, 1983) isolated three unusual cataclysmic variables from a ~6 yr sequence of UK Schmidt plates taken for a field centered in the constellation Grus. One of these objects, referred to as V1, was found to exhibit particularly intense He II λ4686 emission and a high degree of variability. This variability was confined to two distinct states corresponding to $B \approx 18$ and $B \approx 21$, each of which appeared to persist for a time scale of years. These properties suggested that V1 might belong to the rare AM Herculis class comprising a highly magnetic ($B \approx 20$ MG) white dwarf accreting material from a late-type secondary (e.g., Liebert and Stockman 1985). Unfortunately this possibility could not be pursued further because the object reentered the faint state and became essentially unobservable. In 1986 however, V1 returned to the bright state and presented an opportunity for detailed follow-up study.

In this *Letter* we report multicolor and plate photometry of V1, to which we assign the temporary designation Grus V1. The orbital period that we have found and the distinctive nature of the *UBVRI* light curves leave little doubt that Grus V1 is in fact a new AM Her variable. The coordinates for the object are $\alpha = 21^h34^m45^s.2$, $\delta = -43°55'46''$ (1950), and a finding chart (with north at the bottom and east to the right) is presented by Hawkins (1981).

II. OBSERVATIONS AND RESULTS

a) UK Schmidt Plate Photometry

Grus V1 lies in a field which is being regularly monitored to measure medium- and long-term variables, and a large number of UK Schmidt plates have been accumulated over a period of 11 yr. Figure 1 shows the light curve of Grus V1 sampled between 1975 and 1986. The variability is dominated by high and low states around $B_j = 18$ and $B_j = 21$, and as noted from an earlier subset of the data (Hawkins 1983), the two states seem to last for several years. During the period 1977–1978, however, the object underwent violent fluctuations in luminosity of up to 3 mag in a few days before settling down to an apparently uninterrupted high state. The low state from 1983–1985 was followed by a new maximum, during which the *UBVRI* observations discussed below were made. Recently (1987 August), the object appears to have reentered a phase of violent fluctuations, but detailed plate photometry is not yet available.

b) UBVRI Photometry

UBVRI photometry of Grus V1 was obtained on 1986 September 25 and 26 using the ANU 2.3 m telescope at Siding Spring Observatory. The Two-Channel Chopper (see Tuohy *et al.* 1986) was mounted to one of the nasmyth focii and equipped with GaAs and S20 photomultipliers. Simultaneous *UBVRI* light curves with a time resolution of 2.8 minutes were recorded independently by the two detectors for 5 hr on each night. The seeing was ~1″, and an aperture diameter of 9″ was used.

The *UBVRI* light curves for Grus V1 measured on September 25 using the GaAs phototube are displayed in Figure 2 (the data for the S20 tube are identical, except for reduced statistical precision). Pronounced and repeatable modulation in each filter is immediately evident at a period near 110 minutes, and this behavior is equally apparent in the data for September

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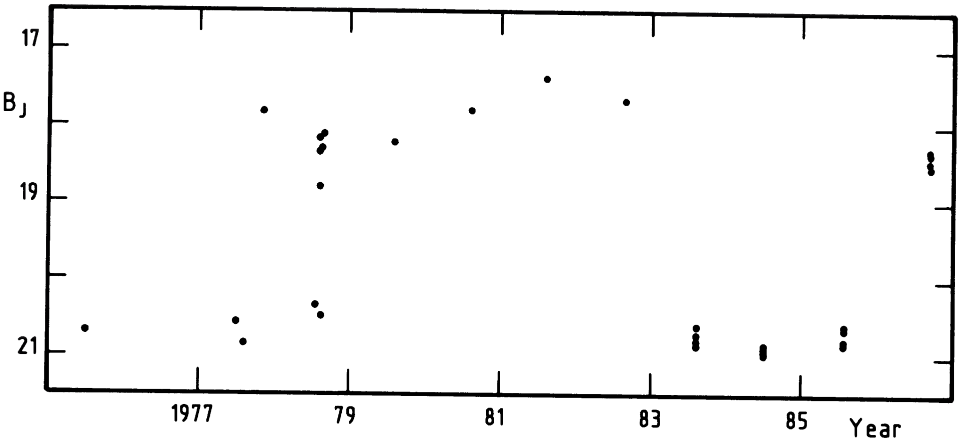

FIG. 1.—Long-term monitoring of Grus V1 between 1975 and 1986. The B_j magnitudes have been measured from UK Schmidt plates and have errors of 0.1 mag.

26 (not shown). A χ^2 folding analysis for the two nights has shown that the five light curves are all consistent with an unambiguously determined period of 108.6 ± 0.4 minutes. Defining phase zero to be the center of the maximum in the U-band light curve, we derive the following heliocentric ephemeris for Grus V1:

$$\mathrm{HJD}\ 2{,}446{,}698.9765 + 0.07537E.$$

47 35

We remark that no other periodicities in the range 10–200 minutes were revealed by our folding analysis, or by Fourier analysis.

In Figure 3 we show the average *UBVRI* light curves for Grus V1 produced by folding the approximately six cycles at a period of 108.6 minutes. Substantial differences in the five filters are evident. In the U band, the modulation is closely sinusoidal with a single peak at $\phi = 0.0$ (by definition), while in the B band, a second peak appears at a phase separation of $\Delta\phi = 0.5 \pm 0.04$ and progressively becomes more dominant toward R and I. This second *red* peak is much narrower than the *blue* peak; the FWHM of the blue peak measured relative to the minimum in the U-band modulation is $\Delta\phi \approx 0.44$, compared with a FWHM of $\Delta\phi \approx 0.17$ for the red peak measured in the R band (the red peak is present only during the brief phase interval $\phi \approx 0.4$–0.6). We also note that there is clear evidence for a progressive phase shift by $\Delta\phi \approx 0.1$ in the centroid of the blue peak between the U and I bands (in the sense that the peak in the I band occurs at a later phase).

The mean B magnitude and colors for Grus V1 averaged over the 108.6 minute period are as follows: $B \approx 18.5$, $U-B \approx -0.64$, $B-V \approx 0.53$, $V-R \approx 0.50$, and $R-I \approx 0.32$. We note that appreciable interstellar reddening is suggested by the position of the object on a two-color diagram for cataclysmic variables (Bruch 1984), but we cannot rule out the possibility that the observed colors are intrinsic to the emission process.

III. DISCUSSION

Our multicolor photometry and long-term monitoring of Grus V1 strongly indicate an AM Her classification. *First*, the binary period of 108.6 minutes lies within the narrow range of 100–115 minutes that characterizes eight of the 13 known AM Her systems (Liebert and Stockman 1985; Remillard *et al.* 1986; Morris *et al.* 1987; Beuermann *et al.* 1987). In fact, all but two of the nine AM Her systems with periods on the short side of the 2–3 hr period gap lie inside this narrow interval. *Second*, the highly repeatable modulation that we observe is typical of that expected from the changing aspect of an accretion column(s), rather than the erratic variability that is common for a system with an accretion disk. In particular, the clear evidence for emission from both a blue and a red component is most easily understood in terms of cyclotron emission from *two* accretion funnels near the surface of a magnetic white dwarf. This interpretation is pursued further below. *Third*, the high and low state behavior of Grus V1 is typical of the long-term variability of AM Her systems and is a consequence of large-scale changes of the accretion rate on to the white dwarf. *Fourth*, the intense He II emission relative to Hβ (Hawkins 1983) is a common property of magnetic variables (e.g., Watts 1985).

We conclude therefore from the cumulative evidence that Grus V1 is almost certainly a new AM Her variable, but we emphasize that polarimetry is necessary to confirm that the emission is predominantly cyclotron in origin, and that other variable sources of radiation are not significant (e.g., the heated secondary). We remark that while soft X-ray emission is a well-known characteristic of AM Her variables, the absence of the source in the *HEAO* A-2 soft X-ray catalog (Nugent *et al.* 1983) is to be expected in view of the optical faintness of the system, even in the high state. For example, using our average V magnitude and a mean value of $F_x/F_{\mathrm{opt}} \approx 32$ (derived from nine other AM Her variables in the units of Morris *et al.* 1987), combined with the IPC flux conversion ratio given in Vaiana *et al.* (1981), we obtain a rough prediction for the 0.2–4 keV flux of $F_x \approx 3 \times 10^{-12}$ ergs cm^{-2} s^{-1} (about an order of magnitude below the limit of the *HEAO* A-2 soft X-ray survey). Both the faintness of the source and the apparently reddened colors suggest that Grus V1 lies at a distance of at least a few hundred parsecs.

We turn now to an interpretation of the light curve behavior of Grus V1 in terms of an AM Her model in which the observed radiation arises from *two* distinct (blue and red) regions on the surface of the white dwarf. The *blue* emission region has the well-known characteristics of a cyclotron funnel that is viewed over a large range of angles θ to the magnetic field (cf. E1405−451; Bailey *et al.* 1983; Tuohy, Visvanathan, and Wickramasinghe 1985; Cropper, Menzies, and Tapia 1986). We identify the light minimum at $\phi = 0.5$ in the U band as corresponding to the phase when the blue emission region is viewed at $\theta = \theta_{\mathrm{min}}$, consistent with the reduced intensity of

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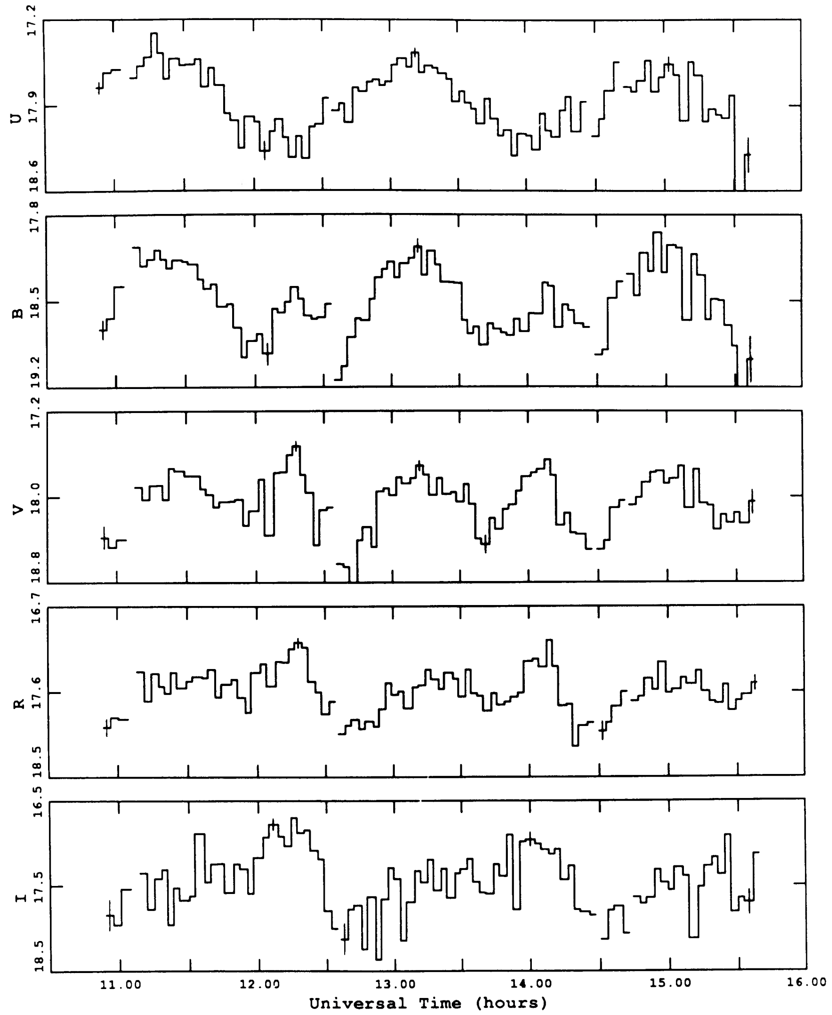

FIG. 2

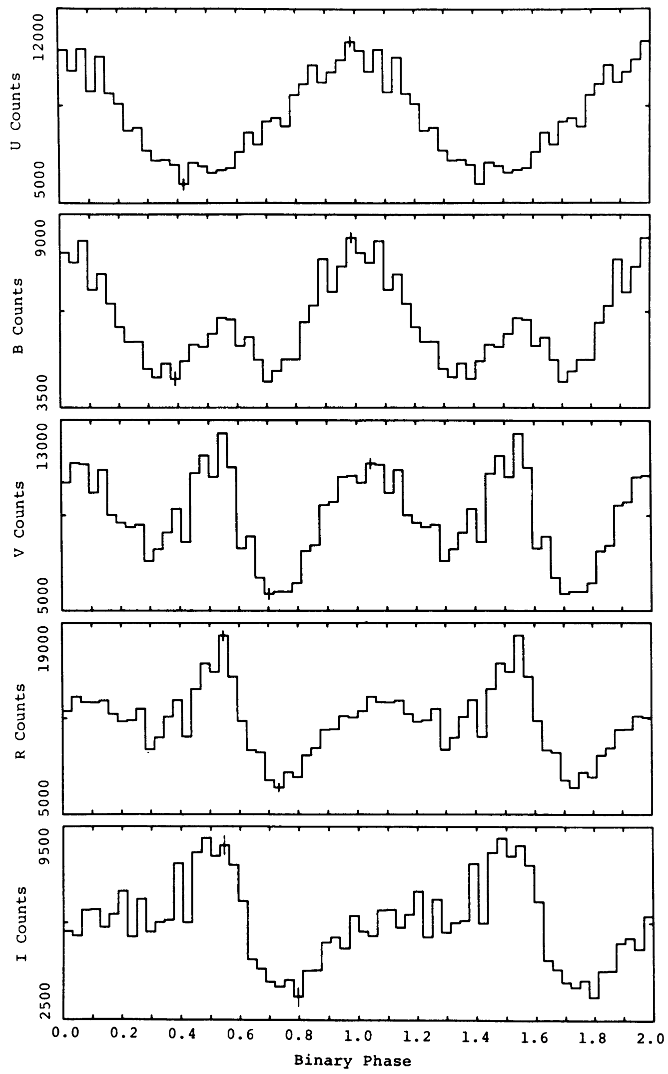

FIG. 3

FIG. 2.—Calibrated *UBVRI* light curves measured for Grus V1 on 1986 September 25 using the ANU 2.3 m telescope and a GaAs photomultiplier. Representative ± 1 σ Poisson error bars are plotted.

FIG. 3.—Average *UBVRI* light curves for Grus V1 produced by folding the data from September 25 and 26 at a period of 108.6 minutes. Two cycles of sky-subtracted counts are shown, together with representative ± 1 σ Poisson error bars.

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high harmonic cyclotron radiation at low angles to the field due to beaming. The phase delay with increasing wavelength noted earlier for the blue emission peak is most probably due to longitudinal density and temperature structure in an extended cyclotron region (e.g., Beuermann, Stella, and Patterson 1987; Wickramasinghe and Ferrario 1988). In any event, the blue region remains in the visible hemisphere of the white dwarf throughout the binary cycle ($\phi = 0.0$–1.0). The *red* region, on the other hand, is visible only between $\phi = 0.4$ and 0.6 and thus behaves as an *eclipsing* region which appears from behind the limb as the white dwarf rotates and is viewed at large angles to the field ($\theta \approx 80°$–$90°$) over a narrow phase interval (cf. VV Puppis; Cropper and Warner 1986; Wickramasinghe and Meggitt 1982).

We have constructed a simplified point-source model for Grus V1 to illustrate the main characteristics. A possible viewing geometry consistent with the above picture is depicted in Figure 4 and is specified by the following parameters: orbital inclination $i = 40°$, colatitude of the blue region $\Delta_b = 40°$, and colatitude of the red region $\Delta_r = 125°$. The blue and red regions share the same longitudinal great circle and are separated by 85°. We emphasize that there are other combinations of i, Δ_b, and Δ_r which can also satisfy the basic geometric constraints discussed earlier. At the same time, however, it is clear that the two emission regions cannot be diametrically opposed, or else there would be no overlap in their visibility between $\phi \approx 0.4$ and 0.6. The overlap is especially evident in the R and I bands of Figure 3.

The radiation properties of the blue and red regions depicted in Figure 4 have been computed assuming point source models following Wickramasinghe and Meggitt (1985). The parameters for the two regions are as follows:

$$T_e = 20 \text{ keV}, \Lambda = 1 \times 10^5, B = 2 \times 10^7 \text{ G (blue region)}$$

and

$$T_e = 10 \text{ keV}, \Lambda = 5 \times 10^6, B = 2 \times 10^7 \text{ G (red region).}$$

Here T_e is the electron temperature, Λ is the path length (opacity) parameter, and B is the magnetic field (assumed to be radial). We note that different electron temperatures for the two regions might arise as a consequence of unequal accretion rates. Figure 5 shows the resulting intensity and polarization curves averaged over the B and R bands. The two light curves are generally similar in appearance to the B and R data of Figure 3. Our preliminary model predicts a broad linear polarization pulse at $\phi = 0.0$ when the blue cyclotron region is viewed at $\theta \approx 80°$, and two barely resolved pulses at $\phi = 0.4$ and $\phi = 0.6$ corresponding to the appearance and disappearance of the red accretion funnel as the white dwarf rotates (i.e., at $\theta = 90°$). The circular polarization shows a reversal in sign between $\phi \approx 0.4$ and 0.6 when the red region is visible, and also a secondary minimum in the R band at $\phi = 0.0$ when the blue cyclotron funnel is viewed almost orthogonally to the field. It is emphasized that these polarization predictions are based on point-source models and, in reality, will differ somewhat as a consequence of source extension and magnetic field spread.

We note that Piirola, Reis, and Coyne (1987) have reported evidence for two cyclotron emitting regions separated in latitude by ~77° in the AM Her system, EF Eri. This separation angle is similar to that inferred in our model for Grus V1. In addition, Cropper (1987) can explain the light curve and

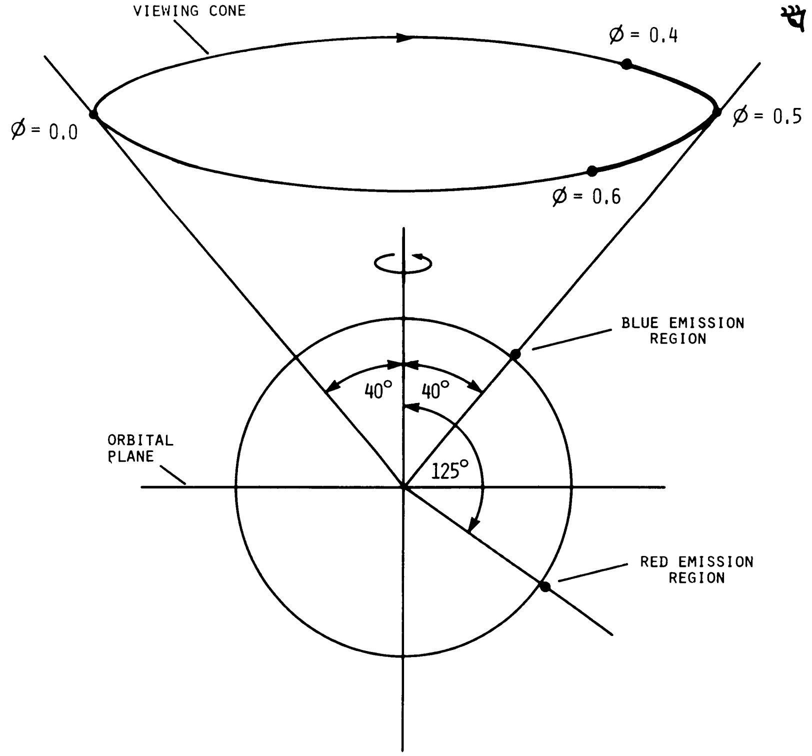

FIG. 4.—A *possible* geometry for Grus V1, showing the location of the blue and red cyclotron emitting regions at colatitudes of 40° and 125°, respectively. The viewing cone for an inclination angle of 40° is also depicted. Note that the blue region is never eclipsed and the viewing angle (θ) ranges between 0° and 80°, while the red region is only visible at viewing angles near 80° corresponding to $\phi \approx 0.4$–0.6 (the latter phase interval is indicated by the thickened section of the viewing cone).

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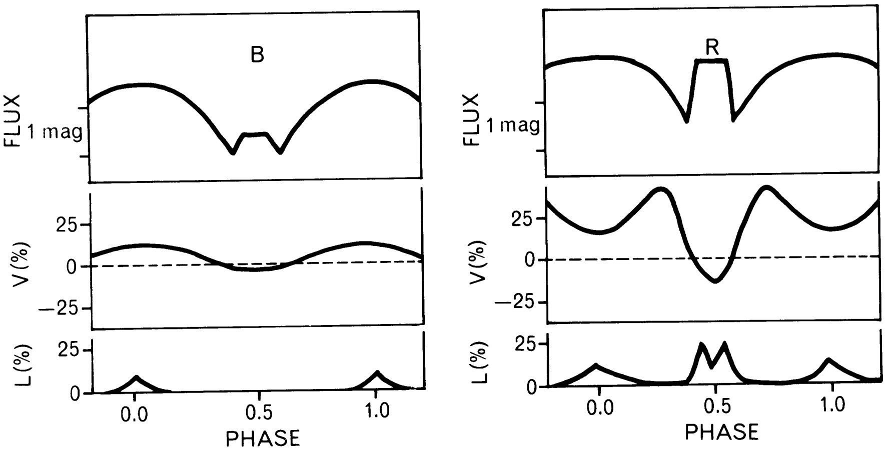

FIG. 5.—The predicted *B*-band and *R*-band intensity and polarization behavior for Grus V1, based on the simple point-source model discussed in the text. The shapes of the *B* and *R* light curves (*top*) are in approximate agreement with those of Fig. 3. Note the predicted reversal in the circular polarization (*V*) between $\phi = 0.4$–0.6 and the potential occurrence of three linear polarization pulses in the *R* band at $\phi = 0.0$, $\phi = 0.4$, and $\phi = 0.6$.

polarization behavior of BL Hyi in terms of emission from two accretion regions that are substantially less than 180° apart.

The occurrence of nondiametric cyclotron emitting regions in AM Her systems does not necessarily imply a complex magnetic field structure such as a quadrupole geometry. Instead, we prefer an accretion model in which the infalling material plunges well into the magnetosphere of the white dwarf before being threaded on to *nonpolar* field lines (Ferrario, Wickramasinghe, and Tuohy 1987, 1988). Such a model can also explain the radial velocity and velocity dispersion behavior of AM Her systems. An obvious consequence of the nonpolar accretion interpretation is that the two emitting regions can be substantially offset from the magnetic dipole axis, depending on the location of the threading region (which in turn depends on the accretion rate).

IV. SUMMARY REMARKS

To conclude, we have demonstrated from both observational and theoretical viewpoints that Grus V1 is most probably a new AM Herculis magnetic variable. It is the first to be selected on the basis of two-state optical variability and is distinguished from other members of the class by showing convincing evidence for two cyclotron emitting regions which are not 180° apart and which are characterized by differing emission properties. We have developed a simple model that can account for the characteristics of the multicolor light curves and also predicts the polarization properties of the source as a function of binary phase. Circular and linear polarimetry to test these predictions is highly desirable, but such measurements will be difficult in view of the faintness of the system, even in the bright state (AAT polarimetry of the object was attempted in 1987 August but was impossible following a return to the faint state). Nevertheless, such measurements are needed to secure the AM Her classification and to record the polarization behavior with phase so that the emission geometry of the system can be refined.

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REFERENCES

Bailey, J., Axon, D. J., Hough, J. H., Watts, D. J., Giles, A. B., and Greenhill, J. G. 1983, *M.N.R.A.S.*, **205**, 1P.
Beuermann, K., Stella, L., and Patterson, J. 1987, *Ap. J.*, **316**, 360.
Beuermann, K., Thomas, H. C., Giommi, P., and Tagliaferri, G. 1987, *Astr. Ap.*, **175**, L9.
Bruch, A. 1984, *Astr. Ap. Suppl.*, **56**, 441.
Cropper, M. 1987, *M.N.R.A.S.*, **228**, 389.
Cropper, M., Menzies, J. W., and Tapia, S. 1986, *M.N.R.A.S.*, **218**, 201.
Cropper, M., and Warner, B. 1986, *M.N.R.A.S.*, **220**, 633.
Ferrario, L., Wickramasinghe, D. T., and Tuohy, I. R. 1987, *Proc. Astr. Soc. Australia*, in press.
———. 1988, in preparation.
Hawkins, M. R. S. 1981, *Nature*, **293**, 116.
———. 1983, *Nature*, **301**, 688.
Liebert, J., and Stockman, H. S. 1985, in *Cataclysmic Variables and Low-Mass X-ray Binaries*, ed. D. Q. Lamb and J. Patterson (Dordrecht: Reidel), p. 151.
Morris, S. L., Schmidt, G. D., Liebert, J., Stocke, J., Gioia, I. M., and Maccacaro, T. 1987, *Ap. J.*, **314**, 641.
Nugent, J. J., *et al.* 1983, *Ap. J. Suppl.*, **51**, 1.
Piirola, V., Reis, A., and Coyne, G. V. 1987, *Astr. Ap.*, **186**, 120.
Remillard, R. A., Bradt, H. V., McClintock, J. E., Patterson, J., Roberts, W., Schwartz, D. A., and Tapia, S. 1986, *Ap. J.* (*Letters*), **302**, L11.
Tuohy, I. R., Buckley, D. A. H., Remillard, R. A., Bradt, H. V., and Schwartz, D. A. 1986, *Ap. J.*, **311**, 275.
Tuohy, I. R., Visvanathan, N., and Wickramasinghe, D. T. 1985, *Ap. J.*, **289**, 721.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **245**, 163.
Watts, D. 1985, in *Recent Results on Cataclysmic Variables* (ESA SP-236), p. 259.
Wickramasinghe, D. T., and Ferrario, L. 1988, *Ap. J.*, **327**, 222.
Wickramasinghe, D. T., and Meggitt, S. 1982, *M.N.R.A.S.*, **198**, 975.
———. 1985, *M.N.R.A.S.*, **216**, 857.

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