Post nova white dwarf cooling in V1500 Cygni

M.W. Somers and T. Naylor

Department of Physics, Keele University, Keele, Staffordshire, ST5 5BG, UK

Abstract. We use the irradiated secondary star in the remnant of Nova Cyg 1975 as a probe of the cooling white dwarf. At superior conjunction the flux in the B band is dominated by the irradiated face of the secondary star. The heated face produces an orbital modulation which is dependent on the strength of the irradiating source. We demonstrate that the cooling rate of the white dwarf is consistent with the theoretical model of Prialnik (1986).

Key words: stars: binaries: spectroscopic – stars: individual: V1500 Cyg – stars: novae, cataclysmic variables – stars: binaries: close – stars: binaries: eclipsing – stars: white dwarfs

1. Introduction

In many close binary systems the hotter star will heat one face of the cooler star. As the orbital motion of the binary brings this face into view the observed flux from the binary will increase, only to fall again as it rotates out of view. After a nova explosion, the hot white dwarf is an obvious candidate for heating its cool companion. Probably the best evidence is in V1500 Cyg (Nova Cyg 1975), where Schmidt et al. (1995) show that the secondary star dominates the photometric modulation. They fitted HST spectra with a red star whose unperturbed temperature was $\simeq$ 3000 K but whose face towards the white dwarf was $\simeq$ 8000 K.

There are three other novae for which there is photometric evidence for heating. The orbital modulation in DN Gem (Nova Gem 1912) was found by Retter, Leibowitz & Naylor (1999) to be well described by a heating model and DeYoung & Schmidt (1994) suggested heating could explain the lightcurve of V1974 Cyg (Nova Cyg 1992). Finally, Somers et al. (1996) found the infrared lightcurve of WY Sge (Nova Sge 1783) required a heated face to be modelled successfully. However, in this case the level of irradiation was so low that it could have been supplied by the accretion luminosity, as occurs in the dwarf nova IP Peg during outburst (Webb et al. 1999).

This led us to ask if there were further evidence available which would help us identify the source of irradiation in old novae as the white dwarf. It is particularly important to do so, as

the irradiated surface of the secondary star may be the most reliable diagnostic we have of the white dwarf luminosity, since its intrinsic radiation is produced in the far UV/soft X-ray regimes, where the effect of interstellar absorption will be very marked. If the irradiating object is the white dwarf, the irradiation should decrease on the white dwarf cooling timescale. Prialnik (1986) shows how the surface layers of a white dwarf are heated during a nova explosion and cool as a power law on a time scale of 200 yrs. (This is in contrast to the cooling of white dwarfs after their initial formation, which involves cooling of the entire star and occurs on a time scale of 10^8 years.)

2. History of the photometric modulation in V1500 Cyg

V1500 Cyg was a naked eye nova, reaching a peak magnitude of V=2.2 in late August 1975. It is thought to be currently a slightly asynchronous AM Her system. The magnetic nature of the white dwarf was first proved by the detection of circularly polarized light (Stockman et al. 1988). The present day photometric period (orbital) is 1.8% longer than the polarimetric period (white dwarf spin). Presumably the two were thrown out of equality by the nova explosion and observations suggest that they will re-synchronize in a time scale of 200 years (Schmidt & Stockman 1991).

Stockman et al. (1988) explain the photometric period evolution as follows:

• The expansion due to the nova explosion increases the moment of inertia of the white dwarf, causing its spin period to increase to 0.141d, breaking the synchronous rotation. At this point the photometric modulation is associated with the spin period of the white dwarf.

• Interaction between the secondary star and the envelope causes the envelope to be spun up to the binary period, strong coupling ensures that the core also achieves synchronism.

• The remnant envelope shrinks back onto the white dwarf surface, reducing its moment of inertia and thus decreasing the spin period to 0.137d.

Currently, therefore, V1500 Cyg displays two periods. There is a polarimetric signal at 0.137d which is the spin period of the white dwarf, and a photometric signal at 0.140d which is the orbital period of the binary. Aside from Schmidt et al's spec-

trophotometry outlined in Sect. 1, further evidence that the secondary star now dominates the photometric modulation comes from the fact that the timing of flux maximum in our own data matches the orbital ephemeris (see Sect. 4). It is also clear however, from the presence of flickering and the slightly asymmetrical B band light-curves, that there is some contamination of the orbital modulation. This could either be due to the accretion stream, or perhaps because the spin period of the white dwarf may also have a photometric signal (Pavlenko & Pelt 1988).

3. Modelling white dwarf cooling after surface heating

Prialnik (1986) modelled the evolution of a classical nova through a complete cycle; accretion, outburst, mass loss, decline and resumed accretion. The model is for a $1.25 M_\odot$ C-O white dwarf. The resulting outburst is fast and similar to that observed in V1500 Cyg, matching the composition of the ejected envelope very well. The white dwarf is modelled allowing for heat transfer via radiation, conduction (Iben 1975, Kovetz & Shaviv 1973) and convection (Mihalas 1978). The result may be fitted well with a power law cooling curve of the form

$$L \propto t^{-1.14}, \tag{1}$$

where L is the luminosity of the white dwarf and t is the time since outburst.

4. Observations

To extend the baseline of photometric amplitude decline we obtained one orbital cycle of B and V band photometry using the JKT on La Palma on the night of 1995 October 3. The TEK4 CCD was used with pixels binned 2 by 2 to achieve $0.6''$x$0.6''$ pixels in rapid readout mode. The seeing was around 2.0 arcsec. The exposures were typically of 120 seconds with filters being alternated between observations.

A bias frame was subtracted from each image, and it was then flatfielded using an image of the twilight sky. The counts for V1500 Cyg and various other stars were extracted from each frame using the optimal weighting procedure described in Naylor (1998). We divided the counts for V1500 Cyg by those for star C1 of Kaluzny & Semeniuk (1987), allowing us to put the lightcurves in Figs. 1 and 2 onto a magnitude scale.

The times of maximum and minimum agree, within errors, with the ephemeris of Semeniuk et al. (1995). The data do not show a pure heating modulation since there is some evidence of a dip in the light curve at time 2 449 994.61. Such dips are not uncommon, see for example the light-curves of Kaluzny & Semeniuk (1987) whose data are from 10 years earlier than our observations. These irregularities add errors in the estimation of the amplitude of the modulation (see Sect. 5).

5. The amplitude v time relationship

By searching through various sources a record of the B band photometric behaviour observed in V1500 Cyg since outburst has been assembled. Table 3.1 gives a list of all references used.
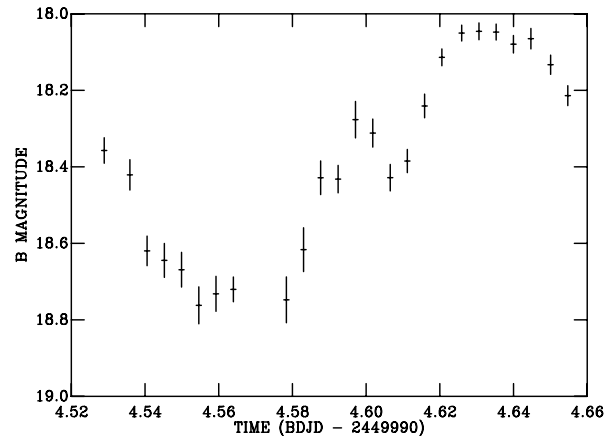

Fig. 1. The B band magnitude of V1500 Cyg plotted against Barycentric Dynamical Julian Date.
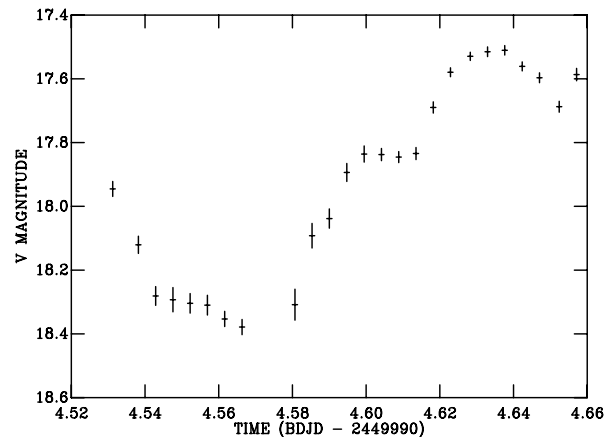

Fig. 2. The V band magnitude of V1500 Cyg plotted against Barycentric Dynamical Julian Date.

The amplitude of the B band photometric modulation versus the time since outburst is plotted in Fig. 3 on logarithmic scales. We immediately note that these points lie roughly in a straight line, implying a power law decay in time, although it should be noted that the first year of data have been omitted. While other authors have attempted to find a trend in the amplitude versus time data they relied on the amplitude in magnitude space. This is a measure of the amplitude relative to the brightness of other parts of the system. Clearly this is inappropriate for V1500 Cyg since the overall brightness in the B band changes due to a large variety of effects. The amplitude in flux space is a good probe of the irradiation since it does not need to be corrected for changes in relative brightness of other parts of the system. Hence, what we refer to as the "flux amplitude" is obtained by converting the magnitudes at orbital maximum and minimum into fluxes (assuming a star of B=0.0 gives 7.2×10^{-9} ergs cm^{-2} s^{-1} Å^{-1}), and differencing them. An unweighted straight line to these data give

$$A \propto t^{-1.26 \pm 0.21}, \tag{2}$$

where A is the flux amplitude, and the error bar corresponds to 1σ.

Table 1. The flux in the orbital modulation of V1500 Cyg.

Days from outburst	Flux amplitude (10^{-16} ergs cm^{-2} s^{-1} Å^{-1})	Reference
320	1060 ± 200	Kemp, Sykes &
329	720 ± 190	Rudy (1977)
357	310 ± 32	Patterson (1978)
714	35 ± 6	"
717	26 ± 6	"
718	30 ± 8	"
742	21 ± 5	"
779	39 ± 6	"
781	38 ± 8	"
803	34 ± 6	"
825	24 ± 8	"
1072	14 ± 0.6	Patterson (1979)
1105	12 ± 0.6	"
1172	22 ± 0.6	"
1172	18 ± 0.6	"
2167	61 ± 0.6	Horne &
2230	12 ± 0.6	Schneider (1989) [†]
4039	3.6 ± 0.6	Kaluzny &
4041	2.9 ± 0.3	Semeniuk (1987)
4305	3.1 ± 0.3	Kaluzny &
4306	3.9 ± 0.3	Chlebowski (1988)
4307	2.8 ± 0.3	"
4308	3.1 ± 0.3	"
7339	2.0 ± 0.3	This Work

[†] These points are from spectroscopy, band pass 4750–4790 Å.

It is apparent that there is an extra source of noise that acts on a short time scale compared with the general trend of amplitude decline. (Hence our choice of an unweighted fit.) This is likely to be due to the aforementioned orbital dips shifting around the orbital light-curve. The position of maximum light from the accretion columns with respect to the secondary star's photometric hump will vary with beat phase. This will cause the apparently random excess scatter in the photometric amplitudes.

6. The irradiating flux v time relationship

The bolometric flux amplitude from the secondary star will be proportional to the irradiating flux. However, the flux measured in any particular bandpass will not follow such a proportionality, as the bolometric correction will change with the temperature of the heated face. To extract how the irradiation is changing from the changing flux amplitude one must determine the response of the heated face of the secondary star to decreasing the heating. One may conveniently approximate the response as

$$A \propto F_{irr}^x \propto t^{x\eta}. \tag{3}$$

Here η is the power law decline predicted by Prialnik to be -1.14 while x is the response of the secondary star to heating. In fact x is not a constant but is a weak function of the temperature of the heated face of the secondary star. We therefore used the code described in Somers et al. (1996) to determine how the amplitude of the modulation changes with the irradiating flux. This
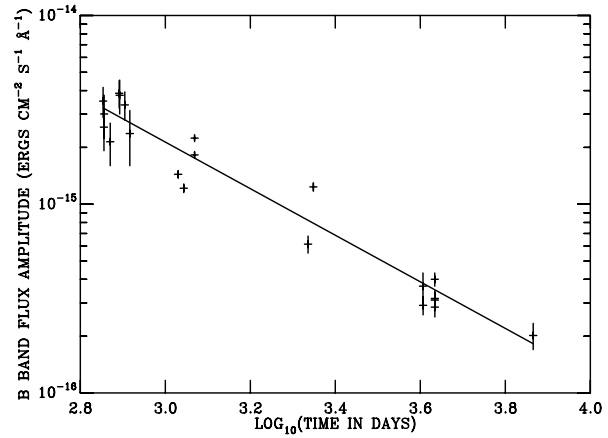
Fig. 3. The decaying photometric variability of V1500 Cyg

model irradiates a Roche-lobe filling star from a point source at the position of the white dwarf. The irradiation then raises the temperature of each surface element in impinges on, such that all the incident energy is re-radiated. We will also assume that the radiation from the secondary star can be approximated as a blackbody, an assumption we shall examine later. We used a mass ratio q=3, inclination i=60° and underlying secondary star temperature of 3000 K. These values are typical of those quoted for V1500 Cyg and the results are, in any case, insensitive to the exact values.

We began by irradiating a 3000 K secondary star such that the flux when the irradiated face was towards the observer was equivalent to a star of 8000 K, matching the front face temperature observed by HST. This model should correspond to the last data point in Fig. 3. The flux amplitude in Fig. 3 declines by a factor of $10^{1.2}$, and so we increased the irradiation in our model until the flux amplitude had increased by this factor. Over this range of interest, we found that

$$A \propto F_{irr}^{0.75} \tag{4}$$

represented the data to better than 25 percent for all values of F_{irr}. We also used tried using the bolometric correction and colours of model atmospheres given in Bessell et al. (1998) instead of blackbodies to represent the flux. We found this changed x by less than 0.06 in the low irradiation case, which is that most affected by the difference between model atmospheres and black bodies.

With a value for x we can now use the observations to derive a value of η by equating (2) to (3). This yields:

$$\eta = 0.94 \pm 0.09. \tag{5}$$

This result is just (2.2σ) consistent with the value Prialnik (1986) finds from purely theoretical considerations of $\eta = 1.14$. Especially given the nature of the approximations made, this seems to support the conclusion that the photometric variation in V1500 Cyg, and by implication other old novae, is caused by irradiation from the white dwarf.

7. Conclusions

The above shows that for at least the first 20 years from outburst the white dwarf cooling models match the available observations. Given the Prialnik-type cooling law, with the observed value of η, and the temperature of the irradiated face at some known time after outburst (from Schmidt et al. 1995) then we can calculate the typical time taken for irradiation of the surface to become negligible. The irradiation will drop off so that the incoming radiation is less than double the unheated surface luminosity of the secondary star about 280 ± 140 years after the outburst of V1500 Cyg. Interestingly, we find that in WY Sge, now over 200 years since nova outburst, the irradiation from the white dwarf has declined to these levels (Somers et al. 1996), although in that system the disc is a complicating factor. Thus both V1500 Cyg, and WY Sge suggest that white dwarfs really do cool as the theory predicts.

References

Bessell M.S., Castelli F., Plez B., 1998, A&A 333, 231
DeYoung J.A., Schmidt R.E., 1994, ApJ 431, L47
Horne K., Schneider D.P., 1989, ApJ 343, 888
Iben I., 1975, ApJ 196, 525
Kaluzny J., Chlebowski T., 1988, ApJ 332, 287
Kaluzny J., Semeniuk I., 1987, Acta Astron. 37, 349
Kemp J.C., Sykes M.V., Rudy R.J., 1977, ApJ 203, L131
Kovetz A., Shaviv G., 1973, A&A 28, 315
Mihalas D., 1978, Stellar Atmospheres. 2nd Edition, San Francisco, Freeman
Naylor T., 1998, MNRAS 296, 339
Patterson J., 1978, ApJ 225, 954
Patterson J., 1979, ApJ 231, 789
Pavlenko E., Pelt J., 1988, IBVS 3252
Prialnik D., 1986, ApJ 310,222
Retter A., Leibowitz E.M., Naylor T., 1999, MNRAS 308, 140
Schmidt G.D., Stockman H.S., 1991, ApJ 371, 749
Schmidt G.D., Liebert J., Stockman H.S., 1995, ApJ 441, 414
Semeniuk I., Olech A., Nalezyty M., 1995, Acta Astron. 45, 747
Somers M.W., Mukai K., Naylor T., 1996, MNRAS 278, 845
Stockman H.S., Schmidt G.D., Lamb D.Q., 1988, ApJ 332, 282
Webb N.A., Naylor T., Ioannou Z., et al., 1999, MNRAS 310, 407