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# OBSERVATIONS OF RAPID BLUE VARIABLES—XIV

## Z CHAMAELEONTIS

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## SUMMARY

Z Cha is a dwarf nova and an eclipsing binary with a period of 107 min. We have made high speed photometric observations both at normal light and during outburst.

The observations at normal light lead to a model for the system in which the bright spot is abnormally situated. Non-synchronous rotation of the secondary may account for this. The eclipse, which is total, shows the disappearance of both the white dwarf primary and the bright spot.

During outburst the eclipses get wider and become partial. These observations clearly establish that the outburst is centred on the primary. The eclipses at maximum light show that the whole disc around the primary is bright. It is suggested that the disc is heated by a thermal pulse or shock wave originating in the outbursting white dwarf. A simple model for the subsequent cooling of the disc leads to a disc mass of $10^{-5}\,M_\odot$.

Oscillations in the light curve with a period of 27·67 s were present during outburst.

## 1. INTRODUCTION

The well-established fact that all novae, recurrent novae and dwarf novae are close binary stars has lead to plausible explanations of the cause of the outbursts of these cataclysmic variables. Whereas there is general agreement that in the case of the novae the explosion is a result of hydrogen accretion on to the white dwarf component; in the case of the dwarf novae some controversy has existed. Although Saslaw's (1968) work has shown that the white dwarf explosion model is capable of providing the ranges of energy and time scale that are observed in the cataclysmic variables, an alternative is possible for the dwarf novae. Paczynski (1965) showed that the cooler components (which we will refer to as the secondaries) of semi-detached binaries may be unstable as a result of the loss of mass from their surfaces. This theory has been developed further by Osaki (1970) and Bath (1969, 1972) and appears capable of explaining the energetics and light curves of dwarf novae but is unable to provide the high velocities of ejection seen in classical novae.

The incentive for developing the 'secondary hypothesis' came from Krzeminski's (1965) interpretation of his extensive observations of U Gem during outbursts. His observations show that the primary eclipse, which is present at minimum light, stays approximately constant in depth (in intensity) during outburst and as a result is essentially absent at maximum light. As it was assumed that the white dwarf was obscured during primary eclipse, this would indicate that the white dwarf does not participate in the outburst.

A way out of this situation was independently proposed by Warner & Nather (1971) and Smak (1971). In their model the eclipse is of a bright spot on a disc surrounding the primary, and the orbital inclination is such that the primary itself is not eclipsed even at maximum light. The constant depth of eclipse thus only implies that the bright spot does not change in brightness during outbursts.

This alternative model, although more consistent with the observations than Krzeminski's model, lacks positive evidence that it is the primary that explodes. Such evidence is, however, indirectly available in the discovery (Warner & Robinson 1972a) of periodic oscillations in the light curves of dwarf novae during outburst. The periods (16–34 s) are far too short to be attributable to the secondaries but are readily understandable if they are non-radial oscillations of the primaries.

Direct evidence of which star outbursts can come from radial velocity observations during outburst—the exploding star develops absorption lines, the radial velocity variations of which can be phased with those seen at minimum. Unfortunately U Gem itself has not been observed in this manner. Radial velocities of SS Cyg (Walker & Chincarini 1968; Walker & Reagan 1971) provide almost unquestionable evidence that the primary is outbursting in this dwarf nova, but orbital period changes observed in this system may still result in the question remaining open.

If the alternative U Gem model is correct, we might hope to see a radically different behaviour of eclipses during outburst if we can find a system with high enough orbital inclination for the primary to be eclipsed at maximum light. Among the dwarf novae, only U Gem, EX Hya and Z Cha are known to show eclipses. U Gem we have already seen does not provide straightforward answers; EZ Hya (Mumford 1964; Warner 1972) has shallow minima of irregular depth apparently caused by partial eclipses of an active bright spot and during outburst will probably behave in a manner similar to U Gem; Z Cha is very promising—it has eclipses (Mumford 1969) 2 mag deep suggesting high orbital inclination, perhaps sufficient to ensure eclipses of the primary during outburst. As a result, Z Cha was placed at top priority in the author's survey of southern hemisphere cataclysmic variables. As the mean outburst period is $96^{d}\cdot 2$ (Bateson 1973, private communication) it is not easy to catch it during outburst. However, its declination of $-76°$ ensures a long observing season. Although the frequency of the author's observing should not have given success until after about 3 yr of persistent observation, serendipity saved the day (night) when Z Cha was observed near maximum on only the second attempt.

## 2. OBSERVATIONS

Photometric observations of Z Cha were made at the Sutherland site of the South African Astronomical Observatory. In 1972 December and 1973 April, when Z Cha was at minimum light, the 40-in. Elizabeth reflector was used; in 1973 January, during an outburst, the 20-in. reflector was used. The data acquisition system was similar to that previously described (Nather & Warner 1971). In all cases ' white light ' was used, i.e. all photons detectable by our Amperex 56 DVP photomultiplier were counted. As Z Cha is strong in ultraviolet light, we have used an extinction coefficient of 0·70 mag in reducing the light curves.

Table I contains details of the observing runs. The heliocentric time of start refers to the beginning of the run; in general the first few channels were used for measuring the sky brightness. The light curves are displayed in Figs 1–8; two separate runs were made on January 9; ingress of the eclipse of January 10 is affected by clouds; the run on January 11 was terminated by clouds and is not shown. A comparison of stars observed with both telescopes shows that the photon count rate on the 20-in. may be scaled up by the expected factor of 4 for comparison with the 40-in. count rate.

Table I

*Observing log*

| Date | JD☉ (start) 2441000+ | Integration time (s) | Depth of eclipse (mag) | Run no. | Fig. |
|---|---|---|---|---|---|
| 1972 Dec. 8 | 660·43588 | 5 | 1·60 | 107 | 1 |
| 1972 Dec. 9 | 661·50387 | 4 | 1·75 | 109 | 2 |
| 1973 Jan. 8 | 691·41566 | 5 | 1·75 | 130 | 4 |
| 1973 Jan. 9 | 692·32444 | 5 | 1·27 | 131 | 5 |
| 1973 Jan. 9 | 692·44062 | 5 | 1·24 | 132 | 6 |
| 1973 Jan. 10 | 693·34006 | 5 | 1·60 | 133 | 7 |
| 1973 Jan. 11 | 694·40300 | 5 | — | 135 | |
| 1973 Jan. 12 | 695·42380 | 5 | 2·06 | 137 | 8 |
| 1973 April 11 | 784·25184 | 5 | 2·40 | 149 | 3 |

## 3. Z CHA AT MINIMUM LIGHT

Mumford (1969) discovered that Z Cha is an eclipsing binary with a period of 107 min. He later (Mumford 1971) gave elements for eclipse minima based on observations over the period 1969 February–July. Times of eclipse minima derived from our observations are given in Table II. Using Mumford's epoch and our December and April observations, during which Z Cha was at normal light, we derive the following revised elements:

$$\text{Minimum light} = \text{JD}_\odot\ 2440264{\cdot}6828 + 0^{\text{d}}{\cdot}07449923\text{E}.$$

Comparison of observed and calculated times of minima are also given in Table II.

Table II

*Times of minima in Z Cha*

| JD☉ (min) 2441000 | O–C |
|---|---|
| 660·5002 | −0·0002 |
| 660·5747 | −0·0002 |
| 661·5435 | 0·0001 |
| 691·4177 | 0·0001 |
| 691·4923 | 0·0002 |
| 691·5668 | 0·0002 |
| 692·3858 | −0·0003 |
| 692·4605 | −0·0001 |
| 693·3542 | −0·0004 |
| 695·4400 | −0·0005 |
| 784·3182 | 0·0001 |

As can be seen from Figs 1–3, at minimum light Z Cha shows periodic features very similar to those found in U Gem (Krzeminski 1965; Warner & Nather 1971) and several other cataclysmic variables. The hump in the light curve, lasting for approximately half the orbital period, shows the same increase in flickering activity at its peak as was found in U Gem. The onset of the hump, which is due to the first appearance of the bright spot around the limb of the disc that surrounds the white dwarf, is very well defined and occurs at phase 0·657. The maximum of the hump is approximately 0·16 $P$ after the first appearance of the spot, whereas we should expect it 0·25 $P$ after. A similar situation exists in U Gem (Smak 1971) and is interpreted as a reduction of light before primary eclipse due to gradual eclipse of the disc. Similarly, after primary eclipse, the brightness of the system is slightly diminished until the disc is fully out of eclipse.

The primary eclipse shows a sudden onset followed by an extremely rapid drop in brightness. At about 62 per cent of the way down to minimum there is a pause lasting approximately 20 s, after which the decline to minimum is relatively slower. Eclipse minimum shows a gently rounded or flat bottom. There is a very rapid rise in the first stage of egress, during which the increase of intensity is closely equal to the initial drop at ingress. The duration of both of these rapid light changes is about 50 s. The final stages of egress show a more gradual recovery of brightness. The width of eclipse at half depth is 340 s. Although the duration of minimum is very short, the scatter of points there is entirely consistent with shot noise and atmospheric scintillation, suggesting that as in U Gem and other eclipsing cataclysmic variables (Warner & Nather 1972a) the flickering activity disappears during eclipse. The depth of primary eclipse—at minimum the intensity is about 15 per cent of the brightness at phase 0·5—and the almost flat bottom indicate that eclipse is total. We may also conclude that the secondary contributes very little light to the system, which is why no secondary eclipse is apparent. We see in Table I that the depth of eclipse (in ultraviolet) at normal light is variable over a range of about 0·8 mag. Mumford (1971) found a range of about 0·4 mag in $V$.

The most significant feature for the interpretation of the structure of Z Cha is the first appearance of the bright spot at phase 0·657. This is much later in phase than occurs for U Gem and VV Pup (0·605 and 0·567, respectively: Warner & Peters (WP) 1972). This implies that the bright spot in Z Cha is relatively closer to the line joining the centres of the stars than is the case for U Gem and VV Pup. In the notation of WP we have $\alpha+\beta = 33^\circ$ for Z Cha. This lies well outside of the range of values possible if the inter-star stream follows the single-particle trajectories of low velocity ejection from the inner Lagrangian point (see WP).

To proceed further we must form an estimate of the mass ratio $q$ ($=M_2/M_1$). In the other ultrashort period binaries we find $q<0{\cdot}15$ for EX Hya ($P$ = 98 min) and $q<0{\cdot}076$ for WZ Sge ($P$ = 82 min) from the absence of radial velocity variations in the emission lines from the disc. Warner & Nather (1972b) and WP give $q \sim 0{\cdot}1$ for VV Pup ($P$ = 100 min) on the basis of spectroscopic and photometric data. Warner (1973a) has shown that there is a close correlation between $P$ and $q$ for cataclysmic variable stars, so we expect that $q$ also will be small in Z Cha.

The width of eclipse at half depth, which is equivalent to 19° in angular extent, when combined with the geometry of a binary system whose secondary fills its Roche Lobe, sets a lower limit of $q \gtrsim 0{\cdot}085$. In absence of radial velocity information, we adopt $q = 0{\cdot}085$, which is equivalent to assuming that the orbital inclination $i$ is 90°. The results we obtain are not changed in their essentials for $85^\circ \leq i \leq 90^\circ$; on the basis of the depth of eclipse we feel confident that $i \gtrsim 85^\circ$ (the eclipse would just be grazing if $i = 80^\circ$).

The geometry of Z Cha for $q = 0{\cdot}085$ is shown in Fig. 9. The condition $\alpha+\beta = 33^\circ$ given above provides a circle on which the bright spot must be situated.

We find from this that the line of eclipse of the white dwarf is close to the line along which the bright spot will be eclipsed. This suggests an interpretation of the phenomena observed during eclipse. The rapid fall at the beginning of eclipse is attributed to eclipse of the white dwarf; this is shortly followed by eclipse of the bright spot. After totality, the white dwarf emerges first, followed by the bright spot.

With this model, the time difference from when the white dwarf is half eclipsed to when the bright spot if half eclipsed is ~70 s and this provides a further line along which the bright spot must be located. The intersection of the two loci lies at a radius vector $r = 1{\cdot}2 \times 10^{10}$ cm, or $r/a \simeq 0{\cdot}21$. For $q = 0{\cdot}1$, WP predict $r/a = 0{\cdot}24$ based on ejection of low velocity particles. The agreement is sufficiently good for us to continue with further implications of the model.

Warner (1973a) has shown that $M_1 \sim 1{\cdot}2\, M_\odot$ in cataclysmic variables. We adopt this mass for Z Cha. Then the relative orbital velocity of the two components is $5{\cdot}5 \times 10^7$ cm s$^{-1}$. The time from 1st to 2nd contact of eclipse of the primary is ~50 s, giving a radius of $1{\cdot}4 \times 10^9$ cm, which is certainly of white dwarf dimensions.

The radius of the bright spot is similarly determined from its (very uncertain) eclipse duration of ~50 s and is also $1{\cdot}4 \times 10^9$ cm. As seen from the white dwarf, the bright spot would then have an angular diameter ~20°. This is a factor of about 3 larger than was estimated for VV Pup (Warner & Nather 1972b). Some supporting evidence for the larger spot diameter comes from the fact that whereas in VV Pup the spot appearance around the edge of the disc is rapid (taking only 125 s), in Z Cha no such sudden appearance is seen. A spot diameter ~20° would imply that the spot should be visible for ~200° of orbital revolution, i.e. the hump should last for ~0·56 *P*. The light curves in Figs 1–3 do not allow the time of disappearance of the hump to be precisely determined, but the impression is that the hump certainly lasts considerably longer than 0·5 *P*.

The onset of eclipse of the disc at minimum light is not always locatable. For example, just prior to the first eclipse in Fig. 1 the flickering activity masks the details of the initial decrease. However, the second eclipse in Fig. 1 and the eclipse in Fig. 8 both show a well-defined drop starting at about phase 0·935. If we identify these with first contact of the disc we deduce an angular extent of 46° for the disc. With the geometry of Fig. 9 this gives a disc radius of $1{\cdot}3 \times 10^9$ cm, which is in good accord with the radius vector of the bright spot found earlier.

A comparison of the ultrashort-period binaries is instructive. Both EX Hya and VV Pup possess large amplitude flickering, showing that the bright spot dominates and as a result neither show absorption lines from the primary. On the other hand, WZ Sge has low amplitude flickering (Warner & Nather 1972c) and clearly shows the broad absorption lines from the white dwarf (Greenstein 1957). If our model of Z Cha is correct, the white dwarf contributes approximately 60 per cent of the light at phase 0·5 so we would predict that the emission lines from the disc will appear superimposed on shallow absorption lines from the primary. Good quality spectra are required to check this; the same spectra could provide radial velocities of the emission lines thus enabling a check to be made of the small value of $q$ adopted in this paper.* The variability of depth of eclipse (Table I) is presumably caused by variations in average brightness of the disc and spot.

* Dr M. W. Feast at the Radcliffe Qbservatory has obtained some weakly-exposed spectra that show the presence of broad, probably doubled, emission lines similar to those seen in EX Hya and VV Pup. The spectra are not adequate for a discussion of radial velocities.

The position and size of the bright spot in Z Cha do not agree with the calculations of WP. A possible explanation is that the secondary is not rotating synchronously with the orbital revolution. The particle trajectories calculated by Kruszewski (1964) show that for non-synchronous rotation, the inter-star stream will meet the disc at a point much closer to the line of centres of the stars and that the stream will be more spread out than is the case for synchronous rotation.

## 4. Z CHA AT MAXIMUM LIGHT

The average outburst cycle for Z Cha is 96 days. The star normally is bright for only two or three days. However, at an average interval of 313 days Z Cha has a much brighter outburst and remains bright for an average of 10 days (Bateson 1973). Such a 'supermaximum' started on 1973 January 2. The star was still bright when the author commenced his observing run on the night of January 8. The light curve is shown in Fig. 10; the first part is constructed from visual estimates obtained by members of the Variable Star Section of the Royal Astronomical Society of New Zealand; the second part is from mean magnitudes determined from the author's observations (an arbitrary vertical adjustment has been made because our magnitudes refer to ultraviolet light). It can be seen that the first of our observing runs in January (run 130) should be representative of Z Cha at maximum, and by the final run Z Cha was almost back to minimum light.

The sequence of light curves is shown in Figs 4–8. At maximum, the primary eclipse is symmetrical except for a slow recovery during the last stages of egress. Z Cha was about 13 times brighter on January 8 than the brightness at phase 0·5 during normal light. The outbursting star therefore was contributing at least 92 per cent of the light from the system. The presence of deep eclipses shows that the outbursting star was being largely obscured; the rounded bottom to the eclipses on January 8 suggests a partial or annular eclipse. From Table II we see that the eclipse minima throughout outburst occur very close to the times predicted from primary minima observed at normal light. This establishes that the same star is eclipsed at minimum and maximum light, and therefore that in Z Cha the primary or its disc is the seat of the outbursts.

In U Gem, Krzeminski (1965) found phase shifts of up to 0·015 *P* on the position of primary eclipse during outbursts. Smak (1971) has attributed these to partial eclipse of the centre of the (brightened) disc which, because of the off-centre location of the bright spot, will occur at different phase than that of the bright spot. In Z Cha we see no significant phase shift in eclipse minima despite the fact that our Run 130 was made near maximum light. This is entirely consistent with the model derived for Z Cha in the previous section; because the eclipse at normal light is predominantly caused by eclipse of the white dwarf, when it brightens during outburst the eclipse minima will remain fixed in orbital phase.

In Fig. 4, the hump due to the bright spot is lost in slow variations in brightness of unknown origin, but in Fig. 5 the hump is clearly defined and has an amplitude of ~750 counts $s^{-1}$ (with the 20-in. telescope). At minimum light (Figs 1 and 3) the amplitude is ~1000 counts $s^{-1}$ (on the 40-in. telescope). The bright spot therefore is a factor ~3 brighter at a time when the system as a whole is a factor ~10 brighter than normal. In Fig. 5, if we have correctly assigned the hump to a spot of increased luminosity, we also see evidence that the spot has increased greatly in size: the hump is visible for at least 0·7 *P*.

In Figs 4–8 we see the primary eclipse evolve from symmetrical with a rounded bottom to being asymmetrical with a flattened bottom. It is evident that we are witnessing the gradual change in size of the outbursting star. Such a sequence of observations is probably unique in the annals of astronomy—as far as the author is aware, no other eclipsing binary has demonstrated gross changes in size of one of the components.

The difference in shape of primary eclipse at maximum and minimum light is better shown in Fig. 11. At maximum, the eclipse has width at half depth of 350 s (i.e. essentially identical to that seen at minimum light) but its width from first contact to last contact is $\sim 825$ s (*vs* $\sim 400$ s at minimum). The similarity of eclipse width at half depth shows that the eclipsing body has a constant diameter; the increase in total width apparently implies, with the geometry of Fig. 9, an increase in radius of the white dwarf from $\sim 10^9$ cm (Section 3) to $\sim 1{\cdot}3 \times 10^{10}$ cm.

The radius of the secondary in our model is $0{\cdot}95 \times 10^{10}$ cm. We therefore ask the following question: if the secondary has a radius $\sim 0{\cdot}7$ times the deduced radius of the outbursting primary, how can we produce eclipses that (Fig. 4) are 80 per cent deep? The answer lies in the non-spherical nature of the outburst. We discuss this in a more general context in the next Section.

## 5. THE NATURE OF DWARF NOVA OUTBURSTS

At maximum light, *UBV* photometry of dwarf novae has shown (Krzeminski 1965; Grant & Abt 1959) that their energy distributions resemble blackbodies with temperature $\sim 15\,000$ K. Spectra at maximum show that any absorption or emission lines present are too weak to significantly affect the broad-band colours. The mean amplitude of outburst for dwarf novae is about 3·5 mag. At minimum light the dwarf novae have absolute magnitudes $M_V \simeq +7{\cdot}5$ (Kraft & Luyten 1965). Adopting a bolometric correction of 2·0 mag we have $M_{\text{bol}} \simeq 2{\cdot}0$ at maximum for dwarf novae. From these data we may derive a radius from the relationship for spherical stars (Allen 1963):

$$\log R = 19{\cdot}31 - 2 \log T_e - 0{\cdot}2\, M_{\text{bol}}$$

which gives $R \simeq 3{\cdot}6 \times 10^{10}$ cm. This result is in fact insensitive to the assumed parameters—increasing $T_e$ to 50 000 K or putting $M_V = +9{\cdot}5$ at minimum both decrease $R$ by only a factor of about two.

This result, added to the more directly observed radius of $1{\cdot}3 \times 10^{10}$ cm deduced in the previous Section, underlines the fact that at maximum light dwarf novae must have radii $\sim 10^{10}$ cm.

At minimum light there can be no doubt that the primary is a white dwarf with radius $10^9$ cm. As evidence we may cite (i) the white dwarf absorption spectrum seen in WZ Sge (which is sometimes classified as a long-period dwarf nova, rather than a recurrent nova), (ii) the masses of $\sim 1{\cdot}2\, M_\odot$ derived for the primaries (Warner 1973b) despite the faint absolute magnitudes (Kraft & Luyten 1965) for these objects, (iii) the primary radius found in Section 3. Another important fact, long overlooked, is the extensive wings to the emission lines observed in the dwarf nova SS Cygni (Elvey & Babcock 1943; Walker & Chincarini 1968). The emission lines arise in the disc that rotates differentially around the primary. The maximum extent of the emission wings gives the projected velocity of rotation of the disc near the primary. In SS Cyg the wings extend to 3000 km s$^{-1}$. This system is not an eclipsing binary, but it has broad emission cores, so orbital inclination will be $\sim 60°$. The equatorial rotational velocity is then 3500 km $s^{-1}$. This is equal to the Keplerian velocity around a white dwarf of mass $\sim 1{\cdot}0\ M_\odot$.

It is not possible for the white dwarf to expand in radius to $\sim 10^{10}$ cm during a dwarf nova outburst. The total energy radiated during an outburst is only $\sim 10^{39}$ erg; there is no evidence of any mass loss during outburst. The mass of the non-degenerate envelope lying above the core of a white dwarf is $\sim 10^{-5}\ M_\odot$; the binding energy of this envelope is $\sim 10^{45}$ erg. In order to increase the radius of the envelope by a factor of ten $\sim 10^{45}$ erg is therefore required—the amount observed in classical nova outbursts where the envelope is ejected as a nova shell.

We are thus confronted with the apparently incompatible facts that at maximum light we deduce a radius $\sim 10^{10}$ cm, but the white dwarf itself cannot attain that radius. The solution to the problem is clear if we consider the nature of the disc.

From the cyclical changes of orbital period seen in cataclysmic variables, Smak (1972) has inferred that there must be extensive angular momentum exchange between the disc and the secondary. This led Smak to deduce a lower limit for the mass of the disc of $\sim 10^{-4}\ M_\odot$, which implies a mean disc density $> 10^{-2}$ g $cm^{-3}$. With such a high density, the disc acts almost as an extension of the outer envelope of the primary. When the white dwarf erupts the thermal pulse that runs through the outer layers of the star will also pass through the disc. At maximum light, therefore, the entire disc will be luminous. We then see that it is no coincidence that the radii at maxima deduced from the *UBV* photometry of dwarf novae are closely equal to the disc radii obtained from observations at minimum light (for example, Warner & Nather (1971) found a disc radius of $3{\cdot}0 \times 10^{10}$ cm in U Gem). We also now have a possibility of understanding the increase in disc radius during outburst and subsequent shrinkage (Smak 1971): a rise in temperature increases the viscosity of the disc, causing increased transfer of angular momentum outwards and a consequent expansion of the disc.

The above hypothesis enables us to understand the eclipse phenomena at maximum of Z Cha. With the high inclination in Z Cha we see the disc almost edge on. The thickness of the disc is not known, but to judge from the model of WZ Sge given by Krzeminski & Smak (1971) it is thin compared to its radius. At maximum light, therefore, eclipses are of an elongated bar having dimensions $\sim 4 \times 10^{10}$ cm by $4 \times 10^{9}$ cm by a star with diameter $2 \times 10^{10}$ cm. Partial eclipses are thus inevitable, and deep eclipses are possible because of the approximately elliptical projection of the disc. Without a model for the distribution of light in the disc at maximum, it is not possible to use the eclipse curves to deduce more of the geometric properties of the system. By comparing the eclipse curves in Fig. 4 with ones predicted for eclipse of a uniformly illuminated ellipse, the author has found that the disc must be brighter in the centre than at its edge.

We will explore some other implications of our model of dwarf novae outbursts. Warner & Robinson (1972a) found short period light oscillations in dwarf novae during outburst. These were interpreted as non-radial oscillations of the white dwarf primaries. In our model, the oscillations will be confined to the primary and therefore have frequencies characteristic of white dwarfs; the disc is almost in a 'zero-g' state and will not be capable of supporting short period pulsations. However, as most of the light from the system at maximum arises from the (non-pulsating) disc, we have an explanation of the very low amplitude of the oscillations seen at maximum (0·001–0·005 mag) of the dwarf novae discussed by Warner & Robinson and the larger amplitude (0·01 mag) seen in VW Hyi (Warner & Brickhill 1974) when it was found oscillating when almost back to normal light after a supermaximum.

There is a well-known period–amplitude relationship for the outbursts of cataclysmic variables. This shows considerable scatter among the dwarf novae which may now be partly attributable to differing geometric aspects of the discs. Thus in Z Cha, which despite its long recurrence timescale, has an average outburst amplitude of only $\sim 2$ mag, we view the disc edge-on and we surmise that if viewed perpendicular to the disc the amplitude would be much larger.

Spectra of dwarf novae during outburst show wide absorption lines, which we now attribute to rotational broadening in the disc rather than pressure broadening in the white dwarf atmosphere. Independent evidence on the distribution of light in the disc may be obtainable from such spectra: the width of the absorption lines will be characteristic of that part of the disc emitting most light. Thus the observations by Herbig (1950) of absorption line widths giving $v \sin i \simeq 1060 \text{ km s}^{-1}$ just after maximum of UZ Ser, increasing to $v \sin i \simeq 1900 \text{ km s}^{-1}$ a few days later suggests that at maximum most of the light is emitted by the outer regions of the disc, but that later the inner regions dominate. This undoubtedly is connected with the expansion and contraction of the disc noted above.

Elsewhere it has been suggested (Warner & Van Citters 1974) that some nova-like variables are Z Cam stars permanently stuck at standstill. Such objects may have permanently luminous discs and we expect to see rotationally broadened absorption lines from them. One of the suggested candidates, which does show broad absorptions, is UX UMa. The analysis of UX UMa eclipses by Warner & Nather (1972d) indicated that the eclipsed object had a radius $\sim 10^{10}$ cm, rather than $10^9$ cm anticipated for a white dwarf. This is consistent with the above hypothesis. The slow recovery at the end of egress (Fig. 4) in Z Cha is very similar to that often seen in UX UMa (Warner & Nather 1972d, and references cited therein).

Finally, in U Gem Smak (1972) and Warner & Nather (1971) concluded that the white dwarf primary and the inner parts of the disc, are not eclipsed at normal light. However, at maximum light Smak shows that the change in position of the eclipse is due to partial eclipse of the disc which has brightened considerably. On the way up to maximum no eclipse of the disc is seen. This establishes that the outburst starts in the centre of the disc and propagates outwards.

## 6. LIGHT CURVES OF DWARF NOVAE

In our model for the outburst of a dwarf nova the initial rise in luminosity is caused by a thermal pulse or shock wave originating in the white dwarf and passing through the disc. The peak luminosity will correspond roughly to the termination of shock heating. Thereafter the disc cools on a radiative diffusion timescale. In what follows, we determine the light curve of the cooling phase of a dwarf nova disc from a simplified model. This leads to an independent determination of the mass $M$ of the disc.

We assume that the disc has radius $R$, thickness $2d$ and a uniform density $\rho$. If $d \ll R$ we may ignore the cooling at the edge of the disc and consequently the disc temperature will be independent of radial position.

The luminosity of the disc as a function of time is then

$$L(t) = -\frac{d}{dt}\int_0^d aT^4(h,t)\, 2\pi R^2\, dh$$

$$= -2\pi a R^2 \frac{d}{dt}\int_0^d T^4(h,t)\, dh.$$

We assume that the internal temperature distribution is given by the Eddington approximation, which for a thin disc is

$$T^4(h,t) = \frac{L(t)}{4\pi\sigma R^2}\left(1+\tfrac{3}{2}\tau\right)$$

where $\tau = \kappa\rho(d-h)$ and $\kappa$ is the absorption coefficient. These equations are integrated to give

$$L(t) = L(0)\exp\left[\frac{-ct}{2d\left(1+\frac{3}{4}\kappa\rho d\right)}\right]$$

where $c$ is the velocity of light.

For large optical depth $\kappa\rho\, d \gg 1$, we have

$$L(t) = L(0)\exp\left(-\frac{8\pi R^2 c}{3\kappa\, dM}\right) t.$$

The outburst light curves of most dwarf novae show a nearly constant rate of decline of $\sim 0{\cdot}25$ mag per day. Therefore

$$\frac{3\kappa\, dM}{8\pi R^2 c} \sim 3{\cdot}5\times 10^5\ \mathrm{s}.$$

Adopting $R = 2\times 10^{10}$ cm, $d = 2\times 10^9$ cm and $\kappa = 0{\cdot}33$ cm$^2$ g$^{-1}$ (for electron scattering) we find

$$M \sim 6\times 10^{28}\ \mathrm{g}$$

$$= 3\times 10^{-5}\, M_\odot$$

lies within the range of $10^{-6}$–$10^{-4}\, M_\odot$ deduced by Smak (1972) on dynamical grounds.

At the maximum of the outburst, the total energy stored in the disc is

$$E = \int_0^d 2\pi R^2 a T(h,0)\, dh$$

$$= \tfrac{3}{8} L(0)\frac{\kappa M\, d}{\pi R^2 c}.$$

This energy is equal to the $\sim 10^{39}$ erg radiated during the whole outburst so that, with the parameters adopted above, we have $L(0) \sim 6\times 10^{33}$ erg s$^{-1}$. Therefore at maximum light, the effective temperature of the disc is given by

$$2\pi R^2 \sigma T^4 = 6\times 10^{33}$$

which gives $T \sim 1{\cdot}4\times 10^4$ K. This is in good agreement with temperatures deduced from photometry of dwarf novae at maximum light.

## 7. PERIODICITIES DURING OUTBURST

High speed photometry of other dwarf novae has shown the presence of rapid oscillations during outburst (Warner & Robinson 1972a; Robinson 1973; Warner & Brickhill 1974). These oscillations have been found to be sinusoidal, of low amplitude, and with periods in the range 16–34 s.

Power spectra have been calculated for all our runs of Z Cha. Details of the method are given by Robinson & Warner (1972). Despite the fact that the white dwarf contributes a substantial fraction of the light at minimum (Section 3) no periodicities were found. However, the power spectrum of the first half of Run 130, made near maximum light, shows a strong periodic signal with a period of 26·7 s (Fig. 12). No harmonics to this period are visible, again showing that the oscillations are pure sinusoids. The power spectrum of the second half of the Run 109 shows no significant features.

In order to make a more detailed study of the oscillations we have filtered the data and computed periodograms using the methods given by Warner & Robinson (1972b). The periodogram of the first half of Run 109 (inset Fig. 12) confirms the presence of a coherent signal with a period of 26·67 ± 0·01 s.

Inspection of the light curve, heavily filtered to retain only power near 27-s period, shows that the coherent oscillations are detectable up to $JD_\odot$ 244691·485 (i.e. just before the second eclipse in Fig. 4) but not afterwards. There is evidence that the oscillations are absent during the first eclipse at least until midway through egress. From a mean light curve constructed at the 26·67 period we find that the mean amplitude of the oscillations is 18 counts per second, or 0·033 mag.

TABLE III

*Periodicities in dwarf novae*

| Star | Periods (s) | Tel (in.) | $I_A$ ($10^3$ c/s) | $A$ (mag) | $A$ (c/s) | $I_{min}$ ($10^3$ c/s) | $\frac{I_A}{I_{min}}$ | $\frac{10^3 A}{I_{min}}$ |
|---|---|---|---|---|---|---|---|---|
| Z Cam | 16·01–18·83 | 82 | 560 | 0·0009 | 500 | 20 | 28 | 25 |
| SY Cnc | 24·62 | 36 | 37 | 0·003 | 110 | 5·2 | 7 | 21 |
| CN Ori | 25·00–24·27 | 82 | 54 | 0·005 | 270 | 7·7 | 7 | 35 |
| KT Per | 26·73–26·82 | 36 | 13·7 | 0·0058 | 80 | 2·7 | 5 | 30 |
| Z Cha | 27·67 | 20 | 5·4 | 0·0033 | 18 | 0·45 | 13 | 40 |
| VW Hyi | 28–34 | 40 | 30 | 0·010 | 300 | 7·0 | 4 | 43 |
| AH Her | 31·26–31·98 | 82 | 130 | 0·003 | 390 | 15 | 9 | 26 |

The discovery of rapid oscillations in Z Cha brings the total of dwarf novae known to show this phenomenon to seven. These are listed in Table III. Two other objects, UX UMa and CD −42°14462, both having periods near 29 s may be dwarf novae in a permanent outburst state as discussed earlier. In Table I we have included details of the photon count rate $I_A$ at the time that oscillations were seen, the average count rate $I_{min}$ at normal light, and the mean amplitude $A$ of the oscillations (both in magnitudes and counts per second). As a variety of telescopes (at McDonald and Sutherland Observatories) have been employed for these studies we list the telescope used in each case; the photometers were essentially identical at all times so scaling according to the squares of their apertures should be adequate.

One general correlation is apparent: the largest relative amplitudes (i.e. $A$ in magnitudes) occur when the systems are relatively faintest ($I_A/I_{min}$ is smallest).

This is understood in terms of the model proposed in Section 5 where we suggested that most of the light arises from the non-oscillating disc. A corollary of this hypothesis is that the true amplitudes are considerably larger than those measured. Another trend is that the absolute amplitudes ($A$ in c/s) are correlated with $I_{\text{min}}$. Thus, whereas $A$ in magnitudes ranges over a factor of 13, the values of $A/I_{\text{min}}$ have a range of only a factor of 2. If we conjecture that all dwarf novae at minimum light have approximately the same intrinsic brightness, $I_{\text{min}}$ will be a measure of the distance. The small range of $A/I_{\text{min}}$ then indicates that the *intrinsic* amplitudes of the oscillations are almost the same from star to star.

In the case of UX UMa (Warner & Nather 1972d) and CD −42°14462 (Warner 1973b) the values of $10^3\, A/I_{\text{A}}$ are 2·0 and 3·3 respectively. For these stars we cannot measure $I_{\text{min}}$ as they seem to be permanently at standstill. If the absolute amplitudes of the oscillations in these stars are similar to those in Table III, we see that $I_{\text{A}} \sim 10\, I_{\text{min}}$, i.e. they are 2½ mag above minimum. This is typical of the standstill in Z Cam stars and further strengthens our hypothesis concerning the nature of UX UMa and CD −42°14462.

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## REFERENCES

Allen, C. W., 1963. *Astrophysical quantities*, Athlone Press, London.
Bath, G. T., 1969. *Astrophys. J.*, **158**, 571.
Bath, G. T., 1972. *Astrophys. J.*, **173**, 121.
Elvey, C. T. & Babcock, H. W., 1943. *Astrophys. J.*, **97**, 412.
Grant, G. & Abt, H. A., 1959. *Astrophys. J.*, **129**, 323.
Greenstein, J. L., 1957. *Astrophys. J.*, **126**, 23.
Herbig, G. H., 1950. *Publ. astr. Soc. Pacific*, **62**, 211.
Kraft, R. P. & Luyten, W. J., 1965. *Astrophys. J.*, **142**, 1041.
Kruszewski, A., 1964. *Acta Astr.*, **14**, 231.
Krzeminski, V., 1965. *Astrophys. J.*, **142**, 1051.
Krzeminski, V. & Smak, J., 1971. *Acta Astr.*, **21**, 133.
Mumford, G. S., 1964. *Publ. astr. Soc. Pacific*, **76**, 57.
Mumford, G. S., 1969. *Sky Telesc.*, **37**, 288.
Mumford, G. S., 1971. *Astrophys. J.*, **165**, 369.
Nather, R. E. & Warner, B., 1971. *Mon. Not. R. astr. Soc.*, **152**, 209.
Osaki, Y., 1970. *Astrophys. J.*, **162**, 621.
Paczynski, B., 1965. *Acta. Astr.*, **15**, 89.
Robinson, E. L., 1973. *Astrophys. J.*, **183**, 193.
Robinson, E. L. & Warner, B., 1972. *Mon. Not. R. astr. Soc.*, **157**, 85.
Saslaw, W. C., 1968. *Mon. Not. R. astr. Soc.*, **138**, 337.
Smak, J., 1971. *Acta. Astr.*, **21**, 15.
Smak, J., 1972. *Acta. Astr.*, **22**, 1.
Walker, M. F. & Chincarini, G., 1968. *Astrophys. J.*, **154**, 157.
Walker, M. F. & Reagan, G. H., 1971. *Inf. Bull. Var. Stars. No.* **544**.
Warner, B., 1972. *Mon. Not. R. astr. Soc.*, **158**, 425.
Warner, B., 1973a. *Mon. Not. R. astr. Soc.*, **162**, 189.
Warner, B., 1973b. *Mon. Not. R. astr. Soc.*, **163**, 25P.

Warner, B. & Brickhill, A. J., 1974. *Mon. Not. R. astr. Soc.*, **166,** 673.
Warner, B. & Nather, R. E., 1971. *Mon. Not. R. astr. Soc.*, **152,** 219.
Warner, B. & Nather, R. E., 1972a. *Sky Telesc.*, **43,** 82.
Warner, B. & Nather, R. E., 1972b. *Mon. Not. R. astr. Soc.*, **156,** 305.
Warner, B. & Nather, R. E., 1972c. *Mon. Not. R. astr. Soc.*, **156,** 297.
Warner, B. & Nather, R. E., 1972d. *Mon. Not. R. astr. Soc.*, **159,** 429.
Warner, B. & Peters, W. L., 1972. *Mon. Not. R. astr. Soc.*, **160,** 15.
Warner, B. & Robinson, E. L., 1972a. *Nature*, **239,** 2.
Warner, B. & Robinson, E. L., 1972b. *Mon. Not. R. astr. Soc.*, **159,** 101.
Warner, B. & Van Citters, G. W., 1974. *Observatory*, in press.

## NOTE ADDED IN PROOF

After this paper was completed, the author received a preprint from Drs S. Starrfield, W. M. Sparks and J. W. Truran giving results of calculations of thermonuclear runaways in white dwarf stars. These authors find that they are able to predict the light curves of classical novae but their models for lower energy outbursts do not agree with the observed light curves of dwarf novae. They then point out that the dwarf novae can be understood when the disc surrounding the white dwarf is included in the model. The expanding outer layers of the outbursting white dwarf collide with the disc and heat it with shock waves. Starrfield *et al.* propose that the light curves of dwarf novae are principally caused by the heating and subsequent cooling of the disc. They have thus arrived by theoretical arguments at the same model for dwarf novae as has been proposed on observational grounds in this paper. Rather than rewrite parts of the present paper to make it more consistent with the paper of Starrfield *et al.*, the author has felt it to be of more value to leave it in its original form so that readers may compare the independent approaches to the same model of dwarf novae.