The massive white dwarf in the recurrent nova T CrB

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Abstract

We have obtained I-, J-, H- and K-band light curves of the recurrent nova T CrB. We find that we can fit the J-band light curve only with a Roche lobe filling secondary star and a dark spot of radius 11°–26° (90 per cent confidence) centred at the inner Lagrangian point. We obtain limits to the binary inclination of 38°–46° (90 per cent confidence) which, when combined with the value for the mass function, allow us to determine the mass of the compact object to be 1.3–2.5 M_⊙ (90 per cent confidence). This mass range is consistent with the Chandrasekhar limiting white dwarf mass, and so we provide evidence needed to support the outbursts in recurrent novae in terms of a thermonuclear runaway process on the surface of a massive ~ 1.4-M_⊙ white dwarf.

Key words: stars: fundamental parameters – stars: individual: T CrB – novae, cataclysmic variables – white dwarfs – infrared: stars.

1 Introduction

T CrB is a well-studied recurrent nova with an M-giant component. It underwent nova-like outbursts in 1866 and 1946, with light curves which were very similar. They are characterized by having a fast rise to maximum and by a secondary, fainter maximum occurring ~ 100 d later. The secondary maximum has a very slow decay time (> 10 yr).

Two competing models have been suggested to account for the peculiar outburst behaviour. One suggestion is that the outburst is due to a thermonuclear runaway (TNR) on the surface of a white dwarf primary. If this is the case, then the short recurrence time implies that the white dwarf must have a mass very close to the Chandrasekhar limit (1.4 M_⊙; Chandrasekhar 1939), and that the ejected envelope should be relatively small (Webbink 1976a). Alternatively, Plavec, Ulrich & Polidan (1973) and Webbink (1976a) proposed that the hot component is a normal main-sequence star, with eruptions being caused by sudden mass accretion events. This model can nicely account for a fading of the system before the outburst and the double maximum in the outburst light curve; however, one is confined to a main-sequence accretor. Selvelli, Cassatella & Gilmozzi (1992) have found evidence from IUE spectra that the accretor is a white dwarf. They point to three pieces of evidence: (1) the bulk of the luminosity is emitted in the ultraviolet, with little contribution from the hot component in the optical, (2) strong He II and N V emission lines suggest temperatures of ~ 10^6 K, and (3) the observed rotational broadening of the high-excitation lines is great.

Sandford (1949) first detected radial velocity variations in the emission lines, while Kraft (1958) established the spectroscopic period of the system to be 227.6 d. Kraft (1958) also derived a mass ratio (q = M_1/M_2) of 0.71 (where M_1 is the mass of the giant component) based in part on radial velocities extracted from emission lines originating in material accreting on to the primary. We now view radial velocities derived from such emission lines as unsound, and thus reject his value for q. Kenyon & García (1986) obtained a lower limit to the binary mass ratio of 2.5 by determining an upper limit to the rotational broadening of the giant star.

In this paper we present a photometric study of the ellipsoidal variations of the M giant. By fitting the J-band light curve, we determine the binary inclination and hence the mass of the compact component.

2 Photometric Observations

The infrared observations were taken at the Crimean Astrophysical Observatory of Sternberg Astronomical Institute using an InSb photometer on the 1.25-m telescope. We obtained J (12500 Å), H (16500 Å) and K (22000 Å)-band photometry of T CrB during the period 1987–1995 (see Table 1). Most of the data have an accuracy of better
than 0.02 mag. The standard star BS 5947 was used as a comparison star, and BS 5972 as a check star.

The I (8500 Å) -band data were taken through a Johnson (1966) filter with the 0.6-m Thornton Reflector at Keele Observatory during 1994–95 using a Santa Barbara Instruments ST-6 CCD camera mounted at the f/4.5 Newtonian focus. The dark current was subtracted for each image using a median stack of several dark frames. Relative photometry was carried out using the routine described in Shahbaz, Naylor & Charles (1994).

The individual data for each band were then folded on the ephemeris given by Kenyon & Garcia (1986), and then binned in orbital phase (see Fig. 1).

The observed ellipsoidal variations are primarily due to the giant star presenting differing aspects of its distortion as it orbits a compact object. By measuring the amplitude of this modulation, the binary inclination can be determined (see Shahbaz, Naylor & Charles 1993, and references within). The J-band data cover ∼11 orbital cycles, and the individual points fit the same light curve. This suggests that the M giant does not vary its intrinsic brightness by more than a few hundredths of a magnitude (Yudin & Munari 1993). The erratic and quasi-periodic variations, with amplitudes larger than the ellipsoidal modulation of the M giant, make interpretation of the optical light curves very difficult (Webbink 1976b; Lines, Lines & McFaul 1988; Peel 1990).

These effects decrease at longer wavelengths, and they should be absent in the infrared, where the emission from the M-giant star dominates. The amplitude of our I-band light curve is ∼0.35 mag, which is more than a factor 2 greater than that expected for the ellipsoidal variations of the M giant inclined at 40° (see Section 4). In the light of the quasi-periodic behaviour of the optical light curves, we fit only the J-band light curve, where one expects these uncertainties to be reduced.

### 4 THE CLASSICAL MODEL

In the M star of a cataclysmic variable secondary, the envelope is deeply convective. Sarna (1989) obtained the gravity-darkening using a modified form of Lucy’s (Lucy 1967) gravity-darkening law appropriate for a star with a convective envelope. One can model the ellipsoidal variations as a function of the binary mass ratio $q$, the inclination $i$, the effective temperature of the secondary star $T_{\text{eff}}$, the limb-darkening coefficient, and the gravity-darkening exponent $\beta$.

Using the ellipsoidal model described in Shahbaz et al. (1993), we performed a least-squares fit to the J-band light curves, grid-searching the variables $q$ and $i$. We used $T_{\text{eff}} = 3500$ K, $\beta = 0.08$ and $i$ in the range 20°–90°. From optical spectroscopy, Kenyon & Garcia (1986) estimate that the mass ratio must be at least 2.5. We therefore searched $q$ in the range 2.0–10.0. The appropriate limb-darkening coefficient for each wavelength and temperature was extrapolated using the values given by Al-Naimiy (1978). We obtained a minimum $\chi^2 = 2.9$ at $q = 3$, $i = 48°$. As one can see, this fit (dotted line in Fig. 2) does not describe the data well.

In an attempt to explain the large difference between the minima we explored fits using different values for the gravity-darkening exponent. We computed fits by grid-searching the variables $q$, $i$ and $\beta$. As explained in Appendix A, we find that the blackbody assumption for the $H$- and $K$- band data is poor. Therefore, in what follows we only use the J-band data where the blackbody assumption is more robust. Fig. 3 shows the $\chi^2$ fit in the $\beta$–$i$ plane, obtained by collapsing the minimum-$\chi^2$ solutions along the $q$ axis on to the $\beta$–$i$ plane. In effect, we have let $q$ run as a free parameter. We obtained a minimum $\chi^2$ of 2.5 at $q = 3$, $i = 43°$ and $\beta = 0.20$. The limits derived are $i = 35°–51°$ and $\beta = 0.05–0.36$ (68 per cent confidence). The 68 and 90 per
cent confidence regions (solid and dashed lines respectively) are shown, calculated according to Lampton, Margon & Bowyer (1976) for two parameters, after the error bars have been scaled to give a minimum $\chi^2$ of 1. The solid line in Fig. 2 shows the best fit to the $J$-band light curve. As one can see, the fit to the data points near phase 0.5 is not very good. There is still an extra component which is introducing an uncertainty of about 60 per cent to the light curves. In the next section we try to explain the large difference between the minima in the $J$-band light curves in terms of a dark spot located at the inner Lagrangian point.

5 THE NEED FOR A DARK SPOT

Star spots have been observed in other interacting binary stars, in particular in those systems in which the mass-losing component is a late-type star, e.g. RS CVn systems (Rodono 1983). Also, there is much stellar activity associated with M stars. Peel (1990) presents marginal evidence for stellar activity in T CrB near phase 0.5 from the observations of ultraviolet flares (Ianna 1964) and the visual brightening of T CrB.

In an attempt to explain the large difference between the minima of the $J$-band light curve, we fit the light curve with the ellipsoidal modulation of the secondary star plus a dark spot. Since the maxima in the light curve are almost equal, for simplicity we centred the spot around the inner Lagrangian point ($L_1$). The spot is described as a circle extending to a latitude $R_{\text{spot}}$ away from the $L_1$ point. The effective temperature in the dark spot region is lower than it would have been in the absence of the spot by 750 K. This is the typical observed temperature difference in RS CVn systems and T Tauri stars (Rodono 1986).

Using the nominal value for the gravity-darkening exponent for a convective star (0.08), we obtained fits in the $q, i$ and $R_{\text{spot}}$ plane. We find $\chi^2_{\text{min}} = 2.6$ at $i = 40^\circ$ and $R_{\text{spot}} = 20^\circ$. The 90 per cent confidence limits are $i = 38^\circ - 46^\circ$ and $R_{\text{spot}} = 11^\circ - 26^\circ$ (see Fig. 4). Lowering the spot temperature by a further 250 K changes the inclination by $<1^\circ$. The dashed line in Fig. 2 shows the best fits to the $J$-band light curve using a dark spot of size $20^\circ$. As one can see, the fit to the light curve has improved.

That using large values for $\beta$ gives fits of similar quality to that using a dark spot placed around the $L_1$ point is not surprising. If we look at the temperature distribution across the secondary star for $\beta = 0.08$ and 0.20 (see Fig. 5), then one can see that the effect of high values for $\beta$ is to simulate two regions of low temperature around the inner Lagrangian point and the opposite hemisphere of the secondary star. This effect can to some degree be reproduced by adding a dark spot round the $L_1$ point.
6 THE EVOLUTIONARY STATUS OF THE SECONDARY

In this section we use theoretical equations which describe the luminosity and radius of the giant star in order to determine the predicted mass transfer rate. For evolved secondary stars, i.e., stars on the first red giant branch and asymptotic giant branch stars, Joss, Rappaport & Lewis (1987) give the results of fitting the luminosity ($L$) and radius ($R$) core mass ($M_c$) relations to numerical models, for $0.17 \leq M_c \leq 1.4 \ M_\odot$. They give the parametrizations

$$L_c = \frac{10^{-2} M_c^6}{1 + 10^{10} M_c^4 + 10^{20} M_c^6},$$

$$R_c = \frac{3.7 \times 10^7 M_c^8}{1 + M_c^4 + 1.75 M_c^4},$$

As noted by King (1988), there is little radius expansion for $M_c \geq 0.7$, and so the mass transfer rates will be very low. However, for $M_c \leq 0.7$ the denominators in the above equations are $\sim 1$. So, if mass transfer is to occur, the stellar radius $R_c$ must equal the Roche lobe radius given by Paczynski’s formula (Paczynski 1971),

$$R \approx \frac{1}{2} \frac{M_2}{M_1 + M_2} \left( \frac{M_1 + 2 M_2}{M_1 + M_2} \right)^{1/3},$$

Eliminating the binary separation $a$ by use of Kepler’s law with the binary period of 227.53 d, the requirement $R_1 = R_c$ implies

$$0.0011 = \frac{M_c}{M_2^{0.5}}.$$

The limiting cases for $M_1$ are given by the extreme values of $M_2$. We must have $M_2 \geq M_1$, while the secondary would have not left the main sequence if $M_2/M_1$ were less than the Schönberg–Chandrasekhar limiting value of 0.17, implying $M_2 \leq 5.88 \ M_\odot$.

Following King (1993), we find the following values for the two limiting cases (see Table 2). The limiting cases give $M_2$, which, when used in equations (1) and (2), give $L_c$ and $R_c$. Use of Stefan’s law then gives $T_{\text{eff}}$ (King 1988) gives the mass transfer rate as a function of $M_c$ and $M_2$,

$$-\dot{M}_2 = 6.4 \times 10^{-6} L_\odot M_\odot \ M_\odot \text{yr}^{-1},$$

which can also be used to obtain the predicted mass transfer rates for the two limiting cases. The lower limit to the compact object mass can also be determined by using the value of the mass function and assuming maximum inclination and the two limiting values for $M_2$. The maximum and minimum solutions correspond to T CrB being near the beginning and the end of its evolution respectively. One can see that the observed spectral type for the secondary star, M3III ($T_{\text{eff}}=3500$ K), and the observed average mass accretion rate of $2.3 \times 10^{-8} \ M_\odot \text{yr}^{-1}$ (Selvelli et al. 1992) lie in between the predicted solutions.

7 DISCUSSION

7.1 The mass of the white dwarf

Here we determine limits to the mass of the compact object using the limits derived for the binary inclination by fitting the $J$-band light curve. Using the equation for the mass function $f(M) = 0.30 \pm 0.01 \ M_\odot$ (Kenyon & Garcia 1986), with values for $i$ and $M_1$, we can determine $M_2$. Fig. 6 shows the $M_1$, $M_2$ solutions at the 68 and 90 per cent confidence levels. We also show the limits placed on the mass ratio of $>2.5$ and the evolutionary constraints on the mass of the secondary star (see Section 6). It can be seen that the mass of the compact object is forced to lie in the range 1.3–2.5 $M_\odot$ (90 per cent confidence).

Harrison, Johnson & Spyromilio (1993) and Ramseyer et al. (1993) show low-resolution $K$-band spectra of T CrB. They find that the spectra resemble that of a late-type giant
The massive white dwarf in the recurrent nova T CrB

star, and comparison with M giants from Kleinmann & Hall (1986) suggests a spectral type of M2–M5III. Fig. 7 shows the flux distribution of T CrB. The optical and infrared magnitudes were taken from Munari et al. (1992) and were dereddened using $E(B-V)=0.15$ (Selvelli et al. 1992). As one can see, the flux distribution of T CrB can be well described by a M3III Kurucz model atmosphere spectrum (Kurucz 1992). Both the infrared spectra and the flux distribution of T CrB suggest that there is little contamination of the infrared flux. A 10 per cent contamination of the $J$-band flux would increase the binary inclination by $\sim 3^\circ$, which would decrease the mass of the compact object by only $\sim 0.3 \, M_\odot$.

### 7.2 The nature of the white dwarf

The main ingredients of the TNR models proposed to explain the outburst behaviour in recurrent novae are as follows.

1. The luminosity at maximum light needs to be greater than the Eddington luminosity.
2. The mass accretion rates during quiescence must be high.
3. The white dwarf must be very massive ($\sim 1.4 \, M_\odot$).

Selvelli et al. (1992) have shown that the outburst in T CrB was indeed superEddington, and that the mass accretion rate during quiescence is very high ($2.3 \times 10^{-8} \, M_\odot \, yr^{-1}$). In the TNR model the white dwarf mass needs to be close to the Chandrasekhar maximum mass for a white dwarf of 1.4 $M_\odot$, or else it cannot accrete enough material from the red giant companion in a short enough time to produce the short recurrence time.

We have obtained limits to the mass of the compact object to be 1.3–2.5 $M_\odot$, which is consistent with the Chandrasekhar maximum mass for a white dwarf of 1.4 $M_\odot$ (Chandrasekhar 1939). In Fig. 8 we show for comparison the mass distribution of white dwarfs, taken from Ritter & Kolb (1995). The compact object cannot be a neutron star because of the observed nova explosions; in neutron stars the strong gravitational potential prevents material being ejected. Our mass estimates for the compact object are such that we can support a massive 1.4-$M_\odot$ white dwarf, thus providing support for the presently untested predictions of TNR theory, namely that recurrent novae occur on massive white dwarfs. White dwarfs with masses $>1.2 \, M_\odot$ and mass accretion rates $>10^{-8} \, M_\odot \, yr^{-1}$ are expected to be net
accretors (Livio & Truran 1992). Since white dwarfs are not generally born with masses of $1.4 \, M_\odot$, our mass determination implies that the white dwarf is a net accretor; eventually it will exceed the Chandrasekhar critical mass and become a type Ia supernova.

8 CONCLUSIONS

We have tried to fit the observed J-band light curve of T CrB with the classical Roche lobe filling secondary star model with a gravity-darkening exponent of 0.08. However, in order to explain the large difference between the minima in the J-band light curve, we find that we can fit the light curve only with the addition of a dark spot centred at the inner Lagrangian point. We obtain the 90 per cent confidence limits to the binary inclination of $38^\circ$–$46^\circ$, which, when combined with the mass function, gives the mass range for the compact object as $1.3$–$2.5 \, M_\odot$ (90 per cent confidence). This mass range is consistent with the Chandrasekhar limiting white dwarf mass $\sim 1.4 \, M_\odot$.

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APPENDIX A

In our model for the ellipsoidal variations of T CrB, we have assumed that each element on the surface of the secondary star emits blackbody radiation of a given temperature. The temperature of each element is governed by the gravity-darkening law that is adopted, depending on the structure of the envelope of the secondary star. A real M giant will obviously not emit as a blackbody, but have rather a complex spectrum with many late-type absorption features. The flux emanating per unit surface area of such an atmosphere may be significantly different from that for a blackbody of the same temperature. We can estimate the accuracy of the blackbody assumption for observations taken through different passbands by comparing the ratio of the blackbody fluxes to the model atmosphere fluxes for different temperatures.

The amplitude of an elliptical light curve can to some degree be approximated by determining the ratio of flux emitted at two different temperatures, governed by the mean temperature of the secondary star at phases 0.0 and 0.5. In order to estimate this temperature change, we computed the ellipsoidal models with no surface temperature variation ($\beta=0.0$) and the maximum expected variation ($\beta=0.25$; see von Zeipel 1924). We then calculated the mean temperature difference between the gravity-darkened inner face of the secondary and the unaltered uniform inner face of the secondary, and we found that the inner face of the secondary is on average cooler than the rest of the star by about 400 K.

We estimated the accuracy of the blackbody assumption by determining the magnitude difference between blackbody spectra at 3500 and 3100 K (after they have been folded through the response of the J, H and K filters) and comparing these values with those obtained using model atmospheres. The model atmosphere spectra for log $g=4.0$ were taken from Allard & Hauschildt (1995). We find the departure from the blackbody assumption in the J, H and K bands to be about 2, 9 and 24 per cent respectively (Table A1).

| Table A1. Comparison of blackbody and model atmosphere fluxes. |
|---------------------------------------------------------------|
|                  Blackbody (mags)                  | Model atmospheres (mags) |
| $J_{3100K}-J_{3500K}$ | 0.48         | 0.46         |
| $H_{3100K}-H_{3500K}$ | 0.38         | 0.47         |
| $K_{3100K}-K_{3500K}$ | 0.31         | 0.54         |

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