DOES THE CATACLYSMIC BINARY Z CHA CONTAIN A BLACK DWARF SECONDARY?

John Faulkner
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
Hans Ritter
Max-Planck-Institut für Physik und Astrophysik, Garching

ABSTRACT

It is shown that the assumption of a black dwarf secondary in Z Cha leads to a number of contradictions with well established theoretical and observational facts. In particular the model predicts the radial velocity K_1 to be much smaller than is observed, the radius of the accretion disk to be smaller than is physically possible and a white dwarf mass which is inconsistent with the white dwarf's radius derived from eclipse analysis. Using the same arguments as for Z Cha it is also possible to exclude a black dwarf secondary in the similar systems OY Car and HT Cas.

1. INTRODUCTION

Z Cha is an eclipsing cataclysmic binary (hereafter CB) with an orbital period of about 107 min. According to the standard model of CB's the binary consists of a white dwarf primary and a low mass secondary which fills its critical Roche-volume (Robinson, 1976; Warner, 1976). The secondary spills mass through the inner Lagrangian point L_1 and thereby gives rise to the formation of an accretion disk around the primary. At the point where the matter, coming from L_1, impacts the disk a shock front is formed which is usually referred to as the hot spot. In Z Cha the hot spot and the center of the accretion disk, i.e. the white dwarf undergo phase shifted total eclipses (Warner, 1974, Bailey, 1979).

There is considerable observational evidence, mainly from investigations of CB's which have longer orbital periods, that the secondaries in CB's are main sequence stars, or at least very nearly so. (For a discussion of this point see Ritter, 1980d). On the other hand recent theoretical studies on the consequences of gravitational radiation in short period CB's predict that gravitational radiation forces the secondary to mass loss which eventually transforms it into a black dwarf (Pacyński and Sienkiewicz, 1981; Joss, Rappaport and Webbink, 1981). In course of its evolution from a CB containing a main sequence secondary

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to a CB containing a black dwarf, the binary's orbital period first decreases, then goes through a minimum of about 80 min and finally increases as the secondary becomes a degenerate star. In the context of these findings the recent observation that the orbital period of Z Cha is currently increasing (Cook and Warner, 1981) has led to the speculation that Z Cha's secondary might be a black dwarf. In this paper we investigate whether the assumption of a black dwarf secondary is consistent with other well established observational facts about Z Cha.

2. PREDICTIONS AND CONFRONTATION WITH OBSERVATIONS

The computations carried out below have been made under the following assumptions:

1) The binary's orbit is circular.
2) The secondary fills its critical Roche-volume.
3) The secondary is a cold degenerate dwarf obeying the mass-radius-relation given by Zapolski and Salpeter (1969).
4) For the eclipse analysis, the eclipsing and the eclipsed objects have a circular shape and a uniform surface brightness. For details see Ritter and Schröder (1979).

The orbital period of Z Cha is $P = 0\overset{d}{.}07449927$ (Warner, 1974; Bailey, 1979; Cook and Warner, 1981). For a given chemical composition, the assumptions 1), 2) and 3) together with the binary's orbital period P and Kepler's third law determine the secondary's mass M_2 and radius R_2 uniquely. Numerical values of M_2 and R_2 for two values of the hydrogen mass fraction X (= 0.7 and = 0.75 resp.) are listed in Table 1. As can be seen, a possible black dwarf secondary of Z Cha is an object of extremely low mass.

X	$M_2/M_\odot$	$R_2/R_\odot$
0.70	0.0149	0.0841
0.75	0.0162	0.0871

Table 1. Mass M_2 and radius R_2 of a possible black dwarf secondary of Z Cha for two different chemical compositions X.

The half width of the white dwarf's eclipse, $\Delta t_{1/2}$, (see Fig. 1) yields a unique relation between the orbital inclination i and the binary's mass ratio $q = M_1/M_2$:

$$i = \arc\cos\left\{\left(\frac{C}{(1+q)^{1/3}}\right)^2 - \left(\frac{\pi\Delta t_{1/2}}{P}\right)^2\right\}^{1/2} \qquad (1)$$

For deriving Eq. (1) we have made use of an approximation for the secondary's Roche-radius (Pacyński, 1971)

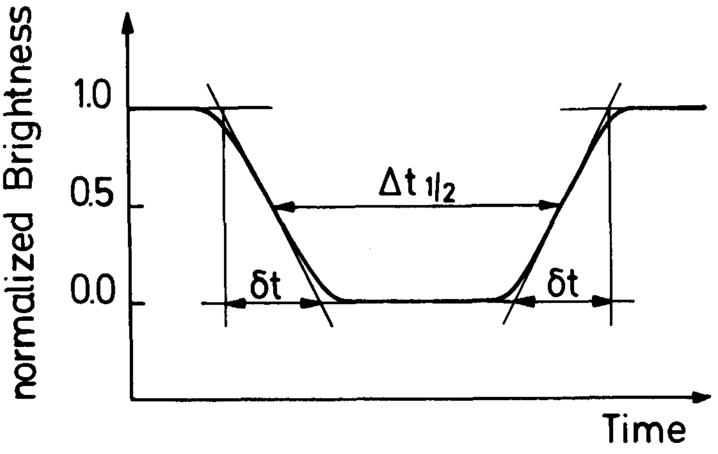

Figure 1. Idealised light curve of a total eclipse. The definitions of the eclipse's half width $\Delta t_{1/2}$ and of the ingress/egress time δt are shown.

$$\frac{R_{2,\mathrm{Roche}}}{A} = C(1+q)^{-1/3} \; , \; C = \frac{2}{3^{4/3}} \; , \quad q \gtrsim 2 \; , \qquad (2)$$

where A denotes the binary's orbital separation. Taking $\Delta t_{1/2} = 344$ s (Bailey, 1979) we find an upper limit of the mass ratio $q \lesssim 20$ and an upper limit for the white dwarf's mass $M_1 \lesssim 0.32\ M_\odot$.

The primary's radial velocity amplitude

$$K_1 = \frac{2\pi R_2}{PC(1+1)^{2/3}} \sin i \qquad (3)$$

depends on q and (via R_2) on the secondary's chemical composition. For any reasonable value of $q \lesssim 20$, however, the predicted value of K_1 is always much smaller than the observed (87±14) km/s (Vogt, 1981).

The fractional radius of the accretion disk (assumed to be in Keplerian roation)

$$\frac{R_{\mathrm{disk}}}{A} = q(1+q)\left(\frac{K_1}{v \cdot \sin i}\right)^2 \qquad (4)$$

turns out to be smaller than the corresponding (minimum) radius of a viscosity free disk (Flannery, 1975; Lubow and Shu, 1976) for any value of $q \lesssim 20$ and even for the lowest published value of $v \cdot \sin i \approx 600$ km/s (Vogt, 1981). The values derived from Eq. (4) are also in contradiction with a determination of the disk's radius which is based only on a light curve analysis (Ritter, 1980c).

The duration δt of the white dwarf's ingress into and egress from total eclipse (see Fig. 1) provides information about the white dwarf's radius R_1. Following Ritter and Schröder (1979) (and neglecting effects of limb darkening) we find

$$R_1 = R_2 \frac{4\pi}{P^2} \Delta t_{1/2} \, \delta t \, \frac{(1+q)^{2/3}}{c^2} \tag{5}$$

Eq. (5) together with the relation $M_1 = q\, M_2$ yields a mass-radius relation for the white dwarf which can be compared with the corresponding theoretical mass-radius-relation. This is shown in Fig. 2. The value of $\delta t = (44 \pm 10)$s has been determined from published light curves (Bailey, 1979). As can be seen from Fig. 2, even in the most extreme case, namely $q \approx 20$, the white dwarf's radius is still smaller than it ought to be for its mass.

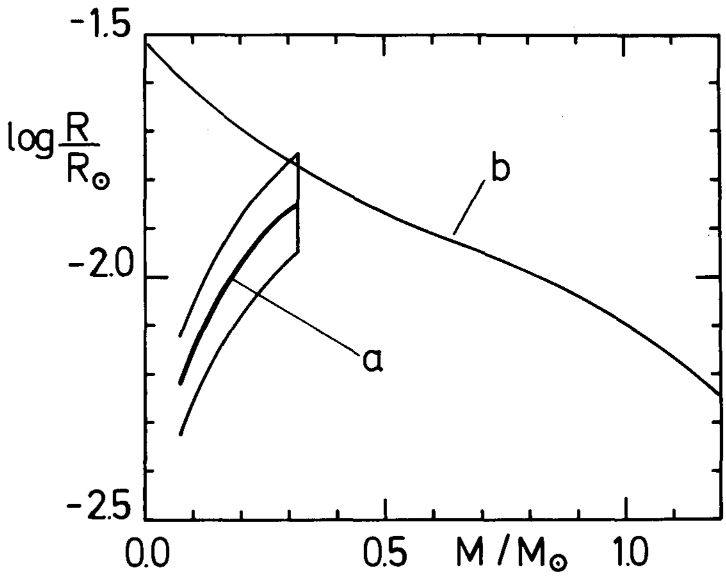

Figure 2. a) Mass-radius relation of the white dwarf derived from eclipse analysis (Eq. 5).
b) Theoretical mass-radius-relation of white dwarfs.

The fact that the white dwarf undergoes an observable eclipse indicates that the orbital inclination is at most 87°. For higher inclinations the white dwarf is permanently eclipsed by the disk's outer rim. This is due to the finite thickness of the disk (see e.g. Meyer and Meyer-Hofmeister, 1981). Therefore the upper limits for the mass ratio and the white dwarf's mass are reduced to $q \lesssim 17$ and $M_1 \lesssim 0.27\ M_\odot$ respectively. On the other hand the observed width of the base of the emission lines indicates a rotational velocity at the white dwarf's surface of at least 2300 km/s (Vogt, 1981). This, however, corresponds to a lower limit of the white dwarf's mass of $M_1 \gtrsim 0.42\ M_\odot$.

If gravitational radiation drives the mass exchange, the predicted mass exchange rate is of the order $10^{-13}\ M_\odot$/yr. This has to be compared with the mass exchange rate predicted for the corresponding system with a main sequence secondary which is $\sim 4 \cdot 10^{-11}\ M_\odot$/yr. In fact a mass exchange rate of this order was determined from observations by Ritter (1980b). Z Cha's luminosity is almost entirely due to accretion. Therefore, if Z Cha has a black dwarf secondary, the low mass transfer rate implies that its distance is at most a tenth of the current estimate of about 100 pc. However, at a distance of about 10 pc, Z Cha would be one of the nearest stars. It should have a large parallax and probably a high proper motion. Thus even astrometrical observations could contribute to deciding whether Z Cha's secondary is a degenerate object or not.

Finally, we mention that although the assumption of a black dwarf secondary accounts for the sign of the period change, the predicted time scale of the period change of 10^{10} yrs is at least three orders of magnitudes longer than is actually observed (Cook and Warner, 1981).

3. CONCLUSIONS

We have shown that the assumption of a black dwarf secondary in Z Cha leads to contradictions with a number of well established observational and theoretical facts. Therefore, Z Cha's secondary is most likely not a black dwarf but rather a low mass main sequence star. The sign and the time scale of the observed period change (Cook and Warner, 1981) still remains to be explained. Applying the same arguments to the CB's OY Car (Ritter, 1980d; Schoembs and Vogt, 1981; Bailey and Ward, 1981) and HT Cas (Patterson, 1981; Young and Schneider, 1981), we can probably also exclude a black dwarf secondary in these systems.

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