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LETTER

Letter to the Editor

An eclipse in the X-ray flux from the dwarf nova Z Cha

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Abstract. Observations obtained with the ROSAT HRI show that the X-rays from the dwarf nova Z Cha in quiescence are eclipsed together with the white dwarf. This confirms the idea that the X-rays are emitted by a narrow boundary layer between the accretion disk and the white dwarf, although a point-like X-ray source near the white-dwarf surface cannot be excluded. The observations further show that during quiescence the mass accretion onto the white dwarf continues, even more than three months after outburst, at a level of $\gtrsim 10^{-12} M_\odot$ yr^{-1}.

Key words: accretion, accretion disks - stars: individual: Z Cha - cataclysmic variables - X-rays: stars

1. Introduction

The most popular theory to explain the X-ray emission from non-magnetic cataclysmic variables is that the X-rays are emitted by the boundary layer between the white dwarf and the Keplerian accretion disk (Pringle & Savonije 1979). In principle, as much as half of the total accretion energy could be liberated in this boundary layer. In the past years, it has become clear that several modifications to the classical boundary-layer theory are required to explain the X-ray observations of non-magnetic cataclysmic variables. In particular, for high-accretion-rate systems the X-ray luminosity is much less than the ultraviolet+optical luminosity from the accretion disk (see e.g. Van Teeseling & Verbunt 1994).

A crucial test to find out whether the X-rays really originate from the boundary layer can be provided by X-ray observations of systems in which the secondary star eclipses the white dwarf and boundary layer. A factor complicating such observations is that eclipsing systems have significantly lower X-ray luminosities than non-eclipsing systems, probably because the X-ray flux is partly absorbed by the accretion disk (Van Teeseling et al. 1996). The few existing X-ray observations of eclipsing non-magnetic cataclysmic variables have given different results. ROSAT PSPC and ASCA observations of the dwarf nova HT Cas in quiescence showed that the X-ray eclipse coincided with the eclipse of the white dwarf, consistent with the idea that the X-rays originate from the immediate neighborhood of the white dwarf (Wood et al. 1995a; Mukai et al. 1996). However, no X-ray eclipses have been detected in OY Car during superoutburst, nor in the nova-like variable UX UMa (Naylor et al. 1988; Wood et al. 1995b). It is possible that in eclipsing high-accretion-rate systems and dwarf novae during outburst, the boundary layer is obscured from view at all orbital phases and that the X-rays are emitted or scattered by a more extended source (cf. Verbunt 1996).

In this article, I present the results of ROSAT observations of the eclipsing SU UMa-type dwarf nova Z Cha. Among the non-magnetic cataclysmic variables which show eclipses of the white dwarf, Z Cha is, together with HT Cas, one of the brightest in X-rays. Together with a relatively short orbital period of 107 min, this makes Z Cha a good system to investigate the location of the X-ray source in non-magnetic cataclysmic variables.

2. Observations and data reduction

The ROSAT data discussed in this article consist of one set of observations obtained in 1992 with the remaining Position Sensitive Proportional Counter (PSPC) and two sets of observations obtained in March/April 1996 and August/September 1996 with the High Resolution Imager (HRI). A log of the observations is given in Table 1. Unfortunately, the PSPC observation did not cover the eclipse phase. This observation has been included to present the X-ray spectral parameters of Z Cha.

All data were reduced using the EXSAS software package (Zimmermann et al. 1994). After contaminating sources were excised from the images, source counts were extracted from a circle centered on the position of Z Cha. This circle has a radius of 150″ for the PSPC data and 25″ for the HRI data. The background count rate was determined from a concentric ring between 200″ and 600″ for the PSPC data, and between 100″ and 200″ for the HRI data. Both the source count rates and the background count rates were corrected for vignetting. All results presented in this article, including the phase-folded

Table 1. ROSAT observations of Z Cha

instrument	date	JD (+ 2 440 000)	exposure[a]	n_o[b]	counts/s[c]	days after max[d]
PSPC	8–14 April 1992	8721.35—8727.10	3 928	6	0.083 ± 0.005	40
HRI	2–9 March 1996	10144.51—10151.82	13 198	9	0.0147 ± 0.0011	71
HRI	1–14 April 1996	10175.06—10188.29	9 577	5	0.0206 ± 0.0015	102
HRI	12–20 August 1996	10308.00—10316.45	3 947	2	0.0238 ± 0.0025	37
HRI	10–12 Sept 1996	10336.63—10338.70	16 933	9	0.0271 ± 0.0013	18

[a] Total exposure (sec) of the intervals selected by the Standard Data Processing
[b] Number of observation intervals
[c] Time-averaged count rate after background subtraction and vignetting correction
[d] Days after outburst maximum from observations by the Variable Star Section of the Royal Astronomical Society of New Zealand (Bateson 1996)

light curves, are based on data from which the time-dependent background has been subtracted.

Observations by members of the Variable Star Section of the Royal Astronomical Society of New Zealand confirm that Z Cha was quiescent during all observations discussed in this article. In Table 1, the number of days after outburst maximum is given for each data set. Note that there was a normal outburst on JD 2 450 318, just one day after the HRI observation on August 20.

To make phase-folded light curves, the X-ray counts were folded with the eclipse ephemeris given by Robinson et al. (1995) which includes observations up to 1992. The PSPC observations were obtained quasi-simultaneously with the HST observations discussed in Robinson et al. (1992), so this ephemeris is certainly sufficiently accurate for the PSPC data. However, on the basis of Hubble Space Telescope data and ground-based V photometry, M. S. Catalán reported (private communication) that on JD 2 450 014 the observed eclipses occurred $\sim$ 64–70 s before the predicted times, which corresponds to a 2σ deviation. In addition, the eclipse times show unpredictable short-term departures from the ephemeris of up to 15 s (Robinson et al. 1995). The difference on JD 2 450 014 was extrapolated to the times of the HRI observations, assuming that the difference has grown quadratically with the cycle number since 1992. This procedure gives a phase-shift of $\sim$ 80 s for the March/April HRI light curve and $\sim$ 100 s for the August/September HRI light curve. These values are justified by the results in Sect. 5, although slightly different values give similar results.

3. PSCP spectral parameters

To obtain the X-ray spectral parameters, the counts in pulse-height channels 11 to 235 were binned in 11 bins in such a way that each bin had a signal-to-noise ratio of 5. An acceptable χ^2 fit was found for a thermal bremsstrahlung spectrum with kT = $4.4^{+15}_{-1.8}$ keV, $n_{\rm H}$ = $(1.9 \pm 0.6) \times 10^{20}$ cm^{-2}, and an unabsorbed 0.1–2.4 keV flux of $(1.17^{+0.10}_{-0.15}) \times 10^{-12}$ erg cm^{-2}s^{-1}. Adopting a distance of 97 pc to Z Cha (Wood et al. 1986), the implied 0.1–2.4 keV luminosity is 1.3×10^{30} erg s^{-1}. The extrapolated 'bolometric' flux of the X-ray component is $\sim 2.5 \times 10^{30}$ erg s^{-1}, which must be regarded as a lower limit if the X-ray spectrum is a multi-temperature optically thin spectrum (such as indicated by X-ray observations of other cataclysmic variables, see e.g. Van Teeseling & Verbunt 1994).

Anticipating the results in Sect. 5, we can estimate the mass accretion rate onto the white dwarf from the X-ray luminosity. With a white-dwarf mass of 0.59 $M_\odot$ and a white-dwarf radius of 8.84×10^8 cm (Wood 1986), this gives a mass accretion rate onto the white dwarf of $\gtrsim 10^{-12} M_\odot$ yr^{-1}. This is comparable with the accretion rate estimated from the optical surface brightness of the inner disk, but $\sim$ 100 times lower than that in the outer disk (Wood et al. 1986). It is possible, however, that a significant part of the X-ray source is obscured by optically thick parts of the accretion disk (Van Teeseling et al. 1996), and that the accretion rate onto the white dwarf is significantly higher than $10^{-12} M_\odot$ yr^{-1}.

The phase-folded light curve of the PSPC observation is shown in the top panel of Fig. 1.

4. Long-term X-ray variability

Using the best-fit thermal bremsstrahlung spectrum, the average PSPC count rate corresponds to an average HRI count rate of $\sim$ 0.028 cts s^{-1}. This count rate is consistent with the count rate during the September 1996 HRI observation, but significantly higher than the HRI count rate detected in March/April 1996. It may be tempting to attribute this to a longer time after outburst in March/April, but there is no real evidence for this. On the contrary: the count rate in April 1996 (102 days after maximum) was higher than in March 1996 (71 days after maximum). This is in contrast to EXOSAT observations of VW Hyi, which showed that the X-ray flux of VW Hyi declines by a factor 1.2–1.6 between outbursts (Van der Woerd & Heise 1987).

The ROSAT observations of Z Cha show that accretion onto the white dwarf continues throughout the quiescence interval at roughly the same level, irrespective of the time that has elapsed since the previous outburst. This supports the theory that the decreasing ultraviolet flux, which has been observed during quiescence in some dwarf novae (e.g. Hassall et al. 1985; Verbunt et al. 1987; Gänsicke & Beuermann 1996), is due to a cooling of the white-dwarf outer layers, and not to a decreasing accretion onto the white dwarf (Pringle 1988). A somewhat elevated white-dwarf temperature immediately after outburst has also been inferred for Z Cha (Robinson et al. 1995).

The continuing accretion onto the white dwarf during the full quiescence interval, with a rate of $\gtrsim 10^{-12} M_{\odot}\,\mathrm{yr}^{-1}$, is also difficult to reconcile with the standard disk instability model for dwarf-nova outbursts. This model predicts, for reasonable values of the viscosity parameter α, a mass accretion rate $< 10^{-12} M_{\odot}\,\mathrm{yr}^{-1}$ onto the white dwarf during quiescence. An accretion rate onto the white dwarf as high as observed could be explained with evaporation of the inner accretion disk by a coronal siphon flow, but this would predict a decreasing X-ray flux as soon as the innermost part of the disk has been evaporated (Meyer & Meyer-Hofmeister 1994).

5. HRI light curves: the X-ray eclipse

The photon-counting statistics of the individual orbits is rather poor. Therefore, in the following analysis only the complete 1996 March/April and August/September data sets are considered. To improve the statistics, these two data sets were also merged into a single data set to which I will refer as the total data set.

In Z Cha, ingress of the white-dwarf eclipse lasts ~ 55 s, near phase -0.03 (Wood et al. 1986). The white-dwarf eclipse from mid ingress to mid egress lasts ~ 340 s. The folded March/April and August/September HRI light curves were binned into 34 phase bins per orbit, which implies that two bins almost cover the full white-dwarf eclipse. These bins were chosen such that the start of one of these bins is at orbital phase 0.0. The total folded light curve was binned into 68 phase bins per orbit, which implies that four bins almost cover the full white-dwarf eclipse.

The phase-folded HRI light curves are shown in Fig. 1. Although there is significant variability out of eclipse, with sometimes even count rates consistent with zero, it is beyond any doubt that the X-rays are eclipsed simultaneously with the white dwarf. When the total data set is folded with the period as free parameter, the orbital period of Z Cha comes out automatically as the best-fitting period. Less significant, but certainly suggestive, is an absorption dip near phases 0.7–0.8, which is reminiscent of the absorption dips in the X-ray light curve of U Gem (Szkody et al. 1996).

The eclipse phase was covered 5 times in the March/April data set and 4 times in the August/September data set. In none of these cases there was a significant non-zero count rate during the eclipse. In Table 2, the count rates in and out of eclipse are summarized for all data sets. In the March/April data, the X-ray eclipse is significant with 9σ, in the August/September data with 11σ, and in the total data with 16σ. In all data sets, the count rate in eclipse is consistent with zero. The 3σ upper limit to the unabsorbed 0.1–2.4 keV flux in eclipse is $2 \times 10^{-13}\,\mathrm{erg\,cm^{-2}s^{-1}}$. This implies that the 0.1–2.4 keV X-ray luminosity of the accretion disk (excluding the boundary layer) plus the companion star is less than $\sim 2 \times 10^{29}\,\mathrm{erg\,s^{-1}}$.

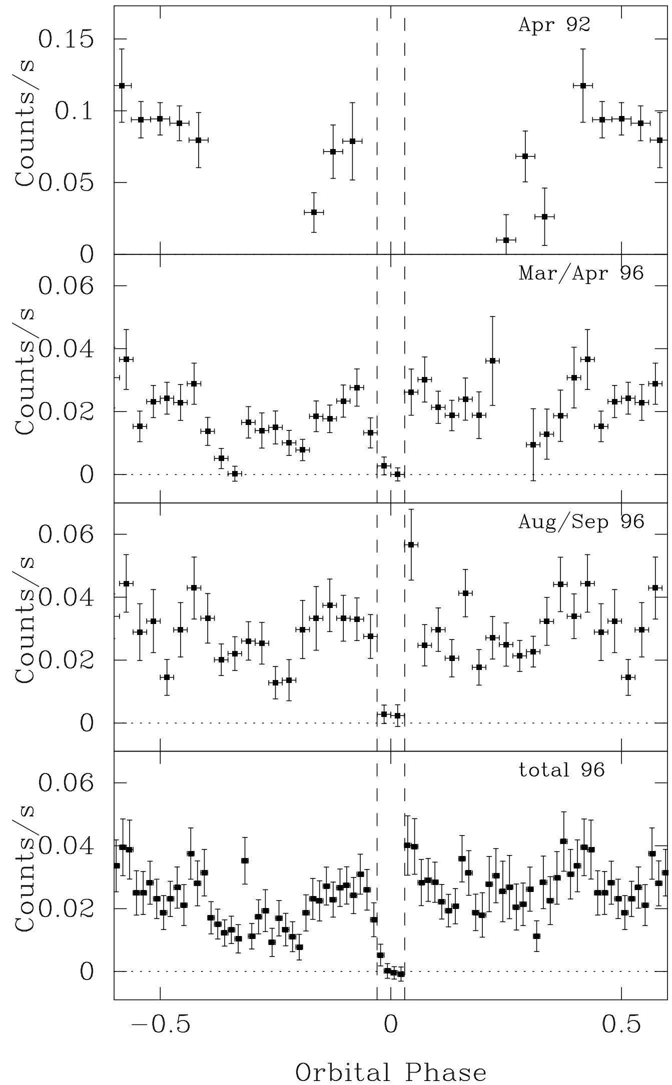

Fig. 1. X-ray light curves of Z Cha folded with the ephemeris derived by Robinson et al. (1995). The top panel shows the PSPC light curve, the middle two panels the HRI light curves in March/April and August/September 1996, and the bottom panel the total HRI light curve. The March/April HRI light curve has been shifted by 80 s, the August/September HRI light curve by 100 s, and the total HRI light curve by 90 s. The dashed lines indicate the phases of ingress and egress of the white-dwarf eclipse

Table 2. Count rates (counts $\mathrm{s^{-1}}$) in and out of eclipse, corrected for vignetting and background

date	out of eclipse	in eclipse
Mar/Apr 1996	0.0175 ± 0.0010	0.0013 ± 0.0017
Aug/Sep 1996	0.0271 ± 0.0012	0.0026 ± 0.0022
total 1996	0.0221 ± 0.0008	0.0011 ± 0.0013

To investigate the width of the X-ray eclipse, the bins of the total phase-folded HRI light curve were shifted forwards and backwards until in one of the four eclipse bins there was a 2σ significant non-zero count rate. The resulting upper limit for the width of the X-ray eclipse is ~ 460 s, which is longer than the eclipse of a point source behind the secondary star.

A robust lower limit for the width of the X-ray eclipse can be obtained by considering simple photon statistics: The number of source counts in the eclipse bins (covering 378 s) is $\lesssim 5$. Suppose that the duration that the X-ray source is completely obscured is shorter than 378 s, and that the few source counts in the eclipse bins were detected when the X-ray source was not yet completely behind the secondary star. What is then the probability that ≤ 5 source counts are detected in a phase interval which is observed 9 times and which has half of the out-of-eclipse count rate of 0.0221 counts s^{-1} (assuming linear ingress and egress of the X-ray eclipse)? For instance, this phase interval has to be shorter than 108 s or otherwise there will be a $> 2\sigma$ probability of detecting more than 5 source counts. This gives a 2σ lower limit for the duration that the X-ray source is completely obscured of ~ 270 s, which implies that the X-ray source has a size comparable to or less than the white dwarf ($R_{\mathrm{x}} \lesssim 1.4 R_{\mathrm{wd}}$).

An alternative way to determine the duration of the X-ray eclipse, is by fitting a function equal to zero in eclipse and equal to a non-zero constant out of eclipse, and with the times of ingress and egress as free parameters. This has been done with the total data set binned into 200 phase bins per orbit. The best-fit phase for the eclipse ingress is -0.035 and the best-fit phase for the eclipse egress is 0.030, which shows that the phase-shift of 90 s used for the eclipse ephemeris is not too bad. The 3σ range for the width of the X-ray eclipse (assuming a negligibly short ingress and egress) is $\sim 350 - 520$ s. The best-fit eclipse light curve is shown in Fig. 2.

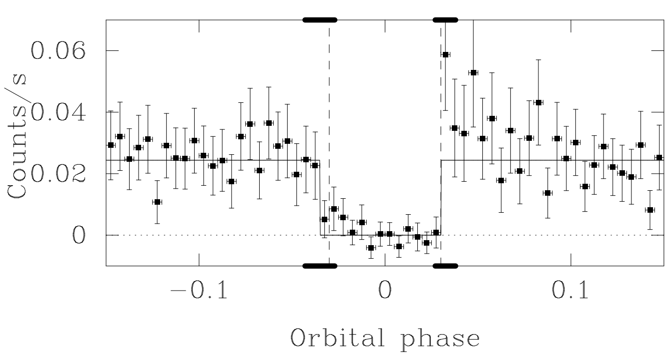

Fig. 2. Same as the bottom panel of Fig. 1, but with 200 orbital phase bins. The solid line is the best-fit eclipse light curve. The thick solid lines on the frame edges indicate the 3σ ranges of ingress and egress

6. Conclusions

The X-ray emission from Z Cha in quiescence is emitted very close to the white-dwarf surface. The mass accretion onto the white dwarf continues during quiescence with a rate of $\gtrsim 10^{-12} M_{\odot}\,\mathrm{yr}^{-1}$.

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