X-rays from eclipsing cataclysmic variable systems: the eclipse profile

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Abstract. A cataclysmic variable is a binary system containing a white dwarf which accretes material from a secondary star through the Roche lobe mechanism. Systems observed at large inclination angles offer the possibility to locate the X-ray emitting region thus allowing to study the behaviour of systems accreting matter in extreme conditions. We briefly review the main properties of a cataclysmic variable and focus on the information possibly derived by high energy observations.

1. Introduction
A binary system constituted by a white dwarf (the primary star) gravitationally interacting with a secondary object (the secondary star) is called Cataclysmic Variable (hereafter CV).

In CV systems, the two stars interact via the formation of a Roche-lobe, and the details of the accretion are governed by many parameters. In particular, depending on the magnetic field, these binary systems are classified as: (i) non-magnetic systems, with a rather weak magnetic field of strength \(\lesssim 0.1\) MG, characterized by a keplerian accretion disk around the compact object; (ii) intermediate polars with magnetic field of the order 0.1-10 MG, where the disk is truncated close to the white dwarf; (iii) polars, i.e. highly magnetized systems with \(\gtrsim 10\) MG, where the accretion occurs via a ballistic jet which hits one of the poles of the primary star.

In a typical non-magnetic CV, half of the potential gravitational energy of the accreting material is dissipated by viscosity, while the remaining part is radiated away by the boundary layer (BL), i.e., a region at the interface between the disk and the white dwarf surface. In
particular, as demonstrated by [1], the total luminosity of the accretion disk of a white dwarf of mass $M_{WD}$ and radius $R_{WD}$ is $L_{\text{disk}} = GM_{WD} \dot{M}/2R_{WD}$. Thus, only half of the gravitational potential energy $L_{\text{acc}} = GM_{WD} \dot{M}/R_{WD}$ is radiated away by the accretion disk, while the other half is released in the form of rotational energy in the accreting material. A fraction of this energy is dissipated at the BL, where the velocity of the accreting gas decreases, with a rate depending on the rotational speed of the white dwarf. Taking into account the energy transferred to spin up the white dwarf, the boundary layer luminosity is $L_{\text{BL}} \simeq 0.125L_{\text{acc}}$ for $\Omega_{WD} \simeq 0.5\Omega_K(R_{WD})$ [1]. Thus, the radiation emitted by the disk reaches a maximum in the optical and ultraviolet spectral regions, while the BL, if exists, may radiate in the extreme ultraviolet and X-rays, with typical luminosities in the range $10^{30}$–$10^{32}$ erg s$^{-1}$ (see e.g., [2], [3]).

The low luminosity of these systems implies that the XMM-Newton satellite [4] is particularly efficient in their study since it has a large effective area and offer the possibility to observe the source simultaneously in the optical band with the onboard optical monitor (OM).

Even if according to the standard accretion scenario the X-ray photons are expected to originate in the BL, what present observations clearly show is that the high energy emission comes from a region very close to the white dwarf. Moreover, no clear correlation between the X-ray luminosity and the accretion rate does exist [5]. In addition, since in many CVs the observed X-ray luminosity is lower than predicted by the BL model, the details of the accretion mechanism are still unclear (but see e.g., [6] for possible solutions about the observed discrepancy).

Systems characterized by large inclination angles with respect to the line of sight offer the unique possibility to study the location of the X-ray emitting region. In fact, under these circumstances, the observed X-ray light curve shows the existence of peculiar features as eclipses whose detailed study allows to constrain the X-ray source size when the mid ingress and egress phases of the occultation are known. Of course, the main difficulty in this kind of researches is that the typical low X-ray luminosity of a CV becomes even lower during an undergoing eclipse phenomenon.

A first notable example of this kind is the well studied dwarf nova system OY Carinae which is nowadays considered as the prototype dwarf novae. In OY Car, the X-ray eclipse was resolved by the XMM-Newton satellite, and, as shown in [7], the size of the X-ray emitting region is comparable with that of the central white dwarf. In addition, a careful re-analysis of the same data by [8] allowed to depict a scenario in which the X-ray emission is probably displaced from the equatorial region. Hence the authors concluded that the X-ray emission in the dwarf nova OY Car could possibly originate at the white dwarf polar cap (see their Fig. 5), so that magnetic accretion may play an important role also in those systems formally recognized as non magnetic ones. However, as the same authors also suggested, the obscuration of the lower WD hemisphere by the inner accretion disk would be a valid alternative model implying that the observed X-ray properties are caused only by projection effects.

In the following we will review the main properties of the high energy light curves of two interesting dwarf novae systems: HT Cassiopea and Z Chamaleontis and show how the size of the X-ray source can be determined from observation.

2. The folded light curves of HT Cassiopea and Z Chamaleontis: two interesting eclipsing dwarf novae systems

HT Cassiopea and Z Chamaleontis (hereafter HT Cas and Z Cha, respectively) are interesting targets for the XMM-Newton satellite for several reasons$^1$: a) they are characterized by high inclination angles ($81^\circ$–$82^\circ$) with respect to the line of sight, b) have orbital periods of the order

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$^1$ For further details on the data reduction scheme, the spectral as well as the timing analysis of the two sources we address the reader to [9] and [10], respectively.
of a few hours ($\simeq 1.77 \text{ h}$ [11], and $\simeq 1.78 \text{ h}$ [12]), and c) emit a sufficient large amount of X-ray photons ($L_{\text{Bol X}} \simeq 7 \times 10^{30} \text{ erg s}^{-1} - 1 \times 10^{31} \text{ erg s}^{-1}$). It is then possible to observe for a sufficiently long time the two luminous CVs and infer the X-ray source size after characterizing the eclipse profile.

HT Cas was observed by XMM-Newton on two occasions in 2002 (Observation IDs 0111310101 and 0152490201), for $\simeq 45 \text{ ks}$ and $\simeq 55 \text{ ks}$, respectively. Here, we refer only to the first observation corresponding to the normal quiescent state of the system. The observation was conducted on 2002/08/20 and started (ended) at 09:23:50 (23:14:42) UT.

Similarly, Z Cha was observed by XMM-Newton in 2003 and 2005 (Observation IDs 0205770101 and 0306560301) for $\simeq 99 \text{ ks}$ and $\simeq 87 \text{ ks}$, respectively. Also in this case, we focused on the X-ray eclipse of Z Chamaleontis so that we used only the observation (ID 0205770101) clearly showing eclipses in the light curves. The observation started on 2003 December 19 (20:45:52) UT and ended on 2003 December 21 (00:56:09) UT.

Figure 1. A piecewise fit (solid green line) to the HT Cas EPIC folded light curve (upper panel), and the residuals (as the difference between the data and the best fit model).

In Figures 1 and 2, we give the high energy light curves (in the energy range 0.5-10 keV band) for HT Cas and Z Cha, respectively. The two light curves were folded at the associated orbital period and two periods are shown clearly demonstrating the existence of deep eclipses. Here (but see also [9] and [10] for details), the light curves are fitted via a phenomenological model consisting of a constant level (outside the eclipse), a flat part inside the eclipse, and two linear ingress and egress functions (not necessarily equal). Thus, after adapting to the data the 6 free parameters via a minimization of the $\chi^2$ function it is possible to determine the so called contact points, i.e. the phases corresponding to which the X-ray emitting region disappears and reappears from behind the eclipsing source (the secondary star). In more details, the X-ray emitting region disappears between phases $\phi_1$ and $\phi_2$, and reappears between phases $\phi_3$ and $\phi_4$, so that the durations of the ingress and egress are $\Delta\phi_{1,2} = |\phi_2 - \phi_1|$ and $\Delta\phi_{3,4} = |\phi_4 - \phi_3|$, respectively. Furthermore, the mid ingress $\phi_i$ and mid egress $\phi_e$ points (i.e. the phases corresponding to which half of the light curve value is eclipsed) are used to estimate the eclipse duration $\Delta\phi_X = |\phi_e - \phi_i|$. These phases are represented in the figures by dashed vertical lines.

The contact point determined by using the X-ray folded light curve can be used in order
Figure 2. The same as in figure 1 but for the Z Cha binary system.

To estimate the size of the X-ray emitting region. Assuming that the cross sections of both the primary star (with radius $r_2$) and the secondary star (with radius $r_1$) remain constant over the eclipse duration, the timescales for the eclipse ingress/egress can be evaluated as [14]

$$\Delta t_{1,2} = \frac{P}{2\pi} \left[ \sqrt{\left( \frac{r_1 + r_2}{a} \right)^2 - \cos^2 i} - \sqrt{\left( \frac{r_1 - r_2}{a} \right)^2 - \cos^2 i} \right].$$  \hspace{1cm} (1)

where $P$, $a$, and $i$ are the orbital period, the semi-major axis and inclination angle, respectively. Note that the phenomenological model used above can be substituted by a more realistic

Figure 3. In the figure, we show the geometry of an undergoing eclipse event and quote all the relevant variables used in the text.
alcharacterization of the eclipse profile. Here, one assumes that the limb of the companion star is completely opaque to the X-ray photons during an eclipse event. In particular, referring to Figure 3 (bottom panels), one can easily understand that the eclipse profile depends on the fraction of the area \((\delta A = S_1 + S_2)\) of the X-ray source covered (at a given time \(t\)) by the limb of the companion star. It is straightforward to verify that the area \(\delta A\) is

\[
\delta A(t) = \begin{cases} 
0, & \text{for } d(t) > r_1 + r_2, \\
\frac{r_1^2}{2} (\theta_1(t) - \sin \theta_1(t)) + \frac{r_2^2}{2} (\theta_2(t) - \sin \theta_2(t)), & \text{for } r_1 - r_2 \leq d(t) \leq r_1 + r_2, \\
\frac{\pi r_2^2}{2}, & \text{for } d(t) < r_1 - r_2.
\end{cases}
\]  

(2)

(3)

(4)

where the projected distance \(d(t)\) between the centers of the X-ray source and the companion star can be evaluated as

\[
d^2(t) = 4\pi^2 a^2 \phi^2(t) + a^2 \cos^2 i,
\]

(5)

where \(\phi(t)\) is the orbital phase and

\[
\theta_1(t) = 2 \arccos \frac{r_2^2 - r_1^2 + d^2(t)}{2r_1 d(t)},
\]

(6)

\[
\theta_2(t) = 2 \arccos \frac{r_2^2 - r_1^2 + d^2(t)}{2r_2 d(t)}.
\]

(7)

Thus, the resulting eclipse profile (e.g. count rate) is

\[
L(t) = L_0 \left(1 - \frac{\delta A}{\pi r_2^2}\right),
\]

(8)

where \(L_0\) is the X-ray count rate outside the eclipse phenomenon.

Using the piecewise phenomenological model and/or the more realistic model described above together with the measured X-ray ingress/egress timescales and the orbital parameters determined by the optical observation (i.e., \(P, a, i,\) and \(r_1\)), one can derive the size the HT Cas and Z Cha X-ray emitting regions to be \(\approx 0.0117\) \(R_\odot\) and \(\approx 0.0119\) \(R_\odot\), respectively. Since these values (and the associated errors) are comparable with the WD radii estimated by using the optical observations (see [13] and [15]), the BL model seems to be enforced.

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