On the diversity and similarity of outbursts of symbiotic binaries and cataclysmic variables

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Abstract. Outbursts in two classes of interacting binary systems, the symbiotic stars (SSs) and the cataclysmic variables (CVs), show a number of similarities in spite of very different orbital periods. Typical values for SSs are in the order of years, whereas for CVs they are of a few hours. Both systems undergo unpredictable outbursts, characterized by a brightening in the optical by 1–3 and 7–15 mag for SSs and CVs, respectively. By modelling the multiwavelength SED of selected examples from both groups of these interacting binaries, I determine their basic physical parameters at a given time of the outburst evolution. In this way I show that the principal difference between outbursts of these objects is their violence, whereas the ionization structure of their ejecta is basically very similar. This suggests that the mechanism of the mass ejection by the white dwarfs in these systems is also similar.

1. Introduction

Symbiotic stars (SSs) and cataclysmic variables (CVs) are interacting binary systems, in which the accretor is a white dwarf (WD). In the former the donor is a red giant, while in the latter it is, in most cases, a red dwarf. Orbital periods are extremely different, being typically in the order of years for SSs, but only of a few hours for CVs. The red giant in SSs underfills its Roche lobe with a factor of \( \sim 0.5 \) (e.g. Mürset & Schmid 1999), whereas the evolved dwarf donor in CVs fills its Roche lobe. This difference dictates the way of the principal interaction between the binary components. The WD in SSs accretes the matter from the stellar wind of the cool giant, while in CVs the mass is transferred onto the WD through the \( L_1 \) point. A review of CVs can be found in the monograph of Warner (1995), and that on SSs in Siviero & Munari (2012).

A common feature of these types of interacting binaries are their unpredictable outbursts observed on a very different and variable time-scale. Here, we compare classical nova (CN) outbursts of CVs and Z And-type outbursts of SSs. The former are characterized by a large brightness amplitude of \( \sim 7 – 15 \) mag, whereas the latter are as low as \( \sim 1 – 3 \) mag in the optical. CN outbursts are believed to be caused by a thermonuclear runaway event on the WD surface, when the accreted matter exerts the critical pressure, at which hydrogen ignites a thermonuclear (CNO) fusion. The CN events need accretion onto the WD at rates \( M_{\text{acc}} \lesssim 10^{-8} M_\odot \text{yr}^{-1} \), giving the recurrence time of CN explosions much longer than human timescales (Yaron et al. 2005). A recent review on CNe is provided by Bode & Evans (2008). As concerns to the Z And-type outbursts, their nature is not well understood yet. To explain the high luminosity of hot components in SSs, it was suggested that they are powered by stable hydrogen nuclear
burning on the WD surface, which requires accretion rates of $\sim 10^{-8} - 10^{-7} M_\odot \text{yr}^{-1}$, depending on the WD mass (Paczyński & Żytkow 1978). The outbursts could result from an increase in the accretion rate above that sustaining the stable burning, which leads to expansion of the burning envelope to an A–F type pseudophotosphere (e.g. Tutukov & Yungelson 1976), and causes a brightening in the optical. Multiwavelength modelling of the SED during Z And-type outbursts revealed that the warm pseudophotosphere is simulated by the outer flared rim of an edge-on disk around the WD with the nebula located above/below the disk (Skopal 2005). Applying the method to the explosion of CN V339 Del (Nova Delphini 2013) a similar ionization structure of the ejecta was indicated (see Skopal et al. 2014).

In this contribution I suggest an idea that, in spite of an extreme difference in the energetic output of a CN and Z And-type outburst, basic ionization structure, and thus the mechanism of the mass ejection by the WD in SSs and CVs is similar.

2. Multiwavelength modelling of the SED

The observed continuum spectrum, $F(\lambda)$, emitted by a CN in the broad range from the supersoft X-rays to the radio can be approximated by two main components: (i) a stellar component, $\mathcal{F}_\lambda(T_{\text{eff}})$ that is produced by the WD pseudophotosphere, and (ii) a nebular component represented by the volume emission coefficient, $\varepsilon_\lambda(T_e)$, of the nebular continuum generated in thermal plasma of the ejecta. Therefore, the CN spectrum can be expressed as a superposition of these components of radiation, i.e.,

$$F(\lambda) = (\theta_{\text{eff}})^2 \mathcal{F}_\lambda(T_{\text{eff}}) + k_n \varepsilon_\lambda(T_e).$$

(1)

The stellar component can be compared with a synthetic spectrum calculated for the effective temperature, $T_{\text{eff}}$. The model is scaled to the observed fluxes by the angular radius $\theta_{\text{eff}} = R_{\text{eff}}/d$, given by the effective radius of the pseudophotosphere, $R_{\text{eff}}$, and the distance $d$. The factor $k_n$ scales the nebular contribution $\varepsilon_\lambda(T_e)$ to observations. Furthermore, the electron temperature, $T_e$, and thus $\varepsilon_\lambda(T_e)$ are assumed to be constant throughout the nebula, an assumption which simplifies determination of its emission measure $EM$. For $T_{\text{eff}} \gtrsim 15000 \text{ K}$, the radiation of the WD pseudophotosphere in the optical can be approximated by the radiation of a blackbody. Fitting parameters are $\theta_{\text{eff}}$ and $T_{\text{eff}}$, which define $R_{\text{eff}}$ and the luminosity $L_{\text{WD}} = 4\pi d^2 \theta_{\text{eff}}^2 T_{\text{eff}}^4$, and $k_n$ and $T_e$, which define $EM = 4\pi d^2 k_n$. In the case of modelling the SED of a SS, the component of radiation from the giant, $\theta_g^2 \mathcal{F}_\lambda(T_{\text{eff},g})$, is added to the model (see Skopal 2005, in detail).

3. Example objects

3.1. Classical nova V339 Del (Nova Delphini 2013)

Nova Delphini 2013 (V339 Del) was discovered by Koichi Itagaki on 2013 Aug. 14.584 UT at the unfiltered brightness of 6.8 mag (CBET No. 3628). Its brightness peaked at $V \sim 4.43$ on Aug. 16.44 UT, i.e. ~ 1.85 days after its discovery. First detailed description of the multicolour optical photometry was provided by Munari et al. (2013) and Chochol et al. (2014), who classified the object as a fast nova, placed at a distance of 3 kpc with a low reddening on the line of sight, $E_{B-V} = 0.18$ mag. A detailed analysis
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Figure 1. Examples of the optical spectra (gray lines) and their models (heavy solid lines). Left: The CN V339 Del (Skopal et al. 2014). Right: The SSs BF Cyg and Z And during active phases (Tarasova & Skopal 2012). Physical parameters of individual radiation components are collected in Table 1.

of the nova evolution from its discovery to day ∼ 40 after its optical maximum was provided by Skopal et al. (2014). During the fireball stage (Aug. 14.8–19.9, 2013), $T_{\text{eff}}$ of the WD pseudophotosphere was in the range of 6000–12000 K, $R_{\text{WD}}^\text{eff}$ was expanding from ∼ 66 to ∼ 300 ($d/3$ kpc) $R_{\odot}$ and $L_{\text{WD}}$ was super-Eddington, but not constant. Contribution to the nebular continuum was negligible. After the fireball stage, a large $EM$ of $1.0 \times 10^{62} (d/3$ kpc)$^2$ cm$^{-3}$ was present in the spectrum of nova V339 Del. Examples of models SED from the fireball stage and just after it are shown in Fig. 1.

3.2. Symbiotic star BF Cyg

BF Cyg is an eclipsing symbiotic binary with an orbital period of 757.2 d, whose donor is a late-type M5 III giant (e.g. Fekel et al. 2001). Its light curve (LC) occasionally shows outbursts of the Z And-type (1920, 1989, 2006). During the 2006 August, BF Cyg underwent an outburst which continues to the present. Spectroscopic observations showed strong P-Cyg type of H\textsc{i}, He\textsc{ii} lines from the beginning of the outburst (e.g. McKeever et al. 2011). Recently, Skopal et al. (2013) reported an evidence of highly-collimated bipolar ejection from the system. The model SED from the recent 2006 outburst is shown in Fig. 1.
Table 1. Physical parameters of the CN V339 Del and symbiotic binaries BF Cyg and Z And derived from their models SED (Fig. 1). \(L_{\text{ph}}\) is the rate of hydrogen-ionizing photons required to produce the measured \(EM\).

| Object      | Date dd/mm/yyyy | \(d\) [kpc] | \(T_{\text{eff}}\) [K] | \(R_{\text{WD}}\) \(\left[ R_\odot \right]\) | \(L_{\text{WD}}\) \(\left[ \text{L}_{\odot} \right]\) | \(T_e\) [K] | \(EM\) \(\left[ \text{erg} \text{cm}^{-3} \text{s}^{-1} \right]\) | \(L_{\text{ph}}\) \(\left[ 10^{37} \text{erg s}^{-1} \right]\) | \(M_{\text{WD}}\) \(\left[ M_\odot \right]\) |
|-------------|----------------|-------------|----------------|---------------------------------|----------------|--------|----------------|----------------|----------------|
| V339 Del\(^1\) | 16/08/2013 | 3.0 | 12000 | 110 | 86 | – | – | – | – |
| BF Cyg\(^4\)  | 24/09/2012 | 3.8 | 8750 | 19 | 0.74 | 30000 | 17 | 1.7×10\(^{48}\) | 4.5×10\(^{-4}\) |
| Z And\(^5\)   | 23/10/2008 | 1.5 | 5750 | 11.5 | 0.05 | 32000 | 3.1 | 3.1×10\(^{37}\) | 2.5×10\(^{-6}\) |

\(^1\) in \(10^{37} \text{erg s}^{-1}\), \(^2\) in \(10^{60} \text{cm}^{-3}\), \(^3\) Skopal et al. (2014), \(^4\) this paper, \(^5\) Tarasova & Skopal (2012)

3.3. Symbiotic star Z And

Z And is considered as a prototype of the class of symbiotic stars. The donor is a late-type M4.5 III giant, and the accretor is a WD on the 758-day orbit (e.g. Nussbaumer & Vogel 1989). More than 120 years of its monitoring (first records from 1887) demonstrated an eruptive character of its LC. From 2000 September, Z And started a series of outbursts with the main optical maxima in 2000 December, 2006 July, 2009 December and 2011 November that peaked between 8 and 8.5 in \(U\) with an amplitude of \(~ 2 \text{–} 3\) mag. During the 2006 outburst, highly collimated bipolar jets were detected for the first time (Skopal & Pribulla 2006). Example of its SED is depicted in Fig. 1.

4. Concluding remarks

Modelling the optical SED of active symbiotic stars Z And and BF Cyg revealed the simultaneous presence of a strong stellar and nebular component of radiation (see Fig. 1 and Table 1). The warm stellar component is not capable of producing the observed nebular emission, which signals the presence of a hot ionizing source in these systems, which is not seen directly by the observer. Skopal (2005) interpreted this two-temperature-type of the spectrum by the presence of an edge-on disk around the accretor, the outer flared rim of which represents the warm WD pseudophotosphere, and the nebula is placed above/below the disk, being ionized by the central hot star.

Evolution of the optical/IR continuum of CN V339 Del during its fireball stage and the following transition to a harder spectrum suggests a similar ionization structure as that which appears to be present around WDs in symbiotic binaries during their outbursts (see Sect. 4.2.3 of Skopal et al. 2014, in detail).

The corresponding ionization structure of both very different types of interacting binaries is sketched in Fig. 2. This suggests that in spite of their extreme different energetic output, the basic ionization structure, which develops during the Z And-type of the outburst, is similar to that which follows the fireball stage of CN outburst. Such a similarity suggests also a common mechanism of the mass ejection by the WDs in these systems. According to Cariková & Skopal (2012), the biconical ionization structure can be formed as a consequence of the enhanced mass-loss rate from the rotating WD during outbursts of symbiotic binaries (see their Figs. 1 and 6). This idea should be further tested by applying the wind compression disk model of Bjorkman & Cassinelli (1993) to a rotating WD in CVs with parameters that represent CN outbursts.

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Figure 2. Top panels show a sketch of the ionization structure of CN V339 Del as seen on a cut perpendicular to the orbital plane containing the burning WD (the black circle). The WD pseudophotosphere is represented by the heavy solid line (adapted from Skopal et al. 2014). Bottom panel shows a model of the ionization structure of the hot components in symbiotic binaries during active phases (adapted from Cariková & Skopal 2012).

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