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Exploring outbursts of accreting white dwarfs in symbiotic binaries – basic concept

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Abstract. In this contribution I summarize the main characteristics and effects that are observed during outbursts of symbiotic stars: properties of the hot- and warm-type outbursts, enhanced mass outflow occasionally followed by ejection of bipolar jets, and the emergence of a neutral near-orbital-plane region. The results presented were largely obtained using small telescopes, supplemented by observations from the archives of terrestrial and space observatories.

Key words: Stars: binaries: symbiotic – Stars: jets – Stars: winds, outflows

1. Introduction

Symbiotic stars (SySts) are the widest interacting binaries with orbital periods typically of a few years. They consist of an evolved giant and, in vast majority, a white dwarf (WD) accreting from the giant's wind (Boyarchuk, 1967; Kenyon, 1986; Mürset & Schmid, 1999; Belczyński et al., 2000). Only a few SySys have been detected to have a neutron star as an accretor (e.g., Chakrabarty & Roche, 1997; Masetti et al., 2007a,b; Yungelson et al., 2019).

The accretion process makes the WD very hot ($> 10^5\,$K) and luminous ($\sim 10^1 - 10^4\,L_\odot$) object, which ionizes a significant portion of the wind from the giant, giving rise to nebular emission (e.g. Seaquist et al., 1984). This configuration represents the so-called *quiescent phase*, during which SySt releases energy at an approximately constant rate. The most prominent feature of the optical light curves (LCs) of luminous SySts during quiescence is the wave-like orbital-related variation (see Figs. 1 and 2).

On the other hand, many SySts undergo unpredictable outbursts observed on a very different and variable timescale. The outbursts, resulting from the prolonged accretion by the WD until the ignition of a thermonuclear event on its surface, are analogous to classical novae in cataclysmic variables. They are called symbiotic novae or recurrent symbiotic novae, depending on the time scale of their recurrence. Due to the presence of the evolved giant in SySts, the brightness amplitude of symbiotic novae is as low as ≈4-9 mag (e.g., Mürset & Nussbaumer, 1994; Bode & Evans, 2008). The typical and most frequently observed outbursts of SySts are the so-called ‘Z And-type’ outbursts. They result from an increase in the accretion rate above the upper limit of the stable burning (see e.g. Fig. 2 of Shen & Bildsten, 2007), which can lead to expansion of the burning envelope simulating an A–F type pseudophotosphere (Tutukov & Yungelson, 1976; Paczynski & Rudak, 1980) and/or blowing optically thick wind from the WD (Kato & Hachisu, 1994; Hachisu et al., 1996). They are characterized by a few magnitude (multiple) brightening(s) in the optical observed on the timescale of a few months to years or even decades (see examples of historical LCs published by Brandi et al., 2005; Leibowitz & Formiggini, 2008; Skopal et al., 2001) with signatures of a mass outflow (e.g., Fernandez-Castro et al., 1995; McKeever et al., 2011). Stages with Z And-type outbursts that interrupt quiescent phase are usually called *active phases* of a SySt (see Fig. 1). Analysing observations of Z And-type outbursts for non-eclipsing SySts AG Peg and V426 Sge, Skopal et al. (2017, 2020) confirmed the above-mentioned nature of this type of outbursts. The authors found that the optical brightening of these SySts is due to an increase of the nebular radiation from the very beginning of the outburst, while the contribution from the hot WD is negligible in the optical. The nebular continuum represents a fraction of the hot WD’s radiation (below 912 Å) converted by the enhanced wind from the WD at rates of a few times $10^{-6}\,M_{\odot}\,\mathrm{yr}^{-1}$ into the nebular emission. The corresponding emission measure and the temperature of the hot WD’s pseudophotosphere ($1.5-2\times10^{5}$ K) yield the WD luminosity of a few times $10^{37}\,\mathrm{erg\,s^{-1}}$ that is close to the Eddington limit. On the other hand, for eclipsing SySts the optical is usually dominated by a warm WD’s pseudophotosphere together with a strong nebular radiation (see Skopal, 2005, and Sect. 2.1 here).

The main goal of this contribution is to show the main common features of Z And-type outbursts. This work summarizes recent published results based on the optical multicolor photometry and, low- and medium-resolution spectroscopy obtained with small telescopes in part collected by amateur astronomers, supplemented by publicly available observations from archives.

2. Basic effects measured during outbursts

2.1. Warm and hot type outbursts[1]

Using the method of multiwavelength modeling of combined spectra, Skopal (2005) found out that the spectrum of the hot component in eclipsing SySts during outbursts consists of two sources of radiation, differing significantly in their temperatures. He called it the two-temperature UV spectrum. This type of the spectrum consists of a relatively cool spectrum produced by a warm stellar pseudophotosphere radiating at $1-3\times10^{4}$ K, and the hot one represented

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[1] The sometimes used division of AG Dra outbursts into hot and cool (see González-Riestra et al., 1999) has nothing to do with the classification of SySts outbursts into warm and hot described in this section.

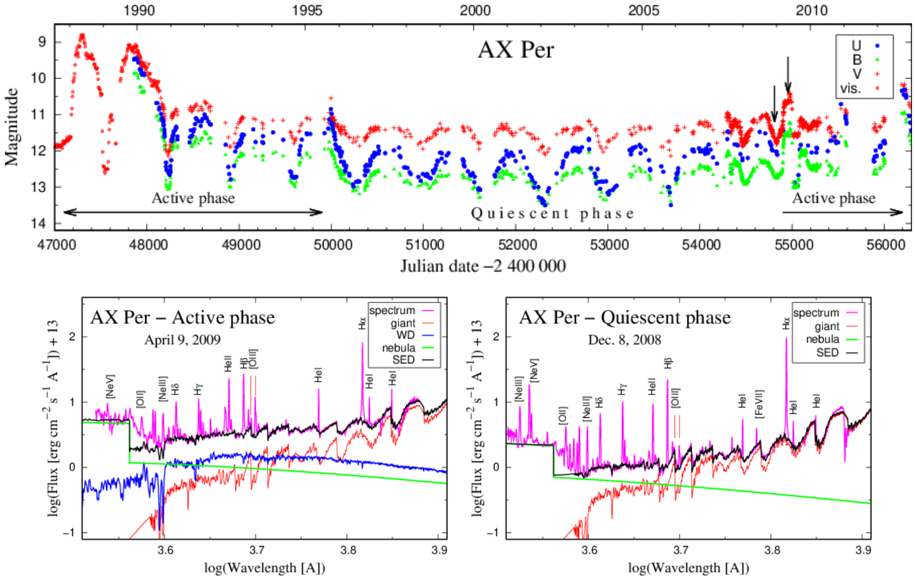

Figure 1. Example of the warm-type outburst observed for AX Per. The top panel shows evolution of multicolor LCs. The parts representing the active and quiescent phases are denoted. Bottom panels show the spectra (in magenta) and their SED models during active phase (left) and quiescence (right). Times of observations are marked by arrows in the top panel. Note the appearance of a strong warm WD's pseudophotosphere (in blue) at simultaneous presence of a strong nebular spectrum (the continuum (in green) and emission lines) during outburst. Adapted according to Skopal et al. (2011).

by a strong nebular radiation. The warm stellar radiation is not capable of producing the measured nebular emission, which implies the presence of a strong ionizing source in the system. This discrepancy in the properties of the main components of radiation in the spectrum determines the disk-like structure of the hot component viewed under a high inclination angle. The outer optically thick flared rim of the disk (which is *the warm WD's pseudophotosphere* with the effective radius of a few $R_{\odot}$), occults the central ionizing source in the line of sight, while the nebula above/below the disk is ionized by the central hot WD (see Fig. 27 of Skopal (2005) and Fig. 6 of Cariková & Skopal (2012)).

As a result, the disk-like structure of the hot component during outbursts is responsible for observing two different types of spectra depending on the orbital inclination (i). Outbursts in systems with a high i show the two-temperature type of the hot component spectrum. These outbursts are classified as the 'warm-type', because the stellar component of radiation is emitted by the warm WD's pseudophotosphere, which usually dominates the optical (see Fig. 1). On the

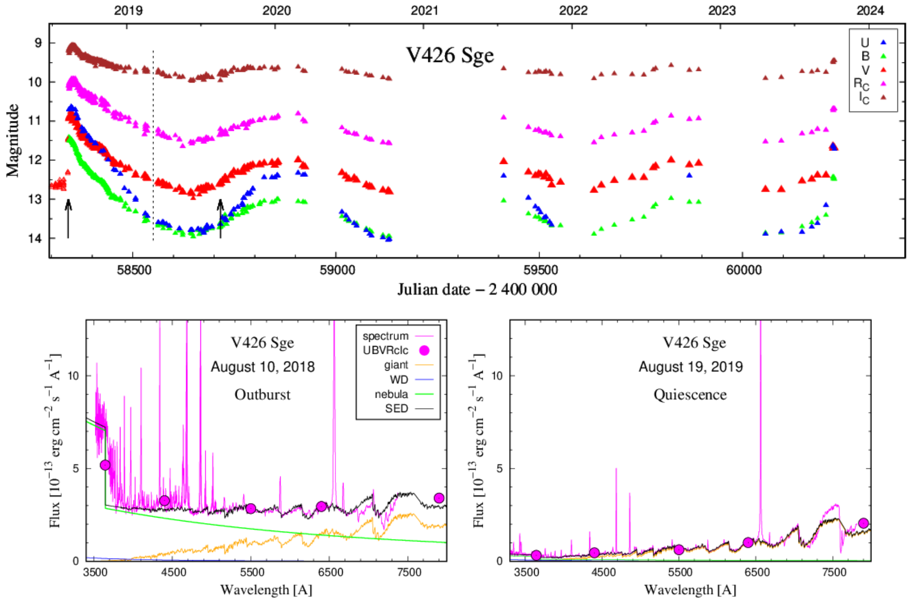

Figure 2. Example of the hot-type outburst observed for V426 Sge in 2018. The plots and their meaning as in Fig. 1. Note the appearance of a strong nebular radiation from the very beginning of the outburst, while the 2×10^5 K hot WD's pseudophotosphere cannot be indicated in the optical. Adapted according to Skopal et al. (2020, 2023).

other hand, outbursts in systems with a low i are classified as 'hot-type', because the stellar component of radiation is emitted by *the hot WD's pseudophotosphere* (i.e., the optically thick interface of the enhanced fast wind from the WD). Its temperature is $\approx 2 \times 10^5$ K and the effective radius $\approx 0.1\,R_{\odot}$. As a result, the contribution of the hot WD's pseudophotosphere is negligible in the optical, while the nebular continuum dominates the near-UV/optical from the very beginning of the outburst (see Fig. 2)[2].

2.2. Slow and high velocity mass-outflow during outbursts

A common feature of outbursts is a distinct increase of the mass-outflow from the burning WD, most often in the form of an enhanced stellar wind, indicated by the broadening of the emission line profiles, which in some cases are of the P Cygni type (e.g., Fernandez-Castro et al., 1995; Skopal, 2006; McKeever et al., 2011). Signs of mass outflow at moderate velocities (~ 100–$500\,\mathrm{km\,s^{-1}}$) are indicated by absorption components of P Cygni profiles in the spectrum of systems

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[2] Originally, Skopal (2005) named these types of outbursts as 1st- and 2nd-type, later Skopal et al. (2020) renamed them to warm- and hot-type to express their physical nature.

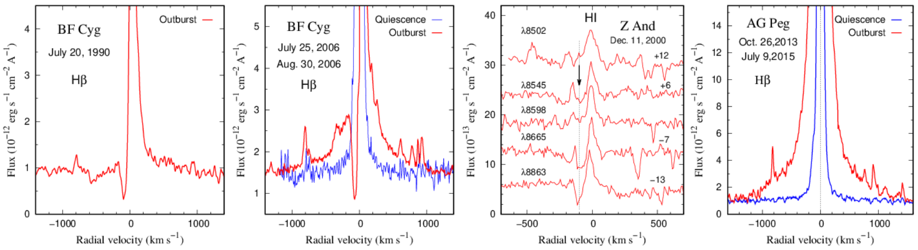

Figure 3. Example of the slow and high velocity mass-outflows indicated by P Cyg profiles and broad wings of emission lines for systems with high (BF Cyg and Z And) and low (AG Peg) i, respectively. Profiles from around the optical maxima and quiescence are in red and blue, respectively. From left to right: BF Cyg 1990 outburst (Skopal et al., 1997) and 2006 outburst (Skopal et al., 2013), Z And 2000 outburst (Skopal et al., 2006), and AG Peg 2015 outburst (Skopal et al., 2017).

with a high i, mostly at the beginning of the outburst, while high velocities ($\approx 1000-2000\,\mathrm{km\,s^{-1}}$) by broad emission wings of permitted lines, which are present in the spectra of all systems during the outburst. Examples are shown in Fig. 3.

Such the two-velocity type of mass-outflow during outbursts can be explained by the disk-like structure of the hot component (see Sect. 2.1), which expands at moderate velocities in the orbital plane, while at higher latitudes a fast optically thin wind escapes the central WD. Next, when viewing the system at a high i, the observer can see the slowly expanding warm WD's pseudophotosphere, which allows the observation of P Cyg line profiles with broad emission wings, and features of the warm-type of outbursts in the spectrum. Conversely, for systems with a low i, we observe just the fast optically thin stellar wind down to the hot WD's pseudophotosphere, which gives rise to the broadening of the profile of the emission lines, especially their wings, and spectral characteristics of the hot-type of outbursts.

Skopal (2006) showed that the broadening of the Hα wings and the significant increase of the emission measure in the continuum during active phases are caused by the enhanced ionized wind from the hot component. Therefore, modeling the wing profiles and/or having the emission measure (EM) from the SED models, we can determine the corresponding mass-loss rate, $\dot{M}_{\rm WD}$. Using a β-law, optically thin bipolar wind model from the hot components[3] the author fitted the broad Hα wings. In this way, he determined $\dot{M}_{\rm WD}$ to a few $\times 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$ and to a few $\times\,(10^{-7} - 10^{-6})\,M_{\odot}\,\mathrm{yr}^{-1}$ during quiescent and active phases, respectively.

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[3] In the model, the central torus blocks the wind in the orbital plane. The model is therefore only applicable for systems with a high i.

In the case of systems with a low i (i.e., for the hot-type outbursts), Skopal et al. (2017, 2020) expressed a relationship between EM and $\dot{M}_{\rm WD}$ for a spherically symmetric β-law wind around the WD. According to the theory of the optically thick wind in nova outbursts (e.g. Kato & Hachisu, 1994), the authors considered two limiting cases for the beginning of the wind – on the WD's surface and on its pseudophotosphere. In both cases, the wind becomes optically thin at the WD's pseudophotosphere. Applying this approach for EM from the SED models and the Hα line luminosity, they obtained $\dot{M}_{\rm WD}$ of a few times $10^{-6}\,M_{\odot}\,{\rm yr}^{-1}$ for both studied objects, AG Peg and V426 Sge, during their Z And-type outbursts.

2.3. Transient jets from a warped disk

The possibility of the formation of collimated bipolar outflows (jets) from the WD in symbiotic binaries seems to be related to the increase of accretion onto the WD during the Z And-type outbursts (Skopal et al., 2018). Usually, jets are observed at, but mainly, after the optical maximum (e.g., Tomov et al., 2007; Skopal et al., 2009). However, their detection is very rare, although a variety of methods from X-rays to the radio has been employed. Typical signatures of jets in the optical spectrum are satellite components to the main emission of the strongest hydrogen and helium lines. To date, such the indication of jets has only been recorded for five objects: Hen 3-1341, StHα 190, Z And, BF Cyg and St 2-22 (e.g., Tomov et al., 2000; Munari et al., 2001; Tomov et al., 2007; Skopal et al., 2013; Tomov et al., 2017).

Spectral properties of the satellite components to Hα during the 2006 Z And outburst suggested an average opening angle of jets of $6^{\circ}.1$, the mass-outflow rate via jets of $\dot{M}_{\rm jet} \sim 2\times10^{-6}(R_{\rm jet}/1\,{\rm AU})^{1/2}\,M_{\odot}\,{\rm yr}^{-1}$, which corresponds to the emitting mass of $M_{\rm jet}^{\rm em} \sim 6\times10^{-10}(R_{\rm jet}/1\,{\rm AU})^{3/2}\,M_{\odot}$ and the emission measure of both jets of $1-2\times10^{58}\,{\rm cm}^{-3}$. During their lifetime (July – December, 2006), the jets released the total mass of $M_{\rm jet}^{\rm total} \approx 7.4\times10^{-7}\,M_{\odot}$ (Skopal et al., 2009).

The repeated ejection of jets during outbursts of Z And was always followed with the simultaneous emergence of the rapid photometric variability ($\Delta m \approx 0.06$ mag) on the timescale of hours. According to models of SED, this type of variability is produced by the warm WD's pseudophotosphere, i.e., the outer rim of the disk that develops during outbursts. Such the higher-amplitude photometric variability can represent observational response of the radiation-induced warping of the inner parts of the disk. According to theoretical modeling, the high luminosity of the central source can illuminate the disk, whose inner parts can become unstable to warping (Iping & Petterson, 1990; Pringle, 1996; Livio & Pringle, 1996). In agreement with the general view that the warped disk starts to wobble or precess (Livio & Pringle, 1997) we can thus observe wobbling of the outer parts of the disk, reflected by the ∼0.6 mag photometric variability. Therefore, it was suggested that the jets ejection and the measured disk–jets

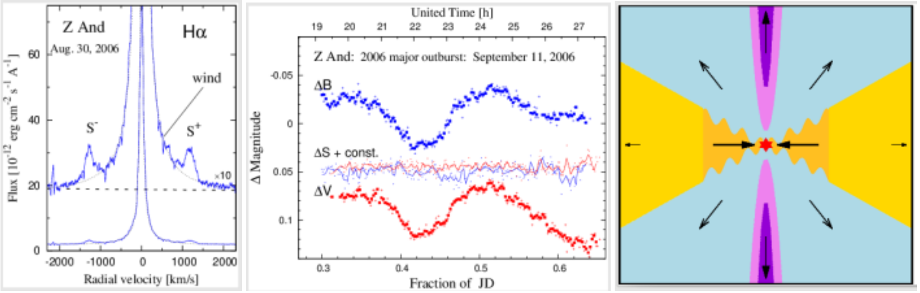

Figure 4. Example of the bipolar jets ejection from the symbiotic prototype Z And. Left: The bipolar jets are indicated by S^- and S^+ satellite components to the Hα line. Middle: Simultaneously, the photometric variation within $\Delta m \sim 0.06$ mag on the time-scale of hours develops. Right: Sketch of a disruption of the inner parts of the disk (dark yellow) due to the outburst of the central WD that can cause sudden increase in mass accretion and the ejection of bipolar jets (violet area) (see Skopal et al., 2018).

connection could be caused by the radiation-induced warping of the inner disk due to a significant increase of the burning WD luminosity during outbursts. In this way, the enhanced accretion through the disk warping, supplemented by the accretion from the wind of the giant, can keep a high luminosity of the WD for a long time, until depletion of the disk (see Skopal et al., 2018, in detail). Example of the relevant observations and a sketch of the disk warping effect are shown in Fig. 4.

2.4. Emergence of a neutral region in the orbital plane during Z And type outbursts

The formation of the disk-like structure of the hot component during outbursts of SySts (Sect. 2.1) represents the key effect for understanding the symbiotic phenomenon. For example, the two-temperature UV spectrum of the hot component, the two-velocity type of mass-outflow, and specific ionization structure that develop during outbursts (see Fig. 2 of Skopal, 2023, for an idea).

Its natural consequence is the simultaneous neutralization of the giant's wind in the orbital plane during outbursts: The flared disk actually blocks ionizing photons from the central hot WD within its vertical extension, which causes the initially ionized wind before the outburst (i.e., during quiescence) to become neutral in the orbital plane during the outburst. Owing to the high densities of the giant's wind in the orbital plane, the hydrogen recombination process occurs within minutes to days. As a result, a neutral wind region emerges in the orbital plane during outbursts of SySts (see Skopal, 2023).

This interesting effect is detectable by Rayleigh scattering on neutral atoms of hydrogen, best observable as a depression of the continuum around the Lyα line (e.g., Isliker et al., 1989; Vogel, 1991). In such the case, the strength of Rayleigh scattering is determined by the number of neutral H atoms on the path between the emitting source (here, it is the warm WD's pseudophotosphere) and the observer, i.e., on the hydrogen column density, $N_{\rm H}$. Given the location of the presumed neutral region in the orbital plane, this effect is measurable for eclipsing systems at any orbital phase, because they are seen edge-on.

Therefore, to prove this effect, we selected eclipsing SySts for which a well-exposed ultraviolet spectrum from an outburst is available. By evaluating all candidates, we found that BF Cyg, CI Cyg, YY Her, AR Pav, AX Per and PU Vul fit best our objectives. Modeling the two-temperature UV spectra of these objects by the stellar continuum from the warm WD's pseudophotosphere and the nebular continuum from the ionized circumbinary matter above/below the disk (see Sect. 2.1), we determined $N_{\rm H}$ values from all suitable spectra (42) of our targets (the targets selection and the modeling are described by Skopal, 2023, in detail).

Figure 5 shows the results. Top panels illustrate the continuum depression around the Lyα line due to Rayleigh scattering on H atoms at two different orbital phases. The bottom panel **c** depicts all $N_{\rm H}$ values as a function of the orbital phase, and panel **d** shows a schematic of the ionization structure of the symbiotic binary during the outburst. It is clear from the figure that the $N_{\rm H}$ measurements follow a common course along the orbit with a difference of more than two orders of magnitude between the values around the inferior and superior conjunction of the giant. High values of $N_{\rm H}$ at any orientation of the binary ($> 10^{22}\,{\rm cm}^{-2}$) prove the presence of a neutral region in the orbital plane because our targets are seen approximately edge-on.

The fact that this region consists of the neutral wind from the giant (see above) is confirmed by the significant difference in $N_{\rm H}$ values measured around the superior and the inferior conjunction of the giant. This is because of measuring $N_{\rm H}$ in the direction to the WD, while the source of neutral hydrogen is associated with the red giant (see Skopal, 2023). Also, the model of $N_{\rm H}$ values from Fig. 5c corresponds to the wind velocity profile of normal giants in SySts (see Skopal & Shagatova, 2023, in detail).

The neutral near-orbital-plane region determines a biconical shape of the ionized region distributed above/below it, with the tops at the burning WD (see Fig. 5d). The nebular radiation is produced by the high-velocity mass-outflow in the form of an enhanced wind during outbursts (see Sect. 2.2). Accordingly, depending on the i, we observe the spectral characteristics of a hot or warm type of outburst (see Sect. 2.1).

3. Conclusion and future work

The key phenomenon for understanding the two-temperature UV spectrum of SySts that develops during outbursts is the formation of the disk-like structure

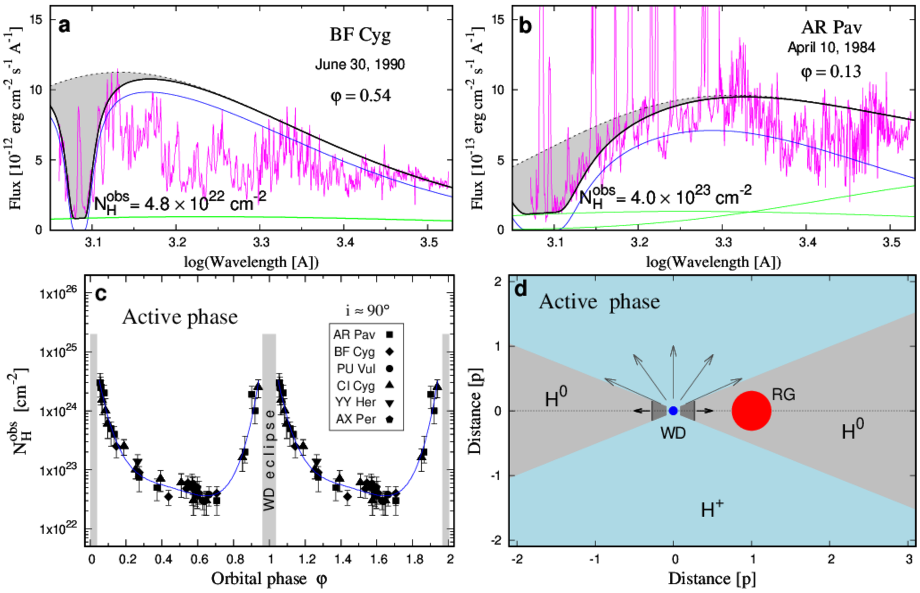

Figure 5. Top: Example of a strong depression of the continuum around the Lyα line due to Rayleigh scattering on H atoms (gray area) around the superior (panel **a**) and inferior (**b**) conjunction of the giant. Dotted line is the unattenuated continuum; meaning of other lines as in Fig. 1. Bottom: Column densities between the observer and the WD measured for our targets as a function of the orbital phase φ (**c**) and the corresponding ionization structure during outbursts is sketched on the right (**d**). The two-velocity type of mass outflow is denoted by arrows of different sizes. Adapted according to Skopal (2023).

around the WD. Such the non-spherical structure of the hot component is constrained by the contradictory properties of the radiation from the warm WD's pseudophotosphere and the strong nebular radiation observed during outbursts in the spectrum of eclipsing systems. (see Sect. 2.1).

The disk-like structure is also responsible for observing the two-velocity type of mass-outflow indicated during outbursts. The slow component is due to the disk expansion in the orbital plane, while the fast component is due to the optically thin stellar wind that is driven by the burning WD through the rest of the sphere (see Sect. 2.2, Fig. 5d).

In rare cases, a significant increase in the luminosity of the burning WD during outbursts can induce warping of the inner disk with a subsequent sudden increase in mass accretion and the ejection of bipolar jets (see Sect. 2.3).

An interesting consequence of the disk-like structure of the hot component is the simultaneous emergence of a neutral near-orbital-plane region consisting of the wind from the giant (see Sect. 2.4).

Based on the given basic characteristics of the SySts outbursts, two main tasks arise for future theoretical modeling directly related to the emergence of the neutral near-orbital-plane region:

- The N_H values measured around the orbit (Fig. 5c) represent a challenge for the theoretical modeling of the wind morphology of wide interacting binaries containing an evolved giant.
- During outbursts of non-eclipsing systems, the presence of the neutral wind region in the orbital plane is probably indicated by significant broadening and high fluxes of the Raman-scattered O VI 6825 Å line relative to the quiescent phase (e.g., Leedjärv et al., 2004; Skopal et al., 2017) because a significant amount of new scatterers appears in the orbital plane. Verification of this hypothesis, however, requires theoretical modeling.

Finally, the finding of the emergence of the neutral near-orbital-plane region can also be conducive to the explanation of more violent classical nova outbursts. Here, a similar structure of the nova ejecta containing a density enhanced equatorial region was directly inferred from radio imaging of the classical nova V959 Mon (see Chomiuk et al., 2014). Disk-like structure in the equatorial plane was also constrained by modeling the energy distribution in the spectrum of the classical nova V339 Del (see Skopal, 2019). Recently, Munari et al. (2022) needed an optically thick mass layer localized in the orbital plane (they called it "the density enhancement on the orbital plane") to interpret radio interferometric imaging of the recurrent symbiotic nova RS Oph after its explosions.

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