MULTI-FREQUENCY STUDY OF SYMBIOTIC NOVAE

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ABSTRACT. Symbiotic novae are subclass of symbiotic stars - interacting binaries with wide orbits, whose photometric history is characterized by a single nova-like outburst lasting decades and caused by a thermonuclear runaway on the surface of a wind accreting white dwarf. Symbiotic novae have been detected in all frequencies from X-rays to radio waves. Multifrequency observations yield complementary information which appears to be crucial for an understanding of the underlying physical processes as an accretion by stellar winds, TNRs on the white dwarf, ionization of the wind from a cool giant, colliding winds, jets and bipolar outflows. The basic properties and multifrequency behaviour of the most studied objects: V1016 Cyg, V1329 Cyg, HM Sge, AG Peg, RT Ser, RR Tel and PU Vul are reviewed.

Key words: Stars: binary: symbiotic novae; stars: individual: V1016 Cyg, V1329 Cyg, HM Sge, AG Peg, RT Ser, RR Tel, PU Vul.

1. Introduction

Symbiotic stars are interacting binaries consisting of a cool evolved mass loosing giant and a hot radiation source ($T_{hot} \approx 100\,000$ K), which is either an accreting main sequence star or a hot white dwarf. The hot star ionizes a portion of the giant's wind, giving rise to nebular emission. The nebula is the main source of the optical continuum. The near-IR colours indicate either the presence of normal giant with $T_{eff} \sim 3000$-4000 K (S-type systems) or the combination of reddened Mira and dust with temperature of ~ 1000 K (D-type systems). The distinction between S and D types (Webster & Allen, 1975) is given by orbital separation of the cool and hot component. The binary must have enough room for Mira-variable. Therefore, the orbital periods of D-type systems are expected in the range 20 - 200 years (Whitelock, 1987). The known orbital periods of symbiotic stars are from 227 days (T CrB) to 5300 days (CH Cyg), most of them run between 1-3 years. New catalogue of symbiotic stars include 188 symbiotic stars and 30 objects suspected of being symbiotic (Belczynski et al., 2000).

Symbiotic novae are subclass of symbiotic stars whose photometric history is characterized by a single nova-like outburst lasting decades. The original Allen's (1980) list of symbiotic novae: AG Peg, RT Ser, RR Tel, V1016 Cyg, V1329 Cyg, HM Sge was later complemented by PU Vul. Recent list including 22 objects was published by Munari (1997). As the symbiotic novae are detected in frequencies from X-rays up to radio, their detailed study requires a multifrequency approach.

The behaviour of symbiotic novae is similar to classical novae, except for much longer time scale. While the mass loser in classical novae is Roche lobe filling red dwarf, in symbiotic novae it is an M giant located well inside its Roche lobe. In both cases the accreting object is a white dwarf. The orbital periods of classical novae are smaller than two days, so the radius of the Roche lobe of the hot component is a few $R_\odot$. During thermonuclear runaway the hot component expands to dimensions $> 10\ R_\odot$ and engulfs the binary system. Common envelope is ejected from the system in a few days or weeks. The orbital periods of symbiotic novae are larger than two years. Therefore both components are well separated, even during the expansion of the outbursting white dwarf to an A-F supergiant. The rise to the maximum luminosity lasts several months so it is slower than in classical novae. The increase of brightness of symbiotic novae due to the outburst does not exceed 7^m in V band. They remain at a steady high luminosity for dozens of years. Typical decline to the preoutburst luminosity lasts about 100 years.

The basic information about the nature of symbiotic novae provides the study of variability of these objects in UV, IR and optical region. Variability can be caused by: the eclipses, the reflection effect, the orbital variations of the emission measure in the nebular continuum, pulsations and/or rotation of the hot and cool component, changes of the structure of the circumstellar matter including accretion and excretion disks, interaction zone of colliding winds, flares, outbursts, dust formation. The most important physical processes which require multifrequency approach are: wind and disk accretion, flares, thermonuclear runaways, ionization of the cool giants winds, colliding winds, jets and bipolar outflows.

2. Basic orbital parameters

Orbital periods of symbiotic novae can be determined either from photometry (periodic brightness variations) or spectroscopy (periodic variations of the continuum or line fluxes, radial velocity curves). The following orbital periods were found from photometry:

V1329 Cyg - 959 days (eclipses in pre-outburst photometry; Stienon et al. (1974)), 956.5 days (post-outburst brightness variations; Schild & Schmid (1997), Chochol et al. (1999)).

RT Ser - 4502 days (post-outburst brightness variations; Pavlenko (1997)).

PU Vul - 4900 days (post-outburst eclipses; Nussbaumer & Vogel (1996), pre-outburst eclipses; Chochol et al. (1997)).

AG Peg - 816.5 days (post-outburst brightness variations; Fernie (1985)).

V1016 Cyg - 5510 days (periodicity in flares; Parimucha et al. (2000)).

The exact determination of the orbital periods of AG Peg and V1329 Cyg found from the photometric minima positions in their light curves is influenced by their apparent changes discovered by Skopal (1998). They are connected with changes of the energy distribution of the hot-star spectrum. The phase shift in the period correlates with the change in the star's brightness. Skopal (2001a) showed that the main source of of the optical continuum is the nebula arising from ionization of the cool giant wind by the hot star radiation. Variation in the emission measure is fully responsible for the observed wave-like modulation of the light curves of symbiotic binaries with the orbital phase. The large amplitude of the orbitally-related wave-like variations, shaping of minima and systematic changes in their positions reject their explanation by the reflection effect. The variation in the optical continuum should always be followed by a similar variation in Balmer emission lines.

Chochol & Wilson (2001) modelled U, B, V light curves of V1329 Cyg in terms of combined wind and chromospheric fluorescence, with eclipses and shadowing of fluorescent regions and conversion of far-ultraviolet energy into the optical bands.

The extended atmosphere of the cool giant scatters the light emitted from the hot component. The dust, Thomson, Rayleigh and Raman scattering play an important role. The previously unidentified emission lines at 6825 Å and 7082 Å were explained by Raman scattering of the far ultraviolet O VI resonance doublet, emitted near the hot compact component, by neutral hydrogen in the extended atmosphere of the cool giant. Periodic changes of the polarization vector due to the orbital motion permit to determine orbital period, inclination and orientation of the orbital plane (Schmid, 1998). Orbital period RR Tel estimated by this method exceeds 100 years.

The 5510 days photometric periodicity in V1016 Cyg was independently confirmed from infrared photometry and UV spectroscopy by Parimucha et al. (2001). They showed that the variations in the $(J-K)$ colour index as well in the UV continuum and O III], N III], C III] and Si III] emission line fluxes exhibit the same periodicity interpreted as the orbital period of the binary (see also Parimucha et al. - this proceedings).

The absolute parameters of AG Peg were determined by Kenyon et al. (1993). Spectroscopic orbits for an M giant and a hot component (found from the radial velocities of He II λ4686 Å emission line) provided the component masses $M_{cool} = 2.6 \pm 0.4$ M$_\odot$, $M_{hot} = 0.65 \pm 0.10$ M$_\odot$ and a semimajor axis $A = 2.5 \pm 0.1$ AU for an orbital inclination $i = 50°$. The red giant does not fill its Roche lobe. The orbit of the cool M giant was slightly improved by Fekel et al. (2000).

Two objects from our sample show the presence of eclipses: PU Vul and V1329 Cyg.

Two subsequent minima in the post-outburst light curve of PU Vul were explained by Nussbaumer & Vogel (1996) as eclipses in a binary system with the orbital period 4900 days. The eclipses were confirmed by Chochol et al. (1997) from the analysis of the pre-outburst photometry published by Liller & Liller (1979). Chochol et al. (1996) studied the radial velocities of the outbursting white dwarf mimicing an F-supergiant in PU Vul from 1979 to 1987 and found a possible 761 days spectroscopic orbit ($f(m) = 1.6$ M$_\odot$). If confirmed, symbiotic nova PU Vul is a triple system similar to the eclipsing symbiotic triple system CH Cyg (Skopal 1997).

The pre-outburst photographic light curve of V1329 Cyg suggested the presence of eclipses with the period 959 days (Stienon et al., 1974). Grygar et al. (1979) confirmed this period by analyzing the radial velocities of optical emission lines and found extremely large semiamplitude of the orbit resulting in a mass function $f(m) = 23$ M$_\odot$, confirmed by Iijima et al. (1981) from optical spectra and Nussbaumer et al. (1986) from UV spectra. This mass function led to a very large mass of the cool component (at least 24 M$_\odot$), which did not seem probable. Ikeda & Tamura (2000) argued that only certain portion of the emission-line profile of Hα, He II and [O III] represents the true orbital motion and found acceptable $f(m) = 1.2 \pm 0.3$ M$_\odot$. Fekel et al. (2001) used infrared radial velocities of the cool giant and determined $K_2 = 7.85 \pm 0.26$ km/s and $f(m) = 0.0481 \pm 0.0047$ M$_\odot$. Both orbits lead to a mass ratio q

= 2.93 and masses of the components $M_{cool} = 2.2$ M$_\odot$ and $M_{hot} = 0.75$ M$_\odot$ for an orbital inclination $i = 86^\circ$ determined by Schild & Schmid (1997).

3. The cool component

Near-infrared region is optimal for the determination of the spectral types of the cool components because it includes the peak emission from the giant and the contamination by thermal dust emission, which dominates in thermal infrared region, is small. The spectral types of the cool giants in symbiotic novae recently determined by Mürset & Schmidt (1999) and Rudy et al. (1999) using infrared TiO and VO molecular bands are as follows: V1016 Cyg: M6-7, HM Sge: M7, V1329 Cyg: M5.5-6, AG Peg: M3, RR Tel: M6, RT Ser: M5.5-6, PU Vul: M4.5-6. The empirically determined dependencies of effective temperature and radius upon spectral type and $V - K$ colour for cool giants and supergiants was published by van Belle et al. (1999). The S-type objects: AG Peg, RT Ser, PU Vul and V1329 Cyg have near-IR colours of a late type giant, the D-type objects: HM Sge, V1016 Cyg, RR Tel indicate presence of a dust shell.

Infrared observations demonstrated that D-type systems contain long-period Mira variables (Whitelock, 1988). Their pulsation periods are in RR Tel: 387 days (Feast et al., 1983), in HM Sge: 527 days (Munari & Whitelock, 1989); 535±5 days (Taranova & Shenavrin, 2000), in V1016 Cyg: 478 days (Munari, 1988); 470±5 days (Taranova & Shenavrin, 2000), 474±6 days (Parimucha et al. - this proceedings). Taranova & Shenavrin (2000) determined the parameters of the cool components in V1016 Cyg: $L_c = 8600$ L$_\odot$, $T_{eff} = 2850$ K, $R_c = 500$ R$_\odot$ and in HM Sge: $L_c = 10\,000$ L$_\odot$, $T_{eff} = 2650$ K, $R_c = 540$ R$_\odot$. They determined the radii of the cool shells in V1016 and HM Sge to be 1400 R$_\odot$ and 1500 R$_\odot$ and their masses (3-3.3) 10^{-5} M$_\odot$ and (4-8) 10^{-5} M$_\odot$.

Chochol et al. (1998) found from the R and V band photometry the pulsation period of the AGB component in PU Vul to be 217 days and determined $L_c = 3820$ L$_\odot$, $R_c = 282$ R$_\odot$ and $M_c = 0.76$ M$_\odot$. The photometric data from the 1993-4 eclipse were used by Chochol et al. (1997) and Chochol & Pribulla (2000) to calculate the radius of the cool component $R_c = 0.208A = 287$ R$_\odot$ in agreement with the radius derived from pulsations. Pavlenko (1997) found the pulsation period of the cool giant in RT Ser $P = 213$ days from the B band photometry.

Cool components are characterized by slow winds with a velocity of about 10-20 km/s. The mass loss rates estimated by Whitelock (1987) and Kenyon et al. (1988) are $\dot{M} \sim 10^{-7}$ M$_\odot$yr^{-1} and $\dot{M} \sim 10^{-5}$ M$_\odot$yr^{-1} for S-type and D-type systems, respectively. Radio continuum measurements at 5-15 GHz confirmed this result (Seaquist & Taylor, 1990).

4. The hot component

The hot components in symbiotic novae have undergone a single outburst lasting decades caused by the TNR on the surface of the wind accreting white dwarf. Historical light-curves of the symbiotic novae based on the published photometry were presented by Mürset and Nussbaumer (1994). We describe the history of the outburst for AG Peg, RR Tel, PU Vul and V1329 Cyg in more details.

AG Peg began the slowest classical nova outburst ever recorded in the mid-1850s, rising from 9^m to 6^m in about decade. The first available spectra from the begining of 20th century revealed Be-type spectrum with strong P-Cygni profiles of emission lines. Then the hot component slowly shrinked, increased its temperature and in 1980's evolved to a Wolf-Rayet star (WN6 spectrum), a hot subdwarf with $T_{eff} > 100\,000$ K (Kenyon et al., 1993). The IUE observations of AG Peg showed broad He II λ1640 Å and N V λ1240 Å emission line profiles. A mass loss from the hot component by a fast wind in AG Peg was proved by Nussbaumer et al. (1995), who detected with the HST the P Cygni profile of N V line. The wind in 1994 had a terminal velocity of 1000 km/s and a mass-loss rate about 10^{-7}M$_\odot$yr^{-1} (Vogel & Nussbaumer, 1994). Historical data together with IUE spectra showed that the hot component maintained a roughly constant bolometric luminosity 3000 L$_\odot$ from 1870 till 1985. During 1992-97 the bolometric luminosity declined by a factor 2-3 in comparison with the 1980-85 data (Kenyon et al., 2001).

RR Tel began its outburst in 1944. The mass-loss history was described by Nussbaumer & Dumm (1997). The nova outburst led to an extended atmosphere with a radius of ≈ 90 R$_\odot$ and no mass loss. Thereafter it slowly shrinked and increased its effective temperature. The transition to the nebular stage was accompanied by a strong mass-loss. The corresponding wind increased its terminal velocity from ≈ 400 km/s in 1949 to ≈ 1300 km/s in 1960. There is no trace of mass loss after 1978. At present, the UV dereddened continuum can be fitted with a black-body emission of $T = 140\,000$ K and $L = 3700$ L$_\odot$, corresponding to a hot star with $R = 0.105$ R$_\odot$. The ROSAT X-ray observations showed that RR Tel exhibits supersoft α pulse height distribution i.e., essentially all counts are below 0.4 keV. The observations can be reproduced by the emission of a white-dwarf model atmosphere with $T_{eff} = 142\,000$ K and $L = 3500$ L$_\odot$ (Jordan et al., 1994).

PU Vul: Liller & Liller (1979) showed that during

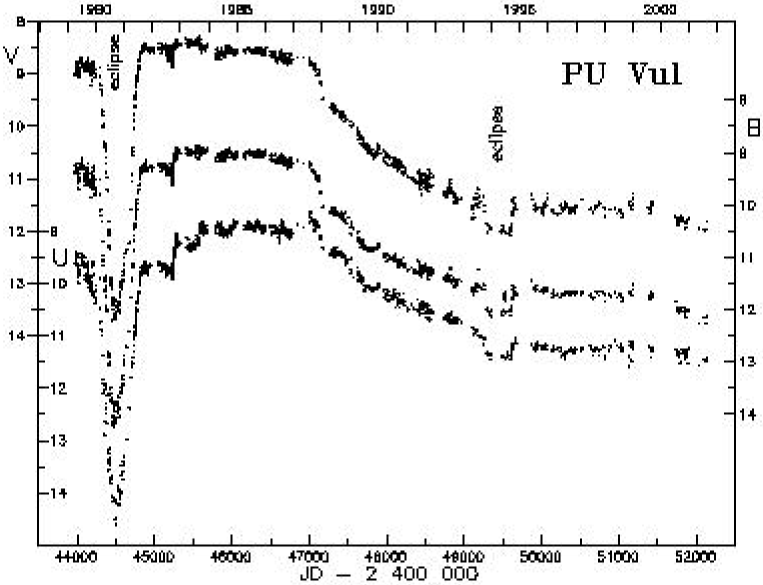

Figure 1: Long-term *UBV* photometry of PU Vul

1898-1956 the brightness of the object fluctuated between 15^m - 16.5^m prior to the slow rise to $B \sim 9.3^m$ in 1977-79. The *UBV* photometry of PU Vul is presented in Fig. 1. In 1979-87 the light curve exhibited almost flat maximum interrupted by an eclipse in 1980-82. The brightness maximum $B \sim 8.9^m$ was reached in 1983. Since 1987 the brightness continuously faded. In 1993-4 another eclipse was detected. During the flat maximum an F supergiant spectrum appeared (Belyakina et al., 1984). In 1987 the wind emerged from the hot star and the envelope was ejected. The nova entered to nebular stage in 1990 showing a rich emission line spectrum. P Cyg profile of Si IV line in IUE spectra taken in 1990-91 gave the evidence for a wind with terminal velocity ≈ 500 km/s (Vogel & Nussbaumer, 1992). Mass loss from the system $\dot{M} = 2.7\ 10^{-7}\ M_\odot yr^{-1}$ was found by Seaquist et al. (1993) from radio observations. He determined an expansion velocity of the ionized shell to be ≈ 70±10 km/s. Chochol et al. (1997) showed that the emision O III] line profile consists of multiple peaks. They interpreted it as approaching and receding parts of the equatorial ring and polar blobs with the expansion velocities ≈ 80 km/s.

V1329 Cyg: In the years 1891-1964 the brightness of the object fluctuated around 15^m with occasional 2.5^m deep decreases, which repeated with a period 959 days (Stienon et al., 1974), interpreted as eclipses of the hot component by a red giant. The nova-like outburst started in 1964. The brightness maximum of 11.5^m was reached in 1966. The brightness decline was accompanied by wave-like variations with the orbital period 956.5 d. The spectral evolution after the discovery of the object in 1979 was characterized by the gradual increase of the ionization level of the emission line spectrum. Crampton et al. (1970) found broad WR emission features with an expansion velocity of ∼ 2300 km/s and a multiple structures of [Ne III] and [O III] emission lines with peaks extending from -240 to +250 km/s. Grygar et al. (1979) explained these structures by existence of ejected polar caps and an equatorial ring. Tamura (1977) noted the appearance of [Fe VII] emission lines and strenghtening of the He II line in 1974-76.

Observations of symbiotic novae during outburst show the presence of fast winds from their hot components. Very broad WR emission features of He II, N III, C III, N V lines during nebular stage can be attributed to this wind.

Symbiotic novae fall into two classes with quite distinct spectral behaviour. In V1016 Cyg, V1329 Cyg and HM Sge the outburst led straight to a nebular emission spectrum. The photosphere of the outbursting white dwarf reached in maximum only few $R_\odot$. In AG Peg, RT Ser, RR Tel and PU Vul outbursting star remains several years in A-F supergiant state before entering the nebular phase. The outburst of symbiotic nova occurs when unstable hydrogen shell burning causes a white dwarf to expand to a radius of 1-100 $R_\odot$. This model predicts a long-duration, constant luminosity phase following the visual maximum. The evolution of luminosity and temperature during the outbursts of symbiotic novae was studied by Mürset & Nussbaumer (1994). They found the peak luminosities in the range 3700 - 37000 $L_\odot$ and slowly increasing temperatures up to 200 000 K during their decline from visual maxima. Different behaviour of two types of symbiotic novae can be explained in terms of degenerate and non-degenerate flashes. White dwarfs undergoing strong, degenerate flash evolve into A-F supergiant resembling the classical novae in maximum. Objects undergoing weak, non-degenerate flash remain at high effective temperatures and resemble planetary nebulae at visual maximum (Iben, 1982; Kenyon & Truran, 1983). The strong degenerate flashes occur at low accretion rates $\dot{M} < 10^{-9}$ $M_{\odot}yr^{-1}$, while non-degenerate flashes at high accretion rates $\dot{M} > 10^{-8}$ $M_{\odot}yr^{-1}$ (Iben, 1982).

Luminosities of the hot components at plateau portion of a white dwarf cooling curve are directly related to their masses by the core mass-luminosity relation (Paczynski, 1971; Joss et al., 1987). The masses of the white dwarfs in $M_{\odot}$, calculated by Mikolajewska & Kenyon (1992) (1) and Mürset & Nussbaumer (1994) (2) are as follows: V1016 Cyg (1.1 (1,2)), HM Sge (0.9 (1); 0.95 (2)), V1329 Cyg (0.68 (1); 0.81 (2)), AG Peg (0.55 (1); 0.54 (2)), RR Tel (0.7 (1); 0.85 (2)), RT Ser (0.99 (2)), PU Vul (0.9 (1); 0.54 (2)). The derived luminosities in plateau phase are responsible for differences in white dwarf masses presented in both papers. The distances to the systems which can resolve the problem are poorly known.

5. The nebula

The rich emission-line optical and UV spectra indicate the presence of a circumstellar ionized nebula formed by a mass loss from one or both components of the symbiotic nova. The diagnostic of the physical conditions within the nebula (electron densities and temperatures) can be accomplished using the forbidden and intercombination emission line fluxes (Viotti & Hack, 1993 and references therein). S-type symbiotics are surrounded by nebulae with electron densities $N_e \sim 10^8$ - 10^{10} cm^{-3}, while the densities of nebulae in D-type systems are $N_e \sim 10^6$ cm^{-3} (Kenyon, 1986). Electron temperatures can be derived also from fitting of spectral energy distribution in the continuum between 0.12 and 5 μm by a three-component model of radiation. Two stellar components are approximated by Planck functions, while the nebular spectrum is represented by the free-bound and free-free emission from hydrogen (Skopal, 2001b). Application of this method allowed to determine electron temperatures of AG Peg and V1329 Cyg as $T_e = 17\,200$ K and $T_e = 19\,500$ K, respectively (Skopal, 2001c).

Taylor (1988) reviewed the radio imaging of symbiotic stars and categorized ionized nebulae into two types: outburst ejecta with strong tendency for bipolar or jet morphology and stellar winds. V1016 Cyg and HM Sge show the characteristics of both types. Extended nebulae can be resolved by radio-interferometric observations and high-resolution CCD imaging. The nebulae of HM Sge, V1016 Cyg and AG Peg were resolved both at radio and optical wavelength (Corradi et al., 1999a and references therein), V1329 Cyg by the HST at optical wavelength (Schild & Schmid, 1997). The UV images of HM Sge were taken by the HST (Hack & Paresce, 1993). Direct images of the extended nebular structures around D-type symbiotics show bipolar geometry. The detailed study of the optical nebulae around HM Sge and V1016 Cyg (Corradi et al., 1999b) shows the evidence of elongated and collimated outflows. HM Sge possesses a curved collimated string of knots as a result of a fast collimated wind from the white dwarf and precessing accretion disk. The bipolar outflow velocities of 120 km/s for V1016 Cyg and 200 km/s for HM Sge were found from long-slit spectroscopic imaging (Solf, 1983; 1984).

The matter lost by a cool giant escapes from the system directly by conventional stellar wind or during the accretion process onto the hot component. This component loose the mass by wind which can be collimated by an accretion disk or by the ejection of the envelope due to the outburst. Binary model for the creation of bipolar circumstellar outflows was proposed by Morris (1987). The wind of the red giant forms an accretion disk around the secondary component and an excretion disk encompassing the whole system. A second wind arises from the interior of the accretion disk. The presence of accretion and excretion disk in V1329 Cyg was proposed by Chochol & Vittone (1986). Long-term photometry of this object shows that the orbital brightness variations are modulated by a secondary period of 553 days and a possible cycle of ≈ 5300 days (Chochol et al., 1999), probably caused by the precession and nutation of the accretion disk. The existence of the accretion disk is supported by the 3D simulation of the wind accretion by compact star (Theuns & Jorissen, 1993) as well as by the 2D gas dynamic simulation of a mass-transfer by stellar wind in symbiotic stars (Bisikalo et al., 1997).

In the standard model (Seaquist et al., 1984; Taylor & Sequist, 1984; Nussbaumer & Vogel, 1987) the nebula is generated in the wind from the cool giant and part of this wind is photoionized by the hot star. Ionized region can be either completely enclosed by neutral material or the cone of ionized material sweeps over the one of the components.

In the colliding-wind model the wind from the hot component interacts with the wind of the cool giant (Wallerstein et al., 1984; Girard & Willson, 1987; Nussbaumer & Walder, 1993). The winds from two components approach from opposite directions colliding head-on in the region between the stars and head-on-tail outside. As a result, the reverse shock propagating in the direction of the white dwarf and expanding shock propagating towards and beyond the giant appear.

Detailed 3D simulations of colliding winds in symbiotics performed by Walder (1998) show the presence of the spiral-shaped interaction zone of the two winds. It consists from the driving part, where the hot-star wind crashes into the slow, dense wind of the cool giant and lagging part characterized by a huge rarefaction of the cold wind.

For the collision region, temperatures of a few milion K and consequently X-ray emision are expected. Symbiotic novae V1016 Cyg and HM Sge were detected as bright X-ray sources by Allen (1981) using the EINSTEIN satellite. The same objects as well as AG Peg and PU Vul were detected also by ROSAT. These objects exhibit harder β pulse height distribution that typically peaks at 0.8 keV and can be reproduced with the emission from a very hot optically thin plasma heated by the shocks in the collision of two stellar winds (Mürset et al., 1995, 1997). All β-type observations were fitted with one point Raymond-Smith type plasma model and temperatures 3.1 - 6.3 milions K were derived.

The colliding wind model was successfully applied to the calculation of the line and continuum spectra of HM Sge (Formiggini et al., 1995), AG Peg (Contini, 1997) and RR Tel (Contini & Formiggini, 1999). The model fits the high- and low-ionization emission lines taking into account both the shock created by the winds and photoionization flux from the hot star.

Kenny & Taylor (1998) applied a model of orbital colliding winds developed by Kenny (1995) to explain radio observations of HM Sge. They derived the orbital period of HM Sge as 80^{+60}_{-20} years. Richards et al. (1999) used the MERLIN and VLA radio observations to show that emission peaks appear to be corotating with the binary orbit as the ionization front and the hot wind from the white dwarf interact with the Mira wind. The development of the radio structure over 5 years allowed to estimate the binary separation A = 50 AU if the distance is $d = 1250 \pm 280$ pc. Eyres et al. (2001) used HST and VLA observations to measure for the first time the positions of the binary components of a symbiotic star HM Sge directly. They estimated the projected angular binary separation to be 40 ± 9 mas. The colliding winds model was succesfully applied also for explanation of the MERLIN radio observations of V1016 Cyg (Watson et al., 2000).

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References

Allen D.: 1980, *MNRAS*, **190**, 75.

Allen D.: 1981, *MNRAS*, **197**, 739.

Belczynski K., Mikolajewska J., Munari U., Ivison R.J., Friedjung M.: 2000, *As.Ap.S*, **146**, 407.

Belyakina T.S., Bondar N.I., Chochol D., Chuvaev K.K., Efimov Y.S., Gershberg R.E., Grygar J., Hric L., Krasnobabtsev V.I., Petrov P.P., Piirola V., Savanov I.S., Shakhovskaya N.I., Shakhovskoy N.M., Shenavrin V.I.: 1984, *As.Ap.*, **132**, L12.

Bisikalo D.V., Boyarchuk A.A., Kuznetzov O.A., Chechetkin V.M.: 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, J. Mikolajewska (ed.), CFPA Warszava, p. 83.

Chochol D., Andronov I.L., Arkhipova V.P., Chinarova L.L., Mattei J., Shugarov S.Y.: 1999, *Contrib. Astron. Obs. Skalnaté Pleso*, **29**, 31.

Chochol D., Pribulla T.: 2000, in *The Impact of Large-Scale Surveys on Pulsating Star Research*, L. Szabados & D.W.Kurtz (eds.), ASP Conf. Ser. 203, p. 125.

Chochol D., Pribulla T., Tamura S.: 1998, *IBVS*, 4571.

Chochol D., Pribulla T., Tamura S., Tajitsu A., Kanamitsu O.: 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, J. Mikolajewska (ed.), CFPA Warszava, p. 127.

Chochol D., Tamura S., Kanamitsu O., Pribulla T., Tajitsu A.: 1996, in *Cataclysmic Variables and Related Objects*, A.Evans & J.H.Wood (eds.), Kluwer Academic Publishers, p. 343.

Chochol D., Vittone A.: 1986, *Ap.Sp.Sci.*, **121**, 225.

Chochol D., Wilson R.E.: 2001, *MNRAS*, **326**, 437.

Contini M.: 1997, *ApJ*, **483**, 886.

Contini M., Formiggini L.: 1999, *ApJ*, **517**, 925.

Corradi R.L.M., Brandi E., Ferrer O.E., Schwarz H.E.: 1999a, *As.Ap.*, **343**, 841.

Corradi R.L.M., Ferrer O.E., Schwarz H.E., Brandi E., Garcia L.: 1999b, *As.Ap.*, **348**, 978.

Crampton D., Grygar J., Kohoutek L., Viotti R.: 1970, *Astrophys. Lett.*, **6**, 5.

Eyres, S.P.S., Bode M.F., Taylor A.R., Crocker M.M., Davis R.J.: 2001, *ApJ*, **551**, 512.

Feast M.W., Whitelock P.A., Catchpole R.M., Roberts G., Carter B.S.: 1983, *MNRAS*, **202**, 951.

Fekel F.C., Hinkle K.H., Joyce R.R., Skrutskie M.F.: 2001, *AJ*, **121**, 2219.

Fekel F.C., Joyce R.R., Hinkle K.H., Skrutskie M.F.: 2000, *AJ*, **119**, 1375.

Fernie J.D.: 1985, *PASP*, **97**, 653.

Formiggini L., Contini M., Leibowitz E.M.: 1995, *MNRAS*, **277**, 1071.

Girard T., Willson L.A.: 1987, *As.Ap.*, **183**, 247.

Grygar J., Hric L., Chochol D., Mammano A.: 1979, *BAC*, **30**, 308.

Hack W.J., Paresce F.: 1993, *PASP*, **105**, 1273.

Iben I.: 1982, *ApJ*, **259**, 244.

Iijima T., Mammano A., Margoni R.: 1981, *Ap.Sp.Sci.*, **75**, 237.

Ikeda Y., Tamura S.: 2000, *PASJ*, **52**, 589.

Jordan S., Mürset U., Werner K.: 1994, *As.Ap.*, **283**, 475.

Joss P.C., Rappaport S., Lewis W.: 1987, *ApJ*, **319**, 180.

Kenny H.T.: 1995, *PhD thesis*, Univ. Calgary, Canada.

Kenny H.T., Taylor A.R.: 1998, *J. R. Astron. Soc. Canada*, **92**, 317.

Kenyon S.J.: 1986, *The Symbiotic Stars*, Cambridge University Press.

Kenyon S.J., Fernandez-Castro T., Stencel R.: 1988, *AJ*, **95**, 1817.

Kenyon S.J., Mikolajewska J., Mikolajewski M., Polidan R.S., Slovak M.H.: 1993, *AJ*, **106**, 1573.

Kenyon S.J., Proga D., Keyes C.D.: 2001, *ApJ*, **122**, 349.

Kenyon S.J., Truran J.W.: 1983, *ApJ*, **273**, 280.

Liller M.H., Liller W.: 1979, *AJ*, **84**, 1357.

Mikolajewska J., Kenyon S.: 1992, *MNRAS*, **256**, 177.

Morris M.: 1987, *PASP*, **99**, 1115.

Munari U.: 1988, *As.Ap.*, **200**, L13.

Munari U.: 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, J. Mikolajewska (ed.), CFPA Warszava, p. 37.

Munari U., Whitelock P.A.: 1989, *MNRAS*, **237**, 45.

Mürset U., Jordan S., Walder R.: 1995, *As.Ap.*, **297**, L87.

Mürset U., Nussbaumer H.: 1994, *As.Ap.*, **282**, 586.

Mürset U., Schmid H.M.: 1999, *As.Ap.S*, **137**, 473.

Mürset U., Wolff B., Jordan S.: 1997, *As.Ap.*, **319**, 201.

Nussbaumer H., Dumm T.: 1997, *As.Ap.*, **323**, 387.

Nussbaumer H., Schmutz W., Vogel M.: 1986, *As.Ap.*, **169**, 154.

Nussbaumer H., Schmutz W., Vogel M.: 1995, *As.Ap.*, **293**, L13.

Nussbaumer H., Vogel M.: 1987, *As.Ap.*, **182**, 51.

Nussbaumer H., Vogel M.: 1996, *As.Ap.*, **307**, 470.

Nussbaumer H., Walder R.: 1993, *As.Ap.*, **278**, 209.

Paczynski B.: 1971, *Acta Astron.*, **21**, 417.

Parimucha Š., Arkhipova V.P., Chochol D., Kroll P., Pribulla T., Shugarov S.Y., Ulyanikhina O., Chinarova L.L.: 2000, *Contrib. Astron. Obs. Skalnaté Pleso*, **30**, 99.

Parimucha Š., Chochol D., Pribulla T., Buson L.M., Vittone A.: 2001, *As.Ap.*, submitted

Pavlenko E.P.: 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, J. Mikolajewska (ed.), CFPA Warszava, p. 205.

Richards A.M.S., Bode M.F., Eyres S.P.S., Kenny H.T., Davis R.J., Watson S.K.: 1999, *MNRAS*, **305**, 380.

Rudy R.J., Meier S.R., Rossano G.S., Lynch D.K., Puetter R.C., Erwin P.: 1999, *As.Ap.S*, **121**, 533.

Seaquist E.R., Krogulec M., Taylor A.R.: 1993, *Ap. J.*, **410**, 260.

Seaquist E.R., Taylor A.R., Button S.: 1984, *ApJ*, **284**, 202.

Seaquist E.R., Taylor A.R.: 1990, *ApJ*, **349**, 313.

Schild H., Schmid H.M.: 1997, *As.Ap.*, **324**, 606.

Schmid H.M.: 1998, *Rev. Modern Astronomy*, **11**, 297.

Stienon F.M., Chartrand M.R., Shao C.: 1974, *AJ*, **79**, 47.

Skopal A.: 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, J. Mikolajewska (ed.), CFPA Warszava, p. 99.

Skopal A.: 1998, *As.Ap.*, **338**, 599.

Skopal A.: 2001a, *As.Ap.*, **366**, 157.

Skopal A.: 2001b, *Contrib. Astron. Obs. Skalnaté Pleso*, in press

Skopal A.: 2001c, in preparation

Solf J.: 1983, *ApJ Lett.*, **266**, 113.

Solf J.: 1984, *As.Ap.*, **139**, 296.

Tamura S.: 1977, *Astrophys. Lett.*, **19**, 57.

Taranova O.G., Shenavrin V.I.: 2000, *Astron. Lett.*, **26**, 600.

Taylor A.R.: 1988, *The Symbiotic Phenomenon*, J. Mikolajewska, M. Friedjung, S.J. Kenyon & R. Viotti (eds.), Kluwer Academic Publ., p. 77.

Taylor A.R., Seaquist E.R.: 1984, *ApJ*, **286**, 261.

Theuns T., Jorissen A.: 1993, *MNRAS*, **265**, 946.

Van Belle G.T., Lane B.F., Thompson R.R. Boden A.F., Colavita M.M., Dumont P.J., Mobley D.W., Palmer D., Shao M., Vasisht G.X., Wallace J.K., Creech-Eakman M.J., Koresko C.D., Kulkarni S.R., Pan X.P., Gubler J.: 1999, *AJ*, **117**, 521.

Viotti R., Hack M.: 1993, in *Cataclysmic Variables and Related Objects*, M. Hack & C. la Dous (eds.), NASA SP-507, p. 663.

Vogel M., Nussbaumer H.: 1992, *As.Ap.*, **259**, 525.

Vogel M., Nussbaumer H.: 1994, *As.Ap.*, **284**, 145.

Walder R.: 1998, *Ap.Sp.Sci.*, **260**, 243.

Wallerstein G., Willson L.A., Salzer J., Brugel E.: 1984, *As.Ap.*, **133**, 137.

Watson S.K., Eyres S.P.S., Davis R.J., Bode M.F., Richards, A.M.S., Kenny H.T.: 2000, *MNRAS*, **311**, 449.

Webster B.L., Allen D.A.: 1975, *MNRAS*, **171**, 171.

Whitelock P.A.: 1987, *PASP*, **99**, 573.

Whitelock P.A.: 1988, *The Symbiotic Phenomenon*, J. Mikolajewska, M. Friedjung, S.J. Kenyon & R. Viotti (eds.), Kluwer Academic Publ., p. 47.