Baltic Astronomy, vol. 21, 105–111, 2012

FORMATION OF NEUTRAL DISK-LIKE ZONE AROUND THE ACTIVE HOT STARS IN SYMBIOTIC BINARIES

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Received: 2011 September 1; accepted: 2011 November 10

Abstract. In this contribution we present the ionization structure in the enhanced wind from the hot star in symbiotic binaries during active phases. Rotation of the hot star leads to the compression of the outflowing material towards its equatorial plane. As a result, a neutral disk-like zone around the active hot star near the orbital plane is created. We modeled the compression of the wind and calculated the neutral disk-like zone in the enhanced wind from the hot star using the equation of the photoionization equilibrium. The presence of such neutral disk-like zones was also suggested on the basis of the modeling the spectral energy distribution of symbiotic binaries. We confront the calculated ionization structures in the enhanced wind from the hot star with the observations. The calculated column density of the neutral hydrogen atoms in the neutral disk-like zone and the emission measure of the ionized part of the wind from the hot star are in a good agreement with the quantities derived from observations during active phases. The presence of such neutral disk-like zones is transient, being connected with the active phases of symbiotic binaries. During quiescent phases, such neutral disk-like zones cannot be created because of insufficient mass-loss rate from the hot star.

Key words: stars: binaries: symbiotic – stars: winds, outflows

1. INTRODUCTION

Symbiotic stars are long-period interacting binary systems, which comprise a late type giant and a hot compact star (most frequently a white dwarf). During quiescent phases part of the material from the wind from the cool giant is accreted by the hot compact star. Accretion process makes the surface of the hot star to be very hot ($\sim 10^5$ K) and luminous ($\sim 10^2 - 10^4\,L_\odot$) and capable of ionizing the neutral surrounding material. It gives rise to a strong nebular radiation (e.g., Seaquist, Taylor & Button 1984). Therefore, we have three basic sources of the radiation: the cool giant, the hot star and the nebula.

Modeling the spectral energy distribution of symbiotic binaries during active phases showed two different cases. In binaries with high orbital inclination the temperature of the hot star rapidly decreases to $\sim 22\,000$ K, while in the systems with low orbital inclination the temperature of the hot star increases to $\sim 165\,000$ K. This inclination dependent behaviour can be explained by the presence of the optically thick disk-like structure created during active phases around the hot star near the orbital plane of the symbiotic binary (Skopal 2005). Modeling the broad Hα wings showed that during active phases stellar wind from the hot star is significantly enhanced to a few $\times(10^{-7} - 10^{-6})$ $M_\odot$ yr^{-1} (Skopal 2006).

In this work we decided to test the idea if this enhanced wind from the hot star can be responsible for creation of the shielding disk-like structure around the hot star during active phases. Further, we calculated the column density of the neutral hydrogen atoms throughout the whole disk in the direction of the central star and the emission measure of the ionized wind from the hot star, and compared our results with quantities derived from observations during active phases. A good agreement is found.

2. WIND COMPRESSION MODEL

The wind compression model was developed by Bjorkman & Cassinelli (1993). This model describes the compression of the radiation driven wind from the rotating hot star towards the equatorial regions. The outflowing material is bent towards the equatorial plane due to the conservation of the angular momentum. If the streamlines of gas do not cross the equatorial plane, then we are talking about the wind compressed zone (WCZ) model, which was described by Ignace, Cassinelli & Bjorkman (1996). We applied this model to stellar wind from the hot star in symbiotic binaries during active phases.

Density in the compressed wind follows from the mass continuity equation as

$$N_{\rm H}(r,\theta) = \frac{\dot{M}}{4\pi r^2 \mu_{\rm m} m_{\rm H} v_{\rm r}(r)} \left(\frac{d\mu}{d\mu_0}\right)^{-1}, \qquad (1)$$

where $\dot{M}$ is the mass-loss rate of the hot star and the compression of the wind is given by the geometrical factor $d\mu/d\mu_0$. This factor depends on the rotational velocity of the hot star as well as on the parameters of the wind. For the wind velocity $v_{\rm r}(r)$ we adopted β-law. More details about the wind compression model can be found in Lamers & Cassinelli (1999).

3. IONIZATION STRUCTURE IN THE WIND

The ionization boundary is defined by the locus of points at which ionizing photons are completely consumed along path outward from the ionizing star. We calculated the ionization boundary in the wind from the hot star using the equation of the photoionization equilibrium. This equation equals the number of ionizations per second with the number of recombinations per second. For the simplicity, we assumed that the wind from the hot star contains only hydrogen atoms. We derived an equation for determining the ionization radius (i.e. the ionization boundary in the direction given by the polar angle θ), which can formally be written as

$$X = f(u, \theta, a, v_\infty, \beta, v_{\rm rot}), \qquad (2)$$

where u, θ are polar coordinates ($\theta = 0$ at the rotational axis), a, v_∞, β are parameters of the wind, $v_{\rm rot}$ is the rotational velocity of the hot star, and the parameter X is given by

$$X = \frac{8\pi \mu_{\rm m}^2 m_{\rm H}^2}{\alpha_{\rm B}} R_\star L_{\rm H} \left(\frac{v_\infty}{\dot{M}}\right)^2, \qquad (3)$$

where $L_{\rm H}$ is the rate of photons from the hot star, capable of ionizing hydrogen (it is given by the temperature $T_{\rm h}$ and luminosity $L_{\rm h}$ of the ionizing source) and $\alpha_{\rm B}$ is the total hydrogenic recombination coefficient in case B. Most of the parameters of the hot star and its wind can be determined from observations. However, the rotational velocities of the hot stars in symbiotic binaries are not commonly known. We calculated models for different rotational velocities from 100 to 350 $\mathrm{km\,s^{-1}}$. Figure 1 shows some examples of the calculated ionization boundaries for two different rotational velocities of the hot star, 200 and 300 $\mathrm{km\,s^{-1}}$ respectively.

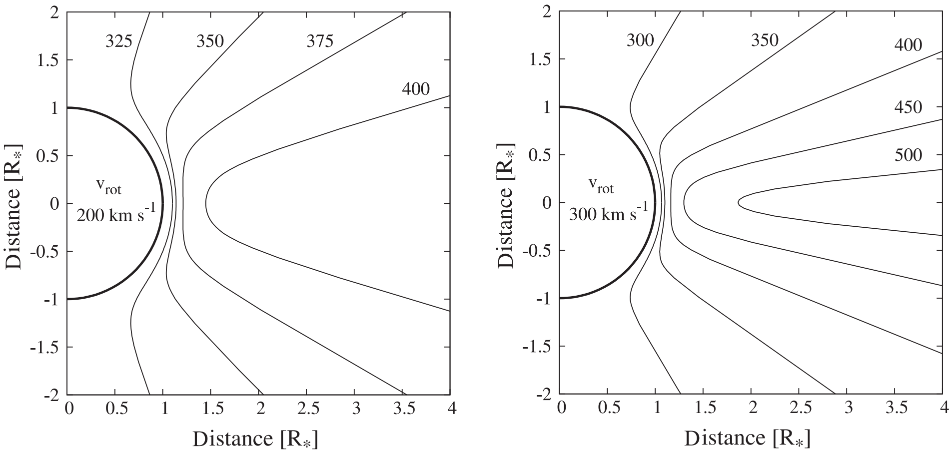

Fig. 1. Some examples of ionization boundaries in the wind for two different rotational velocities of the hot star, 200 and 300 $\mathrm{km\,s^{-1}}$. Individual ionization boundaries are labelled by the value of the parameter X. From an ionization boundary towards the pole of the star (y-axis) there is an ionized zone, and towards the equatorial plane (y = 0) there is a neutral zone. Ionization structures are axially symmetric with respect to the polar (rotational) axis of the hot star. Distances are in units of radius of the active hot star $R_\star$.

There is only a certain range of values of the parameter X, for which a neutral disk-like structure can be created near to the equatorial plane of the hot star. For higher rotational velocities of the hot star (i.e. higher compression of the stellar wind towards the equatorial plane) this range is wider. For a given rotational velocity, small values of the parameter X (~ 200) correspond to the ionization boundaries, which are enclosed in the vicinity of the hot star. On the other hand, increasing value of X corresponds to moving the ionization boundary away from the vicinity of the hot star, as well as to decreasing the opening angle of the neutral disk-like zone until it disappears for very high values of X. However, particular values depend also on the parameters of the hot star wind.

4. DISCUSSION

4.1. Quiescent phase versus active phase

According to Eq. (3), the parameter X strongly depends on the mass-loss rate of the hot star $\dot{M}$ as

$$X \propto \frac{1}{\dot{M}^2}. \tag{4}$$

Other parameters in Eq. (3) do not change significantly between the quiescent and active phases.

Typical mass-loss rate of the hot star during *active phase* is $(10^{-7} - 10^{-6})\,M_{\odot}$ yr^{-1}, while during *quiescent phase* it decreases to a few times of $(10^{-8})\,M_{\odot}\,\mathrm{yr}^{-1}$ (Skopal 2006). Figure 2 shows the dependence of the parameter X on the mass-loss rate of the hot star (all other parameters were fixed to typical values during the active phase, e.g. $v_{\infty} = 2000\ \mathrm{km\,s^{-1}}$). We used two different combinations of the temperature $T_{\rm h}$ and luminosity $L_{\rm h}$ of the hot star during the active phase, which were derived by Sokoloski et al. (2006) for Z And during its 2000–2003 outburst.

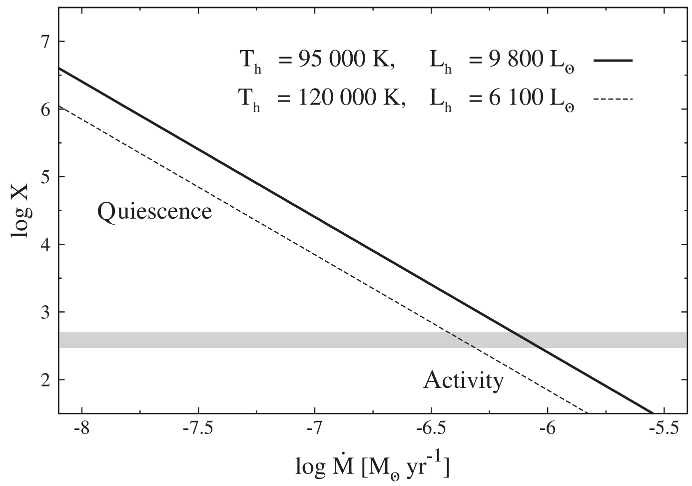

Fig. 2. The value of the parameter X as a function of the mass-loss rate, $\dot{M}$, of the hot star for two different combinations of the temperature $T_{\rm h}$ and luminosity $L_{\rm h}$, derived by Sokoloski et al. (2006) for the hot component in Z And during its 2000–2003 outburst. The shadow belt corresponds to $X = 300$–500 from Fig. 1, which lead to creation of the neutral disk-like zone.

Our calculations (Figure 1) show that creation of the neutral disk-like structure requires values of the parameter X of the order of hundreds. According to Figure 2, such value of the parameter X corresponds to mass-loss rate of a few times of $(10^{-7} - 10^{-6})\,M_{\odot}\,\mathrm{yr}^{-1}$, which is consistent with that derived independently from the broad Hα wings during active phase. Thus the neutral disk-like zone can be created during active phases as a result of the enhanced wind from the hot star. In contrast, during the quiescent phases, the measured quantities $(10^{-8} - 10^{-7})\,M_{\odot}\,\mathrm{yr}^{-1}$, correspond to $X \sim 10^4 - 10^6$, which are far beyond any possibility to form a neutral disk-like zone around the hot star.

4.2. Model versus observations

Figure 3 shows an example of the ionization structure around the hot star during the active phases calculated for the density distribution in the wind according to the WCZ model (Section 2). It is similar to the schematic model proposed on the basis of multiwavelength modeling spectral energy distributions of symbiotic binaries (see Figure 27 of Skopal 2005). In this section we compare the column density of neutral hydrogen atoms and the emission measure of the wind

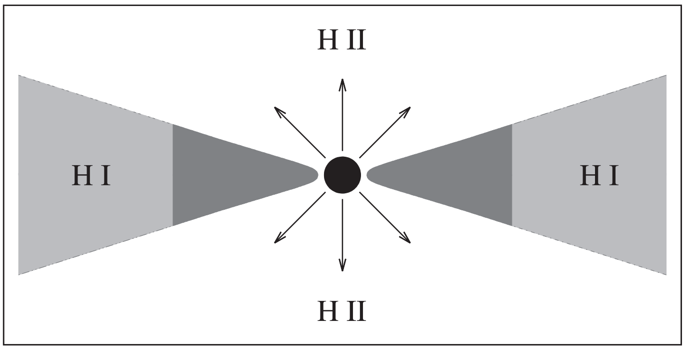

Fig. 3. An example of the ionization structure in the enhanced wind from the hot star during an active phase calculated for $v_{\rm rot} = 200$ km s^{-1} and $X = 400$. The hot star is denoted by the black filled circle and the neutral zone (H I) is shown in grey. Its shape resembles a flared disk. The optically thick part of this neutral zone is shown in dark grey. The boundary between the grey and dark grey regions mimics the false photosphere. In the symbiotic binaries with a high orbital inclination we are looking at this false photosphere, which radiates at significantly lower temperature than the central hot star. The ionized zone (H II) is located above and below the neutral disk-like structure and can be associated with the hot star wind (black arrows).

of our theoretical model with those derived from the observations during the active phases.

Modeling of spectral energy distributions of symbiotic binaries showed that there is a large amount of the neutral hydrogen near to the orbital plane of the binary. Column densities of the neutral hydrogen atoms, derived directly from the ultraviolet spectra, run between $\sim 10^{21}$ and a few times of 10^{23} cm^{-2} (Skopal 2005). This large amount of the neutral material can be detected during active phases even near the orbital phase $\phi \sim 0.5$ (i.e., when the hot star is in front of the cool giant).

Further, this modeling of spectral energy distributions showed that the emission measure of the enhanced wind from the hot star during active phases runs between a few times of 10^{58} and a few times of 10^{60} cm^{-3} (Skopal 2005).

Theoretical column density of the neutral hydrogen $N(\theta)$ in the direction θ throughout the neutral zone was calculated as

$$N(\theta) = \int_r N_{\rm H}(r,\theta)\,{\rm d}r, \tag{5}$$

where $N_{\rm H}(r,\theta)$ is the density of the neutral hydrogen given by Eq. (1). Figure 4 shows examples of the calculated column densities of the neutral hydrogen as a function of the radial distance from the center of the hot star for two different rotational velocities of the hot star, 200 and 300 km s^{-1}. Since the radius of the false photosphere can be of the order of tenths of $R_\odot$, we can easily see that the calculated values of the column densities of neutral hydrogen are in a good agreement with those derived from observations.

Theoretical emission measure $EM(r,\theta)$ of the ionized wind from the active hot

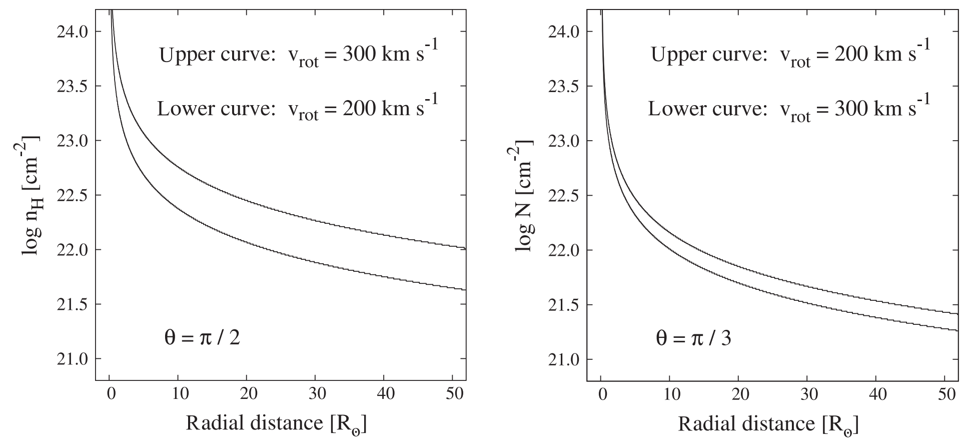

Fig. 4. Examples of the calculated column density $N(\theta)$ of the neutral hydrogen atoms as a function of the radial distance from the center of the hot star for two different rotational velocities, 200 and 300 $\mathrm{km\,s^{-1}}$. The angle between the polar axes of the hot star and the line of sight is $\theta = \pi/2$ (equatorial plane) for the left panel and $\theta = \pi/3$ for the right panel. In these calculations we assumed that the mass-loss rate of the hot star is $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$, and the radius of the hot star is 0.18 $R_\odot$.

star was calculated throughout the ionized zone as

$$EM = \int_V N_\mathrm{H}^2(r,\theta)\,dV, \tag{6}$$

where $N_\mathrm{H}(r,\theta)$ is the density of the ionized hydrogen given by Eq. (1).

In spherical coordinates the volume element dV is

$$dV = r^2 \sin\,\theta\,dr\,d\theta\,d\phi. \tag{7}$$

The density distribution in the WCZ model is azimuthally symmetric. Therefore Eq. (6) can be simplified to

$$EM = 2\pi \int_r \int_\theta N_\mathrm{H}^2(r,\theta)\,r^2 \sin\theta\,dr\,d\theta. \tag{8}$$

Figure 5 shows two examples of the calculated emission measures as a function of the radial distance from the center of the hot star for two different rotational velocities, 200 and 300 $\mathrm{km\,s^{-1}}$. From Figure 5 we can see that the calculated values of the emission measure of the ionized wind from the hot star are in a good agreement with the observed quantities.

5. CONCLUSIONS

We found that the compression of the enhanced stellar wind in active phases from the rotating hot star towards equatorial regions can lead to the creation of the neutral disk-like structure around the hot star near the orbital plane. Figure 1 shows some examples of ionization boundaries in the wind from the active hot star in symbiotic binaries calculated for the density distribution within the WCZ

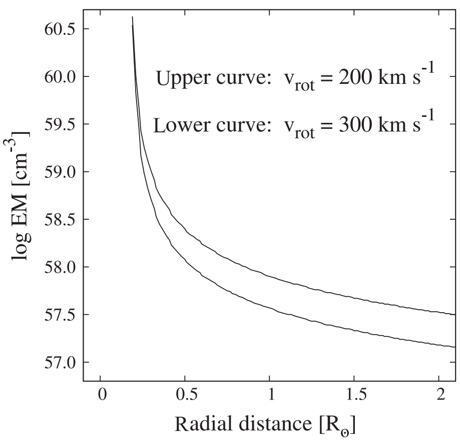

Fig. 5. Two examples of the calculated emission measures EM of the wind from the hot star as a function of the radial distance from the center of the hot star. The emission measures were calculated for the hot star with the mass-loss rate $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$. Further, we assumed that the radius of the hot star is 0.18 $R_\odot$ and the boundary between the neutral and ionized zones is given by the polar angle $\theta = \pi/3$.

model. In symbiotic binaries with high orbital inclination we are viewing through this neutral disk-like zone.

Theoretical ionization structure (e.g., see Figure 3), which we calculated using the WCZ model, is consistent with that derived on the basis of the multiwavelength modeling spectral energy distributions of symbiotic binaries during their active phases (see Figure 27 in Skopal 2005). Also, the calculated column density of the neutral hydrogen atoms throughout the neutral zone and the emission measure of the ionized region are in a good agreement with the quantities derived from observations during the active phases. The large value of the mass-loss rate of the hot star during active phases, a few times of $(10^{-7} - 10^{-6})\,M_\odot\,\mathrm{yr}^{-1}$, derived from the broad Hα wings (Skopal 2006) support the plausibility of the used model.

We explained that due to a low mass-loss rate from the hot star, no neutral disk-like structure can be created during quiescent phases.

ACKNOWLEDGMENTS. This research was supported by a grant of the Slovak Academy of Sciences, VEGA No. 2/0038/10.

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