Wind's emission of the compact secondary in Z And during its 2000 – 2002 outburst*

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(Submitted on 28.03.2014. Accepted on 12.05.2014.)

Abstract. The *UBV* continuum fluxes of the wind of the outbursting compact component of the symbiotic binary Z And have been calculated based on the model of this system for interpretation of its line spectrum during the 2000 outburst. It turns out that 90 per cent of the emission of the wind is from its dense equatorial region and the wind contribute up to 20 per cent to the nebular continuum of the system.

Key words: binaries: symbiotic - stars: activity - stars: winds, outflows - stars: individual: Z And

Introduction

Symbiotic stars are group of eruptive binary systems consisting of a cool visual primary and a hot compact secondary component accreting matter from the atmosphere of its companion. Their photometric behaviour is characterized by an alternance of quiescent periods and phases of activity. The eruptions of the accreting star are often accompanied by intensive mass-loss in the form of single discreet shels or stellar wind. In a number of cases the emission of the outflowing material contributes strongly to the growth of the optical brightness. The system Z And consists of a normal cool giant of spectral type M 4.5 (Mürset & Schmid 1999), a hot compact object with temperature higher than 10^5 K (Fernandez-Castro et al. 1988; Sokoloski et al. 2006) and an extended surrounding nebula partly photoionized by the hot component. Its orbital period is 758.8^d, which is based on both photometric (Formiggini & Leibowitz 1994) and radial velocity (Mikolajewska & Kenyon 1996) data.

The system Z And underwent many active phases – after 1915, 1939, 1960, 1984 and 2000. Each of them includes several optical brightenings with amplitudes up to 2–3 magnitudes. The latest active phase began in August 2000 and lasted till 2013. Seven light maxima were detected during that period of time.

The interacting binary Z And is considered as a classical symbiotic star. Its compact secondary component is supposed to be in a state of steady hydrogen burning in the quiescent phase of the system. Bisikalo et al. (2006) studied the mechanism of increase of the brightness using the photometric data of Sokoloski et al. (2006) obtained in August 2000 – February 2001 during the increase to the first maximum. These data represent the most detailed light curve of Z And. To explain the growth of the bolometric luminosity and the shape of the light curve in details these authors proposed combined mechanism where the increase of the accretion rate due to disruption of the disc leads to increase of the burning rate. According to them the shape of the light curve

* Based on observations collected at the Rozhen National Astronomical Observatory, Bulgaria

is determined from three processes: an increase of the bolometric luminosity and expansion of the compact companion, propagation of the stellar wind of the companion in the nebula and development of shock waves. They calculated the contribution of the companion's wind and the shock waves in the nebular emission of the system. To calculate the contribution of the wind however, they accepted a model of spherically symmetric outflow with a constant velocity and used one rough estimate of the mass-loss rate of the outbursting companion since it was only available.

To explain the behaviour of the line spectrum of Z And during its 2000 – 2002 outburst we proposed a model of the outbursting companion where the high velocity wind of the companion collides with its accretion disc (Tomov et al. 2008). As a result of the collision the spherically symmetric wind changes its configuration and two regions with different velocities and densities appear in it. We estimated the mass-loss rate of the companion from observation using the energy flux of the broad emission component of the Hγ and He II λ4686 lines.

A basic task of the present work is to calculate the UBV continuum fluxes of the stellar wind of the outbursing companion in Z And at the time of the 2000 light maximum accepting the model and the mass-loss rate from the work of Tomov et al. (2008). An other task is to estimate the contribution of the stellar wind in the nebular emission of the system.

2. The multi-stage pattern of the rise of the brightness and the spectral indications of ejection of mass. Interpretation.

The most detailed light curve during the rise of the brightness towards its maximum in the UBV photometric bands was published by Sokoloski et al. (2006). According to Bisikalo et al. (2006) three stages of the rise separated by two plateaus are distinguished on the light curve presented in Fig. 1. The first stage started at the end of August 2000 and continued to about the middle of September lasting for 2.5 weeks. The duration of the first plateau was about one week. The second stage of the rise lasted about 3 weeks – it finished after the middle of October followed by the second plateau when the brightness remained constant and even slightly decreased for about 4 weeks. The brightness began to rise again after November 13 reaching a second maximum (the maximal brightness during the outburst) after approximately 3.5 weeks near December 6, 2000. In this way the growth of the optical brightness was continued for 100 days and the U emission increased to about three magnitudes.

It was obtained that the bolometric luminosity of the outbursting compact companion in the system increases several times reaching a value of about $10^4\ \mathcal{L}_\odot$ (Tomov et al. 2003; Skopal et al. 2006, Sokoloski et al. 2006). According to Bisikalo et al. (2006) the following mechanisms take place in the increase of the optical brightness. During the first stage it increases because of growth of the accretion luminosity. The accretion rate exceeds the upper limit of its range for steady hydrogen burning and it turns out that accreted material of several 10^{-8}–$10^{-7}\ \mathcal{M}_\odot$ is sufficient to change the burning regime, i.e. to lead to growth of the nuclear burning rate. The burning rate begins to increase some time after the accumulation of this amount of material and the first plateau is thus realized. The appearance of a stellar wind prevents accretion during that time.

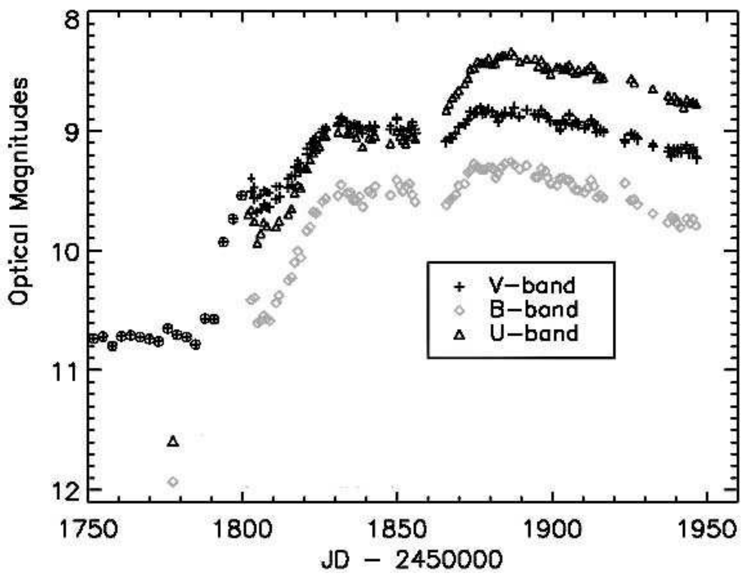

Fig. 1. *UBV* light curves of Z And during its 2000 outburst based on data ot Sokoloski et al. (2006). The figure is from the paper of Bisikalo et al. (2006).

The second stage of the rise of the brightness realizes because of an increase of the luminosity due to change of the nuclear burning rate, expansion of the compact companion leading to strong continuum energy redistribution and development of the stellar wind. This wind collides with the wind of the giant companion (and the accretion disc as well) and begins to form a system of shock waves in the nebula. At some moment the expansion of the pseudophotosphere can be replaced by contraction which is due to decrease (fluctuation) of the mass-loss rate of the companion. This decrease leads to energy redistribution in the reverse order, reduction of the optical flux and a peak (plateau) in the light curve forms. It is supposed that the second plateau is due to a change of the mass-loss rate. The increase of the brightness begins again with the increase of the mass-loss rate.

The luminosity of the companion and the emission of its wind increase at the same time. The 2D gas-dynamical modeling shows that a system of shocks developes after the appearance of the companion wind (Bisikalo et al. 2006). It was established in this work that at the time of the light maximum some part of the nebular continuum is due to shock ionization in agreement with the theoretical expectation. That is why it was concluded that after November 13 the development of the shocks should contribute to the increase of the optical brightness together with the pseudophotosphere and stellar wind.

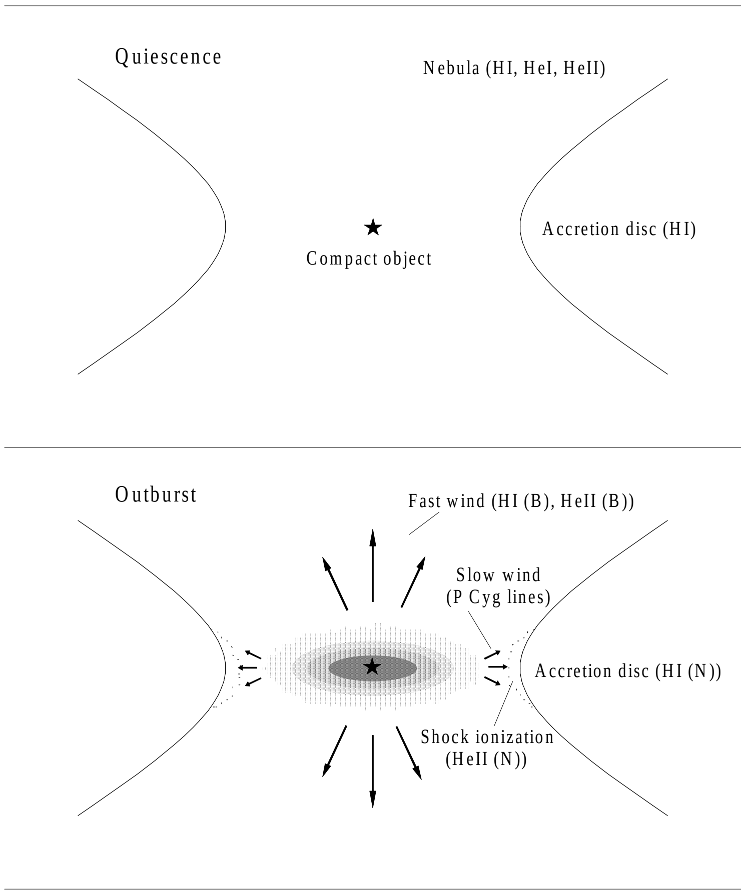

Fig. 2. Schematic model of the hot component of the system Z And in a plane, perpendicular to the orbital plane from the paper of Tomov et al. (2008).

The most important features of the line spectrum of Z And during its 2000–2002 outburst are the spectral indications of ejection of mass (Tomov et al. 2008). At the time of the light maximum the profile of the triplet lines of He I was of type P Cyg determined by optically thick mass outflow (stellar wind) with a velocoty of 50–60 km s^{-1} from the outbursting compact companion. At the same time the emission lines Hγ and He II λ4686 consisted of two component having a central narrow component of nebular type and a broad component with a low intensity indicating a variable optically thin stellar wind with a high velocity of about 500 km s^{-1}These data are interpreted with the supposition that an accretion disc from wind accretion exists in the system (Bisikalo et al. 2006). This disc is responsible for the breaking of the stellar wind of the companion in the orbital plane where its velocity decreases from about 500 km s^{-1} to about 50–60 km s^{-1}At higher latitudes, the velocity of the wind does not change, being 500 km s^{-1} (Tomov et al. 2008).

In this case, the density of the outflowing material will be higher close to the orbital plane because of collision with the disc and the companion will be occulted. This supposition is in agreement with the results of the continuum analysis, which shows that the high temperature compact object is not seen (Tomov et al. 2003; Skopal et al. 2006).

The density of the expanding shell depends on the velocity and when the velocity is changed with the stellar latitude, the photospheric radius also changes. When the velocity decreases close to the orbital plane, the photospheric radius increases in this region. Consequently, the expanding shell will not be spherical, but rather it will be disc-like (Fig. 2).

In the final analysis the presence of an accretion disc in the system leads to appearance of two regions in the stellar wind of the outbursting companion (Tomov et al. 2008). We will calculate the UBV continuum fluxes of this wind which is a subject of the next section.

3. Calculation of the wind's emission

The wind of the outbursting compact object with a velocity of 500 km s^{-1} collides with the accretion disc and its velocity decreases to 50–60 km s^{-1} close to the orbital plane. At higher latitudes it propagates freely and its velocity does not change. For this reason the size of the observed photosphere increases to about 2.3 $\mathcal{R}_\odot$ (Tomov et al. 2003) close to the orbital plane and at high latitudes increases much less – to about 0.3 $\mathcal{R}_\odot$ (Sokoloski et al. 2006). Two regions form in the wind – one of them is a region of a low velocity and a high density and is located close to the orbital plane (equatorial region) and the other one is a region of a high velocity and a low density which is at higher stellar latitudes (polar region). The continuum flux of the wind is a sum of the fluxes of the two regions. We suppose that both polar regions are into a solid angle $\Omega = \pi$ sr corresponding to linear angle of 120°.

The continuum flux determined by recombinations and free-free transitions is given with

$$F_\lambda = \frac{1 + a(\mathrm{He})}{4\pi d^2} \left(\int\limits_V n^2 \gamma_\nu(\mathrm{H}, T_\mathrm{e})\,\mathrm{dv} + \int\limits_V a(\mathrm{He}) n^2 \gamma_\nu(\mathrm{He}, T_\mathrm{e})\,\mathrm{dv} \right) \frac{c}{\lambda^2} 10^{-8}\,, \quad (1)$$

where n is a particle density, $a(\mathrm{He})$ – a gas number abundance of helium relative to hydrogen, d – a distance to the system, $\gamma_\nu(\mathrm{H}, T_\mathrm{e})$ and $\gamma_\nu(\mathrm{He}, T_\mathrm{e})$ are continuum emission coefficients of hydrogen and helium determined by recombinations and free-free transitions, c – the speed of light in vacuum and λ – wavelength position of the UBV photometric bands of 3.65×10^{-5} cm, 4.4×10^{-5} cm and 5.5×10^{-5} cm, respectively.

We will use this formula to calculate the flux of a spherical wind with a constant velocity. The particle density in the wind is expressed via the continuity equation

$$n(r) = \frac{\dot{M}}{4\pi r^2 \mu m_{\rm H} \upsilon} \ , \tag{2}$$

where $\dot{M}$ is the mass-loss rate, r is the distance to the center of the star and μ determines the mean molecular weight $\mu m_{\rm H}$ in the wind where $m_{\rm H}$ is the mass of proton. υ is the wind velocity.

We used formula (1) to calculate the energy flux of each region in the wind – the polar regions and equatorial one. We accept helium abundance of 0.1 (Vogel & Nussbaumer 1994) and a distance to the system of 1.12 kpc (Fernandez-Castro et al. 1988, 1995) as in our previous papers. We use a mass-loss rate at the light maximum of 2.4×10^{-7} (d/1.12 kpc)$^{3/2}$ $\mathcal{M}_\odot\,{\rm yr}^{-1}$ according to Tomov et al. (2008) and a parameter $\mu = 1.4$ (Nussbaumer & Vogel 1987).

The flux of the polar region was calculated as a flux of a spherical sector in the wind and that explains the coefficient $\Omega/4\pi$ included in formula (1). We accept a mean velocity of 500 km s^{-1} based on the velocity of the broad component of the lines Hγ and He II λ4686. Since the high velocity wind is observed in a line of ionized helium we assume that helium is mostly doubly ionized in its region and the continuum is emitted by hydrogen and ionized helium. That is why we use continuum emission coefficients of hydrogen and ionized helium at the positions of the UBV photometric bands (Osterbrock 1974) for $T_{\rm e} = 20\,000$ K which is the mean temperature in the circumbinary nebula of Z And according to Tomov et al. (2003). The position of the U band is close to the Balmer limit. The system Z And in its quiescent state has an apparent continuum which on the long-wavelength side of the Balmer limit has the same flux as on the short-wavelength side because of the blending of the Balmer lines with high numbers.

At the time of the 2000 optical maximum the Balmer lines weakened with respect to the local continuum (Tomov et al. 2008) as a result of strong increase of the nebular and stellar continua (Tomov et al. 2003). The flux on the long-wavelength side of the Balmer limit became smaller than on the short-wavelength side.That is why at the position of the U band we took the arithmetical mean of the values of the hydrogen coefficient on both sides of the Balmer limit.

The continuum of the high velocity wind is emitted by a layer in the spherical sector and the radii of the integration should be estimated. The inner radius is the radius of the effective photosphere. We used the data of Sokoloski et al. (2006) corrected for a distance of 1.12 kpc for the inner radius. The outer radius of integration was accepted as infinity.

The flux of the equatorial region was calculated using the formula (1) again where the coefficient

$$(4\pi - 2\Omega)/4\pi$$

was included. We accept a velocity of 50 km s^{-1} in this region, which is close to the velocity of the absorption component of the triplet lines of He I with a profile of the P Cyg type. Since the low velocity wind is observed in the lines of neutral helium we assume that helium is mostly singly ionized in its region and the continuum is emitted by hydrogen and neutral helium. That is why we used continuum emission coefficients of hydrogen and neutral helium at the position of the UBV photometric bands (Osterbrock 1974) for $T_e = 20\,000$ K again.

The continuum of the low velocity wind is emitted by a spherical layer again and radii of integration should be estimated. The inner radius is the radius of the effective photosphere. Its size in the equatorial region is considerably larger. We used the data of Tomov et al. (2003). We accepted an outer radius of $240.5\,\mathcal{R}_\odot$ – the half of the components separation, since according to the modeling of Bisikalo et al. (2006) the wind of the outbursting component propagates at that distance in direction to the cool giant.

Table 1. Fluxes from different regions of the hot wind in units of 10^{-12} erg cm^{-2} s^{-1} Å^{-1}. P denotes polar region, E – equatorial region and T – total flux.

Date	U			B			V		
	P	E	T	P	E	T	P	E	T
Nov. 22	0.044	0.486	0.530	0.020	0.176	0.196	0.018	0.155	0.173
Dec. 06	0.040	0.469	0.509	0.018	0.169	0.187	0.016	0.149	0.165

The results for the two dates of multicolor photometric observations according to Tomov et al. (2003) for each region in the wind as well as the total emission are listed in Tab. 3. The flux for November 22 is overestimated because of the use of the mass-loss rate for December 6 since only it was available. It is seen that about 90 per cent of the flux of the wind is emitted by the dense equatorial region resulting from collision with the disc.

Table 2. Fluxes from different regions of the nebula in units of 10^{-12} erg cm^{-2} s^{-1} Å^{-1}.

Source	November 22			December 06		
	U	B	V	U	B	V
Whole nebula [a]	1.983	0.717	0.631	2.737	0.989	0.871
Hot wind (second term)	0.530	0.196	0.173	0.509	0.187	0.165
Shock waves (third term) [a]	0	0	0	0.657	0.237	0.209
Other region(s) of the nebula	1.453	0.521	0.458	1.571	0.565	0.497

[a] – the data are from Table 4 in the paper of Bisikalo et al. (2006).

The emission of the different regions of the circumbinary nebula is shown in Tab. 2. It is seen that the contribution of the wind of the outbursting component is fairly large – it is close to the contribution of the shock waves on December 6 and is about 20 per cent from the emission of the whole nebula.

4. Conclusion

The symbiotic binary system Z And underwent its last active phase after 2000. A stellar wind in two-velocity regime – optically thick outflow with a velocity of 50–60 $\mathrm{km\,s^{-1}}$ observed in the P Cyg lines of He I and optically thin outflow with a high velocity of about 500 $\mathrm{km\,s^{-1}}$ observed in the broad emission components of the lines Hγ and He II λ 4686 – developed in the system during the first light maximum in November – December 2000. The behaviour of these lines was interpreted in the framework of a model of an outbursting compact companion with an accretion disc. It is supposed that the two-velocity regime of the outflow results from collision of the high velocity wind with the disc (Tomov et al. 2008). Two regions appear in the wind as a result of that collision. One of them is a polar region with a high velocity and a low density and the other one – an equatorial region with a low velocity and a high density. The UBV continuum fluxes of the wind have been calculated using the mass-loss rate of the companion from the work of Tomov et al. (2008) and the radii of the observed photosphere from the works of Tomov et al. (2003) and Sokoloski et al. (2006). It turns out that 90 per cent of the emission of the wind is from its dense equatorial region. Also the contribution of the wind in the nebular continuum of the system is about 20 per cent and is close to the contribution of the shock ionization supposed to be a result from development of shock waves in the nebula.

Acknowledgments

This study was partially supported by the Russian and Bulgarian Academies of Sciences through a collaborative program in Basic Space Research.

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