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Broad Hα wings in active symbiotic stars: The case of Z Andromedae

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Abstract. During the major 2000-03 outburst of the symbiotic prototype Z And, broad Hα wings extending to about $\pm 2\,000\,\mathrm{km\,s^{-1}}$ developed. We fitted them by the model of a bipolar stellar wind from the hot star. We determined the corresponding mass-loss rates as $2.3\times10^{-6}\,M_{\odot}\,\mathrm{yr}^{-1}$ at the maximum, $3.3\times10^{-6}\,M_{\odot}\,\mathrm{yr}^{-1}$ during the 2002/03 rebrightening and $1.6\times10^{-6}\,M_{\odot}\,\mathrm{yr}^{-1}$ at the end of the outbursts, in 2003 November. A possibility of the Raman scattering as the responsible process for the broad Hα wings is briefly discussed.

1. Introduction

Symbiotic stars are long-period interacting binaries ($\mathrm{P_{orb}} \sim 1 \div 3$ years or more) consisting of a cool giant and a hot compact star, most probably a white dwarf. The giant component loses mass via the wind, part of which is accreted by its companion. This process makes the accretor to be very hot and luminous ($\mathrm{T_{hot}} \sim 10^5\,\mathrm{K}$, $\mathrm{L_{hot}} \sim 10 \div 10^4\,L_{\odot}$), and thus capable of ionizing a fraction of the neutral wind from the giant giving rise to nebular emission. If the processes of the mass-loss, accretion and ionization are in a mutual equilibrium, then symbiotic system releases its energy approximately at a constant rate and spectral distribution. This stage is called as the *quiescent phase* of a symbiotic star. Once the equilibrium between these processes is disturbed, symbiotic system changes its radiation significantly, at least in its spectral distribution. We name this stage as the *active phase* of a symbiotic star. Observationally, active phases are identified by a few magnitude brightening in the optical and signatures of a mass-outflow at moderate (a few × $100\,\mathrm{km\,s^{-1}}$) and/or very high (a few × $1\,000\,\mathrm{km\,s^{-1}}$) velocities in the line spectrum.

An interesting feature in the spectra of symbiotic stars is represented by very broad Hα emission wings. A survey of Hα line profiles made by van Winckel et al. (1993) and Ivison et al. (1994) revealed their terminal velocities to be between about 1 000 and $2\,500\,\mathrm{km\,s^{-1}}$, with larger values during active phases. In spite that their origin has been investigated by many authors, a formation mechanism for such the extended Hα wings has not been identified unambiguously. Recently, Lee (2000) and Lee & Hyung (2000) elaborated a model considering Raman scattering of Lyβ photons on atomic hydrogen to be responsible for filling in the broad Hα wings. Their models fitted well the observed profiles for $|\Delta v| > 200\,\mathrm{km\,s^{-1}}$. Skopal et al. (2002) probed possibility of an optically thin stellar wind on the case of active phases of CH Cyg. Also here comparison between the modeled and observed profiles was satisfactory.

During the major, 2000-03, outburst of the symbiotic prototype Z And, we observed Hα wings with the extent to about $\pm 2\,000\,\mathrm{km\,s^{-1}}$ (Skopal et al. 2006). Simultaneously a significant increase in the emission measure, a faint O VI λ1032 line, its not-detectable Raman scattered counterpart at λ6825 and a faint Lyβ emission (in part of the geo-coronal nature) were present in the spectra from the maximum. Therefore we analyse the broad Hα wings by the model of a fast ionized stellar wind from the hot star with a bipolar structure as suggested by Skopal (2006). In Sect. 2.2 we explain basic structure of the active hot object, in Sect. 2.3 we apply the model to our observations and derive corresponding mass-loss rates. In Sect. 3 we briefly discuss the rival possibility that considers the Raman scattering process to be responsible for the broad Hα wings.

2. Modeling the Hα wings from the active phase of Z And

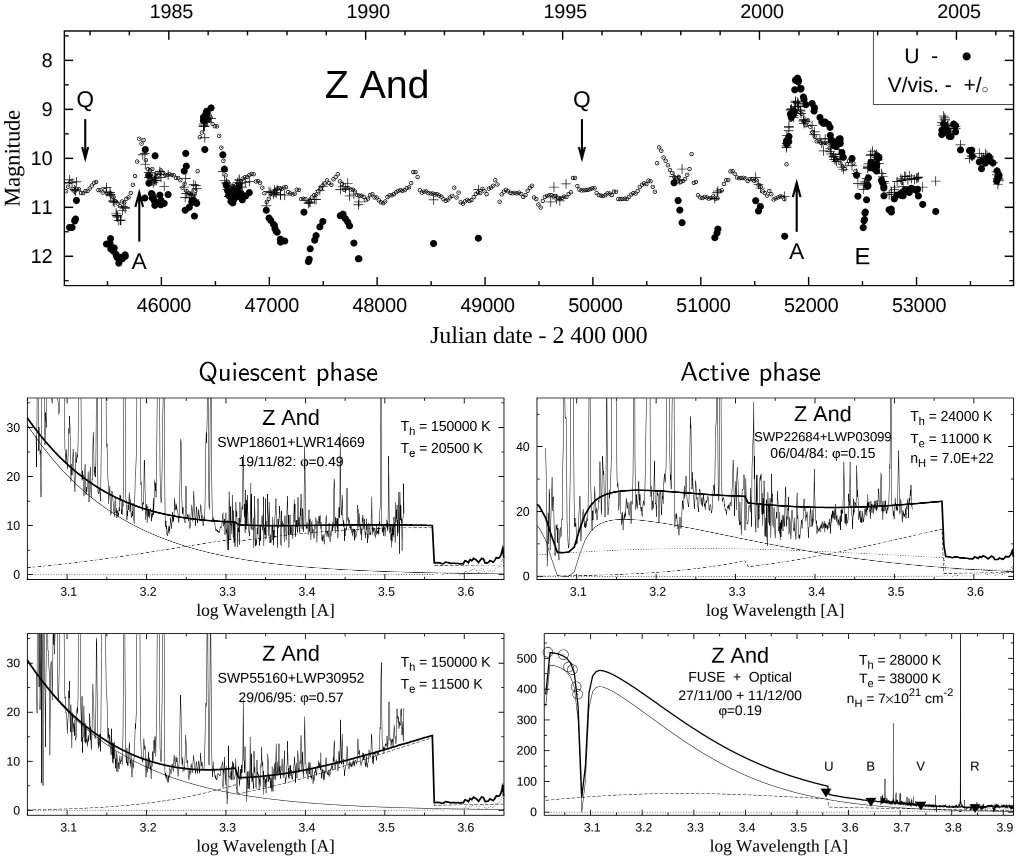
2.1. The recent 2000-03 active phase

Z And is considered as a prototype symbiotic star. The binary consists of a normal M4.5 giant and a white dwarf. The orbital period is 759 days (e.g. Fekel et al. 2000). Inclination of the orbital plane was recently refined to $\gtrsim 76^\circ$ by Skopal (2003). Its light curve is characterized by phases of activity with up to 2-3 mag brightness increases, alternating with periods of quiescence. Fig. 1 demonstrates this case for the recent two major outbursts (1984-86 and 2000-03).

In September 2000, Z And entered the recent major outburst (Skopal et al. 2000) with a maximum around the mid of 2000 December, following a gradual decrease to quiescent values at/after the mid of 2003 (Fig. 1). Photometric and spectroscopic evolution of Z And during the outburst was described in detail by Sokoloski et al. (2006) and Skopal et al. (2006).

2.2. Disk-like structure of the active hot object

Important information on the structure of the hot object during the active phase can be inferred with the aid of the SED and the line spectrum. Figure 1 shows a significant difference of the UV spectrum between quiescent and active phases.



Quiescent phase

Active phase

Figure 1. Top: The U and V light curves of Z And covering its two major outbursts in 1984-85 and 2000-03. The eclipse is denoted by E. Arrows mark positions at which we reconstructed the SED - during outbursts (A) and quiescence (Q). Bottom panels show the observed and modeled SEDs. Dashed and solid thin line represent nebular and hot stellar component of radiation, respectively. Solid heavy line is the resulting modeled continuum. Fluxes are in $10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Å^{-1}}$. Modeling the SEDs in symbiotic stars was described by Skopal (2005).

In the former case the hot stellar source (HSS) radiates at a very high temperature ($T_{\rm h} \sim 150\,000\,$K) producing *sufficient* amount of ionizing photons to give rise the observed nebular emission, whereas during the latter case the HSS in the spectrum radiates at relatively very low temperature ($T_{\rm h} \sim 20\,000 \div 30\,000\,$K), which is *not capable* of producing the nebular emission (emission lines as He II, N V, and the continuum – emission measure $EM \sim 10^{60}\,\mathrm{cm}^{-3}$, Fig. 1). This conflicting situation can be explained by an optically thick disk-like structured material encompassing the white dwarf at the orbital plane that develops during outbursts (Skopal 2005). Then due to a high orbital inclination the outer observer can see just the optically thick matter of the disk-like shell, whose outer flared rim occults the central ionizing source. As a result we indicate a significantly cooler HSS in the spectrum then during quiescence (Fig. 1). However,

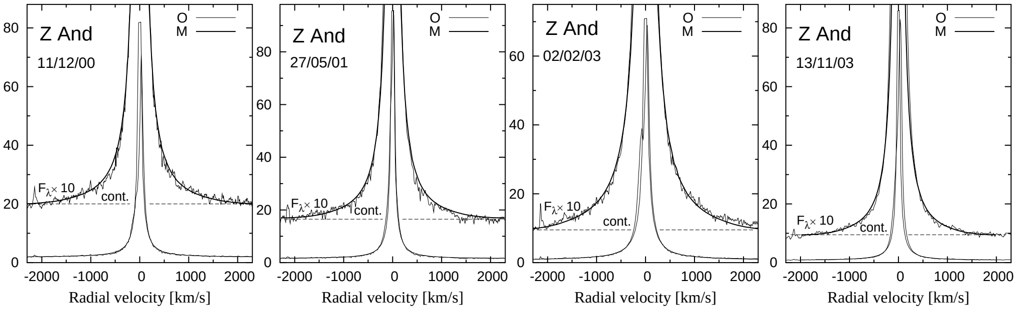


Figure 2. Comparison of the modeled (M) and observed (O) Hα line profiles from the 2000-03 active phase of Z And. Corresponding parameters are in Table 1. Fluxes are in $10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$.

the unseen very hot inner parts of the disk can ionize the surrounding medium from above/below the disk and thus produce the observed nebular emission. At/around the optical maximum of the outburst (2000 November/December), signatures of the mass-outflow at moderate velocities ($\sim 100\div200\,\mathrm{km\,s^{-1}}$) were indicated by the P-Cygni profiles of H I lines of the Paschen series, He I lines and C III, P V lines in the far-UV (Skopal et al. 2006; Sokoloski et al. 2006). In addition, throughout the whole active phase we also detected features signaling the mass-outflow at very high velocities ($\approx 1000\div2000\,\mathrm{km\,s^{-1}}$) having pattern in broad emission wings of Hα, Hβ, He II λ1084 and λ4686. This suggests that the disk-like pseudophotosphere expands at moderate velocities at the orbital plane, while at higher latitudes a fast stellar wind escapes the star.

2.3. A bipolar wind model

The model assumes an optically thin stellar wind with a spherically symmetric velocity profile and the origin at/around the central star. According to the disk-like structure of the hot object and the basic kinematics of the outflowing material (Sect. 2.2) we suggest a bipolar type of the wind. The optically thick disk/torus is characterized with the height H at its edge and the radius $R_{\rm D}$, and is seen edge-on due to a high orbital inclination. The outer rim of the disk then blocks a fraction of the wind around the orbital plane within the angle $2\theta_0 = 2\tan^{-1}(H/R_{\rm D})$, and by this way simulates bipolar shape of the stellar wind with the opening angle $\pi - 2\theta_0$ radians. We adopted $H/R_{\rm D} = 0.3$ for this active phase (Skopal 2006). Geometry of the model and the technique of calculating model luminosities and the line profile were introduced in detail by Skopal (2006). Here we applied the model to fit Hα profiles we observed along the Z And outburst. Observations were described by Skopal et al. (2006). Figure 2 shows a comparison of the modeled and observed profiles and Table 1 summarizes corresponding parameters – the beginning of the wind, $R_{\rm w}$, its terminal velocity, v_∞ and the parameter β, which characterizes an acceleration of the wind (Castor et al. 1975). Models fit excellently the observed profiles for $|\Delta v| \gtrsim 200\,\mathrm{km\,s^{-1}}$. This supports the validity of the optically thin regime from about $1.5\,R_{\rm w}$. As a result we used only this part of the emission wings to derive

Table 1. Parameters of the hot star wind ($R_{\rm w}$, β, v_{∞}) that we used to fit the observed Hα wings. Corresponding mass-loss rates ($\dot{M}_{\rm w}$) are in $10^{-6}\,M_{\odot}\,{\rm yr}^{-1}$. Profiles are plotted in Fig. 2. $F_{\alpha}(200)$ denotes the flux of wings with $|\Delta v| > 200\,{\rm km\,s^{-1}}$ (in $10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$).

Date	$F_{\alpha}(200)$	$R_{\rm w}$ $[R_{\odot}]$	β	v_{∞} $[{\rm km\,s^{-1}}]$	I_3 $[10^{-10}]$	$\dot{M}_{\rm w}$
11/12/00	66.5	1.70	1.70	2 600	1.40	2.3±0.3
27/05/01	60.3	1.70	1.70	2 300	1.27	2.0±0.2
02/02/03	118.2	1.70	1.58	2 800	1.40	3.3±0.4
13/11/03	44.8	1.70	1.70	2 000	1.13	1.6±0.3

the mass-loss rate. We employed expression, which relates the observed Hα flux, F_{α}, to the wind mass-loss rate, $\dot{M}_{\rm w}$, (Skopal 2006)

$$\frac{\dot{M}_{\rm w}}{v_{\infty}} = 8.5\times 10^{-10}\Big(\frac{F_{\alpha}}{I_3}\Big)^{1/2}\times d \qquad \frac{M_{\odot}\,{\rm yr}^{-1}}{{\rm km\,s}^{-1}}, \tag{1}$$

where the distance d is in kpc and the observed bolometric flux F_{α} in ${\rm erg\,cm^{-2}\,s^{-1}}$. Integral I_3 is given by the geometry of the wind and is proportional to the sum of all its visible volume elements. For wing fluxes, $F_{\alpha}(200)$ (Table 1), the I_3 integral includes only contributions with the radial velocity $|\Delta v| > 200\,{\rm km\,s^{-1}}$. The corresponding mass-loss rates are a few $\times 10^{-6}\,M_{\odot}\,{\rm yr}^{-1}$ (Table 1).

3. Discussion

Figure 2 shows that the profiles from the ionized optically thin bipolar wind match well the observed Hα wings for $|\Delta v| \gtrsim 200\,{\rm km\,s^{-1}}$. On the other hand, Lee (2000) demonstrated that the synthetic profiles calculated on the basis of the Raman Lyβ → Hα scattering process also fit well the Hα wings observed in symbiotic stars. This is given by that the Hα wing profiles resulting from both the processes are characterized by the same dependence, which is proportional to $\Delta\lambda^{-2}$ (Lee 2000; Skopal 2006). From this point of view it is not possible to distinguish contributions from the ionized wind and the Raman scattering by only modeling the line profile. However, both the processes take place in very different regions of the binary. The *ionized* stellar wind in our model is located around the hot star, while the Raman-scattered photons originate in the *neutral* part of the wind from the giant. Thus we need independent observations to identify main sources of radiation contributing to the broad Hα wings. First, we point some properties of the Hα emission supporting the kinematics of the ionized medium to be responsible for the broad wings:

(i) During eclipses of the hot component by the giant the Hα emission decreased significantly (e.g. Z And, Skopal et al. 2006, Fig. 4). This suggests that a significant fraction of the broad Hα wings is formed nearby the hot star.

(ii) Ikeda & Tamura (2000) revealed that the radial velocities of Hα wings follow the orbital motion of the hot component in V1329 Cyg. This implies that the region of the Hα wings formation is connected with the hot star.

(iii) Skopal (2006) found that during active phases the Hα-wings luminosity is a function of the EM from the photoionized symbiotic nebula.

Second, we put some arguments supporting the Raman scattering process to be responsible for the extended Hα wings:

(i) A good agreement between the polarization profile of Hα and that of the Raman λ6830 line for AG Dra suggests that the Hα line does include the Raman-scattered component originating from Lyβ (Ikeda et al. 2004).

(ii) Extremely wide Hα wings with a width of 11 000 $\mathrm{km\,s^{-1}}$, as observed for the planetary nebula M2-9, are likely to be formed through the Raman scattering (Lee 2000, and referencies therein). It could be difficult to understand such high wind velocities as in the radiation driven wind theory the wind speed is proportional to the escape speed (Lamers, & Cassinelli 1999).

As a result it is probable that both the processes can take a share in formation the broad Hα wings. A broadening similar to that in Hα should also be seen in other hydrogen lines of the Balmer series, if they are due to the fast stellar wind. This is satisfied for, e.g. CH Cyg (Skopal et al. 2002), but for other cases the extent of Hβ profiles is usually smaller (Arrieta & Torres-Peimbert 2003). During the recent Z And outburst the Hβ wings extended to about $\pm 1\,200\,\mathrm{km\,s^{-1}}$ (Skopal et al. 2006). In part this could be caused by a contamination of the faint Hβ wings in the continuum. However, more observational and theoretical work is required to understand better the nature of the broad Hα wings in symbiotic binaries.

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