Photometric and spectral investigation of the symbiotic binary Z And during its phase of activity in 2000 – 2003

Mima T. Tomova
Institute of Astronomy and National Astronomical Observatory,
Bulgarian Academy of Sciences,
BG-4700 Smolyan, POBox 136
mtomova@astro.bas.bg
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Symbiotic stars are interacting binary systems whose hot compact component (subdwarf, white dwarf, neutron star) accretes matter from the atmosphere of a cool III–II giant or Mira. The third component of these systems is a dense gaseous nebula. Their photometric and spectral variability is determined on one hand from the orbital motion, eclipses and heating/reflection effects and on the other hand from the outburst events of the hot component. The outburst are often accompanied by intensive loss of mass in the form of optically thick shells, stellar wind outflow and bipolar collimated jets. Symbiotic stars propose good possibility to study both the loss of mass by the stars and the accretion and components interaction in binary systems.

The Z And system is considered as a prototype of the classical symbiotic stars. It consists of a normal cool giant of spectral type M4.5 (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 $758\overset{d}{.}8$, which is based on both photometric (Formiggini & Leibowitz 1994) and radial velocity (Mikolajewska & Kenyon 1996) data. The last active phase of Z And began at the end of 2000 August (Skopal et al. 2000). The system Z And underwent two optical eruptions during its stage of activity in 2000 – 2003 whose light maxima were in December 2000 and November 2002. During this period it was investigated by Sokoloski et al. (2006), Bisikalo et al. (2006) and Skopal et al. (2006). However, the profiles of the optical lines of Z And were not analysed in detail and the components of these profiles were not interpreted. This determined the main purpose of our study – to suggest a model to interpret the behaviour of the system during its stage of activity in 2000 – 2003. To achieve this purpose we acquired a broad-band infrared *JHKLM* photometry with the InSb photometer attached to the 125 cm telescope of the Crimean Station of the Sternberg Astronomical Institute, *UBV* photometry with the photoelectric photometer, mounted at the 60 cm tellescope and high-resolution CCD spectral data in the regions of the lines H_α, He II 4686 and H_γ with the Coude spectrograph of the 2m RCC telescope of the National Astronomical Observatory Rozhen.

The main results and conclusions of our investigation can be summarised as follows:

1. An effective temperature of the cool component of 3400 ± 270 K was

obtained on the basis of its spectral type M 4.5 and the calibration of Belle et al. (1999) for normal giants. Its observed bolometric flux of $(2.221 \pm 0.048) \times 10^{-8}$ erg cm^{-2} s^{-1} was also obtained from multicolour $UBVRIJHKLM$ data. These parameters provide a radius of the star of (85 ± 4) (d/1.12 кpc) $\mathcal{R}_{\odot}$(Tomov, Taranova & Tomova 2003).

2. The electron temperature and emission measure of the circumbinary nebula were estimated at five moments of quiescent brightnes of the system. Two of these moments are close to the orbital phase of the photometric maximum and one of them is close to the orbital minimum. The electron temperature and emission measure were estimated at four moments during active phase as well. The emission measure increased by a factor of 4.4 reaching $(20.9 \pm 0.5) \times 10^{59}$(d/1.12 kpc)^2 cm^{-3} at the time of maximal light in December 2000 and the electron temperature was the same as in the quiescent state amounting to $20\,000 \pm 1000$ K (Tomov et al. 2003, Tomov, Tomova & Taranova 2004).
3. During the growth of the light in 2000 the hot component underwent expansion and the radius of its observed photosphere increased by a factor of about 40, reaching a value of (2.36 ± 0.07) (d/1.12 кpc) $\mathcal{R}_{\odot}$ at the time of light maximum. The effective temperature at that time was estimated to $(35\,000 \pm 1000)$ K. These data lead to bolometric luminosity $L_{\rm bol} = 7200\ \mathcal{L}_{\odot}$ which exceeds the quiescent luminosity $L_{\rm bol} = 1600\ \mathcal{L}_{\odot}$ on several occasions. According to the theory, the compact objects – components of the classical symbiotic stars, are in a state of steady hydrogen burning at their surface and during the outburst evolve at constant bolometric luminosity. Our result brings up the question about reconsideration of the theory (Tomov et al. 2003).
   A mass outflow from the hot compact companion in two-velocity regime was observed – an optically thick P Cyg wind with a low velocity of 60 km s^{-1} creating absorption components of lines of He I and H I and an optically thin stellar wind with a high velocity of 500 km s^{-1} giving rise to the broad emission components of the lines H_{γ} and He II 4686.
   The mass-loss rate of the companion was obtained from the energetic flux of the broad emission components of the lines H_{γ} and He II 4686 with the assumption that these components are optically thin. It turns out that the rate decreases from 2.4×10^{-7}(d/1.12 kpc)$^{3/2}$ $\mathcal{M}_{\odot}$yr^{-1} at the light maximum to 1.0×10^{-7}(d/1.12 kpc)$^{3/2}$ $\mathcal{M}_{\odot}$yr^{-1} in October 2001.
   It has been shown that the radius of the observed photosphere based on multicolour photometry on one hand and the velocity of the P Cyg wind and mass-loss rate of the companion based on high-resolution data on the other hand, are in good agreement. A model with an accretion disc (or nebular material with increased density in the orbital plane) and a wind of the companion with a velocity of 500 km s^{-1} is proposed to explain the line spectrum during the outburst. The wind collides with the disc and as a result its velocity decreases to about 60 km s^{-1} close to the orbital plane where an optically thick disc-like shell, playing a role of observed photosphere, forms. At higher stellar latitudes the velocity does not change being 500 km s^{-1}. This model provides explanation to the increase of the size of the observed photosphere based on the multicolour photometry, too (Tomov, Tomova & Bisikalo 2008, 2013).

In the framework of this model the UBV emission of the wind was calculated and it is about 20 per cent of the nebular emission of the system. It turns out that 90 per cent of the emission of the wind is from its dense equatorial region (Tomova 2014).

4. The emission measure increased by a factor of 2.5 reaching $(11.7 \pm 0.3) \times 10^{59}$ (d/1.12 kpc)^2 cm^{-3} at the time of maximal brightness in November 2002, and the electron temperature did not change (Tomov et al. 2004).
5. During the increase of brightness at the end of 2002 the companion underwent small expansion, it remained a hot compact object as it was in the quiescent state of the system. The upper limit of its radius and effective temperature was obtained which amounts to (0.13 ± 0.01) (d/1.12 кpc) $\mathcal{R}_{\odot}$ and $125\,000 \pm 3000$ K (Tomov et al. 2004).
   During the same period of the increase of brightness a broad emission component of the He II 4686 line indicating most probably an optically thin stellar wind with velocity $1050 \div 1200$ km s^{-1} was observed.
   The upper limit of the mass-loss rate of the companion at the time of maximal brightness was obtained from the energetic flux of this line and it amounts to 1.7×10^{-7}(d/1.12 kpc)$^{3/2}$ $\mathcal{M}_{\odot}$yr^{-1} (Tomov, Tomova & Taranova 2005).

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