An investigation of the eclipsing symbiotic binary BF Cyg during a period of activity after 2014*

Nikolai A. Tomov[1], Mima T. Tomova[1], Dmitry V. Bisikalo[2]
[1] Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Science, P.O. Box 136, 4700 Smolyan, Bulgaria
tomov@astro.bas.bg
[2] Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya Str., 119017 Moscow, Russia
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Abstract. The symbiotic system BF Cyg is an eclipsing binary. It flared in 2006 and in 2016 its optical brightness was in its fifth orbital minimum (eclipse) from the beginning of the eruption. We investigated the behaviour of the brightness during this minimum and considered the evolution of the accretion structure surrounding the outbursting compact object. We obtained the basic parameters of this structure from $UBVR_{\rm C}I_{\rm C}$ data at the time of the fifth orbital minimum.
Key words: accretion, accretion disks – binaries: symbiotic – stars: activity – stars: individual: BF Cygni

Introduction

The symbiotic system BF Cyg is an eclipsing binary and the eclipses are observed in its both states the quiescent and active ones. The last period of its activity began in 2006 and continues up to now. In 2006 the brightness increased sharply and reached a maximum. This high state was kept till 2008 and after that time the brightness slowly weakened and reached a minimal value in 2014. Four orbital minima determined by eclipses were observed in this period. The depth of the orbital minimum changes. The second minimum is much shallower than the first one and after the second minimum the depth increases, the third minimum is deeper than the second one and the fourth – deeper than the third one (Skopal et al. 2015b). Since June 2009 satellite components of Balmer lines indicating high velocity bipolar collimated outflow appeared in the spectrum but their velocity decreased in 2013. A new activity developed in the end of 2014 and since March 2015 the satellite components were restored (Skopal et al. 2015a). In our previous works (Tomov et al. 2015; Tomov et al. 2017; hereafter Papers I, II) we interpreted the behaviour of the optical brightness of BF Cyg from the beginning of the outburst to 2014 considering the evolution of the accretion structure surrounding the outbursting compact object. A subject of the current work is to analyse the behaviour of the brightness of this system after that time.

For our consideration we will use the ephemeris of Fekel et al. (2001)

$$\mathrm{JD(Min)} = 2\,451\,395\overset{\mathrm{d}}{.}2 + 757\overset{\mathrm{d}}{.}2 \times \mathrm{E}\,,$$

where the eclipse of the compact object coincides with the inferior conjunction of the giant.

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

1. Analysis and interpretation of the brightness and line spectrum of BF Cyg during its active phase

1.1. A brief review to 2014

The photometric behaviour of the system in the period of activity 2006–2014 was interpreted by us in the light of the model of collimated stellar wind (Papers I, II). We supposed that because of a decrease of the mass-loss rate of the outbursting compact object prior to the first orbital minimum and accretion of material from its potential well, a geometrically thick disk-like envelope forms around the initial accretion disk in the period between the first and second minima and the envelope begins to collimate outflowing material and gives rise to a bipolar ejection. Uneclipsed part of this envelope causes a decrease of the depth of the orbital minimum. Later the envelope is destroyed by the stellar wind which leads to increase of the depth of the orbital minimum again and diminution of the velocity of the satellite components after the beginning of 2013 (Fig. 1, Skopal et al. 2015b). We concluded that the decrease of the optical brightness of the system in the period 2009–2014 results from redistribution of the emission of the outbursting compact object from longer wavelengths towards the UV region and destruction of the disc-like envelope.

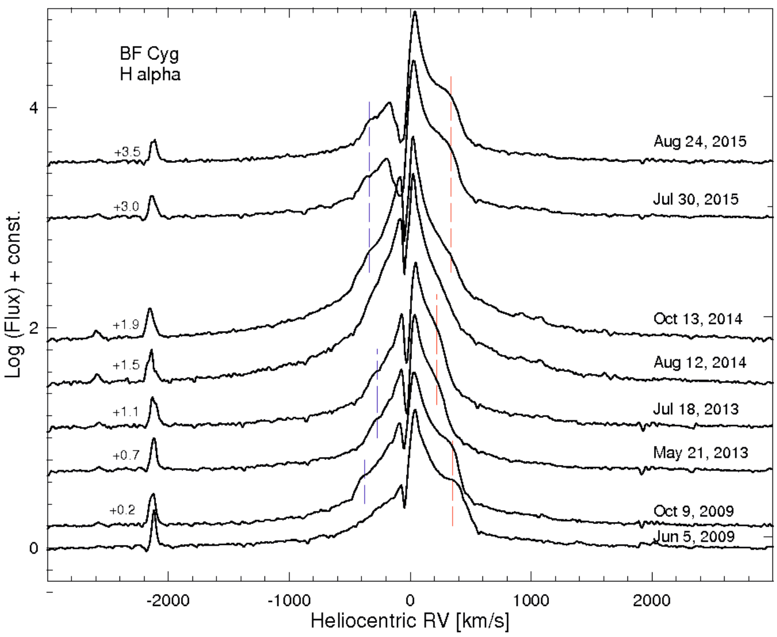

Fig. 1. The Hα line profile in 2009, 2013, 2014 and 2015. The spectra are in relative intensity and are shifted with a constant shown on left. The vertical lines mark the satellite components.

We noted in Paper I that a new activity of the compact object developed after the first orbital minimum in December 2007 and the brightness of the system increased to its maximum at the end of 2008. Strong P Cyg components of some Balmer and metal lines appeared in February 2008 (Siviero et al. 2012) and satellite components indicating bipolar collimated outflow appeared in June 2009 (Skopal et al. 2013). At the same time the depth of the orbital minimum decreased and the next minimum in December 2009 was much shallower. That is why we concluded that the depth decreased because of a change of the geometrical structure of the outbursting compact object and supposed that a disc-like envelope covering its initial accretion disc was formed which has begun to collimate its stellar wind.

1.2. The recent evolution from 2014

A new activity of the compact object developed at the end of 2014, after the fourth orbital minimum, and the brightness began to grow reaching a maximum in February – March 2015. The behaviour of the line spectrum reminded that in 2008–2009. In January 2015 the He I and Na I lines had P Cyg absorptions (Munari et al. 2015), and since March satellite Hα components appeared in the spectrum (Skopal et al. 2015a). In this way the Hα profile in July – August 2015 was very close to the profile in June – October 2009 (Skopal et al. 2013), containing a red emission satellite component with a velocity of about 300 $\mathrm{km\,s^{-1}}$ (Fig. 1), which shows that a collimation mechanism with the same efficiency has probably begun to act in the system in 2015. That is why, by analogy with the period between the first and second orbital minima, we supposed that, as a result of a decrease of the mass-loss rate of the outbursting compact object prior to the fourth orbital minimum and accretion of material from its potential well, the disc-like envelope has restored in the time between the fourth and fifth minima on the basis of its remnant from 2014.

2. Results

2.1. Parameters of the compact object and the circumbinary nebula

For our analysis of the brightness of the system at the time of the fifth minimum estimates of both the size of the observed photosphere of the outbursting compact object and the emission measure of the circumbinary nebula are need. To determine these parameters we will analyse the continuum emission. We carried out our analysis not for the time of the fifth orbital minimum (March 22, 2016), but for its preceding brightness maximum (Feb. 26, 2015), which is very close to the orbital maximum when the nebula is at least occulted by the cool giant, although the nebular emission decreases with time. We used photometric $UBVR_{\mathrm{C}}I_{\mathrm{C}}$ data from the light curves of Skopal et al. (2017). The U flux was not corrected for the energy distribution of BF Cyg in the region of the Balmer jump and the UBV fluxes were not corrected for the emission lines because of absence of spectral data in the range UBV. All data were corrected for the interstellar reddening $E(B-V)=0.35$ (Skopal 2005) according to Cardelli et al. (1989) and are listed in Table 1.

Table 1. Dereddened fluxes of BF Cyg in units of 10^{-12} erg cm^{-2} s^{-1} Å^{-1} with their inner uncertainties at the times of the light maximum and orbital minimum under consideration.

Extremum	Date	JD−2400000	F_U	F_B	F_V	F_{R_C}	F_{I_C}
	Feb. 26, 2015	57080	3.461	3.448	1.841	1.083	0.756
			±0.159	±0.096	±0.050	±0.030	±0.020
Min 5	Mar. 22, 2016	57470	0.830	0.907	0.556	0.376	0.330
			±0.038	±0.025	±0.016	±0.010	±0.009

To obtain the parameters of the outbursting compact object and the circumbinary nebula of BF Cyg we subtracted the fluxes of the cool giant from the observed fluxes. We used the fluxes of a giant with $T_{\rm eff} \sim 3400$ K and $R \sim 150\,\mathcal{R}_\odot$ from the work of Skopal (2005). To approximate the fluxes with a nebular continuum it is needed to know the dominant ionization state of helium in the nebula. Our high resolution data taken in the range of the line He II λ 4686 in 2015–2016 do not show presence of this line in the spectrum. Then we assume that helium is singly ionized and the nebular continuum is emitted by hydrogen and neutral helium. We approximated the fluxes with a nebular continuum and black body emission adopting a distance to the system of 3.8 kpc (Skopal 2005). In this way we obtained the parameters of the components of the system at the time of maximal brightness on Feb. 26, 2015 – an electron temperature and emission measure of the circumbinary nebula of $T_{\rm e} = 30\,000 \pm 3000$ K and $n_{\rm e}^2 V = (2.70 \pm 0.17) 10^{61}$ cm^{-3} and a radius and effective temperature of the observed photosphere (pseudophotosphere) of the outbursting compact object of $T_{\rm eff} = 10\,000 \pm 500$ K and $R = 18.0 \pm 2.2\,\mathcal{R}_\odot$. The spectral energy distribution is shown in Fig. 2.

2.2. Parameters of the disc-like envelope

The next step of our investigation is to determine the parameters of the disc-like envelope. As in the previous works (Papers I, II) we will suppose that its shape is close to cylindrical ring (torus) with an inner radius equal to the radius of the observed photosphere, and its emission measure is smaller than that of the nebula, so that the emission measure of the nebula is an upper limit of the emission measure of the envelope. We adopted the same parameters of the system used in Papers I, II – a binary separation of $492\,\mathcal{R}_\odot$ (Fekel et al. 2001), a radius of the cool giant $R \sim 150\,\mathcal{R}_\odot$ (Skopal 2005) and an orbit inclination of 75° according to Skopal et al. (1997) and Fekel et al. (2001). Moreover, we adopted the same mean density of the disc-like envelope of $7.5\,10^{10}$ cm^{-3} and supposed that its eclipsed and uneclipsed parts are approximately equal and the shadow of the giant passes through the lateral area of the cylinder. The residual of the depths of the first and

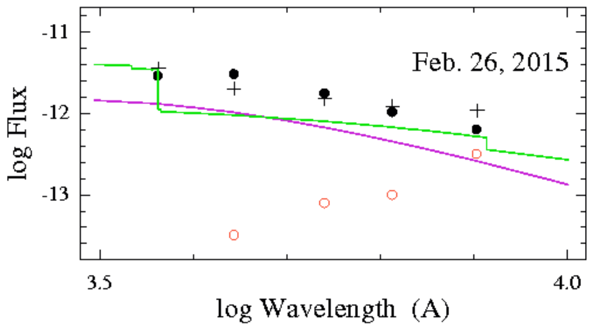

Fig. 2. Spectral energy distribution of BF Cyg in the $UBVR_CI_C$ range at the time of the light maximum on Feb. 26, 2015. The points indicate the observed fluxes. The lines represent the black body and nebular continua and the circles – the fluxes of the giant. The crosses represent the resulting fluxes. The flux unit is $\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$.

Table 2. $UBVR_CI_C$ continuum fluxes and emission measure of the different regions in the circumbinary nebula. The fluxes are in units of 10^{-12} $\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$ and emission measure in 10^{61} $\mathrm{cm^{-3}}$.

Emitting region	F_U	F_B	F_V	F_{R_C}	F_{I_C}	n_e^2V
Whole nebula	2.268	0.948	0.798	0.672	0.509	2.70
Disc-like envelope	0.404	0.168	0.142	0.120	0.092	0.48
Uneclipsed part	0.202	0.084	0.071	0.060	0.046	0.24
Residual of the depths	0.110	0.374	0.189	0.046	0.039	
	±0.053	±0.029	±0.019	±0.013	±0.013	
r^a	84	−78	−62	30	18	

[a] $r = (\mathrm{U} - \mathrm{R})/\mathrm{R}$ in per cent; U – Uneclipsed part, R – Residual of the depths.

fifth orbital minima in the photometric bands $UBVR_CI_C$ was approximated with a nebular emission with $T_e = 30\,000 \pm 3000$ K and an emission measure $n_e^2V = (0.24 \pm 0.07)10^{61}\,\mathrm{cm^{-3}}$ (Table 2), which should be related to the uneclipsed part of the envelope at phase 0.0. Then the emission measure of the whole envelope amounts to $(0.48 \pm 0.14)10^{61}$ $\mathrm{cm^{-3}}$. The approximation was made using the standart relation between the flux and the emission measure described in Paper I. With the density used by us we obtained a volume of the envelope of $8.53\,10^{38}$ $\mathrm{cm^3}$ and a mass $M \sim 0.8\,10^{-7}\,\mathcal{M}_\odot$. The inner radius of the envelope R_1 is not smaller than the radius of the observed photosphere of the outbursting compact object and we will adopt the radius of this photosphere for the inner radius R_1. In regard to the outer radius R_2 and the height H, we can not determine any of them from observation. The emission measure of the envelope at the times of the second and third orbital minima was great and in order its mean density to be close to $\sim 10^{10}$ $\mathrm{cm^{-3}}$, the outer radius had to be equal to the radius of the Roche lobe. At the time of the fifth minimum the emission measure is smaller and the outer radius is probably smaller than the Roche lobe. To determine this radius we supposed that the ratio H/R_1 is within the interval 5–7, since it was in approximately the same interval at the times of the second and third orbital minima, when the Hα profile contained satellite components with the same velocity as in 2015. Using this ratio and an inner radius $R_1 = 18\,\mathcal{R}_\odot$, we obtained that the outer radius R_2 and the height H are in the intervals 93–78 $\mathcal{R}_\odot$ and 90–126 $\mathcal{R}_\odot$. With this values the shadow of the giant will really pass trough the lateral area of the cylinder and our supposition turned out to be true. The mass and sizes of the disc-like envelope obtained show that it is smaller than at the times of the second and third minima. Its mass and sizes, however, are also close to those predicted by the gas-dynamical modeling (Bisikalo et al. 2002; Tomov et al. 2010, 2011), which means that it can be considered as the accretion structure which collimates the gas at the time of the fifth minimum.

Conclusions

The main results of our analysis can be summarized as follows:

- On the basis of the similarity of the behaviour of the optical brightness and line spectrum of BF Cyg in 2008–2009 and 2014–2015 we supposed that based on its remnant from the previous stage of the outburst, the disc-like envelope surrounding the compact object has restored in the period February 2014 – March 2016. We supposed also that the recovery of this envelope results from a decrease of the mass-loss rate of the compact object after the fourth orbital maximum (January 2013) and accretion of material from its potential well in the time between the fourth and fifth orbital minima.
- The continuum energy distribution of the system in the region of the photometric bands $UBVR_CI_C$ at the time of its outburst maximum on Feb. 26, 2015 was analysed and the parameters of the envelope at the time of the fifth orbital minimum on March 22, 2016 were determined. For the envelope we obtained an electron temperature $T_e = 30\,000 \pm 3000$ K, an emission measure of $(0.48 \pm 0.14)\,10^{61}$ cm^{-3}, an inner radius of 18 $\mathcal{R}_\odot$, an outer radius of 93–78 $\mathcal{R}_\odot$, a height of 90–126 $\mathcal{R}_\odot$ and a mass of $\sim 0.8\,10^{-7}\,\mathcal{M}_\odot$. The mass and sizes are close to those predicted by the gas-dynamical modeling which means that it can be considered as an accretion structure collimating the gas.

Acknowledgments

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