

## HALF A CENTURY AFTER THE OUTBURST OF THE SYMBIOTIC NOVA V1016 CYG

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**Abstract.** We present the results of our long-term  $UBVJHKLM$  photometry and spectroscopic monitoring of the symbiotic nova V1016 Cyg. After its outburst in 1964, the star showed fading in the  $U$ ,  $B$ ,  $V$  bands at a rate of about 0.03 mag per year. The behavior of the  $B - V$  and  $U - B$  color indices reflects variations of the emission lines, fading of the erupted component, weakening and reddening of the cool giant. Also, monotonic color and brightness variations in the infrared (IR) were observed at a scale of several thousand days. After 2004, the yearly mean IR brightness showed a decline and IR colors, reddening, due to the increase of the optical depth of the dust. The parameters of the cool star and of the dust envelope were estimated. The pulsation period of the Mira-type variable was refined,  $P = 465 \pm 5$  days. The Mira's photospheric temperature varied from 2100 to 2700 K in the pulsation cycle. The mass of the dust shell has grown twice during the recent decade, at a dust penetration rate of  $\Delta M_{\text{dust}} \sim 10^{-7} M_{\odot}/\text{yr}$ . Our spectroscopic monitoring of V1016 Cyg over 1995–2013 showed variations in the emission line strengths. The absolute fluxes of most lines decreased after 2000, whereas the relative intensities of [O III], [Ar III], [Fe VII], [Ca VII] lines with respect to  $H\beta$  are increasing after the possible minimum that could happen in the 1990s. An essential flux decline (approximately ten-fold between 1995 and 2013) in the Raman scattered O VI line at  $\lambda 6825$  shows the change of conditions in its formation zone, due to absorption of O VI 1032 Å quanta in the new dust shell of the cool component.

**Key words:** binaries: symbiotic – stars: variables: Miras – stars: individual (V1016 Cyg)

### 1. INTRODUCTION

A half-century back, in June 1965, McCuskey (1965) reported the beginning activity of the star MH $\alpha$  328-116 from the Merrill & Burwell (1950) catalogue. In 1965, the star was classified as a nova and designated Nova Cyg 1964. Fitzgerald et al. (1966) made a conclusion that MH $\alpha$  328-116 was a symbiotic star with a nova-like flash. In the General Catalogue of Variable Stars (Kukarkin et al. 1967), it has the designation V1016 Cyg.

After its outburst, the star was studied in detail by many authors in various

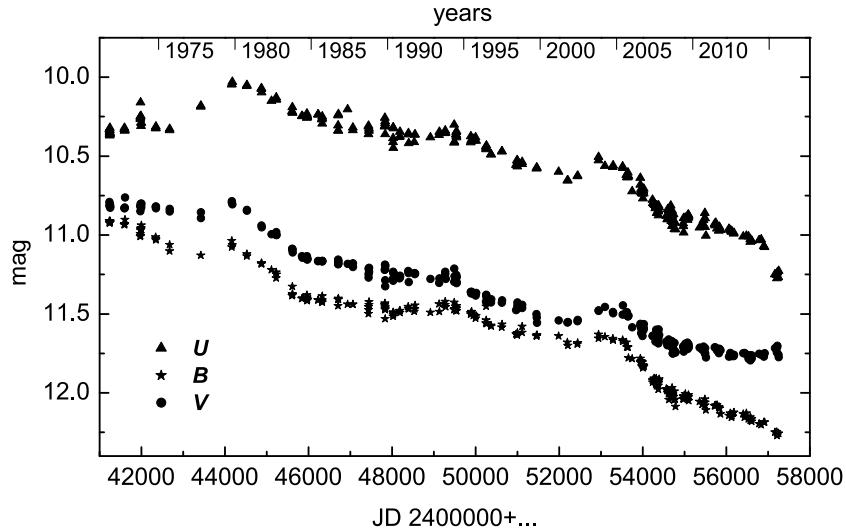


Fig. 1. *UBV* light curves for V1016 Cyg in 1971–2015.

spectral ranges (from the X-ray to the radio). A full review of investigations of V1016 Cyg is given by Hinkle et al. (2013).

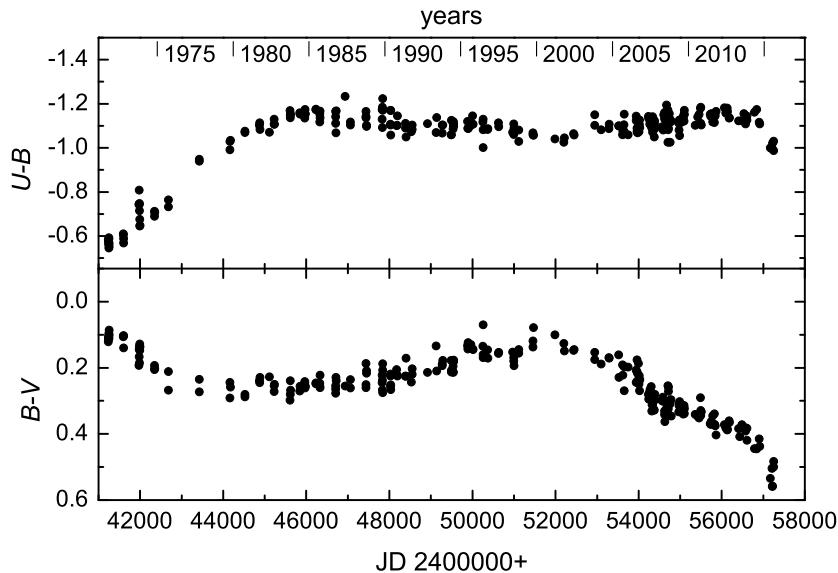
Now it is known that V1016 Cyg is a binary system consisting of a hot subdwarf and a Mira-type star with a dust envelope. The hot star ionizes the gaseous nebula, thrown off during the flash, and the wind of the red giant. V1016 Cyg belongs to the D-type symbiotic stars.

During the recent years, V1016 Cyg exhibited considerable variations in the optical and infrared ranges. In the present paper, we report the results of our photometric and spectroscopic observations.

## 2. *UBV* PHOTOMETRY OF V1016 CYGNI in 1971–2015

Our photoelectric *UBV* observations of the star are being performed at the Crimean Station of the Sternberg Astronomical Institute (SAI) since 1971, using a 60-cm Zeiss telescope and an automated photometer designed by Lyutyj (1971). The photometric system of the instrument is very close to the standard Johnson *UBV* system. Since the photometer is not controlled thermostatically, stellar magnitudes depend on the photometer temperature for all objects with strong emission lines (novae, starlike planetary nebulae, etc.). This is carefully taken into account when the observations are being reduced.

Fig. 1 presents the *UBV* light curves of V1016 Cyg in 1971–2015. The results of our *UBV* observations of V1016 Cyg over the 1971–2014 period were published by Arkhipova (1983), Parimucha et al. (2000), Arkhipova et al. (2008), and Arkhipova et al. (2015). In the optical light curves of the star, it is important to mark the local increase in brightness observed in 1979–1980, 1994, and 2004, while the yearly mean brightness as a whole was decreasing at an average rate of 0.03 mag per year. In 2015, a considerable brightness decline in the *U* band, by 0.1 mag, as well as noticeable reddening of the *U*–*B* and *B*–*V* colors were observed, as compared to



**Fig. 2.** The evolution of the  $B-V$  and  $U-B$  color indices of V1016 Cyg from 1971 to 2015.

2014. We attribute this fact to the growth of the circumstellar dust shell.

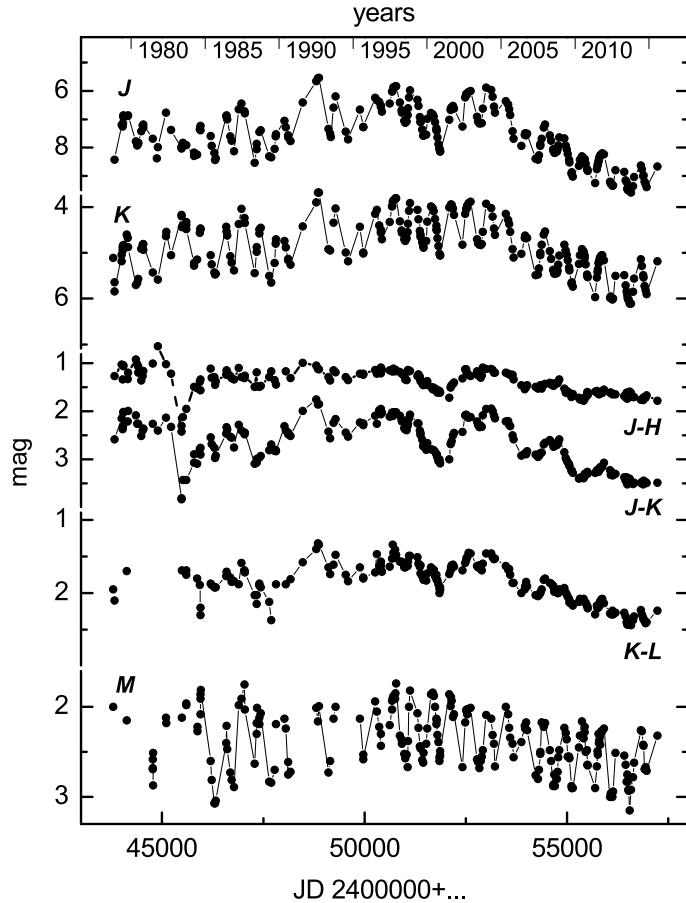
The star's color indices showed strong variations during 1971–2015 (Fig. 2). Before 1980, the  $U - B$  color became bluer and was  $-1.07$  mag in 2000. Subsequently, with some fluctuations, it remained at  $U - B = -1.10 \pm 0.05$  mag till 2014. In 2015,  $U - B$  reddened to about  $-1.0$  mag. The  $B - V$  color index increased by 0.2 mag, to  $+0.3$  mag, from 1971 to 1980, but it was  $+0.1$  mag again through 2000. After 2000, the systematic increase of  $B-V$  was observed, and in 2015 it reached  $+0.52$  mag.

We think that the  $B-V$  reddening through 2014 was related to the Mira's reddening and also with the emission lines that effected variations in the  $B$  and  $V$  bands owing to the rise of relative intensities of the [O III]  $\lambda 4959$  and  $\lambda 5007$  lines. We tend to attribute the mentioned simultaneous reddening of  $U-B$  and  $B-V$ , observed in 2015, to the part of the gaseous nebula entering the Mira's dust envelope.

### 3. INFRARED PHOTOMETRY OF V1016 CYGNI in 1978–2015

The  $JHKLM$  photometry of V1016 Cyg has been performed with the 1.25-m telescope at the Crimean Station of the SAI since 1978. The photometric standard is the star BS 7796. The angular diameter of the photometer aperture is about  $12''$ , and the beam spatial separation during modulation was  $\sim 30''$  in the east-west direction. The uncertainties in the  $JHK$  and  $LM$  magnitude estimates did not exceed 0.03 and 0.05 mag, respectively.

Our results of IR observations for V1016 Cyg in 1978–2014 were published by Taranova & Yudin (1983), Taranova & Yudin (1986), Taranova & Shenavrin (2000), Shenavrin et al. (2011), and Arkhipova et al. (2015).



**Fig. 3.**  $JKM$  light and  $J-H$ ,  $J-K$ ,  $K-L$  color curves for V1016 Cyg in 1978–2015.

The  $JKM$  light and  $J-H$ ,  $J-K$ ,  $K-L$  color curves for V1016 Cyg in 1978–2015 are shown in Fig. 3.

The IR brightness fluctuations of V1016 Cyg in 1978–2015 show a periodic component, and two trends are clearly visible over time intervals of 10–20 years. The Mira star's pulsation period has been confirmed to be  $P = 465 \pm 5$  days. The amplitude of the observed periodic oscillations decreases with increasing wavelength. The phase fluctuations of the  $J$  and  $H$  brightness are the smallest when the  $J-H$  color index is about 1.4 mag. The average  $J-K$  color index thus remains almost constant, and the likely cause of phase changes of IR brightness and color can be the star's periodic radial pulsations.

Prior to 1998, the increase in the mid-IR light happened simultaneously with a decrease in the average infrared color indices. The dust shell, which included both components before the outburst of the hot source in 1964, was scattering. Near the Julian date JD 24 50600 (mid-1998), the optical depth of the dust shell reached its minimum; its scattering lasted for about 20 years. Then, the behavior of the IR

light and color of V1016 Cyg changed dramatically: the mid-IR brightness began to decrease and the average color index began to increase. In other words, the optical depth of the dust shell started to grow again and, to the end of 2014, was several times larger than that in 1978.

The distance from the Mira and the star's parameters were estimated from IR observations of V1016 Cyg at maximum  $J$ -band brightness and minimum  $J - H$  color index:  $D = 2.95 \pm 0.16$  kpc,  $R_* = (470 \pm 50)R_\odot$ , and  $L_* = (9200 \pm 1900)L_\odot$  (see Arkhipova et al. 2015 for details).

Our parameter estimates for the dust envelope are based on a simple model (the Mira heats a spherically symmetric and physically thin dust envelope). The temperature of the dust envelope was assumed to be 600 K. The dust grains are similar in their optical properties to impure silicates, and their radius is  $\sim 0.1 \mu\text{m}$ . An analysis based on this model revealed that the bulk of the observed values of the  $J - K$  and  $K - L$  color indices lied in the range of temperature variations from 2100 to 2700 K and the optical depths 0.5 to 2.5 at a wavelength of 1.25  $\mu\text{m}$ . With increasing temperature, the density of the Mira's dust envelope was decreasing. The weakening of radiation from the Mira's dust envelope in 2014 reached nearly 2 mag in the  $J$  filter and 4.5 mag in the  $V$  filter.

Near the maximum and minimum of IR brightness (in 2004 and 2012–2014), the Mira's temperature was 2500 K and 2400 K; the optical depths of the dust shell (for  $\lambda = 1.25 \mu\text{m}$ ) were 1 and 2.25; the radii of the dust shell were  $10600 R_\odot$  and  $9500 R_\odot$ ; the masses were  $\sim 1.4 \times 10^{-6} M_\odot$  and  $2.5 \times 10^{-6} M_\odot$ , respectively. In 10 years, the mass of the dust shell increased by a factor of almost two, and the rate of its gain was  $\sim 10^{-7} M_\odot/\text{yr}$ .

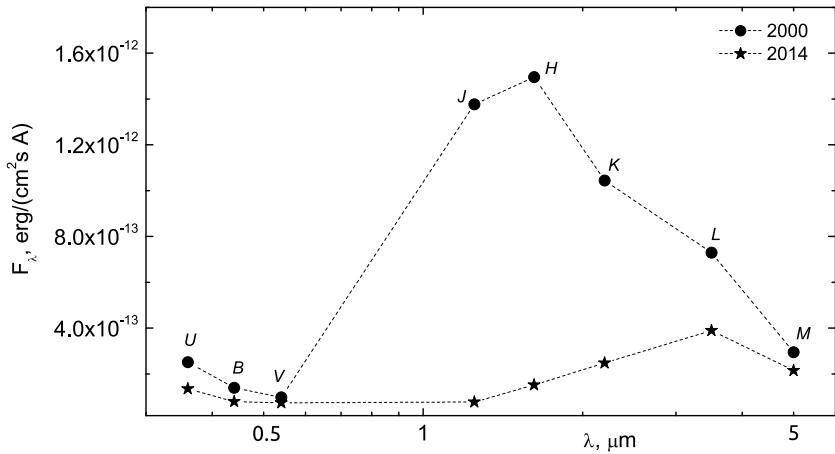
#### 4. SPECTRAL ENERGY DISTRIBUTION

We constructed the spectral energy distribution of V1016 Cyg for two sets of data: for 2000, before forming of a new dust shell, and for 2014, when the system's fading and reddening in the IR reached its extrema during all the time of our observations. The  $UBVJHKLM$  magnitudes of V1016 Cyg were transformed into energy units,  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ , using the absolute calibration from Straizys (1977). The energy distributions observed in 2000 and 2014 are shown in Fig. 4. The new forming dust shell significantly weakened the Mira's radiation in the near IR but had little influence on the optical radiation where the main contributors are the gaseous nebula and the hot star, located at a large distance from the Mira.

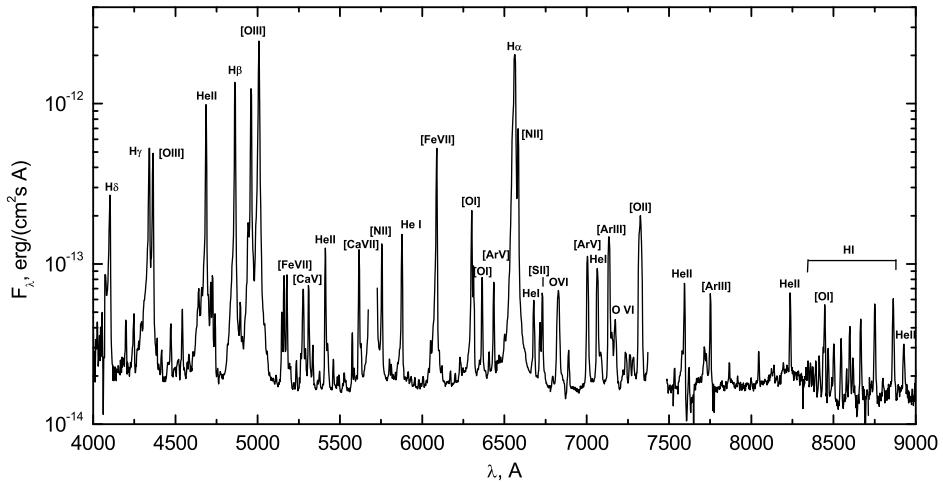
#### 5. ABSOLUTE SPECTROPHOTOMETRY OF V1016 CYGNI IN 1995–2013

The spectroscopic observations of V1016 Cyg were performed at the Cassegrain focus of the 1.25-m telescope at the Crimean Station of the SAI with a fast spectrograph in the 4000–9000  $\text{\AA}$  spectral range. In 1995–2006, the detector was an SBIG ST-6I  $274 \times 375$ -pixel CCD array with a 600 lines/mm grating, giving a resolution of  $\sim 5.5 \text{\AA}$  per pixel. After 2007, the observations were carried out with an SBIG ST-402 ( $510 \times 765$ ) CCD array with a resolution of  $\sim 2.3 \text{\AA}$  per pixel.

Fig. 5 shows the spectrum of V1016 Cyg in the 4000–9000  $\text{\AA}$  range taken on 2012 August 19–21. The emission spectrum of V1016 Cyg shows a great variety of lines belonging to atoms and ions with various ionization potentials. Permitted (H I, He I, He II) as well as forbidden ([O III], [Ne III], [Fe VI], [Fe VII], [O I], [O II], [N II], [S II], [Ar III], [Ar V], [Ca V], etc.) lines, together with emission bands at



**Fig. 4.** The observed spectral energy distribution of V1016 Cyg from *UBVJHKLM* photometry in 2000 and 2014.



**Fig. 5.** The spectrum of V1016 Cyg in 2012. The spectrum covers the 4000–9000 Å wavelength range. Most of the detected strong emission lines are marked.

$\lambda 6825$  and  $7088$  Å associated with the scattering of O VI emission by hydrogen atoms, are present in the spectrum. This spectrum testifies to the high temperature of the exciting star and high electron density of the gaseous nebula.

In the 2012 spectrum, the TiO absorption features belonging to the Mira, very well observed earlier (Fig. 9 in Arkhipova et al. 2008), were absent owing to the absorption of cold-component radiation in the newly forming dust shell of the Mira.

We have derived the absolute emission line fluxes in the  $\lambda 4340-7330$  Å range. A detailed description of the emission-line behavior in the spectrum of V1016 Cyg in 1995–2013 and a comparison of our data to the results of other authors obtained in 1966–1987 can be found in Arkhipova et al. (2015). The absolute fluxes in the H I, He I, He II, [Fe VII], [Ca VII], [O III], [Ar III], [Ar V] lines decreased by factors of 1.3–3.0 compared to earlier data by other authors. The relative intensities of the [O III]  $\lambda 4959$ ,  $\lambda 5007$  forbidden lines compared to H $\beta$  increased considerably after 2000, as did those of [Ar III], [Ar V], though their absolute fluxes in 1995–2013 changed only slightly. The temperature of the hot component, estimated as 145 000 K (Mürset & Nussbaumer 1994) in the beginning of the 1990s, continued to rise till 2000. This fact is confirmed by the increase in the relative intensity of the He II  $\lambda 4686$  line with time. The Raman scattered O VI line at  $\lambda 6825$  passed in its evolution through the absolute intensity maximum in 1995, and it weakened in 2013 almost by a factor of 10 owing to the change in conditions of line formation related to the absorption of O VI  $\lambda 1032$  quanta in the new dust shell.

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