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Photometric and Spectroscopic Study of the Supergiant with an Infrared Excess V1027 Cygni

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Abstract—We present the results of our UBV and $JHKLM$ photometry for the semiregular pulsating variable V1027 Cyg, a supergiant with an infrared excess, over the period from 1997 to 2015 (UBV) and in 2009–2015 ($JHKLM$). Together with the new data, we analyze the photometric observations of V1027 Cyg that we have obtained and published previously. Our search for a periodicity in the UBV brightness variations has led to several periods from $P = 212^d$ to 320^d in different time intervals. We have found the period $P = 237^d$ based on our infrared photometry. The variability amplitude, the light-curve shape, and the magnitude of V1027 Cyg at maximum light change noticeably from cycle to cycle. The deepest minimum was observed in 2011, when the amplitudes of brightness variations in the star reached the following values: $\Delta U = 1\overset{m}{.}28$, $\Delta B = 1\overset{m}{.}10$, $\Delta V = 1\overset{m}{.}05$, $\Delta J = 0\overset{m}{.}30$, $\Delta H = 0\overset{m}{.}35$, $\Delta K = 0\overset{m}{.}32$, $\Delta L = 0\overset{m}{.}26$, and $\Delta M = 0\overset{m}{.}10$. An ambiguous correlation of the $B - V$ and $U - B$ colors with the brightness has been revealed. For example, a noticeable bluing of the star was observed during the deep 1992, 2008, and 2011 minima, while the variations with smaller amplitudes show an increase in $B - V$ at the photometric minima. The spectral energy distribution for V1027 Cyg from our photometry in the range 0.36 (U)–5.0 (M) μm corresponds to spectral types from G8I to K3I at different phases of the pulsation cycle. Low-resolution spectra of V1027 Cyg in the range λ4400–9200 Å were taken during 16 nights over the period 1995–2015. At the 1995 and 2011 photometric minima the star's spectrum exhibited molecular TiO bands whose intensity corresponded to spectral types M0–M1, while the photometric data point to a considerably earlier spectral type. We hypothesize that the TiO bands are formed in the upper layers of the extended stellar atmosphere. We have measured the equivalent widths of the strongest absorption lines, in particular, the infrared Ca II triplet in the spectrum of V1027 Cyg. The calcium triplet (Ca T) with W_λ(Ca T) $= 20.3 \pm 1.8$ Å as a luminosity indicator for supergiants places V1027 Cyg in the region of the brightest G–K supergiants. V1027 Cyg has been identified with the infrared source IRAS 20004+2955 and is currently believed to be a candidate for post-AGB stars. The evolutionary status of the star and its difference from other post-AGB objects are discussed.

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Keywords: *post-AGB stars, photometric observations, photometric variability, spectroscopic observations, spectral classification, evolution.*

INTRODUCTION

The bright ($V \approx 8\overset{m}{.}65$; Hog et al. 2000) variable star V1027 Cyg (BD $+ 29°3865 =$ HD 333385) of spectral type K7 (according to the HD catalogue) had remained a poorly studied object until the mid-1980s. After the detection of a considerable far-infrared (IR) (12–100 μm) excess in the star with the IRAS space telescope, the interest in it has increased significantly. Volk and Kwok (1989) identified V1027 Cyg with IRAS 20004+2955, attributed its IR excess to the radiation from the dust shell formed during a large-scale mass loss on the asymptotic giant branch (AGB), and classified the star as a candidate for post-AGB objects, a star at a late evolutionary stage on its way from AGB stars to planetary nebulae. Subsequent studies, in particular, the analysis of the chemical composition of the stellar atmosphere performed by Klochkova et al. (2000), confirmed that V1027 Cyg belongs to the class of post-AGB stars. Judging by the chemical composition of the dust shell, the star belongs to oxygen-rich objects (Hrivnak et al. 1989; Vandenbussche et al. 2002; He et al. 2014).

Post-AGB objects manifest themselves as supergiants with an IR excess in a wide range of spectral

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types, from late K to early B. Photometric variability that can be due to various factors has been detected in many of them. In particular, semiregular brightness variations caused by pulsations are typical of yellow supergiants. In addition, the photometric behavior of post-AGB supergiants can be affected by a variable stellar wind as well as by changes in the parameters of the star and the circumstellar shell related to rapid post-AGB evolution. All these facts make a photometric monitoring of stars of this class on a time scale of days, months, years, and decades very topical.

The photographic brightness variability in the star BD + 29°3865 from $10^{m}.5$ to $11^{m}.5$ in 1948–1959 was detected by Wachmann (1961). Based on these observations, the star was included in the General Catalog of Variable Stars, where it was designated V1027 Cyg and was attributed to the class of slow irregular L-type variables (Kukarkin et al. 1971). Our UBV observations in 1991–1992 (Arkhipova et al. 1991, 1992) and, subsequently, in 1992–1996 (Arkhipova et al. 1997) revealed quasi-periodic brightness variations in V1027 Cyg with maximum amplitudes up to $1^{m}.0$ in UBV and a cycle duration of $200–250^{d}$. Radial velocity measurements for V1027 Cyg showed that there is a phase shift between the radial velocity curve and the light curves, with the star's maximum contraction occurring on the ascending branch of its deep minimum (Arkhipova et al. 1997).

The IR photometry for V1027 Cyg over 1991–2008 showed quasi-periodic $JHKLM$ brightness variations in the star with amplitudes no greater than $0^{m}.2$ in all bands and a period $P = 237^{d}$. The mean near-IR brightness of the star over 18 years experienced no statistically significant changes (Taranova et al. 2009; Bogdanov and Taranova 2009). Based on their IR photometry supplemented with the mid- and far-IR fluxes, Bogdanov and Taranova (2009) computed the model of a spherically symmetric dust shell composed of silicate particles.

The optical spectroscopy for V1027 Cyg has been performed repeatedly. The spectral type of the star was estimated to be K0Ia (Roman 1973), G7Ia (Keenan and McNeil 1976), ∼G7Iab (Hrivnak et al. 1989), and K2-4I (Winfrey et al. 1994). High-resolution spectroscopy from Klochkova et al. (2000) allowed the fundamental parameters ($T_{\text{eff}} = 5000$ K, $\log g = 1.0$), metallicity ([Fe/H] = −0.2 dex), and atmospheric chemical composition of V1027 Cyg to be determined.

The goal of this paper is to analyze the photometric and spectroscopic variability of V1027 Cyg in the optical and IR ranges based on our own long-term observations and to study the properties of the star as a post-AGB object.

UBV PHOTOMETRY FOR V1027 Cyg

We began the UBV observations of V1027 Cyg in 1991. The results of its observations over 1991–1996 were published in Arkhipova et al. (1991, 1992, 1997).

After 1996 we continued the observations of V1027 Cyg with a 60-cm Zeiss reflector at the Crimean Station of the Sternberg Astronomical Institute with a photon-counting photoelectric photometer (Lyutyj 1971). The observations were carried out with a 14″ aperture to completely eliminate the influence of the neighboring faint blue star located at a distance of ∼25″ from V1027 Cyg.

BD + 29°3871 (Sp = K4–5V; Orosz et al. 2001), whose magnitudes ($U = 11^{m}.44$, $B = 9^{m}.65$, $V = 8^{m}.20$) were determined by tying to photometric standards with an accuracy of $0^{m}.01–0^{m}.02$, served as a comparison star. Comparison of BD + 29°3871 with check stars revealed no variations in its brightness exceeding the measurement errors. The Hipparcos photometric observations in 1989–1993 did not reveal any photometric variability of the comparison star either.

From 1997 to 2015 we obtained a total of 491 magnitude estimates for V1027 Cyg in UBV. The observational errors were, on average, $0^{m}.01$ in B and V and $0^{m}.02$ in U. Table 1[1] presents our UBV photometry for V1027 Cyg reduced to the Johnson system using the equations

$$\Delta V = \Delta v - k_1 \Delta(b - v),$$
$$\Delta(B - V) = k_2 \Delta(b - v),$$
$$\Delta(U - B) = k_3 \Delta(u - b),$$

where $k_1 = 0.082 \pm 0.010$, $k_2 = 0.980 \pm 0.010$, $k_3 = 1.081 \pm 0.015$, and vbu are the magnitudes in the photometer's system.

Figure 1 presents the light curves of V1027 Cyg from 1991 to 2015, where the observations that we obtained and published previously, along with the new data, are shown.

In 1991–2015 the star exhibited semiregular brightness variations. The variability amplitude, the light-curve shape, and the magnitude of V1027 Cyg at maximum light changed noticeably from cycle to cycle. We observed both small-amplitude variations with $\Delta V = 0^{m}.2$ in 1994, 2005, and 2009 and variations with depths up to $0^{m}.6$ as well as deep photometric minima with an amplitude up to 1^{m} in 1992 and 2011. The star has maximum variability amplitudes in U. The brightness level at maxima varied within the ranges: $V_{\text{max}} = 8^{m}.6 \pm 0^{m}.1$, $B_{\text{max}} = 10^{m}.85 \pm 0^{m}.25$,

[1] Table 1 is published in electronic form only and is accessible via http://vizier.u-strasbg.fr/cats/J.PAZh.htx.

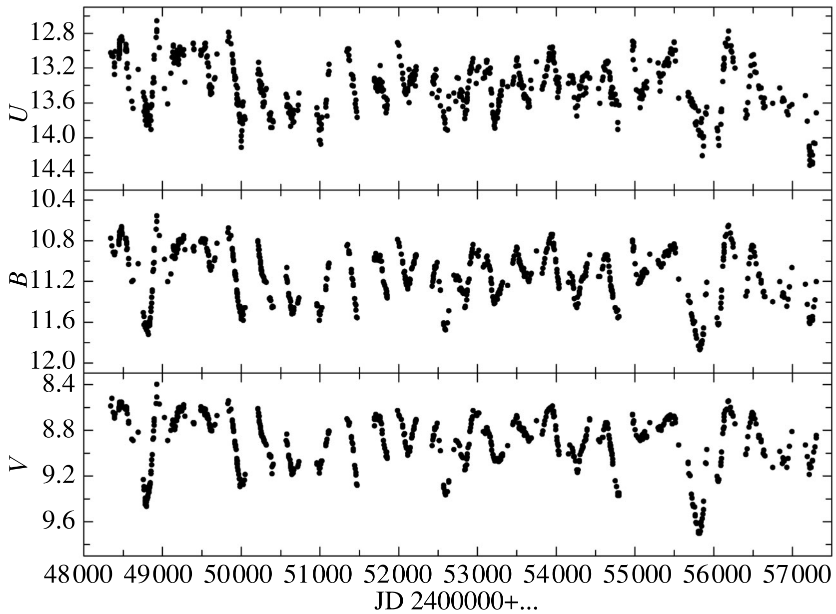

Fig. 1. *UBV* light curves of V1027 Cyg from our Crimean observations from 1991 to 2015.

$U_{\max} = 13^m\!.0 \pm 0^m\!.3$. The time scale of brightness variations was $200{-}300^d$ and was comparable to the duration of observing seasons ($\Delta T = 230 \pm 55^d$).

Relationship between the Brightness and Colors

Figure 2 shows the V light and $B-V$ and $U-B$ color curves over the entire period of observations of V1027 Cyg from 1991 to 2015. As can be seen, the colors changed significantly with brightness. The amplitudes of the $B-V$ and $U-B$ color variations reach $0^m\!.3$ and $0^m\!.45$, respectively. The color, along with the brightness, experiences quasi-periodic variations, but there is no unambiguous correlation between them.

The following peculiarities of the brightness and color variability of V1027 Cyg are noteworthy.

(1) Brightness minima close in depth can have significantly different $B-V$ colors. Over the period 1995–1998 there were four minima of approximately the same depth when the star faded to $V \sim 9^m\!.25$ (3–6 in Fig. 2). The $B-V$ color during these variations as the brightness declined increased to values that differed by $\sim 0^m\!.15$ at the minima.

(2) Close values of $B-V$ are reached at brightness minima different in depth. The 1994 and 1995 variations (2 and 3 in Fig. 2), when at different brightness levels at the minima, $V_{\min}(1994) = 8^m\!.78$ and $V_{\min}(1995) = 9^m\!.26$, the color reached $B-V \sim 2^m\!.3$, can serve as an example.

(3) In general, the UBV light curves of V1027 Cyg are similar, but in 2004 (8 in Fig. 2) the star exhibited variations in which the shapes of the light curves differed in all three bands. After the minimum was reached at JD $\sim 24\,53223$, the V brightness remained at $V = 9^m\!.05 \pm 0^m\!.02$ for ~ 85 days, while in B and U the star lingered at its minimum for no more than 10 days. The brightness then began to rise, and the colors became bluer as long as the star remained at its minimum in V: $B-V$ by $0^m\!.15$ and $U-B$ by $0^m\!.20$.

(4) In the variations with an amplitude up to $\Delta V \sim 0^m\!.75$ the $B-V$ color generally increased as the brightness declined. The behavior of the $U-B$ color in these variations was ambiguous. For example, during the 1995–2002 cycles $U-B$ with slight fluctuations neither reddened nor became bluer. A reddening of $U-B$ on the descending branches of the light curves was observed at the 1993, 1994, 2003, 2007–2010, and 2012 minima.

Particular attention should be given to an appreciable reddening of the star at the shallow 2015 minimum (12 in Fig. 2) when the colors reached their maximum values over the entire period of our observations, $B-V \approx 2^m\!.5$ and $U-B \approx 2^m\!.8$.

(5) The star experiences a bluing at deep brightness minima.

The deep 1992, 2008, and 2011 minima (1, 9, and 10 in Fig. 2) showed that in its bright state the star slightly reddens as it fades and then, starting from some brightness level, the $B-V$ color decreases and at minimum reaches the values corresponding to the

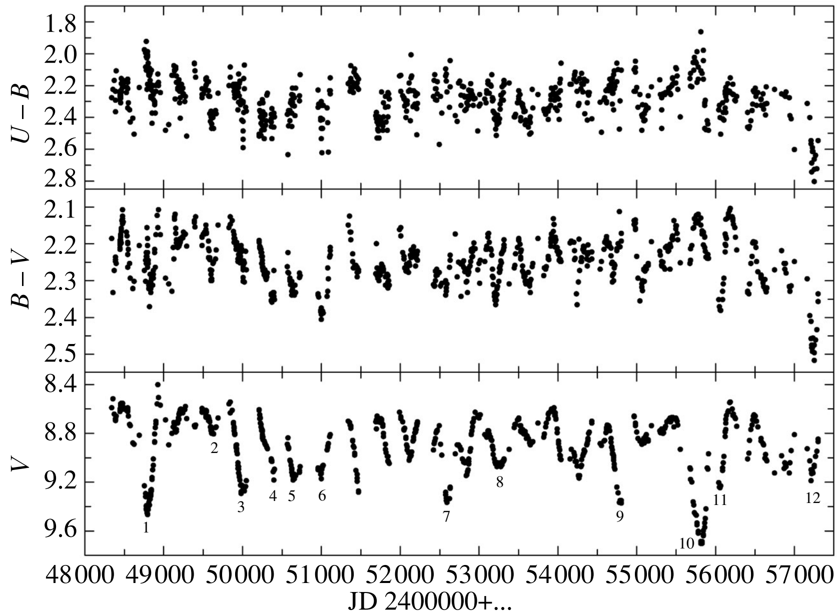

Fig. 2. V light and $B-V$ and $U-B$ color curves from our Crimean observations from 1991 to 2015. The numbers in the figure mark the times of observations that are discussed in the text.

star's brightness at maximum. At the fairly deep 2002 minimum (7 in Fig. 2) $B-V$ barely changed as the brightness declined.

The color–magnitude diagrams (Figs. 3 and 4) show different behaviors of the colors as the brightness declines: a bluing in some variations and a reddening in others. The fragment of the V light and $B-V$ and $U-B$ color curves for 2011–2012 (Fig. 5), where the "blue" and "red" photometric minima are adjacent, convincingly illustrates that the star is characterized by at least two types of variations for which the color variations are different.

The pulsations of V1027 Cyg are mainly responsible for its photometric variability. However, the complex photometric behavior of the star cannot be explained by its pulsations alone. Below we will investigate the nature of the star's variability by invoking our spectroscopic data and IR observations.

Searching for a Periodicity

Previously, we performed a Fourier analysis of our photometric observations for V1027 Cyg in 1991–1996 and detected no prominent peaks on the periodograms. After excluding the data referring to the deep minima from consideration, we found a period of 256 days (Arkhipova et al. 1997).

Here, we present a frequency analysis of our photometric UBV observations for V1027 Cyg over the entire period from 1991 to 2015. The PERIOD04 code (Lenz and Breger 2005) and V.P. Goransky's EFFECT code, which implements the Fourier transform for time series with an arbitrary distribution of observations in time (Deeming 1975), were used to search for a period.

Figure 6 shows the amplitude spectra of the complete series of observations for V1027 Cyg from 1991 to 2015 in U and V in the range of periods 100–1000 days. Groups of peaks corresponding to periods within $201–313^d$ and $450–1000^d$ are identified in the amplitude spectrum. A visual analysis of the light curves shows that the variability time scale for V1027 Cyg does not exceed 320^d. Therefore, the peaks in the range of periods $450–1000^d$ are very likely to be a superposition of shorter periods with one year.

Thus, the frequency analysis of our optical photometric observations for V1027 Cyg based on the entire series of observations revealed no variations with a dominant frequency. Therefore, we analyzed the light curves for periodicity by dividing the entire time of observations into intervals including several observing seasons. Table 2 gives the time intervals, the number of nights (N), the periods and amplitudes in U, B, and V corresponding to the identified frequencies in the specified JD range. We excluded the 2011 event from consideration, which stands out not only by the largest variability amplitude but also by its duration: the time from maximum to minimum was more than 300 days.

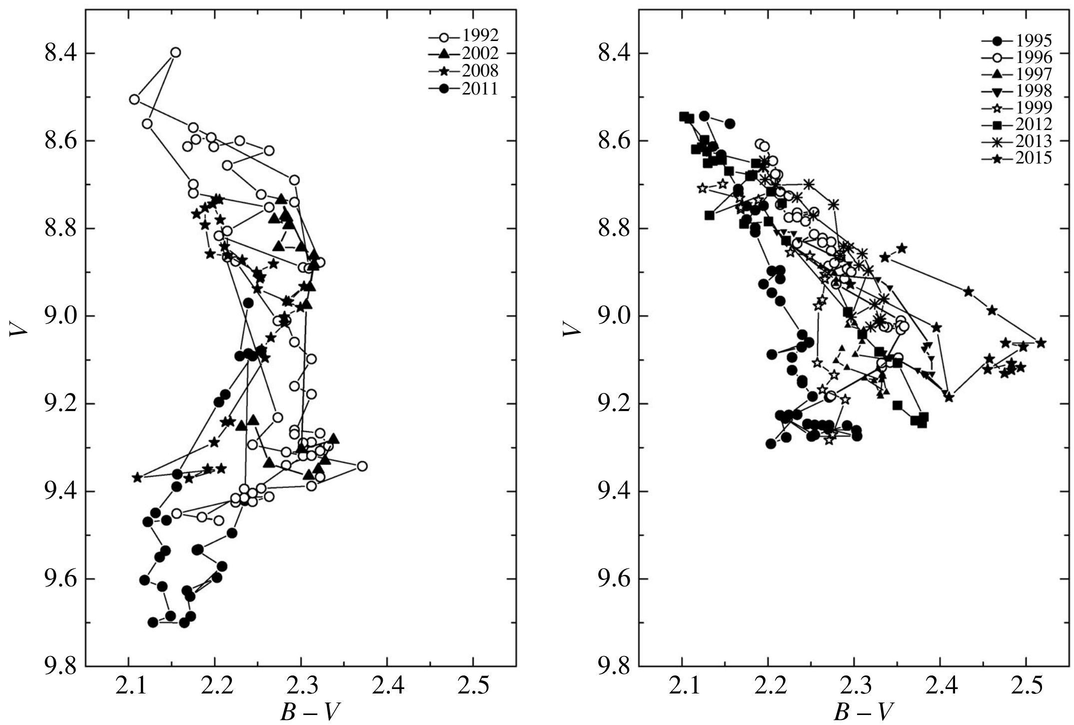

Fig. 3. $V-(B-V)$ diagrams for the deep (a) and shallow (b) photometric minima of V1027 Cyg. Different symbols mark the data for different years of observations.

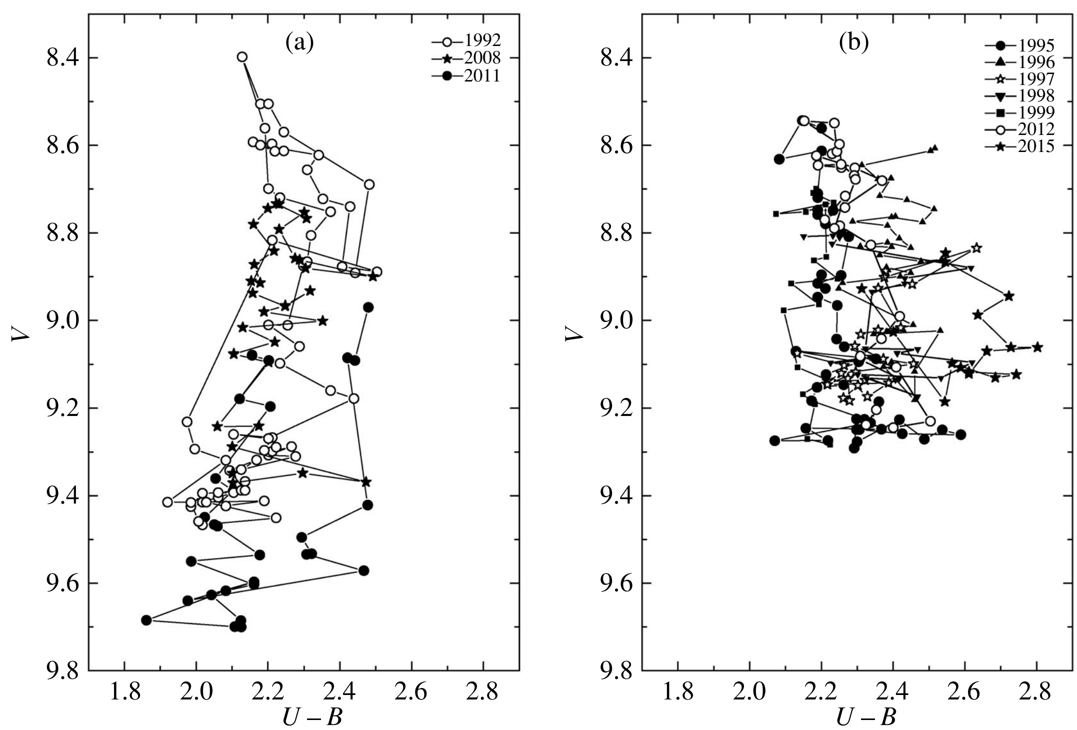

Fig. 4. $V-(U-B)$ diagrams for the deep (a) and shallow (b) photometric minima of V1027 Cyg. Different symbols mark the data for different years of observations.

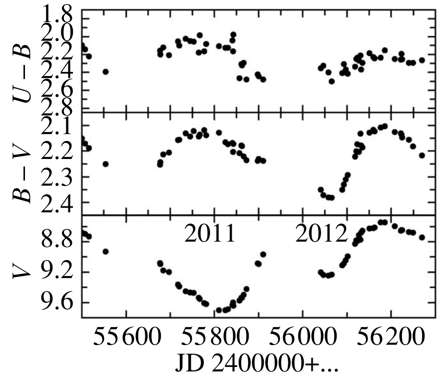

Fig. 5. Light and color curves in 2011–2012.

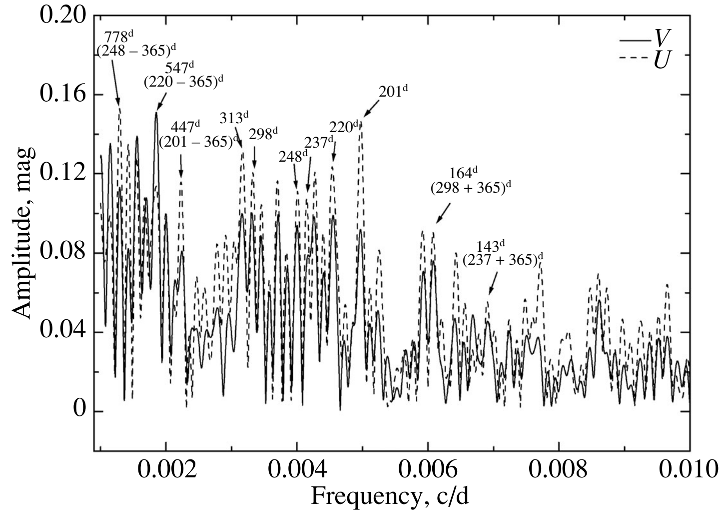

Fig. 6. Amplitude spectra of the complete series of observations for V1027 Cyg from 1992 to 2015 in U and V.

Thus, our UBV observations of V1027 Cyg from 1991 to 2015 revealed quasi-periodic brightness and color variations on a variability time scale from 212 to 320 days. As will be shown below, V1027 Cyg experiences small-amplitude variations in the near infrared that are satisfactorily represented by a sine wave with a period of 237 days, except for the 2011 event.

Extinction for V1027 Cyg

The star lies at a low Galactic latitude ($b = -0^{\circ}.4$), and its emission is severely distorted by interstellar extinction. The maximum extinction toward V1027 Cyg is great, being $E(B-V) = 2^{m}.52 \pm 0^{m}.08$ from the maps of Schlegel et al. (1998). For V1027 Cyg this quantity was undoubtedly overestimated.

The first extinction estimate based on UBV photometry for V1027 Cyg is given in Hrivnak et al. (1989), $A_V = 2^{m}.5$–$3^{m}.0$. The color excesses were also estimated by Vickers et al. (2015) when modeling the spectral energy distribution for post-AGB stars, $E(B-V) = 0^{m}.73$, and by Rayner et al. (2009), $E(B-V) = 1^{m}.08$, as the difference of the observed and normal colors for a G7 supergiant.

To estimate the extinction, we used our optical photometry together with the data on the star's spectral type.

The published estimates of the spectral type for V1027 Cyg lie within the range from G7I to K4I. The discrepancies may be due to a change in the star's spectrum during its pulsations. The optical colors also change significantly; therefore, spectroscopic

Table 2. Results of our search for a periodicity in the UBV observations of V1027 Cyg in different time intervals

JD 2400000+...	N	V		B		U	
		P, d	A, mag	P, d	A, mag	P, d	A, mag
48916–49692	69	277	0.10	277	0.13	282	0.20
49031–51112	127	320	0.22	320	0.29	316	0.32
51687–55554	328	244	0.11	244	0.11	212	0.10
56041–57301	75	293	0.24	293	0.36	303	0.49

and photometric observations close in time should be used, if possible, to properly estimate the extinction.

To estimate the color excess $E(B-V)$, we used the following:

(1) the data from Klochkova et al. (2000), where the parameters of V1027 Cyg $T_{\rm eff} = 5000$ K and $\log g = 1.0$, which correspond to the spectral type G8I in the calibration of Straizys (1982), were obtained from the spectroscopic observations on August 13, 1996 (JD = 2450309.4);

(2) The B and V magnitudes for JD = 2450366, $B = 11\overset{m}{.}36 \pm 0\overset{m}{.}01$ and $V = 9\overset{m}{.}02 \pm 0.01^m$, and the color $B-V = 2\overset{m}{.}34 \pm 0\overset{m}{.}02$;

(3) the normal color $B-V = 1\overset{m}{.}27$ for a G8I star from Straizys (1992);

With these input data the color excess for V1027 Cyg is $E(B-V) = 1\overset{m}{.}07 \pm 0\overset{m}{.}02$.

It should be kept in mind that our estimate of $E(B-V)$ characterizes the total extinction, which includes both interstellar and circumstellar components.

IR PHOTOMETRY FOR V1027 Cyg

The IR photometry for V1027 Cyg was performed in 1991–2015 with a 1.25-m telescope at the Crimean Station of the Sternberg Astronomical Institute using a photometer with a photovoltaic liquid-nitrogen-cooled InSb detector. The photometer was mounted at the Cassegrain focus of the telescope. The diameter of the entrance aperture was $\approx 12''$, while the spatial separation of the beams during chopping was $\approx 30''$ in the east–west direction. The star BS 7615 from the catalog by Johnson et al. (1966) served as a photometric standard. The IR photometry for V1027 Cyg in 1991–2008 and the computation of a spherically symmetric dust shell model were presented in Taranova et al. (2009) and Bogdanov and Taranova (2009). Bogdanov and Taranova (2009) highlight the following characteristics as the main features of the IR brightness and color variations in V1027 Cyg in 1991–2008: first, the brightness variations in all bands did not exceed $0\overset{m}{.}2$; second, the mean brightness in all bands and the mean colors over this period changed only slightly, by no more than a few hundredths of a magnitude.

The results of our 2009–2015 IR photometry are summarized in Table 3. The JKM brightness and $J-H$, $K-L$, and $L-M$ color variations over the entire period of our observations (1991–2015) are shown in Fig. 7, where the filled and open circles refer to the observations before and after 2009, respectively. The vertical bars in Fig. 7 indicate the errors in the M magnitude and $L-M$ color estimates; in the remaining bands the errors did not exceed $0\overset{m}{.}01$. The solid line marks the possible linear IR brightness and color trends.

On the whole, the pattern of IR variability in V1027 Cyg did not change significantly over 25 years (1991–2015). However, an unusual brightness decline whose amplitude was approximately the same $0\overset{m}{.}25 - 0\overset{m}{.}30$ in $JHKL$ and $\sim 0\overset{m}{.}1$ in M, was observed in the IR emission from the star in 2011 near JD 24(55732–55810). As a result, the star's color in the range 1.25–3.5 μm did not change within 1σ; in the range 3.5–5 μm the color excess increased.

For three intervals of observations of V1027 Cyg (1991–2008, 1991–2015, and 2009–2015 (outside and at the 2011 IR brightness minimum)) Table 4 provides the averaged IR magnitudes and colors $\bar{m}$, their standard deviations $\sigma_{\bar{m}}$, and the number of points N over which the data were averaged. All quantities were corrected for extinction with $E(B-V) = 1.07$. It can be seen from Table 4 that the averaged quantities over 1991–2008 and over the longer interval 1991–2015 coincide, within the error limits. A color excess is clearly seen in the mean

Table 3. *JHKLM* photometry for V1027 Cyg over the period 2009–2015

JD	J	H	K	L	M
2454993.5	4.90	4.22	3.90	3.40	3.21
2455016.5	4.86	4.20	3.89	3.38	3.30
2455054.4	4.89	4.20	3.90	3.37	3.25
2455115.3	4.83	4.16	3.88	3.41	3.18
2455408.4	4.81	4.14	3.82	3.34	–
2455433.4	4.80	4.16	3.81	3.34	–
2455494.3	4.84	4.22	3.87	3.40	–
2455697.5	5.03	4.37	4.03	3.51	3.23
2455732.5	5.11	4.46	4.13	3.61	3.30
2455755.4	5.10	4.48	4.14	3.62	3.31
2455781.4	5.09	4.48	4.18	3.64	3.29
2455793.4	5.12	4.50	4.15	3.61	3.29
2455810.3	5.11	4.46	4.16	3.61	–
2456084.5	4.90	4.24	3.93	3.40	–
2456137.4	4.83	4.22	3.89	3.35	–
2456469.4	4.82	4.22	3.92	3.40	–
2456487.4	4.81	4.20	3.89	3.37	3.16
2456498.4	4.79	4.16	3.85	3.38	3.16
2456518.4	4.82	4.17	3.88	3.35	3.13
2456524.4	4.82	4.20	3.87	3.40	3.20
2456579.3	4.80	4.14	3.83	3.31	3.1
2456650.1	4.93	4.28	3.97	3.44	3.19
2456876.4	4.95	4.32	4.04	3.52	3.27
2456915.3	4.94	4.32	4.03	3.50	3.28
2456942.3	4.94	4.29	3.99	3.46	3.19
2456969.2	4.86	4.21	3.91	3.38	3.23
2457232.4	4.87	4.23	3.87	3.33	3.25
2457263.4	4.86	4.19	3.87	3.33	3.23
2457271.3	4.85	4.17	3.85	3.32	3.16
2457288.2	4.76	4.04	3.75	3.23	2.92
2457291.3	4.85	4.17	3.85	3.34	3.13
2457324.2	4.80	4.18	3.86	3.34	3.12

$K-L$ and $L-M$ colors, because $(K-L) < 0\overset{m}{.}2$ and $(L-M) < 0\overset{m}{.}0$ for normal (F5–K5) supergiants (Koornneef 1983).

Based on the data from Table 4, we can estimate the mean flux from the dust shell at 5 μm. Below we assume that $K_* \approx M_*$ for a late-type supergiants (Koornneef 1983). In 1991–2015 at $M_* \approx K_* \sim 3\overset{m}{.}6$ and the observed M magnitude of $\sim 3\overset{m}{.}1$ (Table 4) the flux from the dust shell was then

$$F_{\rm d}(M) \approx F_{\rm obs}(M) - F_*(M)$$
$$\approx (12.2\text{–}7.7) \times 10^{-17}$$
$$\approx 4.5 \times 10^{-17}\ ({\rm W\ cm^{-2}\ \mu m^{-1}}).$$

At the 2011 minimum (Table 4) the mean flux from the star at 5 μm was $F_*(M) \sim 6.14 \times 10^{-17}$ W cm^{-2} μm^{-1} at $M_* \approx K_* \sim 3\overset{m}{.}85$, while the total flux was $F_{\rm obs}(M) \sim 10.5 \times 10^{-17}$ W cm^{-2} μm^{-1} for the observed magnitude $M \sim 3\overset{m}{.}27$. Consequently, the flux from the dust shell was $F_{\rm d}(M) \sim 4.4 \times 10^{-17}$ W cm^{-2} μm^{-1}. Thus, the flux from the dust shell at the 2011 minimum did not change, within the error limits, and the observed reddening at $\lambda > 2.2$ μm is due to a decline in the star's brightness and an increase in the relative contribution of the dust shell to the total flux. Note also that in 1991–2015 the fraction of the stellar radiation in the observed mean flux at 5 μm did not exceed 65%.

The mean IR magnitudes and colors in 1991–2008 and 2009–2015 (outside the 2011 minimum) coincide, within the error limits, with those obtained by averaging the data over the entire period of our observations 1991–2015 (Table 4). The mean fluxes from the dust shell at 5 μm in all these time intervals and at the 2011 minimum are also almost identical, and, consequently, the mean parameters of the dust shell can be assumed to have remain unchanged over 25 years.

Bogdanov and Taranova (2009) performed a Fourier analysis of our series of IR photometry in 1991–2008 and detected a period $P = (237 \pm 1)^{\rm d}$. In this paper we computed a periodogram (Fig. 8) for the complete series of observations of V1027 Cyg in 1991–2015 in J in the range of periods from $10^{\rm d}$ to $1000^{\rm d}$ using the computer code by Lenz and Breger (2005). The observations at the 2011 minimum were excluded from consideration. Analysis of the periodogram confirmed the period $P = (237 \pm 1^{\rm d})$. The two peaks of smaller height corresponding to the $143^{\rm d}$ and $660^{\rm d}$ periods are a superposition of the $237^{\rm d}$ period with one year.

Figure 9 presents the phase J, K, and M light and $J-H$, $K-L$, and $L-M$ color curves constructed with the $237^{\rm d}$ period and the epoch of min-

Table 4. Mean IR magnitudes and colors of V1027 Cyg in 1991–2008, 1991–2015, and 2009–2015 (outside and at the 2011 minimum). The extinction was taken into account with $E(B-V) = 1^m\!.07$

Band	1991–2008			1991–2015			2009–2015					
							outside 2011 min			at 2011 min		
	$\bar{m}$	$\sigma_{\bar{m}}$	N	$\bar{m}$	$\sigma_{\bar{m}}$	N	$\bar{m}$	$\sigma_{\bar{m}}$	N	$\bar{m}$	$\sigma_{\bar{m}}$	N
J	4.01	0.07	60	4.01	0.09	92	3.98	0.06	27	4.23	0.01	5
H	3.72	0.06	51	3.72	0.09	83	3.69	0.07	27	3.96	0.02	5
K	3.60	0.06	60	3.61	0.08	92	3.59	0.07	27	3.85	0.02	5
L	3.24	0.05	55	3.25	0.08	87	3.23	0.06	27	3.47	0.01	5
M	3.11	0.09	48	3.11	0.09	73	3.18	0.03	21	3.27	0.01	4
$J-H$	0.30	0.03	50	0.29	0.03	82	0.28	0.03	27	0.27	0.02	5
$H-K$	0.11	0.03	50	0.11	0.03	82	0.10	0.02	27	0.11	0.02	5
$K-L$	0.36	0.03	54	0.36	0.03	86	0.36	0.02	27	0.38	0.01	5
$L-M$	0.14	0.08	47	0.14	0.08	72	0.13	0.06	21	0.26	0.02	4

imum $JD_{min} = 2448583.7$. The observations at the 2011 minimum drop out of the phase dependence.

Figure 10 shows a color–magnitude $(J-H, J)$ diagram. It can be seen from Fig. 10 that the bulk of the observed quantities lie within the region bounded by the two straight lines A and B. Line A reflects the possible J brightness and $J-H$ color variations in the star surrounded by a dust shell with a variable optical depth whose particles are similar to interstellar ones. Line B is the line of changes in the source's size at a constant optical depth of the dust shell. The numbers near the crosses on line A refer to $E'(B-V) = \Delta(J-H)/0.34$ and the initial values (outside the dust shell) $J_0 = 4^m\!.67$ and $(J-H)_0 = 0^m\!.62$.

The observed brightness and color variations in the near infrared (1.25–1.65 μm), where the radiation completely belongs to the stellar photosphere, can be explained by the combined effects from (i) the variations in the optical depth of the circumstellar dust shell, when $E'(B-V)$ can change from $0^m\!.0$ to $\sim 0^m\!.35$ and (ii) the variations in the source's size. At the observed mean J brightness variations $\Delta J \sim 0^m\!.2$ at a constant $J-H$ color the radial pulsations can reach 10%.

Spectral Energy Distribution for V1027 Cyg

Our $UBVJHKLM$ photometry for V1027 Cyg allows us to construct the spectral energy distribution for the star in the range 0.36–5.0 μm at various phases of the pulsation cycle. Consider two epochs on the light curve of V1027 Cyg: JD $\sim$ 2450672 is the 1997 minimum and JD $\sim$ 2455440 is the 2010 maximum.

We dereddened the 1997 and 2010 photometry with $E(B-V) = 1^m\!.07$, constructed the spectral energy distribution for V1027 Cyg, and fitted our data by the radiation of supergiants of different spectral types (Fig. 11).

At maximum light JD $\sim$ 2455440 the spectral energy distribution for V1027 Cyg in a wide wavelength range, from 0.36 (U) to 3.5 (L) μm, is fitted quite satisfactorily by the radiation of a G8I star for which the normal $U-B$ and $B-V$ colors were taken from Straizys (1992), while the near-IR radiation is presented in accordance with the data from Koornneef (1983). At minimum light JD $\sim$ 2450672 the spectral energy distribution for V1027 Cyg corresponds to a K1 supergiant in the wavelength range from 0.36 (U) to 2.2 (K) μm. The excess in L and

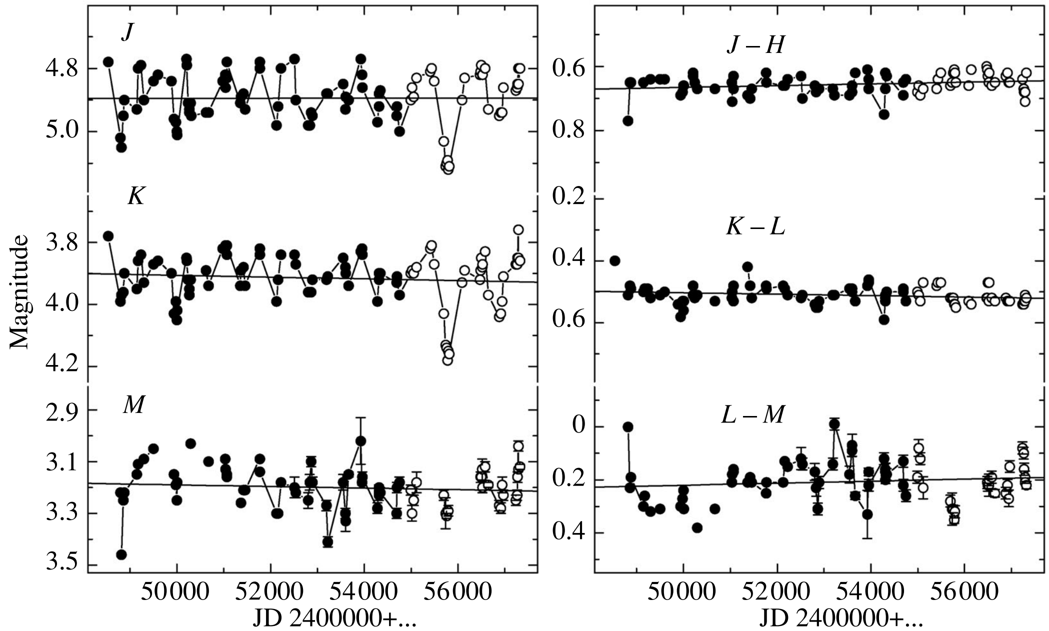

Fig. 7. JKM light and $J-H$, $K-L$, and $L-M$ color curves of V1027 Cyg from our Crimean observations from 1991 to 2015.

M is associated with the contribution from the dust shell radiation. Our estimates of the spectral types for V1027 Cyg are supported by a comparison of the $UBVJHK$ data with the spectral energy distribution for G8 and K1 supergiants from the library of stellar spectra by Pickles (1998).

For V1027 Cyg at its deep 2011 minimum (JD $\sim$ 2455810) we failed to pick the spectral energy distribution of a normal supergiant that would satisfy our photometric data in the entire observed wavelength range. If the spectral type for the star is taken to be K2–K3I, then a close correspondence of the dereddened photometric data to the radiation of a normal K2–K3 supergiant is observed in the range from 0.55 (V) to 3.5 (L) μm. However, a significant excess of emission remains in the U and B bands. When discussing our UBV photometry, we have already pointed out that the star became bluer at the 2011 minimum.

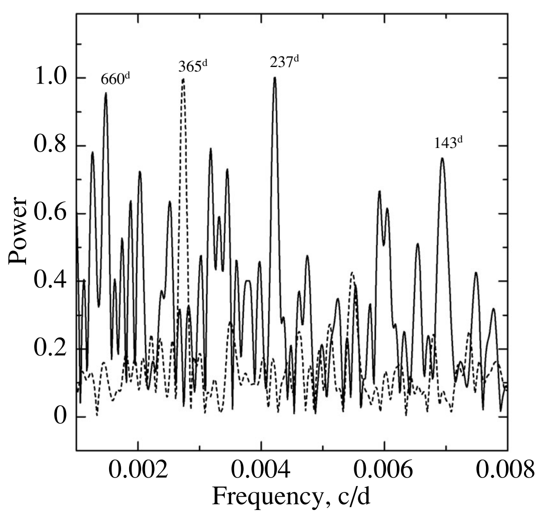

Fig. 8. Periodogram (solid line) and spectral window (dashed line) from our J-band observations of V1027 Cyg from 1991 to 2015.

SPECTROSCOPIC OBSERVATIONS OF V1027 Cyg

The spectroscopic observations of V1027 Cyg were carried out in 1995–2015 with the 1.25-m reflector at the Crimean Station of the Sternberg Astronomical Institute, the Moscow State University, using a spectrograph with a 600 lines/mm diffraction grating and a long slit $\sim 4''$ in width. The following CCD array were used as the detector: ST-6 (372×274-pixel CCD) in 1995–2006 and ST-402 (765×510-pixel CCD) in 2008–2015. The formal spectral resolution was $\sim$5.5 Å/pixel with the ST-6 CCD and $\sim$2.2 Å/pixel with the ST-402 CCD. A log of spectroscopic observations is presented in Table 5, where the dates of observations, the spectral range, and the UBV photometry for the corresponding date are given.

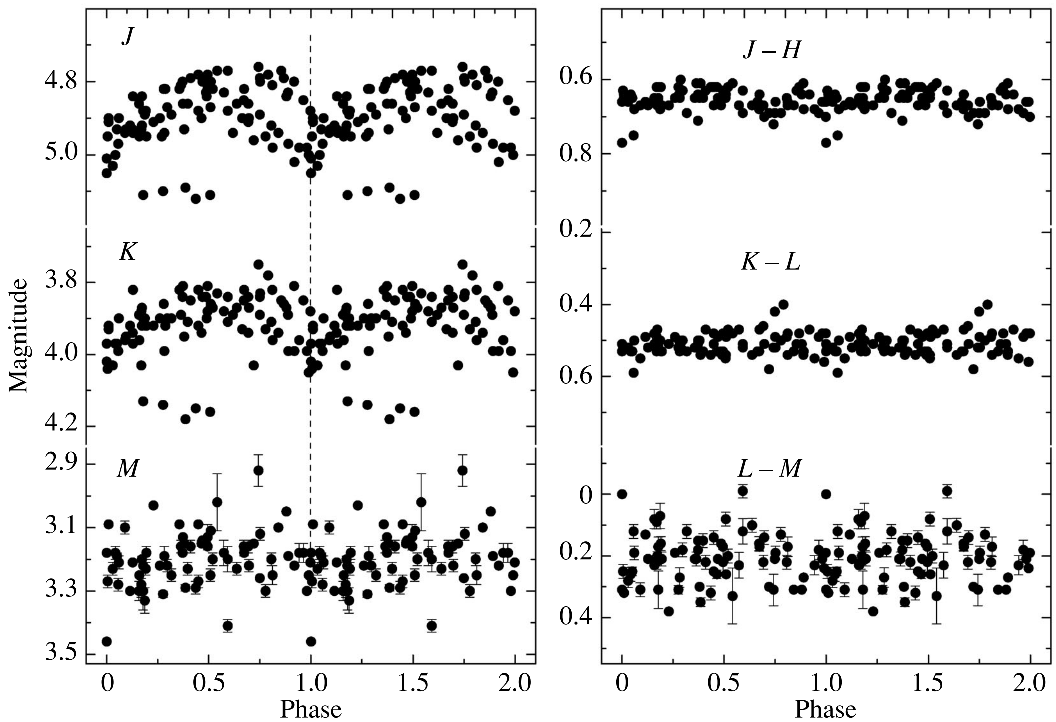

Fig. 9. J, K, and M brightness and $J-H$, $K-L$, and $L-M$ color variations in V1027 Cyg with phase of the 237^d period.

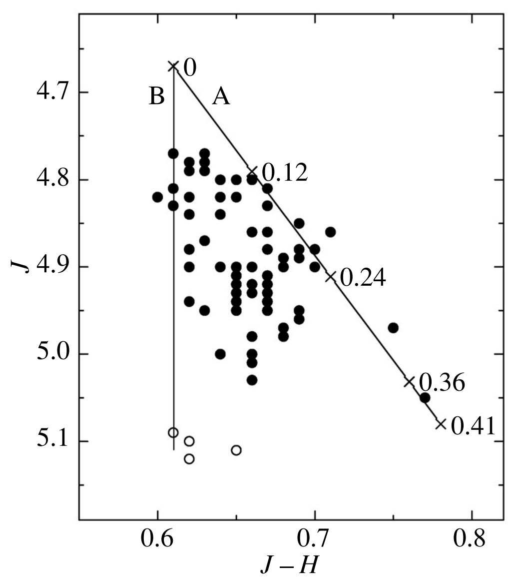

Fig. 10. $(J-H, J)$ diagram for the observed quantities of V1027 Cyg. The bulk of the data are indicated by the circles. The open circles refer to the 2011 minimum. Lines A and B indicate the pattern of J brightness and $J-H$ color variations in the circumstellar dust shell and the J brightness variations at a given optical depth of the dust shell, respectively (see the text).

The spectra were reduced with the standard CCDOPS code and the SPE code (Sergeev and Heisberger 1993). We calibrated the fluxes based on the spectra of the stars 18 Vul and 57 Cyg; their absolute spectral energy distributions in the range λ4000–7650 Å were taken from the spectrophotometric catalog by Voloshina et al. (1982) and ex-

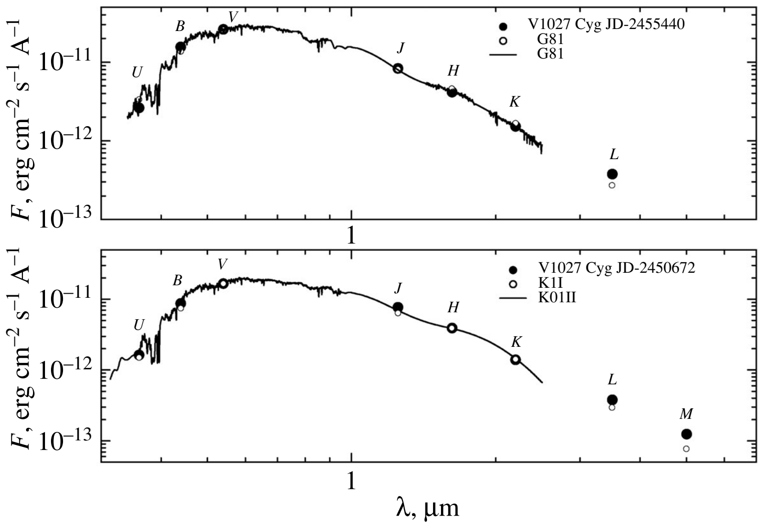

Fig. 11. Spectral energy distribution for V1027 Cyg corrected for extinction with $E(B-V)=1^{m}\!.07$ and the data for normal supergiants normalized to a wavelength of 5500 Å. The upper and lower panels correspond to the maximum (JD $\sim$ 2455440) and the 1997 minimum (JD $\sim$ 2450672), respectively.

tended to λ9200 Å using data from the atlas of standard stellar spectra by Pickles (1985).

Figure 12 shows the times of our spectroscopic observations. We took the spectra in 1995, 1998, 1999, 2003, 2005, 2006, 2007, 2011, and 2015 near the brightness minima, in 2006 at maximum light, in 2008 in the middle of the descending branch of a deep minimum, and in 2009 and 2010 in the middle of the ascending branch of shallow minima.

All of the spectra, except those taken in 1995 and 2011, differed insignificantly at different brightness levels, irrespective of the pulsation phase. Figure 13 shows the absolutized and extinction-corrected (with $E(B-V)=1^{m}\!.07$) spectrum of V1027 Cyg on August 9, 2010, together with the spectrum of a G8I supergiant from the library of stellar spectra by Pickles (1998). The lines typical of late G or early K supergiants, in particular, the numerous Fe I, Ti I, and Ca I absorptions and the Mg I λ5167–5183–5173 triplet, are represented in the wavelength range 4500–8700 Å. The main features of the spectrum for V1027 Cyg are the Ba II absorptions at λ4554, 5853, 6142, and 6497 and the IR Ca II triplet and O I λ7771–7774 triplet lines that are enhanced compared to normal supergiants. The spectra exhibit strong Na I D1 and D2 absorption and a DIB at $\sim\lambda$6282.

TiO absorption bands appeared in the spectrum of V1027 Cyg near the deep 1995 and 2011 minima, whose presence implies a spectral type for the star later than K3. In the optical and near-IR ranges these bands are prominent at λ5847, 6159, 6651, and 7065 Å. In addition, in the 2011 spectrum an emission component is clearly present in the Hα profile. Figure 14 shows fragments of the spectra for V1027 Cyg taken on September 25, 1995, and October 21, 2011, and, for comparison, the spectrum of the post-AGB star IRAS 16476–1122 (sp = M1I) from the Appendix to the spectral atlas by Suárez et al. (2006). We estimated the spectral type of V1027 Cyg in 1995 and 2011 from the intensity of the TiO absorption bands to be M0–M1.

It should be noted that the spectra with TiO molecular bands refer to the 1995 and 2011 minima that differ by their photometric characteristics. The 1995 minimum was "red," while the 2011 one was "blue." In contrast, the 1995 and 1999 minima, which are similar in their photometric behavior, a reddening as the brightness declines, showed different spectra: one with TiO bands and the other without them.

We measured the equivalent widths of the strongest lines in the spectrum of V1027 Cyg in the range λ5857–8670 Å. The equivalent widths did not show any correlations with both brightness and color of the star, and their variations do not exceed the measurement errors. Therefore, in Table 6 we give the equivalent widths of the Na D; Ba II λ5857, λ6497, Hα, O I λ7771–7774 triplet, and Ca II λ8498, 8542, 8662 lines averaged over all spectra.

In all spectrograms, except the 1999 one, the Ba II λ6497 line is slightly stronger than Hα, in contrast to normal supergiants of spectral types close to V1027 Cyg. The IR calcium triplet absorptions are anomalously strong in the spectrum of V1027 Cyg.

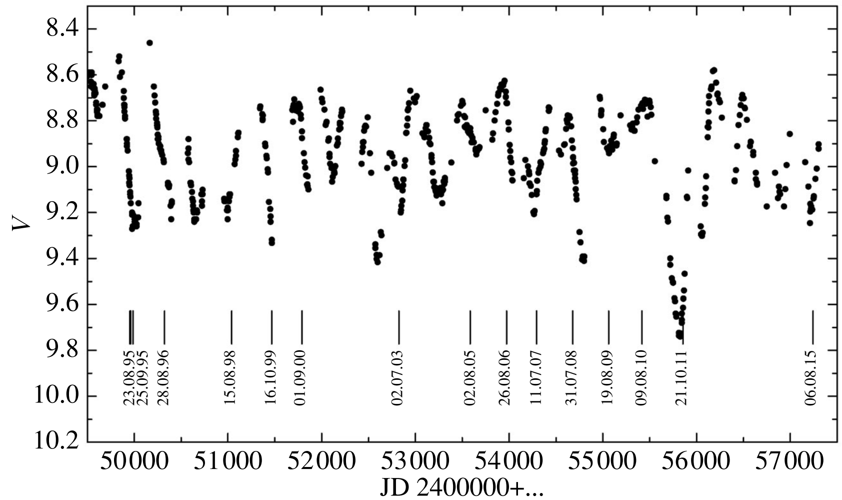

Fig. 12. *V* light curve of V1027 Cyg from 1991 to 2015 with an indication of the times of spectroscopic observations.

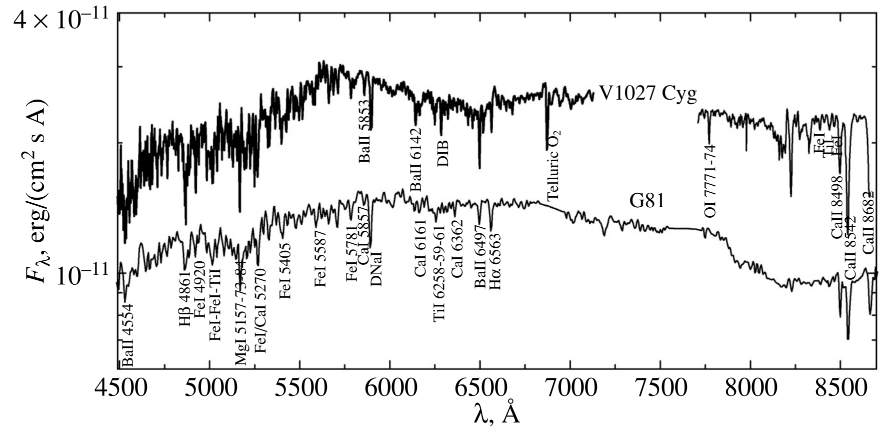

Fig. 13. Extinction-corrected spectrum of V1027 Cyg in absolute energy units on August 9, 2010, and the spectrum of a G8 supergiant (Pickles 1998) whose level was shifted arbitrarily along the vertical axis.

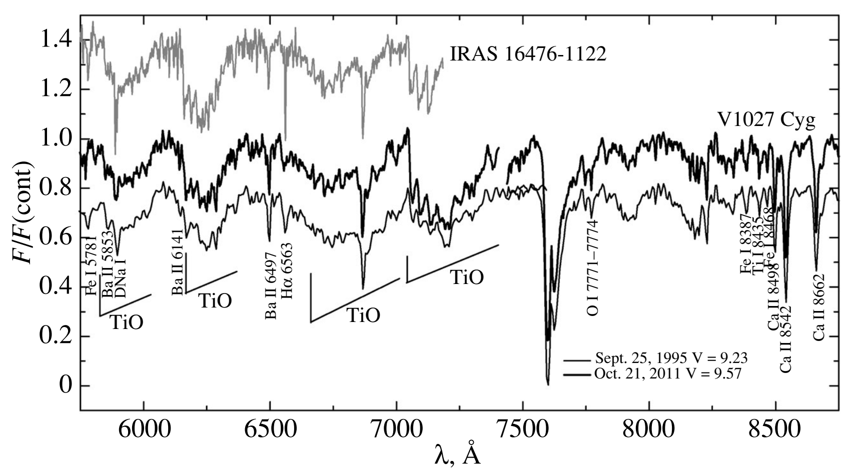

Fig. 14. Fragments of the spectra for V1027 Cyg (black lines) and IRAS 16476−1122 (gray line). The spectra were normalized to the continuum and arbitrarily shifted along the vertical axis.

Table 5. Log of spectroscopic observations and photometric data for V1027 Cyg in 1995–2015

Date	JD	Spectral range	V	$B-V$	$U-B$
Aug. 23, 1995	2449953	4400–7200	9.12	2.23	2.21
Aug. 26, 1995	2449956	4400–9200	9.15	2.23	2.24
Sep. 2, 1995	2449963	4400–9200	9.17	2.25	2.18
Sep. 25, 1995	2449986	4400–9200	9.23	2.21	2.42
Aug. 15, 1998	2451041	4400–7200	9.01	2.36	2.33
Oct. 16, 1999	2451468	4400–7200	9.27	2.28	2.16
Sep. 1, 2000	2451789	4400–9200	8.80	2.27	2.31
July 2, 2003	2452823	4400–7200	9.04	2.28	2.27
Aug. 2, 2005	2453585	4400–7200	8.80	2.30	2.44
Aug. 26, 2006	2453974	4400–7200	8.68	2.21	2.28
July 11, 2007	2454293	4400–7200	9.07	2.25	2.22
July 31, 2008	2454679	4400–7200	8.87	2.23	2.16
Aug. 19, 2009	2455063	4400–9200	8.88	2.31	2.43
Aug. 9, 2010	2455418	4400–9200	8.70	2.20	2.21
Oct. 21, 2011	2455856	5000–9200	9.57	2.21	2.47
Aug. 9, 2015	2457244	4400–9200	9.10	2.48	2.64

The sum of the equivalent widths of all three lines exceeds 20 Å. The IR O I triplet is not resolved in our spectra; its equivalent width is also slightly overestimated compared to normal supergiants.

DISCUSSION

The UBV observations of V1027 Cyg from 1991 to 2015 presented in our paper revealed a photometric variability of the star on time scales from 212 to 320 days with an amplitude up to 1^m in V, a bluing in some variations, and a reddening in others. The complex photometric behavior of the star in the optical range may suggest the existence of an additional factor that, apart from pulsations, causes its photometric variability. The shock waves associated with the radial pulsations contribute to an enhancement of the mass loss by the star, which gives rise to an additional dust component and to a change in the optical depth of the circumstellar dust envelope. It can be assumed that the bluing of the star is due to the scattering of stellar radiation by small dust particles, while its reddening and fading are related not only to a decrease in the temperature during pulsations but also to extinction in the circumstellar dust envelope.

Our near-IR observations allowed the fraction of extinction in the dust shell to be estimated, $E'(B-V) \leq 0^m\!.35$. Based on the entire series of IR observations, except for the 2011 minimum, we found a variability period of $237^{\rm d}$ that can be the pulsation period.

The 2011 event deserves particular attention. It stands out by its longer duration, the maximum variability amplitudes in all optical and IR photometric

Table 6. Equivalent widths of absorption lines in the spectrum of V1027 Cyg

Line	W_λ, Å	σW_λ, Å	N
Ba II λ5857	1.2	0.3	10
Na I λ5890–95	3.3	0.6	11
Ba II λ6497	2.3	0.6	15
Hα λ6563	2.1	0.3	14
O I λ7771–7774	1.7	0.2	7
Ca II λ8498	3.9	0.4	8
Ca II λ8542	9.3	0.9	8
Ca II λ8662	7.2	0.8	8

bands, and the unusual behavior of its colors. At its minimum, when the V brightness of the star dropped by $\sim 1^m$, the $B-V$ and $U-B$ colors became bluer (!) by a few hundredths of a magnitude compared to the maximum brightness level. In J at a variability amplitude of $0\overset{m}{.}25$ the $J-H$ color remained at the level corresponding to the star's maximum light, and only in the range 2.2–5 μm did the colors slightly increase.

The spectroscopy obtained at a time close to the photometric 2011 minimum revealed TiO molecular bands in the star's spectrum whose intensity corresponded to spectral type M0–M1, while at maximum light the star is classified as G7–G8I. The color differences for the spectral types M0I and G8I are $\Delta(U-B) = 0\overset{m}{.}83$, $\Delta(B-V) = 0\overset{m}{.}47$, and $\Delta(J-H) = 0\overset{m}{.}35$. This means that the star must have reddened considerably, which was not observed.

The discrepancy between the spectroscopic and photometric characteristics of the star is most probably due to the existence of a circumstellar gas–dust shell around V1027 Cyg. As Klochkova (2014) pointed out, the optical spectra of post-AGB stars differ from the spectra of classical massive supergiants by the presence of molecular bands superimposed on the spectrum of an F–G supergiant.

V1027 Cyg is one of the coolest investigated post-AGB stars and so far the only known oxygen-rich object of a late spectral type for which long-term photometry is available. At the same time, V1027 Cyg differs from the variable carbon-rich post-AGB stars of late spectral types (for example, IRAS 20000+3239 (Sp = G8I), IRAS Z02229+6208 (Sp = G8–K0Ia), IRAS 05113+1347 (Sp = G8Ia); Hrivnak et al. 2010) by longer periods and larger variability amplitudes. Hrivnak et al. (2015) assumed that the period–temperature relation for oxygen-rich objects could be steeper than that for carbon-rich ones.

Figure 15 shows the period–temperature relation for 12 carbon-rich objects from Hrivnak et al. (2010) and for four oxygen-rich stars: V887 Her, V1648 Aql, HD 331319, and V1027 Cyg. The pulsation periods for V887 Her, V1648 Aql, and HD 331319 were taken from Arkhipova et al. (2010, 2006), while the effective temperatures for V887 Her and V1648 Aql were estimated by Klochkova (1995) and Pereira et al. (2004), respectively. Two effective temperature determinations exist for HD 331319: 7750 ± 100 K (Arellano Ferro et al. 2001) and 7200 ± 100 K (Klochkova et al. 2002).

V1027 Cyg with its parameters $P = 237 \pm 1^d$ and $T_{\text{eff}} = 5000$ K lies above the sequence of carbon-rich objects in Fig. 15 and confirms the assumption of Hrivnak et al. (2015) about a steeper relation for oxygen-rich objects. The long period of V1027 Cyg may suggest a high luminosity of the star.

Spectroscopic criteria also point to a high luminosity of V1027 Cyg. Klochkova et al. (2000) provided the absolute magnitude for this star, $M_V \approx -7^m$, obtained from the calibration relation between the IR O I triplet equivalent width and stellar luminosity (Arellano Ferro and Mendoza 1993). $W_\lambda(\text{O I}) = 1.7 \pm 0.2$ Å from our paper also corresponds to $M_V \approx -7^m$. However, it should be kept in mind that the strengthening of the oxygen triplet can be caused not only by the luminosity effect but also by an enhanced oxygen abundance in an evolved star (Arellano Ferro et al. 2003). Applying a different spectroscopic criterion, the dependence of the Ba II λ 5853 and 6141 Å line equivalent widths on stellar luminosity from Andrievsky (1998), also leads to a high value of $M_V \approx$ from -7^m to -8^m (Klochkova et al. 2000).

Finally, the IR Ca II triplet, whose intensity correlates with $\log g$ (Jones et al. 1984), is considerably strengthened in the spectrum of V1027 Cyg. The sum of the Ca II λ8498, 8542, and 8662 Å line equivalent widths obtained from our observations, $W_\lambda(\text{Ca T}) = 20.3 \pm 1.8$ Å, exceeds the maximum values for supergiants of similar chemical composition and points to a high luminosity of the star (Cenarro et al. 2002). For typical post-AGB stars of late spectral types (V354 Lac, AI CMi, IRAS 13313–5838) the IR Ca II triplet intensity is approximately half that for V1027 Cyg (our unpublished data).

V1027 Cyg lies at a low Galactic latitude, $b = -0\overset{\circ}{.}36$. If the distance to the star is taken to be $d \sim$

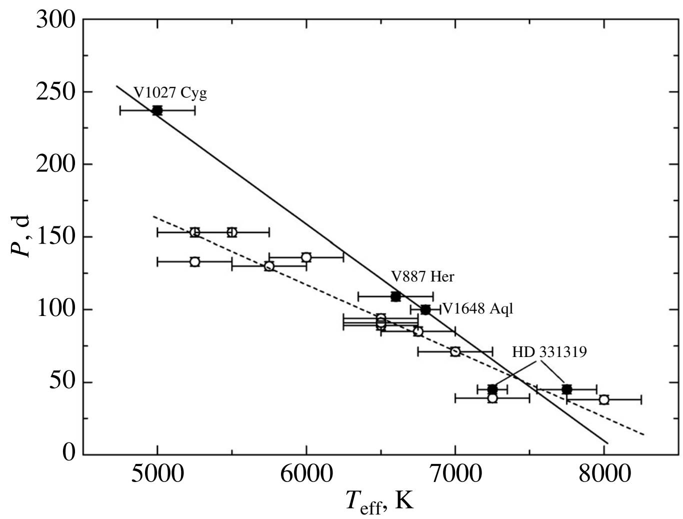

Fig. 15. Pulsation period versus effective temperature for 16 post-AGB stars. The open circles indicate 12 carbon-rich objects from Hrivnak et al. (2010). The oxygen-rich objects are indicated by the filled circles. The dashed line is a linear fit to the period–temperature relation for the carbon-rich objects; the solid line refers to the oxygen-rich objects.

1.26 kpc (Vickers et al. 2015), then its height above the Galactic plane does not exceed $z \sim 10$ pc. This suggests that the star belongs to the flat Galactic disk and, consequently, may be indicative of its enhanced mass.

If V1027 Cyg is assumed to be a post-AGB star of enhanced mass, then one would expect the observational manifestations of fast evolution from it, in particular, a noticeable systematic change in its mean visual brightness. Based on our photometric observations over the last 25 years, we detected no trend in the mean UBV brightness. According to the first observations of the star from Wachmann (1961), its photographic magnitude in the time interval JD 2432700–2436900 (1948–1959) changed within the range $m_{pg} = 10^m_.5{-}11^m_.5$, while in 1991–2015 the range of B magnitude variations was $B = 10^m_.6{-}11^m_.8$. Consequently, the mean brightness of the star has not changed over more than 60 years. The visual magnitude from the BD catalogue, $9^m_.1$, lies within the range of V brightness variations at the present epoch.

There are estimates of the parameters T_{eff} and $\log g$ for V1027 Cyg in the literature. Klochkova et al. (2000) obtained two sets of parameters by comparing the spectra with model atmospheres: $T_{eff} = 5000$ K, $\log g = 1.0$ and $T_{eff} = 4900$ K, $\log g = 0.5$. Meneses-Goytia et al. (2015) estimated $T_{eff} = 5450$ K and $\log g = 1.0$ from their IR data. In both cases, V1027 Cyg turns out to be near the track with the minimum possible stellar mass of $0.53\ M_\odot$ on the evolutionary $\log T_{eff} - \log g$ diagram from Miller Bertolami (2015) for post-AGB stars.

Thus, our analysis of the new photometric and spectroscopic observations together with the archival data does not yet give a definite answer to the question about the status of V1027 Cyg among other post-AGB stars. Some data suggest a high luminosity of V1027 Cyg and, consequently, its enhanced mass, while other data place the star in the region of low-mass post-AGB objects.

CONCLUSIONS

Our long-term observations of the semiregular pulsating variable V1027 Cyg, a supergiant with an IR excess, led us to the following conclusions about the photometric behavior and spectroscopic peculiarities of this star.

In 1991–2015 the star exhibited quasi-periodic brightness variations with variable amplitudes and a changing light-curve shape.

(1) We observed both small-amplitude variations with $\Delta V = 0^m_.2$ in 1994, 2005, 2009 and variations with depths up to $0^m_.6$ as well as deep photometric minima with an amplitude up to 1^m in 1992 and 2011.

(2) The search for a period based on our UBV photometry in 1991–2015 revealed several periods from $P = 212^d$ to 320^d in different time intervals. The deepest 2011 minimum does not satisfy any of these periods.

(3) The correlation of the $U - B$ and $B - V$ colors with the brightness is not unambiguous. The fading of the star is accompanied by its reddening in some variations and by its noticeable bluing at the deepest

1992 and 2011 minima. There were also brightness variations during which the reddest colors occurred at minimum light, while subsequently $B-V$ and $U-B$ decreased and reached their lowest values in the middle of the ascending branch, whereupon the star reddened as it brightened further (the 2004 variation from $\mathrm{JD_{min}} = 2453250$). In 2015 an anomalous reddening of the star was observed as it faded.

(4) Our $JHKLM$ observations of V1027 Cyg in 1991–2015 showed quasi-periodic brightness variations with the most probable period $P = 237^{\mathrm{d}}$ and amplitudes no greater than $0\overset{m}{.}2$. The deep 2011 minimum that occurred in the optical range manifested itself as a brightness decline by $0\overset{m}{.}25$–$0\overset{m}{.}3$ in JHK. This minimum does not satisfy the period $P = 237^{\mathrm{d}}$.

(5) Based on our optical photometry, we determined the color excess for V1027 Cyg: $E(B-V) \approx 1\overset{m}{.}07$. Our IR observations allowed us to estimate the fraction of circumstellar extinction $E'(B-V) \leq 0\overset{m}{.}35$ under the assumption that the dust grains in the circumstellar shell were similar to the interstellar ones.

(6) A joint analysis of our optical and IR photometry allowed us to construct the spectral energy distribution for V1027 Cyg at some phases of the pulsation cycle. The energy distribution was shown to change and to correspond to spectral types from G8I to K3I.

(7) Our low-resolution spectroscopy in the range λ4400–9200 Å showed the appearance of TiO emission bands at the 1995 and 2011 minima. At the same time, no TiO bands were observed near the deep 1992 minimum (Arkhipova et al. 1997) and when the star faded considerably in 1998, 1999, and 2007.

(8) We measured the equivalent widths of the O I λ7774 Å and IR calcium triple absorption lines, which are luminosity criteria. The derived $W(\mathrm{O\,I}) = 1.8 \pm 0.2$ Å and $W(\mathrm{Ca\,T}) = 20.3 \pm 1.8$ Å suggest a high luminosity of the star.

Analysis of our long-term photometry for V1027 Cyg suggests that the pulsational instability, along with the change in the optical depth of the circumstellar dust envelope, is responsible for the optical and near-IR variability of the star.

Simultaneous photometric observations and radial velocity measurements for the star are needed to investigate the variability due to its pulsations.

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