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RECURRENT SYMBIOTIC NOVA V407 CYGNI: BEFORE AND AFTER OUTBURST IN 2010

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Abstract. We present the results of our $UBVJHKLM$ photometric and spectroscopic observations of V407 Cyg obtained in 2003–2015. No fast brightness variations of V407 Cyg have been detected since its RS Oph-type outburst in 2010. Now the binary demonstrates a low-excitation emission spectrum with Hα weaker than the [N II] 6584 Å line. It is a typical spectrum on the way to the passive state.

Key words: binaries: symbiotic – stars: variables: Miras – stars: individual: V407 Cyg

1. INTRODUCTION

A symbiotic star is a long-period interacting binary consisting of a hot component (a hot subdwarf or a neutron star), a cool component (a late-type giant or supergiant), and a gaseous nebula. Different types of activity are observed in such systems (Belczynski et al. 2000). A typical Z And-type outburst is characterized by a moderately fast rise to the maximum brightness (with an amplitude ≤ 3 mag in the B band). Usually a system returns to quiescence after 5–8 years of its active state. A recurrence time for such type of outbursts is several decades. Symbiotic stars that demonstrate Z And-type outbursts are united in the subclass of classical symbiotics. The second subclass is symbiotic novae (the oldest object is AG Peg). All symbiotic novae are very slow novae with only one detected outburst (the constant luminosity phase of the outburst lasts for many decades). The third subclass is recurrent symbiotic novae (RS Oph is the most famous object of this subclass) with fast and bright outbursts ($\Delta B \geq 5$ mag). The spectral and photometric evolution of such an outburst is nearly the same as for classical novae.

Quite recently, there was an opinion that a symbiotic system could demonstrate only one type of activity (or no activity). However, now the situation is different. V407 Cyg is just one of the systems with different types of activity.

V407 Cyg was discovered during its nova-like outburst in 1936–1939 (Hoffmeister 1949). After that, observations of the system could not reveal its symbiotic nature for a long time. Meinunger (1966) analyzed its high-amplitude photographic brightness variations and concluded that the Mira pulsation period was about 745 days. All of the published spectra obtained before 1994 (Esipov et al. 1988; Kolotilov et al. 1998) were typical non-symbiotic Mira spectra contaminated by the gaseous nebula NGC 7000 (V407 Cyg and NGC 7000 are unrelated objects, close only in projection on the celestial sphere). The first typical symbiotic spectrum of V407 Cyg was obtained only in 1994 (Munari et al. 1994).

In 1998, the binary underwent a small outburst (Kolotilov et al. 2003), nearly invisible during the Mira's maximum but prominent near the Mira's minimum. The spectral evolution of this outburst was considered by Tatarnikova et al. (2003a).

Nishiyama & Kabashima (2010) discovered a very bright and fast outburst of V407 Cyg. It looked like a typical outburst of classical novae (Munari et al. 2011). In the group of symbiotic stars, only recurrent symbiotic novae demonstrate such type of outbursts. Note that the two previous outbursts of V407 Cyg differed greatly from the strong outburst observed in 2010. V407 Cyg is the first symbiotic system detected in gamma-ray range. According to Abdo et al. (2010), the first detection of gamma radiation was on the same day when Nishiyama & Kabashima found the star in outburst. Shore et al. (2011, 2012) interpreted the continuum emission in a wide spectral range and analyzed spectral evolution of different emission and absorption lines. All four states of V407 Cyg were considered by Esipov et al. (2012).

Let us note some unusual features observed for V407 Cyg that we will not discuss in our paper. The first one is that the system has an optically thin dust envelope, despite its longest pulsation period among all symbiotic Miras (Yudin 1999). The second one is that a prominent resonance line of Li I is sometimes registered in the spectra of V407 Cyg (Tatarnikova et al. 2003b), though V407 Cyg has no signs of sufficient enrichment in s-process elements (typical of other AGB stars with lithium enrichment). However, Wallerstein et al. (2008) detected the resonance Li I line in two recurrent symbiotic novae, RS Oph and T CrB, with ordinary (not Mira-type) late-type giants as cool components (at that time, there were only four recurrent symbiotic novae). We will consider additional features (including fast brightness variations) in the present paper.

2. OBSERVATIONS

Our photometric $UBVJHKLM$ observations of V407 Cyg were carried out with the 0.6-m and 1.25-m telescopes at the Crimean Station of the Sternberg Astronomical Institute, Moscow State University (see Tables 1 and 2). The photometer parameters and observing techniques were described by Kolotilov et al. (1998). We used the following standards for our photometric observations: BD+43°3770 with $U = 11.01$ mag, $B = 10.17$ mag, $V = 9.14$ mag and BS 8079 ($J = 1.00$ mag, $H = 0.18$ mag, $K = -0.05$ mag, $L = -0.28$ mag, $M = -0.06$ mag). The observational errors in the optical range do not exceed 0.05 mag if the star is brighter than 15 mag but can reach 0.2 mag if the star's magnitude is about 17 mag. In the infrared (IR), the errors are not larger than 0.03 mag in $JHKL$ and 0.05 mag in M.

We carried out several sets of B-band photometric observations with a CCD camera at the 0.6-m telescope of the Crimean Station to look for rapid brightness variations of V407 Cyg; a number of $BVRI$ estimates were also obtained (cf. Table 3).

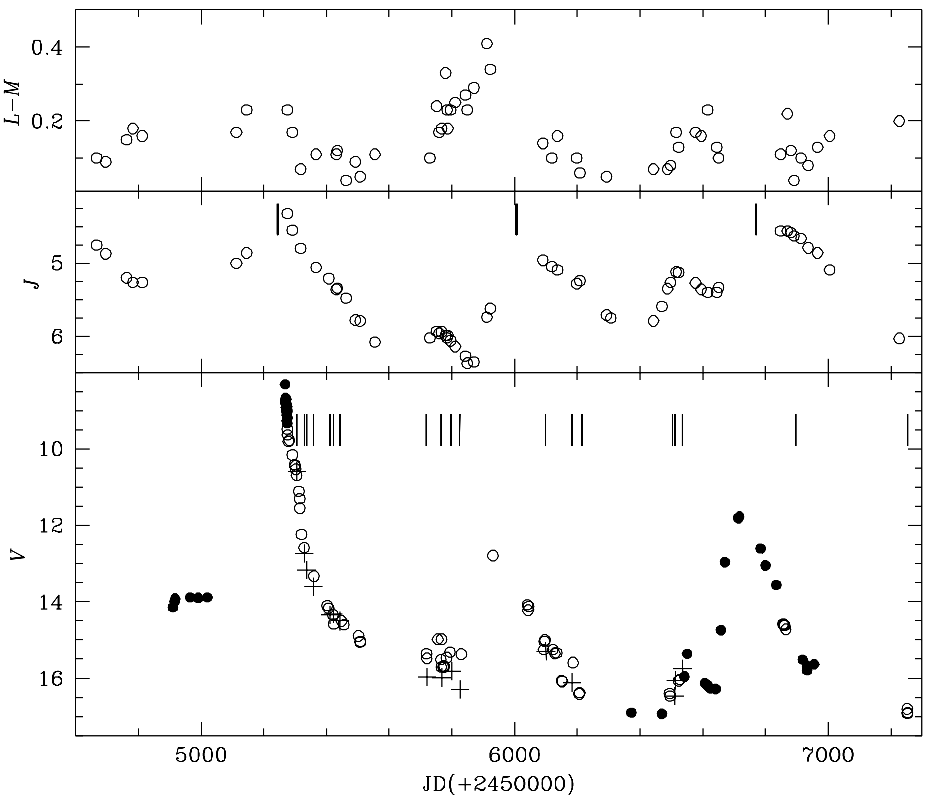

Fig. 1. The V, J light curves and $L - M$ color curve for V407 Cyg. Open circles are our photometric observations; dots denote AAVSO data; crosses are estimates obtained from our spectroscopic observations. The vertical bars above the V-band light curve mark the dates of our spectroscopic observations.

Spectroscopic observations were acquired with the 2.6-m G. A. Shajn reflector of the Crimean Astrophysical Observatory using the SPEM slit spectrograph at the Nasmyth focus (with dispersion about 2 Å/ pixel). We also carried out spectroscopy with the 1.25-m ZTE telescope using a slit spectrograph. The dispersion for these spectra is 5 Å/pixel or 2.3 Å/pixel.

Our observations are shown in Figs. 1 and 2. The dates of the Mira's maxima (marked by vertical bars above the J-band light curve in Fig. 1) were calculated using the ephemeris from Kolotilov et al. (2003). After the RS Oph-type outburst, the ephemeris does not match the maxima observed in the IR light curves any longer (see Fig. 1). The maxima in the visible range are displaced by the same amount ($\sim 0.15P$).

After the outburst in 2010, a step that occurs on the ascending branch of the light curves in the $BVJHKLM$ filters also changed dramatically. It became deeper and wider.

The infrared maximum occurs $\sim 0.15P$ after the visual maximum (Fig. 1). The distance to V407 Cyg, estimated from the P–L relation, is nearly 2.4 kpc.

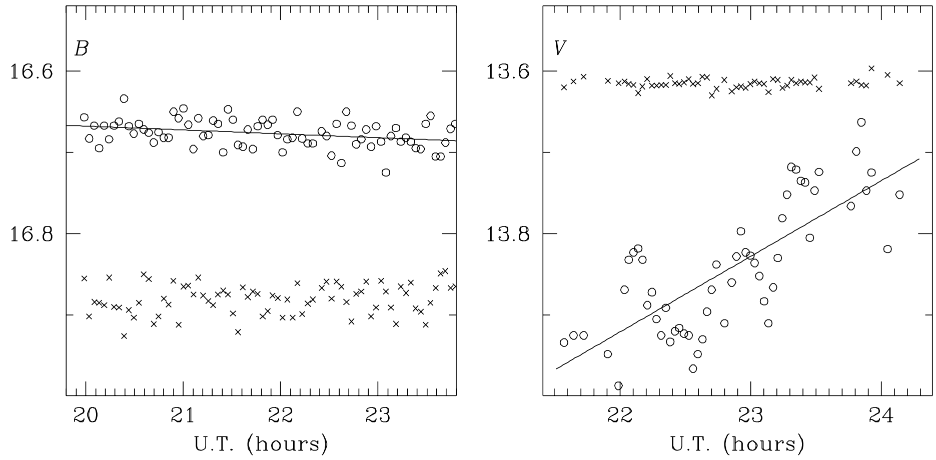

Fig. 2. Rapid brightness variations of V407 Cyg (open circles) after its RS Oph-type outburst (left panel, 2014.07.22) and before it (right panel, 2002.06.20, Kolotilov et al. 2003). Crosses denote the measurements of the comparison stars.

Table 1. UBV photometry of V407 Cyg.

JD(2450000+)	U	B	V	JD(2450000+)	U	B	V
2797	14.64	14.07	12.34	5452			14.56
2823		13.90	11.95	5455	15.69	15.58	14.60
2874	14.37	13.67	11.71	5502	16.32	15.90	14.89
2905	14.46	14.15	12.31	5507	16.48	15.89	15.05
2915	14.76	14.20	12.45	5508	16.10	15.92	15.03
2967	15.06	14.61	13.20	5719		16.45	15.36
2974	15.56	14.97	13.79	5720	16.92	16.70	15.48
5275	10.22	10.28	9.48	5755			14.98
5276	10.50	10.45	9.63	5765			15.51
5279	10.50	10.58	9.81	5766			15.71
5281	10.61	10.68	9.77	5767		16.82	14.98
5291	10.96	11.09	10.16	5783		16.60	15.46
5298	11.26	11.38	10.41	5794		17.03	15.31
5300	11.35	11.39	10.45	5830		16.91	15.37
5302	11.48	11.51	10.53	5931		15.06	12.79
5305	11.65	11.66	10.69	6041			14.08
5312	12.14	12.05	11.11	6043		16.32	14.22
5314	12.32	12.29	11.30	6045		16.32	14.12
5315		12.53	11.55	6093			15.25
5320	12.84	12.88	12.23	6095		16.56	15.03
5360	14.65	14.47	13.33	6097		16.78	15.00
5421	15.70	15.36	14.34	6122		16.80	15.25
5423	15.42	15.59	14.58	6128		17.31	15.35
5445	15.93		14.30	6134		16.87	15.34
5448	16.14	15.98	14.50	6186			15.59

3. DISCUSSION

The early spectral evolution of V407 Cyg was discussed in Munari et al. (2011), Shore et al. (2011, 2012), and Esipov et al. (2013). Now the system demonstrates very strong periodic continuum variations ($\Delta V \approx 5.5$ mag) due to Mira domination

Table 2. *JHKLM* photometry of V407 Cyg.

JD(2450000+)	J	H	K	L	M	JD(2450000+)	J	H	K	L	M
2619.190	5.38	4.09	3.33	2.35	2.22	5759.487	5.96	4.64	3.74	2.58	2.41
2636.176	5.34	4.08	3.35	2.33	2.26	5767.475	5.94	4.66	3.74	2.56	2.38
2809.507	4.94	3.74	3.09	2.16	2.00	5779.481	5.99	4.65	3.77	2.61	2.28
2832.498	4.70	3.53	2.94	2.06	1.88	5784.517	6.02	4.70	3.78	2.59	2.36
2841.474	4.62	3.44	2.87	2.03	1.91	5786.465	5.99	4.69	3.79	2.60	2.42
2869.510	4.48	3.28	2.72	1.92	1.83	5795.453	6.06	4.72	3.82	2.61	2.38
2890.464	4.42	3.22	2.64	1.87	1.78	5810.396	6.14	4.81	3.87	2.66	2.41
2926.343	4.37	3.14	2.54	1.82	1.80	5843.323	6.27	4.91	3.96	2.71	2.44
2984.186	4.38	3.12	2.51	1.78	1.73	5849.335	6.37	4.95	4.01	2.75	2.52
3599.507	4.61	3.52	2.81	1.81	1.64	5870.268	6.35	4.96	4.02	2.76	2.47
3657.261	4.44	3.27	2.63	1.73	1.50	5911.193	5.74	4.52	3.70	2.53	2.12
3923.481	4.89	3.57	2.88	2.07	1.76	5922.130	5.62	4.37	3.61	2.56	2.22
3953.513	5.03	3.67	2.96	2.04	1.94	6090.505	4.96	3.62	3.00	2.18	2.04
3964.439	5.07	3.75	3.00	2.07	2.01	6118.522	5.05	3.68	3.03	2.19	2.09
4021.292	5.36	3.94	3.16	2.23	2.11	6136.510	5.09	3.70	3.03	2.20	2.04
4285.489	4.84	3.64	2.93	1.95	1.76	6198.304	5.28	3.85	3.14	2.25	2.15
4311.518	5.03	3.79	3.04	2.03	1.86	6208.355	5.24	3.85	3.10	2.20	2.14
4338.415	4.95	3.78	3.03	2.01	1.82	6293.145	5.71	4.21	3.39	2.38	2.33
4370.368	4.70	3.51	2.86	1.86	1.56	6307.150	5.75	4.28	3.43	2.42	2.53
4427.232	4.46	3.26	2.59	1.74	1.51	6442.508	5.79	4.32	3.44	2.37	2.30
4666.489	4.75	3.47	2.76	1.88	1.78	6469.510	5.59	4.17	3.30	2.25	2.26
4695.450	4.87	3.56	2.88	1.94	1.85	6487.530	5.35	4.02	3.23	2.18	2.11
4762.290	5.20	3.82	3.07	2.10	1.95	6497.482	5.26	3.97	3.18	2.16	2.08
4782.208	5.26	3.88	3.13	2.18	2.00	6515.492	5.12	3.88	3.12	2.10	1.93
4812.173	5.26	3.87	3.17	2.21	2.05	6523.410	5.13	3.85	3.12	2.10	1.97
5112.312	5.00	3.83	3.09	2.03	1.86	6577.334	5.27	4.00	3.18	2.14	1.97
5145.257	4.86	3.69	2.98	1.93	1.70	6595.263	5.36	4.02	3.26	2.17	2.01
5275.596	4.32	3.26	2.64	1.80	1.57	6616.269	5.40	4.10	3.29	2.22	1.99
5291.562	4.55	3.38	2.78	1.99	1.82	6645.205	5.40	4.10	3.28	2.20	2.07
5317.560	4.80	3.50	2.90	2.15	2.08	6651.184	5.33	4.07	3.28	2.19	2.09
5366.522	5.06	3.73	3.04	2.23	2.12	6848.529	4.56	3.24	2.60	1.76	1.65
5407.421	5.21	3.78	3.12	2.31	2.30	6870.502	4.56	3.24	2.60	1.76	1.54
5431.420	5.36	3.94	3.25	2.38	2.27	6881.469	4.58	3.27	2.60	1.76	1.64
5434.449	5.34	3.99	3.24	2.41	2.29	6891.508	4.63	3.30	2.64	1.82	1.78
5462.372	5.48	4.09	3.34	2.42	2.38	6913.379	4.66	3.30	2.64	1.79	1.69
5492.328	5.78	4.32	3.53	2.53	2.44	6936.404	4.79	3.38	2.72	1.86	1.78
5507.267	5.79	4.38	3.55	2.56	2.51	6966.294	4.86	3.49	2.80	1.90	1.77
5554.156	6.08	4.63	3.75	2.70	2.59	7005.191	5.09	3.70	2.97	2.02	1.86
5729.502	6.02	4.68	3.78	2.61	2.51	7227.473	6.03	4.69	3.79	2.60	2.40
5751.523	5.93	4.65	3.74	2.56	2.32						

in the visual range. The spectral type of the cool component near its minimum (2015.08.21) obtained from the TiO 7100 Å band is near M7, but the very strong VO band near 7500 Å is consistent with a later spectral type.

The behavior of fluxes in different emission lines is presented in Fig. 3. After the summer of 2010, it is consistent with a simple recombination model (with the hot component turned off). According to diagnostics of the [O III], [Ne III] forbidden lines, the electron temperature decreased from 13 000 K (2011.07.24) to 10 000 K (2013.08.09), with constant electron density, $n_e \approx 5 \times 10^6$ cm^{-3}. In 2015, the object was too faint in the B and V bands, and we could obtain only the red part of its spectrum. In 2012–2015, the fluxes in [N II] lines decreased insufficiently in contrast to Hα. Now the spectrum is sufficiently similar to a typical passive-state

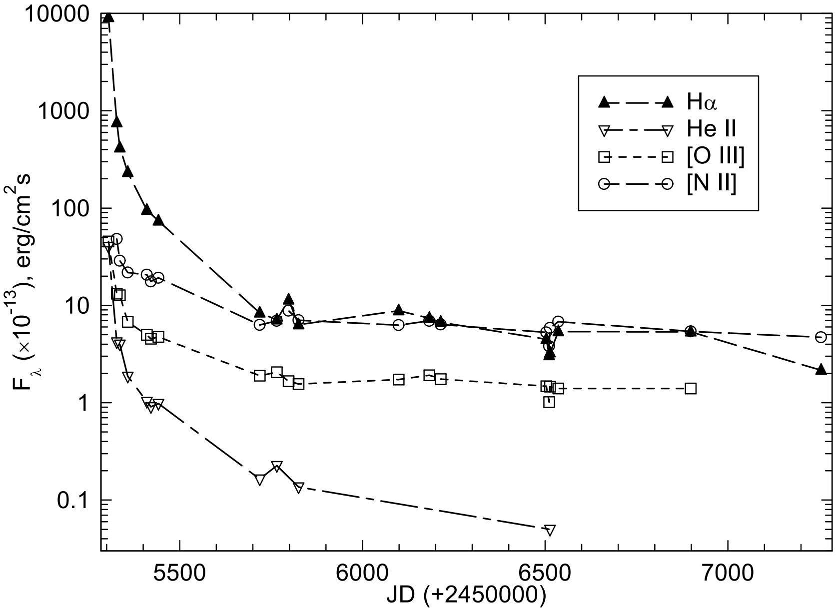

Fig. 3. Fluxes in the Hα, He II 4686 Å, [O III] 5007 Å, and [N II] 6584 Å emission lines.

spectrum (cf. Kolotilov et al. 1998).

Fast brightness variations is a phenomenon observed only for several symbiotic stars (Sokoloski 2001). Even in these systems, fast brightness variations sometimes disappear. The nature of this type of variability in symbiotic systems is usually related to the existence of an accretion disk around a hot subdwarf. Another possibility is magnetic accretion on a hot subdwarf (Sokoloski 2001).

The first observations of flickering (short time-scale aperiodic optical-brightness variations) for V407 Cyg were obtained in 2002 (Kolotilov et al. 2003). They reveal the existence of fast (with a period of 20–30 min) brightness variations with an amplitude of $\Delta V \approx 0.1 - 0.2$ mag. Shugarov et al. (2007) analyzed flickering of V407 Cyg during different pulsation phases of its Mira component. They demonstrated that fast brightness variations were prominent near the Mira's minimum and invisible near its maximum.

We began our search for the flickering effect two months after the star's RS Oph-type outburst. Regularly (since 2010) we tried to register the resumption of optical flickering (see Fig. 2). Now we can conclude that no variations of amplitude above 0.05 mag in B band could be detected. It is a typical situation when flickering disappears during outbursts in symbiotic stars (for CH Cyg, see Stoyanov et al. 2012 and for RS Oph, Zamanov et al. 2006). Worters et al. (2007) detected the resumption of optical flickering in the system of RS Oph on day 241 of the outburst.

During our observations, the Mira was at different phases of its pulsation, but flickering has not been detected so far. According to our spectroscopic observations, V407 Cyg now is on the way to its passive state. Therefore, recovering of its fast brightness variability can take many years.

Table 3. *BVRI* photometry of V407 Cyg (the dates when we attempted to detect flickering are marked with asterisks).

JD(2450000+)	*B*	*V*	*R*	*I*	JD(2450000+)	*B*	*V*	*R*	*I*
5329*	13.76	12.58	9.91	6.92	6523	17.89	16.06	13.28	
5402*	15.35	14.10			6857	16.60	14.58	11.95	8.12
5406	15.36	14.16	10.98	7.53	6858*	16.65	14.60	11.95	8.15
5772	17.02	15.70	13.46	9.74	6859	16.67	14.61	11.97	8.1
5774*	17.06	15.67	13.49	9.72	6860*	16.67			
5775*	17.10	15.71	13.49	9.76	6861*	16.68	14.62	11.97	
6149*	17.57				6496	18.0	16.46	13.81	9.56
6150*	17.63	16.06	13.56	9.59	6865	16.72	14.72	12.04	
6152	17.57	16.08	13.61	9.59	6527	17.76	16.03	13.28	
6206	17.76	16.41	13.99	9.86	7252	18.3	16.8	14.23	10.17
6207*	17.8	16.38	14.02	9.87	7253	18.3	16.92	14.20	10.15
6494*	18.1	16.4	13.9	9.57	7254	18.3	16.9	14.20	10.16

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