Peculiar Red Nova V838 Mon: Accretion and Interaction in a Wide Binary System after Explosion of Its Companion

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Abstract. We report the results of recent multicolor photometry and medium resolution spectroscopy of V838 Mon taken in 2007 – 2008. In the eclipse-like event in December 2006, the hot B3V type companion disappeared. The event accompanied by strengthening emission [FeII]/FeII lines in the spectra. We explain this event as the formation of temporal short-lived accretion disc around the hot companion. Later, in February 2007 the hot star reappeared in its full brightness, but disappeared again for a long time since September 2007. This is the engulf of B3V companion by expanding remnant of 2002 outburst. We assume that the thick accretion disc has formed around B type companion which is moving now inside the envelope of the cool star. There is some evidence of heating this disc and/or cool star envelope. We estimated the radius of expanding cool remnant in December, 2006 of about 150 A.U. or 30000 $R_\odot$.

V838 Mon is a representative of a new enigmatic class of astrophysical objects known as stars exploding into cool supergiants (Munari et al. 2002), or so-called red novae. Other members of this class are V4332 Sgr and V1006/7 in the galaxy M31. In such explosions, the matter of a few solar masses is erupted into space, and therefore the ejected material does not reach optically thin state. Before the outburst, V838 Mon was a system of two B3V stars (Goranskij et al. 2007). The brightest star exploded in January 2002 and reached $M_V = -10^m$ in the light maximum having K – M type spectrum. The exploded star was young and chemically unevolved (Kipper & Skoda 2007), and it was brighter than its companion by factor of 1.36 ± 0.03 (Goranskij et al. 2007). Before the outburst, the exploded star had the reduced luminosity relative to normal B3V stars, its $M_V = +1^m.5$.

The nature of such explosions is still unclear. Hypothesis of star collisions and merging has still heavy grounds (Socker & Tylenda 2007). In the beginning of the XX century, this hypothesis was used to explain the explosions of classical novae (Flammarion & Gore 1907), and historically failed. In the case of V838 Mon, it needs a third star unseen in the spectral energy distributions. Lynch et al. (2004) concluded that the exploded star was G or F star evolved at least to the AGB stage, and perhaps beyond. They report presence of Sr II and possibly other s-process elements. They did not take into account binarity and based on the old unconfirmed information on the progenitor. Moreover, exploded post-AGB stars like FG Sge and V4334 Sgr are carbon-rich objects.
The remnants of V838 Mon and V4332 Sgr are oxygen-rich stars (Lynch et al. 2004; Barsukova et al. 2007). On the contrary, Goranskij & Barsukova (2007) suppose that the explosion was caused by ignition of hydrogen in the centrum of a young massive star in the stage of gravitational contraction.

The expanding remnant of the outburst passes through an unique way of evolution. Evans et al. (2002) using the 0.8 – 2.5 µm spectra of V838 Mon obtained on 2002 October 29 reported that the star became the coolest supergiant ever observed, it might be the first known L type supergiant. The $UBVRI$ photometry by Goranskij & Barsukova (2007) and Crause et al. (2005) along with the spectroscopy by Munari et al. (2005) confirmed that the remnant was so cool that its radiation did not reach $UBV$ bands, the only hot companion radiation filled these bands. A total of the remnant’s flux was radiated in the red and infrared (IR) range. Due to this fact, one can estimate correctly the contribution of the exploded star in the common pre-outburst light of the binary in the $B$ and $V$ bands. The blackbody temperature of the remnant in the Autumn, 2002 was of about 1200K, and increased to 1500K in 2004 (Goranskij et al. 2007). Pavlenko et al. (2007) estimated radius of the expanding remnant as large as 6000 $R_\odot$ in November 2002, and this enormous value did not contradict to the expansion velocity of 145 km/s of stellar photosphere measured by Geballe et al. (2007) using high resolution IR spectra of first overtone CO bands at 2.3 µm. Heating of such a large structure suggests that the energy source...
may have a chemical nature – burning of hydrogen, carbon and metals in oxygen, what means in the simple sense a very large conflagration in the body of the supergiant star.

At last, in the end of 2004 the signs of interaction of ejected material with the hot B3V companion became obvious, first, as rapid strengthening of iron forbidden lines in the blue region of the spectrum (Barsukova et al. 2006). Later, in 2006 very strong emission-line spectrum flared up with numerous lines of [FeII]/FeII, Balmer, and [O I]. The flare of emissions was accompanied with the temporal disappearance of the hot B3V type companion from the spectrum, which looked like eclipse-like event in the short wavelength photometric bands (Goranskij 2006). The largest amplitude of light decay was of about 1$^m$.7 in $U$ band, and the decay was imperceptible in $I_C$ band. The duration of event was of about 70 days with the light minimum at 2006 December 10, JD 2454080 (Munari et al. 2007). The early suggestions on the nature of this event were the following: eclipse by a dust cloud, or by a blob thrown away in the earlier outburst; grazing eclipse by the outer layers of the cool star (Munari et al. 2007). Bond (2006) suggested that this was the engulf of B3V companion by the expanding cool remnant. But Bond’s suggestion contradicted to reappearance of B3V star in February 2007.

In 2007 and 2008, we continued photometric and spectroscopic monitoring of V838 Mon. The multicolor $UBV_{C}I_{C}$ photometry was taken by V. Goranskij and E. Barsukova with SAO 1-m Zeiss reflector. Additional photometry in Johnson $BVR_{J}I_{J}$ bands was taken by A. Zharova with 60-cm Zeiss reflector.
Figure 3. Spectra of V838 Mon in blue and green range contain supergiant M9 and a different amount of B3V companion light.

Figure 4. The spectrum of reflected light of B3V companion of SAI Crimean Station. Our collection of photometry may be examined in detail with Java-compatible browser in the Internet, the tables of observations are located there in the ASCII file (cf. Goranskij et al. (2008)). The columns of the table contain the following data: JD hel.– 2400000, V, B, U, R, I, remark to observation. Figure 1 shows B and R<sub>C</sub> band light curves of V838 Mon taken in the seasons of 2004 – 2008.

On 2007 September 18 in the beginning of the following 2007/2008 observational season, we found V838 Mon in the deep minimum again, and this state continued all this season. The new decay began probably just after rebrightening in February 2007. The brightness in the new deep state was not constant. It increased gradually in all the bands including long wavelength bands R and I (see e.g. Fig. 1 in B and R). Therefore, we do not treat this gradual increase as new reappearance of B3V type companion. Rapid night-to-night variations in the short wavelength bands are superimposed on the trend of such a rebrightening. The biggest rapid decay was by 0<sup>m</sup>.21 in V and 0<sup>m</sup>.43 in B between the nights of 27 and 28 March, 2008 (JD 2454553 – 2454554) with no rapid change in R and I bands.

The spectrum of V838 Mon taken by Munari et al. (2007) on 2006 December 16 does not show any traces of B3V type companion in the blue region. Therefore we can measure the spectral energy distribution of B3V star in UBVRI bands as the light lost in the eclipse-like event. This estimate gives us a possibility to measure energy distribution of the exploded star using archive pre-outburst
observations of progenitor binary in $BVRI$ bands. Earlier we obtained only correct $B$ and $V$ magnitudes of exploded star using Autumn 2002 $BV$ photometry of V838 Mon which did not contain the light of cool remnant in these bands (Goranskij et al., 2007). $R$ and $I$ magnitudes were contaminated by the light of the cool remnant. In the Figure 2 we draw the spectral energy distribution (SED) of progenitor B3V + B3V binary (upper black line), that one of common light measured by us after the optical outburst, in Autumn 2002 (JD 2452530) (black line with the red and IR excess), that one of the B3V companion light lost in eclipse-like event (grey line) and SED of exploded star calculated as a flux difference of progenitor binary and flux of B3V companion lost in the eclipse (medium black line). The SED of exploded star is compared with the SED of HD 29763 (B3V), and this fit is excellent. SEDs of V838 Mon are corrected for interstellar absorption using color excess $E(B-V) = 0^m.77$, and SED of HD 29763 using $E(B-V) = 0^m.07$ (Goranskij, 2004). Additionally, we see good agreement of Autumn 2002 SED of B3V companion in UBV bands with the SED of its lost light in eclipse-like event.

New spectral observations were taken with the Russian 6-m telescope BTA and the SCORPIO spectrograph. The dates of spectra are marked in the Fig. 1 as vertical line segments, modern observations are pointed out by digits 1–3. We have two spectra taken on 2007 February 15 (1) and 2008 February 6 (3) covering the blue region of 3930–5700 $\AA$ with the resolution of 4.5 $\AA$, and one spectrum taken on 2007 November 18 (2) covering all the optical range between 3800 and 7570 $\AA$ with the resolution of 13 $\AA$. Spectral observations taken with BTA were accompanied by $V$ band photometry.

Unfortunately we did not take spectra during the eclipse-like event in the middle of December, 2006 due to bad weather. Munari et al. (2007) have obtained good spectrum in the light minimum on 2006 December 26 using WHT (their Fig. 3). These authors traced successively the changes in the spectrum before, in, and after eclipse-like event (their Fig. 4). The observations showed that the emission-line spectrum gradually strengthened independently on the event, in spite of disappearance of B3V star, the main ionization and excitation source. The maximum intensity of this spectrum was reached in February, 2007, just after the recovery of B3V star. Our spectrum taken on 2007 February 15 is shown in Figure 3 (light grey). In this spectrum, strong emissions of [Fe II], Fe II and H$_\beta$ predominate. In the spectrum taken on 2008 February 6 (dark grey), these emission lines are essentialy depressed, and they are about 10 times fainter than in February 2007. H$_\beta$ emission is not seen or very faint. In this spectrum, very weak blue continuum of B3V type companion is also present along with wide and intense Balmer absorptions and weak HeI absorption lines (Figure 4). This weak blue spectrum seems not reddened and may be reflected on the cloudy structure.

Otherwise, no traces of B3V star are seen in the spectrum with the lower resolution of 13 $\AA$ taken 3 month earlier, on 2007 November 18. There are weak [FeII] emission lines and H$_\alpha$ emission. The spectrum of cool companion looks like that one in 2005 January 15, where the molecular bands were identified by Barsukova et al. (2007). This spectrum of V838 Mon is compared in Figure 5 with the spectrum of another red nova, V4332 Sgr taken with 6-m BTA telescope on 2007 June 18 with the same spectral range and resolution. In 2007, cool
companions of these novae reached equal temperature, and their spectra looked very similar. We classified them as M9 type supergiants. This similarity was the result of evolution from the opposite directions: the remnant of V838 Mon warmed up, but the remnant of V4332 Sgr cooled down during its two-year decay by $2^m$ in $V$ band. Note, that spectral emission-line components in these novae have principally different nature. This is the radiation of hot ionized gas in V838 Mon, and the radiation of cool rarefied atomic and molecular gas in V4332 Sgr.

We assume that the December 2006 light decay was due to formation of highly inclined temporal accretion disc around B3V companion. The rim of this disc might overlap the light of the hot star only for a terrestrial observer, but did not block the ionizing radiation in the both directions above and below the disc plane. The primordial disc might be formed from the ejected matter moving ahead of expanding photosphere of the cool remnant and infalling into the Roche lobe of the B3V star with acceleration, and it was rapidly heated by the hot companion, and dissipated.

Photometry shows that the ejected matter of 2002 outburst riched B3V companion for 1750 days and then formed the accretion disc around it. Using the photosphere expansion velocity of 145 km/s measured by Geballe et al. (2007) we can estimate the radius of the cool remnant to be equal of 30000 $R_\odot$ in December 2006. The distance between companions in this wide system before the explosion of one of them was of about 150 A.U. Assuming the circular orbit, we have raw count of ~500 years for the orbital period of such a binary, and the orbital velocity of about 10 km/s.

In the following season of 2007/2008 B3V type companion disappeared for a long time. This phenomenon seems to be real engulf of the B3V companion by the expanding cool star. Now, B3V star is moving under the remnant’s photosphere. The rapid light variability in the short wavelength bands, reflected light of the blue companion, and presence of forbidden FeII lines in the spectrum suggest that B3V star is seen through cloudy structure of the external shell with an inner void. Such a model was calculated by Lynch et al. (2007). Presence of forbidden lines in the spectrum confirms that the small part of the ionizing radiation of B3V star leaks out through cloudy shell.
Another consequence of engulf is gradual increase of brightness in all the photometric bands which began in the late 2006, before the eclipse-like event. The rise of brightness continues during 2007/2008 season. The increasing excess has red energy distribution. We assume that new thick accretion disc is accumulating around B3V star which moves inside the envelope of cool remnant. The excess of radiation may be explained by heating of this disc and surrounding matter by B3V type star. It is hard to predict further development of the V838 Mon system. The red novae are binary systems, and this fact is well established. The evolution of red nova remnants may pass through individual ways depending on the structure of the systems and the dimensions of their orbits.

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