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Luminous Red Nova Phenomenon

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Abstract. Luminous red novae form a new type of variable stars which explode turning into cool supergiants. We present a review of the main physical properties of the objects of this class. Most of them are mergers in close binary systems, but some of them may have a different nature.

Luminous red novae (LRN) are the stars erupting into cool supergiants (Munari et al. 2002). In other words, they are the stars with cool explosions. Along with the giant eruptions of massive stars, such as the Great eruption of η Car, they form a new class called ILOTs, namely, Intermediate Luminosity Optical Transients. At the outburst maximum, such stars become the brightest in their galaxies, only supernovae exceeded them by luminosity. At maximum, red novae have a definitely red color, K–M spectra of supergiants, evolving to more and more later spectral subclass, and they don't pass a nebular phase characteristic of classical novae. Great interest to red novae is attracted by the assumption on their origin as a result of merging in close binary systems. In a unique case for the first time, merging process in a contact binary system was observed directly. It was succeeded in the research of LRN V1309 Sco pre-explosion condition on OGLE data (Tylenda et al. 2011). During several years, its light curves looked like a double wave with the period of $1\overset{\mathrm{d}}{.}4$. Such curves are usually observed in W UMa-type binaries. To 2007 the curve turned into a single wave, the period decrease was also detected. At first, the star gradually became more brighter and then there was a deep brightness decay by 1^{m} for approximately 1 year before the outburst. It is believed that this brightening was an evidence of forming a common envelope in the system, tidally interaction and spiraling of components towards each other, finished by the merger of stars' cores and a central explosion. The brightness decay was due to a pre-outburst adiabatic expansion of the massive envelope. When the radiation of the explosion comes out to the star surface, its area turns out to be so large, that it cannot be heated up to a high temperature, and that is why the star has low temperature and K–M type spectrum.

V4332 Sgr (1994) is the first well studied red nova in our Galaxy. It is definitely a Galactic halo or an old disk object having Galactic latitude of $-9°$, its distance is uncertain. Based on photographic archives, the brightness of a progenitor increased before the outburst by $2\overset{\mathrm{m}}{.}5$ in the *R* band, and a rate of the rise was the same as in V1309 Sco. However, pre-outburst fading was not detected, probably it was missed. The amplitude of the outburst was 9^{m}, and the spectrum at the maximum was identified as K3–4 III–I by Martini et al. (1999).

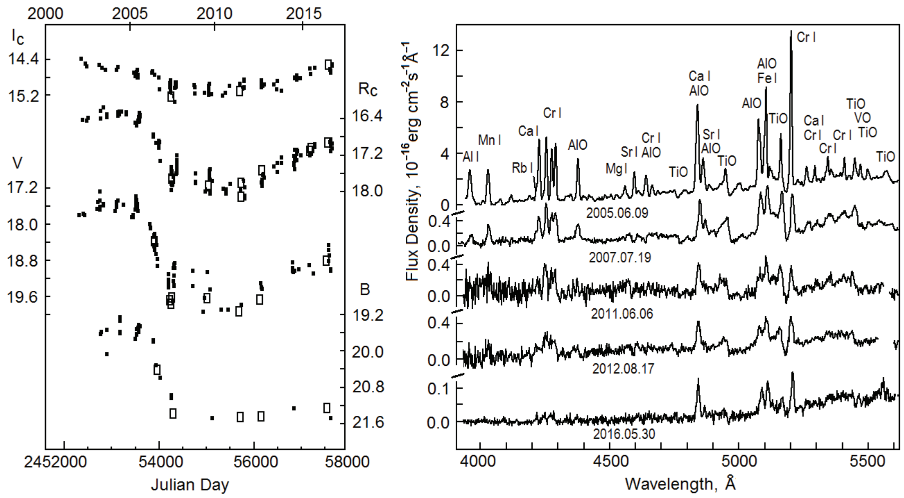

Figure 1. Evolution of the V4332 Sgr remnant. Light curves. BTA data are marked out by light rectangles (left). Spectra in the blue region, and line identification (right).

Information on the progenitor is based on the Palomar Sky Survey plates taken in the 1950s, and additionally on the Moscow SAI plate collection and DSS archives related to 1980s (Barsukova et al. 2014). The spectral energy distribution of the progenitor indicates the presence of a hot star whose radiation disappeared after the outburst. The cool giant with its red continuum remained. That is, there was the cool star in the system, which did not take part in the outburst. It suggests a scenario in which V4332 Sgr was a multiple system, and the blue component was a contact system. In this case, the merger of the binary components could lead to the cold explosion, and the remnant, the cool supergiant was destructed dynamically under an impact of the third component, the red giant.

The spectroscopy of V4332 Sgr at the BTA/SCORPIO began in 2005 and continued till 2016. There are two sources in the spectra of the remnant, a red continuum of an M-type star and an emission of a cool rarefied nebula, which shines in the molecular and neutral metal lines. In the nebular spectrum, the intercombination line of Mg I 4571 Å was present. It is known to be formed in a massive, extended and rarefied gas cloud. The dominant feature of the light curves in the optical range is the brightness decline, which has occurred between 2006 and 2008 (Figure 1, left). The brightness in the *B*-band dropped by 2^{m}. We demonstrated that this decreasing is due to reducing of the cool star temperature by 1000 K. Weakening of emission line fluxes of the nebula between 2003 and 2012 was more gradual and dramatic. They decreased by 30 times, as seen in the spectra in the blue region (Figure 1, right). This gas cloud is undoubtedly the explosion remnant of the 1994 outburst, and the process we observed is radiative cooling. Since 2012, the remnant becomes more bright again. We associate this brightening with the approach of the remnant debris moving on an elliptical orbit with the M-type star, and with the accretion of them onto this star.

An approximation of energy distributions of the remnant reveals the radiation excesses in the shortwave and longwave sites. It is known that the red excess is related with the dust, and the blue excess is related with a faint star. The faint star is of about

$21^{\mathrm{m}}\!.6$ in the *B*-band. Its light is predominating in this filter over the light of the M giant which left this range (Figure 1, left). It may be either a member of the system, a stellar remnant of the explosion, or otherwise it is a field star.

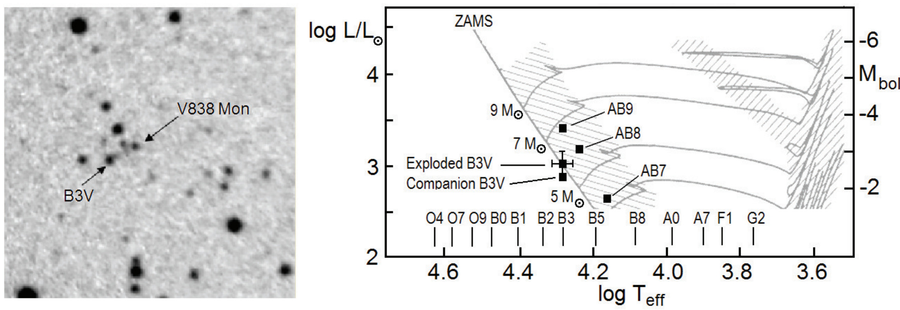

Figure 2. Progenitor of V838 Mon. *Left*: Archive photo taken in 1977. *Right*: Location of V838 Mon components and other cluster members on the Luminosity–Temperature Diagram. Evolutionary tracks from Schaller et al. (1992). ZAMS is zero age main sequence.

V838 Mon (2002) is the most famous red nova. Due to its bright and brilliant light echo, we know the accurate distance to it, 6.1±0.6 kpc, based on the echo polarimetry. Many researchers consider it as a prototype of this class of astrophysical objects. However, there are no proofs that it is a merger. It was the most luminous star in our Galaxy when it brightened up to an absolute magnitude $M_V = -9^{\mathrm{m}}$ in a series of three outbursts and then rapidly evolved through the extremely cool "brown" supergiant phase. We explained the triple outburst as pulsation shock waves going out onto the surface. But there was another hypothesis explaining it as an event in which a star swallowed its planets (Retter et al. 2007). We succeeded in taking the spectrum already in the first peak of the outburst at SAO 1-m Zeiss telescope, the spectrum was identified as K0 I. Near the second peak of the outburst, a high resolution spectrum was taken with the BTA/NES (Kipper et al. 2004). We determined a normal chemical composition that was confirmed from the analysis of the high-resolution spectrum. There was a strong Li I 6708 Å line with P Cyg profile in the spectra. This element is an intermediate unit of thermonuclear fusion, and it occurs in very young stars.

We compared the photometry of the outburst remnant and the archival data from Moscow and Sonneberg plate collections. As a result, we establish that the progenitor was a blue star. In addition, it was a binary system consisted of two stars with the same spectral type B3V. We showed that the exploded B3V star was brighter by 36% than its companion. After the outburst, the weaker B3V star has remained visible. V838 Mon is known to be a member of the cluster which consists of three B-type stars else (Afşar & Bond 2007). The cluster is immersed in a dust nebula, which reflected the light of the echo, and in 2015 we found this nebula illuminated by the remnant in the near infrared. Archival images of V838 Mon suggest that its components are unusual stars of the low luminosity; the progenitor binary is looked weaker than the single B3V cluster star AB9 (Figure 2, left). The exploded B3V star was located exactly on the ZAMS. The survived B3V star is located 0.35 mag lower than ZAMS. One can see that three other cluster members have already evolved from ZAMS. There are some indications against merger in this system: (1) there was no source of a third light before the explosion, on the contrary, it was a deficiency of the luminosity in this pair; (2) the survived B3V component did not take part in explosion, it was engulfed by the cool supergiant remnant in 5 years; (3) there was no brightening in the light curve connected to the formation of the common envelope. Some theorists did not exclude a possible instability of a stellar core at the end of a gravitational collapse of a young star. The instability may lead to a slow shock and an expansion of the envelope.

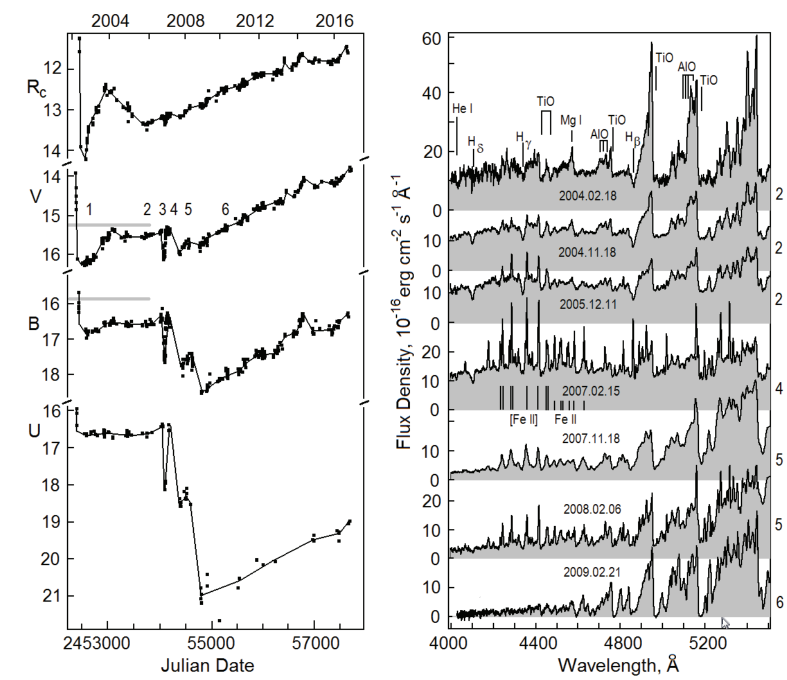

Figure 3. Evolution of the V838 Mon remnant. *Left*: Photometry. Gray lines show the brightness level of the progenitor. Different stages of the evolution are marked by numbers. *Right*: Spectra in the blue region taken with the BTA.

There were many evidences of the interaction of the hot B3V star with the cool remnant, which approached each other, and later the hot star was engulfed by the remnant (1 in Figure 3). There, numbers point to different phases of the remnant evolution. In the "brown" L-supergiant phase 1, its radiation was absent in the *B* and *V* bands, so we saw only the hot B3V companion. The difference between the progenitor's light and the companion's light is equal to the contribution of the exploded star in the common light. Later in the phase 2 (in Figure 3), the hot companion was seen in the spectra against a background of the molecular spectrum of the remnant. Evidently, the companion did not participate in the explosion. To the end of 2005, the iron forbidden lines [Fe II] strengthened in the spectrum due to the approach of the hot star to the cool remnant. In the eclipse-like event 3 (Figure 3) in December 2006 – January 2007, the hot B3V companion totally disappeared, and appeared again in February 2007 (event 4). At this event, a strong permitted emission-line spectrum was excited by the hot star in a dence surrounding medium. This event gives another chance to measure the contribution of the hot star already in all photometric bands. Then the hot star plunged into the remnant scanning its shell. In episode 5 (Figure 3) it was moving during at least 200 days in a void under an outer layer which absorbes its light and the emission spectrum by about six times. Since October 2008, the hot star finally disappeared (6 in Figure 3), so at the time there was a zero signal from it in the depths of the M-type remnant's molecular TiO bands. Later we observed only the M-type remnant, which gradually became brighter and hotter. The light curve in the *R* band suggests that this process is independent on the presence of the hot star inside the remnant, the process has begun in late 2005 (Figure 3).

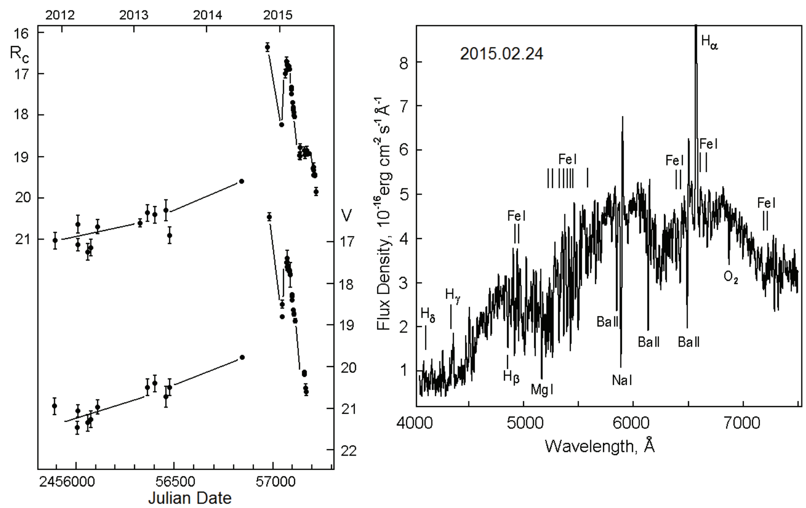

Figure 4. Light curves of LRN 2015 in M101 in the *R* and *V* bands (left). Spectrum of this red nova taken at the second maximum (right).

An example of a large mass merger is a transient discovered in the galaxy M101 in February 2015 and identified as a luminous red nova by a BTA/SCORPIO spectrum (Goranskij et al. 2016a). On the base of the archive data including amateur images on websites, it was established that its brightness was gradually increasing before the outburst (Figure 4, left). This is an evidence of the formation of a common envelope in a binary system before the merger. The event is associated with an OB association in a spiral branch. The progenitor of this system came from the region of the massive blue star sequence and evolved upwards keeping a high temperature. The archives also revealed an outburst three months before its discovery, the red nova was the second outburst with a typical red spectrum (Figure 4, right). The previous outburst suggests that a shock wave is forming in a massive merger when the stars' cores are merged. The star reached a visual absolute magnitude $-12^{\text{m}}.75$ at the first outburst, and $-11^{\text{m}}.65$ in the second one. At the end of 2015, the star disappeared off the optical range beyond the detection limit of the 6m telescope. However, in January 2016 the remnant was detected in the *JHK* bands with the new 2.5 m telescope of the SAI Caucasus Mountain Observatory in the "brown" supergiant stage. Its luminosity at a wavelength of 2.2 microns turned out to be 30 times higher than that of the "brown" supergiant in the system of V838 Mon, and its temperature was then only 1750 K.

In the research of the SN 2015bh/NGC 2770, we suppose that the scenario of a red nova in a massive merger may be broken by a core collapse of an evolved companion (Goranskij et al. 2016b). The progenitor of SN 2015bh was an LBV star with a strong Hα emission and $M_V = -9^{\text{m}}$. The star was at the Humphries-Davidson limit, lost the matter, displayed a large-amplitude variability and an explosion event up to $M_V = -12^{\text{m}}$ (PTF13evf). Since late 2014 it gradually raised in the brightness up to $M_V = -15^{\text{m}}$

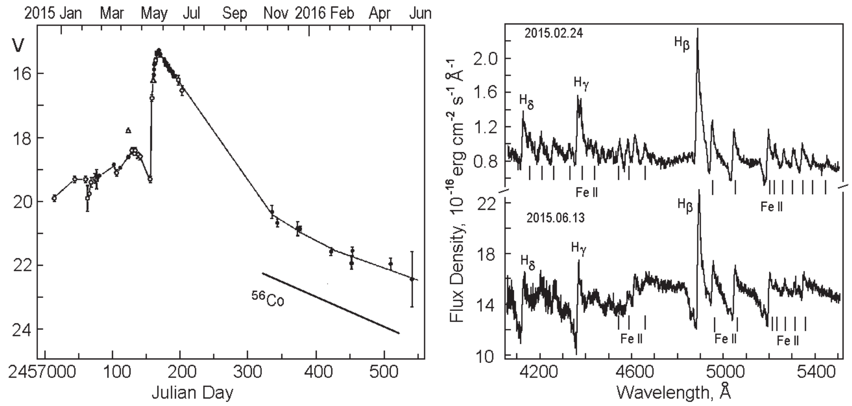

Figure 5. Light curve of SN 2015bh in the V band (left). Spectra of SN 2015bh in the phase of a common envelope formation (right top), and in the phase of a supernova (right bottom).

what is typical for the common envelope formation, and this raise was finished with a $1^{\rm m}$ decline probably due to the adiabatic expansion of the envelope. Later in May 2015, the star had the sudden outburst up to $M_V = -18^{\rm m}$ (Figure 5, left). The explosion had some signs of a supernova: the ejecta with a velocity of 18000 km s^{-1}, the secondary decay corresponding to a radioactive ^{56}Co decay. However, the spectra were specific and reminded spectra of Williams Fe II class novae (Figure 5, right). We supposed that the ejected matter was transferred earlier from the less evolved massive companion in the merger process. Therefore, this event we call as a failed luminous red nova.

Studying red novae we met several evidences of youth of V 838 Mon, and may be its outburst was due to a gravitational collapse of a hydrogen core. On the other hand, we deal with a core collapse of an evolved star in the last case. So, we passed the way from collapse to collapse only among the luminous red novae.

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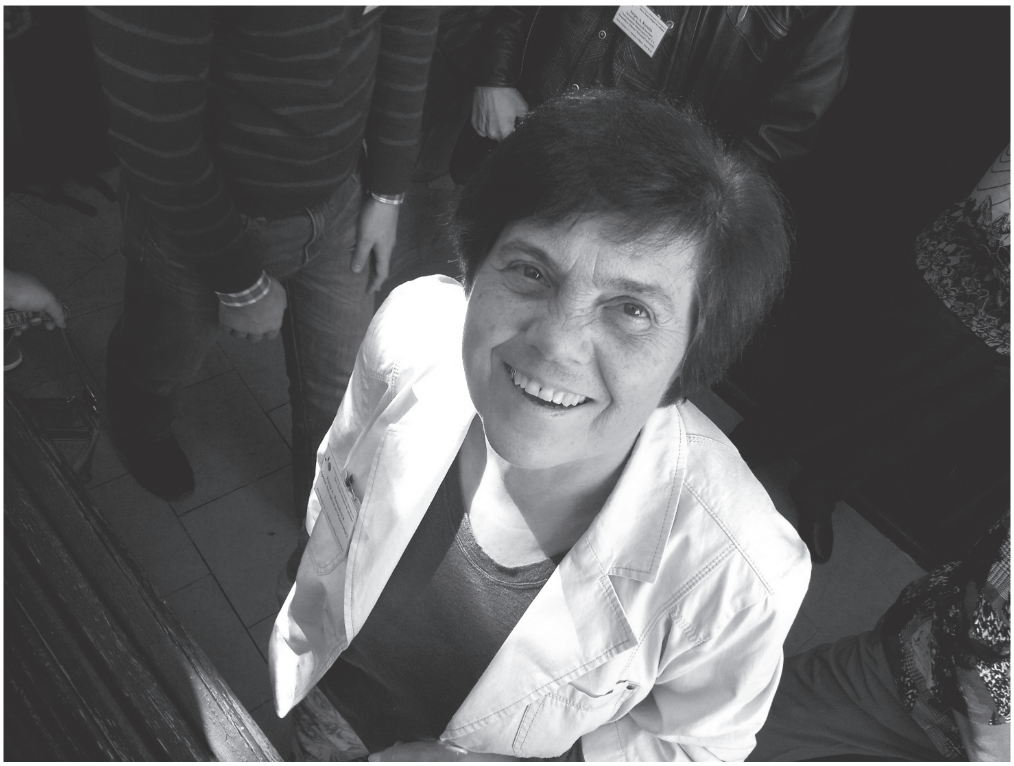

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