Luminous Red Nova 2015 in the Galaxy M 101

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ABSTRACT

We present the results of the study of the red nova PSN J14021678 +5426205 based on the observations carried out with the Russian 6-m telescope (BTA) along with other telescopes of SAO RAS and SAI MSU. To investigate the nova progenitor, we used the data from the Digital Sky Survey and amateur photos available on the internet. In the period between April 1993 and July 2014, the brightness of the progenitor gradually increased by 2.20 magnitudes in the V band. At the peak of the first outburst in mid-November of 2014, the star reached an absolute visual magnitude of −12.75 but was discovered later, in February 2015, in a repeated outburst at the absolute magnitude of −11.65. The amplitude of the outburst was minimum among the red novae, only 5.6 in the V band. The Hα emission line and the continuum of a cool supergiant with a gradually decreasing surface temperature were observed in the spectra. Such process is typical for red novae, although the object under study showed extreme parameters: maximum luminosity, maximum outburst duration, minimum outburst amplitude, unusual shape of the light curve. This event is interpreted as a massive OB star system components’ merging accompanied by the formation of a common envelope and then the expansion of this envelope with minimal energy losses.

Key words: novae, cataclysmic variables—binaries: close—stars: individual: PSN J14021678+5426205

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Luminous red novae are representatives of a sparsely populated class of exploding variables which is known since 1988 when such a star exploded in the M31 galaxy. This was Red Variable = McD 88 No.1 = M31 V1006/7 (Rich et al. 1989; Sharov 1993). Among the Galactic red novae, V4332 Sgr, V838 Mon, and V1309 Sco are the most thoroughly studied. According to the archival data, the Galactic novae CK Vul = N Vul 1670 (Hajduk et al. 2013; Kamiński et al. 2015), V1148 Sgr = N Sgr 1943 (Mayall 1949), and OGLE-2002-BLG-360 (Tylenda et al. 2013) are supposed to belong to this class. The most precise phenomenological definition for the stars of this type is given by Munari et al. (2002) — Stars Erupting into Cool Supergiants (SECS). Such “cool explosions” were not predicted theoretically. The absolute magnitudes of red novae exceed those of classical novae in maximum brightness reaching $M_V = -12^m$ and $M_R = -12^m3$ (OT 2006-1 in M 85, Kulkarni et al. (2007); Pastorello et al. (2007), and PTF10fqs in M 99, Kasliwal et al. (2011)) and fall into the interval of magnitudes between classical novae and supernovae ($-17^m < M_V < -8^m$, Berger et al. (2009)). Red novae together with other optical transients which magnitudes are within this interval are called Supernova (SN) Impostors, or Intermediate Luminosity Red Transients (ILRT).

When the majority of researchers explain the physical nature of red novae, they prefer a merger of components in a binary or multiple system (Soker & Tylenda 2003, 2006) and call them “mergers”. The observations of the star V1309 Sco using the OGLE archive data confirmed this hypothesis (Tylenda et al. 2011). Six years prior to the outburst, this star was a W UMa-type contact binary with an orbital period of 1.44 days. The process of merging of the components that ended with the red nova outburst was directly observed in this system. It is supposed by Barsukova et al. (2014) that the red nova phenomenon is associated with the energy burst in the stellar core after which the envelope passes into expansion stage similar to the adiabatic one (with minimum energy loss); the nova outburst occurs with a delay of a year or even several years. In order to explain the phenomenon of the red nova V4332 Sgr, the hypothesis of a “slow shock” which forces a stellar photosphere to expand has been suggested by Martini et al. (1999). This shock can be caused both by merging of the stellar cores of a binary system and by an instability of the core of a single star. V838 Mon is an example of a red nova not associated with the component merging (Goranski et al. 2014). It is a wide detached system containing the B3 V-type component (Wagner et al. 2003) which did not participate in the outburst of 2002 but was later engulfed by the explosion remnant. Thus, there can be objects of different nature among red novae.
remnants of some red novae contain dust and cool rarified gas emitting in atomic and molecular lines.

The most valuable information on the red nova phenomenon can be obtained using the archival data and studying the stars, for which the accurate distances are possible to determine. Such objects can be situated in the nearby galaxies, however one usually needs large telescopes to observe them.

In the first half of 2015, two red novae have been discovered in the nearby galaxies: MASTER J004207.99+405501.1 in M 31 = M31N 2015-01a (Shumkov et al. 2015; Williams et al. 2015; Kurtenkov et al. 2015) and PSN J14021678+5426205 or Luminous Red Nova, LRN 2015 in M 101 (Gerke et al. 2015; Cao et al. 2015; Vinko et al. 2015; Kelly et al. 2015; Goranskij et al. 2015). M31N 2015-01a is similar to V1006/7 in M 31 at the brightness maximum $V = 15^{m}4$ and with the absolute magnitude $M_{V} = −9^{m}$, although, its outburst duration was twice shorter than that of V1006/7. The LRN 2015 in M 101 reached the absolute magnitude at the maximum of $M_{V} = −12^{m}75$, and demonstrated unusual properties not observed earlier in other red novae. It is a SN impostor in its absolute magnitude at the brightness maximum. Four actual SNe of I and II types were observed earlier in M 101: 1909A, 1951H, 1970G, and 2011fe. The present paper is dedicated to the investigation of the LRN in M 101.

The luminous red nova PSN J14021678+5426205 in M 101 was discovered by C. D. Vîntde-vară1 at the Bârlad Astronomical Observatory in Romania on February 10, 2015. According to our measurements of the CCD frame in which it was discovered, the star brightness was 17$^{m}50$ in $V$ band. According to Cao et al. (2015), on November 10, 2014 the star was brighter, 16$^{m}36$, in the $R$ filter. However, the observations on January 19, 2015 by Gerke et al. (2015) showed the star was considerably fainter, $R = 18^{m}23$ and $V = 18^{m}80$. These observations proved that the brighter outburst took place in November 2014, after which the star brightness notably weakened. The red nova was discovered in the repeated outburst, the brightness maximum of which was in February 2015.

2 STUDY OF THE NOVA PROGENITOR WITH ARCHIVAL DATA

The earliest published SDSS sky survey observations of the progenitor of the LRN outburst in M 101 refer to March 2003. Stellar magnitudes in the $ugriz$ system relative to Vega in these filters are $21.1 ± 0.3$, $21.6 ± 0.3$, $21.0 ± 0.3$, $20.6 ± 0.3$, and $21.9 ± 0.9$ respectively (Kelly et al. 2015). One can determine the value $V = 21^{m}2$ and color indices $B − V = 0^{m}4$ and $V − R_c = 0^{m}3$ in the

1 http://www.rochesterastronomy.org/snimages/ (2016)
Johnson–Cousins system using the interpolation method. According to the archival data of the Large Binocular Telescope (LBT) from the middle of 2012 to the middle of 2014 the brightness of the nova progenitor star increased from $20^m97$ to $19^m78$ in the $V$ band, and from $20^m69$ to $19^m59$ in the $R$ band (Gerke et al. 2015).

We found only one faint image of the star in the DSS sky survey archives on the photo from the Palomar sky survey POSS-II taken with the Palomar 48-inch Schmidt telescope on April 15, 1993 using the Kodak IIIaJ emulsion. The maximum sensibility of this emulsion lies between the $B$ and $V$ bands. We estimate the brightness of the star at that moment as $22^m0 \pm 0.3$ in $V$ band. To conduct the photometric measurements we created a local standard in the vicinity of the LRN in M 101 with a reference to the standard near the blazar S4 0954+65 (Raiteri et al. 1999), and then we extended it to weak magnitudes. The map in Fig. 1 shows our standard stars and Table 1 contains their coordinates and values.

One can find the image of the LRN progenitor in many amateur color photos of the galaxy M 101 on the internet. Note that they contain color information (see Flickr.com, for example). So, the blue color of the star is seen in the images of 2011–2013. One of the authors of this paper, Terry Hancock, carried out his observations using the Astro-Tech 250-mm Ritchey–Chrétien...
Table 1. Coordinates and $BVR$ magnitudes of the comparison stars in the vicinity of the LRN in M 101

| Star No. | RA, hh mm ss | Dec, dd mm ss | $B$, mag | $V$, mag | $R_c$, mag |
|----------|--------------|---------------|----------|----------|------------|
| 1        | 14 02 19.12  | 54 26 57.2    | 16.044   | 15.030   | 14.276     |
|          | ±0.019       | ±0.018        | ±0.019   |          |            |
| 2        | 14 02 16.94  | 54 27 29.2    | 18.006   | 16.879   | 16.024     |
|          | ±0.02        | ±0.02         | ±0.02    |          |            |
| 3        | 14 02 13.94  | 54 26 34.2    | 20.135   | 19.555   | 19.158     |
|          | ±0.033       | ±0.034        | ±0.055   |          |            |
| 4        | 14 02 36.42  | 54 26 46.9    | 16.996   | 16.100   | 15.476     |
|          | ±0.018       | ±0.018        | ±0.045   |          |            |
| 5        | 14 02 32.88  | 54 26 52.0    | 17.496   | 16.460   | 15.684     |
|          | ±0.014       | ±0.012        | ±0.039   |          |            |

We converted color images in other formats into the BITMAP format and measured separate RGB components with the reference to the standard $R_c$, $V$, and $B$ respectively. The accuracy of measurements kept within the limits of $0''$.2–$0''.3. We also conducted the photometry of the images by K. Itagaki, the references to which were given in the Central Bureau for Astronomical Telegrams (CBAT)\(^2\) of the International Astronomical Union. The observations by Itagaki confirm the first and brightest star outburst in November 2014 and its further weakening by $2''$.5 prior to the second outburst. These estimates of the brightness and color indices are in good agreement with the SDSS and LBT observations.

Table 2 shows the results of our measurements of the Digital Sky Survey (DSS) images, the CBAT, and the amateur ones in the period from 1993 to 2015, before the discovery, and the published data referring to this time period. The light curves in the $BVR_c$ filters prior to and during the outburst, the color indices $B - V$ and $V - R_c$ are presented in Fig. 2 and 3. They may be studied in detail interactively with a Java-compatible browser\(^3\).

These estimates show that the star brightness prior to the outburst was gradually increasing from a level of $22''.0$ in the $V$ filter (detected in 1993 in the DSS) up to $19''.78$ $V$, stated with the LBT in summer 2014. The data did not make it possible to determine if there was a faster outburst in November 2014.

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\(^2\) http://www.cbat.eps.harvard.edu/unconf/tocp.html

\(^3\) http://jet.sao.ru/~goray/psn1492.htm

(2016)
brightness variability during this brightness increase. Deviations of some measurements from the central trend do not exceed $3\sigma$, as a rule. As it is known, the orbital variability was observed in the V1309 Sco red nova system during the brightness increase prior to the outburst (Tylenda et al. 2011). In the case of the LRN in M 101, there is unique information indicating that the pre-outburst brightness increase happened with holding the surface temperature of the star constant. The color indices stayed almost constant at $(B - V) \approx 0.2$ and $(V - R_c) \approx 0.2$. At that time, the star moved upward along the main sequence of hot massive supergiants in the “color–magnitude” diagram.
Figure 3. Color-index curves $B - V$ (top) and $V - R_c$ (bottom) constructed for the LRN in M 101 using the observations in 2012–2015.

$V - (B - V)$ (see Fig. 4). The diagram for normal stars in this figure is plotted based on the photometry by Grammer & Humphreys (2013) conducted with the Hubble Space Telescope. The data are taken for the 9492_12 field which is situated closest to the site of outburst of the LRN in M 101. The red nova is located outside, in 36″ from its eastern border. The earliest measurements of LRN colors in 2012 show an evident deviation of the star toward the red region of the main sequence OB-supergiant branch; this can indicate the ending of the main sequence stage and the beginning of evolution into red giant of the brighter and more massive component of the system. In 2012, the position of the star in the diagram was close to the position of the well-known massive eclipsing system of high luminosity Hα19 in the galaxy M 33 denoted with the circle in Fig. 4. The orbital period of Hα19 is equal to $33^{d}108$, the absolute magnitude is $M_V = -7^{m}6$. Mass estimations of the Hα19 system components are 40–50 $M_\odot$ (Goranskij & Barsukova 2011). This is a semidetached system with so high mass transfer rate that on the surface of its hot component there is a bright spot associated with the circulation in the envelope of this component of a gas from an accretion flow of its companion and with the transfer of material from the depth of the envelope to the surface. The contribution of this spot can be seen in the light curve. The earliest
Figure 4. Shift of the LRN progenitor in M 101 in the “color–absolute magnitude” diagram before the outburst in 2014. (1) Brightness level of the star in 1993 according to the data from POSS-II. The rectangles correspond to its position in the diagram in 2012 (2); in 2013 (3); in the middle of 2014 (4) (Gerke et al. 2015). The asterisks denote the position of the star at the stop of brightness decline in May 2015 (5) and in the middle of June 2015 (6). The circle denotes the position of the massive semidetached system Hα19 from the galaxy M 33 with a high mass transfer rate in the phase of components merging. The diagram was constructed for the 9492_12 field in the galaxy M 101.

observations of the LRN in M 101 in 1993 detected the star at $M_V = -7^m 1$. It is weaker than Hα19 by $0^m 5$ only. Probably, the progenitor of the LRN in M 101 was a similar massive system with the mass a bit smaller than that of the Hα19 components.

3 PRESENT-DAY PHOTOMETRY

The photometric observations of the LRN in M 101 in the repeated outburst were carried out with several telescopes of SAO RAS and SAI MSU in the $BVR_c$ system from February 15 to June 13, 2015. Table 3 shows the photometry results, the data on telescopes and instruments used are given in the last column. We made the photometric reference to the comparison stars (see Table 1). The mean measurement accuracy at the level of 16–18$^m$ was $0^m 01$, at the level of 19–20$^m$ it was about $0^m 02–0^m 04$, but at the level weaker than 21$^m$ it could be up to $0^m 1$.
Table 2. Pre-discovery observations of the LRN/M101

| Date            | JD 2400000 + | B, mag | V, mag | R, mag | Source                           |
|-----------------|--------------|--------|--------|--------|----------------------------------|
| Apr 15, 1993    | 49093        | –      | 22.0   | –      | POSS II, Kodak IIIaJ             |
| Mar 07–10, 2003 | 52707        | 21.6   | 21.2   | 20.90  | SDSS, ATel 7062^1(1)             |
| Nov 25, 2011    | 55891        | 20.95  | 20.95  | 21.03  | R. Pece, Flickr.com              |
| Feb 14–27, 2012 | 56007        | 21.74  | 21.47  | 21.13  | D. Hartmann, Astrobin^2          |
| May 10, 2012    | 56058        | 21.12  | 21.35  | 21.30  | O. Bryzgalov, Flickr.com         |
| May 26, 2012*   | 56074        | 21.55  | 21.27  | 21.20  | O. Bryzgalov, Flickr.com         |
| Jan–Jun 2012    | 56109        | 21.30  | 20.97  | 20.69  | ATel 7069, LBT                   |
| Feb 01, 2013    | 56324        | –      | –      | 20.60  | ATel 7070, PTF                   |
| Apr 2013        | 56360        | 20.48  | 20.50  | 20.36  | Z. Orbanic, Flickr.com^4         |
| Jun 11, 2013    | 56435        | 20.95  | 20.73  | 20.30  | S. Furlong, Flickr.com           |
| Jun 29, 2013    | 56473        | 21.0   | 20.5   | 20.9   | C. Frenzi, Flickr.com            |
| Jun-Jul 2014    | 56839        | 20.02  | 19.78  | 19.59  | ATel 7069, LBT                   |
| Nov 10, 2014    | 56971        | –      | –      | 16.36  | ATel 7070, PTF                   |
| Nov 13, 2014    | 56975        | –      | 16.40  | –      | K. Itagaki, CBAT^5               |
| Jan 19, 2015    | 57042        | 20.20  | 18.80  | 18.23  | ATel 7069, LBT                   |
| Jan 20, 2015    | 57043        | –      | 18.50  | –      | K. Itagaki, CBAT^5               |
| Feb 10, 2015    | 57064.4      | –      | 17.50  | –      | C. D. Vintevara, discovery       |

^1(1) the SDSS-values in the ugriz system (Vega) recounted to the BVR system.

^2(2) http://www.astrobin.com/users/DetlefHartmann/

^3(3) the 25-cm Ritchey-Chretien astrograph the CCD QHY9M Monochrome (Kodak KAF 8300 chip), 24-hour exposure.

^4(4) Uploaded on June 30, 2014. Approximate time of imaging, April 2013, can be determined from the brightness of SN 2011fe.

^5(5) http://www.cbat.eps.harvard.edu/unconf/followups/31492616875426205.html.

* Misprint in Astrophys. Bull. V.71, 82. This date is corrected.

According to the observations of the LRN in M 101 carried out before its discovery, during the first outburst the star reached 16.4 in the V filter at the time JD 2456975.3 and 16.36 in the Rc filter at the time JD 2456971. This corresponds to the absolute magnitudes $M_V \approx -12.75$ and $M_R \approx -12.80$. As it is seen in the light curve (Fig. 2), the star brightness in the V filter at the maximum of the first outburst was higher by at least 1.1 than at the maximum of the second outburst. The same difference between the values in the outbursts turned out to be significantly smaller in the Rc filter, 0.4. From the observations in the first maximum, we cannot estimate the stellar temperature in the luminosity peak, as the response curves of the amateur instruments are not known exactly; it is obvious, however, that the star was hotter in the peak of the first outburst than in the peak of the second one. At the maximum of the second outburst, the color indices of the star considerably increased compared to those before the outburst at the end of the gradual brightness increase in summer 2014. The $B - V$ color index increased from 0.2 to 1.3, and the $V - R_c$ increased from 0.2 to 0.9 (Fig. 3). In the Rc band, the star was observed more intense than in other bands and the time of the secondary maximum can be reliably estimated as JD 2457069. At that, the color indices already were: $B - V = 1.36 \pm 0.03$ and $V - R_c = 0.87 \pm 0.01$ and corresponded to the spectral class K2I–K3I. The brightness decrease in the $R_c$ filter in the period of JD 2457080–2457132 continued with an average velocity of 0.041 per day; and then stopped for (2016)
Table 3. The photometry of the LRN in M 101

| JD⊙ 2400000 + | B | V | R_ι | Remarks | JD⊙ 2400000 + | B | V | R_ι | Remarks |
|--------------|---|---|------|--------|--------------|---|---|------|--------|
| 57069.3642   | – | 17.664 | 16.776 | KG | 57105.5199 | – | – | 18.009 | SO |
| 57069.4892   | 18.862 | 17.666 | 16.784 | KG | 57106.3933 | – | 18.901 | 18.041 | SO |
| 57071.5603   | 18.988 | 17.649 | 16.771 | SO | 57133.2957 | – | – | 18.977 | SO |
| 57071.5784   | 18.988 | 17.655 | 16.776 | SO | 57135.5288 | – | – | 18.991 | SO |
| 57072.5776   | 19.034 | 17.667 | 16.803 | SO | 57136.4051 | – | – | 18.785 | SO |
| 57072.5894   | – | 17.663 | 16.793 | SO | 57138.3710 | – | – | 18.859 | SO |
| 57074.5439   | 19.086 | 17.708 | 16.825 | KG | 57160.3074 | – | – | 18.952 | SO |
| 57075.5213   | 19.045 | 17.704 | 16.815 | SO | 57161.3043 | – | – | 18.915 | SO |
| 57075.5326   | – | 17.669 | 16.808 | SO | 57162.3288 | – | – | 18.853 | SO |
| 57076.5682   | 19.082 | 17.687 | 16.815 | SO | 57163.3073 | – | – | 18.928 | SO |
| 57076.5790   | – | 17.690 | 16.808 | SO | 57164.3126 | 21.87 | 20.075 | 18.928 | SO |
| 57077.5862   | 19.066 | 17.690 | 16.826 | SO | 57165.3147 | 21.70 | 20.160 | 18.954 | SO |
| 57077.5793   | – | 17.699 | – | SO | 57166.3898 | – | 20.158 | 18.967 | SO |
| 57078.3967   | 19.088 | 17.698 | 16.827 | SO | 57182.3213 | – | – | 19.291 | SO |
| 57078.4095   | – | 17.708 | 16.829 | SO | 57183.2694 | – | – | 19.334 | CR |
| 57078.4318   | 19.037 | 17.691 | 16.816 | 6m | 57183.3529 | – | – | 19.233 | SO |
| 57081.5474   | 19.086 | 17.784 | 16.901 | KG | 57184.34 | – | 20.72 | 19.267 | SO |
| 57081.5639   | – | 17.796 | 16.896 | KG | 57185.29 | 22.38 | 20.55 | 19.278 | SO |
| 57090.4413   | 19.832 | 18.268 | 17.325 | SO | 57185.3360 | – | – | 19.352 | 6m |
| 57090.4629   | 18.239 | 17.322 | SO | 57185.3373 | – | – | 19.313 | 6m |
| 57091.5366   | 19.814 | 18.305 | 17.375 | SO | 57185.3382 | – | – | 19.316 | 6m |
| 57091.5485   | – | 18.307 | 17.380 | SO | 57186.2240 | – | – | 19.332 | CR |
| 57092.5591   | 19.856 | 18.399 | 17.489 | SO | 57186.3192 | – | – | 19.330 | SO |
| 57097.3654   | 20.070 | 18.633 | 17.696 | SO | 57187.2308 | – | – | 19.374 | CR |
| 57100.3466   | 20.241 | 18.742 | 17.881 | SO | 57187.3792 | – | – | 19.365 | SO |
| 57104.3638   | – | 17.931 | – | SO | 57188.4180 | – | – | 19.332 | CR |
| 57111.5364   | 20.070 | 18.633 | 17.696 | SO | 57187.2308 | – | – | 19.374 | CR |

6m — 6-m BTA telescope and the SCORPIO focal reducer with BVR_ι filters (Afanasiev & Moiseev 2005).
KG — 2.5-m telescope of the SAI MSU Caucasian Mountain Observatory with the CCD-cameras Proline KAF 39000 and NBI 2k2k with BVR_ι filters.
SO — 1-m Zeiss telescope of SAO RAS and the UBVR_ι-c filters with the CCD EEV 42-40.
CR — 0.6-m Zeiss telescope of the Crimean laboratory of SAI MSU and the UBVR_ι-R_j I_j-photometer with the CCD camera Apogee-47p.

Table 4. Spectra of the LRN in M 101 obtained with the BTA/SCORPIO∗)

| Date       | JD⊙ 2400000 + | λ, Å | R_ι, Å | Grism | ∆v_r, km s⁻¹ | S/N |
|------------|--------------|------|--------|-------|--------------|-----|
| Feb 24, 2015 | 57078.4531 | 4052–5848 | 5.0 | VPHG1200G | +5.0 | 180 |
| Feb 24, 2015 | 57078.5829 | 5751–7498 | 5.0 | VPHG1200R | +4.9 | 50 |
| Jun 11, 2015 | 57185.3412 | 4000–7919 | 14 | VPHG500G | –14.9 | 12 |

∗) Misprint in Astrophys. Bull. V.71, 82. Dates are corrected.

about 30 days at the brightness level of 18.0 m R_ι. Later, the brightness decline continued with the velocity twice lower. In the V and B filters, the brightness decline rates were notably higher, 0.044 and 0.055 per day respectively. The brightness decline stopping or slowing down took place in these filters too, although, the data available do not allow us to observe them so thoroughly as in the R filter. In the “color–magnitude” diagram, the position of the star at the moment of the brightness stop is marked with an asterisk and the number 5. At that time, the star was a red supergiant with the luminosity exceeding that one of the extreme red supergiant from the field 9492_12 in the galaxy M 101 (Grammer & Humphreys 2013) by 1.7. After the brightness decrease stopped, the star went on evolving toward red supergiants and in June 2015 reached the position marked with
an asterisk and the number 6 in Fig. 4. Multicolor photometry conducted on June 11 yields the following values: $V = 20^m55; B - V = 1^m83; V - R_c = 1^m27$.

Based on the photometry results, the star can be reliably classified as a luminous red nova, although, its light curve has a specific feature distinguishing it from other red novae: the repeated outburst. Repeated outbursts were also observed in the red nova V838 Mon, however, with a considerably smaller amplitude. Those outbursts were explained by shock waves coming out to the surface, which were caused by pulsations Barsukova et al. (2002); Goranskij et al. (2007), or swallowing of three massive planets by an expanding red giant Retter & Marom (2003).

4 SPECTROSCOPY

Spectroscopic observations of medium resolution were carried out at SAO RAS on the 6-m BTA telescope with the SCORPIO focal reducer (Afanasiev & Moiseev 2005) on February 24 and June 11, 2015. Table 4 contains the main data on the obtained spectra: date, Julian day, total exposure in seconds, spectral range, spectral resolution, grism, heliocentric correction, and the signal-to-noise ratio in the continuum in the middle of the spectral range. The reduction of the spectra was conducted in the OS Linux using the ESO MIDAS medium and the LONG context (for the long-slit spectra). The spectra obtained on June 11, 2015 were distorted by fringes at wavelengths $\lambda > 6800$ Å. To compensate the fringes, we took exposures with the shift of the star along the slit and, as a result of subtracting the shifted spectra, the fringes were removed. As the signal-to-noise ratio in the total spectrum was too small, we smoothed the data using moving average method with an averaging interval of 14 Å, which was equal to the actual spectral resolution. To convert the spectra into energy units, we used the spectrophotometric standards HZ 44 and GRW +70°5824 by Oke (1990), and simultaneous photometric observations. In digitized form, the spectra are available on the internet.4 In the $R_c$ light curve (Fig. 5), the times of the spectral observations are denoted as follow: near the maximum of the second outburst and at the brightness decline which followed after its stop.

The whole spectrum obtained on February 24, 2015 is shown in Fig. 6, where the strongest lines are identified. Figure 7 shows the fragments of this spectrum with identification of the weaker lines. The continuum of the cool star predominates in the spectrum. From the collection of spectra by Jacoby et al. (1984), the star HD 1069 (K2 I) approximates the energy distribution of the LRN well. The $H\alpha$ line is asymmetric, fully in emission with the intensity maximum at a velocity of

4 http://jet.sao.ru/~bars/spectra/psn1402/
Figure 5. Light curve of the LRN in M 101 in the $R_c$ band constructed for the second outburst. The times of taking the BTA/SCORPIO spectra are noted as Sp.

Figure 6. Spectrum of the LRN in M 101 obtained on the BTA telescope with the SCORPIO focal reducer on February 24, 2015 near the maximum of the second outburst.

300 km s$^{-1}$, equivalent width $EW = 28$ Å, instrumental-profile corrected FWHM = 535 km s$^{-1}$. Note that the heliocentric velocity of the galaxy M 101 equals to $241 \pm 2$ km s$^{-1}$ (from the NED database). The full width at zero intensity of the line equals to $FWZI = 1370$ km s$^{-1}$. The Ba II $\lambda 6496$ Å line, the Ba II $\lambda 6136, 6142$ Å blend, and the Na I D$_2$D$_1$ $\lambda 5890, 5896$ Å blend have P Cygni profiles, the maximum of the emission intensity in these profiles is at 330 km s$^{-1}$. The minima of absorption components of these lines are located at $-260$ km s$^{-1}$, and the absorption
Figure 7. Fragments of the spectrum of the LRN in M 101 obtained on February 24 and identification of the spectral lines. (a) the depression region $\lambda$4800–5700 Å associated with the absorption of neutral atoms. (b) the H$\alpha$ and Ba II 6496 Å line profiles. (c) the Na I D$_2$D$_1$ and Ba II 5854 Å line profiles.

spread till $\sim$620 km s$^{-1}$. The lines of H$\beta$, Ba II $\lambda$$\lambda$4709, 4957, 5874 Å, Mg I $\lambda$5167, 5173 Å, and numerous Fe I, Ti I, and Cr I lines are observed in the absorption. Radial velocities of these lines are similar to the velocities in absorption components of P Cygni profiles of the strong lines. The set of absorption lines of chemical elements duplicates in detail the set of lines for the red nova V838 Mon in the January 2002 outburst, when its spectrum was classified as K0 I (Goranskii et al. 2016).
Figure 8. Spectrum of the LRN in M 101 obtained on the BTA telescope with the SCORPIO reducer on June 11, 2015. The original spectrum with a small S/N ratio is averaged with the window 14 Å which corresponds to the spectral resolution. The symbol $\bigoplus$ denotes the molecular bands of the terrestrial origin.

The significant difference of the LRN spectrum was the absence of the Li I $\lambda$6708 Å line, which was very strong in the V838 Mon spectrum and having a P Cygni profile.

From the observations carried out in February, the velocity of the envelope expansion of the LRN in M 101 at the peak of the second outburst was 500–540 km s$^{-1}$. By comparison, the velocity of the envelope expansion of V838 Mon at the outburst peak was only 150 km s$^{-1}$, which was 3.5 times less.

Cross-correlation of the LRN/M101 normalized spectrum of February 24, 2015 with the normalized spectra of the supergiants by Jacoby et al. (1984) determines the LRN spectrum in a wider range as K0 I–K5 I (from spectral lines). The strength of the absorption lines in the LRN/M 101 spectrum 4–6 times exceeds the strength of the lines of normal stars. Thus, the depressions of the continuum in the ranges $\lambda$5000–5500 Å and 6100–6400 Å are due to line blanketing.

Figure 8 shows the red nova spectrum obtained on June 11, 2015. This spectrum has resolution three times lower than that one obtained on February and, therefore, the narrow absorption lines are seen not so clearly. Energy distribution in the spectrum shifted toward the long-wave region. It can be best approximated with the distribution of the star HD 13136 (M2 Ib), although, there are no later spectral type stars among the class I luminosity objects for comparison in the collection.
by Jacoby et al. (1984). This is an M1 I–M4 I type star by the color index $B - V = 1^{m}83 \pm 0^{m}10$. The dominant Hα emission with an equivalent width of $\text{EW} = 107$ Å is more symmetric than that in the February spectrum. Its instrumental-profile corrected halfwidth is $\text{FWHM} = 900$ km s$^{-1}$. One can see weak emission wings in this line which determine the full width of $\text{FWZI} = 189$ Å ($8600$ km s$^{-1}$). These wings are probably formed due to Thomson scattering. There may be a weak emission in Hβ and Na I D$_2$D$_1$.

The TiO bands can be noticed in the absorption spectrum, the strongest of which have heads at wavelengths of $\lambda4955, 5450, 5498, 5597, 6159, 6659, 6715, 6817, 7054, 7090, 7126$ Å, and the strongest one—at $\lambda7589$ Å. Atomic absorptions can be hardly seen due to the low resolution, only the Mg I $\lambda5167$–$5183$ Å triplet and some Fe I blends can be identified.

Spectral observations, as well as the photometry, show the energy distribution shift towards the long-wave region. These are low-excitation spectra in which the atomic lines predominate and then the molecular bands appear when the brightness declines. Such development is characteristic of red novae.

5 DISCUSSION OF RESULTS

The LRN in M 101 proves to be a massive young star, the outburst of which took place in the spiral arm of the M 101 galaxy in the region of the hot OB-supergiant association. It is not associated with nebulae. Red novae belong to different types of galaxy populations and show different amplitudes, outburst durations, and shapes of light curves. PTF10fqs emerged in the spiral arm of the M 99 galaxy and was associated with the OB-supergiant association (Kasliwal et al. 2011) as well as the LRN in M 101. The other red nova PTF10acbp Kasliwal et al. (2010) in the spiral galaxy UGC 11973 has exploded on the outskirts of this galaxy and obviously belongs to the young population of the disk. The red nova OT 2006-1 (Kasliwal et al. 2010) in the galaxy M 85, classified as S0, has appeared on the edge of the galaxy and is not evidently associated either with the H II region or with any other star formation region (Ofek et al. 2008). The red nova V838 Mon is associated with the population I of our Galaxy and with the young cluster of B stars (Afşar & Bond 2007). V1006/7 in M 31 and the Galactic red novae V4332 Sgr and V1309 Sco are the objects of a galactic bulge or a thick disk. In the V4332 Sgr system there is an evolved star, a red giant, the radiation from which is detected in energy distribution of the outburst progenitor and also in the spectrum after the outburst (Barsukova et al. 2014). The last three objects are obviously old star systems which got through the long-term evolution process.
The duration of red nova outbursts varies in the range of 58 days for M31N 2015-01a (in the V filter) to 135 days for PTF10fqs/M 99 (in the R filter), if the duration is estimated as a time when the star resides over the level 3\text{m} below the brightness maximum. Red nova outbursts have similar light curves: slow brightness weakening immediately after the maximum ("flat maximum" or "plateau") which ends in the steep fall, although there are some exceptions. The LRN in M 101 exceeds all other red novae in the outburst duration. If we estimate the second outburst duration by this criterion, we obtain 154 days (in the V filter). In case we count from the first outburst in November 2014, which was brighter at the maximum, we obtain the outburst duration longer than 154 days. There are some other special features of the light curve of the LRN in M 101 which become apparent when compared to other red novae. In the second outburst in February 2015, neither flat maximum nor steep fall were observed. Moreover, there was the pause of the brightness decline for 30 days. It is interesting that in the V1309 Sco red nova there were two similar stops of the brightness variation (see fragments 9 and 10 in the light curve in Fig. 1 and 6 by Tylenda et al. (2011)). These stops in the brightness decline can also be associated with the outgoing of the weak shockwaves to the envelope surface. It should be noted that the shape of the V1309 Sco light curve also differed from those of other red novae with the absence of the flat maximum, its brightness decline after the outburst was gradual and with the following slowdown similar to that of the LRN in M 101.

If we take the minimum brightness observed in 1993 (DSS, POSS II) as a reference point for the LRN in M 101, then the outburst amplitude will be equal to 5\text{m}6, which is the lowest amplitude measured for a red nova. Still, in absolute magnitude at the brightness first maximum, \(M_V = -12^{m}75\), it is probably the most luminous red nova. The star OT 2006-1 in the galaxy M 85 reached the same absolute magnitude but in the red spectral domain, \(M_R = -12^{m}7\) (Pastorello et al. 2007), the authors classified it as SN IIp.

The characteristic feature of the light curve of the LRN in M 101 is the gradual increase of brightness before the outburst, which was at least 2\text{m}2. As can be seen from the observations of the red nova V1309 Sco (Tylenda et al. 2011), such an increase in brightness takes place when the common envelope is forming before star merging in a contact system; thus, the event of the LRN in M 101 in 2015 most probably is a merger. In the case of V1309 Sco, the gradual brightness increase stopped a year before the maximum with the abrupt weakening of brightness by 1\text{m}. In the case of the LRN/M 101, the brightness weakening was not detected between the last observation at the brightness increase stage in July 2014 (LBT, Gerke et al. (2015)) and the first observation at the outburst peak on November 10, 2014 (PTF, Cao et al. (2015)). Such brightness weakening
can be expected when the common envelope is expanding in the adiabatic-like mode after the energy burst and the internal impulse at the merging of two stars’ cores. However, we can see the result of such an expansion in the second outburst as a considerable reddening of the color indices. Under the assumption that the common envelope had already formed by July 2014, we estimated the variations of its radius using the Stefan–Boltzmann law and the photometric parameters of the star. The envelope photosphere has increased by eight times approximately from 400 \( R_\odot \) in July 2014 to 3300 \( R_\odot \) in February 2015. In June 2015, it grew up to 4700 \( R_\odot \). These estimates can be inaccurate because of the complex structure of the outburst remnant, however, they prove that the expansion of the envelope photosphere happened in the period between July 2014 and February 2015. The velocities determined from the absorption lines and components in the P Cygni profiles (500–540 km s\(^{-1}\)) do not correspond to such envelope radius variations estimated with the Stefan–Boltzmann method, and 2–3 times exceed these estimates. The similar effect was also observed in V838 Mon.

Taking into account that the expansion velocities of the LRN in M 101 based on the absorption lines and components are three times more than the velocities of the envelope expansion of V838 Mon and V1309 Sco at this stage, the duration of the envelope expansion can be significantly shorter, only several months. As the outburst developed at such great rates, it could be assumed that the shockwave formed after the stars’ cores merging and the energy impulse from the inside, and the first outburst in November 2014 was associated with emerging of this shockwave. It was most probable that thereby some line absorbing layer separated from the envelope and moved at a higher velocity than the photosphere. It is due to the absorption of light in this additional layer both in the LRN in M 101 and in V838 Mon, the absorption spectrum lines are several times stronger than the lines of normal stars of the same spectral type.

After emerging of the shockwave, in December 2014 and January 2015, the envelope expanded with the decrease of energy output, which resulted in the brightness decrease at least by 2\( m \). We assume that this brightness decline is similar to that brightness decrease by 1\( m \) which we observed a year before the maximum in V1309 Sco. It is not excluded that the shockwave formation in the LRN in M 101 is associated with the high mass of this system. The second outburst in February 2015 is due to an arrival of the outburst thermal energy to the surface of the expanding envelope. This scenario can be confirmed or disproved by the dynamic model calculations or by the analysis of the archival data obtained in the period between July 2014 and February 2015.

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6 CONCLUSIONS

The LRN in M 101 has emerged in the spiral galaxy in the region of the OB-star association and is a massive system, the bright component of which leaves the main sequence and shifts toward the red region in the “color-magnitude” diagram. Over 11 years prior to the outburst, the brightness of the system gradually increased by $2^{m}2$. As the brightness increase before the outburst takes place when the components form a common envelope and spiral towards each other, we identify this event with a merger of the components in a massive system.

The star had an unusual light curve with two maxima. It was discovered in the repeated outburst that followed in three months after the first maximum, in which it has reached the visual absolute magnitude $M_V = -12^{m}75$. The star envelope expanded prior to the repeated outburst increasing its radius by a factor of 8. In the maximum of the repeated outburst, the star spectrum was approximately classified as K2 I. We detected the H$\alpha$ emission, strong Ba II and Na I lines with the P Cygni profiles, and the extremely strong absorption in the Fe I, Ti I, Cr I, and Mg I metal lines. Formation of such a spectrum is obviously associated with the ejection of the absorbing layer at the shockwave outgoing during the first outburst. The rates of the absorbing layer expansion are 500–540 km s$^{-1}$. Then within four months after the maximum at the same time with the temperature decrease, the spectral type was changing to about M2 I. The weak TiO molecular bands emerged. The spectral development is typical for the red novae and leaves no doubt about the classification.

The outburst of the LRN in M 101 is a record of the duration among the known red novae (>153 days), of the absolute visual magnitude at the maximum ($M_V = -12^{m}75$), and of the outburst amplitude ($5^{m}6V$) which is the smallest of those ones observed in red novae.

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