New luminous blue variable candidates in the NGC 247 galaxy

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Accepted 2020 July 15. Received 2020 July 15; in original form 2020 February 3

ABSTRACT

We search for luminous blue variable (LBV) stars in galaxies outside the Local Group. Here we present a study of two bright Hα sources in the NGC 247 galaxy. Object j004703.27–204708.4 ($M_V = -9.08 \pm 0.15$ mag) shows the spectral lines typical for well-studied LBV stars: broad and bright emission lines of hydrogen and helium He I with P Cyg profiles, emission lines of iron Fe II, silicon Si II, nitrogen N II and carbon C II, forbidden iron [Fe II] and nitrogen [N II] lines. The variability of the object is $\Delta B = 0.74 \pm 0.09$ mag and $\Delta V = 0.88 \pm 0.09$ mag, which makes it a reliable LBV candidate. The star j004702.18–204739.93 ($M_V = -9.66 \pm 0.23$ mag) shows many emission lines of iron Fe II, forbidden iron lines [Fe II], bright hydrogen lines with broad wings, and also forbidden lines of oxygen [O I] and calcium [Ca II] formed in the circumstellar matter. The study of the light curve of this star did not reveal significant variations in brightness ($\Delta V = 0.29 \pm 0.09$ mag). We obtained estimates of interstellar absorption, the photosphere temperature, as well as bolometric magnitudes $M_{bol} = -10.5^{+0.4}_{-0.4}$ and $M_{bol} = -10.8^{+0.5}_{-0.6}$, which correspond to bolometric luminosities $\log(L_{bol}/L_\odot) = 6.11^{+0.20}_{-0.16}$ and $6.24^{+0.20}_{-0.25}$ for j004703.27–204708.4 and j004702.18–204739.93, respectively. Thus, the object j004703.27–204708.4 remains a reliable LBV candidate, while the object j004702.18–204739.93 can be classified as a B[e]-supergiant.

Key words: stars: emission-line, Be – stars: massive – stars: variables: S Doradus – galaxies: individual: NGC 247.

1 INTRODUCTION

Luminous blue variables (LBVs) are a rare type of massive ($M \gtrsim 25 M_\odot$; Humphreys et al. 2016) post-main-sequence stars that are characterized by a high luminosity of $>10^4 L_\odot$ and significant spectral and photometric variability on different time-scales.

The evolutionary status of LBVs is still unclear. The classic view of LBVs is that they correspond to a very short transition phase from single massive O-type stars to Wolf–Rayet (WR) type stars (Groh et al. 2014). The evolution of O-stars of different initial masses can be described by the following scheme:

- $M \sim 25–40 M_\odot$: O $\rightarrow$ LBV/RSG $\rightarrow$ WN(H-poor) $\rightarrow$ SN Ib;
- $M \sim 40–75 M_\odot$: O $\rightarrow$ LBV $\rightarrow$ WN(H-poor) $\rightarrow$ WC $\rightarrow$ SN Ic;
- $M > 75 M_\odot$: O $\rightarrow$ WN(H-rich) $\rightarrow$ LBV $\rightarrow$ WN(H-poor) $\rightarrow$ WC $\rightarrow$ SN Ic.

Some studies (Kotak & Vink 2006; Gal-Yam & Leonard 2009) have suggested that they could be direct progenitors of core-collapse supernovae (SNe). Groh, Meynet & Ekström (2013) have shown that rotating massive stars with initial masses of $20–25 M_\odot$ can evolve according to the following scheme:

- $20 M_\odot$: O7.5V $\rightarrow$ BSG $\rightarrow$ RSG $\rightarrow$ BSG/BHG $\rightarrow$ LBV $\rightarrow$ SN;
- $25 M_\odot$: O6V $\rightarrow$ OSG $\rightarrow$ RSG $\rightarrow$ OSG/WNL $\rightarrow$ LBV $\rightarrow$ SN.

Smith & Tombleson (2015) have shown that LBVs may be the result of the evolution of close binaries, as evidenced by their noticeable isolation from massive O-type stars compared with other massive stars (O star subtypes, WR stars and other classes of evolved stars). However, in work of Humphreys et al. (2016), these results are called into question.

The phenomenon of LBVs is still not well understood, and it is mainly associated with a rareness of known LBVs. Only LBVs and candidate LBVs (cLBVs) in the galaxies of the Local Group were studied in detail (Richardson & Mehnert 2018): by 2018, only 41 LBVs and 108 cLBVs had been discovered. However, data about the objects of this type in the Local Volume are scarce and only a few LBVs are known beyond 1 Mpc (e.g. Drissen, Roy & Robert 1997; Goranskij et al. 2016; Pustilnik et al. 2017; Humphreys et al. 2019; among others). Consequently, the discovery of new LBVs would significantly help us to understand the evolutionary status and interconnection of LBVs with other massive stars. In addition, an increase in the number of known LBVs will make it possible to find out whether LBVs are really deficient in luminosity between $\log(L_{bol}/L_\odot) = 5.6$ and 5.8, or whether this is the result of a small number of known LBVs (Smith, Vink & de Koter 2004).

The search for LBVs in our Galaxy is complicated by the low accuracy of distance determination caused by strong dust absorption in the Galactic plane. Many LBVs are surrounded by compact circumstellar envelopes of different morphology (Nota et al. 1995;
Weis 2001) that originated during eruptions, and therefore they are invisible in the optical range. Therefore, the most effective way to detect circumstellar shells is to use infrared (IR) telescopes (e.g. the Spitzer Space Telescope, the Wide-field Infrared Survey Explorer). Over the past decade, several new LBVs and cLBVs in our Galaxy have been discovered using this method (Gvaramadze et al. 2010a; Gvaramadze, Kniazev & Fabrika 2010b; Gvaramadze, Kniazev & Berdnikov 2015; Kniazev, Gvaramadze & Berdnikov 2016). Unfortunately, distances to these Galactic LBVs are often not accurately determined even with Gaia data. This leads to unreliable estimates of their luminosities.

The mostly accurate distance measurements and the slight interstellar absorptions make nearby galaxies the ideal laboratory for studying LBVs, which may help to bridge the gap between theory and observations. One of the most commonly used searching methods involves looking for Hα and observations. One of the most commonly used searching methods involves looking for Hα emissions associated with blue stars (Neese, Armandroff & Massey 1991; Corral 1996; Sholukhova et al. 1997; Massey et al. 2006; Valeev, Sholukhova & Fabrika 2010).

The variability of LBVs is irregular and often has a form of outburst. The most extreme outbursts, or giant eruptions, having amplitudes of >2.5 mag are very rare; they are observed at times of hundreds to thousands of years. The stars that exhibit such a type of variability are called η Car variables (Humphreys, Davidson & Smith 1999). During the giant eruptions, the bolometric luminosity of the star does not remain constant, and a noticeable increase in the mass-loss rate may occur, which can lead to the formation of an emission nebula (as in the case of η Carinae).

The more frequent outbursts with amplitudes from 0.1 to 2.5 mag (S Dor variables) are observed on time-scales of years to decades (van Genderen 2001). In such outbursts, the bolometric luminosity remains approximately constant. The apparent brightening of the star occurs due to changes in the bolometric correction with decreasing star temperature. During the visual maximum, the LBV absorption spectrum is similar to spectra of A–F-type supergiants. When the visual brightness decreases, the LBV spectrum resembles that of an evolved hot supergiant of B-type or an Of/late-WN stars (Vink 2012) and the stellar temperature can reach more than 35 000 K (Clark, Larionov & Arkharov 2005).

In some periods of their lives, LBVs show spectra very similar to those of B[e] supergiants (sgB[e]; Zickgraf 2006, and references therein) – another type of bright (4 ≤ log (Lbol/L⊙) ≤ 6) post-main-sequence star (Kraus 2005). In contrast to LBVs, sgB[e] are not so variable (about 0.1–0.2 mag; Lamers et al. 1998) and demonstrate a substantial infrared excess, which also supports the idea of the hot circumstellar dust envelope (Zickgraf et al. 1986; Bonanos et al. 2009).

Humphreys et al. (2014) have divided all high-luminosity stars into six types according to their spectral and photometric features: Of/late-WN stars, LBVs, warm hypergiants, Fe II-emission stars, hot and intermediate supergiants. Despite the similarity of some observational features (spectra,SEDs) of these types of stars, the evolutionary connections between them have not yet been understood. Of all these types of massive stars, only LBVs have significant brightness variability, which make the detection of the S Dor-type variability the most important and classifying property. However, it is worth noting that this type of variability can also be observed in B-type supergiants (Kalari et al. 2018), but it is not accompanied by spectral variability. Kalari et al. (2018) concluded that B-supergiants and LBVs are likely objects of a different nature, and not all B-supergiants become S Doradus variables.

We search for LBVs and similar objects in Local Volume galaxies using the archival broad-band and near-Hα narrow-band images, obtained with the ACS, WFPC2 and WFC3 cameras of the Hubble Space Telescope (HST). The new candidates, which show the Hα emission of a point-like blue stellar source, were based on the following selection criterion: the source should be point-like and bright in all filters.

So, our survey of Local Volume galaxies, with the aim of discovering LBVs, first presented in Solovyeva et al. (2019), is continuing with the study of NGC 247. The dwarf spiral galaxy (SAB(s)d) NGC 247 is one of the closest spiral galaxies of the Southern sky. The star formation rate and metallicity of this galaxy are similar to those of the M33 galaxy, but NGC 247 is more inclined towards the line of sight. The Hα luminosity of NGC 247 is comparable with that of M31, M33 and the Large Magellanic Cloud (Kennicutt et al. 2008).

In this paper, we present the discovery and detailed investigation of the S Dor-type variables in NGC 247: j004703.27–204708.4 and j004702.18–204739.93 (hereafter cLBV1 and cLBV2, respectively).

2 OBSERVATIONS AND DATA REDUCTION

In this work, we used long-slit spectroscopic observations obtained with the Subaru telescope (Hawaii) and the Southern African Large Telescope (SALT; South Africa), as well as photometry from the HST, Spitzer and ground-based telescopes.

2.1 Spectra

We downloaded the Subaru data for cLBV1 from the SMOKA Science Archive. The observation was conducted on 2016 October 8 (proposal ID o16146) with the Faint Object Camera and Spectrograph (FOCAS; Yoshida et al. 2000; Kashikawa et al. 2002). The 300B grating together with a 0.4-arcsec slit (its orientation is shown in Fig. 1) was used. The original spectral range was 3650–8300 Å and the resolution was 5 Å, but, because of contamination by scattered light at shorter wavelengths and order overlapping at longer wavelengths, we decided to trim the range by 3800–7400 Å. Seeing was 0.4–0.6 arcsec, which allowed us to separate cLBV1 from the nearest bright star (V = 19.78 ± 0.03 mag, Hα = 19.37 ± 0.04 mag) located 1.0 arcsec away from the object (Fig. 1, left panel).

The SALT (Buckley, Swart & Meiring 2006; O’Donoghue et al. 2006) spectrum of cLBV1 was obtained on 2017 November 11 with the RSS spectrograph (Burgh et al. 2003; Kobulnicky et al. 2003) using the PG0900 grating and a slit of 1.25 arcsec, which revealed the spectral range 4300–7400 Å and resolution 5.3 Å. To suppress contribution from higher spectral orders, the PC03850 UV filter was used. Seeing turned out to be relatively bad ≈1.7 arcsec, which did not allow us to resolve cLBV1 and the nearest star. However, after the data reduction, we did not find any changes in the emission lines compared with the spectrum obtained in 2016 with the Subaru telescope. Therefore, below we discuss only the spectrum obtained in 2016.

The spectrum of cLBV2 was obtained on 2018 October 7 with the SALT telescope using the same equipment as in the case of the previous object. The seeing was 1.6 arcsec.

1https://smoka.nao.ac.jp/
The Subaru spectrum was reduced with the context LONG of MIDAS using the standard algorithm. A correction for the distortion was performed with the FOCASRED package in the IRAF environment. The primary processing of the SALT spectra was carried out with the PSALT package (Crawford et al. 2010), and further reduction was performed in MIDAS. The spectra were extracted using the SPEXTRA package (Sarkisyan et al. 2017) developed to deal with long-slit spectra in crowded stellar fields.

2.2 Imaging

Images of the region containing both LBV candidates were obtained by the Subaru telescope together with the spectroscopic data. Additionally, we observed the objects with the 2.5-m telescope of the Caucasian Mountain Observatory of the Sternberg Astronomical Institute of Moscow State University (SAI MSU) and the Zeiss-1000 of the Special Astrophysical Observatory of the Russian Academy of Science (SAO RAS). We also involved archival data from other telescopes: the Danish 1.54-m telescope, the Cerro Tololo Inter-American Observatory (CTIO) 0.9-m telescope, and the Jacobus Kapteyn Telescope (JKT). We also use archival data from Very Large Telescope (VLT) and the 2.2-m Max Planck Gesellschaft (MPG) telescope of the European Southern Observatory (ESO). Only images with seeing of \( \approx 0.8 \) arcsec or better were chosen, where cLBV1 and its neighbour star are resolved. A summary of the utilized observations is given in Table 1. Primary data reduction was performed with MIDAS. We carried out an aperture photometry with the APPHOT package of IRAF by applying aperture correction to measure the observed magnitudes and using 13 nearby stars as reference stars for absolute calibration. The aperture sizes were from 0.3 to 1.2 arcsec depending on seeing in a particular observation. The background level was measured within source-free ring apertures, the size of which was selected depending on seeing.

To perform an absolute photometric calibration, we used archival HST observations. Each of the objects was observed once in the optical band (with the ACS/WFC camera, and the F435W, F606W and F658N filters) and once in the IR band (with the WFC3/IR camera, and the F105W and F160W filters). Optical photometry was carried out using a 0.15-arcsec circular aperture. Such a small aperture size was chosen to avoid contamination from nearby sources. The background was determined in a ring aperture with an inner radius of 0.25 arcsec and a thickness of 0.2 arcsec. The aperture correction was taken into account by photometric measurements of 20 single bright stars in large (1 arcsec) and small (0.15 arcsec) apertures.

The measured HST magnitudes were converted into the standard Johnson–Cousins system with the pySYNPHOT package assuming spectral indices \(-1.2\) for cLBV1 and \(-1.7\) for cLBV2, obtained from spectroscopy. The F435W filter passband is close to B, while the passband of the F606W filter is between V and R, and its peak is close to the H\( \alpha \) line. Therefore, to prevent overestimation of the obtained V-band magnitudes due to the presence of bright H\( \alpha \) emission lines in the spectra of our objects, we estimated the contribution of the H\( \alpha \) emission using the available spectral data and subtracted it from the observed F606W fluxes. All the optical magnitudes are shown in Table 1.

The IR source fluxes were measured using archival data of the WFC3/IR camera of HST in a 0.32-arcsec circular aperture, the background level in the 1.3–2.6-arcsec annulus. Aperture corrections were calculated by measuring the fluxes of ten single bright stars in 0.32- and 0.42-arcsec apertures. The results are presented in Table 2.

Also, we used archival data obtained with the Spitzer telescope in the 3.6- and 4.5-\( \mu \)m bands of the IRAC camera. We did not analyse observations in the other IRAC filters because of their low spatial resolution. We performed absolute photometry of the objects using a 0.9-arcsec aperture. The choice of aperture size was due to the crowded field of stars. The background level was determined in a ring aperture with an inner radius of 1.5 arcsec and a thickness of 0.9 arcsec. Aperture corrections were calculated from photometry of 25 single bright stars in large (6 arcsec) and small (0.9 arcsec) apertures. Then we compared our results for single stars with the photometry from the Spitzer point source catalogue (Khan et al. 2015). The results have coincided within the errors for the 25 reference stars and for cLBV2, while the fluxes of cLBV1 (together

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2https://www.naoj.org/Observing/DataReduction/Cookbooks/FOCAS_coobook_2008dec08

3IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4https://sha.ipac.caltech.edu/applications/Spitzer/SHA
Table 1. Results of the optical photometry. The columns show the instruments, dates and observed stellar magnitudes (not corrected for reddening). Asterisks denote photometric observations that are simultaneous or quasi-simultaneous with spectroscopy.

| Telescope           | Date        | $U$, mag | $B$, mag | $V$, mag | $R$, mag | $H_{r}$, mag | $I$, mag |
|---------------------|-------------|----------|----------|----------|----------|--------------|----------|
| 2.2-m ESO/MPG/WFI   | 2002/10/08  | –         | 19.39 ± 0.08 | 19.27 ± 0.08 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2003/06/24  | –         | 19.29 ± 0.07 | 19.17 ± 0.08 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2003/10/19  | –         | 19.17 ± 0.07 | –         | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2003/10/22  | –         | 19.30 ± 0.07 | –         | –       | –         | –       |
| ESO/VLT/FORS2       | 2004/06/19  | –         | 19.38 ± 0.05 | 19.22 ± 0.06 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2004/10/17  | –         | 19.28 ± 0.09 | 19.17 ± 0.07 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2005/01/06  | –         | –         | 19.10 ± 0.09 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2005/06/09  | –         | –         | 18.83 ± 0.08 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2005/09/26  | –         | 19.15 ± 0.08 | 19.01 ± 0.09 | –       | –         | –       |
| 2.2-m ESO/MPG/WFI   | 2006/09/25  | –         | 19.30 ± 0.08 | 19.22 ± 0.10 | –       | –         | –       |
| HST/ACS/WFC         | 2011/10/11  | –         | 19.89 ± 0.04 | 19.71 ± 0.04 | 17.34 ± 0.03 | –         | –       |
| Subaru              | 2016/10/09* | 18.83 ± 0.10 | 19.54 ± 0.11 | 19.45 ± 0.09 | 19.13 ± 0.09 | –       | 19.10 ± 0.09 |
| 2.5-m, SAI MSU      | 2018/09/20  | –         | –         | 19.37 ± 0.10 | 19.01 ± 0.10 | –       | –       |

with the nearest star that Spitzer cannot resolve) in the 3.6- and 4.5-μm filters appeared to be lower by 25 and 15 per cent, respectively, as a result of the more accurate accounting for the background in our work. Extrapolating the spectral slope between the F105w and F160w band flux to the range of 3.6- and 4.5-μm, we estimated the contribution of the nearest star to the total flux as ≤ 10 per cent. The flux measured in the 0.9-arcsec aperture includes a significant part of the flux of the relatively compact nebula that surrounds cLBV1 and part of the nearby stellar association, the value of which we cannot reliably estimate. The obtained Spitzer magnitudes are also shown in Table 2.

### 3 RESULTS

#### 3.1 cLBV1 (J004703.27–204708.4)

The Subaru spectrum of cLBV1 is presented in Fig. 2 (top panel). It shows broad and strong emission lines of hydrogen and helium $\text{He}^+ \text{P Cyg}$ profiles. Also, there are many lines of iron Fe II, Fe III, silicon Si II and weak emission lines of nitrogen N II 4631 and carbon C II λλ7053. The presence of these lines indicates that the photospheric temperature should be about $T_{\text{pec}} = 20000 ± 5000$ K. Using the full width at half-maximum (FWHM) of the forbidden nitrogen line $\text{[N II]} \lambda \lambda 6548,6583$ and $\text{[S II]} \lambda \lambda 6717,6731$ are probably emitted from the surrounding nebula. Based on the ratio of the hydrogen lines in the surrounding nebula, we estimated the reddening as $A_V = 0.80 ± 0.10$ mag assuming the case B photoionization (Osterbrock & Ferland 2006).

The temperature was also measured from the photometric data. We have constructed a SED of the object (Fig. 3a) combining the $UBVR_I$, photometry from Subaru with the IR photometry obtained with the $HST$ and $Spitzer$ telescopes (however, we should note that the IR data are not simultaneous with the optical data). The photometric data shown in the figure are corrected for the contribution of the emission lines. However, because the spectrum does not completely cover the filter $U$ range, the contribution of emission lines to the flux in this filter might be underestimated. The SED was fitted by the Planck function taking into account interstellar absorption with $R_V = 3.07$ ( Fitzpatrick 1999). Possible variations of the temperature and reddening were restricted to vary within uncertainties obtained from the spectroscopy $T_{\text{pec}} = 20000 ± 5000$ K and $A_V = 0.80 ± 0.10$ mag. Eventually we have obtained the best-fitting temperature of

### Table 2. Results of the IR photometry.

| Object | $F_{105W}$, mag | $F_{160W}$, mag | $3.6 \mu m$, mag | $4.5 \mu m$, mag |
|--------|----------------|----------------|-----------------|----------------|
| cLBV1  | 19.17 ± 0.04   | 18.57 ± 0.04   | 16.20 ± 0.16    | 16.09 ± 0.14   |
| cLBV2  | 18.67 ± 0.04   | 18.13 ± 0.04   | 15.91 ± 0.13    | 15.25 ± 0.11   |

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Figure 2. Top panel: spectrum of cLBV1 obtained with the Subaru telescope. The unlabelled long and short ticks designate the hydrogen Balmer lines and [He I] lines, respectively. Narrow components of H\(\alpha\), H\(\beta\), H\(\gamma\) and H\(\delta\) as well as forbidden lines [O I], [N II] and [S II] belong to the surrounding nebulae. Bottom panel: spectrum of cLBV2 obtained with SALT. The unlabelled ticks designate the Fe II lines.

Figure 3. SEDs of cLBV1 (left-hand panel) and cLBV2 (right-hand panel). The circles indicate the UBVR\(c\)I\(c\) photometry from Subaru (2016), filled circles denote the fluxes corrected for the contribution of bright emission lines, and unfilled circles denote original fluxes. The squares and crosses indicate the IR photometry obtained with HST/WFC3/IR in the F105W and F160W bands (2014) and Spitzer/IRAC in the 3.6- and 4.5-\(\mu\)m bands (2012), respectively. Observed spectra are shown in grey, as in Fig. 2. The SEDs were fitted by the model (solid line) consisting of two blackbody components describing emission from the stellar photosphere (dashed line) and the IR excess (dash-dotted line) arising probably due to the dust envelope around the star. The best-fitting model parameters are \(T_{\text{SED}} = 18000 \pm 2000\) K and \(15000 \pm 2000\) K, \(A_V \approx 0.9\) and \(0.7\), and \(T_{\text{dust}} \approx 1400\) K and \(1300\) K for cLBV1 and cLBV2, respectively.

\(T_{\text{SED}} = 18000 \pm 2000\) K for \(A_V \approx 0.9\). Also, we have found evidence of significant IR excess, probably caused by the presence of a circumstellar dust envelope. We fitted this excess by adding an extra blackbody component with temperature \(T_{\text{dust}} \approx 1400\) K (Fig. 3a).

Based on the SED best-fitting temperature \(T_{\text{pec}} = 18000 \pm 2000\) K and the reddening \(A_V = 0.80 \pm 0.10\) mag obtained from spectroscopy, we estimated the absolute V-band and bolometric magnitudes as \(M_V = -9.08 \pm 0.15\) mag and \(M_{\text{bol}} = -10.5^{+0.5}_{-0.4}\) mag, which...
corresponds to the bolometric luminosity of $\log(L_{\text{bol}}/L_\odot) = 6.11^{+0.20}_{-0.16}$. Both derived magnitudes are quite typical for LBVs (Humphreys & Davidson 1994).

The object cLBV1 demonstrated significant variability from 2005 (2.2-m ESO/MPG/WFI) to 2011 (HST/ACS/WFC) (Table 1): the source $B$- and $V$-band magnitudes changed by 0.74 ± 0.09 and 0.88 ± 0.09 mag, respectively. Such a strong change in brightness makes this object a reliable candidate for a bona fide LBV. The light curve of this object is shown in Fig. 4. Further observations of the object are necessary to study the nature of the photometric variability.

### 3.2 cLBV2 (j004702.18–204739.93)

The spectrum of cLBV2 contains broad emission Balmer lines Hα and Hβ as well as a large number of iron lines Fe II and Fe III. The multiple forbidden iron lines [Fe II] indicate the presence of the powerful outflow of the stellar matter. The observed lines Fe II have a maximum intensity when the temperature is about 15 000 K, and weaken if the temperatures decrease below 10 000 K or increase above 20 000 K. Therefore, we estimate the photosphere temperature of cLBV2 as $T_{\text{spec}} = 15 000 \pm 5000$ K. The reddening measured from the ratio of the hydrogen lines in the surrounding nebula is $A_V = 0.90 \pm 0.20$ mag.

The SED of cLBV2, as in the case of cLBV1, was constructed using the photometric data from the Subaru telescope together with the IR observations from HST and Spitzer. The star did not show any brightness variations from 2016 to 2018, so we have used the spectrum from the SALT telescope obtained in 2018 to take into account the contribution of emission lines to the photometric data obtained with Subaru in 2016. The SED was approximated by the Planck function with the best-fitting temperature $T_{\text{SED}} = 15 000 \pm 2000$ K. As in the case of the previous object, the SED of cLBV2 also shows an IR excess, which may be produced by the dust envelope. We estimated the temperature of the dust component as $T_{\text{dust}} \approx 1300$ K.

#### Table 3. Parameters of the studied stars. The columns show the object name, the reddening measured from the nebular hydrogen lines, the photosphere temperature estimated from both the spectra and SEDs, the absolute $V$-band and bolometric magnitudes and the bolometric luminosity.

| Star   | $A_V$, mag | $T_{\text{spec}}$, K | $T_{\text{SED}}$, K | $M_V$, mag | $M_{\text{bol}}$, mag | $\log(L_{\text{bol}}/L_\odot)$ |
|--------|------------|----------------------|----------------------|------------|------------------------|-----------------------------|
| cLBV1  | 0.80 ± 0.10 | 20000 ± 5000         | 18000 ± 2000         | -9.08 ± 0.15 | -10.5 ± 0.5            | 6.11 ± 0.20                  |
| cLBV2  | 0.90 ± 0.20 | 15000 ± 5000         | 15000 ± 2000         | -9.66 ± 0.23 | -10.8 ± 0.6            | 6.24 ± 0.25                  |

Using the photosphere temperature $T_{\text{SED}} = 15 000 \pm 2000$ K and the reddening estimated from the nebular hydrogen lines $A_V = 0.90 \pm 0.20$ mag, we determined the absolute and bolometric magnitudes $M_V = -9.66 \pm 0.23$ mag and $M_{\text{bol}} = -10.8 \pm 0.6$ mag, which corresponds to the bolometric luminosity $\log(L_{\text{bol}}/L_\odot) = 6.24^{+0.20}_{-0.25}$.

The photometric variability of cLBV2 is $\Delta V \approx 0.29 \pm 0.09$ mag from 2011 (HST/ACS/WFC) to 2018 (2.5-m, SAI MSU), which only slightly exceeds the $3\sigma$ level. The light curve of this object is shown in Fig. 4.

#### 4 DISCUSSION AND CONCLUSIONS

We have measured the stellar parameters of our LBV candidates residing in the galaxy NGC 247 (Table 3) and found them very typical for LBV stars. In Fig. 5, we show the temperature–luminosity diagram overplotted with the evolutionary tracks of massive stars. As there are no spectroscopic estimates for the metallicity of this galaxy, and different authors use values from $Z = 0.004$ (Wagner-Kaiser et al. 2014) to $Z = 0.0152$ (Rodriguez, Baume & Feinstein 2019), we have assumed the metallicity of $Z = 0.008$ (as in Davidge 2006) to plot the evolutionary tracks (Tang et al. 2014). Grey areas show the ranges of possible photosphere temperatures and luminosities of the candidates. As can be seen in the figure, both cLBV1 and cLBV2 have to be more massive than 25 M$_\odot$, which is enough for a star to pass the LBV stage. Our objects are located near the area of LBV stars in the temperature–luminosity diagram.
Figure 6. HST/ACS/WFC image of cLBV1 (left) and cLBV2 (right) in the F435W band. Studied cLBVs are marked with arrows. The squares designate stellar associations with sizes of $8 \times 8$ and $16 \times 16$ arcsec$^2$, which were used to construct the CMDs.

Figure 7. CMDs for stellar associations close to cLBV1 (left) and cLBV2 (right). The grey dots and the black triangles denote the large ($16 \times 16$ arcsec$^2$) and small ($8 \times 8$ arcsec$^2$) areas of stars, respectively, and black circles denote cLBVs. Theoretical isochrones (Marigo et al. 2017) for metallicity $Z = 0.008$ of 5, 10 and 30 Myr are shown (from top to bottom).

We have found that cLBV1 shows brightness variations of $0.74 \pm 0.09$ and $0.88 \pm 0.09$ mag in the $B$ and $V$ bands, respectively, which noticeably exceed the $3\sigma$ level. Moreover, its spectrum is similar to that of the Galactic bona fide LBV WS 1 (Kniazev, Gvaramadze & Berdnikov 2015) obtained in 2011. However, the SED of cLBV1 shows a noticeable near-IR excess: we obtained a flux ratio of $F_V/F_{3.6\mu m} \approx 60$, while confirmed LBVs have $F_V/F_{3.6\mu m} > 100$ (e.g. Humphreys et al. 2014). Thus, the IR excess of cLBV1 is two times higher than the values observed in confirmed LBVs. However, this may be due to the underestimation of the contribution of the neighbouring star and the nebula surrounding the cLBV1. Moreover, we also do not observe spectral variability, although we have only two spectra obtained with a time interval of 1 yr (2016 and 2017). Therefore, this object still has LBV candidate status.
The second object cLBV2 shows the forbidden emission lines [Ca II] $\lambda\lambda$ 7291,7324 and [O I] $\lambda\lambda$ 6300,6364, which are assumed to be indicators of the innermost disc regions in sB[e] (Kraus, Borges Fernandes & de Araújo 2007; Aret et al. 2012). These lines are also observed in warm hypergiants (Humphreys et al. 2013). In addition, cLBV2 shows a noticeable IR excess, which is characteristic of stars of these types. Because of the lack of absorption features in its spectrum, the object cannot be attributed to warm hypergiants. So, taking into account the presence of forbidden iron lines [Fe II] along with forbidden lines of oxygen and calcium, we could classify cLBV2 as a B[e] supergiant (Humphreys et al. 2017a, and references therein).

Both studied stars are close to stellar associations that are likely to be parental to them. There are relatively small groups of stars around the cLBVs, as well as rich star-forming regions at some distances (see Fig. 6). The sizes of the areas where most of the blue stars are located are $8 \times 8$ and $16 \times 16$ arcsec$^2$. To estimate the ages of these groups, we have performed point spread function (PSF) photometry of the stars and have constructed colour–magnitude diagrams (CMDs).

Photometry for selected regions was performed using DOLPHOT and archival images, obtained on the F435W and F606W bands of HST/ACS/WFC. The CMDs were constructed, taking into account a mean extinction $E(B-V) = 0.18$ in NGC 247 (Gieren et al. 2009) (Fig. 7). Theoretical isochrones from work of Marigo et al. (2017) for metallicity $Z = 0.008$ and cLBVs were also plotted on the diagram.

Comparison with theoretical isochrones shows the possible continuous star formation in the studied stellar associations. However, the position of the majority of the stars in the CMDs is well described by the isochrones of 10–30 Myr. It is worth noting that both cLBVs lie on the diagram noticeably higher than most stars (excluding the bright star nearby cLBV2). This can be explained by the younger age of the candidates in the case of the single star evolution. However, due to the relatively small number of stars in the studied associations, the upper part of the diagram may be poorly populated. Therefore, we can overestimate the age of the host star-forming region: the age of the last outburst of star formation can be much smaller and corresponds to the age of the candidates. This assumption is confirmed by the bright star mentioned above, which is not a cLBV, but is in the same region of the diagram as the candidates.

The positions of the studied cLBVs in the CMDs can be explained in an alternative way. If we assume that both stars are the result of the evolution of close binaries with mass exchange, and the observed objects may be ‘rejuvenated’ due to the accretion (Smith & Tombleson 2015; Beasor et al. 2019), then this can explain the apparent isolation of the candidates from the stars of the nearest associations in the observed CMDs.

It is worth noting that the question of the observed age of the studied objects and neighbouring star-forming region requires a more detailed study, which is planned in the future.

Finally, we note that for a more accurate classification of cLBV1 and cLBV2, additional observations are necessary in order to search for more prominent photometric and spectral variability.

ACKNOWLEDGEMENTS

This work is based in part on data collected at Subaru telescope, which is operated by the National Astronomical Observatory of Japan. This research was supported by the Russian Foundation for Basic Research 19-52-18007 and 19-02-00432. The authors acknowledge partial support from M.V.Lomonosov Moscow State University Program of Development. Based on data obtained from the ESO Science Archive Facility under request numbers Yusoloveva/543153, Yusoloveva/543857 and Yusoloveva/543876. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. This work is based in part on observations (archival data) made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Some spectral observations reported in this paper were obtained with the Southern African Large Telescope (SALT) under program 2017-1-MLT-003. A. Kniazev acknowledges support from the National Research Foundation (NRF) of South Africa. Observations with telescopes of the SAO RAS are carried out with the support of the Ministry of Science and Higher Education of the Russian Federation (including agreement No05.619.21.0016, unique project identifier RFMEFI61919X0016).

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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