New Luminous Blue Variables in the Andromeda galaxy

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ABSTRACT
We performed spectroscopy of five Luminous Blue Variable (LBV) candidates and two known LBV stars (AE And and Var A-1) in M31. We obtained the same-epoch near-infrared (NIR) and optical spectra of these stars. The NIR spectra were taken with Triplespec spectrograph at the 3.5-m telescope at Apache Point Observatory, and the optical spectroscopy was done with SCORPIO focal reducer at the 6-m BTA telescope (SAO RAS). The candidates demonstrate typical LBV features in their spectra: broad and strong hydrogen lines, HeI, FeII, and [FeII] lines. All our candidates show photometric variability. We develop a new approach to the LBV parameters estimation based on the inherent property of LBVs to change their spectral type at constant bolometric luminosity. We compare the spectral energy distributions of the variable stars obtained in two or more different states and estimate temperatures, reddening, radii and luminosities of the stars using this method. Two considered candidates (J004526.62+415006.3 and J004051.59+403303.0) have to be classified as new LBV stars. Two more candidates are, apparently, B[e]-supergiants. The nature of one more star (J004350.50+414611.4) is not clear. It does not show obvious LBV-like variability and remains an LBV-candidate.

Key words: stars: variables: S Doradus - stars: massive - stars: emission-line, Be - infrared: stars - galaxies: individual (M31)

1 INTRODUCTION
Luminous Blue Variables are massive evolved stars of the highest luminosity. Atmospheres of the stars may be highly unstable at the stages when hydrogen is exhausted. Change in ionization state of the most abundant elements determines changes in the gas opacity and in the mass loss rate, thus it creates a variety of LBV observing manifestations. At the maximum visual brightness LBVs show A-F supergiant spectrum, while at the minimum the same star can have a WNL spectrum. The relation between LBVs and B[e] supergiants (B[e]SG) is still unclear: they are comparable in luminosities, and similar in spectrum when LBVs are in their hot phase, but B[e]SGs do not change their brightness significantly.

The standard evolution theory does not predict the existence of LBVs. There are two possible explanations for LBVs. In the first one (Humphreys & Davidson 1994) it is considered that LBV is a transition stage from the Main Sequence to Wolf-Rayet (WR) stars. The second scenario assumes that LBV is a final stage of high mass star’s life before Supernova (SN) explosion. An assumption also was made by Smith & Tombleson (2014) that LBV can be a product of stellar evolution in binary systems.

Recent observations of gamma-ray bursts and Supernovae gave an evidence that the SN shock travels through an extended stellar wind envelope, as in LBV or WR. It was shown that stars can explode as SN at both LBV or WR stages (Groh et al. 2013 Gräfener & Ekström 2013 Gräfener et al. 2012).

LBV is a rare class of stars at a particular stage of evolution. Like other massive stars, they tend to reside close to the galactic midplane, where their study is difficult because of high dust extinctions. An additional problem is the uncertainty in distance estimation. It makes studies of extragalactic LBVs with known distances especially valuable. Humphreys & Davidson (1994) listed five LBVs (four LBV candidates) in the Milky Way and 15
in other Local Group galaxies. Four were identified in M31 and four more in M33. Since that time, 38 LBVs or LBV candidates in the Milky Way have been reported (Vink 2012), 24 in M31, and 37 in M33 (Massey et al. 2007). We have confirmed 4 LBVs in M31 (Fabrika et al. 2003), 24 in M31, and 37 in M33 (Massey et al. 2004). Using the Spitzer Space Telescope archival data one more LBV and several WN stars in our Galaxy (Gvaramadze et al. 2009, 2007). We have confirmed 4 LBVs in M33 (Fabrika et al. 2011) and 37 in M33 (Massey et al. 2012). Several WNL stars in our Galaxy (Massey et al. 2007) have been reported or LBV candidates in the Milky Way have been reported to date: for Var A-1 and AE And we used U, B, V, R, & I photometry from September 1976, and J, H, & K from November 1980 from Humphreys et al. (1984). For J004051.6 Berkhuijsen et al. (1988) published the U, B, V, R, & I photometry from August - September 1963.

The JHK photometry is available from the 2MASS survey (Skrutskie et al. 2006). To watch the variability, we used two versions of the catalog: 2MASS-1 (Cutri et al. 2003) and 2MASS-2 (Cutri et al. 2012) (November 2000). There are also JHK magnitudes obtained in November 1980 by Humphreys et al. (1984) for Var A-1. The TripleSpec guider at the 3.5-m telescope provides simultaneous K photometry. We estimate the K magnitudes for our objects by the comparison with five non-variable reference stars in the 5-arcmin guider field (using their 2MASS magnitudes).

Accuracy of our optical photometry is not worse than 0.05 mag. The Massey’s estimates have 0.01 mag uncertainty, and those by Humphreys et al. (1984) have 0.05 mag uncertainty (0.1 mag in their IR data). Our K estimates have 0.1 mag accuracy, while NIR magnitudes from Berkhuijsen et al. (1988) are 0.2 mag accurate, and the 2MASS-1 and -2 data have 0.1 mag accuracy. Results of the optical and NIR photometry are summarized in Table 2.

3 RESULTS

3.1 Spectroscopy and Spectral Energy Distributions

Fig. 1 shows spectra of seven considered stars in six spectral ranges. The principal lines are identified and marked in Fig. 1: Balmer, Brackett, and Paschen lines, as well as HeI, HeII, FeII, [FeII], and SiII lines. Some of these lines demonstrate P Cyg-type profiles. The spectra are typical for LBV stars. Object J004417.10 has 12CO lines in its spectrum, which is typical for B[e]SGs (an indicator of warm stellar media).

We use the collected photometry (Table 2) and our spectra to study SEDs for our objects. To increase the flux calibration accuracy, we tied our calibration to simultaneous observations in the V and K bands. Fig. 4 demonstrates our optical spectra together with the simultaneous and historical photometric data.

Our spectra allow us to estimate approximate ranges of photospheric temperature ($T_p$, in Table 3). We used simple criteria of the line relative intensities (HeI, HeII, FeII, and FeII) in the spectra (Jacoby, Hunter, & Christian 1984). Next, the optical spectra were fitted with a Planck function taking account the extinction with $R_V = 3.07$ ( Fitzpatrick 1999).

There is a well-known degeneracy between the reddening and temperature, which makes estimation of the parameters ambiguous. Nevertheless, when the temperature
Figure 1. The spectra of J004051.59, J004350.50, J004417.10, J004444.52, J004526.62, Var A-1, AE And in the optical spectral ranges. The principal strongest lines are identified. Unsigned short and long tick marks designate the FeII and [FeII] lines, respectively. The spectra are left on their original wavelength scale.
Figure 2. The same as in Fig. 1 but in the J NIR range. The IR spectrum of J004350.50 is not shown.
Figure 3. The same as in Fig. 1 but in the H & K NIR ranges. The IR spectrum of J004350.50 is not shown.
Figure 4. The SED modeling. Crosses indicate the B, V, R, K photometry observed simultaneously with our spectra, filled circles are the data by Massey et al. (2006), open circles from Humphreys et al. (1984), and Berkhuijsen et al. (1988) (Table 2). Filled and open squares are the data from 2MASS-1 and 2MASS-2 (Cutri et al. 2003, 2012) respectively. The curves designate the black body approximation with reddening applied according to Table 1. The solid curves show our fits to the optical part of our spectra, the dashed curves — to the data of Humphreys et al. (1984) and Berkhuijsen et al. (1988), and the short dashes — to Massey et al. (2006) data. The IR excesses are clearly seen in the stars. The best-fit temperatures are indicated at the legends in each panel.
is comparatively low, given the \(T_{sp}\) ranges, we can constrain the extinction \(A_V\) rather tightly. We also used the Balmer line ratio \(H_\alpha / H_\beta\) in the case of Var A-1 and J004350.50 to estimate the reddening \(A_V\) of surrounding nebulas, (see e.g. Valeev, Sholukhova, & Fabrika 2009). All estimates mentioned above were used as the initial parameters for the further SED fitting.

LBV-type variability allows us to break the degeneracy problem when the star gets cooler and brighter, or hotter and dimmer in the optical bands (Humphreys & Davidson 1994) with about constant bolometric luminosity. The variability should be large enough (\(\Delta V \gtrsim 0.2\) mag) and rather slow (at least a few months, Sholukhova et al. 2011). In this case the constancy of the bolometric luminosity (\(\sigma T^4 \pi R^2\), where \(R\) is the stellar radius) is a correct assumption.

We conclude that four object out of seven in our sample show such a slow and large variability. In this case we can fit SED for different data sets assuming that the interstellar reddening \(A_V = \text{const}\). Assuming \(T^4 R^2 = \text{const}\), we can estimate the photospheric temperature from known V-magnitude in a new state of the star. Fitting the SEDs, we use a black-body approximation for continuum spectra masking strong emission lines and the Balmer jump.

For J004051.59 and J004526.62 we have data from two epochs, which record two different stellar states, and which allow for two temperature solutions. In the case of Var A-1 and AE And, we have data for three solutions, which enables us to constrain the temperatures \(T_{SED}\), \(A_V\), and \(R\) even more precisely. We fit each data set, both photometric and spectroscopic. The results of the fitting are summarized in Table 3, where we show the reddening \(A_V\), stellar tem-

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**Table 1.** Spectroscopy observing log. The columns show the object name, the date of NIR Triplespec observations (spectral range 0.95 - 2.46 \(\mu\)m, resolution 5\(\AA\)), and the optical SCORPIO spectroscopy epochs for the ranges of 3500-7200 \(\AA\) (resolution 10\(\AA\)), 4000 - 5700 \(\AA\) (resolution 5.5\(\AA\)), and 5700-7500 \(\AA\) (resolution 5.5\(\AA\)). The seeing is shown in parentheses.

| Object       | Date/seeing (arcsec) | TripleSpec | SCORPIO          |
|--------------|----------------------|------------|------------------|
| J004051.59   | 10.10.12 (1.0)       | 18.09.12 (1.3) | 26.10.11 (1.5)  |
| J004350.50   | 17.10.12 (1.1)       | 16.09.12 (1.0) | 04.11.11 (1.4)  |
| J004417.10   | 24.09.11 (1.3)       | 16.09.12 (1.0) | 26.10.11 (1.5)  |
| J004444.52   | 28.09.11 (1.1)       | 19.07.12 (2.6) | 04.11.11 (1.3)  |
| J004526.62   | 24.09.11 (0.9)       | 19.07.12 (2.1) | 26.10.11 (1.3)  |
| Var A-1      | 24.09.11 (1.0)       | 16.09.12 (1.0) | 26.10.11 (1.3)  |
| AE And       | 28.09.11 (1.2)       | 16.09.12 (1.0) | 27.01.12 (2.0)  |

**Table 2.** The photometric data used in the paper. The columns show the object names along with corresponding U, B, V, R, I, J, H, and K magnitudes. For each object, the first line shows our B, V, R, and K photometry made simultaneously with our spectra. The second line shows the data from Massey et al. (2006) obtained between October 2000 and October 2001, and the J, H, and K from 2MASS-1 and 2MASS-2 (Cutri et al. 2003, 2012), obtained in December 1998 and November 2000, respectively. The third line shows the data from Berkhuijsen et al. (1988) for J004051.6 (August - September 1963) and from Humphreys et al. (1984) for Var A-1 and AE And (optical photometry from September 1976, and J, H, & K from November 1980). The data uncertainties are described in the text.

| Object       | U       | B       | V       | R       | I       | J       | H       | K       |
|--------------|---------|---------|---------|---------|---------|---------|---------|---------|
| J004051.59   | 17.29   | 16.99   | 16.76   |         |         |         |         | 15.96±0.05 |
|              | 16.444  | 17.205  | 16.989  | 15.96   | 16.38/16.18 | 15.59/15.98 | 15.75/15.06 |
|              | 16.93   | 17.67   | 17.43   | 17.08   | 16.84   |         |         |         |
| J004350.50   | 18.32   | 17.73   | 17.19   |         |         |         |         | 15.56±0.28 |
|              | 17.986  | 18.342  | 17.700  | 17.229  | 16.74   | 16.25/16.21 | 15.85/15.80 | 15.95/15.71 |
| J004417.10   | 17.37   | 17.27   | 17.05   |         |         |         |         | 15.2±0.28   |
|              | 16.494  | 17.26   | 17.113  | 16.78   | 16.610  | 15.97/16.06 | 15.58/15.55 | 14.73/14.63 |
| J004444.52   | 19.0    | 18.16   | 17.40   |         |         |         |         | 14.4±0.1    |
|              | 18.978  | 19.062  | 18.073  | 17.326  | 16.561  | 15.81/15.75 | 15.23/15.10 | 14.38/14.26 |
| J004526.62   | 16.82   | 16.37   | 16.08   |         |         |         |         | 15.0±0.2    |
|              | 16.92   | 17.662  | 17.36   | 17.02   | 16.920  | 15.93/16.62 | 15.76/15.84 | 15.13/15.37 |
| Var A-1      | 17.14   | 16.77   | 16.47   |         |         |         |         | 15.5±0.2    |
|              | 16.75   | 17.364  | 17.08   | 16.76   | 16.641  | 15.75/16.14 | 15.54/16.07 | 15.46/15.66 |
|              | 16.13   | 16.67   | 16.260  | 15.76   | 15.55   | 15.47    | 15.24    | 15.13    |
| AE And       | 16.616  | 17.385  | 17.373  | 17.242  | 17.241  | 16.39/16.90 | 15.89/16.64 | 15.89/16.33 |
|              | 16.29   | 17.1    | 17.00   | 16.66   | 16.48   |         |         |         |
peratures, radii, and absolute magnitudes in the V-band and bolometric.

LBVs and B[e]SGs often show infrared excess that is caused by free-free emission or thermal dust emission in the near-infrared (JHK) range. The excesses are clearly seen in Fig. 4. In two stars (which we classify below as B[e]-supergiants) the IR excesses are very strong. In our forthcoming paper we will present spectroscopy of more LBVs and LBV candidates in M31. In that paper we will analyze IR excesses of these and new stars to have more representative data.

3.2 Notes on individual objects

\textbf{J004051.59+403303.0} The brightness and color were estimated by Berkhuijsen et al. (1988): in 1963 it had V = 17.43 ± 0.18; Magnier et al. (1992): in 1990 it had V = 17.33, (B - V) = 0.09. Our estimate, V = 16.99 ± 0.05, is well consistent with that by Massey et al. (2006). The collected photometry suggests a gradual increasing of stellar optical brightness. Our optical spectrum is similar to that published by Massey et al. (2006): it has absorption HeI, FeII and SiII 6347, 6371 Å lines. The brightest FeII lines have P Cyg profiles. There are weak [CaII] 7291, 7323 Å emission lines. The data by Berkhuijsen et al. (1988) agree well with a hotter state of this object (Fig. 4 and Table 3), and they are confirmed by the Magnier et al. (1992) data. The photometric variability of this object between its two states (Δ U = -0.49, Δ B = 0.46) is LBV-like. Given the spectral and photometric variability, and the location on the JHK diagram (Kraus et al. 2014), we conclude that J004051.59 may belong to the LBV class.

\textbf{J004350.50+414611.4} In the DIRECT project (1996-1997, Stanek et al. 1999) this star is classified as a Miscellaneous Variable (Bonanos et al. 2003). Its variability was also detected by Vilardell, Ribas, & Jordi (2006) (ΔB = ΔV = 0.16 with uncertainty under 0.01 mag). Our spectra are similar to those by Massey et al. (2007). They have broad Balmer emission lines. FeII lines have P Cyg profiles, but HeI and SiII lines are in the absorption. The interstellar reddening estimated using the emission from surrounding HII regions AV = 1.6 agrees well with estimates made from our SED fitting. Humphreys et al. (2014) classified this star as an intermediate-type supergiant (A5I). The location on the JHK diagram (Kraus et al. 2014) suggests that J004350.50 may belong to the LBV class. The star is similar to LBV by its spectra and luminosity. However, its relatively small brightness variations resemble those of a Cyg type, which may be caused by fluctuations in the stellar wind. The brightness variation amplitude seen up to date does not allow us to classify the star as an LBV. The star may be a dormant LBV, however its nature is not clear yet. It remains an LBV-candidate. We need to look more additional criteria (e.g. to study helium content in its wind) to verify the star’s LBV classification.

\textbf{J004417.10+412804.0} It was referred to as a variable with the amplitude of 0.15 in the V band by Mochejska et al. (2001). We notice its spectral variability. Our spectra show the line HeI 5876 Å while it was not seen in September 1995 by King, Walterbos, & Braun (1998). In addition, FeII emission lines got significantly brighter that in the spectra from Massey et al. (2007). Our spectra show bright lines [CaII] 7291, 7323 Å, which suggests that a warm dust envelope surrounds the star. Humphreys et al. (2014) also detected CO lines in the spectra. The CO lines are very weak (although detectable) in our spectra, which can be explained by variability of these lines. That was noticed before in the case of HR Car by Morris et al. (1997). From the presence of [CaII] and CO lines, and from the location at the B[e]SG region on the JHK diagram, Humphreys et al. (2014) have concluded that this object is a B[e]SG star. Humphreys et al. (2014) classify it as a FeII-emission line star. Our results confirm these two conclusions.

Interesting that while B[e]SGs do not show significant spectral variability, this star was variable during last 17 years. To date, only one B[e]SG, S18 (Clark et al. 2013), showed such a variability. Note however that classification of S18 as a B[e]SG is not ultimate yet. The spectral variability of J004417.10 requires further investigation.

\textbf{J004444.52+412803.0} Variability of this star (ΔB = 0.27, ΔV = 0.22) was noticed in the DIRECT project (Stańek et al. 1999). Vilardell, Ribas, & Jordi (2006) confirmed the variability with amplitudes of ΔB = 0.30 and ΔV = 0.25 between 1999 and 2003. Their mean magnitudes correspond to those measured by us (Table 2). Our spectrum is almost identical to that by Massey et al. (2007) and similar to that by Humphreys et al. (2013, 2014). The spectra show emission lines FeII and [FeII]. Helium lines 5876 Å and 6678 Å have P Cyg profiles. We also observe bright emission lines [CaII] 7291, 7323 Å, and [2CI] CO. Humphreys et al. (2013) conclude that the star is a warm supergiant, but their parameters AV = 1.5 ± 2.6 mag, T = 7000 ± 9000 K (correspond to F0Ia spectral class) do not agree with our estimates from SED. This spectral class also does not agree with the presence of HeI emission in our spectra, same to the spectra by Massey et al. (2007). The spectrum taken by Humphreys et al. (2013) also shows HeI line, however, it also has signatures of OI λ7774, CaII H and K, TiII blends in absorption. The latter means a lower gas temperature. Probably, the star has very extended atmosphere with a lower wind ionization in outer parts.

The star locates at the B[e]SG region on the JHK diagram. This is the second bright star (together with J004417.10) located in the B[e]SG region (Kraus et al. 2014) that shows a significant brightness variability. We classify this star as a B[e]SG. However, its optical variability is marginal for LBVs (≈ 0.3 mag). A long-term photometric monitoring of the star is needed to confirm its nature.

\textbf{J004526.62+415006.3} Vilardell, Ribas, & Jordi (2006) identified this object as a variable star. Our data suggest its clear LBV-like variability: the star reddens when the brightens (Fig. 4 and Table 2). The photometric variability (ΔV = 1.0 mag) is followed by the spectral one: the spectra by Massey et al. (2007) show numerous FeII emission, weak HeI emission, whereas in our spectra FeII got much weaker or even turned to the absorption and no HeI was detected. Our spectrum is cooler than Massey’s; our SED suggests T = 12000 K, while fitting SED to that from Massey et al. (2007) gives T = 18300 K, given AV = 1.3 ± 0.1. The photometric and spectroscopic variability allow us to classify this object as an LBV.

Humphreys et al. (2014) noticed that the star’s spectrum closely resembles that of J004444.52. However, they did not have information about ∼ 1 mag LBV-like variabi-
ity, which we demonstrate in this paper. This gives us a sign that J004444.52 might also show a strong variability in the future.

Var A-1 Our spectra show broad Balmer lines, bright HeI emission, and numerous strong FeII and [FeII] lines. The spectrum obtained by us is similar to that published by Humphreys et al. (2014). We use three data sets to fit SEDs: that by Humphreys et al. (1984) obtained in 1976, ours described in this paper, and photometry by Massey et al. (2003) from 2000 - 2001. The SED fitting suggests $T=20,400$ K for the maximum brightness by Humphreys et al. (1984), for the intermediate brightness (our data) we find $T=25,000$K, and $T=28,100$K for the minimum (Massey et al. 2006). The estimated temperatures agree with the observed spectral features. The reddening $A_V = 1.8$ mag estimated for the nearby nebula corresponds to our SED estimate ($A_V = 1.7 \pm 0.1$ mag).

AE And Our spectra show broad Balmer lines, and numerous and strong FeII and [FeII] lines. Our spectrum is similar to that shown by Humphreys et al. (2014). We also identify [NiII] 6668, 6813 Å lines, in our spectra, the same lines we find in the spectra published by Szeifert et al. (1996). In the contrast to the spectra by Massey et al. (2007), the [FeII] and [NiII] 5755 Å lines disappear, FeII lines got weaker, and HeI lines are barely seen in our spectra. Due to a good contrast to the spectra by Massey et al. (2007), the [FeIII] lines got stronger, and numerous strong FeII and [FeII] lines. The spectrum obtained by us is similar to that published by Humphreys et al. (1984). We identify two stars J004417.10 and J004444.5 as B[e]-supergiants. They have an excess in the JHK bands, especially prominent in the K. They are located in the B[e]SG region on the JHK diagram (Kraus et al. 2014). Nevertheless, both stars indicated variability, J004417.10 changed its spectrum, whereas J004444.5 changed its optical brightness. Because of the variability we do not exclude that the B[e]SG classification of these stars can be changed in the future.

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Table 3. Results of our SED modeling. The columns show the object name, the photosphere temperature range preliminary estimated from spectra, the best-fit temperature, the reddening, the stellar radius in the solar units, the V-band and bolometric absolute magnitudes.

| Object         | $T_{sp}$, K | $T_{SED}$, K | $A_V$, mag | $R/R_\odot$ | $M_V$, mag | $M_{bol}$, mag |
|----------------|-------------|--------------|------------|-------------|------------|----------------|
| J004051.59     | 18000 - 24000 | 22000±2000   | 1.5±0.1    | 90          | -9.0       | -10.9±0.2     |
| J004350.50     | 10000 - 15000 | 13000±2500   | 2.0±0.2    | 130         | -8.7       | -9.4±0.2      |
| J004417.10     | 15000 - 20000 | 18000±1000   | 1.0±0.2    | 70          | -8.1       | -9.6±0.1      |
| J004444.52     | 15000 - 20000 | 18000±2000   | 3.6±0.1    | 160         | -9.8       | -11.2±0.2     |
| J004526.62     | 10000 - 15000 | 12000±2000   | 1.3±0.1    | 200         | -9.4       | -10.0±0.2     |
| Var A-1        | 20000 - 27000 | 25000±1000   | 1.7±0.1    | 90          | -9.3       | -11.5±0.1     |
| AE And         | 15000 - 20000 | 18000±1000   | 1.0±0.2    | 100         | -8.9       | -10.3±0.2     |

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