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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 the Triplespec spectrograph at the 3.5-m telescope at the Apache Point Observatory, and the optical spectroscopy was carried out using the SCORPIO focal reducer at the 6-m BTA telescope (Special Astrophysical Observatory of the Russian Academy of Science). The candidates demonstrate typical LBV features in their spectra: broad and strong hydrogen lines, and He I, Fe II and [Fe II] lines. All our candidates show photometric variability. We develop a new approach to the estimation of LBV parameters 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 we estimate the 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: emission-line, Be – stars: massive – stars: variables: S Doradus – galaxies: individual: M31 – infrared: stars.

1 INTRODUCTION

Luminous blue variables (LBVs) are massive evolved stars of the highest luminosity. The atmospheres of the stars can be highly unstable at the stages when hydrogen is exhausted. A change in the ionization state of the most abundant elements determines changes in the gas opacity and in the mass-loss rate, and thus it creates a variety of LBV observing manifestations. At the maximum visual brightness, LBVs show the 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]SGs) is still unclear (Kraus et al. 2014): they have comparable luminosities, and are 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 explanation (Humphreys & Davidson 1994; Maeder & Meynet 2000), the LBV is considered to be a transition stage from the main sequence to Wolf–Rayet (WR) stars. The second scenario assumes (Meynet et al. 2011) that an LBV is the final stage of a high-mass star's life before a supernova (SN) explosion. Smith & Tombleson (2015) have also assumed that LBVs could be a product of stellar evolution in binary systems.

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

An LBV is a rare class of star at a particular stage of evolution. Like other massive stars, they tend to reside close to the galactic mid-plane, where it is difficult to study them because of high dust extinctions. An additional problem is the uncertainty in distance estimation, which 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 have been reported in the Milky Way (Vink 2012), 24 in M31 and 37 in M33 (Massey et al. 2007). We have confirmed four LBVs in M33 (Fabrika et al. 2005; Valeev, Sholukhova & Fabrika 2009, 2010). Using the *Spitzer* Space Telescope archival data, one more LBV and several

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

Object	Date/seeing (arcsec)			
	TripleSpec	SCORPIO		
J004051.59	12.10.10 (1.0)	12.09.18 (1.3)	11.10.26 (1.5)	11.11.03 (1.3)
J004350.50	12.10.17 (1.1)	12.09.16 (1.0)	11.11.04 (1.4)	11.11.04 (1.2)
J004417.10	11.09.24 (1.3)	12.09.16 (1.0)	11.10.26 (1.5)	11.11.03 (1.3)
J004444.52	11.09.28 (1.1)	12.07.19 (2.6)	11.11.04 (1.3)	12.01.26 (1.5)
J004526.62	11.09.24 (0.9)	12.07.19 (2.1)	11.10.26 (1.3)	11.11.04 (1.3)
Var A-1	11.09.24 (1.0)	12.09.16 (1.0)	11.10.26 (1.3)	11.11.04 (1.3)
AE And	11.09.28 (1.2)	12.09.16 (1.0)	12.01.27 (2.0)	12.01.26 (1.5)

WNL stars have been found in our Galaxy (Gvaramadze et al. 2009, 2010a,b). Humphreys et al. (2014) added two more LBV candidates to M33 and one more to M31.

Massey et al. (2007) classified LBVs by types from their spectral features: cool, hot and P Cyg LBVs. Humphreys et al. (2014) divided the high-luminosity stars into six classes based on their spectrophotometric features: LBVs, Fe II emission-line stars, Of/late-WN stars, hot supergiants, intermediate-type supergiants and warm hypergiants. van Genderen (2001) selected several optical variability types for LBVs: variables with amplitudes greater than and less than 0.5 mag, ex-/dormant LBVs and candidates.

The majority of LBVs show an infrared (IR) spectral excess, which makes their IR observations favourable. Oksala et al. (2013) and Kraus et al. (2014) proposed a new classification scheme for LBVs based on their near-infrared (NIR) photometry. Massive stars on the $(H-K)$–$(J-H)$ diagram (*JHK* diagram) are subdivided into two groups: B[e]SGs have $(H-K) > 0.7$ mag, and LBVs show $(H-K) < 0.4$ mag. This simple criterion is attractive, although derived from a small sample.

The sample of LBVs with known IR spectra is small, just a few for galactic LBVs (Morris et al. 1996; Voors et al. 2000; Groh, Damineli & Jablonski 2007). Kraus et al. (2014) have presented IR spectra for four LBV candidates, one of which is studied by us in this paper. They have also proposed the use of CO lines for identifying B[e]SGs, and have found two such objects. It is important to collect more NIR spectral observations in order to derive a reliable classification of the highest luminosity stars.

In this paper, we present quasi-simultaneous optical and NIR spectroscopy for LBVs (Var A-1 and AE And) and LBV candidates (J004051.59 + 403303.0, J004350.50 + 414611.4, J004417.10 + 411928.0, J004444.52 + 412804.0, J004526.62 + 415006.3) in the Andromeda galaxy. Here, we refer to the stars using their first RA coordinate. We describe their spectral energy distribution (SED) and check their LBV nature. The objects were selected from Massey et al. (2007), whose list consists of four known LBVs (AE And, AF And, Var 15, Var A-1), two objects Ofpe/WN9, and 18 more LBV candidates. We adopt the distance to M31 of 752 ± 27 kpc (Riess, Fliri & Valls-Gabaud 2012).

2 OBSERVATIONS

Optical spectroscopy and photometry were performed with the SCORPIO focal reducer (Afanasiev & Moiseev 2005) at the BTA 6-m telescope in 2011 October and 2012 October. The observing log is shown in Table 1. The data were reduced using the standard IDL data reduction package.

The NIR spectroscopy was conducted with the TripleSpec spectrograph at the 3.5-m ARC telescope at the Apache Point Observatory in 2011 September and 2012 October. The spectra were reduced using SPEXTOOL (Vacca, Cushing & Rayner 2003; Cushing, Vacca & Rayner 2004).

The *BVR* photometry was observed simultaneously with the optical spectroscopy. We compare our photometry with the *U*, *B*, *V*, *R* and *I* data from Massey et al. (2006) obtained between 2000 October and 2001 October. Some stars have additional photometry data points published to date: for Var A-1 and AE And, we used *U*, *B*, *V*, *R* and *I* photometry from 1976 September, and *JHK* from 1980 November from Humphreys et al. (1984). For J004051.6, Berkhuijsen et al. (1988) published the *U*, *B*, *V*, *R* and *I* photometry from 1963 August–September.

The *JHK* photometry is available from the Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006). To watch the variability, we used two versions of the catalogue: 2MASS-1 (1998 December; Cutri et al. 2003) and 2MASS-2 (2000 November; Cutri et al. 2012). There are also *JHK* magnitudes obtained in 1980 November 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 comparing with five non-variable reference stars in the 5-arcmin guider field (using their 2MASS magnitudes).

The accuracy of our optical photometry is no worse than 0.05 mag. The estimates of Massey et al. (2006) 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 2MASS-2 data have 0.1-mag accuracy. The results of the optical and NIR photometry are summarized in Table 2.

3 RESULTS

3.1 Spectroscopy and spectral energy distributions

Figs 1–3 show the spectra of seven considered stars in six spectral ranges. The principal lines are identified and marked in Figs 1–3: Balmer, Brackett and Paschen lines, as well as He I, He II, Fe II, [Fe II] and Si II lines. Some of these lines demonstrate P Cyg-type profiles. The spectra are typical for LBV stars. Object J004417.10 has ^{12}CO 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

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 2000 October and 2001 October, and the *J*, *H* and *K* from 2MASS-1 and 2MASS-2 (Cutri et al. 2003, 2012), obtained in 1998 December and 2000 November, respectively. The third line shows the data from Berkhuijsen et al. (1988) for J004051.6 (1963 August–September) and from Humphreys et al. (1984) for Var A-1 and AE And (optical photometry from 1976 September, and *J*, *H* and *K* from 1980 November). 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	16.769	16.576	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				15.03 ± 0.2
	16.92	17.662	17.36	17.02	16.920	15.93/16.62	15.76/15.84	15.13/15.37
		17.14	16.77	16.47				15.5 ± 0.2
Var A-1	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
		16.77	16.57	16.31				15.9 ± 0.09
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			

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_{sp} in Table 3). We used the simple criteria of the line relative intensities (He I, He II 4686 Å and Fe II) in the spectra (Jacoby, Hunter & Christian 1984). Next, the optical spectra were fitted with a Planck function taking into 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 is comparatively low, given the T_{sp} ranges, we can constrain the extinction A_V rather tightly. We also used the Balmer line ratio Hα/Hβ in the case of Var A-1 and J004350.50 to estimate the reddening A_V of surrounding nebulas, (e.g. Valeev et al. 2009). All estimates mentioned above were used as the initial parameters for the further SED fitting.

The LBV-type variability allows us to break the degeneracy problem when the star becomes 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 ($\sigma T^4 4\pi R^2$, where R is the stellar radius) is a correct assumption.

We conclude that four objects out of seven in our sample show such a slow and large variability. In this case, we can fit SEDs for different data sets, assuming that the interstellar reddening $A_V =$ const. Assuming $T^4 R^2 =$ const, we can estimate the photospheric temperature from the known *V* magnitude in a new state of the star. Fitting the SEDs, we use a blackbody 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 temperatures, radii and absolute magnitudes in the *V*-band and bolometric.

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

3.2 Notes on individual objects

J004051.59+403303.0

The brightness and colour were estimated by Berkhuijsen et al. (1988), who found that in 1963 it had $V = 17.43 \pm 0.18$, and by Magnier et al. (1992), who found that in 1990 it had $V = 17.33$, $(B - V) = 0.09$. Our estimate, $V = 16.99 \pm 0.05$, is consistent with that of Massey et al. (2006). The collected photometry suggests a gradual increase of stellar optical brightness. Our optical spectrum is similar to that published by Massey et al. (2006): it has absorption He I, Fe II and Si II 6347, 6371 Å lines. The brightest Fe II lines have P Cyg profiles. There are weak [Ca II] 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 are confirmed by the Magnier

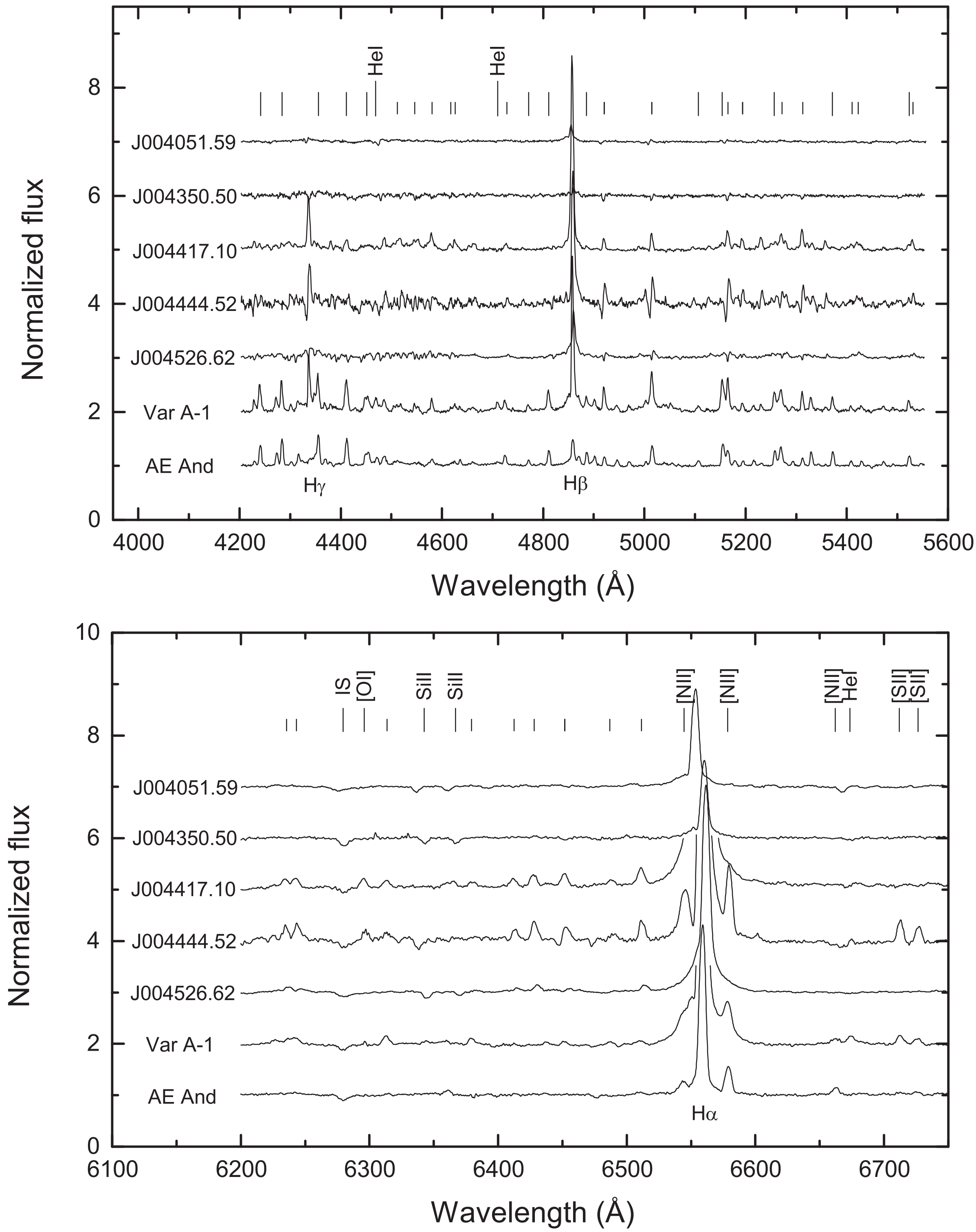

Figure 1. Spectra of J004051.59, J004350.50, J004417.10, J004444.52, J004526.62, Var A-1 and AE And in the optical spectral ranges. The principal strongest lines are identified. The unlabelled short and long tick marks designate the Fe II and [Fe II] lines, respectively. The spectra are left on their original wavelength scale.

et al. (1992) data. The photometric variability of this object between its two states ($\Delta\ U = 0.49$, $\Delta\ B = 0.46$) 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 might belong to the LBV class.

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)

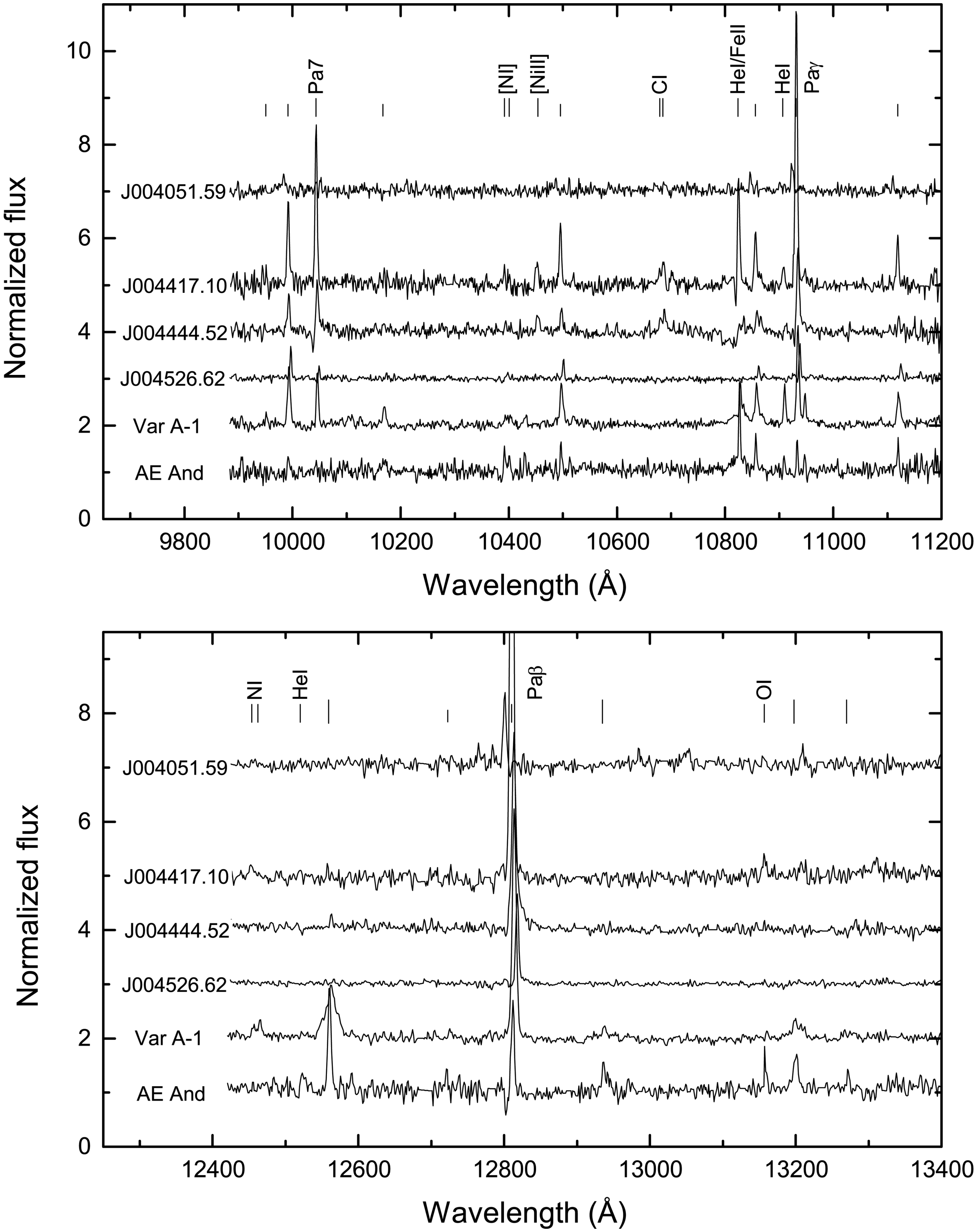

Figure 2. Same as in Fig. 1 but in the *J* NIR range. The IR spectrum of J004350.50 is not shown.

($\Delta B = \Delta V = 0.16$ with uncertainty under 0.01 mag). Our spectra are similar to those by Massey et al. (2007). They have broad Balmer emission lines. Fe II lines have P Cyg profiles, but He I and Si II lines are in the absorption. The interstellar reddening estimated using the emission from surrounding H II regions $A_V = 1.6$ 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 might belong to the LBV class. The star is similar to an LBV in its spectra and luminosity. However, its relatively small brightness variations resemble those of α Cyg type, which might be caused by fluctuations in the stellar wind. The brightness variation

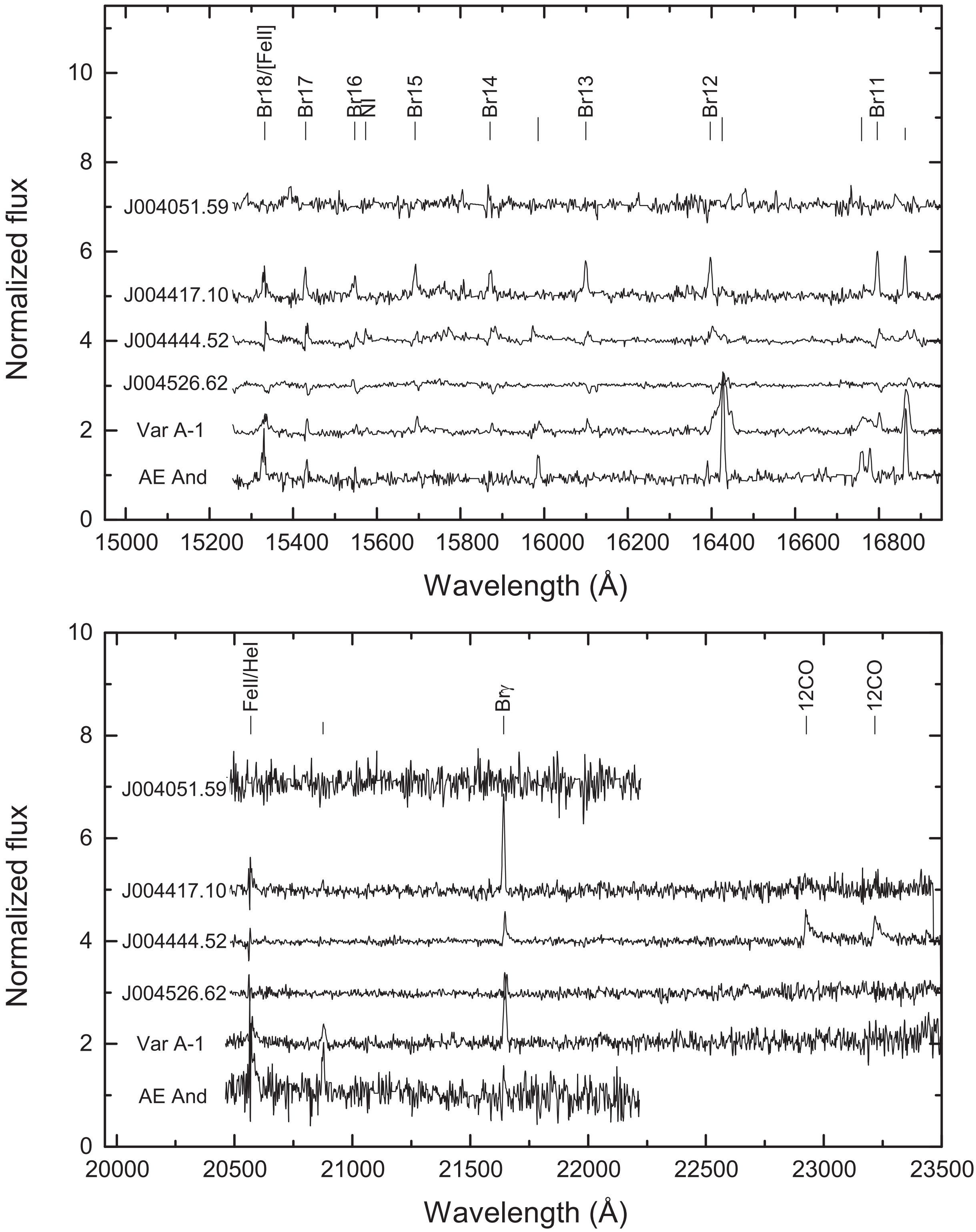

Figure 3. Same as in Fig. 1 but in the *H* and *K* NIR ranges. The IR spectrum of J004350.50 is not shown.

amplitude seen up to date does not allow us to classify the star as an LBV. The star might be a dormant LBV, but its nature is not clear yet. It remains an LBV candidate. We need to look at more additional criteria (e.g. to study helium content in its wind) to verify the star's LBV classification.

J004417.10+411928.0

This 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 He I 5876 Å while it was not seen in 1995 September by King, Walterbos & Braun (1998). In addition,

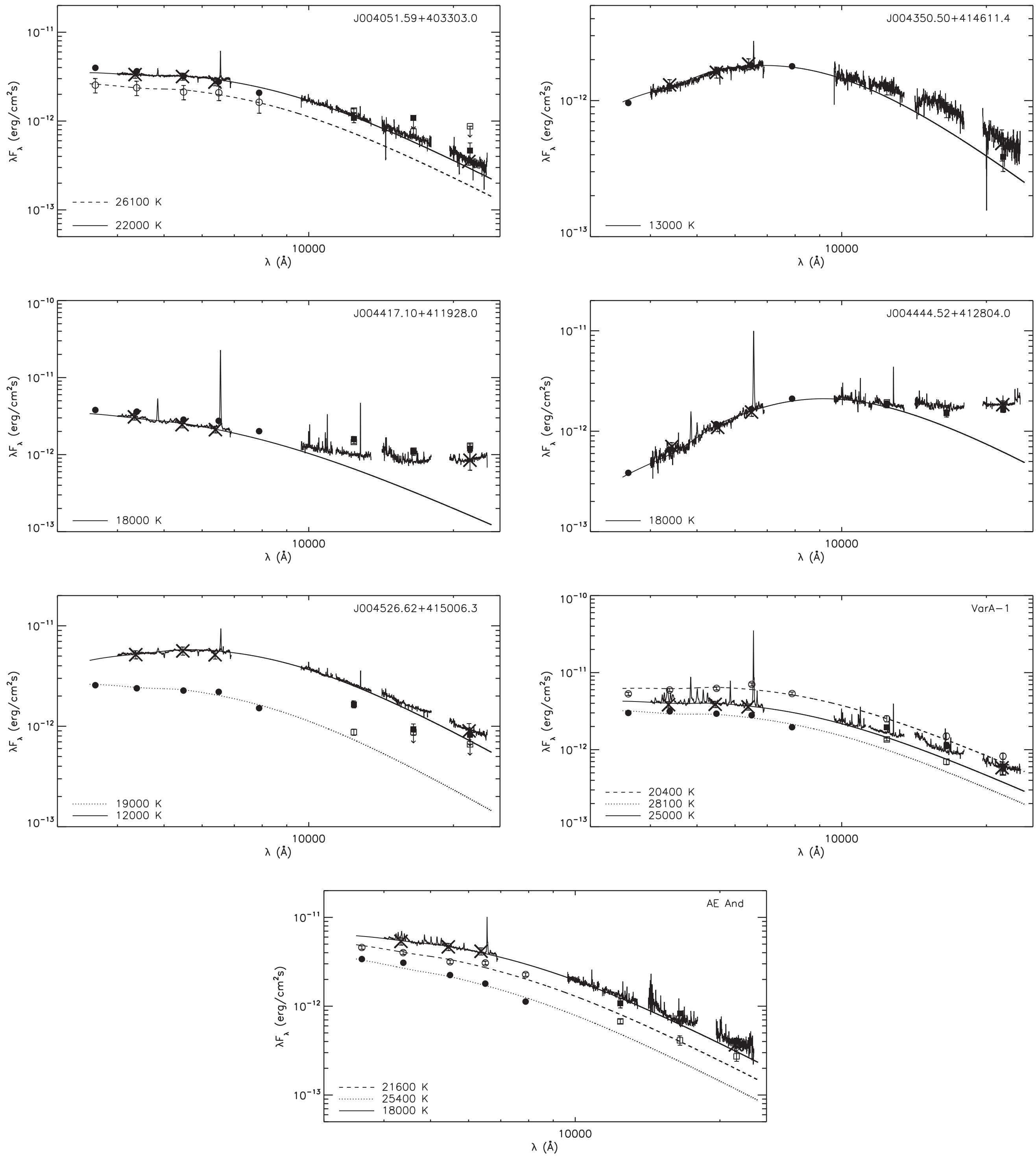

Figure 4. SED modelling. Crosses indicate the *B*, *V*, *R* and *K* photometry observed simultaneously with our spectra, filled circles are the data by Massey et al. (2006), open circles are data from Humphreys et al. (1984) and Berkhuijsen et al. (1988); see Table 2. Filled and open squares are the data from 2MASS-1 and 2MASS-2 (Cutri et al. 2003, 2012), respectively. The curves designate the blackbody approximation with reddening applied according to Table 1. The solid curves show our fits to the optical part of our spectra, the dashed curves show the fits to the data of Humphreys et al. (1984) and Berkhuijsen et al. (1988), and the short dashes show the fits to the data of Massey et al. (2006). The IR excesses are clearly seen in the stars. The best-fitting temperatures are indicated in the legends of each panel.

Fe II emission lines became significantly brighter than in the spectra from Massey et al. (2007). Our spectra show bright lines [Ca II] 7291, 7323 Å, which suggests that a warm dust envelope surrounds the star. Kraus 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 the variability of these lines. This was noticed before in the case of HR Car by Morris et al. (1997). From the presence of [Ca II] and CO lines, and from the location at the B[e]SG

Table 3. Results of our SED modelling. The columns show the object name, the photosphere temperature range preliminarily estimated from spectra, the best-fitting temperature, the reddening, the stellar radius in the solar units and 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	18 000–24 000	22 000 ± 2000	1.5 ± 0.1	90	−9.0	−10.9 ± 0.2
J004350.50	10 000–15 000	13 000 ± 2500	2.0 ± 0.2	130	−8.7	−9.4 ± 0.2
J004417.10	15 000–20 000	18 000 ± 1000	1.0 ± 0.2	70	−8.1	−9.6 ± 0.1
J004444.52	15 000–20 000	18 000 ± 2000	3.6 ± 0.1	160	−9.8	−11.2 ± 0.2
J004526.62	10 000–15 000	12 000 ± 2000	1.3 ± 0.1	200	−9.4	−10.0 ± 0.2
Var A-1	20 000–27 000	25 000 ± 1000	1.7 ± 0.1	90	−9.3	−11.5 ± 0.1
AE And	15 000–20 000	18 000 ± 1000	1.0 ± 0.2	100	−8.9	−10.3 ± 0.2

region on the *JHK* diagram, Kraus et al. (2014) have concluded that this object is a B[e]SG star. Humphreys et al. (2014) classify it as a Fe II-emission line star. Our results confirm these two conclusions.

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

J004444.52+412804.0

The variability of this star ($\Delta B = 0.27$, $\Delta V = 0.22$) was noticed in the DIRECT project (Stanek et al. 1999). Vilardell et al. (2006) confirmed the variability with amplitudes of $\Delta B = 0.30$ and $\Delta V = 0.25$ between 1999 and 2003. Their mean magnitudes correspond to those measured by us (Table 2). Our spectrum is almost identical to that of Massey et al. (2007) and similar to that of Humphreys et al. (2013, 2014). The spectra have emission lines Fe II and [Fe II]. Helium lines 5876 and 6678 Å have P Cyg profiles. We also observe bright emission lines [Ca II] 7291, 7323 Å, and ^{12}CO. Humphreys et al. (2013) conclude that the star is a warm supergiant, but their parameters $A_V = 1.5$–2.6 mag, $T = 7000$–9000 K (corresponding to the F0Ia spectral class) do not agree with our estimates from the SEDs. Also, this spectral class does not agree with the presence of He I emission in our spectra, similar to the spectra by Massey et al. (2007). The spectrum taken by Humphreys et al. (2013) also shows the He I line, but it also has signatures of O I λ7774, Ca II H & K, Ti II blends in absorption. The latter means a lower gas temperature. Probably, the star has a very extended atmosphere with a lower wind ionization in the outer parts.

The star is located 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.

J004526.62+415006.3

Vilardell et al. (2006) identified this object as a variable star. Our data suggest its clear LBV-like variability: the star reddens when it brightens (Fig. 4 and Table 2). The photometric variability ($\Delta V = 1.0$ mag) is followed by the spectral variability: the spectra by Massey et al. (2007) show numerous Fe II emission, weak He I emission, whereas in our spectra Fe II became much weaker or even turned to the absorption and no He I was detected. Our spectrum is cooler than that of Massey et al. (2007): our SED suggests $T = 12\,000$ K, while fitting the SED to that from Massey et al. (2007) gives $T = 18\,300$ K, given $A_V = 1.3 \pm 0.1$. The photometric and spectroscopic variability allow us to classify this object as an LBV.

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

Var A-1

Our spectra show broad Balmer lines, bright He I emission and numerous strong Fe II and [Fe II] 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, our data set described in this paper and photometry by Massey et al. (2006) 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 Fe II and [Fe II] lines. Our spectrum is similar to that shown by Humphreys et al. (2014). We also identify [Ni II] 6668, 6813 Å lines, in our spectra, the same lines we find in the spectra published by Szeifert et al. (1996). In contrast to the spectra by Massey et al. (2007), the [Fe III] and [N II] 5755 Å lines disappear, the Fe II lines become weaker and the He I lines are barely seen in our spectra. As a result of the good number of photometric data points and the strong variability of the star, we can employ the data for three epochs that are well separated in time: our data, the photometry by Massey et al. (2006) for 2000–2001 and the photometry by Humphreys et al. (1984) for 1976. The obtained temperatures are in good agreement with the brightness and the spectral features seen in each data set. Our spectra indicate the coolest temperature ($T = 18, 000$ K), the hottest temperature is found for the data of Massey et al. ($T = 25$, 400 K) and the intermediate temperature is found for the data of Humphreys et al. ($T = 21$, 600 K). We find $A_V = 1.0 \pm 0.1$ mag. Because our analysis is based on the data sets corresponding to the different states of the LBV stars, we believe that the parameters we have derived are more reliable.

4 CONCLUSIONS

We develop a new method of SED fitting applicable for LBV stars. It breaks a well-known reddening–stellar temperature degeneracy by an additional assumption that the bolometric luminosity remains constant while the optical *V* brightness can vary significantly. This is an inherent property of LBVs to change their spectral type while keeping the bolometric luminosity constant. Having the bolometric luminosity and the reddening fixed, we calculate the *V* magnitudes and the stellar temperatures for different states of LBVs. Our approach is successfully verified with two known LBVs in the Andromeda galaxy: Var A-1 and AE And.

All the considered LBV candidates show spectra typical for either LBVs or B[e]SGs. The luminosity ranges are in agreement with those for known LBVs in M31. All the stars show brightness variability, both in our data set and in the literature data. In two stars, J004417.10 and J004526.62, we have also detected spectral variability. We conclude that two studied stars, J004051.59 and J004526.62, are LBVs, because they show significant brightness variability. Because J004350.50 does not show sufficient variability, we cannot classify the star confidently, although in its spectrum, luminosity and location in the *JHK* diagram, the star is similar to LBVs. The star does not show an obvious LBV-like variability and therefore it remains an LBV candidate. It would be necessary to use additional criteria (e.g. helium content) to clarify its nature.

We identify two stars, J004417.10 and J004444.5, as B[e]SGs. They have an excess in the *JHK* bands, especially prominent in *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 the possibility that the B[e]SG classification of these stars could be changed in the future.

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