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DISCOVERY OF THE FIRST B[e] SUPERGIANTS IN M 31*

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ABSTRACT

B[e] supergiants (B[e]SGs) are transitional objects in the post-main sequence evolution of massive stars. The small number of B[e]SGs known so far in the Galaxy and the Magellanic Clouds indicates that this evolutionary phase is short. Nevertheless, the strong aspherical mass loss occurring during this phase, which leads to the formation of rings or disk-like structures, and the similarity to possible progenitors of SN1987 A emphasize the importance of B[e]SGs for the dynamics of the interstellar medium as well as stellar and galactic chemical evolution. The number of objects and their mass-loss behavior at different metallicities are essential ingredients for accurate predictions from stellar and galactic evolution calculations. However, B[e]SGs are not easily identified, as they share many characteristics with luminous blue variables (LBVs) in their quiescent (hot) phase. We present medium-resolution near-infrared *K*-band spectra for four stars in M 31, which have been assigned a hot LBV (candidate) status. Applying diagnostics that were recently developed to distinguish B[e]SGs from hot LBVs, we classify two of the objects as bonafide LBVs; one of them currently in outburst. In addition, we firmly classify the two stars 2MASS J00441709+4119273 and 2MASS J00452257+4150346 as the first B[e]SGs in M 31 based on strong CO band emission detected in their spectra, and infrared colors typical for this class of stars.

Key words: circumstellar matter – infrared: stars – stars: early-type – stars: massive – supergiants

Online-only material: color figure

1. INTRODUCTION

Massive stars ($>8\,M_\odot$), though few in number, play a fundamental role in the evolution of their host galaxies. Via high-density stellar winds, these objects strongly enrich the interstellar medium with chemically processed material, and deposit large amounts of momentum and energy into their surroundings during their entire lifetime, until they explode as spectacular supernovae. The post-main sequence evolution of massive stars contains several short-lived transition phases, in which stars undergo strong mass loss and mass ejections. The mass loss during each phase greatly drives the subsequent evolution of the star (e.g., Maeder et al. 1980; Meynet & Maeder 2005; Georgy 2012). However, the amount of mass lost in each transition phase is still highly uncertain as it depends on many parameters, such as stellar rotation, metallicity, magnetic fields, etc., several of which are still poorly constrained. Hence, for accurate predictions from stellar evolution calculations, detailed knowledge of the properties of these massive stars in transition is of vital importance (e.g., Langer et al. 1994; Puls et al. 2008; Langer 2012).

Two types of massive stars in transitional evolutionary stages, which occupy and share the upper-left domain in the Hertzsprung–Russell (H-R) diagram, are particularly puzzling: luminous blue variables (LBVs) and B[e] supergiants (B[e]SGs). Stars in both groups are rare (e.g., Clark et al. 2013b), indicating that these intermediate stages have rather short lifetimes. Nevertheless, these are extremely important objects as they undergo strong, often asymmetric mass loss, driving the dynamics and chemical evolution of the interstellar medium, as well as dust formation in their circumstellar environments. The ejected material of LBVs usually accumulates in either elliptic or bipolar nebulae of ionized gas (e.g., Nota et al. 1995; Weis 2003), often with indication for clumped wind structures (Davies et al. 2005), and cool dusty rings (Clark et al. 2003). On the other hand, B[e]SGs have dense, high-ionized polar winds and equatorial rings or disks (Zickgraf et al. 1986), which are detached from the star and consist of low-ionized or neutral atomic material (Kraus et al. 2007, 2010; Aret et al. 2012) and hot molecular gas and warm dust (e.g., McGregor et al. 1988; Morris et al. 1996; Kastner et al. 2006, 2010; Meilland et al. 2010; Cidale et al. 2012; Wheelwright et al. 2012; Kraus et al. 2013). The mass ejection and disk formation mechanisms in both types of stars are still largely unknown, however, it has been suggested that binarity, rapid rotation, or stellar pulsations might play a significant role.

LBVs undergo episodic mass loss and eruptions. They typically occur in two “flavors”, hot and cool (following the notation of Massey et al. 2007). Cool LBVs are in “outburst”, and as such undergo an excursion to the red side of the H-R diagram, i.e., they appear to evolve from a hot into a cool supergiant and simultaneously brighten until they reach visual maximum when approaching the cool edge. At visual minimum, LBVs reside on the blue side, where they are considered to be in their hot or “quiescent” phase. These periodic outbursts (so-called S-Dor cycles) happen on timescales of months to years. On much longer timescales (of a thousand years), LBVs may experience phases of very strong or eruptive mass loss.

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Several B[e]SGs are found to show some sort of variability and sudden, enhanced mass loss similar to what is reported for LBVs (e.g., Kraus et al. 2010; Aret et al. 2012; Oksala et al. 2012; Torres et al. 2012; Clark et al. 2013a), suggesting an evolutionary link, with B[e]SGs as either the progenitors or the descendants of LBVs (e.g., Stothers & Chin 1996). While evolutionary calculations fail so far to predict the B[e]SG phase, the enrichment of the disk material in ^{13}CO, which reflects the stellar surface enrichment in ^{13}C, suggests that most (if not all) B[e]SGs are in an evolutionary stage just beyond the main sequence (Oksala et al. 2013). No information on the ^{13}C surface enrichment is available for LBVs, so that other criteria for a possible link need to be considered. The occurrence of the LBV phase in the evolution of massive stars depends on the stellar mass (e.g., Meynet et al. 2011). Stars with initial masses lower than $\sim$40 $M_{\odot}$ turn into LBVs as post-red supergiants, and it seems that these low-luminosity LBVs could directly explode as core-collapse supernovae of Type II (Groh et al. 2013). In this scenario, a direct LBV progenitor or descendant stage for B[e]SGs appears unlikely. However, a star in this mass range can pass through a B[e]SG phase before evolving into a red supergiant. Stars with higher initial masses turn into LBVs much earlier, i.e., already during their redward evolution. B[e]SGs lack extended large-scale structures that might be identified with LBV nebula remnants, rendering it questionable that they could be LBV descendants. On the other hand, B[e]SGs have been suggested to be the predecessor of blue supergiants with bipolar ring nebulae, in which the hot molecular disk material has expanded and cooled and condensed into dust particles (Smith et al. 2007). Two well-known representatives of such blue supergiants are SBW1 and Sher 25, and both of them are in turn very similar to the precursor of SN1987A (Smith et al. 2013; Hendry et al. 2008, respectively). Notably, Clark et al. (2013a) recently suggested the B[e]SG S18 in the Small Magellanic Cloud to be a viable SN1987A progenitor candidate. Hence, B[e]SGs might themselves be supernova progenitors without evolving through an LBV phase.[5] Whether all high-luminosity B[e]SGs will directly evolve into SN1987A progenitors, or whether maybe a subset might indeed become LBVs, is currently unknown, but underlines the need for larger samples of these rare objects.

Identification of members of these two groups can be quite difficult. The best known sample of B[e]SGs to date is located in the Magellanic Clouds, while unambiguous classification of Galactic counterparts is usually hampered by the lack of proper distances (and hence luminosity values), so that they can be easily confused with other objects surrounded by dense disks, such as the Herbig Ae/Be stars, unless near-infrared spectra display emission from ^{13}CO (see Kraus 2009). B[e]SGs are found exclusively on the luminous, blue side of the H-R diagram, and their optical spectra are practically indistinguishable from those of hot LBVs, as both types of stars display strong line emission formed in their dense circumstellar matter (King et al. 1998; Massey et al. 2007; Clark et al. 2012). Classification of bonafide LBVs without evidence of a giant eruption is particularly difficult, and requires both long-term and multi-wavelength monitoring. Much effort has been undertaken in recent years to resolve massive star populations and, in particular, to identify LBVs and B[e]SGs in the Milky Way and Local Group Galaxies (e.g., Massey et al. 2007; Gvaramadze et al. 2010; Wachter et al. 2010; Clark et al. 2012) for obvious reasons: (1) samples of these rare objects are increased, which is vital to improve our understanding of stellar evolution of massive stars in general, and to study evolutionary connections between LBVs and B[e]SGs in particular, (2) extragalactic B[e]SGs are easily distinguished from, e.g., Herbig stars due to well constrained distances, and hence luminosities, and (3) the occurrence of these particular evolutionary phases can be studied as a function of metallicity. Potential LBVs are identified by searching for stars that are spectroscopically indistinguishable from known LBVs. These stars are called "LBV candidates." However, given the difficulties in disentangling spectroscopically between hot LBV candidates and B[e]SGs, every hot LBV candidate is at the same time also a B[e]SG candidate.

In a recent near-infrared survey, Oksala et al. (2013) reveal that hot LBVs and B[e]SGs have clearly distinct infrared characteristics. The two groups populate discrete regions in the $J-H$ versus $H-K$ color–color diagram, due to the larger amount of hot dust in the environment of B[e]SGs. Furthermore, while both types of stars display practically identical emission features in their K-band spectra, the study found CO emission only in stars classified as B[e]SGs, likely a consequence of their massive, stable dusty disks, which allow molecules to form at significant rates for easily detectable emission. Although a few B[e]SGs were found to lack CO band emission, the presence of these molecular bands in combination with near-infrared colors typical for B[e]SGs provide clear evidence for a B[e]SG rather than an LBV nature of the star.[6] These two characteristics hence seem to provide an ideal tool to separate B[e]SGs from hot LBVs, and we apply it to identify B[e]SGs in Local Group Galaxies, which are hidden in hot LBV candidate samples. In this Letter we present our first results on four objects in M 31.

2. OBSERVATIONS

We selected four stars in M 31 with Two Micron All Sky Survey (2MASS) object names J00404307+4108459, J00433308+4112103, J00441709+4119273, and J00452257+4150346. Three were identified by Massey et al. (2007) as hot LBV candidates, while J00433308+4112103 (=AF And) is a bonafide LBV (Hubble & Sandage 1953). K-band spectroscopic observations of the targets were obtained in 2013 August and October at GEMINI North with the GEMINI Near InfraRed Spectrograph (GNIRS). Using the longslit mode with the 0$''$.30 slit, the short camera, and the 110 l mm^{-1} grating, we achieved a resolving power of $\sim$5900 and a wavelength coverage from 2.23 to 2.40 μm. Several ABBA sequences (nodding along the slit) were taken for each target. An early A-type star (close to the target in position and airmass) was observed immediately before or after each sequence for telluric absorption correction. Flats and arcs were taken with each source. We used IRAF[7] software package tasks to extract and calibrate the spectra. The data reduction steps included subtraction of the AB pairs, flatfielding, telluric-correction, and wavelength calibration. Finally, the spectra were corrected for heliocentric and systemic velocities, and normalized. Observation details are listed in Table 1.

[5] We would like to stress that despite the fact that some B[e]SGs display variabilities that might be associated with LBV behavior (such as S18, see, e.g., Clark et al. 2013a), none of them was so far observed to perform S-Dor-like cycles, i.e., none appeared as a cool supergiant. Hence, they are (still) considered "real" (or typical) B[e]SGs.

[6] The star HR Car is unique, as it is the only LBV with occasional, highly variable CO band emission (Morris et al. 1997). However, its JHK magnitudes position it clearly in the LBV corner of the color–color diagram.

[7] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

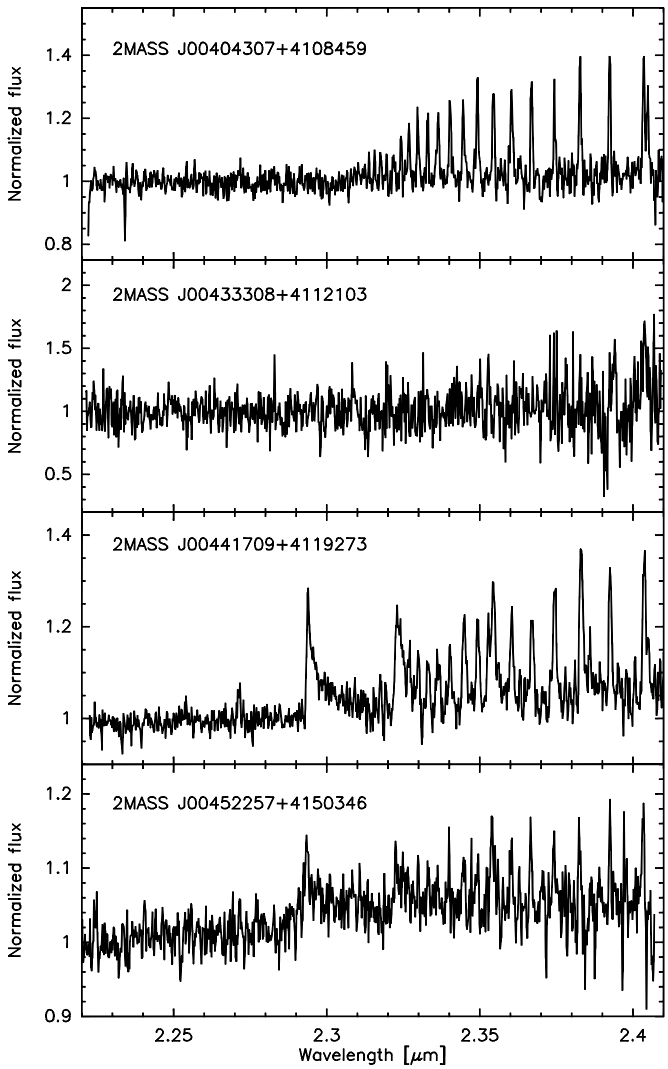

Figure 1. Normalized K-band spectra of sample stars in M 31 obtained with the GNIRS near-infrared spectrograph.

Table 1
Observations

2MASS Object Name	K_s[a]	T_{exp}	S/N
J00404307+4108459	15.300	1.22 hr	30
J00433308+4112103	15.406	1.12 hr	9
J00441709+4119273	14.728	1.26 hr	50
J00452257+4150346	15.415	1.80 hr	35

Note. [a] Magnitudes are from the 2MASS point source catalog (Cutri et al. 2003).

3. RESULTS

The final normalized K-band spectra of the objects are shown in Figure 1. The spectra of J00441709+4119273 and J00452257+4150346 clearly display CO band emission and emission from the hydrogen Pfund series. J00404307+4108459 only shows emission from the Pfund series. The spectrum of J00433308+4112103 is rather noisy, but there is no evidence for either CO band or Pfund line features. We model the emission of the Pfund line series (Section 3.1) and the two molecular components ^{12}CO and ^{13}CO (Section 3.2); the best model fits to the observations are shown in Figure 2.

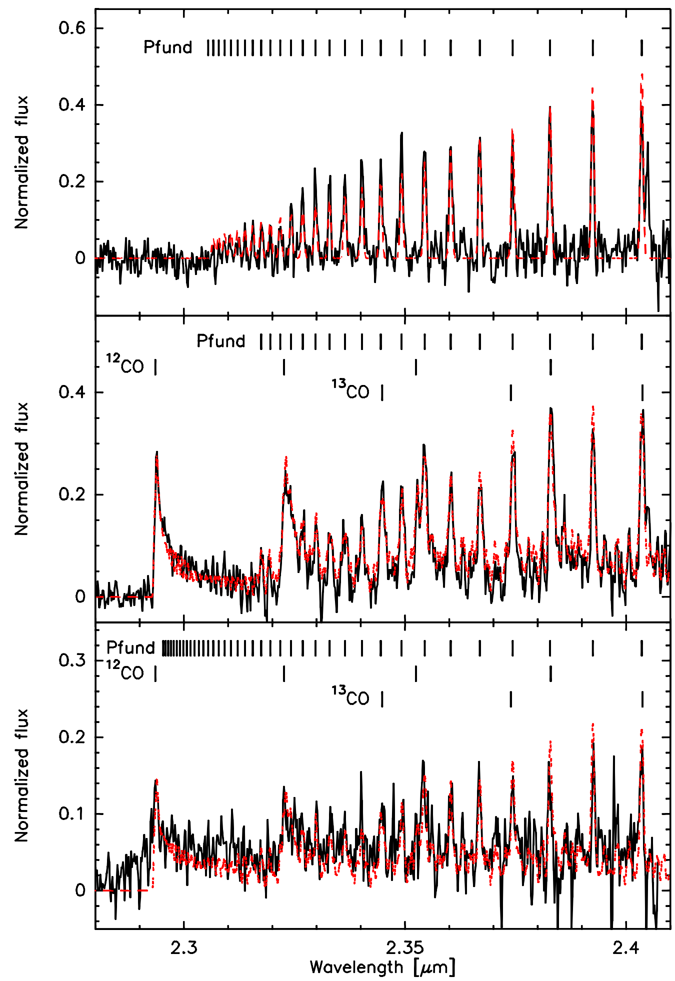

Figure 2. Fit (gray/red in the online version) to the continuum subtracted Pfund line spectrum of J00404307+4108459 (top) and to the CO band plus Pfund line spectra of J00441709+4119273 (middle) and J00452257+4150346 (bottom). The ticks mark the wavelengths of the hydrogen Pfund lines and of the ^{12}CO and ^{13}CO band heads.

(A color version of this figure is available in the online journal.)

3.1. Pfund Line Emission

Typically, emission from the hydrogen Pfund series originates from a dense wind. This high-density environment can lead to pressure ionization effects, and hence to a sharp cut-off in the maximum number of detectable Pfund lines. We model the Pfund recombination line spectra using the code developed by Kraus et al. (2000). The line emission is not sensitive to the electron temperature. We therefore fix the temperature at $T_e = 10{,}000$ K, which is a typical value for an ionized wind. The line profiles show no indication for rotational broadening beyond the spectral resolution of $\sim$50 km s^{-1}. We thus adopt a pure Gaussian profile, which is a reasonably good approximation for optically thin recombination lines formed in a stellar wind.

3.2. CO Band Emission

We model the emission from the CO first-overtone bands using the code developed by Kraus et al. (2000), extended by Kraus (2009) and Oksala et al. (2013). The appearance of the band heads is caused by the superposition of many individual ro-vibrational CO lines. Profiles of the ro-vibrational lines are typically double-peaked, indicating that the emission

Table 2
Best Fit Model Parameters

Object	Pfund Lines				CO Bands			
	$v_{\mathrm{gauss,Pf}}$ (km s^{-1})	T_e (K)	n_{max}	n_e (cm^{-3})	$v_{\mathrm{rot,CO}} \sin i$ (km s^{-1})	T_{CO} (K)	N_{CO} (10^{21} cm^{-2})	^{13}C/^{12}C
J00404307+4108459	50 ± 5	10,000	47	1.8×10^{13}	...	...	...	...
J00441709+4119273	70 ± 10	10,000	39	5.7×10^{13}	50 ± 5	1850 ± 150	1.5 ± 0.5	7 ± 2
J00452257+4150346[a]	70 ± 10	10,000	~60	~4.3×10^{12}	50 ± 5	1850 ± 150	1.3 ± 0.7	7 ± 2

Note. [a] Due to the poor quality of the spectrum, the derived values are only rough estimates.

originates from a (Keplerian) rotating disk or ring, and the first CO band head, appearing at 2.3 μm, displays a characteristic structure consisting of a blue shoulder and a red peak (see, e.g., Kraus et al. 2000). In the spectrum of J00441709+4119273, the first CO band head lacks this characteristic structure indicative of rotational broadening. Consequently, any present rotational velocity, projected to the line of sight, must be comparable or smaller than the spectral resolution, and we obtain a reasonably good fit for $v_{\mathrm{rot,CO}} \sin i = 50 \pm 5\,\mathrm{km\,s^{-1}}$. No satisfactory fit was obtained when using a pure Gaussian profile for the individual ro-vibrational lines, excluding a spherical wind or shell as the location of the CO molecules. The spectrum of J00452257+4150346 is too noisy to make any inferences about the shape of its first band head, but, as the spectral features look very similar to those in J00441709+4119273, we adopt the same rotational broadening. From the strength of the higher band heads and the level of the quasi-continuum in between them, we obtain the molecular temperature and column density. The spectra also contain emission from the molecular isotope ^{13}CO, and we determine a value of 7 ± 2 for the ^{12}CO/^{13}CO ratio in both stars. This value mirrors the stellar surface enrichment in ^{12}C/^{13}C at the time of mass ejection. The complete set of model parameters derived from the fitting is given in Table 2. The CO emitting regions are confined to relatively cool but dense rotating rings of material, detached from the surface of the star, as was also found in Galactic and Magellanic Cloud B[e]SGs (e.g., Liermann et al. 2010; Cidale et al. 2012; Kraus et al. 2013; Oksala et al. 2013).

3.3. Color–Color Diagram

According to Oksala et al. (2013), LBVs and B[e]SGs are located in distinct regions in the $J-H$ versus $H-K$ color–color diagram (Figure 3). Using the colors of the sample stars, obtained from the *JHK* magnitudes from the 2MASS point source catalog (Cutri et al. 2003), with the exception of J00452257+4150346 whose J and H band magnitudes are taken from Humphreys et al. (2013), and plotting them together with the objects from Oksala et al. (2013) demonstrates that two objects, J00441709+4119273 and J00452257+4150346, reside in the region populated by B[e]SGs. The star J00433308+4112103 falls into the LBV corner of the color–color diagram, confirming its bonafide LBV status. The location of J00404307+4108459 is difficult to ascertain as for this star only the K-band magnitude is accurately known. Its J- and H-band values, and hence $H-K$, are only upper limits. The $H-K$ value is smaller than those of typical B[e]SGs, indicating that J00404307+4108459 might belong to the group of hot LBVs.

4. DISCUSSION AND CONCLUSIONS

We present near-infrared spectra of three hot LBV candidates and one bonafide LBV star in M 31. The chosen spectral range

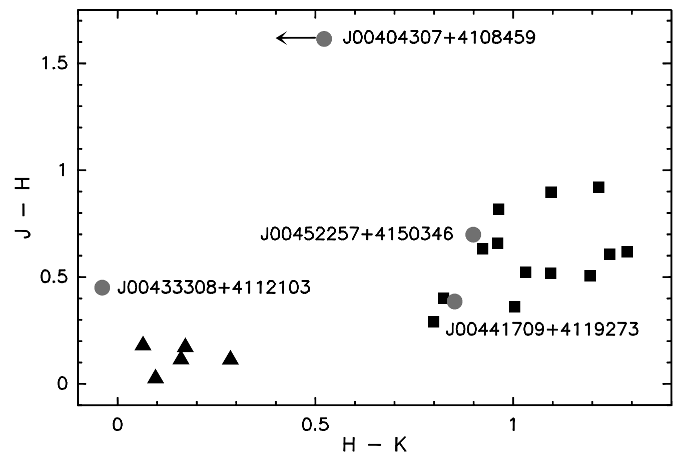

Figure 3. $J-H$ vs. $H-K$ color–color diagram. Values of known B[e]SGs (squares) and LBVs (triangles) are taken from Oksala et al. (2013). Our sample stars are plotted as circles. The $H-K$ value of J00404307+4108459 is an upper limit; its $J-H$ value is uncertain.

covers the wavelength region of the CO bands. Although not all confirmed B[e]SGs do show CO band emission, their presence is an encouraging indication of a B[e]SG (Oksala et al. 2013). A further, necessary criteria for classification as a B[e]SG is provided by the star's position in the $J-H$ versus $H-K$ color–color diagram, in which LBVs and B[e]SGs populate clearly distinct regions.

The bonafide LBV star in our sample, J00433308+4112103, shows no indication for CO band emission, and its *JHK*-band magnitudes place it into the LBV corner of the color–color diagram, confirming its LBV status. Furthermore, while Massey et al. (2007) caught the star in its hot phase, its current featureless near-infrared spectrum resembles that of LHA 120-S 155, an LBV in the LMC found in outburst (Oksala et al. 2013), indicating that J00433308+4112103 is currently also in outburst.

Not much is known at present about the object J00404307+4108459. Based on its optical spectra, Massey et al. (2007) classify it as hot LBV candidate. Its near-infrared spectrum clearly displays emission from the hydrogen Pfund series, but no indication for CO band emission. As not all B[e]SGs show CO band emission, the absence of CO bands alone does not prohibit per se a B[e]SG nature of the object. However, considering the location of the star in the infrared color–color diagram, which falls clearly outside the typical region for B[e]SGs, we can classify this star as a hot LBV.

CO emission has been detected in the objects J00441709+4119273 and J00452257+4150346, suggesting that these stars are in fact B[e]SGs. In an earlier study, King et al. (1998) mention that the star J00441709+4119273 (which they named k350) shares many characteristics with B[e]SGs, but as their optical spectrum does not show forbidden emission lines, these authors tentatively classify J00441709+4119273 as an LBV candidate. In contrast, the higher quality optical spectrum of Massey et al. (2007) shows these forbidden lines, typical criteria for B[e]SGs. Massey et al. (2007) also saw forbidden line emission in the spectrum of J00452257+4150346. This object was recently included in the study of Humphreys et al. (2013), who suggest that the star is a warm hypergiant of spectral type A1 Ia, similar to the yellow hypergiants. However, yellow hypergiants with CO band emission are found in an area close to the LBVs in the color–color diagram, and usually lack Pfund line emission (Oksala et al. 2013). Based on the clear presence of CO band emission in our near-infrared spectra, and the location of the stars in the B[e]SG domain of the color–color diagram, we firmly classify J00441709+4119273 and J00452257+4150346 as the first B[e]SGs identified in M 31.

The discovery of B[e]SGs in M 31 opens new perspectives in studying members of this enigmatic group, which seem to be linked to progenitors of supernovae of type SN1987 A. With a metallicity about twice solar (e.g., Sanders et al. 2012), M 31 is an ideal laboratory for testing massive star evolutionary models at high metallicity. The ^{13}CO enrichment of the circumstellar material found from our analysis is stronger than that typically found in Galactic and Magellanic Cloud B[e]SGs (e.g., Oksala et al. 2013). As the evolution of massive stars changes severely with metallicity and rotation speed (Meynet & Maeder 2005), this might indicate that either these stars were initially rapidly rotating, or they are very massive, with surface enrichment strongly enhanced due to the increased mass loss at higher metallicity.

To improve our understanding of stellar evolution of massive stars and their mass-loss behavior at different metallicities, it is essential to continue to resolve massive star populations and identify B[e]SGs and LBVs in other Local Group Galaxies. Furthermore, the methodology used here to distinguish between types of pre-supernova objects will be a crucial tool to study these stars in more obscured areas, such as the Galactic center or other highly reddened regions, where optical observations are not possible. This will increase both our knowledge and sample size leading to better statistics and more reliable conclusions about the nature and origin of B[e]SGs and LBVs.

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