Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **443,** 947–956 (2014) doi:10.1093/mnras/stu1174

A *K*-band spectral mini-survey of Galactic B[e] stars*

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Accepted 2014 June 12. Received 2014 June 11; in original form 2014 March 25

ABSTRACT

We present a mini-survey of Galactic B[e] stars mainly undertaken with the Large Binocular Telescope (LBT). B[e] stars show morphological features with hydrogen emission lines and an infrared excess, attributed to warm circumstellar dust. In general, these features are assumed to arise from dense, non-spherical, disc-forming circumstellar material in which molecules and dust can condensate. Due to the lack of reliable luminosities, the class of Galactic B[e] stars contains stars at very different stellar evolutionary phases like Herbig AeBe, supergiants or planetary nebulae. We took near-infrared long-slit *K*-band spectra for a sample of Galactic B[e] stars with the LBT-LUCI 1. Prominent spectral features, such as the Brackett γ line and CO band heads are identified in the spectra. The analysis shows that the stars can be characterized as evolved objects. Among others we find one luminous blue variable candidate (MWC 314), one supergiant B[e]candidate with ^{13}CO (MWC 137), and in two cases (MWC 623 and AS 381) indications for the existence of a late-type binary companion, complementary to previous studies. For MWC 84, IR spectra were taken at different epochs with LBT-LUCI 1 and the GNIRS spectrograph at the Gemini North telescope. The new data show the disappearance of the circumstellar CO emission around this star, previously detectable over decades. Also no signs of a recent prominent eruption leading to the formation of new CO disc emission are found during 2010 and 2013.

Key words: circumstellar matter – stars: emission line, Be – supergiants – stars: winds, outflows – infrared: stars.

1 INTRODUCTION

B[e] stars are enigmatic objects. Their optical spectra show strong Balmer emission lines as well as permitted and forbidden emission lines of lowly ionized metals. In addition, B[e] stars display a near- and mid-infrared excess that is attributed to hot and warm circumstellar dust. However, because the definition of the B[e] class is purely morphological, it contains objects that are physically very different in terms of their initial mass and evolutionary phase: B[e] supergiants (B[e]SGs), Herbig AeBe (HAeBe) stars, compact planetary nebulae, and symbiotic objects (e.g. Lamers et al. 1998). Especially, B[e]SGs and HAeBe stars are difficult to distinguish; they have dense, cool, and dusty equatorial discs, which are related to either accretion and disc winds (in the case of HAeBe stars) or equatorially enhanced stellar winds (B[e]SGs). These discs give rise to molecular emission such as the first overtone bands of carbon monoxide (CO) in the near-infrared which are observed in both

* Based on data acquired using the Large Binocular Telescope (LBT) and Gemini Observatory. The LBT is an international collaboration among institutions in Germany, Italy, and the United States. LBT Corporation partners are LBT Beteiligungsgesellschaft, Germany, representing the Max Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; Istituto Nazionale di Astrofisica, Italy; The University of Arizona on behalf of the Arizona university system; The Ohio State University, and The Research Corporation, on behalf of the University of Notre Dame, University of Minnesota, and University of Virginia. Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

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Published by Oxford University Press on behalf of the Royal Astronomical Society

HAeBe stars and B[e]SGs (McGregor, Hyland & Hillier 1988a; Morris et al. 1996; Bik, Kaper & Waters 2006). In addition, the position of HAeBe stars in the empirical Hertzsprung–Russell diagram overlaps with that of the low-luminosity B[e]SGs.

So far, comprehensive studies of B[e] stars, focused on the spectral classification and characterization, were mostly based on optical spectra. Over the last two decades, new instruments have given access to the infrared (IR) spectral range and allowed high-quality spectra with the necessary spectral resolution to be obtained. But only now projects are checking systematically how appropriate spectral classification based on IR spectra alone is for general application purposes. For example, Oksala et al. (2013) find that based on *K*-band spectra three distinct groups of stars can be identified: (1) 'regular' B[e]SGs with the expected spectrum of emission lines including the Pfund series and CO in emission, (2) S Dor-like luminous blue variables (LBVs) with a variety of strong emission lines but lacking the expected circumstellar CO emission, and (3) a group of cool stars, consisting of LBVs in outburst and Yellow Hypergiants , showing the Pfund series in absorption.

The CO bands can be used to obtain an age estimate for a star. As proposed by Kraus (2009), stellar evolution models with rotation predict the enhancement of the carbon isotope ^{13}C on the stellar surface during the core-hydrogen burning of massive stars through mixing. Via mass loss, it is transported into the circumstellar environments and locked into ^{13}CO molecules. Hence, in evolved stars (i.e., supergiants), the enriched isotope should become detectable as ^{13}CO bands. This was confirmed by detection of ^{13}CO emission in known, extragalactic B[e]SGs (Liermann et al. 2010); vice versa, the ^{13}CO absorption can be used to distinguish late-type supergiants from dwarf stars (Wallace & Hinkle 1997).

We have embarked on a mini-survey of a sample of Galactic B[e] stars to investigate their evolutionary status and characterize their age and circumstellar material from *K*-band spectra. We present our observations in Section 2 with the results of the spectral analysis following in Section 3. The final part of the paper is dedicated to the discussion and conclusion of our findings (Sections 4 and 5).

2 OBSERVATION AND DATA REDUCTION

Our sample stars (cf. Table 1) were observed with the Large Binocular Telescope (LBT) in Arizona, USA, during three runs in 2010 November, 2011 April and May. We used the LBT-LUCI 1 spectrograph (Seifert et al. 2003) to obtain seeing-limited high-quality long-slit spectra with the N1.8 camera, a slit width of 0.5 arcsec, and the *K*-band filter (1.93–2.48 µm) with the 210_zJHK grating tilted to centre on λ = 2.24 µm to have best wavelength coverage for the CO bands redwards of 2.29 µm. The resulting spectra have a spectral resolution of about $R = 6100$ and a signal to noise ratio of S/N ≈ 700.

Table 1. Log of the LBT observations.

Object	RA($^{h:m:s}$)	Dec.(°:′:″)	Date (UT)	t_{int} (s)
Science:				
MWC 137	06:18:45.52	+15:16:52.25	2010-11-10	900
MWC 84	04:19:42.14	+55:59:57.70	2010-11-10	120
MWC 314	19:21:33.97	+14:52:56.89	2010-11-13	240
AS 381	20:06:39.95	+33:14:28.10	2010-11-13	600
MWC 300	18:29:25.69	−06:04:37.29	2011-05-12	200
MWC 623	19:56:31.54	+31:06:20.12	2011-05-12	80
Standards:				
HD 44585	06:23:09.15	+15:50:32.33	2010-11-10	1440
HD 29371	04:40:49.54	+57:52:46.63	2010-11-10	600
HD 185195	19:37:17.84	+15:15:02.41	2010-11-13	900
HD 196006	20:33:30.39	+32:54:27.78	2010-11-13	900
HD 175644	18:56:47.20	−14:01:40.76	2011-05-12	400
HD 191720	20:10:01.65	+36:58:42.47	2011-05-12	400

Telluric standards were observed immediately before or after the science targets at similar airmass. B main-sequence stars were used as standard stars, to avoid the contamination of the CO bands with intrinsic features from a B supergiant or solar-type standard star. Table 1 lists the details of the observations.

Additional data for MWC 84 were obtained during 2011 April and 2013 October with GEMINI/GNIRS (programmes GN-2011B-Q-24 and GN-2013B-Q-11) in high-resolution mode ($R = 18\,000$), using the 110.5 l/mm grating, the long camera (0.05 arcsec pix^{-1}), and the 0.10 arcsec slit. We obtained spectra in the *K*-band (2.28–2.34 µm) centred on λ = 2.31 µm to cover the first two CO band heads.

Data sets from both telescopes were reduced using standard IRAF[1] routines for long-slit spectroscopy including removal of cosmic rays and dead pixels, dark frames, division by a normalized flat-field, distortion correction, and wavelength calibration. Sky subtraction was done by subtracting offset frames per target (AB pattern) correspondingly before the spectra extraction.

The frames of the telluric standard stars were treated in the same way. We produced calibration curves as the ratio of the extracted standard star spectra and Kurucz models (corresponding to the spectral types of the standard stars; Kurucz 1993) scaled to the stars' 2MASS *K*-band magnitudes. As the Kurucz models do not reproduce the observed Br γ line in the standard star spectra that part of the calibration curve was smoothed by linear interpolation between 2.15 and 2.17 µm. For flux calibration, the extracted science-target spectra were divided by the corresponding calibration curves.

3 ANALYSIS AND RESULTS

The flux-calibrated spectra of the sample stars are presented in Fig. 1. Most spectra show more or less pronounced telluric residuals at about 2.316 and 2.370 µm. We attribute this to the not always perfect match of observing conditions between the science target and standard star.

For all sample stars, we clearly detect the Brackett γ line (Br γ, λ 2.166 µm) in emission. Additionally, iron (Fe II λ 2.089 µm) and a magnesium doublet (Mg II λ 2.138/144 µm) are detected. Three stars, MWC 314, MWC 84, and AS 381, also show features of the sodium doublet (Na I λ 2.206/209 µm) and helium (He I λ 2.112 µm) in emission. In Table 2, we list the measured equivalent widths of these lines for all stars.

Remarkably, MWC 314 is the only star whose spectrum shows very prominently lines of the Pfund series (see Fig. 1, topmost panel). Overall its spectral appearance is close to S Dor-like LBVs and B[e]SGs (Oksala et al. 2013); a classification of MWC 314 as LBV will be discussed below (see Section 4.1). Also, no molecular CO bands, neither in emission nor in absorption, are present in the spectrum.

However, CO bands are detected in the spectra of three stars: MWC 137 (in emission), MWC 623 and AS 381 (in absorption).

[1] IRAF 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.

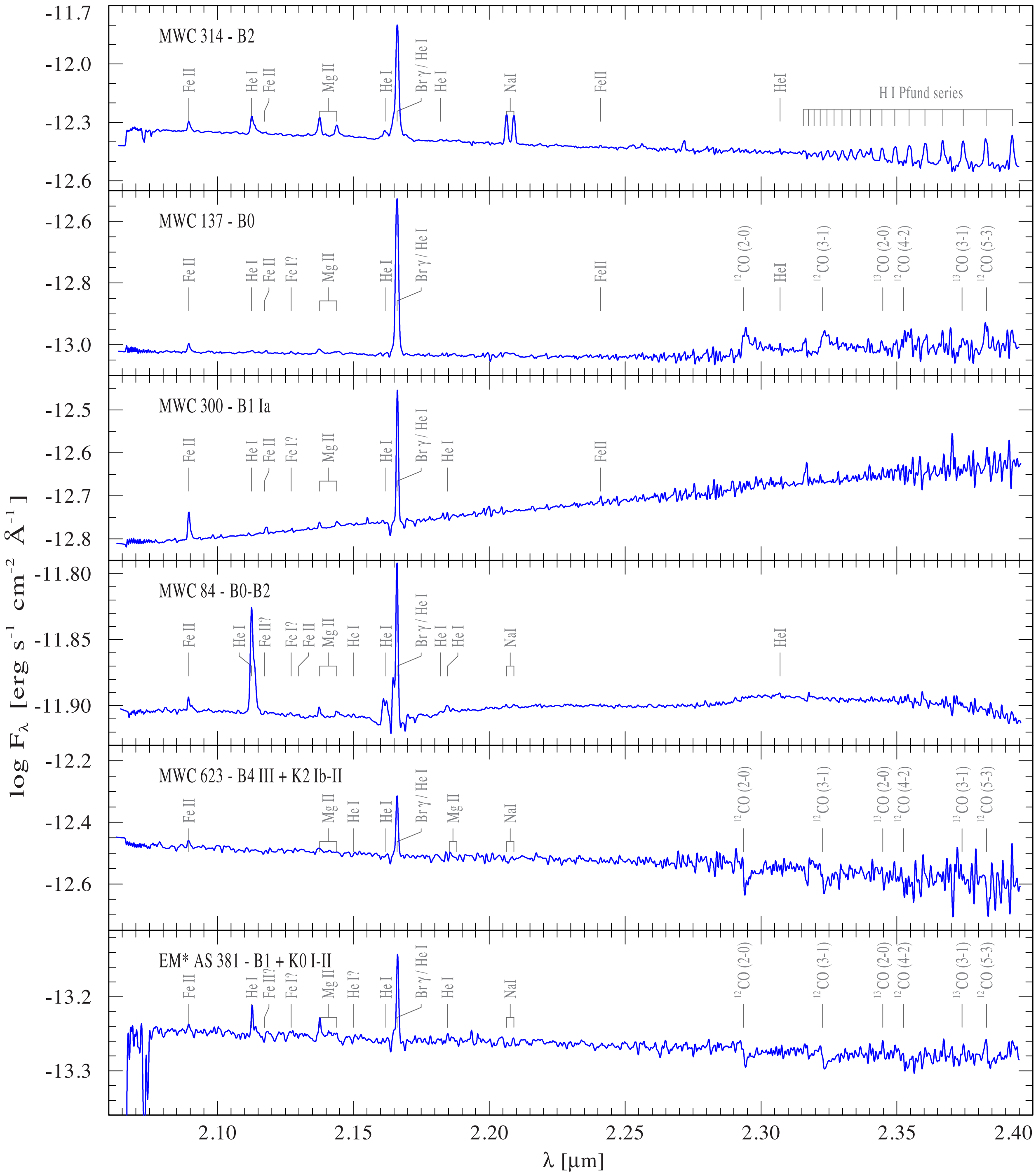

Figure 1. Flux-calibrated *K*-band spectra of our sample stars observed with LBT-LUCI 1. Line identifications of prominent emission lines and the band heads of ^{12}CO and ^{13}CO are indicated. Please note that the scaling of the flux axis is different for each panel. Spectral types listed for the individual stars are taken from the literature as listed in Table 4.

Details of the spectra are shown in Figs 3 and 6. MWC 137 displays ^{13}CO in emission which shows that the star is evolved, i.e. possibly a B[e]SG.

Both MWC 623 and AS 381 have been suspected to be binary stars; for MWC 623 Zickgraf & Stahl (1989) find a spectroscopic binary with two sets of spectral lines (SB2) and for AS 381 Miroshnichenko et al. (2002a) find neutral metal lines inferring a cool companion. Indeed, the spectra of both stars display CO absorptions which we attribute to a cool late-type companion, respectively. We measure the equivalent widths of the first band head (CO 2–0), see Table 2. Following González-Fernández et al. (2008, see equations 5 and 6), the equivalent width can be used to derive both the effective temperature and a spectral type of the companion (the indicator $G = 0,\ldots,13$ corresponds to spectral types K0,. . . , M7).

Table 2. Equivalent-width measurements (in Å) for prominent emission lines (negative) and absorption lines (positive).

Star	Fe II 2.089 µm	He I 2.112 µm	Mg II 2.138/144 µm		Br γ 2.166 µm	Na I 2.206/209 µm		CO (2–0) 2.293 µm	CO (3–1) 2.322 µm
MWC 314	−2.0	−3.6	−3.3	−2.7	−32.1	−5.1	−5.0	–	–
MWC 137	−0.9	–	−0.8	−0.4	−25.6	–	–	−21.1	−19.1
MWC 300	−1.9	–	−0.3	−0.5	−8.7	–	–	–	–
MWC 84	−0.4	−3.4	−0.3	−0.4	−4.3	−0.1	−0.2	–	–
MWC 623	−0.9	–	−0.8	–	−5.8	–	–	14.0	11.6
AS 381	−0.5	−0.8	−1.2	−1.3	−3.6	−0.6	−0.4	5.5	5.3

For MWC 623, we find a K4 companion (G = 3.2–5.1 corresponding to spectral types between K3 and K5) with an effective temperature of $T_{\rm eff} = 4030 \pm 100$ K. In the case of AS 381, we determine a spectral type of the companion of K0 (G = 0.09–0.20 corresponding to a spectral type K0) with an effective temperature $T_{\rm eff} = 4550 \pm 100$ K. Errors on the effective temperature are dominated by those given in equation 5 of González-Fernández et al. (2008). In both cases, one can argue for the detection of weak ^{13}CO absorptions in the spectra, indicating a slightly evolved giant or supergiant companion (luminosity class of II to I).

Both MWC 84 and MWC 300 do not show any Pfund lines or CO emission in their spectra. However, MWC 84 shows the strongest He I and MWC 300 the strongest Fe II and Br γ lines in emission, of all the sample stars.

4 DISCUSSION

4.1 MWC 314 – a quiescent B[e]SG/LBV?

For high-mass stars, stellar evolution models predict a short transitional phase as LBV from the core hydrogen-burning OB star progenitors to the core helium-burning Wolf–Rayet stars (e.g. Maeder et al. 2008). During the LBV phase, the stars undergo extreme mass-loss events (‘outbursts’) after or followed by a rather stable (‘quiescent’ or ‘dormant’) state and are often associated with circumstellar nebulae. In addition, significant variability in brightness and spectral appearance can be detected more readily in the outburst phase but also are present in the quiescent state.

For MWC 314, spectral, photometric, and polarimetric variability was found covering different periods, e.g. Miroshnichenko (1996), Wisniewski et al. (2006), Groh, Damineli & Jablonski (2007). A detailed spectral analysis by Miroshnichenko et al. (1998), finding photospheric lines for the first time, classified the star as B0 supergiant with $T_{\rm eff}$ = 25 000 K. Additionally, the authors present indications for a non-spherical wind and derive a distance of $d = 3.0 \pm 0.2$ kpc from radial velocity (RV) measurements. This makes MWC 314 one of the most luminous stars in the Milky Way with $\log (L/{\rm L}_{\odot}) = 6.1 \pm 0.3$ (Miroshnichenko et al. 1998).

Later studies find different (effective) temperatures, based on different indicators and methods, e.g 26 700–32 000 K (Cidale, Zorec & Tringaniello 2001), 16 200 K (Carmona et al. 2010), 18 000 K (Lobel et al. 2013). At the same time, different studies report the rather stable photometric appearance of MWC 314 in *UBVRIJHK* filter observations with about 0.3 mag variability, e.g. Bergner et al. (1995) and Miroshnichenko (1996, covering the time span from 1954 to 1995). This results in a conflicting situation to determine the spectral type and evolutionary state of MWC 314.

The star was first proposed as LBV candidate by Miroshnichenko (1996). In case the above listed temperatures reflect a real change over the last 20 years, MWC 314 would be rather similar to other LBVs (see Table 3), thus supporting the classification of MWC 314 as LBV candidate. In Fig. 2, we show MWC 314 in the Hertzsprung–Russell diagram (HRD) among known Galactic LBVs and LBV candidates. It is located between the empirical Humphreys–Davidson limit (Humphreys & Davidson 1994, solid line in Fig. 2) and the hot temperature LBV minimum light strip (Clark, Larionov & Arkharov 2005, dashed line in Fig. 2).

In our spectrum of MWC 314, we find pronounced lines of hydrogen, Br γ and Pfund series, and prominent emission lines of Fe II, Mg II, and Na I. Comparing the spectra of MWC 84, MWC 137, and MWC 314, we find most pronounced Na I and Mg II emission for the latter with remarkable line strengths. Typically, comparable line strengths are only found in late-type (F and G) supergiants (Hanson, Conti & Rieke 1996; Wallace & Hinkle 1997). In B-type emission-line stars these lines are usually (much) weaker, but with a slight trend for an increase towards later types (see Oksala et al. 2013). If we consider that the temperature obtained by Lobel et al. (2013) within the past years is the currently most reliable one, then we can assign MWC 314 a spectral type of B2 according to the temperature-spectral type relation for Galactic supergiant stars of Searle et al. (2008).

Table 3. Comparison of stellar parameters for LBV stars.

Star	$T_{\rm eff}$ (K)	$\log(L/{\rm L}_{\odot})$	Reference
MWC 314 (1986/91)	25 000	6.10	(1)
MWC 314 (1997/98)	32 000	–	(2)
MWC 314 (2007)	16 200	–	(3)
MWC 314 (2009–2011)	18 000	5.84	(13)
η Car	25 000	6.57	(4)
η Car	9400	6.70	(11)
η Car	35 300	6.74	(12)
AG Car (min 1985–1990)	22 800	6.17	(5)
AG Car (min 2000–2001)	17 000	6.17	(5)
AG Car (max 2002–2003)	14 000	6.00	(6)
FMM 362	11 300	6.25	(7)
Pistol star	11 800	6.20	(7)
AFGL 2298 (min 2006)	10 300	6.30	(14)
AFGL 2298 (max 2001)	15 000	6.10	(8)
ζ Sco	19 500	6.02	(9)
P Cyg (min 1980−2000)	18 200	5.70	(9)
HR Car	17 900	5.70	(10)

Note: (1) Miroshnichenko et al. (1998), (2) Cidale et al. (2001), (3) Carmona et al. (2010), (4) Humphreys & Davidson (1994), (5) Groh, Hillier & Damineli (2011), (6) Groh et al. (2009a), (7) Najarro et al. (2009), (8) Clark et al. (2003), (9) van Genderen (2001), (10) Groh et al. (2009b), (11) Groh et al. (2012), (12) Hillier et al. (2001), (13) Lobel et al. (2013), (14) Clark et al. (2009).

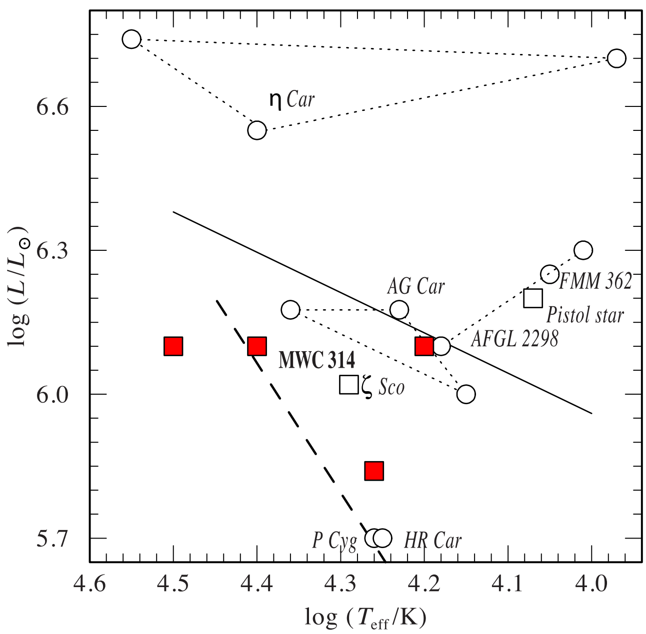

Figure 2. HRD for known Galactic LBV stars (circles) and LBV candidates (squares). The empirical Humphreys–Davidson limit (Humphreys & Davidson 1994, solid line) and the hot LBV minimum light strip (Clark et al. 2005, dashed line) are indicated for illustration. For MWC 314, we show a range of fundamental parameters listed in Table 3; for temperatures with no simultaneous luminosity determinations we adopt $\log{(L/L_{\odot})} = 6.1$ from Miroshnichenko et al. (1998).

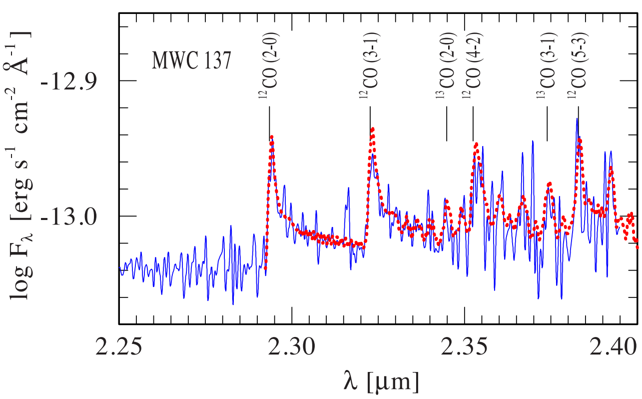

Figure 3. Detail of the spectrum of MWC 137 (solid line) showing the CO emission. The overplotted model (dotted line) combines CO and Pfund emission added to the observed continuum.

Previous studies by Muratorio, Rossi & Friedjung (2008) found indications for a quasi-Keplerian[2] circumstellar disc from double-peaked emission lines. We do not detect any significant IR excess that one would expect from warm/hot dust in the circumstellar disc; this result is highly indicative for the absence of such dust. We also do not find any CO emissions or absorptions. This is comparable to other LBV candidates where the lack of CO emission has been attributed to the circumstellar material having too low a density (Morris et al. 1996; Oksala et al. 2013).

[2] A disc in Keplerian rotation displaying simultaneously a small outflow component, see e.g. Krtička, Owocki & Meynet (2011), Kurfürst, Feldmeier & Krtička (2013).

The presence of a dense and compact gas disc in MWC 314 can be concluded from the detection of double-peaked [Ca II] emission together with the non-detection of [O I] by Aret et al. (in preparation). Aret et al. (2012) show that [Ca II] traces regions of higher densities, i.e. closer to the star. Thus, the lack of [O I] in MWC 314 must be attributed to a dense but compact disc. On the other hand, the presence of the strong emission from neutral sodium, which has a very low ionization potential, indicates the existence of a second very dense, but cool region of circumstellar material. To allow for the emission of Na I, that region should be shielded from direct stellar radiation. In a spherically symmetric stellar wind, too high densities would be required. But in such a high-density environment the emission of [O I] can be expected. Hence, it seems more logical to assume that the Na I emission arises from a cool circumstellar disc (or ring), which provides ideal shielding conditions (e.g. Scoville et al. 1983; McGregor et al. 1988a; McGregor, Hyland & Hillier 1988b). However, at this point we cannot exclude the option that the Na I emission arises from the environment of the companion.

Oksala et al. (2013) present the *K*-band spectrum of LHA 120−S 127 and S Dor which look remarkably similar to MWC 314, finding disc tracers and no CO emission. The authors state that CO molecules should form between the locations traced by the Ca and O emitting material and dust particles, and conclude that the disc of S 127 might not be a continuous disc but rather consisting of rings/shells. This cannot be explained with the model of a continuous B[e] wind but rather requires an LBV eruption scenario. Hence, for MWC 314 we can assume a similar scenario, i.e. the presence of at least two different rings, a hot and compact one close to the star from which the [Ca II] lines arise, and a very cool one at a much larger distance, where the Na I lines are excited. The intermediate region must be of very low density due to the lack of both [O I] and CO band emission.

A study by Marston & McCollum (2008) found a bipolar nebula around MWC 314 that is similar in morphology to the one around η Car. Their results are not conclusive whether or not that nebula was ejected in a past LBV outburst or not.

Recently, it has been discussed for a large fraction of the known LBV stars that bipolar nebulae might be linked to a possible binary nature of these stars. For MWC 314, the binary status is still under debate. Early reports of photometric variations (Miroshnichenko 1996) were interpreted as being more consistent with the pulsations of a slightly evolved supergiant (or LBV candidate) rather than being attributed to a binary companion. However, Muratorio et al. (2008) find indications for binarity based on RV variations with an orbital period of $P = 30.7$ d. More recent studies continue the ambiguity of the binary status, e.g. Rossi et al. (2011) cannot detect any periodic RV variations. However, Lobel et al. (2013) find variations with a period of $P = 60.7$ d (and an orbital eccentricity of $e = 0.26$), inferring a massive, possibly evolved supergiant companion to MWC 314. Our spectrum does not show any CO absorption indicative for cool companions. Thus, K- and M-type companions can be excluded for MWC 314. However, a massive companion as suggested by Lobel et al. (2013) cannot be ruled out. Further high-resolution spectroscopy and/or spatially resolved imaging is necessary to confirm or contradict the binary suspicion.

4.2 MWC 137 – a B[e]SG candidate with ^{13}CO emission

This star is a typical example for the difficulty to distinguish B[e]SG and HAeBe stars. Based on the preferred distance estimate, the star has been considered to be a young unevolved object, e.g. with a low luminosity around $\log{(L/L_{\odot})} = 4.4$, assuming $d = 1.3$ kpc

(Hillenbrand et al. 1992). Also, Testi et al. (1997) report the detection of an embedded cluster around MWC 137 supporting the young nature of this object. However, Esteban & Fernandez (1998) derived $T_{\rm eff} = 30\,000$ K and $\log{(L/{\rm L}_{\odot})} = 5.37$ based on a re-assessment of the distance to a lower limit of $d = 6$ kpc, and concluded that the star should be classified as B[e]SG. In addition, the authors argue that the small photometric variations but stable spectral line profiles found for MWC 137 indicate the star being a B[e]SG rather than an HAeBe star (see also Zickgraf 1992). Moreover, Esteban & Fernandez (1998) find the associated ring nebula S 226 around MWC 137 to be isolated and not attached to any large-scale star-forming region as might be expected for an HAeBe star. In contrast, these authors remark the spectroscopical resemblance of the nebula to those observed around LBVs or Wolf–Rayet stars (Esteban & Fernandez 1998, and references therein).

Marston & McCollum (2008) confirm the ring nebula and in addition find a bipolar structure in their narrow-band images. However, the nebula material seems chemically unprocessed which might indicate that the circumstellar material either is swept-up interstellar matter or was ejected during an early stellar-evolution phase.

MWC 137 was listed by Miroshnichenko (2007) as FS CMa candidate star which implies that it is a binary system. However, neither Baines et al. (2006) nor Wheelwright, Oudmaijer & Goodwin (2010) found evidence for the binary status of MWC 137 from their spectro-astrometric observations (a method sensitive down to about 100 mas binary separation; e.g. Bailey 1998). HIPPARCOS data suggest that MWC 137 is an astrometric binary (Makarov & Kaplan 2005), possibly with a white dwarf or subdwarf companion (Lanning & Lépine 2006).

In our spectrum (see Fig. 1), we do not find indications for a cool companion in terms of CO absorption or a set of emission or absorption lines accountable to a hot main-sequence companion; instead, a closer look at our spectrum shows prominent CO band heads in emission, both of ^{12}CO and ^{13}CO. In Fig. 3, we overplot a model combining CO and Pfund emission added to the observed continuum. The model was computed using the codes of Kraus et al. (2000), Kraus (2009), and Oksala et al. (2013), and parameters of the Pfund and CO emitting regions as obtained by Oksala et al. (2013). The excellent agreement of the model and the observations confirms the results by Oksala et al. (2013). In particular, the presence of clearly detectable emission from ^{13}CO implies that the circumstellar material is enriched in the ^{13}C isotope. This excludes a pre-main-sequence nature according to the stellar evolution models by Ekström et al. (2012) and MWC 137 has to be classified as evolved, post-main-sequence object.

4.3 B[e] supergiant candidates

In two further stars of our sample, MWC 300 and MWC 84, we do not detect CO emission in their spectra. However, in the following we summarize the evidences for their classification as B[e]SG: *MWC 300*. According to Appenzeller (1977) this star is classified as B1 Ia. Miroshnichenko et al. (2004) detect photospheric lines and their spectral analysis indicates the supergiant status of the star, with $T_{\rm eff} = 20\,000$ K. From comparison of equivalent-width measurements they derive a luminosity of $\log{(L/{\rm L}_{\odot})} = 5.1 \pm 0.1$ assuming a distance of $d = 1.8 \pm 0.2$ kpc. RV variations (Miroshnichenko et al. 2004) and a clear signal from spectro-astrometry (Takami, Bailey & Chrysostomou 2003) suggest that MWC 300 is a binary. From near-IR interferometry, Wang et al. (2012) find evidence for a dusty circumstellar (maybe even circumbinary) disc and a binary companion at a projected separation of about 7.9 au. No extended circumstellar material has been detected in Hα imaging by Marston & McCollum (2008).

Our spectrum shows a clear IR excess that we attribute to the circumstellar/circumbinary dust, but we do not detect CO emission. As for MWC 314, this might indicate that the material's density is too low to give rise to molecular emission. In addition, we do not find evidence for a cool companion by the lack of CO absorption expected for late-type stars. As Miroshnichenko et al. (2004) suggest a companion of about 6 M$_{\odot}$, i.e. a B-type star, we scanned the spectrum for the expected hydrogen absorption lines with no result. This might indicate a supergiant companion for which the spectral lines are less pronounced, such that basically only a contribution to the continuum flux might be considered. Interestingly, models of Wang et al. (2012), fitted to their interferometric data, suggest the two binary components to be about similar in effective temperature and to have a brightness ratio of about 2.2.

MWC 84. Also known as CI Cam, MWC 84 had a spectacular outburst in 1998 March, detected from γ-rays to radio emission (e.g. Clark et al. 1999; Robinson, Ivans & Welsh 2002). Hynes et al. (2002) classified the star as spectral type B0–B2, finding its emission-line spectrum typical for a B[e]SG. The authors refer to the star as an atypical high-mass X-ray binary but speculations about the existence and nature of the compact companion are ongoing. Hjellming et al. (1998) describe the star as X-ray binary/X-ray transient radio source, and detect a slow, decelerating shell in radio emission. However, the nature of this emission is also still under debate (e.g. Rupen, Mioduszewski & Hjellming 2003). In addition, a faint circumstellar shell has been detected by Marston & McCollum (2008), but the authors find no clear evidence to determine whether this is stellar ejecta or the illuminated local interstellar material.

The analysis of spectral line profiles, the derived extinction, and interferometric observations suggest that MWC 84 has an equatorial disc wind with a dust-free high-temperature zone close to the star, and that it is viewed almost pole-on (e.g. Hynes et al. 2002; Miroshnichenko et al. 2002b; Thureau et al. 2009). The latter authors revised the distance estimate based on RV measurements and interstellar Na I D-lines, to about 2.2 kpc, placing the star in the Perseus arm; with that distance, an upper-limit luminosity of $\log L/{\rm L}_{\odot} < 4$ is derived. Other studies find both smaller ($d = 1.1$–1.9 kpc by Barsukova et al. 2006; Clark et al. 2000, ≈2 kpc) and larger (e.g. $d \approx 5$ kpc; Robinson et al. 2002) distances, hampering reliable estimates of the luminosity.

Clark et al. (1999) present *J*-, *H*- and *K*-band spectra obtained one month after the outburst that are rich in hydrogen, helium and iron emission lines and clearly show lines of the Pfund series and the presence of CO emission in the *K* band. The authors argue that the molecular emission likely arises due to collisional excitation from regions shielded from the stellar radiation, which requires high densities. In addition, Clark et al. (2000, covering 1998–1999) and Thureau et al. (2009, data for 2004 and 2005) present *UBVRIJHK* photometry showing that the star is slightly brighter than in pre-outburst state, but rather stable over the long time range of seven years. Also near-IR interferometric data (Thureau et al. 2009, covering 1998–2006) have supported the scenario of a stable circumstellar disc in the last decade.

Our spectra (see Fig. 4) do not show any indication of Pfund lines or CO emission or absorption, neither in 2010 (LBT-LUCI 1) nor in 2011 or 2013 (both Gemini-GNIRS). We attribute this disappearance of Pfund and CO emission to the loss/dilution of the high-density circumstellar material and the return of MWC 84 to its pre-outburst stage.

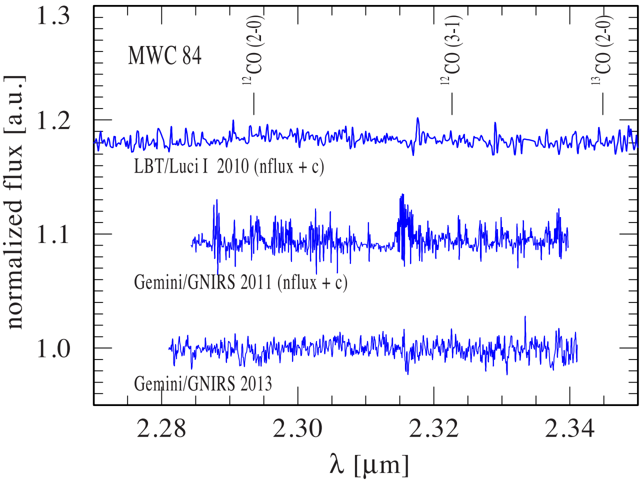

Figure 4. Comparison of the spectra of MWC 84 taken at the LBT and Gemini; spectra are shifted by a constant for better viewing. Over the covered time span of three years no CO emission is detected.

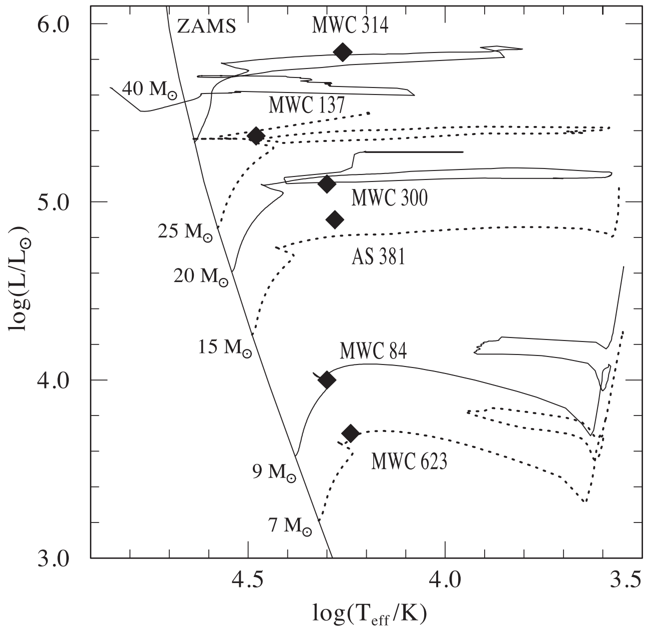

Figure 5. HRD with our sample stars (stellar parameters listed in Table 4) and single-star stellar evolution models for different initial masses by Ekström et al. (2012). The models account for the effects of stellar rotation.

4.4 Unclassified B[e] stars

For both MWC 623 and AS 381, it has been suggested that the stars are in binary systems with a cool companion. Our finding of prominent CO absorption bands supports this position (Fig. 6) and we determined the spectral types for the companions from the CO band head equivalent widths, see Section 3 and Table 2.

MWC 623. Based on the detection of a set of early-type (emission) and late-type (absorption) optical lines, Zickgraf & Stahl (1989) conclude that MWC 623 is a spectroscopic binary (SB2) of type B2+K2. However, they find no indication for RV variations, attributing this to a binary period longer than covered by their range of observational data of two years. Zickgraf (2001) reclassifies the spectral types of the binary components to B4 III+K2 II-Ib but no periodic RV variations are found even in long-time observations (Zickgraf 2001; Polster et al. 2012). This might indicate a pole-on orientation of the system, e.g. Miroshnichenko (2006).

Based on the K star's luminosity class, Zickgraf (2001) derives a spectroscopic distance of $d = 2.4$ kpc. Our derived spectral type of the cool component is a slightly cooler K4 I-II star, but with the same range for the luminosity class. We take MWC 623's 2MASS magnitude $K_S = 5.38$ mag and assume that the K-band emission is dominated by the cool companion. With the distance and reddening as listed in Table 4, and bolometric corrections determined following Levesque et al. (2005), we derive the companion's luminosity as $\log(L/L_\odot) = 3.61$. Assuming that MWC 623 is a physical long-period binary and not a chance superposition detected in the spectrum, each component in all likelihood has evolved like a single star. From comparison with the stellar-evolution track of 7 $M_\odot$ initial mass (see Fig. 7), we find an age difference of 1.8 Myr of the components. This seems negligible compared to the total age of the system of about 50 Myr.

AS 381. The star was first listed in the Hα surveys by Merrill & Burwell (1950) and Henize (1976) as emission-line star; Thé, de Winter & Perez (1994) classify it as Be star with IR excess.

Table 4. Stellar parameters for the sample stars.

Star	SpT	$T_{\rm eff}$ (K)	$\log(L/L_\odot)$	d (kpc)	$E(B-V)$ (mag)	$M_{\rm ini}$ ($M_\odot$)	Age^a (Myr)	Reference
MWC 314	*B2*	18 000	5.84	1.5 ± 0.4	1.45 ± 0.15	*40*	*6*	(1),(8)
MWC 137	B0	30 000	5.37	≥6	1.22	30, *25*	*8.0–8.4*	(2)
MWC 300	B1 Ia	20 000	5.1 ± 0.1	1.8 ± 0.2	0.84 ± 0.02	20, *20*	*9.5–10.3*	(7)
MWC 84	B0-2	20 000 ± 2000	< 4.0	2.2	0.85 ± 0.05	*9*	*29.6–31.3*	(5), (6)
MWC 623-a	B4 III	17 200 ± 3000	3.7 ± 0.4	2.4	0.8 ± 0.2	7,*7*	50, *50.0–51.4*	(3)
MWC 623-b	K2 Ib-II	4300 ± 200	3.5 ± 0.4	2.4	–	7.5	50	(3)
MWC 623-b	*K4 I-II*	*4030 ± 100*	*3.6*	–	–	*7*	*52*	This work
AS 381-a	B1	19 000	4.9	4 ± 1	2.3 ± 0.3	19 ± 3, *16*	∼*13*	(4)
AS 381-b	K	–	3.6	4 ± 1	–	7	–	(4)
AS 381-b	*K0 I-II*	*4550 ± 100*	*3.94 ± 0.10*	–	–	*10*	*25*	This work

Note: Parameters given in italic are from this work, others according to the indicated references: (1) Carmona et al. (2010, distance and $E(B-V)$), Miroshnichenko et al. (1998, luminosity), (2) Esteban & Fernandez (1998), (3) Zickgraf (2001), (4) Miroshnichenko et al. (2002a), (5) Hynes et al. (2002, spectral type), (6) Miroshnichenko et al. (2002b), (7) Miroshnichenko et al. (2004), (8) Lobel et al. (2013, $T_{\rm eff}$ and luminosity).
^{a}Age estimates derived by comparison with single-star evolution models (Ekström et al. 2012), see Fig. 5 and discussion of individual stars for further details.

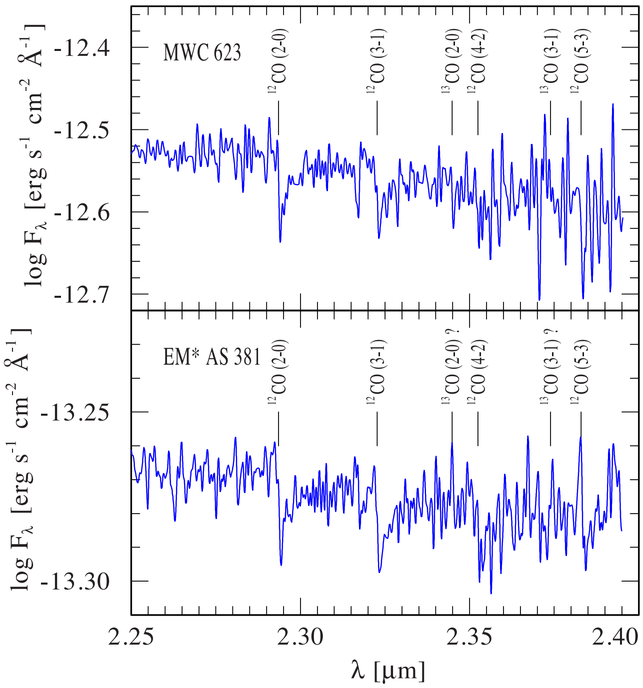

Figure 6. Detail of the spectra of MWC 623 and AS 381 showing the CO absorption attributed to their cool companions.

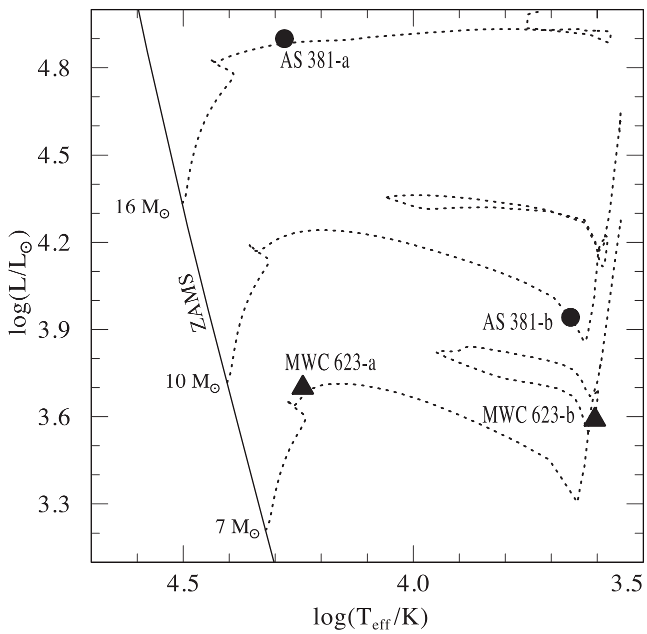

Figure 7. HRD for MWC 623 and AS 381 and their cool companions; single-star stellar evolution models for different initial masses by Ekström et al. (2012) accounting for the effects of stellar rotation.

Miroshnichenko et al. (2002a) detected absorption lines of neutral metals in their near-IR spectra and ^{12}CO absorption bands, concluding that the star is a B1 + K binary system. The authors also derive a lower limit for the orbital period of $P \approx 30$ d. They estimate the distance to be $d = 4 \pm 1$ kpc deriving luminosities of $\log(L/L_\odot) = 4.9$ and $\log(L/L_\odot) = 3.6$ for the B and K components, respectively. In addition, the authors claim to find signs of ongoing mass transfer between the binary components. Miroshnichenko (2007) lists an effective temperature of $\log(T_{\rm eff}/{\rm K}) = 4.28$ for the B star and an interstellar reddening of $E(B-V) = 2.2$ mag.

As described in Section 3, we derive a spectral type of K0 for the companion from the equivalent width measured for the first ^{12}CO band head. However, the determination of the luminosity class is not that unambiguous, as a clear detection of ^{13}CO is not confirmed.

Assuming that the flux in the IR-wavelength range is dominated by the cool companion, we use the mean K-band magnitude of those listed by Miroshnichenko et al. (2002a, cf. Table 2), $K = 6.58$ mag, to derive the companion's luminosity. Including the distance and reddening as listed in Table 4, and the bolometric corrections for the K band according to Levesque et al. (2005), we obtain $\log(L/L_\odot) = 3.94 \pm 0.10$. Within the errors, this result is robust enough to allow up to 25 per cent of the K-band flux to be contributed from the B-type companion.

According to the stellar evolution tracks in Fig. 7, we determine lower-limit initial masses of about 16 and 10 M$_\odot$, and ages of about 13 and 25 Myr for the B-type and K-type star, respectively. Fig. 7 also suggests that the B component of AS 381, although more massive, seems to be less evolved than the K companion. Given the short lower-limit orbital period of the system, it seems possible to consider that mass transfer might have happened at some stage of the evolution of this binary star. In that case, single-star stellar evolution models are of course not adequate for mass and age determination.

5 CONCLUSION

We conducted a mini-survey of Galactic B[e] stars with the LBT-LUCI 1 and Gemini-GNIRS to characterize their near-IR K-band spectra. The most dominant emission line feature detected is the Br γ line that is present in all our sample stars. In many cases, iron and magnesium emission can be identified, while helium and sodium emission lines are less common. In addition, the detection and analysis of molecular lines like from CO is a very helpful and powerful tool for the classification of the stars and their circumstellar material, or for the confirmation of a cool companion respectively.

Summarizing the results of our B[e] survey:

(i) MWC 314 shows a spectrum rich in lines of hydrogen, including pronounced lines of the Pfund series. Several lines of sodium, magnesium, and iron are present as well. Only a weak IR excess is detected and CO emission is lacking at all. The K-band spectrum of MWC 314 strongly resembles the ones of LBV stars and candidates, e.g. S Dor and LHA 120−S 127. Tracers for circumstellar material indicate the presence of a non-continuous gas disc, i.e. rings, around MWC 314. We determine a spectral type of B2 and an age of about 6 Myr; with a lower-limit initial mass of 40 M$_\odot$ it is the most luminous and most massive star in our sample.

(ii) We detect ^{13}CO bands in emission in the spectrum of MWC 137 indicating an evolved nature of the star. However, the classification of MWC 137 as Galactic supergiant B[e] star has to be confirmed with more data.

(iii) MWC 84 shows prominent He I line emissions. After an outburst event in 1998, circumstellar material was clearly and stable detected over decades, e.g. Pfund lines and CO emission. We observed the star at different epochs with LBT-LUCI 1 and Gemini-GNIRS and no signs of a recent prominent eruption was found during 2010 and 2013. Moreover, the observations reveal the disappearance of the circumstellar Pfund lines and the CO emission.

(iv) MWC 300 is a B[e] supergiant candidate in a binary system. Its spectrum does not show CO emission or absorption at the time of observation.

(v) CO absorption bands are found in the spectra of MWC 623 and AS 381. Both stars have been suspected to be binary systems previously. Attributing the observed CO absorption to cool companions, we find a spectral classification of B4 II + K4 I-II (MWC 623) and B1 + K0 I-II (AS 381) and derive the fundamental stellar parameters of the companions.

All sample stars are slightly evolved (ages of 6–50 Myr) with progenitor masses in the intermediate to high-mass range (7–40 $M_{\odot}$). In the cases of binary stars and candidates, episodes of mass transfer might have to be considered in the evolution of the components, thus hampering the exact characterization of the systems. Future observations, for example RV variations, pronounced variability, and higher spectral resolution might be needed to ultimately confirm the binary companions.

Particularly, MWC 84 and MWC 300 might be considered as binary supergiant B[e] candidates in a quiescent transition phase, showing very low densities in their circumstellar envelopes to sustain molecular lines. Unfortunately, some supergiant B[e] stars cannot be distinguished as unambiguously as expected (Oksala et al. 2013) and further observation are needed to clarify the evolutionary status of these stars.

ACKNOWLEDGEMENTS

The authors thank Jochen Heidt for useful discussions about planning the observations and valuable help in preparing the observing scripts; Steve Allenson and the LBTO team for the support during the observing runs at the LBT. We thank our referee A. Miroshnichenko for valuable comments that helped to improve this manuscript.

AL and AK receive(d) financial support from the Max-Planck-Institut für Radioastronomie. MK acknowledges financial support from GAČR under grant number 14-21373S. The Astronomical Institute Ondřejov is supported by the project RVO:67985815. MK, MLA, and LSC acknowledge financial support from International Cooperation of the Czech Republic (MŠMT, 7AMB14AR017) and Argentina (Mincyt-Meys ARC/13/12 and CONICET 14/003). MLA and LSC acknowledge financial support from the Agencia de Promoción Científica y Tecnológica (Préstamo BID, PICT 2011/0885), from CONICET (PIP 0300), and the Programa de Incentivos G11/109 of the Universidad Nacional de La Plata, Argentina.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

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