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The ^{13}Carbon footprint of B[e] supergiants★

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ABSTRACT

We report on the first detection of ^{13}C enhancement in two B[e] supergiants (B[e]SGs) in the Large Magellanic Cloud. Stellar evolution models predict the surface abundance in ^{13}C to strongly increase during main-sequence and post-main-sequence evolution of massive stars. However, direct identification of chemically processed material on the surface of B[e]SGs is hampered by their dense, disc-forming winds, hiding the stars. Recent theoretical computations predict the detectability of enhanced ^{13}C via the molecular emission in ^{13}CO arising in the circumstellar discs of B[e]SGs. To test this potential method and to unambiguously identify a post-main-sequence B[e] SG by its ^{13}CO emission, we have obtained high-quality *K*-band spectra of two known B[e] SGs in the Large Magellanic Cloud, using the Very Large Telescope's Spectrograph for INtegral Field Observation in the Near-Infrared (VLT/SINFONI). Both stars clearly show the ^{13}CO band emission, whose strength implies a strong enhancement of ^{13}C, in agreement with theoretical predictions. This first ever direct confirmation of the evolved nature of B[e]SGs thus paves the way to the first identification of a Galactic B[e]SG.

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

1 INTRODUCTION

B[e] supergiants (B[e]SGs) are massive and luminous B stars with strong, non-spherical, disc-forming winds. The conditions in terms of density and temperature within these discs are ideal for efficient molecule and dust formation, traced by CO band emission (McGregor, Hillier & Hyland 1988; Morris et al. 1996) and a strong near- and mid-infrared excess (Zickgraf et al. 1986). However, the usual distance issue renders it difficult to obtain useful luminosity estimates to classify a Galactic B[e] star definitely as B[e]SG (e.g. Lamers et al. 1998; Kraus 2009). An additional complication arises from the position of Galactic B[e]SG candidates in the empirical Hertzsprung–Russell diagram, which they share with the pre-main-sequence Herbig Ae/Be stars. Even worse, the latter are also surrounded by gas and dust discs (Waters & Waelkens 1998; Waters 2006), giving rise to identical observable features such as the infrared excess and the well-pronounced CO band emission (Bik & Thi 2004; Thi et al. 2005; Bik, Kaper & Waters 2006). For an unambiguous classification of a Galactic B[e] star as B[e]SG, a reliable tracer based on chemical processing during the evolution of a massive star is thus needed.

Based on stellar evolution models for Galactic stars (Schaller et al. 1992; Meynet & Maeder 2005), Kraus (2009) recently pointed out the significant enrichment of the stellar surface abundance in ^{13}C already during the main-sequence evolution of massive stars. However, while the surface of B[e]SGs is usually hidden within their dense winds and discs, Kraus (2009) proposed that this enrichment should be detectable in the ejected material via strongly enhanced ^{13}CO band emission from the disc-forming winds of B[e]SGs. If true, we would have, for the first time, an easy and robust method to unambiguously distinguish between pre- and post-main-sequence evolution and to classify Galactic B[e] stars as supergiants, because Herbig Ae/Be stars do not show any ^{13}C enhancement. However, before this method can be applied to the Galactic B[e] stars, its validity needs to be tested on well-known B[e]SGs. The best-known sample of confirmed B[e]SGs is located in the Magellanic Clouds (Lamers et al. 1998; Zickgraf 2006).

To test the ^{13}CO method, we have observed two B[e]SGs in the Large Magellanic Cloud (LMC) which are known to display ^{12}CO band emission originating in their circumstellar discs. In this Letter, we report on the first definite detection of ^{13}C enrichment from B[e]SGs via enhanced ^{13}CO band emission whose presence is direct evidence for the evolved nature of our programme stars.

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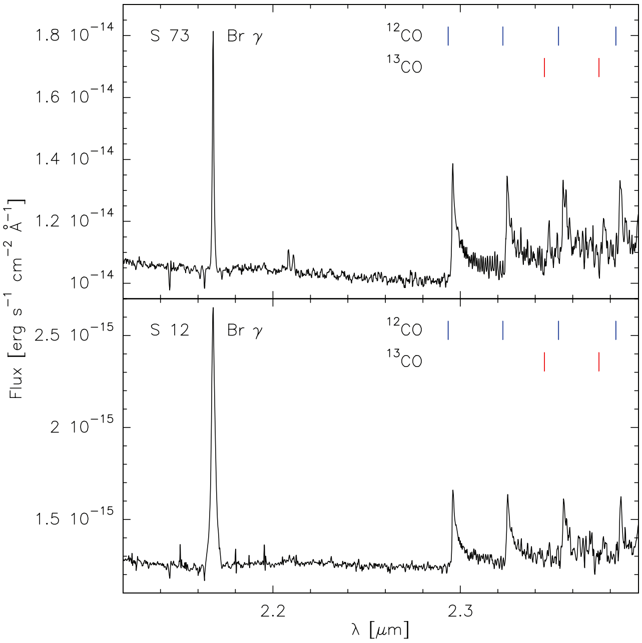

Figure 1. Parts of the observed, flux-calibrated SINFONI *K*-band spectra of the B[e]SG stars S 73 (top) and S 12 (bottom) covering the Brγ line and the first-overtone bands in both ^{12}CO and ^{13}CO. The wavelengths of the band heads are indicated by vertical ticks.

2 OBSERVATION AND REDUCTION

Between 2009 October and November, we have obtained high-quality *K*-band spectra (1.95–2.45 μm) of the two LMC B[e]SG stars LHA 120-S 12 and LHA 120-S 73 (in the following S 12 and S 73, respectively), using the Spectrograph for INtegral Field Observation in the Near-Infrared (SINFONI) (Eisenhauer et al. 2003; Bonnet et al. 2006). Observations were carried out in an AB pattern with a field of view of 8 × 8 arcsec^2. B-type standard stars for flux calibration were observed at similar air mass.

Data reduction was performed with the SINFONI pipeline (version 2.0.5). Raw frames were corrected for bad pixels, distortion and flat-field, followed by the wavelength calibration. For flux calibration, we extracted the standard-star spectra and scaled them with the according Kurucz model (Kurucz 1993) to their Two Micron All-Sky Survey (2MASS) K_s-band magnitude (Skrutskie et al. 2006) to obtain calibration curves. The final flux-calibrated spectra have a signal-to-noise ratio S/N $\sim$ 500 and a spectral resolution $R \sim 4500$ at 2.3 μm. Fig. 1 shows parts of the *K*-band spectra covering the Brγ line of hydrogen and the CO bands.

3 ANALYSIS AND RESULTS

The two LMC B[e]SGs listed in Table 1 were selected because they are known to display strong ^{12}CO band emission (McGregor et al. 1988). The pole-on or intermediate orientation of their discs guarantees that we see the complete CO emitting disc area. The spectral range of SINFONI covers the first four band heads of ^{12}CO and the first two of ^{13}CO. Visual inspection of the spectra (Fig. 1) reveals that the ^{12}CO band heads are prominent in both stars; while ^{13}CO is clearly visible in S 73 (top panel), its presence in S 12 is slightly less obvious.

We corrected the spectra for the systemic velocity and dereddened them with the $E(B-V)$ values from Table 1 applying the interstellar extinction curve of Howarth (1983) and using $A_V/E(B-V) = 3.1$. To obtain a flux-calibrated, quasi-pure CO emission spectrum, we fitted and subtracted a linear pseudo-continuum longwards of 2.25 μm. The spectra of the two stars do not show indication for significant emission of the hydrogen Pfund series, but some minor contribution cannot be excluded and might have to be taken into account later on in the analysis.

Inspection of the CO spectra reveals that the band heads of ^{12}CO all have about equal strength, which means that, surprisingly, the CO gas is rather cool ($T_{\rm CO} < 3000$ K). We will come to this aspect again in Section 4. On the other hand, the excitation of pronounced band head structures requires CO temperatures in excess of $\sim$2000 K. Therefore, the location of the CO emitting region must be closer to the star than the dusty regions, because dust sublimates at $\sim$1600 K (e.g. Lodders 2003). Moreover, the rise of the CO quasi-continuum towards longer wavelengths indicates substantial optical thickness of the emission. To model the CO bands we can thus assume that the emission is in local thermodynamical equilibrium (LTE) and, pre-empting results from Section 4, that the CO gas is located in a ring around the star which has constant temperature and column density. These assumptions are reasonable since the hottest CO component, which arises close to the star where usually the disc density is highest, dominates the total CO spectrum completely. For details on the CO band modelling we refer to Kraus et al. (2000) and Kraus (2009).

To constrain the range of the ^{12}C/^{13}C abundance ratio in the disc, we took expected ^{12}C/^{13}C surface abundance ratios from the stellar evolution models of Meynet & Maeder (2005) for massive stars with LMC metallicity and initial rotation velocities of 300 km s^{-1}. Fig. 2 shows how this ratio decreases with time for stars of different initial mass. The stars S 12 and S 73 have evolved from progenitors with $M_{\rm ini} = 25$–$30\,{\rm M}_\odot$ (see Table 1) whose surface abundance should have dropped to a value ^{12}C/^{13}C $\lesssim 20$ at the turn-off from the main sequence and decreases down to a value of $\sim$4 at late evolutionary phases. We computed synthetic CO band spectra for temperatures in the range 2000–3000 K, ^{12}C/^{13}C ratios varying from 4 to 20, and CO column densities higher than 10^{21} cm^{-2} to account for the optical depth effects. We did not find any indication for additional line broadening from either Keplerian rotation or outflow signatures, meaning that the CO gas has no significant line-of-sight velocity component, in agreement with an (almost) pole-on orientation of the discs. Therefore, we used the thermal velocity as the intrinsic gas velocity and convolved the resulting spectrum with the resolution of SINFONI. Pure CO models that match the observations best are shown in red in the top panels of Fig. 3, with the parameters listed in Table 2.

Table 1. Parameters of the observed B[e]SGs.

Object LHA	Sp. type	$T_{\rm eff}$ (10^3 K)	L_* ($10^5\,L_\odot$)	R_* ($R_\odot$)	$M_{\rm ini}$ (M$_\odot$)	$E(B-V)$	$v_{\rm sys}$ (km s^{-1})	Inclination	Reference
120-S 12	B1 I	23	2.2	30	$\sim$25	0.25	285 ± 10	intermediate	Zickgraf et al. (1986)
120-S 73	B8 I	12	3.0	125	25–30	0.12	264 ± 3	$\sim$ pole-on	Stahl et al. (1983)

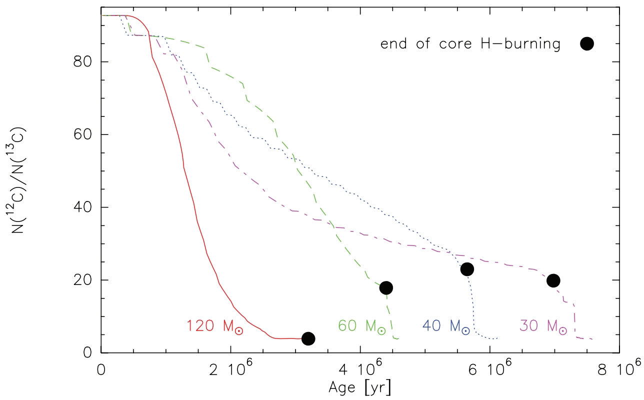

Figure 2. Change in $^{12}C/^{13}C$ surface abundance ratio during the evolution of rotating massive stars at LMC metallicity, based on the models of Meynet & Maeder (2005).

Table 2. Best-fitting parameters for the CO band emission from the discs of S 12 and S 73.

Object LHA	T_{CO} (K)	N_{CO} (10^{21} cm^{-2})	$^{12}C/^{13}C$	$A_{CO} \cos i$ (au^2)
120-S 12	2800 ± 500	2.5 ± 0.5	20 ± 2	2.58 ± 0.15
120-S 73	2800 ± 500	3.5 ± 0.5	9 ± 1	21.0 ± 0.3

The presence of some additional emission features, especially at the red end of the spectrum, can be explained by the (if weak) recombination lines of the hydrogen Pfund series. Following the description of Kraus et al. (2000), we modelled the Pfund series assuming a constant electron density and an electron temperature of $T_e = 10^4$ K. The lack of Pfund lines higher than Pf 34 (S 73) and Pf 31 (S 12) means that due to pressure ionization in a high-density gas, recombination into such high-energy states is suppressed. This is in good agreement with the electron densities of $n_e \gtrsim 10^9$ cm^{-3} needed for the lines to be formed in LTE conditions, as is obvious from their intensity ratios. As in the case of the CO bands, no additional line broadening is required to match the width of the Pfund lines. This could indicate that the Pfund emission is generated either in the disc but much closer to the star than the CO bands, or in the polar wind regions so close to the star that the wind velocity is still very small compared to the velocity resolution of SINFONI. The resulting synthetic Pfund series are included as the blue lines in the top panels of Fig. 3, and the combined model spectra of CO bands and Pfund lines are overplotted in red on the observed spectra in black in the bottom panels.

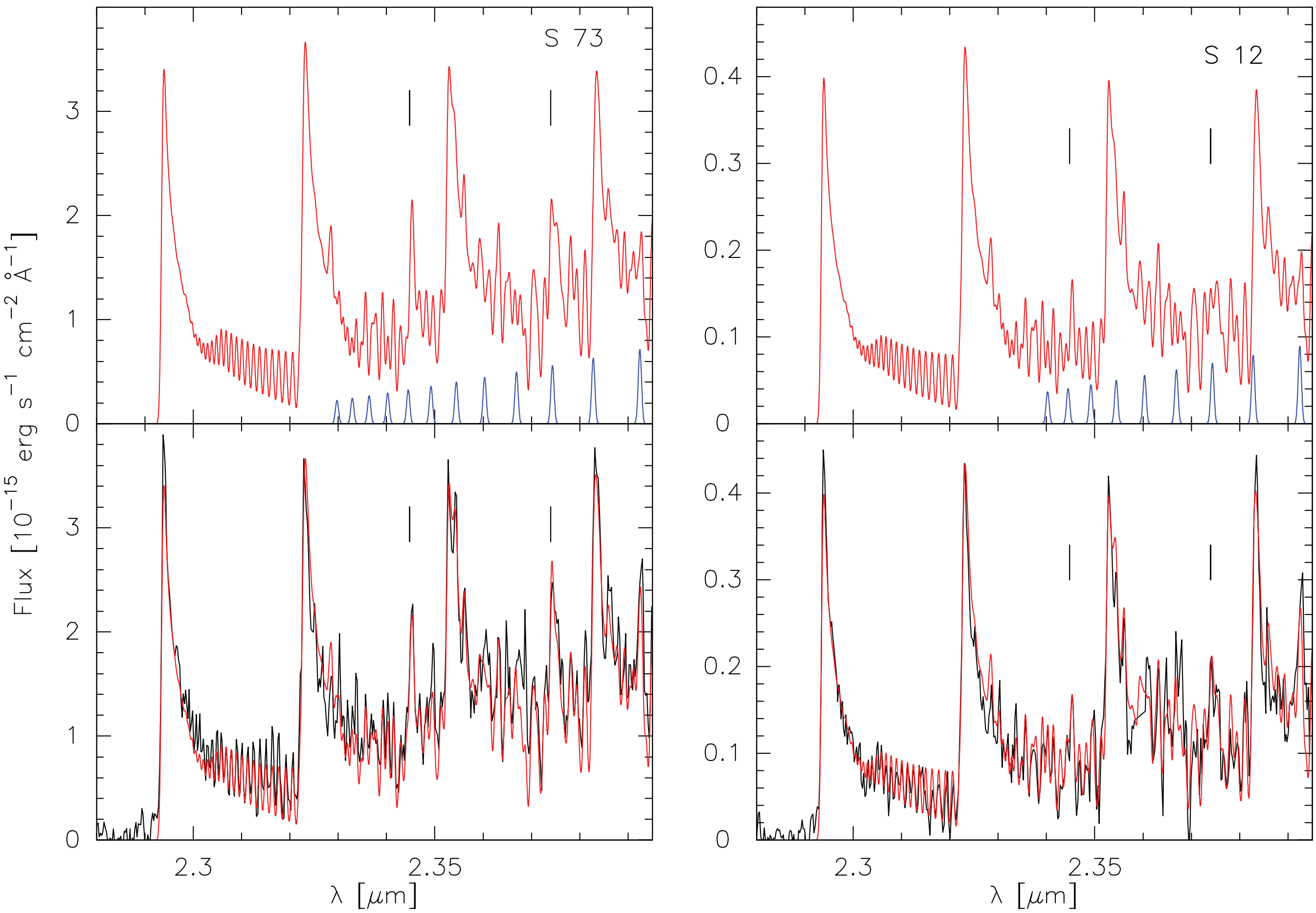

Figure 3. Top: synthetic spectra of the CO bands (red) and of the Pfund series (blue). Bottom: combined CO band plus Pfund spectra (red) overlaid on the observed (black), flux-calibrated CO band spectra of S 73 (left) and S 12 (right). The vertical ticks in the respective panels indicate the positions of the ^{13}CO band heads.

4 DISCUSSION

Our analysis has shown that the spectra of the B[e]SGs S 73 and S 12 display emission from the ^{13}CO band heads (see Fig. 3), which means that their circumstellar disc material is strongly enriched with ^{13}C; hence, these stars are indeed evolved post-main-sequence objects.

Our model computations have also confirmed the relatively low temperature of the CO gas as indicated by the approximately equal strengths of the ^{12}CO band heads. Such low temperatures are not expected within the canonical picture of B[e]SGs, which assumes that their discs are formed by enhanced mass flux from the stars' equatorial regions. If the discs of the two B[e]SGs studied here were continuously supplied, then the CO in the gaseous parts of the disc should be visible from the hottest component having temperatures close to the CO dissociation temperature of 5000 K. In this case the observable CO band spectrum, which always reflects the hottest available CO component, would be dominated by the peaks of the higher vibrational transitions occurring at longer wavelengths, while the lowest band head (at 2.3 μm) would be strongly suppressed (see Kraus 2009). The apparent deficiency in CO gas hotter than ~2800 K therefore suggests that there is no CO gas closer to the star. Hence, the discs seen around S 12 and S 73 cannot extend down to the stellar surface. Instead, it would be more appropriate to assume that the stars are surrounded by a dense and cool *ring* of material. Support for such a scenario comes from the recent detection of a detached ring in quasi-Keplerian rotation around the Small Magellanic Cloud (SMC) B[e]SG star LHA 115-S 65 (Kraus et al. 2010).

Alternatively, gravitational darkening according to the von Zeipel theorem (von Zeipel 1924) in rapidly rotating stars can lead to equatorial temperatures being sufficiently low (i.e. $\lesssim$3000 K) for the hottest CO gas to not exceed ~2800 K. In this picture, the disc still could extend from the stellar surface out to large distances, with the CO emitting gas located closest to the star within the innermost, hottest disc region. While this scenario is somewhat speculative (and heating of the disc through light from hotter regions of the star would have to be considered as well), we can estimate the minimum rotation speed of the stars required to achieve an equatorial surface temperature of 3000 K.

Stellar rotation leads the poles to be hottest. Assuming that both stars are seen pole-on and that their effective temperatures, $T_{\rm eff}$, listed in Table 1 correspond to the polar values, requires a decrease in $T_{\rm eff}$ from polar to equatorial values by factors of 7.7 (S 12) and 4 (S 73). This, in turn, requires the stars to rotate with ≫99 per cent of their critical velocity (see fig. 5 of Kraus 2006). The assumed pole-on orientation only provides us with *lower limits* of the real rotation velocity, but even in the unexpected case that both stars are seen perfectly pole-on, rotation rates close to or even at the critical limit are highly unlikely. For comparison, the two most rapidly rotating B[e]SGs known, the SMC stars LHA 115-S 23 and LHA 115-S 65, rotate with $\gtrsim$75 per cent of their critical velocity (Zickgraf 2000; Kraus et al. 2008, 2010). If our program stars rotated at ~75 per cent of their critical velocity, resulting equatorial temperatures would still be ~72 per cent of the polar values (cf. Table 1), i.e. much hotter than 3000 K. The deficiency of CO gas hotter than 2800 K is thus real, and the most plausible scenario is hence that the molecular gas is located within a detached ring of material rather than in a disc extending down to the stellar surface.

In Table 2 we include the sizes of the CO emitting regions (projected to the line of sight, $A_{\rm CO}\cos i$) as obtained from our best-matching models. From these sizes, we estimate the radial extension of the emitting CO rings. We compute the outer radius of the ring as a function of its inner radius. The results for both stars are depicted by the solid lines in Fig. 4, indicating that for increasing inner radii the emission area converges towards infinitesimally narrow rings. With the stellar luminosities given in Table 1 and an assumed dust sublimation temperature of $T_{\rm sub} \simeq 1600$ K (e.g. Lodders 2003), we find individual sublimation radii of $R_{\rm sub} \simeq 24\,R_*$ and $\simeq 86\,R_*$ for S 73 and S 12, respectively. These maximum outer edges of the CO rings are shown in Fig. 4 as dashed lines. An estimate for the inner edge of the CO ring is less precise. The CO gas has to have a temperature of about 2800 K, only slightly higher than the dust sublimation temperature but definitely much lower than the effective temperatures of the stars. A reasonable estimate could thus be $R_{\rm in} \gtrsim 10\,R_*$ for S 73 and (much) larger for S 12. For the latter, we plotted the relation between inner and outer radius for two different values of disc inclination. However, independent of the exact value

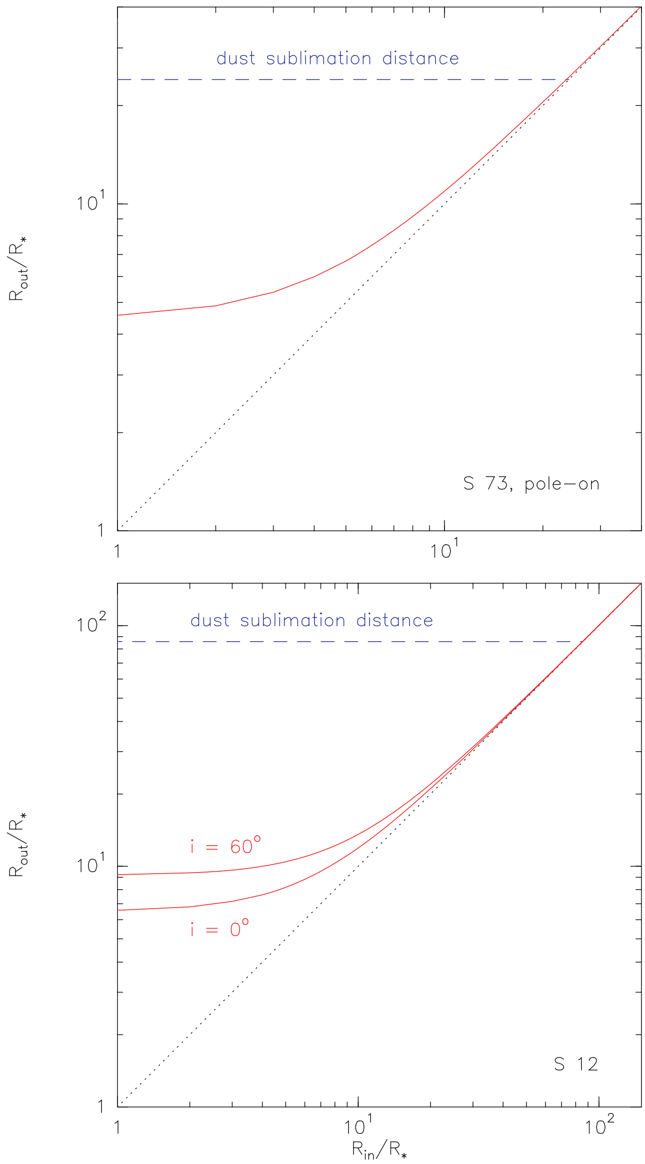

Figure 4. Outer radius of the CO emitting ring as a function of inner radius (solid lines) for S 73 (top) and S 12 (bottom). The maximum outer radius is set in both cases by the distance for dust sublimation (dashed lines). For S 12 two inclination angles for the disc are considered.

of $R_{\rm in}$ (and i as in the case of S 12) we can conclude that the CO emitting area is concentrated within a rather narrow ring at short distance from the central star.

5 CONCLUSIONS

Using high-quality K-band spectra obtained with SINFONI, we detected, for the first time, a 13C enhancement in two B[e]SGs in the LMC, thereby confirming their evolved nature. The enrichment of their disc-forming wind material with ^{13}C and the resulting strong ^{13}CO band emission, as was suggested by Kraus (2009), is thus shown to be a robust method for the identification of evolved stars. This method can now be applied to the Galactic B[e]SG candidates to disentangle the real Galactic B[e]SGs from the more abundant Herbig Ae/Be stars.

In our analysis, we also found a deficiency of hot CO gas in the discs of both stars. This can be explained in two ways. Either both stars rotate at their critical limit so that equatorial surface temperatures (and hence, maximum disc temperatures) drop below $\sim$3000 K and no hot CO gas is expected or the CO emitting region is located in a high-density, detached ring of material rather than in an equatorially enhanced, disc-forming wind. While the former scenario cannot be excluded, we consider the latter as the more realistic one since it also agrees with the recently found detached gas ring around the SMC B[e]SG star LHA 115-S 65 by Kraus et al. (2010).

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