The sudden appearance of CO emission in LHA 115-S 65[★]

M. E. Oksala,[1]† M. Kraus,[1] M. L. Arias,[2,3] M. Borges Fernandes,[4] L. Cidale,[2,3] M. F. Muratore[2,3] and M. Curé[5]

[1]*Astronomický ústav, Akademie věd České republiky, Fričova 298, 251 65 Ondřejov, Czech Republic*
[2]*Departamento de Espectroscopía Estelar, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, B1900FWA La Plata, Argentina*
[3]*Instituto de Astrofísica de La Plata, CCT La Plata, CONICET-UNLP, Paseo del Bosque s/n, B1900FWA La Plata, Argentina*
[4]*Observatório Nacional, Rua General José Cristino 77, 20921-400 São Cristovão, Rio de Janeiro, Brazil*
[5]*Departmento de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso Av. Gran Bretaña 1111, Casilla 5030, Valparaíso, Chile*

ABSTRACT

Molecular emission has been detected in several Magellanic Cloud B[e] supergiants. In this Letter, we report on the detection of CO band head emission in the B[e] supergiant LHA 115-S 65, and present a *K*-band near-infrared spectrum obtained with the Spectrograph for INtegral Field Observation in the Near-Infrared (SINFONI; $R = 4500$) on the ESO VLT UT4 telescope. The observed molecular band head emission in S65 is quite surprising in the light of a previous non-detection by McGregor, Hyland & McGinn, as well as a high-resolution ($R = 50\,000$) Gemini/Phoenix spectrum of this star taken nine months earlier showing no emission. Based on analysis of the optical spectrum by Kraus, Borges Fernandes & de Araújo, we suspect that the sudden appearance of molecular emission could be due to density build-up in an outflowing viscous disc, as seen for Be stars. This new discovery, combined with variability in two other similar evolved massive stars, indicates an evolutionary link between B[e] supergiants and luminous blue variables.

Key words: circumstellar matter – stars: emission-line, Be – stars: individual: LHA 115-S 65 – supergiants – stars: winds, outflows.

1 INTRODUCTION

Massive stars evolving off the main sequence pass through several phases of strong mass loss before ending their lives as supernovae. B[e] supergiants (B[e]SGs) represent one of these phases. These stars are surrounded by massive discs or rings of cool and dense material, confirmed by polarimetry (Magalhães 1992; Oudmaijer & Drew 1999; Melgarejo et al. 2001; Magalhães et al. 2006) and optical interferometry observations (Domiciano de Souza et al. 2007). They are hence ideal environments for efficient dust and molecule condensation. Dust is evident from a prominent near- and mid-infrared excess emission (e.g. Zickgraf et al. 1986; Bonanos et al. 2009, 2010) and from spectroscopic features in the infrared indicating that the disc contains both oxygen-rich (crystalline silicates) and carbon-rich (polycyclic aromatic hydrocarbons) dust (Kastner et al. 2010). The presence of molecules in the discs of B[e]SGs is obvious from detections of TiO band emission at optical wavelengths (Zickgraf et al. 1989; Torres et al. 2012) and of the much more prominent CO band emission arising at near-infrared wavelengths (McGregor, Hillier & Hyland 1988a,b; McGregor, Hyland & McGinn 1989; Morris et al. 1996).

The study of CO molecules in the spectra of B[e]SGs is an important tool to understand the inner portion of their dusty discs. CO first-overtone band head structure, arising at 2.3 µm, is particularly sensitive to the motion of the hot gas disc, allowing study of the disc kinematics and structure (Keplerian disc, slow outflowing winds or accretion discs). Complementary to this molecule, optical forbidden lines, mainly [O I] (Kraus, Borges Fernandes & de Araújo 2007, 2010) and [Ca II] lines (Kraus et al. 2010; Aret et al. 2012), are excellent tracers of the inner regions of the disc. In addition, the ratio ^{12}CO/^{13}CO in B[e]SGs could be used as an age indicator of the star (Kraus 2009; Liermann et al. 2010), allowing constraint on their evolutionary phase with respect to other evolved phases of massive stars, i.e. yellow hypergiants (YHGs; Muratore et al. 2010).

Table 1. Parameters of S65.

Object	Sp. type	$E(B-V)$	T_{eff} $(10^3$ K$)$	L $(10^5$ L$_\odot)$	V_{sys} (km s^{-1})	$v \sin i$ (km s^{-1})	References
S65	B2-3	0.15–0.20	17	5.0	191	150	1, 2, 3

References: (1) Zickgraf et al. (1986); (2) Zickgraf (2000); (3) Kraus et al. (2010).

Recently, we obtained data for a near-infrared survey to study the molecular circumstellar material (in terms of CO band emission) and possible evolutionary links between YHGs and B[e]SGs based on their ^{13}C footprint (Liermann et al. 2010; Muratore et al. 2010). The survey sample consists of Galactic B[e]SG candidates with CO band emission and all Magellanic Cloud B[e]SGs [however, the stars S111 from the Large Magellanic Cloud (LMC) and S23 from the Small Magellanic Cloud (SMC) are excluded due to magnitude limitations]. In this Letter, we report on one result from this survey, the new and sudden detection of CO emission in the SMC B[e]SG LHA 115-S 65 (hereafter S65). We discuss the significance of this event in the context of disc kinematics and stellar evolution.

Zickgraf et al. (1986) studied the photometric and spectroscopic properties of several B[e]SGs, and determined the stellar parameters for the SMC star S65 (summarized in Table 1). The observed optical spectrum consists of not only many faint absorption lines (e.g. He I, N II and Si II), but also emission lines of Fe II, [Fe II] and [O I]. The Fe II emission lines show a central absorption; forbidden emission lines are not double peaked. Hydrogen Balmer lines have broad wings and consist of both an emission and an absorption component. Absorption lines of Ti II and Cr II are assumed to be shell absorption features. Optical spectra of S65 taken over the past 30 years do not show any variation (Kraus et al. 2010); no brightness variations exceeding 0.02 mag have been reported since the initial observation in 1960 (Zickgraf et al. 1986).

2 OBSERVATIONS

We obtained a high-quality, medium-resolution ($R = 4500$) K-band (1.95–2.45 μm) spectrum of the SMC B[e]SG S65 using the Spectrograph for INtegral Field Observation in the Near-Infrared (SINFONI; Eisenhauer et al. 2003; Bonnet et al. 2004) on the VLT UT4 telescope. The observation was taken on 2011 October 6 with an 8×8 arcsec^2 field of view and an AB nod pattern. A B-type standard star was observed at similar airmass for telluric correction and flux calibration.

Data reduction was performed with the SINFONI pipeline (version 2.2.9). Raw frames were corrected for bad pixels, flat-fields and distortion, and then wavelength calibrated. The standard star observation was similarly reduced. For flux calibration, the standard star spectrum was scaled with the corresponding Kurucz flux model (Kurucz 1993) to its Two Micron All-Sky Survey (Skrutskie et al. 2006) K_S-band magnitude to create a calibration curve. The IRAF task *telluric* was used to remove atmospheric lines using the B-type telluric standard spectrum. The final spectrum has a signal-to-noise ratio ∼250–300. The spectrum was corrected for the systemic and heliocentric velocities and dereddened with the $E(B-V)$ value in Table 1 according to the interstellar extinction relation of Howarth (1983). Fig. 1 shows the final spectrum displaying the CO band heads, located longwards of 2.29 μm.

A spectrum of S65 was obtained on 2011 January 5 with the Phoenix high-resolution ($R = 50\,000$) near-infrared spectrograph at the Gemini Observatory using the K 4396 filter centred at 2.2725 μm. The observations were reduced using standard IRAF tasks. Observation was taken with the offset pattern ABBA, and pairs were subtracted to remove sky background. The spectrum was flat-fielded, telluric corrected and wavelength calibrated. We again selected a B-type telluric standard. The final spectrum is shown in the top portion of Fig. 2.

3 RESULTS

3.1 CO detection in S65

From visual inspection of the S65 CO spectrum (Fig. 1), the band head structures appear quite narrow. Based on the analysis of Kraus et al. (2010), the CO should be located beyond $3000\,R_\star$ in the edge-on viewed disc, where the Keplerian rotation has reached a value <5 km s^{-1}. Therefore, the profiles contain no significant
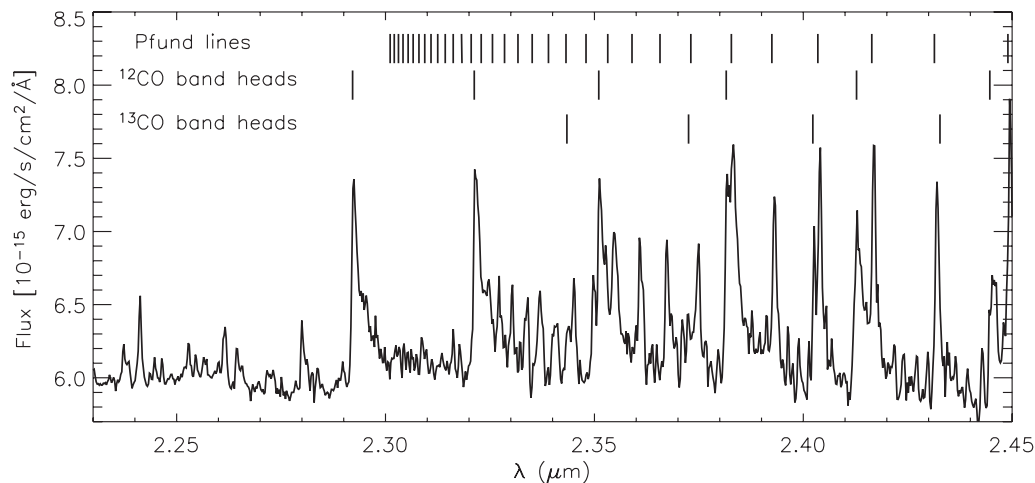

Figure 1. Flux-calibrated SINFONI CO band spectra of S65. The location of the ^{12}CO and ^{13}CO band heads and the lines of the Pfund series are indicated.
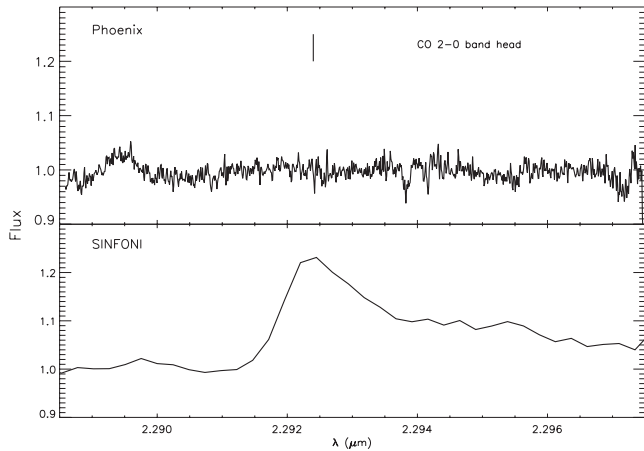
Figure 2. Top: normalized Phoenix high-resolution ($R = 50\,000$) K-band spectrum of S65. Bottom: normalized SINFONI ($R = 4500$) K-band spectrum of S65. The position of the 2–0 band head of CO is indicated in the top frame. Note the absence of detectable emission in the Phoenix spectrum, taken just nine months prior to the SINFONI spectrum. The emission feature at 2.2895 μm is likely a blend of two Si lines.

kinematical broadening, leaving mainly the instrumental broadening. The first three band heads appear approximately equal in strength, while the intensity of the higher band heads quickly drops. This behaviour hints towards a relatively cool CO gas ($T < 2800$ K), and a moderately high CO column density (0.5–5×10^{21} cm^{-2}), which is high enough so that the transitions at longer wavelengths start to become marginally optically thick. Such conditions were also recently found for two B[e]SGs in the LMC (Liermann et al. 2010). The continuum is flat and Pfund lines contaminate the region where these CO emission bands appear. ^{13}CO emission is present in the spectrum; however, proper modelling of the spectrum is necessary to determine the ^{12}CO/^{13}CO ratio.

The discovery of CO band emission in S65 is quite surprising, considering the previous non-detection by McGregor et al. (1989), further augmented by a new high-resolution ($R = 50\,000$) Phoenix spectrum of the star (top portion of Fig. 2) displaying absolutely no evidence of the 2–0 first-overtone band head of CO. The absence of CO in this detailed spectrum is particularly perplexing considering it was acquired just nine months prior to our SINFONI observation. This very sudden appearance of molecular emission indicates that the disc of S65 must in fact be variable.

3.2 CO variability of other evolved massive stars

While the abrupt appearance of CO emission in S65 is interesting, it is not the first instance of such variability among evolved massive stars. LHA 115-S 18 (S18), another B[e]SG located in the SMC, has shown fluctuation in a number of different spectral features. In the UV and optical spectra observed by Shore, Sanduleak & Allen (1987), C IV and N IV resonance lines were variable, as well as the He II 4686 Å line. In fact, He II was absent in the spectrum of Zickgraf et al. (1989). The spectrum also contained a broad feature at 6159 Å attributed to TiO emission. It was therefore expected by McGregor et al. (1989) that the K-band spectrum of S18 would show CO emission, as TiO presumably traces a more dense region of material than CO. Curiously though, the spectrum of this star showed no evidence of CO band head structure. The star was observed again in the K-band region by Morris et al. (1996), who found that the spectrum had not only detectable CO emission, but

also other spectral changes compared to the spectrum of McGregor et al. (1989). The He I 2.058 μm line strength greatly increased, and the He I 2.112 μm line (which is typically in absorption for B-type stars) was found to be in emission. While Shore et al. (1987) suggested that the changes seen in the spectrum of S18 were due to interaction between a companion star and the stellar wind, Morris et al. (1996) determined that the varying He I was not due to the wind, but instead a result of a recent increase in density such as a variable equatorial outflow, and likely related to the appearance of CO. Torres et al. (2012) have recently detected variability in various optical spectral lines, as well as the presence of Raman-scattered lines that provide evidence of a dense H I region. A recent SINFONI K-band observation confirms the continued presence of the CO emission in S18 (Oksala et al., in preparation).

Although observed spectral variation in luminous blue variables (LBVs) is not noteworthy, the presence and variability of the first-overtone CO band head emission in the spectrum of HR Car is unique. No other LBV has shown such spectral features to date. The K-band spectrum of HR Car was first observed by McGregor et al. (1988a) during three separate periods from 1984 to 1986. The CO emission was clearly detected during the first period, marginally detected during the second, and completely absent during the third. A later observation by Morris et al. (1997) revealed the emission had reappeared, even stronger than observed previously. The authors find a photometric brightness correlation with the appearance and disappearance of K-band CO emission, and determine the location of the CO-emitting region to be at 3–$4\,R_\star$. At this distance, a shielding mechanism is necessary to protect the CO molecules from the stellar radiation. As in S65, the most plausible model for the production of this emission is an outflowing disc. Although HR Car hosts a large bipolar nebula, spectroscopy (Nota et al. 1997) and polarization (Clampin et al. 1995) show support for a more dense, flattened central region or waist, likely the location of the CO-emitting region.

4 DISCUSSION

4.1 Disc formation in B[e]SGs

The kinematics determined within the gaseous disc parts around S65 were found to be (quasi-)Keplerian by Kraus et al. (2010). Furthermore, the authors found that the outflow velocity of the disc material seems to decrease with distance from the star. This type of disc has been seen for rapidly rotating Be stars, and is likely driven by viscosity (see e.g. Porter 1999; Okazaki 2001; Jones, Sigut & Porter 2008). If the velocity decreases to a static point, the material closer to the star will still move outwards, creating an accumulation or high density of material at that distance in the disc. Detectable CO band emission would thus only be observed as soon as the density is high enough for the band heads to peak above the continuum.

As in Be stars (Porter 1999), the discs of B[e] stars are thought to be formed via a two-component stellar wind (see e.g. Zickgraf et al. 1985; Zickgraf 2006) consisting of a fast polar wind and a slow equatorial disc wind. It is possible that the discs of B[e]SGs are similarly outflowing viscous decretion discs, creating the conditions for detection of molecular emission. The stability of the molecular emission in the discs of these highly luminous stars is yet to be determined. Could the observed CO simply be a feature of a transient disc, as in the Be stars, or are the circumstellar environments of these massive supergiants more persistent? Could these discs be products of LBV-type eruption, but on a smaller scale, or are they remnants of a red supergiant phase? To determine the mechanism creating

and changing these discs, we need more consistent monitoring of this whole class of stars with data that will allow in-depth study of the kinematics, as well as determination of the evolutionary state.

4.2 Evolutionary links

Besides B[e]SGs, the much cooler YHGs also display CO band emission. These stars represent another post-main-sequence evolutionary phase in which stars undergo strong mass loss (e.g. de Jager 1998) forming a disc, ring or shell of high-density material. YHGs are proposed to evolve bluewards in the Hertzsprung–Russell diagram (HRD), and several studies have suggested that they could be the progenitors of lower luminosity (log $L/L_{\odot} \leq 5.8$) B[e]SGs (Kastner et al. 2010; Muratore et al. 2010; Aret et al. 2012).

On the other hand, B[e]SGs share their location in the HRD with LBVs, suggesting that an evolutionary connection between these two classes of stars might exist as well. Predicted blueward evolution of lower luminosity LBVs suggests they are in a post-YHG (or post-red supergiant) phase (Humphreys & Davidson 1994; Meynet et al. 2011). Moreover, S65 has recently been found to be in a pre-LBV phase (e.g. Kraus et al. 2010). Hence, the blueward evolution could proceed from YHG through B[e]SG to LBV. Still, the evolutionary connection in the uppermost part of the HRD (log $L/L_{\odot} \geq 5.8$) where LBVs and B[e]SGs are also found to coexist is not well understood, and thus the evolutionary link between these most massive stars is yet unknown. Morris et al. (1996) suggested that the spectral morphologies of S18 and two known LBV stars, AG Car and P Cygni, are similar, implying S18 is an LBV candidate and providing evidence of an evolutionary connection between B[e]SGs and LBVs.

The results presented in this Letter provide further evidence for the connection between these ambiguous transition objects. In addition to the observed variability of CO emission in both S65 and HR Car, both stars are rotating near critical rotation (valid for HR Car at visual minimum phase; Groh et al. 2009; Kraus et al. 2010) and are located in a similar position on the HRD near to the LBV instability strip determined by Groh et al. (2009). Based on the observed properties of S65, we assert that this star is in a pre-LBV state due to the multitude of shared characteristics and lack of an eruptive event, such as S-Dor-type variability. If we presume that all B[e]SGs eventually evolve into LBVs, what remains particularly puzzling is the timing and physical conditions at which the transition from one class to the other occurs, and what role critical stellar rotation plays in influencing the transformation.

5 CONCLUSION

Although we have mentioned here only two stars straddling the line between B[e]SG and LBV, it is quite possible that a larger number of these stars are evolving towards, or currently in, a pre-LBV state (Oksala et al., in preparation). Close to critical stellar rotation, an additional link between these objects, may be supported. As one of the major defining characteristics of LBV stars, the spectral variability of S65 and S18 suggests concrete evidence of their evolutionary connection. Whether this remains true for all B[e]SGs cannot be determined with the current collection of observations. Further monitoring of the spectral features of these fascinating and enigmatic stars is essential to reveal the true nature and kinematics of their discs, as well as to disclose their evolutionary paths.

REFERENCES

Aret A., Kraus M., Muratore M. F., Borges Fernandes M., 2012, MNRAS, 423, 284
Bonanos A. Z. et al., 2009, AJ, 138, 1003
Bonanos A. Z. et al., 2010, AJ, 140, 416
Bonnet H. et al., 2004, The Messenger, 117, 17
Clampin M. et al., 1995, AJ, 110, 251
de Jager C., 1998, A&AR, 8, 145
Domiciano de Souza A. et al., 2007, A&A, 464, 81
Eisenhauer F. et al., 2003, in Iye M., Moorwood A. F. M., eds, Proc. SPIE Vol. 4841, Instrument Design and Performance for Optical Infrared Ground-based Telescopes. p. 1548
Groh J. H. et al., 2009, ApJ, 705, L25
Howarth I. D., 1983, MNRAS, 203, 301
Humphreys R. M., Davidson K., 1994, PASP, 106, 1025
Jones C. E., Sigut T. A. A., Porter J. M., 2008, MNRAS, 386, 1922
Kastner J. H. et al., 2010, AJ, 139, 1993
Kraus M., 2009, A&A, 494, 253
Kraus M., Borges Fernandes M., de Araújo F. X., 2007, A&A, 463, 627
Kraus M., Borges Fernandes M., de Araújo F. X., 2010, A&A, 517, A30
Kurucz R. L., 1993, VizieR Online Data Catalog, 6039, 0
Liermann A., Kraus M., Schnurr O., Borges Fernandes M., 2010, MNRAS, 408, L6
McGregor P. J., Hillier D. J., Hyland A. R., 1988a, ApJ, 334, 639
McGregor P. J., Hyland A. R., Hillier D. J., 1988b, ApJ, 324, 1071
McGregor P. J., Hyland A. R., McGinn M. T., 1989, A&A, 223, 237
Magalhães A. M., 1992, ApJ, 398, 286
Magalhães A. M., Melgarejo R., Pereyra A., Carciofi A. C., 2006, in Kraus M., Miroshnichenko A. S., eds, ASP Conf. Ser. Vol. 355, Stars with the B[e] Phenomenon. Astron. Soc. Pac., San Francisco, p. 147
Melgarejo R., Magalhães A. M., Carciofi A. C., Rodrigues C. V., 2001, A&A, 377, 581
Meynet G. et al., 2011, Bull. Soc. R. Sci. Liege, 80, 266
Morris P. W. et al., 1996, ApJ, 470, 597
Morris P. W., Voors R. H. M., Lamers H. J. G. L. M., Eenens P. R. J., 1997, in Nota A., Lamers H. J. G. L. M., eds, ASP Conf. Ser. Vol. 120, Luminous Blue Variables: Massive Stars in Transition. Astron. Soc. Pac., San Francisco, p. 20
Muratore M. F. et al., 2010, Bol. Asociación Argentina Astron., 53, 123
Nota A. et al., 1997, ApJ, 486, 338
Okazaki A. T., 2001, PASJ, 53, 119

Oudmaijer R. D., Drew J. E., 1999, MNRAS, 305, 166

Porter J. M., 1999, A&A, 348, 512

Shore S. N., Sanduleak N., Allen D. A., 1987, A&A, 176, 59

Skrutskie M. F. et al., 2006, AJ, 131, 1163

Torres A. F. et al., 2012, MNRAS, submitted

Zickgraf F.-J., 2000, in Smith M. A., Henrichs H. F., Fabregat J., eds, ASP Conf. Ser. Vol. 214, The Be Phenomenon in Early-type Stars. Astron. Soc. Pac., San Francisco, p. 26

Zickgraf F.-J., 2006, in Kraus M., Miroshnichenko A. S., eds, ASP Conf. Ser. Vol. 355, Stars with the B[e] Phenomenon. Astron. Soc. Pac., San Francisco, p. 135

Zickgraf F.-J. et al., 1985, A&A, 143, 421

Zickgraf F.-J. et al., 1986, A&A, 163, 119

Zickgraf F.-J., Wolf B., Stahl O., Humphreys R. M., 1989, A&A, 220, 206

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