The Astrophysical Journal Letters, 800:L20 (5pp), 2015 February 20 doi:10.1088/2041-8205/800/2/L20

DISCOVERY OF SiO BAND EMISSION FROM GALACTIC B[e] SUPERGIANTS*

M. Kraus[1], M. E. Oksala[2], L. S. Cidale[3,4], M. L. Arias[3,4], A. F. Torres[3,4], and M. Borges Fernandes[5]
[1] Astronomický ústav, Akademie věd České republiky, Fričova 298, 251 65 Ondřejov, Czech Republic; michaela.kraus@asu.cas.cz
[2] LESIA, Observatoire de Paris, CNRS UMR 8109, UPMC, Université Paris Diderot, 5 place Jules Janssen, F-92190, Meudon, France
[3] Departamento de Espectroscopía Estelar, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina
[4] Instituto de Astrofísica de La Plata, CCT La Plata, CONICET-UNLP, Paseo del Bosque s/n, B1900FWA, La Plata, Argentina
[5] Observatório Nacional, Rua General José Cristino 77, 20921-400 São Cristovão, Rio de Janeiro, Brazil
Received 2014 December 12; accepted 2015 January 24; published 2015 February 13

ABSTRACT

B[e] supergiants (B[e]SGs) are evolved massive stars in a short-lived transition phase. During this phase, these objects eject large amounts of material, which accumulate in a circumstellar disk-like structure. The expelled material is typically dense and cool, providing the cradle for molecule and dust condensation and for a rich, ongoing chemistry. Very little is known about the chemical composition of these disks, beyond the emission from dust and CO revolving around the star on Keplerian orbits. As massive stars preserve an oxygen-rich surface composition throughout their life, other oxygen-based molecules can be expected to form. As SiO is the second most stable oxygen compound, we initiated an observing campaign to search for first-overtone SiO emission bands. We obtained high-resolution near-infrared *L*-band spectra for a sample of Galactic B[e]SGs with reported CO band emission. We clearly detect emission from the SiO first-overtone bands in CPD-52 9243 and indications for faint emission in HD 62623, HD 327083, and CPD-57 2874. From model fits, we find that in all these stars the SiO bands are rotationally broadened with a velocity lower than observed in the CO band forming regions, suggesting that SiO forms at larger distances from the star. Hence, searching for and analyzing these bands is crucial for studying the structure and kinematics of circumstellar disks, because they trace complementary regions to the CO band formation zone. Moreover, since SiO molecules are the building blocks for silicate dust, their study might provide insight in the early stage of dust formation.

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

1. INTRODUCTION

Massive stars, when evolving off the main sequence, undergo phases of strong mass loss, often resulting in the formation of shells, disks, or rings of circumstellar material. One class of evolved massive stars, B[e] supergiants (B[e]SGs), are early-type emission line stars with high-density gaseous and dusty circumstellar disks of yet unknown origin (see de Wit et al. 2014 for a recent review). The gaseous inner disk is traced by the emission of low-ionized metal lines from both permitted and forbidden transitions (e.g., Zickgraf et al. 1985). Of these, the lines of [Ca II] and [O I] are particularly useful. While their intensities probe regions of high and medium densities, where the transition between the two regimes might be settled at an electron density of $\sim 10^7$ cm^{-3}, their line profiles contain the information on their kinematics (Kraus et al. 2007, 2010; Aret et al. 2012). Farther out, molecules form via gas phase chemistry, and intense band emission from CO molecules has been reported for many of these stars (McGregor et al. 1988a, 1988b, 1989; Morris et al. 1996; Kraus et al. 2000, 2014; Liermann et al. 2010; Cidale et al. 2012; Wheelwright et al. 2012; Oksala et al. 2012, 2013). In addition, the presence of TiO band emission features in optical spectra of several B[e]SGs has been suggested (Zickgraf et al. 1989; Torres et al. 2012), but still lacks confirmation. Besides atomic and molecular gas, these stars are also surrounded by warm circumstellar dust, as is obvious from their strong infrared excess emission (Zickgraf et al. 1986; Bonanos et al. 2009, 2010), interferometric observations (Domiciano de Souza et al. 2007; Millour et al. 2011; Cidale et al. 2012), and resolved spectral dust features (Kastner et al. 2006, 2010).

Kinematic studies of the atomic and CO gas reveal that the material is confined to detached (sometimes multiple) rings rotating around the star on Keplerian orbits (e.g., Kraus et al. 2010, 2013, 2014; Aret et al. 2012; Cidale et al. 2012; Wheelwright et al. 2012; Muratore et al. 2015). Abundance studies of these rings reveal an enrichment in the isotopic molecule ^{13}CO, in agreement with an evolutionary stage just beyond the main sequence (Kraus 2009; Liermann et al. 2010; Kraus et al. 2013; Oksala et al. 2013; Muratore et al. 2015).

Furthermore, B[e]SGs could be the progenitors of a group of early-type blue supergiants (BSGs) with ring nebulae such as, e.g., Sher 25 and SBW 1. Optical images of these two stars display equatorial rings and bipolar lobes, and Smith et al. (2007) propose that as soon as the rings or disk-like structures seen around B[e]SGs have expanded and cooled they would look exactly like these objects. Support for such a possible evolutionary link comes from the fact that, like B[e]SGs, neither Sher 25 nor SBW 1 has evolved yet through a red supergiant phase, indicating that in both cases, the ejection of the material forming the disks or rings must have happened during their BSG phase. Such a scenario has a much wider impact: as the BSGs with rings closely resemble the progenitor star of the supernova (SN) SN 1987A, B[e]SGs might be regarded as the most plausible candidates for SN explosions of the SN 1987A-type. Notably, two B[e]SGs were recently suggested to be viable SN 1987A-type progenitor candidates: LHA 115-S 18 in the SMC (Clark et al. 2013) and the Galactic object MWC 137 (Muratore et al. 2015). For a better understanding of the evolution of these stars up to the SN stage, it is hence essential to study B[e]SGs in great detail, and

* Based on observations collected with the ESO VLT Paranal Observatory under program 093.D-0248(A).

in particular their mass-loss behavior and the chemistry involved in the formation of the observed dense molecular and dusty rings or disk-like structures.

The atmospheres of massive stars have an oxygen-rich composition, which means that the abundance of oxygen atoms greatly exceeds that of carbon atoms. The same trend is then expected in their disks, because they form from the material released from the stellar surface. Consequently, carbon atoms in the disks are locked in CO, which, as the most stable molecule with a dissociation energy of 11.2 eV, forms as soon as the gas temperature drops below the dissociation temperature of CO, for which a value of ∼5000 K is typically quoted. The excess oxygen atoms will form other molecules, and a rich chemistry is expected at larger distances from the star.

The SiO molecule is the second most stable oxygen compound. Its binding energy of 8.0 eV is higher than that of other oxides or oxygen compounds such as NO, OH, or water, but lower than that of CO, and thus SiO should form in slightly cooler environments ($T_{\rm SiO} < T_{\rm CO} < 5000$ K). As with CO, the rather high gas temperature of the SiO forming region guarantees that high vibrational levels will be excited, causing coupled rotational–vibrational transitions, detectable via prominent band and band head features. And in fact, SiO bands are commonly observed in absorption in the atmospheres of Mira stars, cool giants, and red supergiants (Hinkle et al. 1976; Geballe et al. 1979; Aringer & Jorgensen 1997; Aringer et al. 1999). In these objects, SiO is an important molecule, based on which the physical properties in the transition region between the outer atmosphere and the innermost circumstellar envelope can be studied (e.g., Ohnaka 2014).

To our knowledge, rotational–vibrational SiO bands in emission have only been reported for SN 1987A (Aitken et al. 1988; Roche et al. 1991; Liu & Dalgarno 1994). These emission bands appeared 160 days after the outburst and were not detectable beyond day 578. The rise of the SiO features had a time delay of 48 days with respect to that of CO molecular bands. This is in agreement with the lower binding energy, requiring a cooler environment for the formation of SiO molecules by gas phase chemistry. The disappearance of the emission bands agrees with the onset of dust formation in the ejecta, which is interpreted as depletion of molecular SiO due to condensation of silicate dust, for which the SiO molecule is proposed to be a major building block within an oxygen-rich environment.

Unlike the transient phenomena of a rapidly expanding, diluting ejecta of a SN, the rings or disks around B[e]SGs seem to be quite stable structures of accumulated material. This guarantees these disks as ideal chemical laboratories to study molecule formation and dust condensation. However, apart from CO band emission, detected in most of these objects, and warm circumstellar dust, no information exists about the chemical composition of these disks. Hence, it is necessary to begin searching for other molecular emission features that can be used to study the structure and kinematics of B[e]SG stars' disks comprehensively.

To pioneer this work, we selected a sample of Galactic B[e] SGs, with known CO band emission, to search for molecular rotational–vibrational band emission from SiO.

2. OBSERVATIONS

During the period of 2014 March–May, we observed four Galactic B[e]SGs in the *L*-band wavelength region using the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES, Käufl et al. 2004) on the ESO VLT UT1-Antu 8 m telescope. Details on the objects and their observations are given in Table 1. Data were obtained at four different standard settings with reference wavelengths of 4048.6, 4060.1, 4135.5, and 4147.0 nm, so that the total spectra cover a continuous wavelength range from 3.988–4.176 μm. This range contains the first four band heads of the SiO first-overtone bands. We used the 0″.4 slit, which provides a spectral resolution of $R \sim 50{,}000$, corresponding to a velocity resolution of ∼6 km s^{-1}.

Data reduction was performed with the ESO CRIRES pipeline (version 2.3.2). The observations were taken in an ABBA nod pattern for proper sky subtractions. Raw frames were corrected for bad pixels, flat fields, nonlinearity, and then wavelength calibrated using OH lines in the standard star spectrum. A telluric standard star observation was similarly reduced. For telluric correction, a B-type standard star was observed immediately after the target at a similar airmass. The IRAF[6] task *telluric* was used to remove the atmospheric features. The final spectra were normalized and continuum subtracted.

3. RESULTS

We clearly detect emission from the first three band heads of the SiO first-overtone bands in CPD-52 9243 (Figure 1), and from the first band head in the spectra of the other three stars, CPD-57 2874, HD 327083, and HD 62623 (Figure 2).

In each star's spectrum, the band heads display a blueshifted shoulder and a redshifted maximum with respect to the laboratory wavelength. Their separation is marked by the bar in Figures 1 and 2. Such structures are also typically observed in the band heads of CO, and are an unequivocal manifestation of rotational broadening.

To confirm that the observed features are emission from SiO molecules, we compute synthetic band head models. For this, we modify our existing CO disk code (Kraus et al. 2000) by implementing the SiO line lists and Einstein transition probabilities provided by Barton et al. (2013). For each of our targets, information about the rotation velocity of the CO region and disk inclination angles are listed in Table 2. The rotation velocities of the CO gas have been obtained from the broadening of the first band head of the CO first-overtone bands resolved in high-resolution spectra, and the disk inclination angles have been determined from interferometric observations. From the wavelength separation between the position of the blue shoulder and the red peak of the first band head, we obtain an estimate of the SiO rotation velocity projected to the line of sight. This parameter is refined during the fitting procedure. The final rotation velocities, corrected for disk inclination, are included in Table 2. The high spectral resolution, combined with the sensitivity of the synthetic spectra to rotation velocity, guarantee that these values have a precision of ±1 km s^{-1}. Comparing the velocities obtained in the two molecular band emitting regions, we find a consistently lower value for SiO, suggesting that this molecule is formed within the Keplerian disk at larger distances from the star.

[6] 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.

Table 1
Observed Objects

Object	α (J2000)	δ (J2000)	K (mag)	Obs. Date	$T_{\rm eff}$ (K)	$M_\star$ ($M_\odot$)	$\log L/L_\odot$	D (kpc)	References
HD 62623	07 43 48.469	−28 57 17.37	2.340	2014 Mar 27	8 500–9 500	31–39	4.8–5.2	1.7 ± 0.5	1, 2
CPD-57 2874	10 15 21.971	−57 51 42.71	4.281	2014 Apr 16	9 000–10 000	15–20	6.00	1.7 ± 0.7	3
CPD-52 9243	16 07 01.968	−53 03 45.75	4.443	2014 Mar 22	15 800	17.4–18.6	4.97	3.44 ± 0.8	4, 5
HD 327083	17 15 15.374	−40 20 06.74	3.296	2014 Jun 31	11 500	60	6.00	4.80	6
…	…	…	…	…	20 000	25	5.00	1.50 ± 0.5	7

References. (1) Plets et al. (1995), (2) van Leeuwen (2007), (3) Domiciano de Souza et al. (2011), (4) Cidale et al. (2012), (5) Swings (1981), (6) Machado & de Araújo (2003), (7) Miroshnichenko et al. (2003).

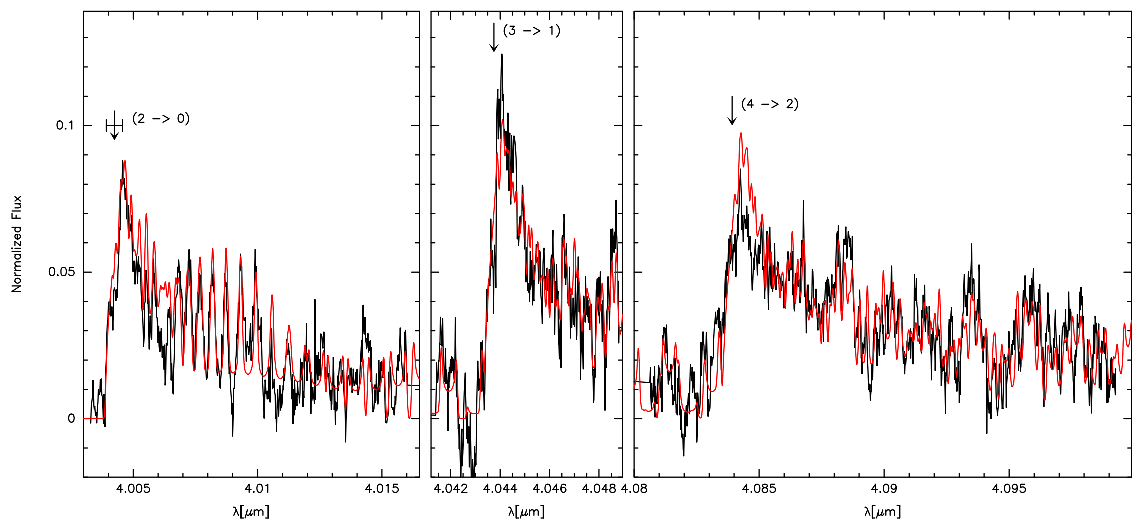

Figure 1. Model fit (red) to the observed (black) three band heads of the SiO first-overtone band emission detected in CPD-52 9243. The arrows mark the wavelength of the unbroadened band heads, and the bar in the panel of the first band head marks the separation between the blueshifted shoulder and the redshifted maximum.

For CPD-52 9243, where three observed band heads are available, we can also constrain temperature and column density, for which we find $T_{\rm SiO} = 2000 \pm 200$ K and $N_{\rm SiO} = (5 \pm 2) \times 10^{21}$ cm^{-2}. With this column density, most of the individual SiO rotation–vibration lines within the observed wavelength range are optically thick. Although the SiO rotation velocity in this object is only marginally lower, both temperature and column density are significantly lower than the values obtained from the CO modeling (see Cidale et al. 2012). This suggests that the two band head formation regions are physically disjoint.

For the other three objects, where solely the first band head is detected, it is only possible to constrain the rotation velocity, because different combinations of temperature and density result in almost identical synthetic spectra. Hence, the fits shown in Figure 2 are only to demonstrate that the observed features can indeed be assigned to SiO band emission, and to determine the SiO rotation velocity.

Under the assumption of Keplerian rotation of the disks and using the stellar mass ranges of the objects (Table 1), the radii of both (CO and SiO) molecular rings can be computed. These values are included in Table 2. Furthermore, considering that the circumstellar dust is mainly composed of silicates, we can calculate the dust evaporation distances. Assuming that the grains are spheres with a maximum size of $\sim$1 μm, and that the silicate evaporation temperature is ~1500 K, the minimum dust evaporation radii follow from the stellar luminosities (listed in Table 1) and are added to Table 2. Obviously, the much hotter molecular rings reside within the dusty disks.

4. CONCLUSIONS

We report on the detection of SiO first-overtone band emission in the high-resolution L-band spectra of four Galactic B[e]SGs, which are known to display strong CO band emission. While SiO bands are commonly seen in absorption from the atmospheres of cool stars and giants, they were detected in emission, so far, only in spectra of SN 1987A during the post-explosion period from day 160 to day 578. Hence, to our knowledge, this is the first discovery of SiO first-overtone band emission from hot, high-density environments of evolved massive stars.

The high spectral resolution of our data allows us to precisely determine the rotation velocity of the SiO gas. For all of our target stars, this velocity is lower than that determined from the CO band forming region. Moreover, model fits to the three band heads observed in CPD-52 9243 demonstrate that, in contrast to the CO band emitting region, the emission of the SiO bands originates from a cooler and less dense disk region,

Table 2
Rotation Velocities and Radii of the CO and SiO Disk Regions, and Silicate Dust Evaporation Distances

Object	i (°)	v_{rot}(CO) (km s^{-1})	References	v_{rot}(SiO) (km s^{-1})	r(CO) (AU)	r(SiO) (AU)	r_{evap}(Silicates) (AU)
CPD-52 9243	46	36	1	35.5	11.9–12.7	12.2–13.1	16.1
CPD-57 2874	60	130	2, 3	110	0.8–1.0	1.1–1.5	52.7
HD 327083	50	86	4	78	3.0 / 7.2	3.6 / 8.7	16.7 / 52.7
HD 62623	38	53	3, 5	48	9.8–12.3	11.9–15.0	17.5

References. (1) Cidale et al. (2012), (2) Domiciano de Souza et al. (2011), (3) Muratore et al. (2012), (4) I. Andruchow et al. (2015, in preparation), (5) Millour et al. (2011).

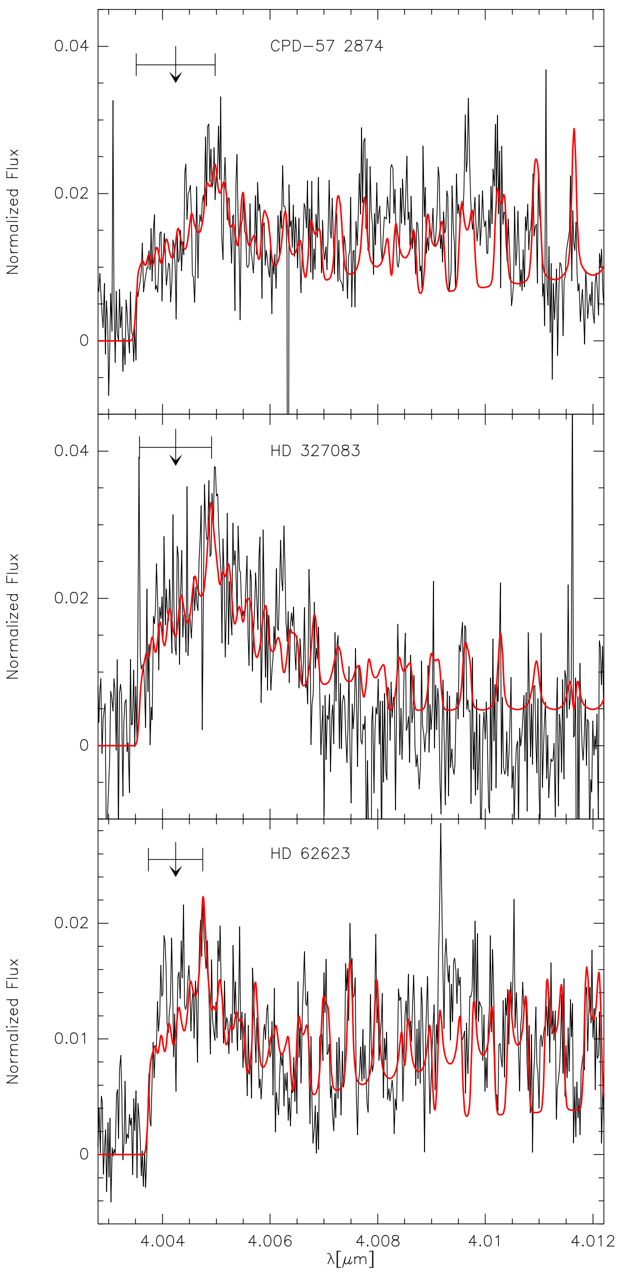

Figure 2. Model fits (red) to the observed (black) first SiO band head. The arrow marks the wavelength of the unbroadened band head, and the bar marks the separation between the blueshifted shoulder and the redshifted maximum.

indicating that SiO molecules form at larger distances within the Keplerian disks. For all four objects, we find, in addition, that the SiO ring radii are smaller than the silicate dust evaporation distances.

This finding is of great importance, because it demonstrates that molecules provide an excellent tool to study B[e] SG stars' disks. The emission features of both molecules detected so far, CO and SiO, carry all the essential information about the physical properties (temperature, density) and kinematics of their formation region. As different molecules require diverse conditions, a huge variety can be expected to form throughout the disk, filling the space between the hottest inner rim traced by CO bands, and the dust condensation region. Hence, it is essential and timely to search for emission features from many more molecules that are expected to form within the oxygen-rich environment of these disks. Moreover, molecules such as CO and SiO are also indispensable to study the disk structure at much larger distances. With their numerous pure rotational transitions, these molecules are also suitable to trace much cooler environments. The rotational transitions spread over the submm and radio regime, making the disks of B[e]SGs ideal targets to be observed with high spatial and spectral resolution facilities such as ALMA. Combining the results obtained from different molecular species tracing diverse temperature regions, and hence distances from the star, will greatly improve our knowledge and comprehension of the disk structure, and help to understand the disks' possible formation history.

In addition, the discovery of SiO band emission has an even wider impact. Evolved massive stars, such as red supergiants, B[e]SGs, and supernovae (e.g., SN 1987A), are the main sources of silicate dust, for which SiO molecules are regarded as a major building block. Studying the physical properties of SiO gas in the disks of B[e]SGs might, hence, provide indispensable insight into the early stage of silicate dust formation within the oxygen-rich environment of these enigmatic stars.

We thank the referee, Dr. John Bally, for his valuable comments on the manuscript. This research made use of the NASA Astrophysics Data System and of the SIMBAD database, operated at CDS, Strasbourg, France. M.K. acknowledges financial support from GAČR (grant number 14-21373S). The Astronomical Institute Ondřejov is supported by the project RVO:67985815. L.C., M.L.A., and A.F.T. acknowledge financial support from the Agencia de Promoción

Científica y Tecnológica (Préstamo BID PICT 2011/0885), CONICET (PIP 0300), and the Universidad Nacional de La Plata (Programa de Incentivos G11/109), Argentina. Financial support for International Cooperation of the Czech Republic (MŠMT, 7AMB14AR017) and Argentina (Mincyt-Meys ARC/13/12 and CONICET 14/003) is acknowledged.

REFERENCES

Aitken, D. K., Smith, C. H., James, S. D., et al. 1988, MNRAS, 235, 19
Aret, A., Kraus, M., Muratore, M. F., & Fernandes, M., Borges. 2012, MNRAS, 423, 284
Aringer, B., Jorgensen, U. G., & Langhoff, S. R. 1997, A&A, 323, 202
Aringer, B., Höfner, S., Wiedemann, G., et al. 1999, A&A, 342, 799
Barton, E. J., Yurchenko, S. N., & Tennyson, J. 2013, MNRAS, 434, 1469
Bonanos, A. Z., Massa, D. L., Sewilo, M., et al. 2009, AJ, 138, 1003
Bonanos, A. Z., Lennon, D. J., Köhlinger, F., et al. 2010, AJ, 140, 416
Cidale, L. S., Borges Fernandes, M., Andruchow, I., et al. 2012, A&A, 548, A72
Clark, J. S., Bartlett, E. S., Coe, M. J., et al. 2013, A&A, 560, A10
de Wit, W. J., Oudmaijer, R. D., Vink, J. S., et al. 2014, AdAst, 2014, 270848
Domiciano de Souza, A., Driebe, T., Chesneau, O., et al. 2007, A&A, 464, 81
Domiciano de Souza, A., Bendjoya, P., Niccolini, G., et al. 2011, A&A, 525, A22
Geballe, T. R., Lacy, J. H., & Beck, S. C. 1979, ApJL, 230, L47
Hinkle, K. H., Barnes, T. G., Lambert, D. L., & Beer, R. 1976, ApJL, 210, L141
Käufl, H. U., Ballester, P., Biereichel, P., et al. 2004, Proc. SPIE, 5492, 1218
Kastner, J. H., Buchanan, C., Sahai, R., Forrest, W. J., & Sargent, B. A. 2010, AJ, 139, 1993
Kastner, J. H., Buchanan, C. L., Sargent, B., & Forrest, W. J. 2006, ApJL, 638, L29
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
Kraus, M., Krügel, E., Thum, C., & Geballe, T. R. 2000, A&A, 362, 158
Kraus, M., Oksala, M. E., Nickeler, D. H., et al. 2013, A&A, 549, A28
Kraus, M., Cidale, L. S., Arias, M. L., Oksala, M. E., & Borges Fernandes, M. 2014, ApJL, 780, L10
Liermann, A., Kraus, M., Schnurr, O., & Fernandes, M. B. 2010, MNRAS, 408, L6
Liu, W., & Dalgarno, A. 1994, ApJ, 428, 769
Machado, M. A. D., & de Araújo, F. X. 2003, A&A, 409, 665
McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988, ApJ, 324, 1071
McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988, ApJ, 334, 639
McGregor, P. J., Hyland, A. R., & Mcginn, M. T. 1989, A&A, 223, 237
Millour, F., Meilland, A., Chesneau, O., et al. 2011, A&A, 526, A107
Miroshnichenko, A. S., Levato, H., Bjorkman, K. S., et al. 2003, A&A, 406, 673
Morris, P. W., Eenens, P. R. J., Hanson, M. M., Conti, P. S., & Blum, R. D. 1996, ApJ, 470, 597
Muratore, M. F., de Wit, W. J., Kraus, M., et al. 2012, in ASP Conf. Ser. 464, Circumstellar Dynamics at High Resolution, ed. A. C. Carciofi, & T. Rivinius (San Francisco, CA: ASP), 67
Muratore, M. F., Kraus, M., Oksala, M. E., et al. 2015, AJ, 149, 13
Ohnaka, K. 2014, A&A, 561, A47
Oksala, M. E., Kraus, M., Arias, M. L., et al. 2012, MNRAS, 426, L56
Oksala, M. E., Kraus, M., Cidale, L. S., Muratore, M. F., & Borges Fernandes, M. 2013, A&A, 558, A17
Plets, H., Waelkens, C., & Trams, N. R. 1995, A&A, 293, 363
Roche, P. F., Aitken, D. K., & Smith, C. H. 1991, MNRAS, 252, 39
Smith, N., Bally, J., & Walawender, J. 2007, AJ, 134, 846
Swings, J. P. 1981, A&A, 98, 112
Torres, A. F., Kraus, M., Cidale, L. S., et al. 2012, MNRAS, 427, L80
van Leeuwen, E. 2007, A&A, 474, 653
Wheelwright, H. E., de Wit, W. J., Weigelt, G., Oudmaijer, R. D., & Ilee, J. D. 2012, A&A, 543, A77
Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., & Klare, G. 1985, A&A, 143, 421
Zickgraf, F.-J., Wolf, B., Leitherer, C., Appenzeller, I., & Stahl, O. 1986, A&A, 163, 119
Zickgraf, F.-J., Wolf, B., Stahl, O., & Humphreys, R. M. 1989, A&A, 220, 206