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Infrared [Fe II] emission in the circumstellar nebulae of luminous blue variables

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ABSTRACT

After a serendipitous discovery of bright [Fe II] λ16435 emission in nebulae around η Carinae and P Cygni, infrared spectra of other luminous blue variables (LBV) and LBV candidates were obtained. Bright infrared [Fe II] emission appears to be a common property among LBVs with prominent nebulae; this is an interesting discovery because strong [Fe II] λ16435 is typically seen in shock-excited objects like supernova remnants and outflows from newly formed massive stars, as well as in active galactic nuclei (AGN), where the excitation mechanism is uncertain. This paper presents spectra in the H-band (1.5 to 1.75 μm) for the central stars and nebulae of η Car, AG Car, P Cyg, Wra 751, HR Car, HD 168625, HD 160529, R 127 and S Doradus. Seven of nine targets show bright [Fe II] λ16435 in their nebulae, while it is absent in all central stars except the LBV candidate Wra 751. The two objects (S Dor and HD 160529) without prominent [Fe II] λ16435 are not yet known to have nebulae detected in optical images, and both lack bright thermal infrared emission from dust. The possible excitation mechanisms for this line and the implications of its discovery in LBV nebulae are discussed; there are good reasons to expect shock excitation in some objects, but other mechanisms cannot be ruled out.

Key words: circumstellar matter – stars: evolution – stars: mass-loss.

1 INTRODUCTION

Soon after massive stars evolve off the main sequence, they presumably must shed their H-rich envelopes before becoming He-burning Wolf–Rayet (WR) stars. During this brief and sometimes violent evolution, a star might be classified as a luminous blue variable (LBV; see Humphreys & Davidson 1994) if it is observed to exhibit a particular kind of instability usually accompanied by severe mass-loss. The perpetually elusive mechanism behind the LBV instability can manifest itself as either an S Doradus outburst (Wolf 1989) when the bolometric luminosity of the star stays roughly constant, or a giant η Carinae-like eruption (Davidson 1989; Humphreys, Davidson & Smith 1999) where the bolometric luminosity increases. Giant eruptions in particular may be critical to pre-WR mass-loss, as an LBV may lose considerable mass in a single outburst ($\gtrsim 2.5\ \mathrm{M}_{\odot}$ in η Car's eruption; Smith, Gehrz & Krautter 1998). In our Galaxy giant eruptions have only been witnessed in η Car and P Cyg, but nebulae around other Galactic LBVs imply that they may have already experienced such events.

CNO-processed material has been detected around several LBVs (Davidson et al. 1986; Johnson et al. 1992; Smith et al. 1997, 1998); see also Lamers et al. 2001). At infrared (IR) wavelengths, many LBVs show excess dust emission (e.g.McGregor et al. 1988; McGregor 1989; Hutsemékers et al. 1997); an extreme example is η Carinae (Westphal & Neugebauer 1969). Near-IR spectroscopy of LBVs has focussed mostly on the bright central stars (e.g. McGregor et al. 1988; Morris et al. 1996), whereas their nebulae have been studied less with IR long-slit spectroscopy.

Recent near-IR spectroscopy of η Carinae (Smith & Davidson 2001) and P Cygni (Smith 2001) revealed bright [Fe II] λ16435 emission. This discovery prompted a search for [Fe II] λ16435 in other LBV nebulae, the results of which are reported here. Seven Galactic objects were selected (η Car, AG Car, P Cyg, Wra 751, HR Car, HD 168625, and HD 160529) based on their status as a confirmed LBV or the presence of an LBV-type nebula, and the two most famous LBVs in the LMC (S Dor and R 127) were also observed. IR spectra are presented in Section 2, excitation mechanisms are discussed in Section 3, and Section 4 summarizes the results.

2 OBSERVATIONS OF [Fe II] EMISSION

Near-IR spectra for nine LBVs are discussed here; all except P Cygni are in the southern sky and were observed using OSIRIS[1] on the CTIO 4-m telescope on 2001 March 12 and 14. Long-slit spectra in the H-band (1.5 to 1.75 μm) were obtained with the 0.5-arcsec wide slit oriented in the east–west (E/W) direction, and sky subtraction was accomplished by chopping 30 arcsec along

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[1] See http://www.ctio.noao.edu/instruments/ir_instruments/osiris/index.html

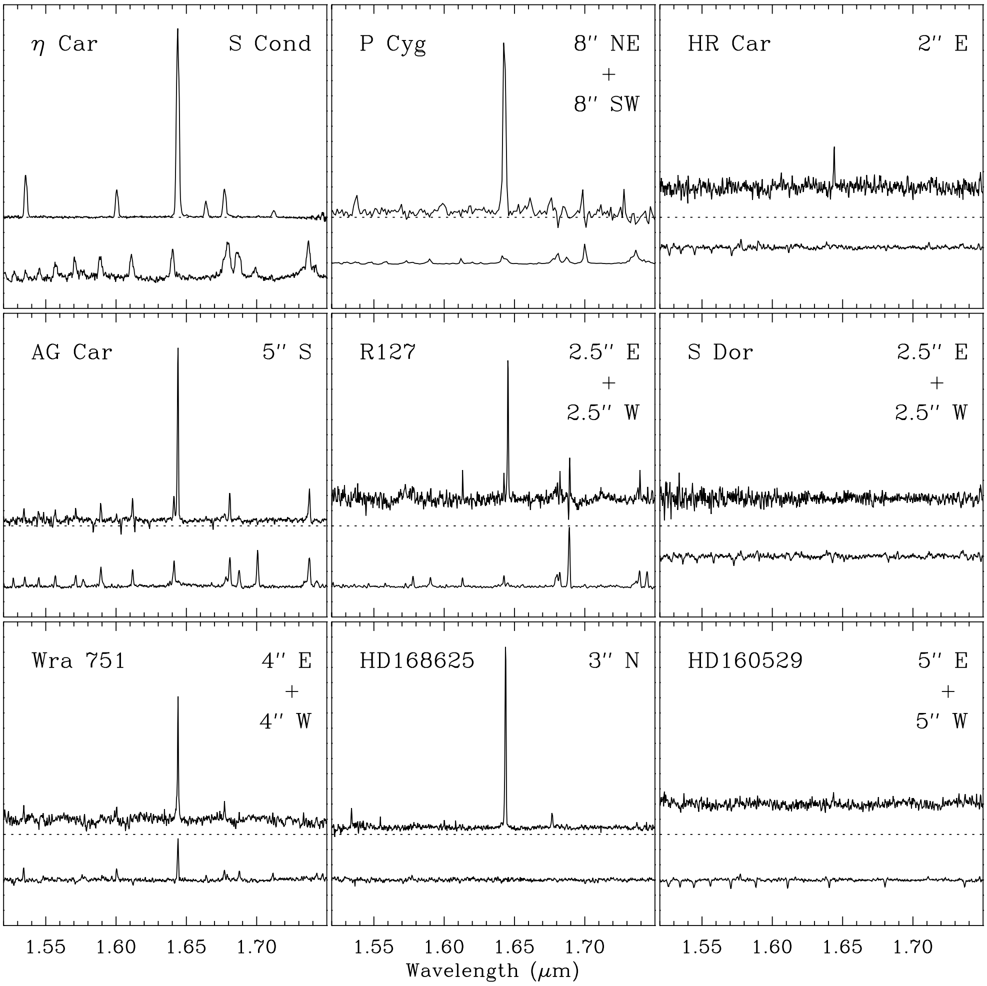

Figure 1. H-band spectra for nine LBVs. The lower tracing in each panel is the normalized spectrum of the central star. The upper tracing is the spectrum at an offset position in the nebula (see text). The dotted line is the zero level for each nebular spectrum.

the slit. Wavelengths were calibrated using an internal emission lamp, and telluric absorption was removed with reference to spectroscopic standard stars. The effective 2-pixel resolution is ∼100 km s^{-1} ($R \sim 3000$).

Long-slit IR spectra of P Cygni were obtained separately on 2000 June 12 using CRSP on the KPNO 2.1m telescope. The 0.8-arcsec wide slit aperture was oriented along P.A. = 58°. Data reduction and analysis of these spectra have already been discussed in more detail elsewhere (Smith 2001). Spectral resolution is about 600 km s^{-1} ($R \sim 500$).

Fig. 1 shows 1.52- to 1.75-μm spectra for all nine LBVs; each panel includes the central star (bottom) and one position (or the average of two) in the circumstellar environment. Individual sources are described below. Observational parameters are listed in Table 1, and general properties of the objects are summarized in Table 2. The Brγ intensity used for [Fe II] λ16435/Brγ in Table 2 is extrapolated from Br10, assuming case B recombination. Values for this ratio are lower limits when Br10 is not detected.

Table 1. Near-IR spectroscopic observations.

Star	Obs. Date	Instrument	Exp. Time (min)
Eta Car	2001 March 14	OSIRIS	10
AG Car	2001 March 12	OSIRIS	30
R 127	2001 March 12	OSIRIS	40
P Cyg	2000 June 12	CRSP	5
S Dor	2001 March 12	OSIRIS	8
Wra 751	2001 March 12	OSIRIS	8
HR Car	2001 March 12	OSIRIS	8
HD 168625	2001 March 12	OSIRIS	20
HD 160529	2001 March 12	OSIRIS	8

Eta Carinae. The famous bipolar Homunculus Nebula around η Car is a complex source, and its IR spectrum will be discussed elsewhere.[2] The ‘S Condensation’ is part of η Car’s ‘outer ejecta’, which reside well outside the Homunculus and may have originated in an early eruption of the star (Walborn, Blanco & Thackeray 1978). The S Condensation is probably dominated by shocks, since it emits copious soft X-rays (Seward et al. 2001); it may be composed of material from multiple ejection epochs (see Morse et al. 2001). Fig. 1 shows the IR spectrum of the bright S Condensation, located roughly 12 arcsec south-west (SW) of the star. This spectrum is dominated by [Fe II] transitions of the a^{4}F – a^{4}D multiplet and no other lines are visible; the brightest line is [Fe II] λ16435. The stellar spectrum in Fig. 1 is actually the spectrum observed in the bright core of the Homunculus with the contribution of compact circumstellar ejecta

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[2] Note, however, that the Homunculus does show bright [Fe II] λ16435 emission (Smith & Davidson 2001).

Table 2. Summary of physical properties of LBVs and the measured [Fe II] λ16435/Brγ flux ratio.

Star	$\log_{10}L$ ($L_\odot$)	T[a] (K)	$\dot{M}$ ($M_\odot$ yr^{-1})	V_∞ (wind) (km s^{-1})	V_{exp} (neb) (km s^{-1})	[Fe II] λ16435 Brγ	Dust?	Refs.[b]
Eta Car (Homunc.)	6.7	20 000–30 000	10^{-3}	500–1000	$\sim$600	>35	Yes!	3, 4, 10
Eta Car (S Cond.)	6.7	20 000–30 000	10^{-3}	500–1000	800?	>66.2	No	3, 4
AG Car	6.2	30 000	$10^{-4.2}$	250	70	1.20 ± 0.05	Yes	4, 6, 8, 13, 15
R 127	6.1	30 000	$10^{-4.2}$	110–150	30	1.21 ± 0.09	Yes	4, 5, 11, 12, 18
P Cyg	5.9	19 000	$10^{-4.7}$	206–220	110–140	>32.3	No	1, 4
S Dor	5.8	8000	$10^{-4.3}$	130	15–20?	–	?	4, 11
Wra 751	5.7	25 000	$10^{-5.5}$	180	26	>22.1	Yes	2, 4, 15, 16
HR Car	5.6	10 000–14 000	$10^{-4.2}$	150	75	>3.05	Yes	4, 7, 17
HD 168625	5.4	12 000	$10^{-4.7}$	250	10–20	>35.8	Yes	5, 9
HD 160529	5.3	8000–11 000	$>10^{-5}$	120	–	–	No	4, 5, 14

[a] Rough value for the apparent temperature of escaping radiation (see Humphreys & Davidson (1994)), or if appropriate, T_{eff}. [b] References: (1) Barlow et al. (1994); (2) Garcia-Lario et al. (1998); (3) Hillier et al. (2001); (4) Humphreys & Davidson (1994); (5) Hutsemékers et al. (1997); (6) Leitherer et al. (1994); (7) Machado et al. (2002); (8) Nota et al. (1992); (9) Robberto & Herbst (1998); (10) Smith & Davidson (2001); (11) Stahl & Wolf (1986); (12) Stahl et al. (1983); (13) Stahl et al. (2001); (14) Sterken et al. (1991); (15) Voors et al. (2000); (16) Weis (2000); (17) Weis et al. (1997) and (18) Wolf et al. (1988).

subtracted; the star shows only broad H, He I, and Fe II lines from its wind.

AG Carinae. An elegant ring nebula roughly 30 arcsec across surrounds this high-luminosity LBV (Stahl 1987; Nota et al. 1992), but it has no historical record of an observed giant eruption. Far-IR excess emission arises from cool dust in the ring (McGregor 1989; Lamers et al. 1996a). The nebular spectrum in Fig. 1 was extracted from the limb-brightened edges with the E/W slit offset 5 arcsec south of the central star. The nebula shows bright [Fe II] λ16435 that is absent in the spectrum of the star, as well as some intrinsic H recombination emission.

P Cygni. This famous star is the only source in the present sample besides η Car observed to undergo a giant eruption. It is known to have a circumstellar ring nebula within $\sim$10 arcsec of the star (Barlow et al. 1994; O'Connor, Meaburn & Bryce 1998; Meaburn 2001), although the nebula is faint and does not produce a strong IR excess from dust (Gehrz, Hackwell & Jones 1974; Lamers et al. 1996b). Fig. 1 shows bright [Fe II] λ16435 emission seen at 6 to 10 arcsec from the star along the slit on either side of the star; the extended emission out to $\sim$10 arcsec is obvious in long-slit spectra (see Smith 2001). The central star shows weak [Fe II] emission blended with Br12, but this may be emitted by a compact nebula known to reside within 1 arcsec of the star (Chesneau et al. 2000).

Wra 751 (Hen 3-591). This star has usually been considered a candidate LBV[3] because it has not shown evidence for an outburst, but some authors have suggested a possible LBV classification anyway (Weis 2000; Garcia-Lario, Riera & Manchado 1998). Wra 751 is surrounded by a nearly symmetric nebula about 20 arcsec across, with bright far-IR emission from dust (Hutsemékers & Van Drom 1991a; Weis 2000; Voors et al. 2000). Wra 751 is unique in the observed sample in that it is the only object for which the central star shows bright [Fe II] λ16435. Compared to the reflected continuum, however, extended regions in the nebula at $\sim$4 arcsec to the E and W of the star do show excess emission (see Fig. 1).

HR Carinae. HR Car is a low/intermediate-luminosity LBV with a distinctly bipolar circumstellar nebula (Hutsemékers & Van Drom 1991b; Nota et al. 1997; Weis et al. 1997), in contrast to the ring nebulae seen around some other LBVs. This nebula shows clear [Fe II] λ16435 emission in Fig. 1, although not as prominent as some others in the same sample. The central star has an almost featureless continuum spectrum in the H-band.

HD 168625 and HD 160529. These relatively cool low-luminosity LBVs occupy the same region of the HR Diagram and the almost featureless H-band spectra of their central stars are similar. HD 168625 is known to have a dusty circumstellar ring nebula (Nota et al. 1996; Robberto & Herbst 1998) but not HD 160529. This has obvious consequences for their nebular spectra in Fig. 1; HD 168625 has strong [Fe II] λ16435, while it is barely perceptible in the nebula of HD 160529.

R 127 and S Doradus. These luminous LBVs both reside in the LMC (remaining LBVs in the LMC have not yet been observed in the H-band). R 127 is a near-twin of AG Carinae in many respects, and their circumstellar ring nebulae are similar as well (Humphreys & Davidson 1994; Stahl 1987; Stahl et al. 1983; Clampin et al. 1993). The nebula around R 127 has clear excess [Fe II] emission compared to the central star, as indicated in Fig. 1. Even though S Dor is the prototype for the characteristic 'S Dor outbursts' that define LBVs, it is not surrounded by a prominent ring nebula, and the consequence is evident in Fig. 1. S Dor does show evidence for a spatially unresolved nebula emitting [N II] lines in optical spectra, but this emission is much fainter than in R 127. Like HD 160529, which is not known to have a circumstellar nebula, [Fe II] λ16435 is barely perceptible or completely absent in S Dor's vicinity.

Seven of nine LBVs in Fig. 1 show prominent [Fe II] λ16435 in their nebulae. The emission is present in objects with a wide range of stellar parameters listed in Table 2. For the two objects where this emission is weak or absent (S Dor and HD 160529), circumstellar ejecta have so far escaped detection in images at other wavelengths where most LBVs show prominent nebulae. Thus, it seems fair to conclude based on the present sample of objects that all LBVs known to have prominent nebulae also show extended [Fe II] λ16435 emission in their circumstellar environments.

3 EXCITATION MECHANISMS

[Fe II] λ16435 emission seems to be a common property of LBV nebulae. Are there special conditions in LBV environments that give rise to it? Is a nebula ejected during a previous giant eruption a *prerequisite* for the presence of a strong [Fe II] line? Its excitation

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[3] Spectra were also obtained for the candidate LBV and Ofpe/WN9 star Hen 3-519 (not Hen 3-591 = Wra 751). [Fe II] λ16435 was not detected in a 20-min exposure, but the nebula is faint (see Stahl 1987) and the non-detection is inconclusive.

mechanism needs to be understood before the implications of this strong emission line are clear. [Fe II] λ16435 is a collisionally excited $a^4F - a^4D$ transition, with an upper level only ∼1 eV above the ground state. When it overwhelms H recombination emission (as in most of these nebulae), it suggests that the gas is thermalized at a few 10^3 K, but that H is not strongly ionized. Shock heating or radiative heating are both candidates for the excitation mechanism, and are not mutually exclusive.

3.1 Qualitative reasons to expect shocks

Models for IR emission from interstellar shocks (e.g. McKee et al. 1984; Shull & Draine 1987) predict strong [Fe II] λ16435 compared to infrared H lines. Supernova remnants show high ratios of [Fe II] λ16435/Brγ $\gtrsim$ 30 (Graham, Wright & Longmore 1987; Oliva, Moorwood & Danziger 1990), whereas H II regions typically have ratios $\lesssim$1. Excluding AG Car and R 127, most LBVs show high values for the [Fe II] λ16435/Brγ ratio in Table 2, so shock excitation seems at least plausible. There are qualitative reasons to suspect that strong [Fe II] in LBV nebulae might be due to shocks, as follows.

(i) The cleanest example of strong collisionally excited [Fe II] ($a^4F - a^4D$) emission in Fig. 1 is the S Condensation around η Carinae. Because this diffuse nebulosity is well outside the Homunculus, radiative excitation from η Car is unlikely. More importantly, independent observations indicate that the S Condensation is indeed excited by shocks – it is the brightest feature in a soft X-ray shell seen in recent *Chandra* images (Seward et al. 2001).

(ii) Another object with strong collisionally excited [Fe II] emission in Fig. 1 is P Cyg. Based on various clues in optical images and spectra, Barlow et al. (1994) conclude that P Cygni's inner shell (radius ∼11 arcsec) is shock-excited, presumably as a result of the 50 to 100 km s^{-1} difference in outflow speed between the stellar wind and nebula. However, Lucy (1995) has shown that bright red/near-IR lines of [Ni II] may be excited by ultraviolet (UV) continuum fluourescence in P Cygni; it would be useful to examine these lines in the rest of the present sample of LBVs.

(iii) Normal S Doradus outbursts and giant eruptions of LBVs probably occur when the atmosphere of the star cools enough to be within dangerous proximity of an opacity-modified Eddington limit (e.g. Humphreys & Davidson 1994). In general, shells ejected during such a phase should have slower expansion speeds than the normal wind of the star, due to reduced effective gravity that accompanies the Eddington limit. In that case, the post-eruption wind will presumably expand faster than the ejected shell and overtake it. As the velocity difference is typically 50 to 150 km s^{-1} (see Table 2), shock excitation might prevail.

(iv) Finally, LBVs in Fig. 1 with strong [Fe II] λ16435 in their nebulae extend over a wide range of spectral type and other properties. The two weakest [Fe II] sources, S Dor and HD 160529, are the coolest stars in the sample. S Dor was probably still in a cool state at the time of the observations (Massey 2000). However, HD 168625, which is very similar in spectral type and luminosity to HD 160529, has strong [Fe II] λ16435. Also, bright [Fe II] emission is seen in nebulae with strong far-IR dust emission (e.g. the Homunculus of η Car and AG Car), as well as sources with little circumstellar dust (e.g. the S Condensation of η Car and P Cygni). This makes it doubtful that the presence or lack of dust strongly effects the [Fe II] emission strength in LBV nebulae.

3.2 Radiative heating

Then again, excitation of [Fe II] lines through collisions with electrons from photoionized gas seems likely for AG Car and R 127, the two hottest LBVs in the present sample. These are the only two objects in Fig. 1 with conspicuous H recombination lines in their nebular spectra, with [Fe II] λ16435/Brγ ratios near 1 (Table 2). This ratio is typical of H II regions, as noted above, and indicates a stronger UV flux escaping the wind as compared to other LBVs. It will be interesting to see if the [Fe II] λ16435 emission persists during an excursion to lower apparent temperatures in a future S Doradus phase of either star (or, if S Dor shows this emission in a later hot phase).

Normal photoionization by Lyman or Balmer continuum photons seems unlikely for LBV nebulae other than those around AG Car and R 127, but shock heating is not necessarily the only option for the remaining objects with [Fe II] λ16435 emission. Strong Balmer continuum radiation may photoionize some metals and may photoelectrically heat the gas through absorption by dust grains. The apparent [Fe II] λ16435/Brγ ratio also depends on the gas-phase abundances; much of the iron may not be liberated from grains in such a photodissociation region. Ferland, Davidson & Smith (in preparation) will present a quantitative model for this type of excitation in the dusty Homunculus of η Carinae, for which observational constraints are plentiful; it may apply to other nebulae in Fig. 1 as well. This type of heating could produce a spectrum that mimics shock radiation.

4 CONCLUSION

There does not appear to be a universal excitation mechanism for [Fe II] λ16435 in LBV nebulae. Shock heating seems to dominate in the S Condensation of η Car and the nebula around P Cyg, which lack dust and have independent signs of shocks. Photoionization seems to dominate the nebulae around the two hottest LBVs, AG Car and R 127. For the remaining sources in Fig. 1, the excitation mechanism is unclear. Regardless, bright [Fe II] λ16435 in most LBVs – and apparently *all* LBVs with prominent nebulae – has important observational implications.

Bright [Fe II] λ16435 provides a useful way to perform more detailed study of known LBV nebulae. Either their shape and structure with high-resolution imaging, or their kinematics with high-resolution spectroscopy could be investigated using this line. This could be especially beneficial for study of LBVs that are optically obscured by dust in the Galactic plane. This line could also be a useful tracer of LBV nebulae in other galaxies, especially with future NGST observations. In the mean time, it would be wise to search for [Fe II] λ16435 emission from LBVs and candidates in the LMC, as only two have been observed here.

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REFERENCES

Barlow M. J., Drew J. E., Meaburn J., Massey R. M., 1994, MNRAS, 268, L29
Chesneau O. et al., 2000, A&ASS, 144, 523
Clampin M., Nota A., Golimowski D. A., Leitherer C., Durrance S. T., 1993, ApJ, 410, L35
Davidson K., 1989, in Davidson K., Moffat A. F. J., Lamers H. J. G. L. M., eds, Physics of Luminous Blue Variables. Kluwer, Dordrecht, p. 101

Davidson K., Dufour R. J., Walborn N. R., Gull T. R., 1986, ApJ, 305, 867
Garcia-Lario P., Riera A., Manchado A., 1998, A&A, 334, 1007
Gehrz R. D., Hackwell J. A., Jones T. W., 1974, ApJ, 191, 675
Graham J. R., Wright G. S., Longmore A. J., 1987, ApJ, 313, 852
Hillier D. J., Davidson K., Ishibashi K., Gull T. R., 2001, ApJ, 553, 837
Humphreys R. M., Davidson K., 1994, PASP, 106, 1025
Humphreys R. M., Davidson K., Smith N., 1999, PASP, 111, 1124
Hutsemékers D., 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. 316
Hutsemékers D., Van Drom E., 1991a, A&A, 251, 620
Hutsemékers D., Van Drom E., 1991b, A&A, 248, 141
Johnson D. R. H., Barlow M. J., Drew J. E., Brinks E., 1992, MNRAS, 255, 261
Lamers H. J. G. L. M. et al., 1996a, A&A, 315, L225
Lamers H. J. G. L. M. et al., 1996b, A&A, 315, L229
Lamers H. J. G. L. M., Nota A., Panagia N., Smith L. J., Langer N., 2001, ApJ, 551, 764
Leitherer C. et al., 1994, ApJ, 428, 292
Lucy L. B., 1995, A&A, 294, 555
Machado M. A. D., Araujo F. X., Pereira C. B., Fernandes M. B., 2002, A&A, 387, 151
Massey P., 2000, PASP, 112, 144
McGregor P. J., 1989, in Davidson K., Moffat A. F. J., Lamers H. J. G. L. M., eds, Physics of Luminous Blue Variables. Kluwer, Dordrecht, p. 165
McGregor P. J., Hyland A. R., Hillier D. J., 1988, ApJ, 324, 1071
McKee C. F., Chernoff D. F., Hollenbach D. J., 1984, in Kessler M. F., Phillips J. P., eds, Galactic and Extragalactic Infrared Spectroscopy. Reidel, Dordrecht, p. 103
Meaburn J., 2001, in de Groot M., Sterken C. eds, ASP Conf. Ser. Vol. 233, P Cygni 2000: 400 Years of Progress. Astron. Soc. Pac., San Francisco, p. 253
Morris P. W., Eenens P. R. J., Hanson M. M., Conti P. S., Blum R. D., 1996, ApJ, 470, 597
Morse J. A., Kellogg J. R., Bally J., Davidson K., Balick B., Ebbets D., 2001, ApJ, 548, L207
Nota A., Leitherer C., Clampin M., Greenfield P., Paresce F., 1992, in Drissen L., Leitherer C., Nota A., eds, ASP Conf. Ser. Vol. 22, Nonisotropic and Variable Outflows From Stars. Astron. Soc. Pac., San Francisco, p. 377
Nota A., Pasquali A., Clampin M., Pollacco D., Scuderi S., Livio M., 1997, ApJ, 473, 946
O'Connor J. A., Meaburn J., Bryce M., 1998, MNRAS, 300, 411
Oliva E., Moorwood A. F. M., Danziger I. J., 1990, A&A, 240 453
Robberto M., Herbst T. M., 1998, ApJ, 498, 400
Seward F. D., Butt Y. M., Karsovska M., Prestwich A., Schliegel E. M., Corcoran M., 2001, ApJ, 553, 832
Shull J. M., Draine B. T., 1987, in Hollenbach D. J., Thronsen H. A., eds, Interstellar Processes. Reidel, Dordrecht, p. 283
Smith L. J., Stroud M. P., Esteban C., Vilchez J. M., 1997, MNRAS, 290, 265
Smith L. J. et al., 1998a, ApJ, 503, 278
Smith N., 2001, in de Groot M., Sterken C., eds, ASP Conf. Ser. Vol. 233, P Cygni 2000: 400 Years of Progress. Astron. Soc. Pac., San Francisco, p. 125
Smith N., Davidson K., 2001, ApJ, 551, L101
Smith N. et al., 1998b, AJ, 116, 1332
Stahl O., 1987, A&A, 182, 229
Stahl O., Wolf B., 1986, A&A, 158, 371
Stahl O., Wolf B., Klare G., Cassatella A., Krautter J., Persi P., Ferrari-Toniolo M., 1983, A&A, 127, 49
Stahl O., Jankovics I., Kovacs J., Wolf B., Schmutz W., Kaufer A., Rivinius T., Szeifert T., 2001, A&A, 375, 54
Sterken C., Gosset E., Jüttner A., Stahl O., Wolf B., Axer M., 1991, A&A, 247, 383
Voors R. H. M. et al., 2000, A&A, 356, 501
Walborn N. R., Blanco B. M., Thackeray A. D., 1978, ApJ, 219, 498
Weis K., 2000, A&A, 357, 938
Weis K., Duschl W. J., Bomans D. J., Chu Y. H., Joner M. D., 1997, A&A, 320, 568
Westphal J. A., Neugebauer G., 1969, ApJ, 156, L45
Wolf B., 1989, A&A, 217, 87
Wolf B., Stahl O., Smolinski J., Cassatella A., 1988, A&A SS, 74, 230

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