INFRARED OBSERVATIONS OF CIRCUMSTELLAR EJECTA AROUND LUMINOUS BLUE VARIABLES

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ABSTRACT. Recent infrared spectroscopy and imaging of LBVs lead to the following results. CO overtone emission at 2.3 μm has been found in 13 LBVs in the Galaxy and the LMC. This emission is collisionally excited in warm (3000 - 5000 K), dense ($N_H > 10^{10}$ cm^{-3}) circumstellar material. Circumstellar disks offer favorable conditions for the formation and excitation of CO molecules and are very likely the location of the observed emission. It is proposed that the LBVs showing 2.3 μm CO overtone emission possess the highest density circumstellar disks.

A group of eight LBVs has been identified in the LMC with He I 2.058 μm emission stronger than H I Brγ. This group includes the CO emission star HD 37836. Helium is over-abundant in these stars with N(He)/N(H) ranging from 0.2 to >0.5. Remarkably five of the helium strong stars belong to the small class of Ofpe/WN9 stars and a further two are probably related to this class.

Slit scans of the galactic LBV AG Car have resolved the far-infrared emission from this star, clearly showing it to originate from cool dust in the circumstellar ring structure. Thermal equilibrium considerations require large grains in the ring in order to match the measured grain temperature and radial distance. Similar slit scans of the galactic B[e] star HD 87643 fail to resolve the far-infrared emission from this star at the 10" level.

1. INTRODUCTION

It has long been recognized that the near-infrared (1 - 5 μm) continua of luminous blue variables (LBVs) are dominated by emission from their circumstellar envelopes in the form of either dust emission or free-free emission from the ionized wind (Allen 1973). Medium resolution spectra of these stars have, however, been difficult to obtain because of instrumental limitations. Technological advances in the last few years have overcome this problem and detailed spectra in the 1 - 5 μm region of LBVs in the Galaxy and the Magellanic Clouds are now available.

Some LBVs have also been detected in the far-infrared by *IRAS*. Cool dust might be expected in the envelopes of LBVs showing strong

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thermal near-infrared continua, but the detections at far-infrared wavelengths by *IRAS* of galactic and LMC LBVs, such as AG Car (McGregor et *al.* 1988) and R71 (Wolf and Zickgraf 1986), which lack thermal near-infrared emission are surprising results. These recent near-infrared and far-infrared observations of LBVs are reviewed below.

2. NEAR-INFRARED SPECTROSCOPY

2.1. Galactic Stars

Spectra of galactic LBVs in the 1 - 2.5 μm region (Allen, Jones, and Hyland 1985; McGregor, Hyland, and Hillier 1988) show atomic emission lines of H I, He I, Fe II, [Fe II], Mg II, Na I, and O I. While no one object displays all the features listed, a generic envelope structure can be defined, based on the near-infrared spectra of galactic LBVs, which broadly accounts for those features present in each star. The presence of an ionized stellar wind is required to account for the H I and He I emission. The Brackett decrement indicates that Brγ is optically thick in all objects and this is confirmed by calculations based on the Sobolev approximation. A common property of galactic LBVs is that Balmer continuum ionizations from the H I n = 2 level are needed to account for the observed level of hydrogen ionization in the wind. He I $3p^3P^0$-$4d^3D$ 1.700 μm emission is formed by recombination in a He II region. This line is present in AG Car, HD 316285, η Car, BI Cru, and HD 326823. The strength of He I $2s^1S$-$2p^1P$ 2.058 μm relative to H I Brγ suggests that helium is over-abundant in AG Car, HD 316285, HD 326823, and η Car. Allen, Jones, and Hyland (1985) estimate $N(\mathrm{He})/N(\mathrm{H}) > 0.16 \pm 0.03$ in η Car from a consideration of the He I 1.700 μm and 1.197 μm line strengths relative to H I Brγ.

The strongest [Fe II] lines are $a^6D_{9/2}$-$a^4D_{7/2}$ 1.257 μm and $a^4F_{9/2}$-$a^4D_{7/2}$ 1.644 μm, which are prominent in HR Car and η Car. These lines arise from the same upper level, but other weaker lines such as $a^6D_{5/2}$-$a^4D_{5/2}$ 1.294 μm, $a^6D_{1/2}$-$a^4D_{3/2}$ 1.298 μm, and $a^4F_{7/2}$-$a^4D_{3/2}$ 1.599 μm probe densities near ~ 10^5 cm^{-3} where these transitions collisionally de-excite. An electron density of $\log (N_e) = 4.6 \pm 0.3$ in the [Fe II] region of η Car is derived from these lines (Allen, Jones, and Hyland 1985).

Na I 2.206/9 μm emission is seen in CPD -57°2874, He3-1359, η Car, BI Cru, and possibly in HD 316285. This emission arises from fluorescent absorption of the 3303 Å continuum. The 2.206/9 μm feature is anomalously strong, based on a calculation of the Sobolev optical depth at 3303 Å (McGregor, Hyland, and Hillier 1988). Strong line blanketing by Fe II and other metals in the ultraviolet may lower the ionization level of sodium within the envelope while maintaining the 3303 Å flux necessary to excite the fluorescence.

CO first-overtone band-head emission at 2.3 μm has been detected in the high luminosity galactic stars CPD -57°2874, CPD -52°9243, GG Car, HR Car, BI Cru, and He3-1359 (McGregor, Hyland, and Hillier 1988). The first three stars are probably related to the B[e] stars, HR Car may be of the S Doradus type, and the nature of BI Cru and that of He3-1359 are less certain. This was the first detection of a molecular component associated with stars of the LBV type. CO molecules cannot survive in the hot photospheres of these stars so this emission must have a circumstellar origin. Vibrational temperatures of ~ 3000 - 5000 K are derived from the approximately equal strengths of the (2-0), (3-1), and (4-2) bands. Similar rotational temperatures are required to populate the high rotational levels near the band-head ($J \sim 50$). CO emission can be excited in any of three ways; by collisions, by ultraviolet fluorescence in cascades from excited electronic states, or by direct pumping in the fundamental bands at 4.6 μm (Scoville, Krotkov, and Wang 1980; Krotkov, Wang, and Scoville 1980; Scoville *et al.* 1983). Collisional excitation at high densities ($N_H > 10^{10}$ cm^{-3}) is probably responsible for the CO emission in the LBVs because the band strength ratios are inconsistent with ultraviolet fluorescence, and a collisional mechanism is required to excite the high J levels seen. Direct infrared pumping may contribute in some stars but HR Car, which has on occasions shown weak CO emission, lacks significant thermal near-infrared emission and so cannot be pumped in this way.

The mass of emitting CO gas generally lies in the range 10^{-9} - 10^{-8} $M_\odot$ which for solar carbon and oxygen abundances relative to hydrogen corresponds to gas masses in the range 10^{-7} - 10^{-6} $M_\odot$. These masses are comparable to the ionized wind mass out to the densities of ~ 10^9 cm^{-3} required for collisional excitation, so the CO emitting material is a significant component of the circumstellar envelope. Nevertheless, the low excitation CO emitting region must be separate and shielded from the ionized hydrogen zone as hydrogen ionizing photons can dissociate CO. This fact requires that the CO emitting material forms an additional component in the circumstellar envelope, separate from the ionized stellar wind and confirms that both high and low excitation envelope regions coexist in at least some galactic LBVs (Zickgraf *et al.* 1986). Recently discovered ultraviolet predissociation bands in the CO molecule are largely responsible for its radiative dissociation under these conditions (Letzelter *et al.* 1987; Viala *et al.* 1988). These transitions will quickly become optically thick and allow efficient self-shielding of the CO gas to occur in this region, as long as some CO can form initially.

High resolution, higher signal-to-noise ratio spectra of the CO emission bands in the galactic stars (McGregor, Hillier, and Hyland 1989; Figure 1) confirm the approximately equal strengths of the (2-0), (3-1), and (4-2) bands and show what may be weak CO emission in the galactic B[e] star HD 87643. The higher resolution spectra also reveal the presence of ^{13}CO emission in CPD -52°9243 and possibly HD 268835. If the ^{12}CO emission in these stars is optically thin, the ^{12}C/^{13}C ratio is ~ 3. However, the optical depths in the ^{12}CO first-overtone bands are difficult to determine and remain a major uncertainty in the analysis of the CO emission spectra. Nevertheless, values of the ^{12}C/^{13}C ratio as low as 7 have been found in red supergiant atmospheres (Hinkle, Lambert, and Snell 1976), and even lower values may arise in evolved massive blue supergiants as material processed in the CNO cycle is exposed. Prantzos *et al.* (1986) predict ^{12}C/^{13}C ~ 3 during the Of stage of the evolution of a 60 $M_\odot$ star. Similar results were obtained by Maeder (1983, 1987). Thus if the low ^{12}C/^{13}C ratio really applies in the envelope of CPD -52°9243, this envelope material could either have been expelled by the present blue supergiant or while the star was a red supergiant.

Hot dust emission is seen in the B[e] stars and η Car, but is absent in the S Doradus star AG Car and in HD 316285, a star similar to P Cygni. The blackbody hot dust radii are generally near 10^{15} cm and correspond to the inner edge of the circumstellar dust shell as the grain temperatures inferred are near the evaporation temperatures of silicate and graphite grains. Hot dust masses in the range 10^{-8}-10^{-7} $M_\odot$ are derived. For a canonical gas-to-dust mass ratio of ~ 100 this corresponds to gas masses in the range 10^{-6}-10^{-5} $M_\odot$, significantly larger than the mass of emitting CO gas. The dust envelope is therefore far more extensive than the CO emitting region of the envelope.

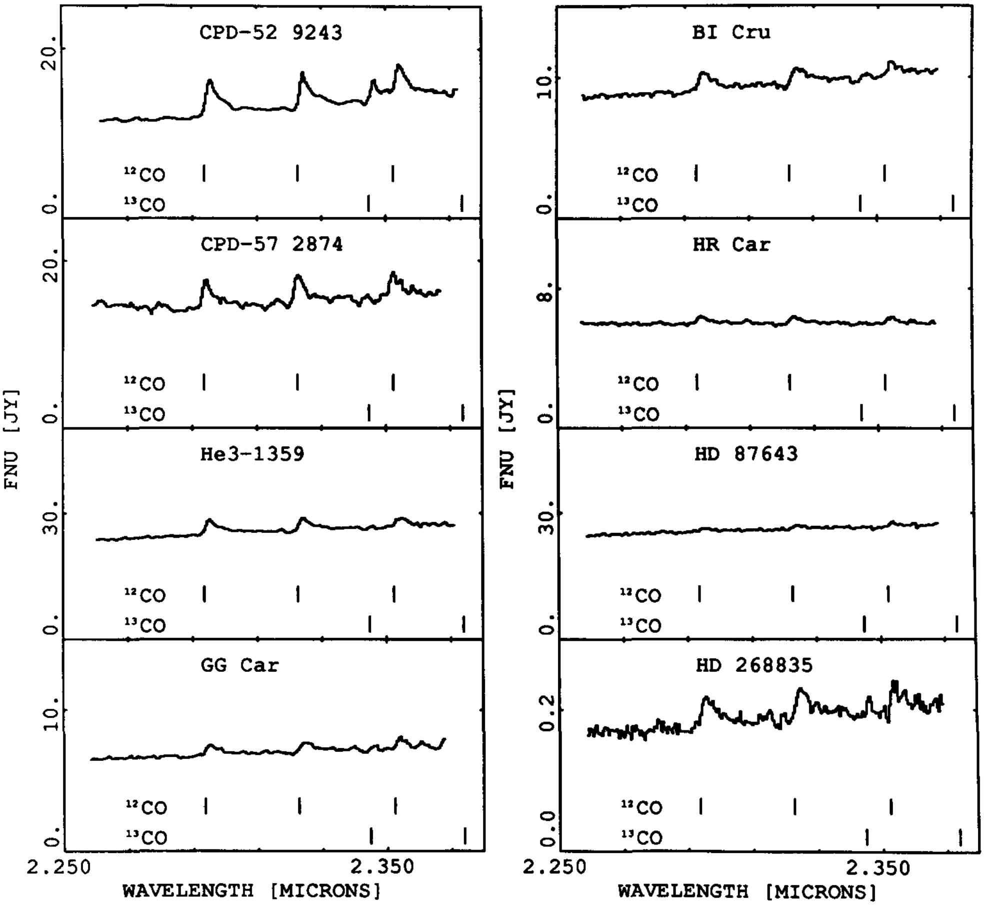


Figure 1. Spectra of the CO first-overtone emission bands in galactic supergiants and the LMC star HD 268835. The spectra were measured with a resolving power $\lambda/\Delta\lambda \sim 2000$. The (2-0) band head of ^{13}CO is clearly seen in CPD-52°9243 and possibly HD 268835. Weak CO emission may be present in HD 87643.

Several LBVs have been detected in the far-infrared by *IRAS* (McGregor, Hyland, and Hillier 1988). This emission is thermal from cool dust with temperatures near 100 K and masses in the range 10^{-3}-10^{-2} $M_{\odot}$. Again, for a canonical gas-to-dust mass ratio this corresponds to a gas mass range of 0.1-1.0 $M_{\odot}$. At a steady mass loss rate of 10^{-5} $M_{\odot}$ yr^{-1} the star takes 10^4-10^5 yr to lose this material. Considerable evolutionary changes can occur in high mass stars on these timescales so the cool dust emission may contain a fossil record of the mass loss histories of these stars over a significant fraction of their evolution.

2.2. Magellanic Cloud LBVs

2.2.1. CO Emission

A clearer picture of trends in the near-infrared spectra of LBVs is obtained from the larger numbers of LBVs in the Large Magellanic Cloud. Spectra in the 2.0 - 2.4 μm region of 63 luminous supergiants in the LMC have been obtained by McGregor, Hillier, and Hyland (1988). CO emission at 2.3 μm was detected in six stars (Figure 2); HD 37836 is a peculiar O supergiant, HD 268835, Hen S12, and HD 38489 are B[e] stars, and HD 269953 and HD 269723 are G supergiants. HD 37836 in particular is a most unusual object in that it displays high excitation O star wind features in the ultraviolet (Stahl and Wolf 1987) and yet molecules exist in its circumstellar envelope. The LMC CO emission stars show a range of other properties which are also seen in program stars lacking CO emission. Clearly stellar effective temperature does not strongly influence the existence of CO emission since both O and G supergiants show the emission. The lack of reported photometric variability among the LMC CO emission stars suggests that these are relatively stable objects and that the CO emission is probably not transient. Circumstellar disks are believed to be associated with all B[e] stars (Zickgraf *et al.* 1986) so such disks are expected around the three B[e] stars showing CO emission. Although different from the B[e] stars, HD 37836 also possesses a circumstellar disk (Stahl and Wolf 1987). Circumstellar disks are expected to provide conditions that are conducive to CO formation, they can reach the high densities required to collisionally excite CO overtone emission and shield the CO gas from dissociating stellar radiation, and they are likely to be relatively stable envelope structures. It is therefore most probable that the CO overtone emission seen in LMC LBVs arises in the circumstellar disks associated with these stars. Since CO overtone emission is an excellent tracer of high density ($N_H > 10^9$ cm^{-3}) material, *the LBVs showing this emission will be those with the highest density disks.* Similar stars lacking detectable CO overtone emission, such as the other B[e] stars, may possess circumstellar disks but their densities must be below that required to collisionally excite this emission. Other LBVs, such as the S Doradus variables, appear to lack circumstellar disks.

The origin of the circumstellar disks associated with high luminosity evolved stars is of fundamental importance. Near-infrared spectra indicate that high density envelope material is present around

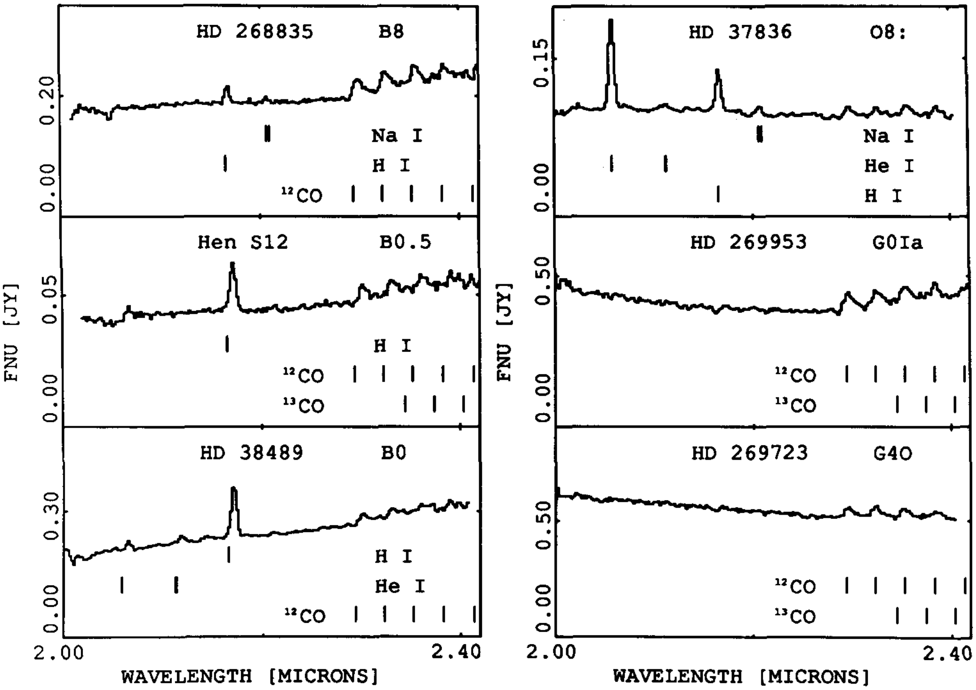


Figure 2. Spectra of LMC CO emission stars. HD 268835, Hen S12, and HD 38489 are B[e] stars, HD 37836 is a peculiar O star possibly related to the Ofpe/WN9 stars, and HD 269953 and HD 269723 are G supergiants.

supergiants with a wide range of temperatures. This may suggest that the circumstellar disk structure seen in B[e] stars forms earlier in their evolution, possible as red supergiants. The CO emitting G supergiants HD 269953 and HD 269723 are then viewed as post-red supergiants and may be the precursors of B[e] stars. Indeed, HD 269953 possesses a cool dust envelope which has been detected at 3.6 and 10 µm (Glass 1974; Ney 1972; Glass 1984), and there is abundant evidence for the production of dense circumstellar dust envelopes by high luminosity red supergiants such as the supergiant OH/IR stars VY CMa and VX Sgr. However, HD 37836, for example, possesses a dense circumstellar disk but is believed to be of too high a luminosity to have evolved through a red supergiant phase. This fact and the presence of similar high luminosity stars with circumstellar disks make a red supergiant origin for all such disks difficult to maintain. An intrinsic, but as yet poorly understood, property of the star appears responsible. CO emission has been seen in the galactic F supergiants ρ Cas and BS 8752 (Lambert, Hinkle, and Hall 1981) where high resolution spectra showed a dense shell being expelled and subsequently falling back onto the star. If unrelated to the B[e] star phenomenon, the CO emission in HD 269953 and HD 269723 may have a similar origin to the galactic star emission.

2.2.2. Helium Strong Stars

Nine LMC stars have been identified with He I $2s^1S-2p^1P$ 2.058 μm stronger than H I Brγ (McGregor, Hillier, and Hyland 1988) and include the O8 CO emission star HD 37836 (Figures 2 and 3). Five of these stars belong to the group of Ofpe/WN9 stars [HD 269445, Hen S61 (Walborn 1977, 1982); HD 269582 (Stahl 1986); Hen S9 (Walborn 1986); HD 269687 (Bohannan and Walborn 1988)] and a further two are probably related objects [HD 37836 and Hen S131 (Stahl and Wolf 1987)]. The remaining two helium strong stars are HD 268840 and Hen S101, the latter of which being a border-line member of the group. The Ofpe/WN9 class is distinguished by the presence of N III and He II emission in comparable strength with N II and He I emission (Walborn 1977).

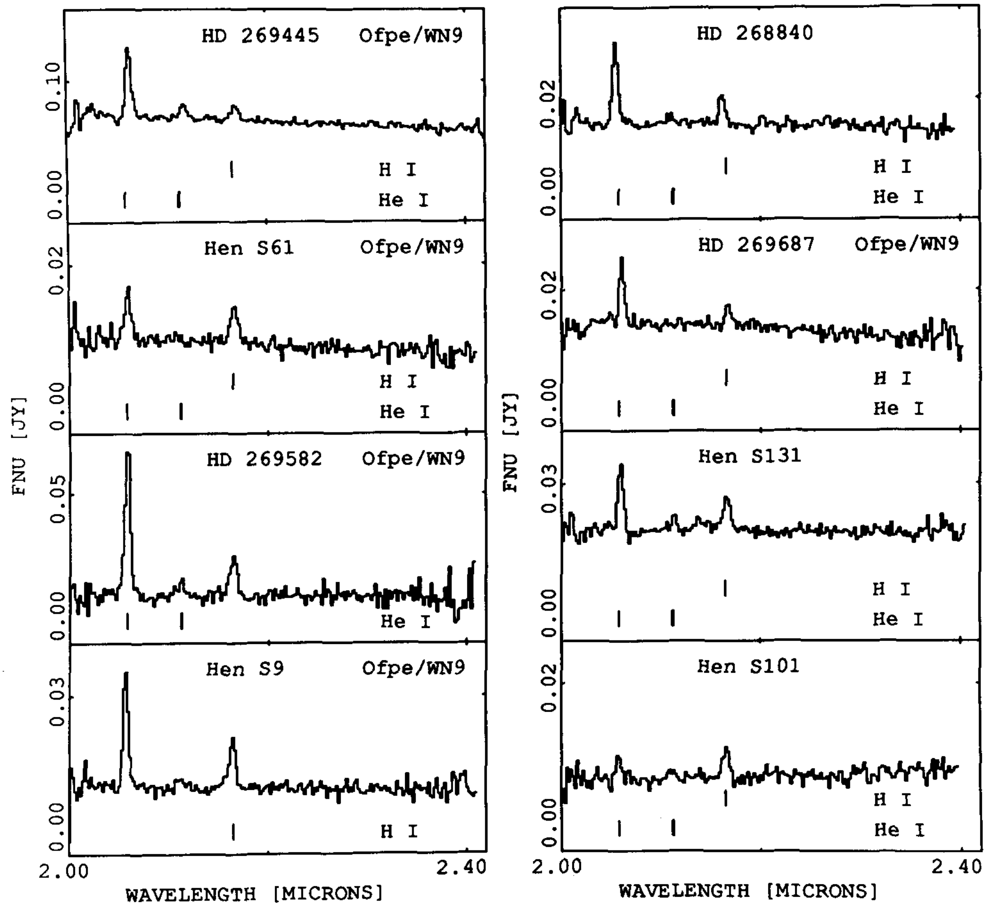


Figure 3. Spectra of LMC supergiants showing He I 2.058 μm emission stronger than H I Brγ 2.167 μm emission. The CO emission star HD 37836 also belongs to this class. Five of these stars are classed as Ofpe/WN9.

Enhanced nitrogen abundances relative to hydrogen and oxygen suggests CNO processing of the envelope material (Walborn 1982). An evolutionary state intermediate between Of and WN stars may be indicated (Stahl 1986).

The strength of the near-infrared He I emission indicates that helium must also be over-abundant relative to hydrogen in the atmospheres of these stars; although difficult to quantify, $N(\mathrm{He})/N(\mathrm{H})$ is estimated to range from ~ 0.2 in Hen S9 and Hen S61 to greater than 0.5 in HD 269445 and HD 269582. Certainly the near-infrared spectrum provides a much clearer indicator of helium over-abundance than is possible from optical spectra. Of the Ofpe/WN9 stars not listed above, HD 269227 is dominated by its M supergiant companion in the near-infrared, BE 381 and HD 269927C were not measured, and the S Doradus star HD 269858f, which was classified as OIafpe in 1977 (Walborn 1977), now lacks near-infrared He I emission.

The 2 μm spectrum of the galactic supergiant HD 326823 is similar to those of the helium rich LMC stars (McGregor, Hyland, and Hillier 1988); this star may therefore also be related to the Ofpe/WN9 stars.

3. FAR-INFRARED MEASUREMENTS

Far-infrared emission from cool dust was detected by *IRAS* in the galactic LBVs η Car, AG Car, HR Car, HD 87643, and CD -42°11721 (McGregor, Hyland, and Hillier 1988), and in the LMC S Doradus star R71 (Wolf and Zickgraf 1986). The far-infrared emission in η Car, HD 87643, and CD -42°11721 is accompanied by near-infrared emission from hot dust, suggesting that the range of thermal emissions is due to temperature gradients in the dust shells. In contrast, AG Car and R71 lack thermal emission from hot dust in the near-infrared making it unlikely that the cool emitting dust is associated with the immediate circumstellar environment. Slit scans of AG Car in a NE-SW direction at 50 and 100 μm obtained from the Kuiper Airborne Observatory clearly resolve the far-infrared emission from this object into two peaks centered on the circumstellar ring structure (Figure 4; McGregor *et al.* 1988). Maximum entropy deconvolution shows the peaks to be at radii of ~ 9" from the star with very little emission coming from between the peaks at the position of AG Car itself. The emitting grains have a temperature of ~ 60 K and the 100 μm optical depth is $< 5 \times 10^{-5}$. Thus the emitting dust absorbs very little of the stellar luminosity. The dust mass is estimated to be between 0.002 and 0.02 $M_{\odot}$ depending on the adopted grain characteristics. Large grains with radii of ~ 1.0 μm are required if they are in thermal equilibrium with the stellar radiation field at the observed distance from the star. However, the lack of mid-infrared emission from the ring indicates that no corresponding population of small grains exists. The presence of dust in the AG Car ring is also inferred from the ultraviolet spectrum of the ring which is due to scattered starlight (Viotti *et al.* 1988). AG Car shows similarities in the optical and ultraviolet to the LMC S Doradus star R71 and to other stars showing spectroscopic evidence for detached ionized shells, the Ofpe/WN9 stars in particular (Walborn 1982; Stahl 1986). Thus circumstellar gas and dust ring structures like the AG Car ring may frequently be associated with evolved massive emission-line stars.

The origin of the AG Car ring bears on questions of the nature of the S Doradus phenomenon and the mass loss histories of massive stars and has been considered by McGregor *et al.* (1988). They conclude that the ring is most likely a "mass loss bubble" formed as the present hot supergiant wind compresses material lost in a cooler supergiant wind (cf., Johnson 1980; Weaver *et al.* 1977). Steady blue supergiant mass loss and a nova-like explosion were rejected. The formation of a mass loss bubble requires that previous mass loss occurred at a slower velocity than the present blue supergiant wind velocity. If wind velocity decreases abruptly in cooler supergiants (as seems to be the case) the requirement may be simply that the high luminosity stars have experienced *a cooler evolutionary phase* rather than that they have necessarily experienced significant red supergiant evolution. Main sequence mass loss is excluded because the present wind velocity is only ~ 290 km s^{-1}. The model proposed is similar to current theories of planetary nebula formation (Kwok, Purton, and FitzGerald 1978), but is here applied to a more massive star. The ring structures may well be precursors of the mass loss bubbles seen on larger scales around Wolf-Rayet stars (Chu 1982; van der Hucht *et al.* 1985).

Similar unpublished slit scans at 50 and 100 μm of HD 87643, a galactic B[e] star, show that this star is unresolved at the 10" level

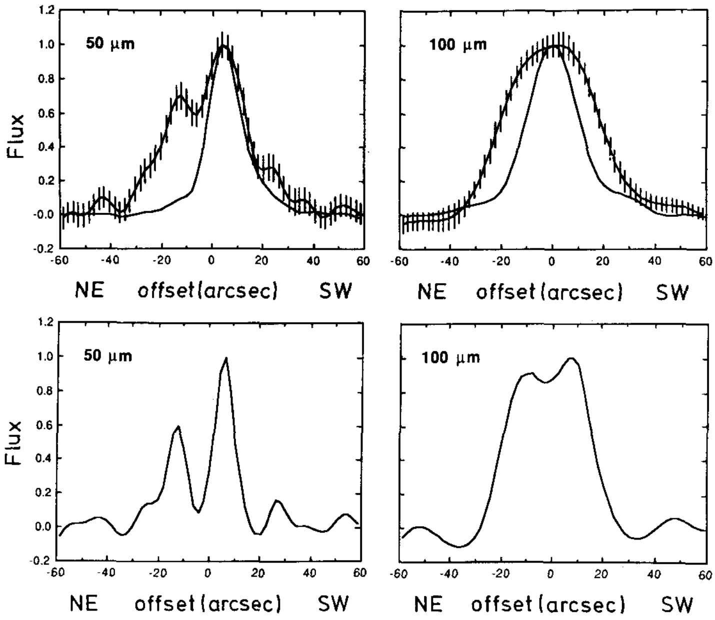


Figure 4. Slit scans of AG Car at 50 and 100 μm compared with similar scans of a point source (*upper frames*) show the far-infrared emission to be resolved. The deconvolved scans (*lower frames*) clearly show the far- infrared emission to come from two peaks at the position of the ring with little emission from the position of AG Car itself.

at these wavelengths, despite the presence of prominent optical reflection nebulosity over a region ~ 90" x 65" around the star. The measured flux densities at 50 and 100 μm are 290 Jy and 248 Jy, respectively. These compare well with the *IRAS* results. The cool dust mass in HD 87643 is ~ 5 times that detected around AG Car. Unlike AG Car, the hotter inner regions of the dust shell in HD 87643 shield the cool dust. This hot dust is not present in AG Car.

REFERENCES

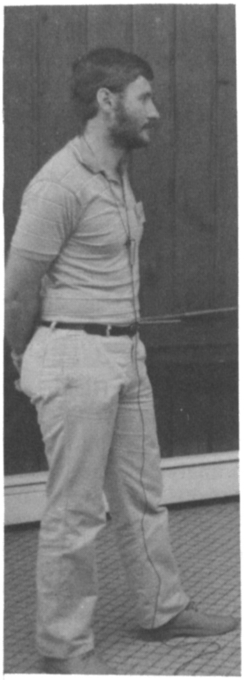
Allen, D. A. 1973, *M.N.R.A.S.*, **161**, 145.
Allen, D. A., Jones, T. J., and Hyland, A. R. 1985, *Ap. J.*, **291**, 280.
Bohannan, B., and Walborn, N. R. 1988, in preparation.
Chu, Y.-H. 1982, *Ap. J.*, **254**, 578.
Glass, I. S. 1974, *M.N.R.A.S.*, **168**, 249.
__________ 1984, *M.N.R.A.S.*, **209**, 759.
Hinkle, K. H., Lambert, D. L., and Snell, R. L. 1976, *Ap. J.*, **210**, 684.
Johnson, H. M. 1980, *Ap. J.*, **235**, 66.
Krotkov, R., Wang, D., and Scoville, N. Z. 1980, *Ap. J.*, **240**, 940.
Kwok, S., Purton, C. R., and FitzGerald, P. 1978, *Ap. J. (Letters)*, **219**, L125.
Lambert, D. L., Hinkle, K. H., and Hall, D. N. B. 1981, *Ap. J.*, **248**, 638.
Letzelter, C., Eidelsberg, M., Rostas, F., Breton, J., Thieblemont, B. 1987, *Chem. Phys.*, **114**, 273.
Maeder, A. 1983, *Astr. Ap.*, **120**, 113.
__________ 1987, *Astr. Ap.*, **173**, 247.
McGregor, P. J., Finlayson, K., Hyland, A. R., Joy, M., Harvey, P. M., and Lester, D. F. 1988, *Ap. J.*, **329**, 874.
McGregor, P. J., Hillier, D. J., and Hyland, A. R. 1988, *Ap. J.*, in press.
__________ 1989, in preparation.
McGregor, P. J., Hyland, A. R., and Hillier, D. J. 1988, *Ap. J.*, **324**, 1071.
Ney, E. P. 1972, *Pub. A.S.P.*, **84**, 613.
Prantzos, N., Doom, C., Arnould, M., and de Loore, C. 1986, *Ap. J.*, **304**, 695.
Scoville, N. Z., Kleinmann, S. G., Hall, D. N. B., and Ridgway, S. T. 1983, *Ap. J.*, **275**, 201.
Scoville, N. Z., Krotkov, R., and Wang, D. 1980, *Ap. J.*, **240**, 929.
Stahl, O. 1986, *Astr. Ap.*, **164**, 321.
Stahl, O., and Wolf, B. 1987, *Astr. Ap.*, **181**, 293.
van der Hucht, K. A., Jurriens, T. A., Olnon, F. M., Thé, P. S., Wesselius, P. R., and Williams, P. M. 1985, *Astr. Ap.*, **145**, L13.
Viala, Y. P., Letzelter, C., Eidelsberg, M., and Rostas, F. 1988, *Astr. Ap.*, **193**, 265.
Viotti, R., Cassatella, A., Ponz, D., and Thé, P. S. 1988, *Astr. Ap.*, **190**, 333.
Walborn, N. R. 1977, *Ap. J.*, **215**, 53.
__________ 1982, *Ap. J.*, **256**, 452.
__________ 1986, in *IAU Symposium 116, Luminous Stars and Associations in Galaxies*, ed. by C. W. H. de Loore, A. J. Willis, and P.

Laskarides, (Dordrecht: Reidel), p. 194.

Weaver, R., McCray, R., Castor, J., Shapiro, P., and Moore, R. 1977, *Ap. J.*, **218**, 377.

Wolf, B., and Zickgraf, F.-J. 1986, *Astr. Ap.*, **164**, 435.

Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., and Appenzeller, I. 1986, *Astr. Ap.*, **163**, 119.



Peter McGregor

DISCUSSION

Gallagher: In your discussion of ejection processes, you used a nova analogy. Because of the large gravitational binding energy on the surface of a white dwarf, the mechanical energy in a nova is at least comparable to the integrated photon luminosity. This may give you more room to work with in a model in which material is ejected because of a transient energy input deep in the system.

McGregor: The model I propose is similar to that suggested for planetary nebulae; the ring is a shock region between a fast blue supergiant wind and an earlier slow wind.

Zickgraf: (1) For one of the Galactic B[e] stars with CO emission, CPD -52° 9243, Swings found polarimetric evidence for a disk. (2) In our study of the Magellanic Cloud B[e] supergiants we found evidence for a dependence of the TiO emission strength on the density in the proposed disk. This agrees with your finding of CO emission in denser environments. (3) Polarization measurements of Galactic B[e] stars (to appear in *Astr. & Astrophys.*) show that the polarizing particles should not be much smaller than 0.1 μm. This would agree with the large dust particles that you find around AG Car.

McGregor: The TiO emission that you observe may require even higher densities than those needed to produce the CO emission; this should be calculated.

Maeder: You mentioned Na I lines in two of your O and B stars. Is this element overabundant in relation to recent results by Dearborn and others? Also, do you think you can measure the $^{16}O/^{17}O$ ratio? It should differ from the Solar value by about 2 orders of magnitude.

McGregor: Sodium abundances will be difficult to determine from the fluourescent 2.206/9 μm lines, as the sodium ionization depends on blanketing in the UV. Possibly the optical Na I D lines will help here. $^{16}O/^{17}O$ will be difficult to determine in the near-infrared but should be considered in analyzing the TiO emission bands in B[e] stars reported at this meeting.

Humphreys: It has frequently been mentioned that the ejecta of some of these stars may be fossil remnants from the red supergiant stage, but many LBV's are above the luminosities where we observe M supergiants. Do you know of any IR data, say from IRAS, that show potential red supergiants at these luminosities? For example, two IRAS sources in the LMC are considered to be highly obscured M supergiants (Elias, Frogel, & Schwering 1986, *Astrophys. J.* **302**, 675), but their luminosities are not above the RSG limit.

McGregor: I know of no evidence for the existence of red supergiants at luminosities above your limit. In referring to a star evolving through a red supergiant phase, I meant normal red supergiants; this can't happen for the most luminous stars.

Walborn: A very interesting current study by Linda Smith, Max Pettini, *et al.*, shows interacting fast and slow material in the ring nebula RCW 58 which surrounds the WN8 star HD 96548; this suggests a post-red-supergiant interpretation. There may be similarities to the AG Car nebula.

Humphreys: The kinematic distance for AG Car seems to rule out a red supergiant stage. With the luminosity estimated by Henny Lamers in a poster paper at this meeting, $M_{bol} \approx -8.8 - 5\,log(D/2.5\,\text{kpc})$, any distance beyond 3.5 or 4 kpc implies a luminosity too high for RSG's.