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Dust in LBV-type Nebulae

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Abstract. Some systematic properties of dust in LBV-type nebulae are reviewed, on the basis of the far-infrared thermal emission measured by the IRAS satellite, and the scattering of visible stellar light.

1. Introduction

In the framework of a systematic study of infrared properties of emission-line stars, McGregor et al. (1988a) found that LBVs are surrounded by cool dust, while B[e] stars are predominantly associated with hot dust (although a few objects like η Car, or the B[e] star HD87643, both embedded in nebulosities, are simultaneously associated with hot and cool dust). They showed that, if in equilibrium, the cool dust must lie at large distances from the star, most probably in the optical nebula surrounding some of these objects. McGregor et al. (1988b) subsequently resolved the far-infrared emission from AG Car, showing that it actually arises within the optical nebula.

Table 1 summarizes the present situation for Galactic and Large Magellanic Cloud (LMC) LBVs, together with four Galactic WR stars associated with ejecta-type nebulae (Esteban et al. 1992). For the Galactic objects, there is a nearly one-to-one correlation between the presence of cool dust and that of a nebula. Also, HD160529 and HD168607 have been imaged with no detection of any optical nebulosity, and do not show any infrared excess indicating the presence of dust. For the LMC objects, the observations are much more incomplete: due to the larger distance, only the biggest nebulae have been resolved (Nota et al. 1995, 1996). The fluxes measured by IRAS are low, or contaminated by a relatively high background: only three objects are detected at 25 and 60 μm with a color temperature significantly different from that of the background. Nevertheless, the presence of cool dust in two nebulae, the detection in S119 of an excess at 25 μm, as well as the fact that the nebula around R71 is spectroscopically detected (Stahl & Wolf 1986) and probably very small (see next section), suggest that the nebulae around LMC LBVs are not different from the Galactic ones as far as dust is concerned.

The only nebula without dust is that around P Cygni: at a distance of 1.8 kpc, and assuming a dust-to-gas ratio comparable to that estimated in other nebulae, far-infrared emission (other than wind free-free emission) should have been detected. Compared to the other objects, this is not the only difference of

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Table 1. Dust and nebulae around LBV and WR stars

Object	Type	Optical nebulosity?	Dust?
η Car	LBV	yes	cool + hot
AG Car	LBV	yes	cool
HR Car	LBV	yes	cool
WRA751	LBV	yes	cool
P Cygni	LBV	yes	no
HD160529	LBV	no	no
HD168607	LBV	no	no
HD168625	LBV?	yes	cool
He3-519	Of/WN	yes	cool
R127	LBV	yes	cool
R71	LBV	~	cool
S Dor	LBV	?	?
R110	LBV	?	?
R143	LBV	yes?	?
BE294	LBV	?	?
S61	Of/WN	yes	cool
S119	Of/WN	yes	~
BE381	Of/WN	yes	?
HD269927c	Of/WN	?	?
R99	Of/WN	?	?
R84	Of/WN	?	?
S9	Of/WN	?	?
WR124 /M1-67	WN8	yes	cool
WR40 /RCW58	WN8	yes	cool
WR136 /NGC6888	WN6	yes	cool
WR6 /S308	WN5	yes	cool

the P Cygni nebula: it has a much smaller ionized gas mass, as well as different morphology, excitation mechanism, and abundance pattern (Johnson et al. 1992, Barlow et al. 1994, Nota et al. 1995). This possibly suggests a different origin.

2. Dust properties derived from the far-infrared emission

For an optically thin cloud of N dust grains of uniform size, composition, and temperature, the received flux density is equal to

$$F_\nu = N \frac{\pi a^2}{d^2} Q_\nu \, B_\nu(T_d), \qquad (1)$$

where a is the grain radius, T_d the grain temperature, and d the distance to the cloud. In the far-infrared, the grain efficiency Q_ν is $\propto \nu^\beta$ with $\beta \simeq 1-2$, and T_d may be derived from two values of F_ν measured at different wavelengths. Dust temperatures are reported in Table 2, for $\beta = 1.5$. Whatever the nature of the central object, the dust temperature correlates with the optical nebular radius (Fig. 1a), hotter dust being in smaller nebulae, as expected at least in first approximation if the dust is mixed with the ionized gas or very close to it. On the basis of this correlation, one can predict the size of the nebula around R71 in the LMC: with $T_d = 127$ K, we expect $R_{neb} \sim 0.1$ pc, or $0\farcs3$.

Table 2. Dust properties in LBV and WR nebulae

Object	d(kpc)	$\log(L/L_\odot)$	R_{neb}(pc)	T_d(K)	$\log(M_d/M_\odot)$
η Car	2.5	6.70	0.08	133	-1.41
AG Car	6.0	6.22	0.50	88	-2.00
HR Car	5.2	5.58	0.43	100	-3.02
WRA751	7.1	6.06	0.40	103	-2.23
HD168625	2.2	5.34	0.08	124	-3.51
He3-519	7.6	6.03	1.0	73	-2.23
R127	51.	6.12	1.0	85	-2.04
R71	51.	5.90	?	128	-2.29
S61	51.	6.03	0.3:	99	-2.50
WR124 /M1-67	4.5	5.97	0.92	69	-2.51
WR40 /RCW58	2.5	5.78	3.1	59	-2.77
WR136 /NGC6888	1.8	5.74	3.7	62	-2.22
WR6 /S308	1.8	5.50	9.2	55	-2.43

For the Galactic LBVs, data are from Hutsemékers (1994, Paper I), with the difference that optical nebular radii measured in the continuum are preferred whenever available. Nebular radii are from Clampin et al. (1993) for R127, Stahl (1987) for S61, and from Esteban et al. (1993) for the WR nebulae. Stellar luminosities are from Stahl et al. (1983) for R127, Wolf et al. (1987) for S61, and Lennon et al. (1994) for R71. For the WR stars, we used the absolute magnitudes from Hamann et al. (1995) together with the bolometric corrections from L.F. Smith et al. (1994). The distances are also from Hamann et al. (1995), except for WR124 (Crawford & Barlow 1991). Whenever necessary, parameters are re-scaled to the adopted distances. Dust temperatures and masses are calculated as in Paper I, following McGregor et al. (1988a), i.e. using the 25 and 60 μm IRAS flux densities (color-corrected when necessary), β=1.5, and K_{60}=230 cm^{2}g^{-1}. For the LMC LBVs, IRAS flux densities are from the IRAS PSC when available with good accuracy, otherwise from Schwering (1989). For the WR nebulae, the IRAS flux densities are from the IRAS PSC (M1-67) and from Mathis et al. (1992). Estimates of uncertainties are discussed in Paper I.

The total dust mass may be evaluated using the relation (Hildebrand 1983)

$$M_d = \frac{F_\nu \, d^2}{B_\nu(T_d)\, K_\nu} \; , \tag{2}$$

where $K_\nu = 3\,Q_\nu/4\,a\,\rho$, and ρ is the density of the grain material. Adopting a suitably weighted average of K_ν, Eq. 2 may be used to estimate the total dust mass without detailed knowledge of the grain size distribution. Dust masses are reported in Table 2, using $K_\nu = 230$ cm^{2}g^{-1} at 60 μm. Considering only Galactic LBVs, we found in Paper I a correlation between the nebular dust mass and the stellar luminosity. Fig. 1b illustrates this relation. The LMC LBVs seem to behave similarly, although the dust masses are more uncertain (due to the lower IRAS fluxes). The two WN8 objects are in excellent agreement with the LBVs, supporting the relationship suggested by Smith et al. (1994) and Crowther et al. (1995). On the contrary, S308 and NGC6888 (WN5-6) do not follow the general trend, possibly indicating that these nebulae -more massive- are not, or no longer, constituted of similar material, or that they have a different origin and/or progenitor (Mathis et al. 1992, Smith 1996).

It is important to note that, due to our poor knowledge of grain properties, orders-of-magnitude differences exist in *absolute* dust mass estimates when different grain models are considered. However, if we change β and K_ν for all

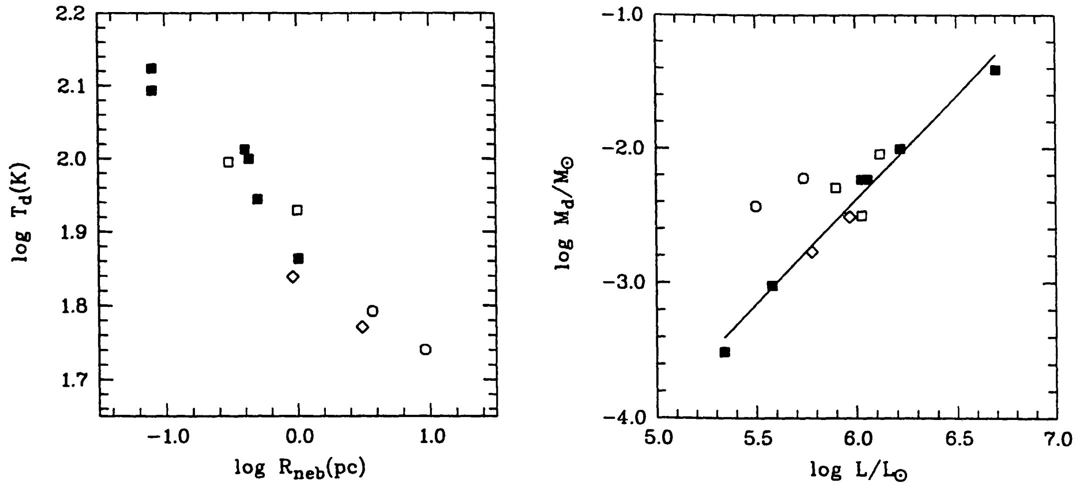

Figure 1. (A, left) The nebular dust temperature as a function of the optical nebular radius. (B, right) The nebular dust mass as a function of the stellar luminosity; the fitted line is based on Galactic LBVs (filled squares, cf. Paper I). Open squares represent LMC LBVs, losanges WN8, circles WN5-6.

objects, *relative* dust masses are essentially unchanged, and the slope of the "$\log M_d - \log L$"relation is unaffected. This can be seen in eliminating T_d from Eq. 2: within a good approximation, $M_d \simeq 1.7\,10^{-4}\,(1.85)^{\beta}\,K_{60}^{-1}\,d^2\,F_{\nu_{25}}^{-0.71}\,F_{\nu_{60}}^{1.71}$, if F_ν is in Jy, K_ν in cm^{2}g^{-1}, d in kpc. The basic assumption is that the grain properties are similar in all LBV-type nebulae (i.e. LBV+WN8 nebulae), an hypothesis which in view of the observed correlation seems a posteriori reasonable. Also, systematic differences in luminosities like those reported between empirical estimates and values derived from models will not affect the correlation as long as these differences remain systematic.

Further, it is interesting to consider the highly reddened objects G79.9+0.46, G25.5+0.2, and M1-78, suspected to contain LBV or WN central stars (Higgs et al. 1994, Subrahmanyan et al. 1994, Gussie 1995). For G79.9+0.46, the IRAS flux densities from Waters et al. (1996) give $\log M_d = -1.87$ at $d = 2$ kpc; this perfectly fits the correlation in Fig. 1b with $\log L/L_\odot = 6.30$ from Higgs et al. (1994), supporting the LBV nebula identification. On the contrary, the dust masses evaluated for G25.5+0.2 ($d \simeq 14$ kpc) and M1-78 ($d \simeq 8$ kpc) using IRAS PSC flux densities ($\log M_d = -1.22$ and -1.13, respectively) are definitely larger than for any other object (cf. Table 2), casting some doubts on their identification as LBV-type nebulae.

More detailed modelling has been carried out in a few cases, providing some information on the grains. After considering several models, McGregor et al. (1988b) and Hyland & Robinson (1991) concluded that large grains ($a \simeq 1\ \mu$m) dominate in the AG Car nebula. The preponderance of large grains was also suggested in the η Car homunculus (Mitchell & Robinson 1986), and possibly in He3-519 (Davidson et al. 1993). while Mathis et al. (1992) showed that complex distributions of small grains may reproduce the observations in three WR nebulae.

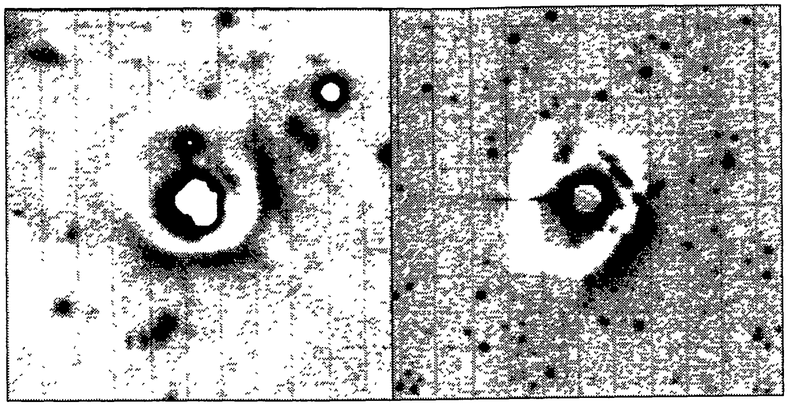

Figure 2. (A, left) HD168625: a 2.2 μm continuum image divided by a Hα+[NII] one, both from Hutsemékers et al. (1994). (B, right) AG Car: a red continuum image divided by a Hα+[NII] one, both obtained with the ESO 3.6m telescope + EFOSC. The darker regions in the nebulae are those where dust scattering dominates. Note that the AG Car nebula is also detected at 2.2 μm but the image, fainter, is of poor quality.

3. LBV-type nebulae as reflection nebulae

In addition to the well-known η Car homunculus, dust scattering has been convincingly detected in two LBV-type nebulae: AG Car (Viotti et al. 1988), and HD168625 (Hutsemékers et al. 1994). Why not in other LBV-type nebulae? Assuming the continuum surface brightness $S_{cont} \propto S_{H\alpha}/R_{neb}$, it appears that the other LBV-type nebulae are expected to be considerably fainter in the continuum, and therefore probably yet to be discovered as reflection nebulae.

The reflection nebula around AG Car has neutral colors relative to the star, while that around HD168625 is abnormally red. In both cases, this suggests the presence of large grains (Paresce & Nota 1989, Hutsemékers et al. 1994). Dust scattering seems to extend to the near-IR (as in η Car, Allen 1989), although this continuum could be due to the so-called extended 2.2 μm emission observed in many reflection nebulae (Sellgren et al. 1996). Imaging polarimetry could distinguish between these two hypotheses. In fact, detailed studies are complicated by the fact that LBVs are variable in magnitude and color, the light reaching the nebula with a time delay (typically one year for AG Car, which is comparable to the time-scale of the stellar variations).

The size and shape of the reflection nebulae are in rough agreement with the Hα nebulae, although clear differences exist (cf. Nota et al. 1995, and Fig. 2). For HD168625, the reflection nebula extends beyond the Hα ring, outlining the southern rim; this is also the case in some parts of the AG Car nebula, and for the HR Car nebula (Voors et al. 1997).

4. Conclusions

- Dust is a main feature of LBV-type nebulae (= LBV+WN8 nebulae, except P Cygni).
- Dust and ionized gas nebulae have roughly similar size and shape, but their

detailed morphology differs.

• The smaller nebulae have the hotter dust, and the most luminous stars have the most massive nebulae. The latter relation ($M_d \propto L^{1.5}$) constrains the instability and/or nebula formation mechanisms (Maeder 1997, Stothers & Chin 1996).

• There are several indications for the presence of large dust grains ($a \simeq 1\mu$m). The grain composition is unclear: silicate features are detected in η Car and R71 (Roche et al. 1993), while PAH emission is observed in HD168625 and AG Car (Cohen et al. 1986, Trams et al. 1997).

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