Astron. Astrophys. 281, L81–L84 (1994)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Evidence for violent ejection of nebulae from massive stars

D. Hutsemékers

Institut d'Astrophysique, Université de Liège, 5 av. de Cointe, B-4000 Liège, Belgium

Received 4 November 1993 / Accepted 19 November 1993

Abstract. We report the results of a systematic search for nebulae around Luminous Blue Variables (LBVs) and the discovery of a strong correlation between the mass of the nebulae and the luminosity of the central stars. This correlation holds for both the dust and ionized gas masses of the nebulae.

The existence of a "nebular mass – stellar luminosity" relation and the fact that not all LBVs are presently associated with a nebula give evidence against a continuous mass-loss mechanism for the formation of these nebulae. Further, the good agreement found between the observed relation and predictions by Maeder (1989), suggests that all these nebulae may be due to a violent ejection of matter caused by an instability of structural origin.

Key words: Luminous Blue Variable stars – mass-loss – emission nebulae

1. Introduction

Luminous Blue Variables (LBVs) are extreme supergiant stars located in the Hertzprung-Russell diagram near the Humphreys-Davidson instability limit (Humphreys & Davidson 1979). They are generally thought to represent a short-lived intermediate stage in the evolution of massive stars from O to WR stars (Maeder 1989, Humphreys 1989). About ten LBVs are presently known in our Galaxy.

One of the most remarkable characteristics of LBVs is the presence of a ring nebula surrounding some of them (Stahl 1989). In order to see if the association with a nebula is a generic property of these stars, we have searched for nebulosities around galactic LBV candidates using CCD imaging through narrow-band filters which isolate nebular lines. In addition to the previously known nebulae around η Car, AG Car, and He3-519, three new nebulae have been found surrounding HR Car, WRA751, and HD168625 (Hutsemékers & Van Drom 1991a, 1991b, Hutsemékers et al. 1993, hereafter Papers I, II and III). Nothing has been detected around HD160529 and HD168607.

Spectroscopic investigations of LBV nebulae have revealed abundance anomalies suggesting that they are constituted of nuclear processed material ejected by the central stars (Davidson et al. 1982; Mitra & Dufour 1990; de Freitas Pacheco et al. 1992; Papers I, II). If, for η Car, the mass-loss was directly observed to occur in one great eruption (e.g. Davidson 1989), the origin of most LBV nebulae is still unclear: they may be formed either by the interaction of continuous stellar winds like planetary nebulae (e.g. Robberto et al. 1993), or by a single violent ejection of matter possibly due to an instability of atmospheric (e.g. Lamers & Fitzpatrick 1988) or structural (e.g. Maeder 1989) origin.

In order to distinguish between these interpretations, we investigate in the present work how the mass of the nebular material surrounding LBVs correlates with the luminosity of the central stars.

2. The mass of LBV nebulae

2.1. The stellar parameters

The stellar luminosities and distances of LBVs may be found in the literature. For HR Car, we use the average of our values (Paper I) and those of Van Genderen et al. (1992). For He3-519, we have obtained low and high resolution spectra of the nebula, the observations being similar to those reported in Paper II (a more detailed account of these data will be given elsewhere). From the radial velocity of the [NII] and $H\alpha$ nebular lines, a kinematic distance of 7.6 kpc has been estimated for He3-519. Its luminosity has been calculated using $V = 10.97$ (Stahl 1986) and a visual extinction $A_V = 3.9 \pm 0.4$ mag intermediate between the value derived from the nebular $H\alpha/H\beta$ ratio (~ 3.4) and the higher values (~ 4.3) suggested by Stahl (1986) and Davidson et al. (1993). Considering that He3-519 is hotter than AG Car during minimun, we use a bolometric correction $\sim$ -3.0 ± 0.3 mag.

The adopted distances and luminosities (L, expressed in solar luminosity units $L_\odot$) are given in Table 1. Since

---

* Based on observations collected at the European Southern Observatory (ESO) and by the Infrared Astronomical Satellite (IRAS)

the nebular masses and stellar luminosities similarly depend on the distance, the errors reported in Table 1 and 2 do not account for the uncertainties on the distances.

Table 1. Stellar parameters

Object	Distance (*kpc*)	$\log L/L_\odot$	Ref.
η Car	2.5	6.70 ± 0.01	1,2
AG Car	6.0	6.22 ± 0.02	3
WRA751	7.1	6.06 ± 0.20	4
He3-519	7.6	6.03 ± 0.28	5
HR Car	5.2	5.58 ± 0.12	5
HD168625	2.2	5.34 ± 0.12	6

References: (1) Van Genderen & Thé 1984, (2) Tapia et al. 1988, (3) Humphreys et al. 1989, (4) Paper II, (5) this work, (6) Van Genderen et al. 1992

2.2. The nebular dust masses

All the six LBVs associated with an optical nebula show an infrared excess at 25 and 60 μm detected by the Infrared Astronomical Satellite (IRAS) and due to the presence of cool dust around the star (Mc Gregor et al. 1988a; Chentsov & Luud 1989; Hu et al. 1990; Davidson et al. 1993). If in thermal equilibrium, the dust should lie at distances corresponding to the optical nebula, as directly seen on far-infrared images (Mc Gregor et al. 1988b; Allen 1989), or revealed by the presence of dust-scattered stellar light within the nebula (Paresce & Nota 1989; Allen 1989; Paper III). The nebular mass may therefore be estimated from the dust masses. The 100 μm measurements being not always reliable, dust masses were computed following McGregor et al. (1988a) from the 60 μm flux density, using formulae given by Soifer et al. (1986). The flux densities were obtained from the IRAS Point Source Catalog and colour corrected according to the IRAS Explanatory Supplement (1985). For η Car, the 25 μm value is taken from Mc Gregor et al. (1988). The 60 μm mass absorption coefficient K_λ is estimated by extrapolating at longer wavelengths the value at 20 μm for silicate dust (Draine & Lee 1984), using $K_\lambda \propto \lambda^{-\beta}$ with $\beta = 1.5$. The characteristic dust temperature was estimated from the 25-60 μm colour temperature and a grain emissivity proportional to $\lambda^{-\beta}$. Dust temperatures (T_d) and masses (M_d, expressed in solar mass units $M_\odot$) are given in Table 2. It should be noticed that the two LBVs imaged with no detection of any optical nebulosity, HD168607 and HD160529, do not show any infrared excess indicating the presence of dust. This suggests that these non-detections are due to the real absence of an associated nebula and not to the inability of these cooler stars to ionize their surroundings.

In Figure 1, we have reported the nebular dust mass against the luminosity of the central stars. A strong correlation between these two quantities may be seen. Changing the mass absorption coefficient of the grains affects similarly all dust masses but do not modify the relation: with $\beta = 1$ rather than 1.5, all masses are simply shifted by ~ -0.4 dex. The basic assumption is that the grain properties are essentially similar for all these nebulae, an hypothesis which, in view of the observed correlation, seems a posteriori reasonable.

2.3. The nebular ionized gas masses

The mass of the ionized gas in LBV nebulae may be evaluated independently from the total flux emitted in the $H\alpha$ line, $F(H\alpha)$, and the electron density n_e using formulae given e.g. in Aller (1984). The small dependence on the electron temperature is neglected. The $H\alpha$ fluxes of the nebulae around HD168625, HR Car, WRA751 and He3-519 have been measured by integrating over the whole nebula the light received through narrow-band filters centred on the $H\alpha$ line. For HD168625 and HR Car a continuum image has been subtracted before. Taking into account the transmission of the filters and using available spectra of the nebulae, the fluxes were de-contaminated from the [NII] lines and de-reddened with nebular $E(B-V)$ estimated from the $H\alpha/H\beta$ line ratios. Finally, the fluxes were calibrated by comparison with other nebulae for which the $H\alpha$ flux is known and which have been imaged with the same filters during the same observing run. After re-scaling to our reddening value, the $H\alpha$ flux of the He3-519 nebula is in good agreement with that reported by Stahl (1987), and the mean value is taken. For AG Car, the flux is averaged from Stahl (1987), Nota et al. (1992) and de Freitas Pacheco et al. (1992). No reliable $H\alpha$ flux is available for the η Car nebula, essentially due to the strong contamination by reflected stellar light. The electron densities were re-derived homogeneously from the observed [SII] $\lambda\lambda$ 6717,6731 line ratios. These measurements are given in Table 2, together with the derived mass of the ionized gas (M_i), and the nebular radii measured on $H\alpha$+[NII] frames.

The mass of ionized gas in LBV nebulae is reported in Figure 2 against the luminosity of the central stars, confirming the dependence of the nebular mass on the stellar luminosity. The average ionized gas-to-dust ratio is comparable to values reported for other objects like planetary nebulae or HII regions. The slope of the "$\log M_i - \log L$" relation is apparently steeper when compared to the "$\log M_d - \log L$" one. It is possible that the ionized fraction of the total gas is smaller in the nebulae around HR Car and HD168625, as could be expected from the lower temperature and luminosity of these stars. The detection of molecular gas in the vicinity of HR Car but not around AG Car nor around η Car (Mc Gregor et al. 1988a) could support this view.

Table 2. Nebular parameters

Object	Radius (pc)	T_d (K)	$\log M_d/M_\odot$	$\log F(H\alpha)$ ($ergs\, cm^{-2} s^{-1}$)	$\log n_e$ (cm^{-3})	$\log M_i/M_\odot$
η Car	0.15	133 ± 8	-1.41 ± 0.12			
AG Car	0.50	88 ± 5	-2.00 ± 0.15	-9.76 ± 0.05	2.77 ± 0.10	0.60 ± 0.15
WRA751	0.40	103 ± 5	-2.23 ± 0.11	-10.29 ± 0.15	2.56 ± 0.20	0.43 ± 0.35
He3-519	1.02	73 ± 3	-2.23 ± 0.12	-10.55 ± 0.15	2.56 ± 0.15	0.24 ± 0.30
HR Car	0.43	100 ± 4	-3.02 ± 0.10	-11.20 ± 0.20	2.72 ± 0.15	-0.91 ± 0.35
HD168625	0.11	124 ± 7	-3.51 ± 0.12	-11.60 ± 0.15	2.80 ± 0.20	-2.14 ± 0.35

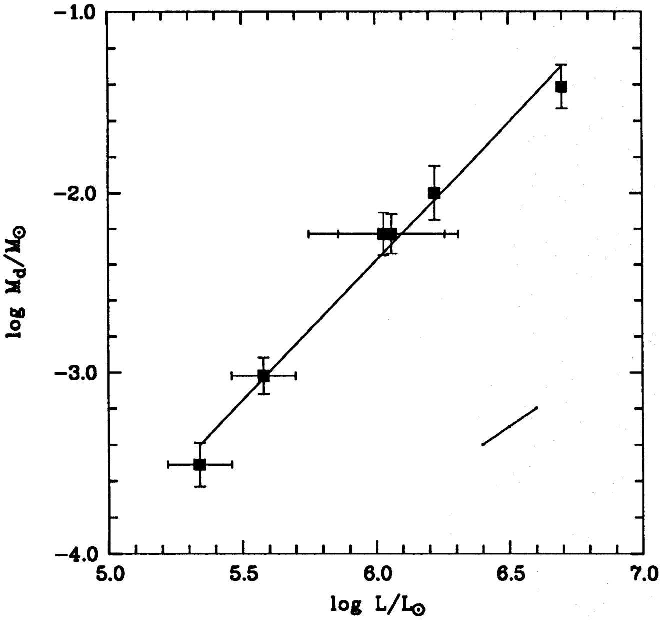

Fig. 1. Dust mass of LBV nebulae reported as a function of the luminosity of the central stars. The straight line resulting from a least square fit is plotted and illustrates the strong correlation between the nebular dust masses and the stellar luminosities. The error bars do not account for the uncertainties on the distances since both mass and luminosity similarly depend on it. A typical uncertainty on the distances is represented by the small oblique error bar.

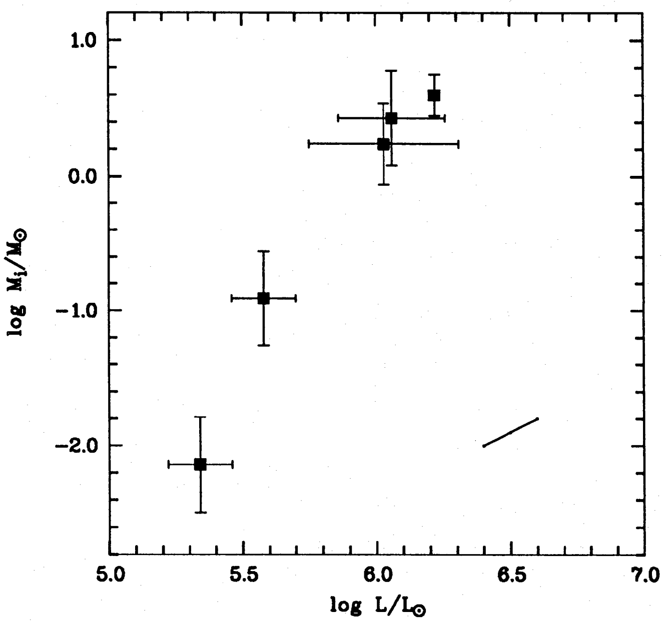

Fig. 2. Ionized gas mass of LBV nebulae reported as a function of the luminosity of the central stars. The uncertainties on the ionized gas masses are larger due to the difficulty of measuring a reliable $H\alpha$ flux for faint nebulae near bright stars and of obtaining a good estimate of the average electron density.

2.4. A "nebular mass-stellar luminosity" relation

The relation between the nebular mass M_{neb} and the stellar luminosity L is therefore better expressed by

$$\log(\frac{M_{neb}}{M_\odot}) = (1.55 \pm 0.10)\ \log(\frac{L}{L_\odot}) + C, \qquad (1)$$

fitting a straight line to the data displayed in Figure 1. If M_{neb} refers to the dust mass (computed with $\beta = 1.5$), $C = -11.7 \pm 0.1$. If we assume that the total gas-to-dust ratio is comparable in all LBV nebulae, M_{neb} may refer to the total nebular mass and the constant C may be fixed using the gas mass of the AG Car nebula ($M_{neb} \simeq 4.0 M_\odot$) which is presently the nebula with the best available mass estimate and known to be density bounded (Robberto et al. 1993). In this case, $C \simeq -9.0$.

3. Discussion and Conclusions

The mere existence of a relation between the mass of the LBV nebulae and the luminosity of the central stars constrains the models proposed to explain the formation of such nebulae. If LBV nebulae result from matter continuously ejected during a previous evolutionary stage and swept up by the present stellar wind, we expect the nebular mass to continuously increase with time. Since at the considered evolutionary stage, a massive star keeps its luminosity nearly constant (e.g. Maeder 1989), such an interpretation would imply that the LBVs of our sample have exactly the right age to have their nebular masses correlated with their luminosities, which is very unlikely. Further, if this kind of interpretation is correct, we would also expect nebulae around all LBVs including HD160529 ($\log L/L_\odot \simeq 5.50$, Sterken et al. 1991) and HD168607 ($\log L/L_\odot \simeq 5.38$, Van Genderen et al. 1992). The existence of a relation between the mass of LBV nebulae and the luminosity of the central stars therefore argues against the continuous mass-loss mechanism for explaining the formation of these nebulae. The absence of any correlation between the nebular masses and radii (cf. Table 2) also supports this view.

Maeder (1989) has given an estimate of the maximum possible mass ΔM ejected in one episode during some dynamical time scales: if R and M denote the radius and mass of the star, $\Delta M \propto R^{5/2}M^{-3/2}L$. Using the mass-luminosity relation for massive stars $M \propto L^{0.47}$ (Lamers & Fitzpatrick 1988), and the maximum stellar radius $R \propto L^{1/2}$ which is independent of the effective temperature (Wolf 1989), we find $\Delta M \propto L^{1.55}$, in excellent agreement with the relation found observationally (Eq. 1). This suggests that a structural instability mechanism may be at the origin of the ejection of the LBV nebulae. In this case, the maximum possible mass could be ejected during a single violent event occuring at the LBV evolutionary stage, possibly when the stars are located in the region of the HR diagram where the relation $R \propto L^{1/2}$ is valid for most LBVs (cf. Wolf 1989). It is also interesting to note that the two LBVs without nebulae are cooler than HR Car and HD168625 which are of comparable luminosities, as can be expected from stars having not yet ejected their outer layers.

The reality of a relation between the mass of LBV nebulae and the luminosity of the central stars seems well established giving some evidence that a single violent ejection is at the origin of all these nebulae. However, the exact shape of the observed relation will only be known with certainty if the total mass of the nebula can be evaluated, including the mass of the molecular gas. Also, the status of faint nebulosities, like those recently detected around P Cygni (Johnson et al. 1992) which apparently contain much less material and are only marginally associated with dust (Waters & Wesselius 1986; Luud et al. 1988) should be clarified.

Clearly, the functional dependence of a "nebular mass -stellar luminosity" relation for massive stars may constrain evolutionary models and instability mechanisms like those proposed by Maeder (1989) and Stothers and Chin (1993). It may also provide us with a useful tool for evaluating the mass deposition into the ISM during the LBV stage. It will be interesting to obtain similar data for LBV nebulae in other galaxies (e.g. LMC) in order to see if this relation depends on the metallicity.

Acknowledgements. It is a pleasure to thank J. Surdej for reading the manuscript. This research is supported in part by contracts ARC 90/94-140 "Action de recherche concertée de la Communauté Française" and SC005 " Service Centers and Research Networks of the SPPS" (Belgium).

References

Allen, D.A., 1989, *MNRAS* **241**, 195

Aller, L.H., 1984, *Physics of Thermal Gaseous Nebulae*, Reidel, Dordrecht

Chentsov, E.L., Luud, L., 1989, *Astrophys.* **31**, 5

Davidson, K., Humphreys, R. M., Hajian, A., Terzian, Y., 1993, *ApJ* **411**, 336

Davidson, K., Walborn, N.R., Gull, T.R., 1982, *ApJ* **254**, L47

Davidson, K., 1989, *Physics of Luminous Blue Variables*, IAU Coll. 113, p.101

Draine, B.T., Lee, H.M., 1984, *ApJ* **285**, 89

de Freitas Pacheco, J.A., Damineli Neto, A., Costa, R.D.D., Viotti, R., 1992, *A&A* **266**, 360

van Genderen, A.M., Thé, P.S., 1984, *Sp. Sc. Reviews* **39**, 317

van Genderen, A.M. et al., 1992, *A&A* **264**, 88

Hu, J.Y., de Winter, D., Thé, P.S., Pérez, M.R., 1990, *A&A* **227**, L17

Humphreys, R.M., Davidson, K., 1979, *ApJ* **232**, 409

Humphreys, R.M., 1989, *Physics of Luminous Blue Variables*, IAU Coll. 113, p.3

Humphreys, R.M., Lamers H.J.G.L.M., Hoekzema, N., Cassatella, A., 1989, *A&A* **218**, L17

Hutsemékers, D., Van Drom, E., 1991a, *A&A* **248**, 141 (Paper I)

Hutsemékers, D., Van Drom, E., 1991b, *A&A* **256**, 620 (Paper II)

Hutsemékers, D. et al., 1993, in preparation (Paper III)

Johnson, D.R.H., Barlow, M.J., Drew, J.E., Brinks, E., 1992, *MNRAS* **255**, 261

Lamers , H.J.G.L.M., Fitzpatrick, E.L., 1988, *ApJ* **324**, 279

Luud, L., Tuvikene T., Ruusalepp, M., 1988, *Astrophys.* **29**, 97

Maeder, A., 1989, *Physics of Luminous Blue Variables*, IAU Coll. 113, p. 15

McGregor, P.J., Hyland, A.R., Hillier D.J., 1988a, *ApJ* **324**, 1071

McGregor, P.J., Finlayson, K., Hyland, A.R., Joy, M., Harvey, P.M., Lester, D.F., 1988b, *ApJ* **329**, 874

Mitra P.M., Dufour R.J., 1990, *MNRAS* **242**, 98

Nota, A., Leitherer, C., Clampin, M., Greenfield, P., Golimowski, D.A., 1992 *ApJ* **398**, 621

Paresce, F., Nota, A., 1989, *ApJ* **341**, L883

Robberto, M., Ferrari, A., Nota, A., Paresce, F., 1993 *A&A* **269** , 330

Soifer , B.T., Rice, W.L., Mould, J.R., Gillett, F.C., Rowan Robinson, M., Habing, H.J., 1986, *ApJ* **304**, 651

Stahl, O., 1986, *A&A* **164**, 321

Stahl, O., 1987, *A&A* **182**, 229

Stahl, O., 1989, *Physics of Luminous Blue Variables*, IAU Coll. 113, p. 149

Sterken, C., Gosset, E., Juttner, A., Stahl, O., Wolf, B., Axer, M., 1991, *A&A* **182**, 229

Stothers, R.B., Chin, C.-W, 1993, *ApJ* **408**, L85

Tapia, M., Roth, M., Marraco, H., Ruiz, M.T., 1988, *MNRAS* **232**, 661

Waters, L.B.F.M., Wesselius, P.R., 1986, *A&A* **155**, 104

Wolf, B., 1989, *A&A* **246**, 441