Ring Nebulae Abundances: Probes of the Evolutionary History of Luminous Blue Variable Stars*

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1 Introduction and Observations

The ring nebulae that surround most Luminous Blue Variable (LBV) stars are believed to be the relics of one or more giant eruptions (cf. Nota, these proc.). The nebulae thus represent the stellar surface layers at the time of the eruption(s) and by analysing their chemical composition and dynamics, it is possible to infer the past evolutionary state of the star.

Observations with the *Hubble Space Telescope* (HST) and the Faint Object Spectrograph (FOS) were obtained for the nebulae around the two LMC LBVs R127 and R143, and the Ofpe/WN9 star S119 for the purpose of obtaining abundances. The spectra cover the wavelength range 3235–6818 Å and a slit of dimensions $1''.7 \times 0''.2$ was placed on the brightest portion of each nebula. Full details of these observations are given in Smith et al. (1998).

2 Analysis and Results

Interstellar reddenings, electron densities N_e and temperatures T_e were derived for the three nebulae using the Balmer series, [S II] $\lambda6717/\lambda6731$ and [N II] $\lambda6584/\lambda5755$ ratios. For the R127 nebula, we derive $E(\mathrm{B-V}) = 0.16 \pm 0.03$, $N_e = 720 \pm 90\,\mathrm{cm^{-3}}$, and $T_e = 6420 \pm 300\,\mathrm{K}$. For the S119 nebula, we find $E(\mathrm{B-V}) = 0.05$, $N_e = 680 \pm 170\,\mathrm{cm^{-3}}$, and an upper limit to T_e of 6800 K. In contrast to the similar physical parameters we derive for the R127 and S119 nebulae, the R143 nebula has $N_e < 100\,\mathrm{cm^{-3}}$ and $T_e = 12\,000\,\mathrm{K}$. These parameters and the abundances (see below) indicate that the region observed with FOS is part of the 30 Dor H II complex. The real ejecta nebula is located just $2''$ from the star (see Smith et al., 1998; Nota, these proc.)

* Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA under contract NAS5-26555.

Nitrogen and oxygen abundances were determined for the ejecta nebulae directly from the strengths of the [N II] λ6584 and [O II] λ3727 lines. Correction for unseen ionization stages is unnecessary because the nebulae have low values of T_e. For the S119 nebula, [N II] λ5755 was not detected; approximate upper and lower limits to the abundances were derived using the measured upper limit to T_e, and the value of T_e which reproduces the observed S^+/H in the R127 nebula. For the R143/30 Dor nebula, [O III] λ5007 is observed, and the abundances have been determined using the ionization correction factors of Kingsburgh & Barlow (1994).

In Table 1, we list the derived N/O ratios, the N enrichment factor Δ N, and the O depletion factor $1/\Delta$ O for the three nebulae. The mean of the LMC H II region abundances of Dufour (1984) and Russell & Dopita (1990) were used to calculate these factors. For comparison, we list the abundances for other objects containing processed stellar material in the LMC; non-type I PNe (nebulae which show CN-processed material), and the inner ring of SN 1987A which is believed to consist of red supergiant (RSG) wind material.

Table 1. Nebular abundances

Object	SpT	N/O	Δ N	$1/\Delta$ O	Ref.
R127	LBV	0.89 ± 0.40	10.7 ± 2.2	2.0 ± 1.0	1
S119	Ofpe/WN9	1.41–2.45	11.5–24.5	1.4–5.1	1
R143/30 Dor	LBV	0.04 ± 0.04	0.5 ± 0.6	2.2 ± 1.1	1
Non-Type I PNe		0.19 ± 0.09	4.6 ± 2.9	1.0 ± 0.5	2
SN 1987A	RSG?	1.55 ± 0.40	11.5 ± 2.3	3.2 ± 0.7	3
⟨H II⟩		0.04	1.0	1.0	4

1. this paper; 2. Barlow (1991), Walton et al. (1991); 3. Panagia et al. (1998, & in prep.); 4. Dufour (1984), Russell & Dopita (1990).

3 Discussion and Conclusions

For the R127 nebula, we derive an N/O ratio of 0.89 with N enriched by a factor of 11, and O showing little, if any, depletion. For the S119 nebula, we derive a similar N/O ratio of 1.41–2.45, where the range reflects the uncertainty in T_e. The R143/30 Dor abundances agree well with the mean H II region abundances listed in Table 1. Comparing first the R127 nebular abundance pattern with non-type I PNe, we find that while N is a factor of ≈ 2 more enriched, O is the same within the errors. Comparison with the SN 1987A abundances shows that the N enrichment is identical and that the O

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abundances agree reasonably well. We conclude that the high N enrichment and minimal O depletion in the R127 nebula are consistent with material that has been CN-processed only. The remarkable agreement with the SN 1987A inner ring abundances and the low expansion velocity of the nebula (Smith et al. 1998) suggests that the R127 nebula was once the CN-processed convective envelope of a RSG.

Comparison of the nebular abundances with those determined for LBVs from atmospheric analyses (e.g. Lennon et al. 1994; Venn 1997) shows that the atmospheres should consist of CNO-processed material. It thus appears that the R127 nebular abundances do not reflect the current surface composition assuming it has CNO-equilibrium abundances, and suggests that the nebula was ejected before, or at the very start of, the LBV phase. Interestingly, the η Car nebula shows extreme CNO-processing (Dufour et al. 1997).

We have examined whether the R127 nebular N/O abundance ratio can be reproduced by the evolutionary tracks of Meynet et al. (1994). We find that the amount of mass loss is the critical parameter. If it is too high, the observed N/O ratio occurs while the star is still on the main-sequence and the evolutionary timescale is then too long to produce a small nebula in the LBV phase. We find best agreement for a $60\,M_\odot$ model where the pre-LBV mass loss is low enough to allow the star to evolve redward, and $N/O \approx 1$ occurs when the star is a cool supergiant inside the Humphreys-Davidson limit.

Our finding that the R127 nebula was once a RSG convective envelope is also supported by recent *ISO* observations. Waters et al. (these proc.) find that the crystalline dust structure in LBV nebulae is suggestive of formation in RSG envelopes. How can we reconcile these findings with the observed absence of RSGs above the Humphreys-Davidson limit? First, the RSG phase must be brief. The model of Stothers & Chin (1996 and refs. therein) has the LBV eruption occurring in a brief RSG phase. Second, it is possible that the RSG phase does not correspond to an evolutionary phase in the usual sense, but rather to a pseudo-RSG phase, occurring as a result of encountering the Eddington limit. What happens at this point is very complicated. According to the model of Owocki & Gayley (1997), it is possible that the star will respond to the super-Eddington condition by developing a convective envelope and becoming very bloated such that it will have the appearance of a RSG. The outer envelope may then become detached due to a density inversion (Owocki & Gayley 1997).

On the basis of our observations we suggest the following picture for the formation of LBV nebulae. The pre-LBV does not lose enough mass while on the main sequence, and evolves redward. At some point it encounters the Eddington limit, and develops a deep convective envelope which is gently ejected to reveal the LBV underneath. LBVs should therefore be surrounded by massive RSG envelopes which in most cases, will be neutral because of the low ionizing fluxes.

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Discussion

J. Cassinelli: About 10 years ago Kris Davidson found that stars could appear to the right of the Humphreys-Davidson limit at $\sim$ 8000 K. So, are your "pseudo red supergiants" really at the far right side (T_{eff} ~3000 K) of the HR diagram or is there a large uncertainty concerning T_{eff} at the cool phase? This is important for deciding whether dust can from or not.

L. Smith: There is a large uncertainty regarding T_{eff} since the amount of mass loss is the critical parameter in determining how far to the red a star will evolve.

M. Magalhães: Were the evolutionary tracks you used for non-rotating stars?

L. Smith: Yes, the tracks are those of Meynet et al. (1994) and do not include rotation.

R. Humphreys: How short do you expect the time scale to be for the red supergiant phase? We observe several stars now in different galaxies

(IRC +10420, Var A) undergoing evolutionary changes that take only 2000–3000 years. So for your proposed red supergiants to exist, they have to be < 1000 years and not be observed. Alternatively, the stars could be optically obscured. The LMC has been surveyed in the infrared. The two most luminous M supergiants are IRAS sources; they are OH/IR supergiants. They have $M_{bol} \sim -9.5 - -9.7$. There are no more luminous M supergiants known in the LMC.
So your proposed red supergiant phase will have to be extremely brief (R 127 is very unlikely given the size of red supergiants). HR Car is below the Humphreys-Davidson limit.
For a pseudo-RSG phase, take a look at Var A in M 33 (Humphreys et al. 1987) and ρ Cas – two F supergiants that temporarily became M supergiants.

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