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Gone with the wind: Nebulae around LBVs

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Abstract: The LBV phase is a short and active phase very massive stars may pass. Strong stellar winds and possibly giant eruptions of the stars in this phase lead to the formation of small (≤ 5 pc) circumstellar nebulae. A significant fraction (about 50%) of these nebulae show—to different degrees—a bipolar structure. Such a morphology, together with the presence of LBVs at lower bolometric luminosity, supports the newer stellar evolution models including rotation. Morphology, kinematics and the chemical composition of LBV nebulae are useful tracers to reveal the star's previous history, answer questions about the stellar interior and finally the stellar evolution of massive stars in general. A summary of our knowledge of the currently known LBV nebulae will be presented with a short special emphasis on a new analysis of the nebula around AG Carinae. Deep images and echelle spectra of this nebula show it to be much larger in size as known so far, and reveal in much more detail the—so far only hinted—highly bipolar structure of the nebula.

1 Luminous Blue Variables

Massive evolved stars—somewhat depending on their metallicity and rotation—do have a certain potential to enter an instable phase, as they turn into *Luminous Blue Variables* (LBVs, for details see e.g. Humphreys & Davidson 1994). LBVs, as the name indicates, are characterized by being luminous and blue stars, the latter however is no necessarily true all the time. LBVs are subject to photometric as well as spectral variabilities with various amplitudes (both in time and brightness/spectral type). A variability intrinsic to LBVs, is the S Dor variability. Depending on the direction of its evolution—redward or blueward in the HRD—the star gradually brightens, or gets fainter in the V band. This S Dor cycle (see e.g. van Genderen 2001, and Burggraf et al. 2011) draws back to the change of the stellar spectrum from a hot O-B to a cooler A-F star. The star is dimmer in the visual band in to the hot phase, and brighter while being cool. Balmer, He I and He II lines are seen in emission and often with P Cygni profiles. Therefore, LBVs can be found in the hot as well as in the cooler upper regime of the HRD. Nevertheless they are limited towards lower temperatures by the Humphreys-Davidson limit, which they may pass and violate for a short time. LBVs can exhibit so called *giant eruptions* in which the stars brightness increases significantly (several magnitudes), rapidly and only for a short time (several month to a few years, Humphreys et al. 1999). These LBVs are also dubbed *supernova impostors* (e.g. Van Dyke et al. 2000). While we have a good handle on the way stars loose mass by stellar winds, the underlying mechanism for the onset of the S Dor variability and the giant eruptions are still not fully understood. The star's proximity in the LBV phase to theoretical instability limits like the Γ- and or Ω-limit (e.g. Maeder & Meynet 2000), which roughly fall together with the observed Humphreys-Davidson limit, pose very likely scenarios. Initial mass, metallicity, stellar wind, and in particular rotation impact on the star's possible passage through an LBV phase, which is estimated to

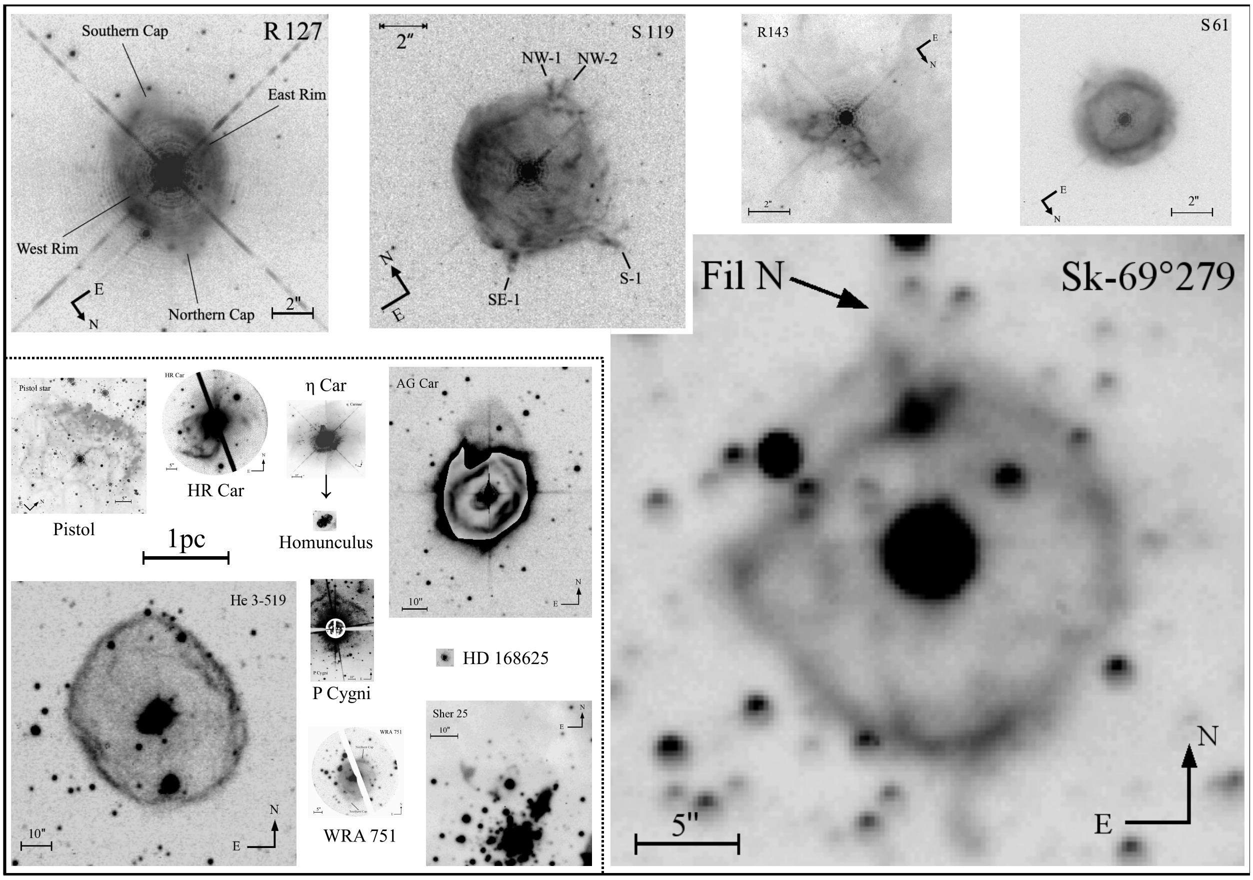

Figure 1: LBV nebulae of the Milky Way—concentrated in the lower left section within the dashed line—and the LMC on scale. Images taken from: Pistol (Figer et al. 1999), P Cygni (Barlow et al. 1994), S 119 (Weis et al. 2003, also published by Danforth & Chu 2001), HD 168625 (Weis 2000, also published by Pasquali et al. 2002). All other images are observed or published first by the author.

last several 10^4 yrs. Originally the lower limit of stars to enter the LBV phase used to be $50\,M_\odot$, stellar evolution model which include an initial rotation of $300\,\mathrm{km\,s^{-1}}$ (Meynet & Maeder 2005) propose that stars with masses as low as $22\,M_\odot$ (for Z=0.02) may encounter the LBV phase. This matches better the observations for some low luminosity LBVs but at the same time poses that the number of LBVs we see should be higher, or the LBV phase must be shorter.

2 Nebulae around Luminous Blue Variables

Increased mass loss by stellar winds in the LBV phase (up to $10^{-4}M_\odot\mathrm{yr}^{-1}$) and sometimes the massive giant eruptions provoke the formation of small circumstellar LBV nebulae (see e.g. Nota et al. 1995, Weis 2000). The nebulae are strong [N II] emitter, as CNO processed material is mixed up and carried away. Nebulae in the Milky Way and LMC which are resolved spatially (no SMC nebula is known) can be characterized further in morphology, size and kinematics (Tab. 1 and Fig. 1).

Morphology & Sizes: The morphologies in LBV nebulae are manifold, from quite spherical ring nebulae (e.g. S 61) and slightly elliptical structures (e.g. He 3-519), to one irregular object (R 143). A significant number of nebulae do show bipolarity or at least bipolar components. They are either of hourglass shape (η Car or HR Car) or show attached bipolar components dubbed caps (WRA 751 or R 127). A statistic of the morphologies (from Tab. 1) yields that about 50% of the nebulae show bipolarity (hourglass or caps), 40% are spherical and only 10% irregular. The frequency of bipolarity

Table 1: Parameters of LBV nebulae in the Milky Way and LMC. Slashes separate values for nebulae that consist of two distinct parts. Maximum size are either the largest extent as diameter or major and minor axes. For hourglass shaped bipolar nebulae, the radius and expansion velocities (marked with *) is given for one lobe. Table adapted from Weis (2001) and Weis (2003).

LBV	host galaxy	maximum size [pc]	radius [pc]	$v_{\rm exp}$ [km/s]	kinematic age [10^3 yrs]	morphology
η Carinae	Milky Way	0.2/0.67	0.05/0.335	$300^*/10-3200$		bipolar
AG Carinae	Milky Way	1.4×2	0.4	$\sim 25^*$	~ 30	bipolar
HD 168625	Milky Way	0.13×0.17	0.075	40	1.8	bipolar ?
He 3-519	Milky Way	2.1	1.05	61	16.8	spherical/elliptical
HR Carinae	Milky Way	0.65×1.3	0.325	75^*	4.2	bipolar
P Cygni	Milky Way	0.2/0.84	0.1/0.42	$110-140/185$	0.7/2.1	spherical
Pistol Star	Milky Way	0.8×1.2	0.5	60	8.2	spherical
Sher 25	Milky Way	0.4×1	0.2×0.5	$30-70$	$6.5-6.9$	bipolar
WRA 751	Milky Way	0.5	0.25	26	9.4	bipolar
R 71	LMC	< 0.1?	< 0.05?	20	2.5 ?	?
R 84	LMC	< 0.3 ?	< 0.15?	24 (split)	6 ?	?
R 127	LMC	1.3	0.77	32	23.5	bipolar
R 143	LMC	1.2	0.6	24 (split)	49	irregular
S Dor	LMC	< 0.25?	<0.13?	< 40 (FWHM)	3.2 ?	?
S 61	LMC	0.82	0.41	27	15	spherical
S 119	LMC	1.8	0.9	26	33.9	spherical/outflow
Sk $-69°$ 279	LMC	4.5×6.2	2.25	14	157	spherical/outflow

is higher among Galactic LBVs ($\sim$75%) than it is for LMC objects ($\sim$20%). Some nebulae have outflows like Sk $-69°$ 279 (see Fil N in Fig. 1). In size LBV nebulae span a range from roughly 0.2 pc, the diameter of the nebula around HD 168625, to 4.5 pc for the ring around Sk $-69°$ 279 (4.5 pc$\times$6.2 pc with the outflow). The LMC objects are generally larger, but note that with the lower resolution in the LMC (1 pc $\sim 4''$), small nebulae are overlooked more easily.

Kinematics: The expansion velocities of LBV nebulae range between 14 km s^{-1} (Sk $-69°$ 279, Weis & Duschl 2002) to 185 km s^{-1} (P Cyg, outer nebula, Barlow et al. 1994). η Car is an exceptional case with velocities of 300 km s^{-1} for the Homunculus and some 3200 km s^{-1} (Smith & Morse 2004) detected in the outer ejecta. Typical values, however, are around 50 km s^{-1} for Galactic and about half of that for LMC nebulae. Morphologically identified bipolar nebulae are also detected kinematically. They exhibit a red and blue-shifted shell (two expansion ellipses in the spectra) or a bi-directional expansion of the attached caps with a red- one blueshifted side. Some nebulae have outflows (Sk $-69°$ 279, S 119) or deformations (AG Car, see below) which are moving faster.

Origin & Bipolarity: LBV nebulae can be formed by continuous winds or during a short outburst (giant eruption). Given the small sample of well studied and observed eruption LBVs with nebulae (η Car and P Cyg) it is hard to identify any differences of the nebulae to those around non-eruptive LBVs. With the nebulae's large kinematic ages (Tab. 1) it cannot be excluded that other LBV nebulae might result from an eruption, which just has not been observed. Why do quite a number of nebulae show a bipolar shape? Several physical mechanism are conceivable to support bipolarity. Examples are fast stellar rotation, or a density gradient in the stellar wind (or the ISM) from the star's pole to the equator. This migh occur as the star passes the bistability jump and the wind changes from polar to equatorial. Bipolarity might result from a binary system, but with only two proposed LBV binaries (η Car, Damineli et al. 1997 and HD 5980, Hoffmann et al. 1978) seems not the dominant process.

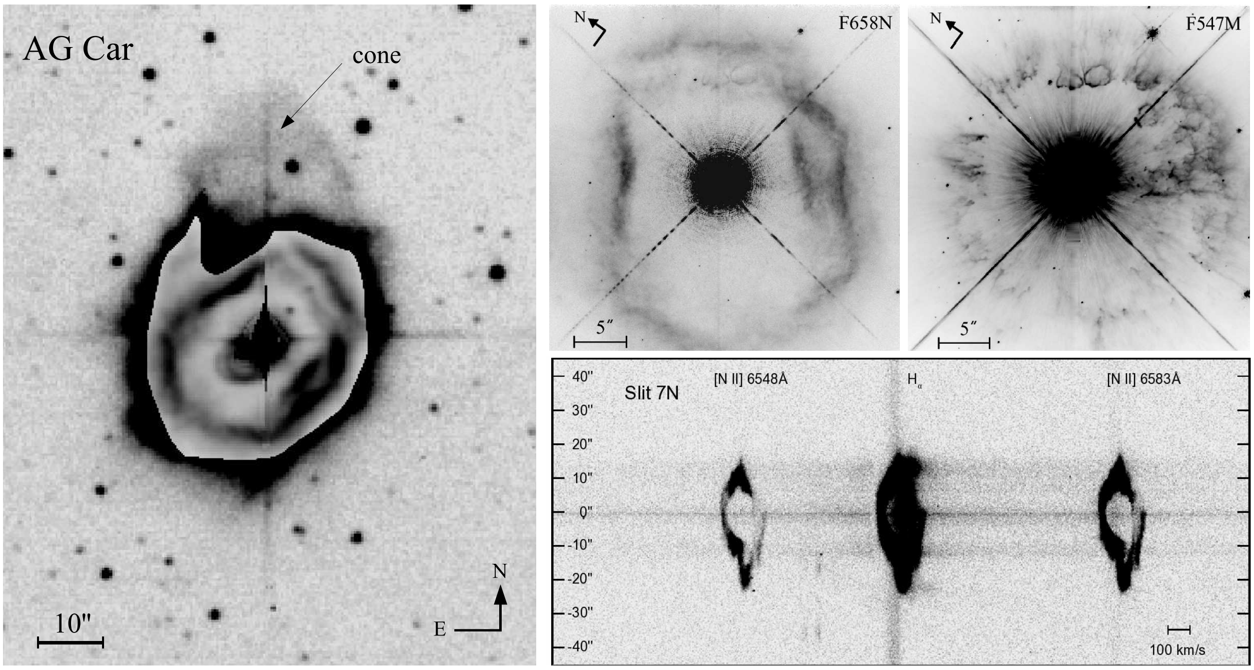

Figure 2: *Left:*Deep [N II] image of AG Car's nebula showing the fainter–and overlayed in the center the brighter–emission. To the north-east extends the cone-like structure. *Upper right:* HST-PC images of the central nebula taken in the F658N and the F547M filter (previouly published by Nota et al. 1995). *Lower right:* A long-slit echelle spectrum revealing two attached expansion ellipses.

3 The nebula around AG Carinae

AG Carinae is a classical LBV, it lies in the very upper part of the HRD, has a well documented S Dor cycle and a nebula. First pictures of its nebula date back to Thackeray (1950) and showed that it is an elliptically shaped ring slightly quenched in the middle with a size of $40'' \times 30''$ or $1.2\,\mathrm{pc} \times 0.9\,\mathrm{pc}$. In the south-west side an additional half-shell is present, in the north-east an arm like extension stretches out with a length of $20''$ (0.6 pc). First measurements of the expansion velocities ranged from $80\,\mathrm{km\,s^{-1}}$ (Johnson 1976), and line splits of 20-120 $\mathrm{km\,s^{-1}}$ (Thackeray 1977) to $70\,\mathrm{km\,s^{-1}}$ (Smith 1991). With new images and spectra, some of these nebula parameters can be updated.

Morphology: Deep [N II] ground based images of AG Carinae reveal that, taking the faintest emission into account, the dimension (with the current detection limit) of the nebula has increased to $70'' \times 48''$ or $2\,\mathrm{pc} \times 1.4\,\mathrm{pc}$ (Fig. 2), making it nearly twice the size reported before. This increase is in particular due to the discovery of a very faint cone shaped structure that extends to the north. The cone directly merges into the arm-like filament already reported by Thackeray. Taken together arm and cone have a total length of 1.4 pc (see Fig. 2). The same figure features two HST images of the central brighter part of the nebula. The F658N image shows the [N II] emission while the F547M frame shows scattered stellar light tracing the nebula's dust. Together with the kinematic data (see below), it was found that AG Car shows a two shell structure, the shells being superimposed in line of sight, with a marginal shift to the north-east of one shell. This shift is best seen in the south-west, here for about a length of $10''$ the bright rims of the shell are seen to be parallel.

Kinematics: Mapping the nebula the global expansion pattern was reconstructed. In the lower left section of Fig. 2, a typical echellogram of slit 7N ($7''$ north of the star, PA = 45°) is depicted. Two expansion ellipses are detected – one redshifted, one blueshifted – which are attached to each other. This further manifests the nebula's bipolar structure with an approaching and a receding shell. The shells are either connected to each other at the center (ellipses not closed) or the walls of the shells are

very thin and below our detection limit. The expansion ellipses yield a maximum expansion velocity of 20-30 $\mathrm{km\,s^{-1}}$ for each shell. Taken together that matches earlier measurements (remember the shells are superimposed in line of sight). The cone (Fig. 2) is part of the receding shell, moves about 75 $\mathrm{km\,s^{-1}}$ faster as the center of this shell and manifesting a larger dent or outflowing region.
Rotation & Bipolarity : It has been shown that AG Car is a fast rotating star, so is HR Car (Groh et al. 2006, 2009). Both do show bipolar nebulae. Therefore at least in these cases, rotation could be the explanation for bipolarity.

4 Summary or info to take home with!

Part I: LBV nebulae are formed by interaction of stellar winds and/or in giant eruptions. The morphology of the nebulae is, besides spherical (to some degree elliptical) and irregular, in many cases bipolar. Bipolarity is seen in hourglass shapes or as caps attached to the nebula's main body. The sizes of LBV nebulae range between 0.2 pc to about 5 pc. Their expansion velocities are typically several tenths to slightly above 100 $\mathrm{km\,s^{-1}}$. LBV nebulae in the LMC (compared with the Galactic) are generally larger in size, have lower expansion velocities (factor two) and fewer bipolar nebulae.
Part II: AG Carinae has a nebula that is, including the faintest emission, with a size of 2 pc$\times$1.4 pc, significantly larger than previously reported. The nebula consists of two shells which expand bipolar with velocity between 20-30 $\mathrm{km\,s^{-1}}$. A larger conical structure to the north (the cone) is a faster moving part of the redshifted shell and an extension of the arm reported by Thackeray (1950). The origin of the bipolar nebula might be linked to the star's fast rotation.

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