*Active OB stars: structure, evolution, mass loss, and critical limits*
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# Nebulae around Luminous Blue Variables – large bipolar variety

**Kerstin Weis**

Astronomisches Institut, Ruhr-Universität Bochum,
Universitätsstr. 150, 44781, Bochum, Germany
email: `kweis@astro.rub.de`

**Abstract.** During the LBV phase—a short transitional phase of only the very massive stars—strong stellar winds sometimes accompanied by eruptions form small circumstellar LBV nebulae around a substantial number of LBV stars. Analyzing the morphology and and kinematics of the LBV nebulae even weakly bipolar components can be detected, leading to the conclusion that about 50% have—to some degree—a bipolar structure. A global overview of our current observational knowledge of LBV nebulae is summarized, including their morphology, sizes and kinematic parameters.

**Keywords.** stars: variables: other, stars: circumstellar matter

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## 1. Stars in the LBV phase

In recent years the number of *Luminous Blue Variables (LBVs)* listed in the literature has increased substantially. What is a LBVs? In 1984 Conti introduced the name LBV to unite the Hubble-Sandage, S Dor variables with the P Cyg and $\eta$ Car type stars into one class, see Conti (1984). Are all LBVs luminous, bright and variable? Yes and no. LBVs do show photometric variations that are irregular and with different timescales and amplitudes. The variability intrinsic to LBVs, is the S Dor variability (for a detailed description see e.g. van Genderen 2001). This variability has its origin in the change of the stellar spectrum, and therefore is accompanied by a change in color. In addition some LBVs show *giant eruptions*, in which their brightness increases significantly for only a few years. Are LBVs blue? The answer is sometimes. If the star is in the hot phase within the S Dor cycle it is a blue supergiant. In the cool phase the LBV however can have a spectrum as cool as type A or F. Are LBVs luminous? The LBV phase is encounter by massive stars, the most luminous. The current list of LBVs however includes stars which show a luminosity as low as $\log L/L_\odot \sim 5.5$ or equivalent to an initial mass of $25\,M_\odot$. This is lower as original proposed for LBVs (mass limit $50\,M_\odot$), but well within the limit of about $22\,M_\odot$ set by stellar evolution models that include an initial rotation rate of $v_{rot} = 300\,\mathrm{km\,s^{-1}}$ (Meynet & Maeder 2005). Therefore, LBVs are luminous but not necessarily all are very luminous.

LBVs are stars in a short, a few $10^4$ years, instable phase. Most likely their proximity to the Humpheys-Davidson limit—or from the theoretical point of view the $\Omega$- and/or $\Gamma$-limit—causes their photometric and spectroscopic variability as well as increases their mass loss rate (up to $10^{-4}\,M_\odot \mathrm{yr}^{-1}$), and maybe to the formation of nebulae. For further details on the LBV phase the reader is referred to Humphreys & Davidson (1994) and the more recent proceedings of conferences on the topic. Note however, that currently a clear definition of a LBV is missing! The stars show no really unique spectral feature, not for all a S Dor cycle has been observed and not all do have a nebula.

## 2. LBV nebulae

The LBVs larger mass loss and sometimes eruptions form LBV nebulae which show strong [N II] emission (CNO processed material), which have the following parameters.

**Morphology:**

Among the resolved LBV nebulae (Fig. 2 & 3), several are spherical, an example is S 61 (Weis 2003). Some nebulae do show an additional outflow or convexity, e.g. Sk $-69^\circ$ 279 has an outflow to the north (Fig. 1, Weis & Duschl (2002)). A complete irregular structure is rare, with R 143 the best and only example (Weis 2003). Situated within the 30 Dor region R 143 lies in an area of higher density and interstellar turbulence, making it likely that the ambient medium had a larger impact on the nebula's structure. A large fraction of nebulae are bipolar. Bipolarity is seen either as an hourglass shape like in $\eta$ Car (Weis 2001) and HR Car (Weis *et al.* 1997), or bipolar attachments—*caps*—as in WRA 751 (Weis 2000) or R 127 (Weis 2003). At least $\eta$ Car and P Cyg show several distinct nebula parts, the *outer ejecta*, *Homunculus*, and *Little Homunculus* for $\eta$ Car and the inner and outer shell of P Cyg. A current statistic of the morphology of the nebulae (Tab. 1) yields that about 50% are bipolar, 40% spherical and only 10% are of irregular shape. Taking only the Galactic objects into account bipolarity increases to 75% !

**Size:**

The smallest LBV nebula, diameter of $\sim 0.2\,\mathrm{pc}$, surrounds HD 168625 (Fig. 1). The Homunculus and inner nebula of P Cyg are comparable in size. Sk $-69^\circ$ 279 (Fig. 1) has with diameter of 4.5 pc or $4.5\,\mathrm{pc}\times 6.2\,\mathrm{pc}$ including its outflow the largest nebula. Typical sizes of the nebulae are about 1-2 pc (Tab. 1). A collage of the LBV nebulae drawn to scale is given in Fig. 3. It visualize that all LMC nebulae are larger as the Galactic. This may be due a detection problem caused by the lower resolution ($1\,\mathrm{pc} \sim 4''$).

**Kinematics:**

So far, with the exception of $\eta$ Car, expansion velocities for LBV nebulae have been determined through radial velocities (as in Tab. 1). The slowest expansion velocity, $14\,\mathrm{km\,s^{-1}}$, is detected in Sk $-69^\circ$ 279 the physically largest nebula. Including $\eta$ Car, the largest expansion velocity is detected in the outer ejecta with $3200\,\mathrm{km\,s^{-1}}$ (Smith & Morse 2004). Otherwise P Cyg (140 and $185\,\mathrm{km\,s^{-1}}$, inner and outer shell respectively) and HR Car

**Table 1.** Parameters of LBV nebulae in the Milky Way and LMC. Slashes separate values for nebula that consists 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), Weis (2003).

| LBV | host galaxy | maximum size [pc] | radius [pc] | $v_{\rm exp}$ [km/s] | kinematic age [$10^3$ yrs] | morphology |
|---|---|---|---|---|---|---|
| $\eta$ Carinae | Milky Way | 0.2/0.67 | 0.05/0.335 | $300^*/10 - 3200$ | | bipolar |
| AG Carinae | Milky Way | $1.4 \times 2$ | 0.4 | $\sim 25^*$ | $\sim 30$ | bipolar |
| HD 168625 | Milky Way | $0.13 \times 0.17$ | 0.075 | 40 | 1.8 | bipolar ? |
| He 3-519 | Milky Way | 2.1 | 1.05 | 61 | 16.8 | spherical/elliptical |
| HR Carinae | Milky Way | $0.65 \times 1.3$ | 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 | $0.8 \times 1.2$ | 0.5 | 60 | 8.2 | spherical |
| Sher 25 | Milky Way | $0.4\times1$ | $0.2\times0.5$ | $30 - 70$ | $6.5 - 6.9$ | 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 $-69^\circ$ 279 | LMC | $4.5 \times 6.2$ | 2.25 | 14 | 157 | spherical/outflow |

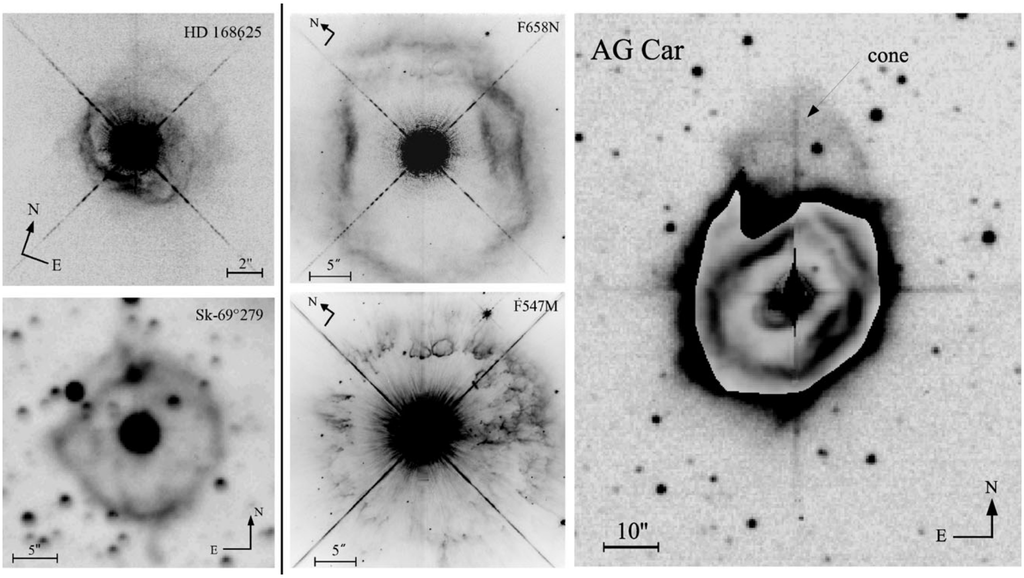

**Figure 1.** *Left section:* On top a HST image of HD 168625 the smallest and below a ground based frame of Sk −69° 279 the largest nebula. *Right section:* AG Car HST images in the F658N filter showing [N II] emission and the F547 frame with scattered light from dust. A deep [N II] ground based image shows the fainter (including the cone) and superimposed the brighter emission.

(75 km s$^{-1}$) hold the record. More typical or average values lie around 50 km s$^{-1}$. LBV nebulae in the LMC, compared to the Galactic, have on average a slower expansion velocity. Some nebulae do show outflows or regions that move faster than the main body. S 119 has an outflow which moves with 140 km s$^{-1}$ but the expansion velocity is only about 25 km s$^{-1}$ (Weis, Duschl & Bomans 2003). Bipolarity of the nebulae is also detected kinematically. The hourglass shaped nebulae reveal two expansion ellipses one for each of the two lobes (e.g. HR Car). Nebulae that own their bipolar appearance to attached caps (e.g. WRA 751) have a redshifted and an antipodal blueshifted cap.

## 3. AG Carinae

Fig. 1 shows HST- and ground based images of the nebula of AG Car. The new deep image at the right reveals a total extend of 1.4×2 pc. Compared to earlier measurements it nearly doubled in size! Our analysis of long-slit echelle observations shows the presence of two expansion ellipses, manifesting a blue and a redshifted shell which are spatially superimposed (with the redshifted shell shifted to the north-east), proving a bipolar nebula. A large, cone shaped structure is part of the redshifted shell. The nebula is consequently larger and bipolar, with two distinct shells (Weis & Duschl in prep.).

## 4. The case of bipolarity

A significant fraction, about 50%, of the nebulae are bipolar—both in morphology and kinematics. Bipolarity appears as hourglass shaped structures or is seen in attached caps. Both types of bipolarity are confirmed kinematically. It is worth noting that also Planetary Nebula do show the same types of bipolar morphologies! The PN Hubble 5 (alias Hb 5, see e.g. Corradi & Schwarz (1993)) looks indeed like a tiny twin to the Homunculus, while the Cat's Eye nebula (NGC 6543, e.g. Balick & Preston 1987) is similar to R 127. In

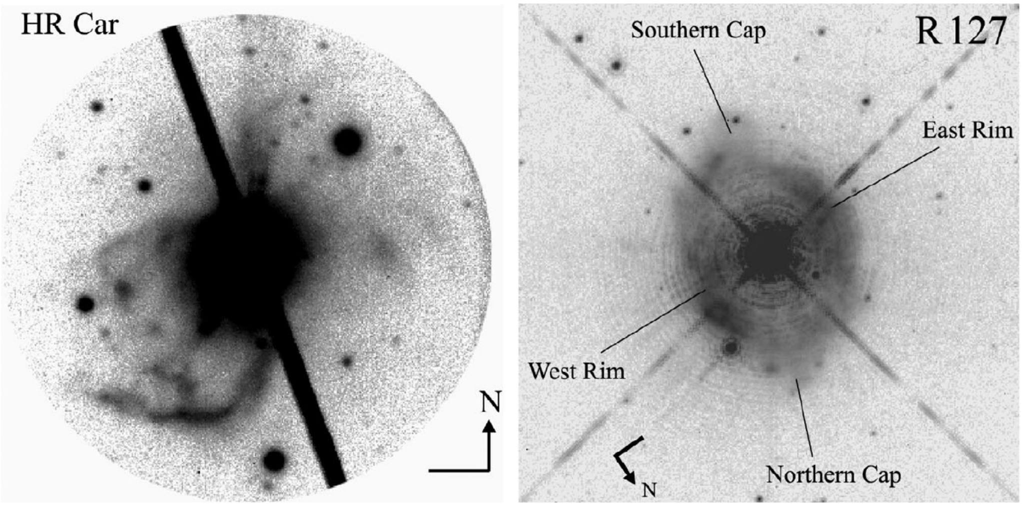

**Figure 2.** Two of a kind. The bipolarity in LBV nebulae is manifested either as in classical hourglass shapes like seen here in HR Car (left, Weis (2001)) or in bipolar caps that are attached to the main body of the nebula as in the case of R 127 (right, Weis 2003) .

general there is a large similarity of the morphologies and kinematics of LBV nebulae and PNs, implying, at least to some degree, the same physical—hydrodynamical—scenario for their formation, as for example discussed in Frank (1999).

Which physical processes would help to make bipolar LBV nebulae? Among the most natural mechanism is rotation and/or the formation of an equatorial density enhancement (maybe disk) or gradient either by the stellar wind or the ISM. Different mass loss phases in which the wind changes from equatorial to polar like during the passage of the bistability jump could do it, as it should be the case as the LBV passes through an S Dor cycle. Binary evolution may provide a scenario for forming a preferentially bipolar structure. What may prevent a bipolar structure? A very dense and/or turbulent ISM might suppress or destroy a bipolar shape originally inhibited. Does metalicity play a role? Connected to that: Why is the percentage of bipolar LBVs higher in the Milky Way as in the LMC? Metalicity decreases the mass loss rate for line driven winds, it may also have an effect on the bistability jump (change of mass loss from polar to equatorial)! With a lower metalicity, the effect could be weaker and the change of the orientation of the wind be not as strong and yield fewer/weaker bipolar structures in the LMC. Any hints on which scenario works? For at least two objects, AG Car (see previous chapter) and HR Car (Weis *et al.* (1997)) there is a good indication that the bipolar nebulae might be the result of rotation, as both stars have been identified as fast rotators (Groh, Hillier & Damineli (2006) and Groh *et al.* (2009)).

## 5. Summary and Conclusions

Now, what is already known, what has to be done and what is striking?

**To know list:**

LBV nebulae show a large range of shapes and sizes. Regarding their morphology about 50% are bipolar. Bipolar is popular ! Several are spherical, some do show an outflow structure and only one so far is irregular. The average size of a LBV nebula is 1-2 pc, and at least for now none is larger than about 5 pc. Typical expansion velocities of LBV nebulae are of the order 50 km $s^{-1}$ but can be as low as a few km/s and as high as several

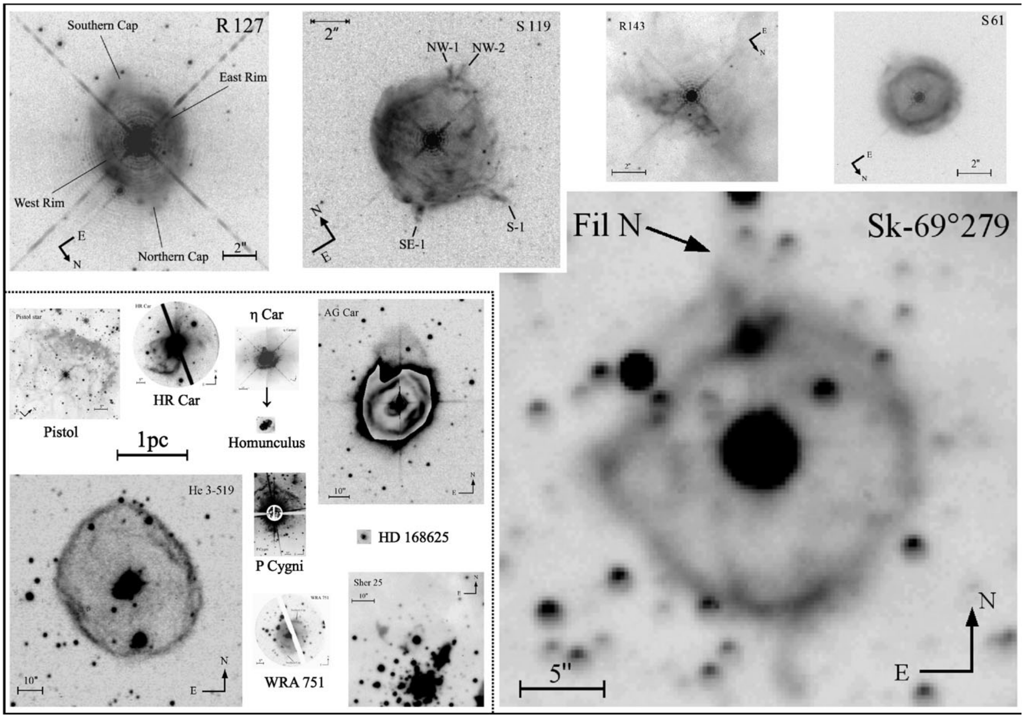

**Figure 3.** Resolved Galactic and LMC LBV nebulae drawn to scale. All images, except for the Pistol star, are taken either with an $H_\alpha$ or [N II] filter. Galactic nebulae are concentrated in the lower left section, within the dashed line.

thousand ($\eta$ Car). The kinematic ages are for most of the nebulae several thousand years and therefore well within the expected duration of the LBV phase. The LBV nebulae in the LMC are larger and expand slower, compared to those in the Milky Way.

**To do list:**

Are all nebulae created equal, or are some the result of wind-wind interaction while other have been created by eruptions? With only two LBVs with nebulae known to have had a giant eruption ($\eta$ Car, P Cyg), that question is hard to answer. Given the large kinematic ages, other LBV nebulae could have been formed in an eruption that has not been observed. Finding many bipolar nebulae we need to ask: How far does fast rotation play role? At least for AG Car and HR Car this seems to be the case. Therefore it is of interest to check other LBVs with bipolar nebulae, also to figure if the two types of bipolarity (hourglass and caps), results from stars with a higher and slower rotation rate.

**To wonder list:**

Finally why do not all LBVs do have a nebula? Do LBVs need to pass at least one cycle of the S Dor variability, switching from a hot to cool to hot phases, to form a nebula? Are different wind phase (keyword: bistability jump) responsible for the nebulae to form? Is this effect weaker in the more metal poor galaxies (lower Z) and might prevent the formation of LBV nebulae at all? And/or is it the proximity of the stars to the instability limits ($\Omega$- or $\Gamma$-limit)? Are the nebulae formed by instability and ejection, rather than a continuous hydrodynamic processes? At least for $\eta$ Car this seems a likely scenario. What forms LBV nebulae? Wind-wind interaction, instability and eruptions or are all scenarios possible and if differentiable?

**L**uminous **B**lue **V**ariables are stars that show a **L**arge **B**ipolar **V**ariety in their nebula. Rotation, binarity, eruptions and the bistability jump are likely origins for the formation of these geometrically distinct structures. Which scenario holds?

**...the answer my friend is blowing in the wind...**

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## Discussion

Meynet: LBV phenomena can arise from a relative broad range of initial mass stars. Is there any trend of the frequency of bipolarity with mass/luminosity?

Weis: So far I do not see a clear trend. Bipolar nebula are found around very massive/luminous LBVs (e.g $\eta$ Car and AG Car) as well as around lower mass and less bright LBVs (e.g. HR Car). There is also not a difference concerning hourglass shaped and bipolarity due to caps (R 127 is massive/luminous and WRA 751 fainter and less massive).

Prinja: You presented an interesting analogy between LBV nebulae and PN—in PN, binaries may be very important in sculpting the nebulae (during the commen envelope phase)—so to what degree do you think binarity may dominate in the formation of bipolar nebulae in LBVs?

Weis: Currently I know only two LBVs for which a binary scenario has been invoked, that is $\eta$ Car and HD 5980. All others and therefore all other bipolar nebulae result from apparently single stars.

Smith: You showed a faint outer shell around AG Car. What is the kinematic age of this outer shell, and what is the age of the previously known inner shell?

Weis: There is not an inner and an outer shell. The fainter emission detected further out is only an extension of the nebula. It is not an additional outer structure or new nebula but an attached feature. Therefore there is only one kinematic age indicated in my table.