LBV and WR nebulae in and beyond our Galaxy

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Luminous Blue Variables – characteristics and definition

> I shall refer to the non W-R or "other," hot stars as "luminous blue variables," or LBV, in my talk.

With that remark during a talk in 1984, Peter Conti induced the term LBVs more or less ad hoc. He expicitily excluded main-sequence and Wolf-Rayet star and by chance united the already know classes of S Dor, P Cygni and Hubble Sandage Variables into one, the LBV class. This rather vague original definition of LBVs has changed over time…indeed several characteristics exit, to pin point an LBV ... ☺

LBVs are luminous evolved stars that show unique photometric and spectral variabilities !

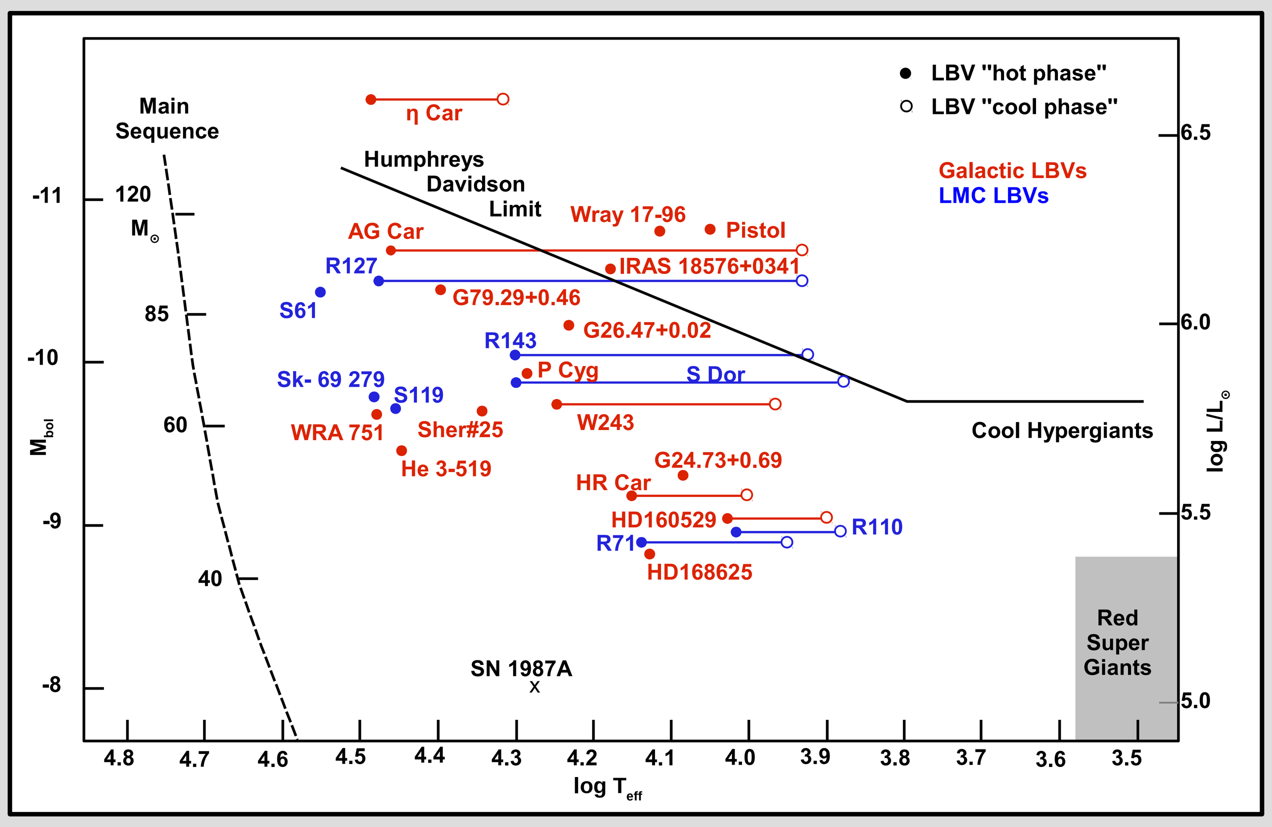


Fig1.: HRD with hot and cool phase position of Galactic and LMC LBVs. The main- sequence, RSG and cool hypergiant regions are plotted as reference. Figure adapted from Weis & Duschl (2002)

S Dor variability or **S Dor cycle :**
Within a **few years to decades by enlarging and shrinking the radius the spectral type of an LBV changes** from O-B to A-F and back. Changing to an A-F spectrum causes a increase in the V magnitude (typically below 1^{mag}) and a redder B-V color. In one cycle the star moves accross the HRD from a "hot" to a "cool" and back to the "hot" phase (Fig. 1). Doing so the stellar wind changes from a fast, low density wind (hot) to a slower optically thick wind (cool). Variations of the wind density and velocity gives rise to wind-wind interactions and can lead to the formation of circumstellar LBV nebulae.

Giant eruption:
Significantly larger photometric variations occur during a **giant eruptions outburst**. The brightness of an LBV increases spontaneously by **several magnitudes** and larger amounts of mass are ejected within a few years. **LBV giant eruptions** have been **mistaken** for **supernovae** (e.g. SN1954J) !

> Remember what is said about ducks:
> it may look like a duck, walk like a duck, but is not a duck until it quacks².
> quack

With that remark during a talk in 1997, Bruce Bohannan stated that **LBVs can be distinct** from **other** hot or cold massive stars, by seeing it quack. **The quack being an S Dor cycle or giant eruption.**

Evolutionary state:
LBVs are **evolved massive stars** in **transition** from the main sequence to Wolf-Rayet stars. Observations and theoretical stellar evolution models which include rotation (Maeder et al. 2005) find LBVs to stars with an initial mass **as low** as **M_{ini} ~ 22 $M_\odot$ up to 120 $M_\odot$.**

$M > 90 M_\odot$:	O - Of - WNL - (WNE) - WCL - WCE - SN (Hypernova low Z ?)
$60 - 90\ M_\odot$:	O - Of/WNL< – >LBV - WNL(H poor)- WCL-E - SN(SNIIn?)
$40 - 60\ M_\odot$:	O - BSG - LBV < – > WNL -(WNE) – WCL-E - SN(SNIb)
	- WCL-E - WO SN (SNIc)
$30 - 40\ M_\odot$:	O - BSG - RSG – WNE - WCE - SN(SNIb)
	OH/IR < – > LBV ?
$25 - 30\ M_\odot$:	O -(BSG)- RSG – BSG (blue loop) – RSG – SN(SNIIb, SNIIL)
$10 - 25\ M_\odot$:	O - RSG - (Cepheid loop, $M < 15\ M_\odot$) RSG – SN (SNIIL, SNIIP)

Tab.1: Taken from Maeder et al. (2005), this tables illustrates the various ways how stars may evolve and enter the LBV and WR phase.

LBV nebulae … bipolar jewels

Circumstellar LBV nebulae are created either by the **wind-wind interaction** of faster and slower wind phases during the LBV phase or via the **ejection of outer layer of the star during a giant eruption.**

All LBV nebulae show a **stronger [N II] emission**, as CNO processed material is mixed up and peeled off by stellar winds or in a giant eruption. Fig. 3 shows the images of the galactic and LMC LBV nebulae, their basic values are listed in Tab. 2. Bipolar morphology appears either in a typical hourglass shape like the Homunculus around η Car (Fig. 2) or as bipolar attachments (caps) (e.g. R 127, Fig. 3).

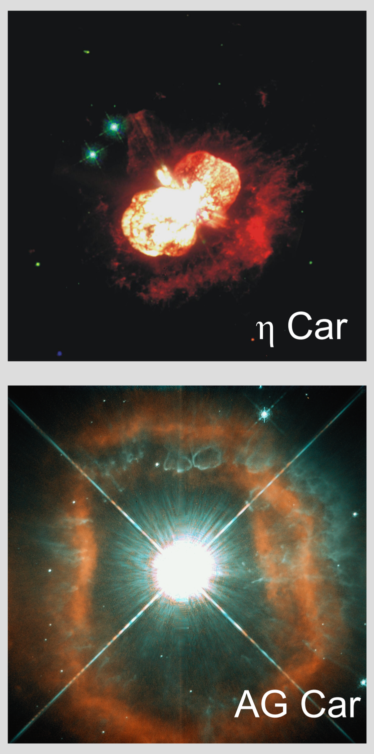
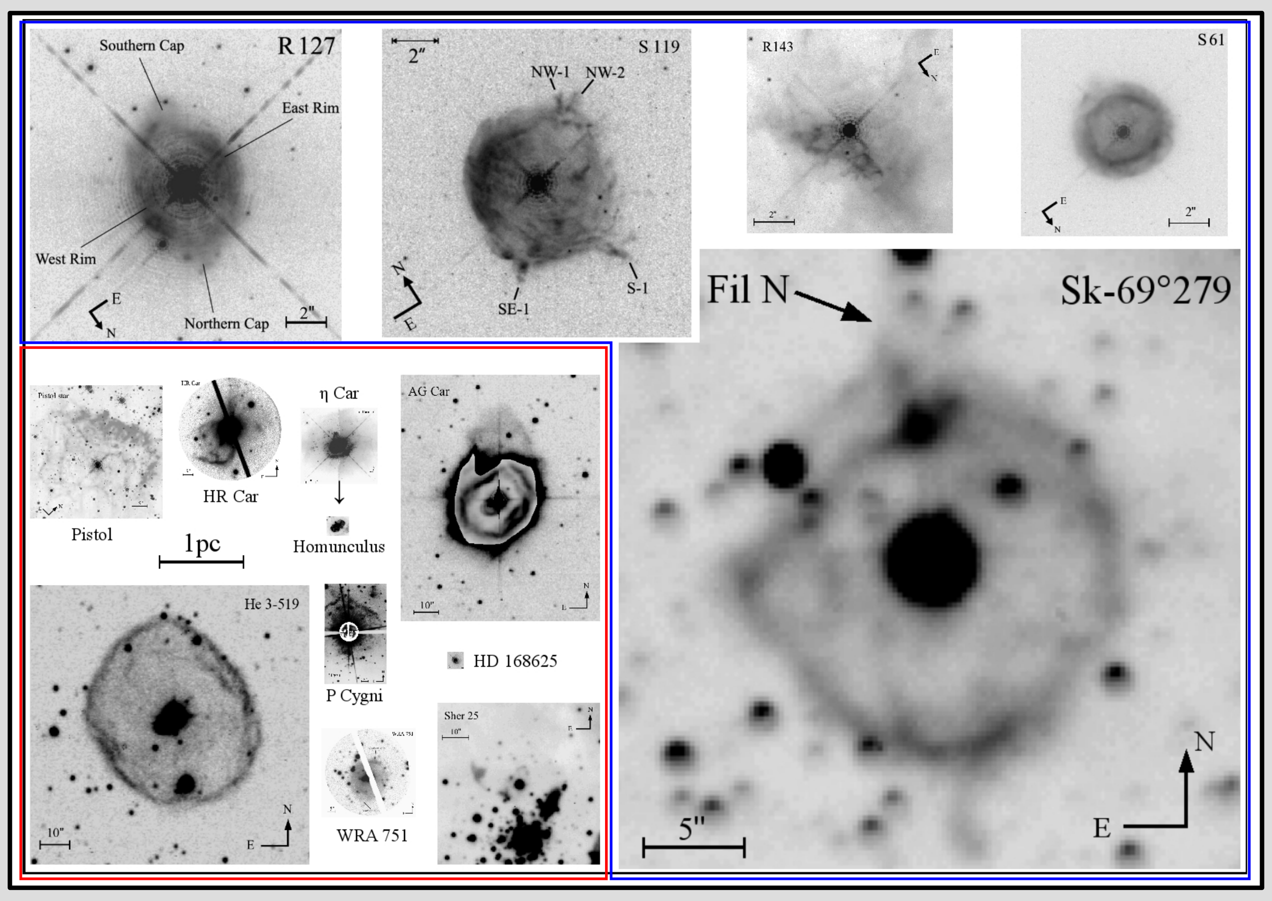


Fig.2: HST images of two bipolar LBV nebulae (from Weis 1999, 2011).

Galactic LBV nebulae (excluding η Car)
- **Size:**
  0.15-2 pc, average ~ 1 pc
- **Morphology:**
  33% spherical/elliptical
  0% irregular
  67% bipolar
- **Expansion velocities:**
  25-150 km/s

LMC LBV nebulae
- **Size:**
  0.82-6.2 pc, average ~ 2.1 pc
- **Morphology:**
  50% spherical/elliptical
  25% irregular
  25% bipolar
- **Expansion velocities:**
  12-27 km/s

Galactic versus LMC LBV nebulae: Comparing Galactic and LMC nebulae indicates that LMC nebulae are generally larger and expand slower. The **fraction of bipolar nebulae** is **larger** among **galactic LBVs**, in the LMC so far only shows R127 bipolarity.



↑ **Fig.3:** Galactic and LMC nebulae on scale

↓ **Tab.2:** Sizes, expansion velocities, ages and morphologies of LBV nebulae

LBV	host galaxy	maximum size [pc]	radius [pc]	v_{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	~ 25*	~ 30	bipolar
HD 168625	Milky Way	0.13 × 0.17	0.075	30	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

(tabel & figure Weis 2012)

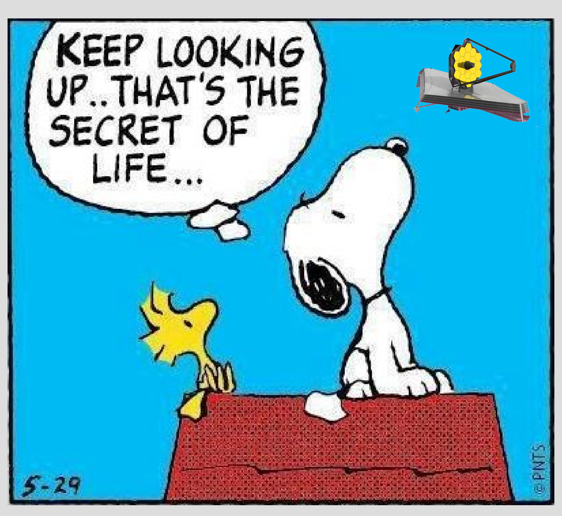
Why are there many bipolar LBV nebulae ?

Looking at the **morphology** of **LBV nebulae** it is obvious that a **significant** fraction of LBVs are **bipolar**, for the galactic LBVs its as high as **67%**. One clue for that high rate of bipolarity comes from that fact that LBVs can show a large rotation. **Large rotational** velocities are reported for AG Car (Groh et al. 2006) and HR Car (Groh et al. 2009), both with bipolar nebulae. Strong mass loss, the stars proximity to stability limits, either **Eddington** or **ΩΓ-limit**, and a high rotation yields ideal conditions to form and **favor bipolar nebulae !!!**

LBV nebulae … what JWST can do?

LBVs are known in many other local group galaxies and as far out as M101 (about 7 Mpc). A large sample of LBVs (the former Hubble-Sandage Variables) are in M33 and M31, the only other spiral galaxies in the Local Group host LBV stars . With distances of 850 kpc (M33) and 773 kpc (M31) LBV nebulae, assuming similar sizes as in the Galaxy and LMC, are **½ to 1"** large. So a direct search for nebulae is not possible, but we find hints for nebular emission from [NII] lines (5755, 6543, 6583Å) in MMT spectra and IFU data from different telescopes.
Even short observations with the JWST/NIRCAM however would give way to direct imaging of these nebulae.Using Pα (F187N) images LBV nebulae with a size of 0.15" can be resolved, maybe even smaller with an adeqate PSF substraction. Assuming a typical radius of 2pc LBV nebula could be detected in galaxies out to a distance 1.5 to 4 Mpc.

Fig.4: M33 host of many LBVs and LBV candidates. (figure Burggraf et al. 2014)



Most important will be a rough estimate of the morphology of the nebulae. Is the large fraction of bipolar nebulae also present in other galaxies, or not. The numbers for the galactic and LMC bipolar nebulae show a lower value among the LMC, but with a rather small number statistics it is to early to draw a good conclusion, whether or not a lower metalicity could play a role.

Observations of LBV nebulae with the JWST in galaxies beyond the LMC will significantly change our understanding of the LBV phase and the formation of LBV nebulae. It will contribute to the identification of what physical mechnism causes the S Dor variability and which instabilities drives the really energetic the giant eruption !