LBV nebulae in the Local Group

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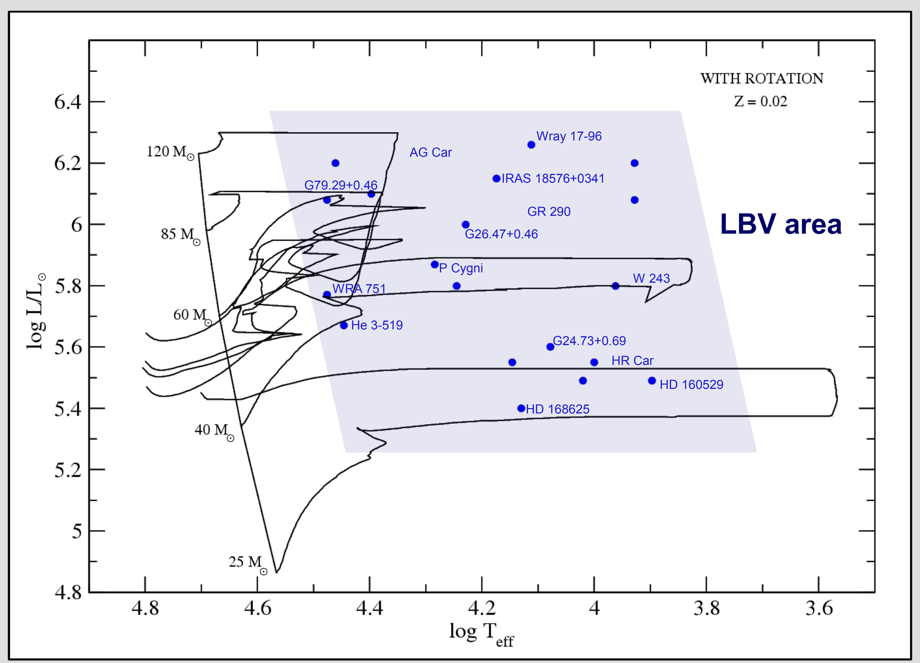


Fig.1: HRD with Geneva tracks (with initial v = 300 km/s) and positions of LBVs (for some in both their hot and cool phase).

$M > 90 M_\odot$:	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 enter the LBV and WR phase.

A LBV primer

Massive stars, Luminous Blue Variables and Wolf-Rayet star

According to our current understanding of stellar evolution (e.g. Geneva models, with rotation ↔ Tab. 1 & Fig. 1), massive stars – depending on their initial mass, metalicity and rotation – may enter after their main-sequence phase an unstable phase and turn into **Luminous Blue Variable stars (LBVs)**. Independently, all stars above 30 $M_\odot$ will enter the **Wolf-Rayet (WR)** phase.

LBVs and their nebulae

LBVs, as the name indicates, are characterized by being luminous stars with photometric and spectral variabilities on various timescales and magnitudes. A variability intrinsic to LBVs, is the S Dor variability (e.g. van Genderen 2001) where changes in temperature (hot O-B to cooler A-F) and radius occur with a few years (→ Fig. 1 for the LBVs in the HRD). LBVs might undergo a giant eruption, shedding larger amounts of mass and increasing their brightness spontaneously by several magnitudes. While LBVs do show certain characteristics, still no clear classification scheme exists, to uniquely categorize a star as a LBV, in contrast to e.g. Wolf-Rayet stars. Therefore all new candidates are addressed by a slightly modified:

To be or not to be a LBV? ☺

The large mass loss of LBVs leads to the **creation** of **circumstellar LBV nebulae** by

a) wind-wind interaction of faster and slower wind phases (LBV + MS wind or a cool+hot LBV phase)
b) the stellar ejecta of the star during a giant eruption

LBV Nebulae

Studying LBV nebulae within the Local Group is in so far limited to nebulae in the Milky Way and the LMC, as only in these galaxies nebulae are resolved spatially (no LBV nebula is known in the SMC). Typical for all nebulae is a **strong [NII] emission** (→ CNO processed material). Further characteristics are (→ Fig. 4, Tab. 2):

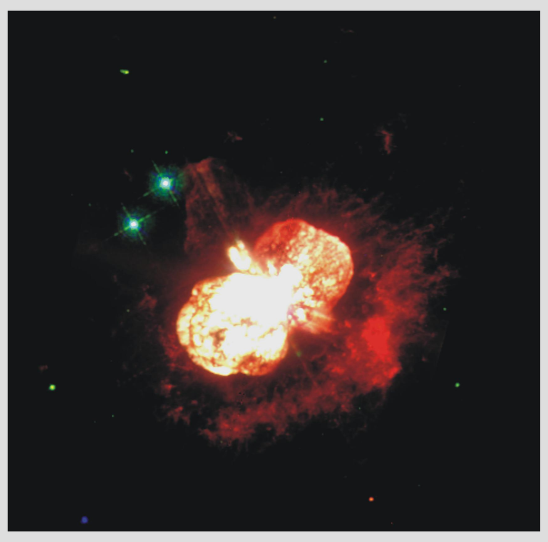


Fig.2: HST color image of the bipolar Homunculus nebula around η Car (Weis 1999).

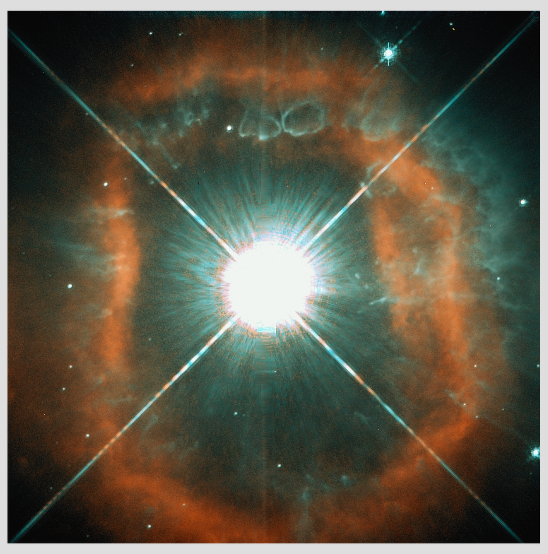


Fig.3: HST color image of the bipolar nebula around AG Car (Weis 2011).

Morphologies & Sizes

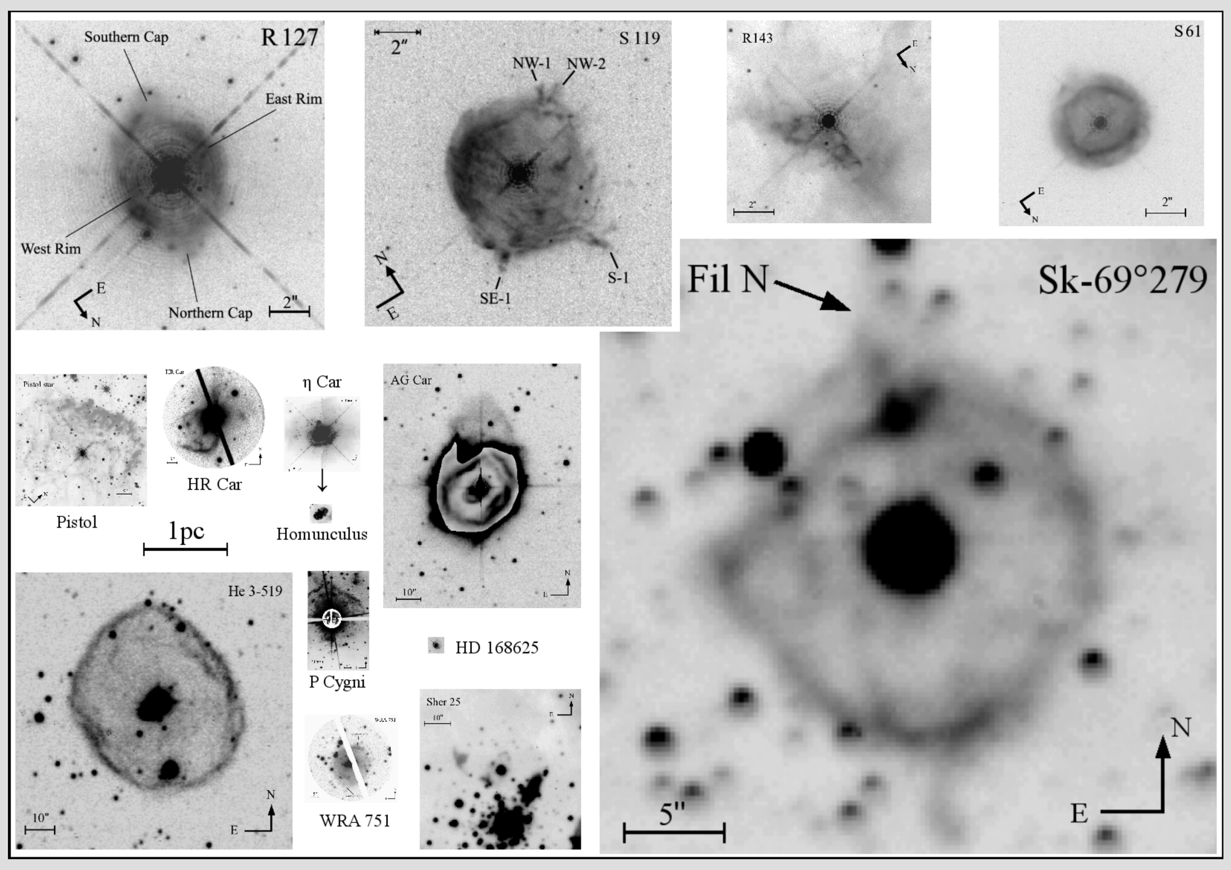
- morphologies range from **spherical** (S61) and **elliptical** (He 3-519), to one **irregular** object (R143)
- a **significant** number is **bipolar** or **hourglass** shaped like η Car and HR Car, or reveal **bipolar components** like the caps in R 127 and WRA751
- **a statistical** analysis of all resolved nebulae (Fig. 4) shows a distribution of **50% bipolar**, **40% spherical/elliptical** and **10% irregular**
- the maximum **sizes** of LBV nebulae roughly range between **0.1 to 5 pc** with an **average** around **~1.3 pc**
- the, with **0.13pc× 0.17pc**, **smallest** nebula surrounds galactic star **HD 168625**
- by far the **largest** nebula is detected around the LMC star **Sk-69°279** and has a size of **4.5pc× 6.2pc** (including the filament N)

Kinematics

- expansion velocities range between **20-150 km/s**
- η Car is exceptional, with velocities of **600 km/s** (Homunculus) and **3200 km/s**

Comparing Galactic & LMC LBV nebulae

- **LMC nebulae** are on average **larger** as those in the Milky Way
- the **expansion velocities** of **LMC nebulae** is on average **smaller**
- the fraction for bipolar nebula is **75%** for **galactic** and only **20%** for the **LMC**



↑ **Fig.4:** Galactic and LMC nebulae on scale

↓ **Tab.2:** Locations, 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

AG Carinae: Bigger, Better, Bipolar!

Weis & Duschl 2012 in prep

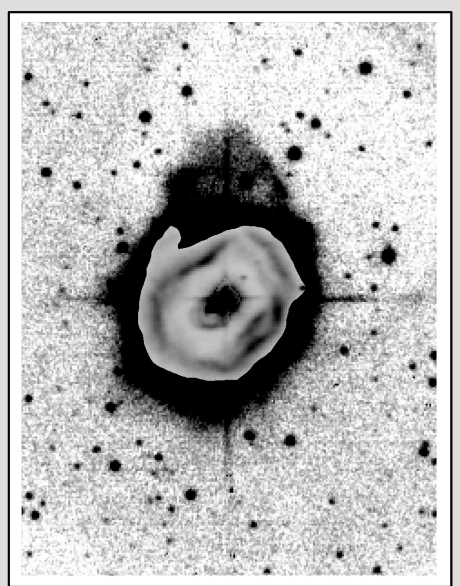


Fig.5: Composite-[NII]-image (short and long exposure)

Morphology & Size

HST (see Fig. 3)
- elliptically+quenched shaped ring, size 40"x30" (1.2pc x 0.9pc)
- half-shell is present south-west side
- arm like extension to the north-east, length 20" (0.6pc)

CTIO (see Fig.5)
- further **faint** emission is detected **in all directions**
- the arm-like extension is part of a larger cone like filament
- the nebulae **size increases** to **70" x 50" or 2pc x 1.4pc**
- the total length of the arm + cone filament **is 1.4pc**

Kinematics

- **two shells** one approaching, a second receding → it manifests a **bipolar structure**
- shells are superimposed in line of sight, with the receding shell offset to the east
- the expansion ellipses as derived from longslit spectra (→ Fig. 6) shows **expansion velocity** of **25 km/s** for the **approaching shell** and **27 km/s** for the **receding shell**
- the cone is part of the receding shell but moves **100 km/s faster** (in reference to the center)

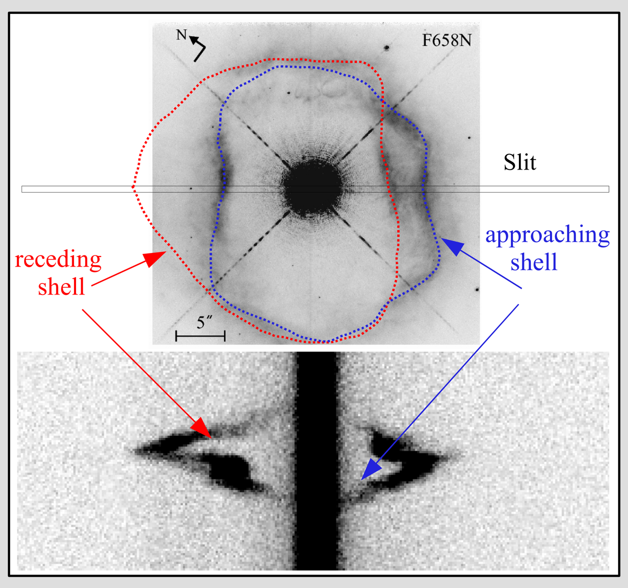


Fig.6: Combination of a HST F658N image (top) and an echellogram (bottom, [N II] line).

LBV nebulae – near and far

Results for the LMC & Milky Way sample

Clues on the differnt sizes, expansion velocities and morphologies

- **size & expansion velocities**

→ might result from the lower metalicity in the LMC
↔ to some degree, i.e. line driven winds, lower wind velocities
↔ difference in the underlying instabilities for giant eruptions
→ environmental differences, medium of lower and higher density ?
↔ LBVs are in both galaxies in regions covering high and low density

- **morphologies**

→ as analysis for AG Car and HR Car, both bipolar nebulae show a high stellar rotation could be accounted for the bipolarity
↔ higher on average stellar rotation favors bipolarity
↔ fits to the fact that LMC B supergiants show a lower rotation rate as expected from theory (Hunter et al. 2008)

Digging even deeper and further

To extend our knowledge of LBVs (nebulae) and study the role of metalicity on winds and eruption mechanism our analysis was extended to other galaxies in the local group and beyond

- **local group**

→ indications for LBV nebulae were seen in images or spectra of M31 (Massey 2006), M33 (Fabrika et al. 2002) and IC 10 (Bomans & Weis in prep).

- **beyond the local group**

→ extended emission was detected for the LBV V37 (=SN2002kg , Weis & Bomans 2005), and the supernova impostor in NGC 3109 (Bomans et al. 2012, in print)