Wolf-Rayet Stars
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Family ties of WR to LBV nebulae yielding clues for stellar evolution

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Luminous Blue Variables (LBVs) are stars is a transitional phase massive stars may enter while evolving from main-sequence to Wolf-Rayet stars. The to LBVs intrinsic photometric variability is based on the modulation of the stellar spectrum. Within a few years the spectrum shifts from OB to AF type and back. During their cool phase LBVs are close to the Humphreys-Davidson (equivalent to Eddington/Omega-Gamma) limit. LBVs have a rather high mass loss rate, with stellar winds that are fast in the hot and slower in the cool phase of an LBV. These alternating wind velocities lead to the formation of LBV nebulae by wind-wind interactions. A nebula can also be formed in a spontaneous giant eruption in which larger amounts of mass are ejected. LBV nebulae are generally small ($< 5\,\mathrm{pc}$) mainly gaseous circumstellar nebulae, with a rather large fraction of LBV nebulae being bipolar.

After the LBV phase the star will turn into a Wolf-Rayet star, but note that not all WR stars need to have passed the LBV phase. Some follow from the RSG and the most massive directly from the MS phase. In general WRs have a large mass loss and really fast stellar winds. The WR wind may interact with winds of earlier phases (MS, RSG) to form WR nebulae. As for WR with LBV progenitors the scenario might be different, here no older wind is present but an LBV nebula! The nature of WR nebulae are therefore manifold and in particular the connection (or family ties) of WR to LBV nebulae is important to understand the transition between these two phases, the evolution of massive stars, their winds, wind-wind and wind-nebula interactions. Looking at the similarities and differences of LBV and WR nebula, figuring what is a genuine LBV and WR nebula are the basic question addressed in the analysis presented here.

1 Massive stars, LBVs and WRs

Nearly all massive stars will turn into *Wolf-Rayet (WR)* stars at the end of their life. The WR star population spans an initial mass range of stars as low as $20\,\mathrm{M}_\odot$ to stars above $90\,\mathrm{M}_\odot$. Several evolutionary scenarios are proposed that lead to WR stars. One found and published by Meynet & Maeder (2005) is valid for stars with a rotation of $\mathrm{v_{ini}} \sim 300\,\mathrm{km/s}$ and will be be used here to put WR stars in context to other evolutionary phases.

M>90 M$_\odot$:
O–Of–WNL–(WNE)–WCL–WCE–SN
M = 60–90 M$_\odot$:
O–Of/WNL–LBV–WNL(H poor)–WCL-E–SN(SNIIn?)
M = 40–60 M$_\odot$:
O–BSG–LBV–WNL–(WNE)–WCL-E–SN(SNIb)
alternative way:
O–BSG–LBV–WCL-E–WO–SN(SNIc)
M = 30–40 M$_\odot$:
O–BSG–RSG–WNE–WCE–SN(SNIb)
alternative way:
O–BSG–OH/IR–LBV–SN(SNIb)

In several cases the WR phase is reached after the star was an *Luminous Blue Variable (LBV)*. The term LBV was introduced by Peter Conti rather ad hoc during a conference, stating that: "…I shall refer to the non W-R or other, hot stars as luminous blue variables, or LBV, in my talk..." (Conti 1984). Obviously not planned as a real definition but rather an easy reference for a diverse group of stars, this comment unified the already known Hubble-Sandage and S Dor variables, with the P Cygni and η Car type stars into one new class: the LBVs. It also explicitly excluded Wolf-Rayet stars from this group.

2 LBVs and LBV nebulae

Since then the LBV group has grown considerably and a clear definition of the term and class has been established. Luminous and blue are qualifications many massive stars possess, but variability is a or rather **the** key to identify LBVs. Two very distinct types of variability are known for LBVs.

The so called *S Dor variability* or S Dor cycle is a combined photometric and spectroscopic variation, see for example van Genderen et al. (1997); van Genderen (2001). During the S Dor cycle the star changes its radius and thereby spectrum. It moves from a hotter (visibly fainter) phase to a cooler (visibly bright) state and finally closes the cycle by returning to the hot (visibly faint) regime. During such a cycle the spectrum changes, as does the brightness in the visual regime of the light curve. This simultaneous change of visual brightness and stellar spectrum is observed in LBVs only. Even more energetic events are the *Giant Eruptions*. Here the visible brightness increases spontaneously by several magnitudes (Humphreys et al. 1999). Best known and well documented is the giant eruption of

η Carinae (in 1843), other giant eruptions are those of P Cygni, SN1961V, SN1954J. While LBVs have multiple S Dor cycles on very various timescales, spanning a few years to decade (van Genderen 2001) it is not clear if an LBV can undergo more than one giant eruption. LBVs can show one or both of these variations, but the detection of one is already sufficient for a star to qualify as LBV.
In the wake of several SN search programs so called SN imposters are found. These are SN-like events that for one or the other reasons (brightness, spectrum, lightcurve) are not clearly a SN. Many of these are good candidates for being an LBV giant eruption. Note however that a giant eruption may look like a SN imposter but not all SN imposters may be giant eruptions.

LBVs have a large mass loss rate and by changing their spectra an alternation of fast and slow wind phases. This gives rise to wind-wind interaction of the older, slow and dense wind during the cool spectral phase with the fast, less dense wind shedded during the hot phase. This interaction and sweeping up of material can lead to the formation of small and dense LBV nebulae. Alternatively a nebula is created as mass and several layers of the stars envelope are be ejected during a giant eruption.

LBV nebulae are small circumstellar structures with sizes of a fractions to a maximum of a few parsec (Weis 2011, 2013). With these sizes so far only galactic and LMC LBV nebulae are resolved (there is no SMC LBV nebula). Galactic LBV nebulae are generally smaller than nebulae around LMC LBVs. All nebulae show a nitrogen enhancement from the CNO processed material they contained. Expansion velocities are generally between 10–100 km/s (Weis 2011), with one major exception — structures in the outer ejecta of η Carinae reach several 1000 km/s (Weis et al. 2004), maybe even above 3000 km/s (Smith & Morse 2004). The expansion velocities are larger for galactic and lower for LMC nebula. As for the morphology, a few are spherical, so far only one, the nebulae around R 143, is rather irregular (Weis 2011). Given the star is situated in the middle of 30 Dor region and therefore subject to larger turbulent motions of the surrounding gas, this shape is not too surprising (Weis 2003). An astonishingly large fraction (77% of the galactic and 24% of the LMC nebulae) are bipolar. Bipolarity is found either in hourglass shapes like the Homunculus around η Car or in attachments often dubbed caps to the main body that kinematically manifest bipolar features by expanding in opposite directions, see the galactic LBV WRA 751 or R 127 in the LMC (Weis 2000, 2003). LMC nebulae are larger, expand slower and have a lower rate for bipolar morphology compared to the galactic LBV nebulae. Several physical mechanism are likely that lead to bipolarity.

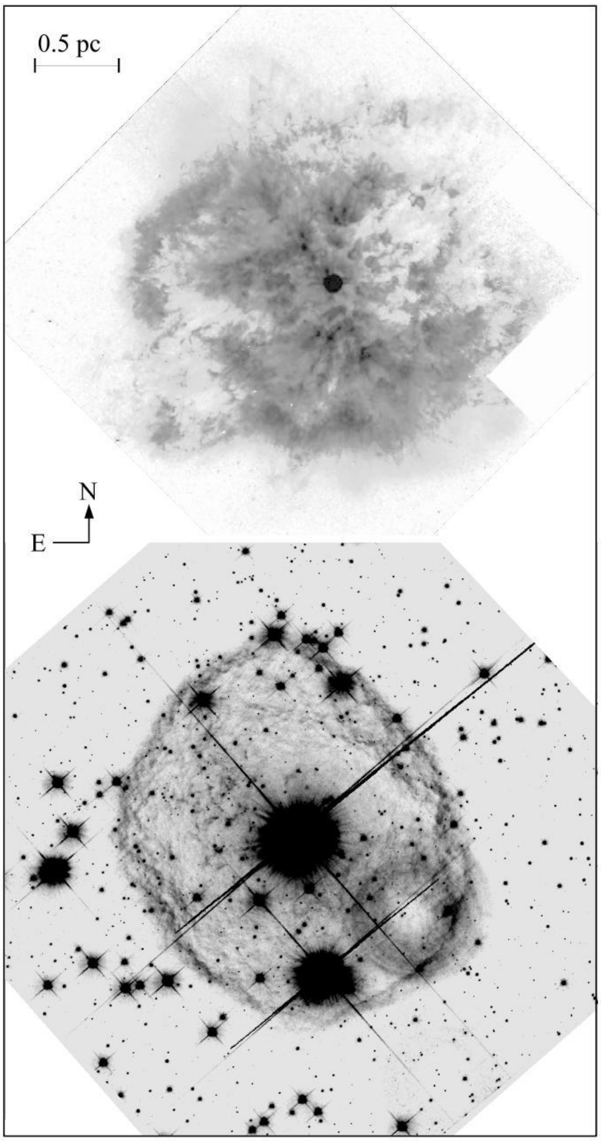

Fig. 1: The LBV nebulae around the Wolf-Rayet star WR 124 (top) and the LBV He 3-519 (bottom). A spherical structure SE of He 3-519 is caused by internal reflection in the instrument.

Promising scenarios are stellar rotation or a density gradient in the stellar wind. The latter might occur if the star passes the bistability limit (in a S Dor cycle) and the wind changes from polar to equatorial. Finally a binary system could do the job. There are two known LBV binaries, HD 5980 (Hoffman et al. 1978) and η Car (Damineli et al. 1997), but only one, η Car with a bipolar nebula, so this seems not the dominant process.

For at least two objects bipolarity can be linked to rotation. Both AG Car (Weis 2013, 2015) and HR Car (Weis et al. 1997) have bipolar nebulae and are fast rotators (Groh et al. 2006, 2009).

Are LBV nebulae formed via wind-wind interaction or eruptions? With the small sample of known giant eruption LBVs and nebulae formed thereby (2 known), it is currently hard to identify any differences in the scenarios. With the large kinematic ages of the known LBV nebulae ranging from 10^{3-4}yrs (Weis 2011) it also is not possible to exclude a giant eruption for all other LBVs since the eruption might have been several 1000 years ago and at that time was not observed or no records exits.

3 WR stars and WR nebulae

At the beginning it was shown that via various evolutionary scenarios nearly all massive stars turn into a WR star. Fast stellar winds ($>$ 1000–2000 km/s) during the WR phase will compress remnant wind material shed during the star's previous phases (MS, LBV or RSG) and eventually for a WR nebula. The sizes WR nebulae are on average around 20–50 pc, the morphology is mostly spherical, elliptical or irregular but rarely if any bipolar. The expansion velocities range between a 10–80 km/s (few above 100 km/s), with an average around 50 km/s. The LMC WR nebulae are smaller and somewhat slower compared to the galactic objects, the same trend as observed for LBV nebulae!

4 LBV and/or WR nebulae

The major, maybe even the only difference between LBV and WR nebula as it turns out, is the lack of bipolar WR nebulae. Indeed only one object, the nebulae M1-67 around WR 124 (Sirianni et al. 1998) has been reported to have a bipolar component!

WR 124 and the M1-67 nebula:
The top panel in Fig. 1 shows the central part of the HST image of the nebula. The size is only 2–3 pc, making it one of the if not the smallest WR nebula. Already Sirianni et al. (1998) noticed and recent work by Fernández-Martín et al. (2013) further supported that the nebula abundances are with a N over and O underabundance atypical. The most straight forward conclusion for these values is simply that the nebula was formed during the LBV phase of the star. M1-67 is therefore a bipolar LBV nebula around a retired LBV, now a Wolf-Rayet star (WN8). So the count for known bipolar WR nebula should be set back to zero!

He 3-519:
The LBV He 3-519 has with about 2 pc one of the largest galactic LBV nebulae. In an ongoing analysis I found from kinematics hints that beside the more spherical or elliptical shape from the images (see Fig. 1) a weak but noticeable bipolar structure is present. The size of the nebula, the weak photometric variability and the spectral type WN11, suggest that He 3-519 is an LBV currently in transition to the WR phase. It is an LBV on the way to retirement.

5 The family ties

The examples of WR 124 and He 3-519 show nicely the transition – or family ties – of LBV to WR stars. The nebulae analysis helped to pinpoint the evolutionary status of the stars, both spectral classification WN, even better. WR 124 is the older retired LBV, He 3-519 is on the way to retirement.

The major difference of LBV and WR nebula is the lack of bipolar WR nebula. With the only bipolar WR nebulae actually being an LBV or ex-LBV nebulae this difference is gone. With other rather good similarities this gives rise to speculate about a new scenario: WR nebulae being aged, inflated LBV nebulae.

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Jesús A. Toalá: If you take a look at the nebula around WR31a you will easily see that it is a bipolar WR nebula. Another WR nebula result of an LBV phase could be NGC2359 around WR7.

Götz Gräfener: Why is He3-519 classified as an LBV?

Kerstin Weis: While it is only slightly variable now (in van Genderen's classification = dormant) larger variability in the light curve is known from earlier observation. In my LBV definition term: it quaked.

Anthony (Tony) Moffat: Another indicator that WR124 in M1-67 may be at the beginning of its WR phase is that it is WN8h (as opposed to WN8o), implying that with relatively high H-abundance, it has just entered the WR stage.

Kerstin Weis: Thanks for the additional argument that is in well support of my scenario.

Anthony Marston: One note: LBV & WR nebulae basically form from LBV ejecta and should have similar metallicity. But WR stars show only ejecta nebulae in one third of the cases. Why might this be?

Kerstin Weis: In the WR phase, the strong stellar winds will act on the nebula. It will be inflated and the density decreases. So it might/will fall below the detection limit. Furthermore, not all WR stars are post-LBV objects.

Jose Groh: Are there estimates of nebular mass and dynamical age for WR124? In principle, the star would need to lose several $M_{\odot}$ to support the "retirement" scenario.

Kerstin Weis: The rough estimate I remember of the mass in the nebula as seen in the HST image (= the inner part) is around $1\,M_{\odot}$. The nebula however is much larger, so this is a lower limit, roughly consistent with what one expects.