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Review

Luminous Blue Variables

Kerstin Weis [1,*] and Dominik J. Bomans [1,2,3]

1 Astronomical Institute, Faculty for Physics and Astronomy, Ruhr University Bochum, 44801 Bochum, Germany; bomans@astro.rub.de
2 Research Department Plasmas with Complex Interactions, Ruhr University Bochum, 44801 Bochum, Germany
3 Ruhr Astroparticle and Plasma Physics (RAPP) Center, 44801 Bochum, Germany
* Correspondence: kweis@astro.rub.de

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Abstract: Luminous Blue Variables are massive evolved stars, here we introduce this outstanding class of objects. Described are the specific characteristics, the evolutionary state and what they are connected to other phases and types of massive stars. Our current knowledge of LBVs is limited by the fact that in comparison to other stellar classes and phases only a few "true" LBVs are known. This results from the lack of a unique, fast and always reliable identification scheme for LBVs. It literally takes time to get a true classification of a LBV. In addition the short duration of the LBV phase makes it even harder to catch and identify a star as LBV. We summarize here what is known so far, give an overview of the LBV population and the list of LBV host galaxies. LBV are clearly an important and still not fully understood phase in the live of (very) massive stars, especially due to the large and time variable mass loss during the LBV phase. We like to emphasize again the problem how to clearly identify LBV and that there are more than just one type of LBVs: The giant eruption LBVs or η Car analogs and the S Dor cycle LBVs.

Keywords: Luminous Blue Variables; giant eruption; massive stars; stellar population; Wolf-Rayet stars; Eddington limit; mass loss rate; nebulae of Luminous Blue Variable; Supernova impostors, bistability limit

1. Historic Background and Naming

Studying the brightest stars in M 31 and M 33 Hubble and Sandage [1] found irregular variable stars that defined a new object class: Var 19 in M 31 and Var 2, Var A, Var B and Vary C in M 33. The variability of Var 2 has been recognized already 1922 by Duncan [2] and 1923 by Wolf [3]. All irregular variable stars Hubble and Sandage found showed the three common characteristics: high luminosity, blue color indice and at the date of observation an intermediate F-type spectrum. Objects of this class became known as *Hubble-Sandage Variables*. In 1974 Sandage and Tammann [4] observed bright stars in NGC 2366, NGC 4236, IC 2574, Ho I, Ho II, and NGC 2403 originally to further constrain the Hubble constant using Cepheids. In some of these galaxies however they identified stars they designated as *Irregular Luminous Blue Variables*. At the same time Humphreys [5] published additional spectral analysis on the M 31 and M 33 Variables and put them into context to the η Carina-like objects. Few years later Humphreys and Davidson [6] studied our galaxy and the LMC and identified the most luminous and massive stars. In that work it became more and more obvious that a certain region in the HRD is not populated: very luminous cool stars seems to not exist or more likely stay for only for a very short time in this region. The boundary to that area was defined by the authors and has been referred to as the Humphreys-Davidson limit. Shortly after in his publication entitled "The stability limit of hypergiant photospheres" de Jager [7] was the first to addressed the presence of such a limit and related possible instabilities from a more theoretical perspective. His argumentation

was based on turbulent pressure initiating an instability. Lamers & Fitzpatrick [8] however showed in a 1986 publication that —as still accepted now—radiation and not turbulent pressure is the driver. This linked Humphreys and Davidson observations to the fact that stars will become unstable in this cool and luminous state.

The variability of S Doradus in the LMC was first notices by Pickering in 1897 [9], he also found the star to be bright in H_β, H_γ and H_δ. Later further studies of its variability [10] showed that S Dor characteristics are very similar to those of the Hubble-Sandage Variables. In our own galaxy, a class known as the P Cygni type stars also showed the same behavior. Note in that context that not all stars that show P Cygni line profiles were automatically members of this historically defined class. Humphreys noted already in her 1975 paper [5] that: "The spectral and photometric properties of these extragalactic variables suggest that they may all be related to stars like η Car in our Galaxy and S Dor in the Large Magellanic Cloud.". This hints to the fact that all are only samples of one larger class of variable stars.

In 1984 Peter Conti [11] used the term Luminous Blue Variable during a talk at the IAU Symposium 105 on Observational Tests of the Stellar Evolution Theory. Herewith he finally united—as Humphreys already suggested in her 1975 paper—the earlier defined stellar subgroups of Hubble-Sandage Variables, S Dor Variables, P Cygni and η Car type stars, and explicitly excluded Wolf-Rayet stars and normal blue supergiants from LBVs.

2. Characteristic of Luminous Blue Variables

The name already suggests that features that LBVs seem to have in common are being blue and luminous stars that are variable. This however is a rather weak constraint and not even true for a LBV all the time.

It is not simple to disentangle a LBV from a blue O B supergiant and even cooler supergiant of spectral type A of F. A significant number of LBVs have at least temporarily an Of/WN type spectrum [12,13], indicating the presence of emission line and in particular a larger amount of nitrogen in their photosphere. Others were detected with a Be or B[e] spectrum.

It is not possible to identify and classify an LBV by its spectrum or analog its color. It is the a specific variability or an eruption that distinguishes LBVs from "normal stars". The variability of LBVs is a combination of a photometric brightness and color change, caused and accompanied by changes in the stellar spectrum. During such a S Dor variability or S Dor cycle which lasts years or decades [14,15] the star varies from a optically fainter to a brighter star and back. This variability is therefore caused by the star changing from an early (hot) to a late (cool) spectral type, it implies also that not only brightens up but also goes from a blue to a redder color. Historically the brightening of a LBV in the bright (cool) phase during an cycle has also been called an eruption (or S Dor eruption). As we will see later this term is confusing.

With S Doradus in the Large Magellanic Cloud as the first to show this and therefore the prototype, this alternation from hot to cool and back was accordingly named a S Dor cycle and is observed in LBVs only!. The S Dor variability is the one and only clear distinction of LBVs from other massive evolved stars. An example of a long term lightcurve is given for the LBV Var B in M 33 in Figure 1, the analog version for Var C was published by Burggraf [16]. Also plotted here are the changes of the spectral type for the star, that mark an S Dor cycle.

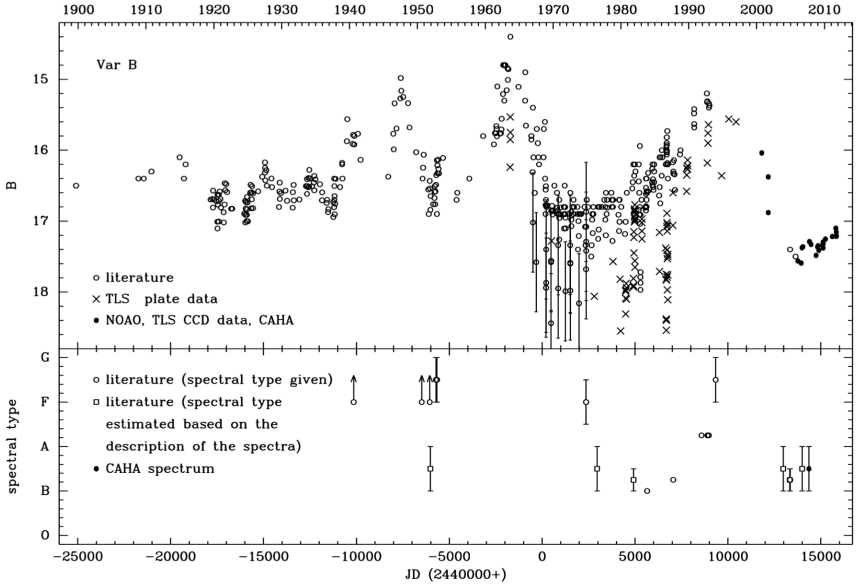

Figure 1. This figure taken from Burggraf (2015) [17] shows a lightcurve spanning more than 100 years of the LBV and original Hubble Sandage Variable Var B in M 33. In addition to the B magnitudes upper section the spectral type if know for the same date is plotted in the lower section. Note the for S Dor cycles typical changes in the spectral type.

Bernhard Wolf [18] noticed that the change of the spectrum (or equivalent T_{eff}) within an S Dor cycle from a hot to a cool type is larger for more luminous LBVs. This became known as the *amplitude-luminosity-relation*. His plot as well as a new version we made to visualize this relation is given in Figure 2. Instead of a classical HRD we plotted the change of Temperature (ΔT_{eff}) versus the Luminosity L by using the LBVs given in the HRD in Figure 3. The new plot visualizes nicely how tight this relation really is.

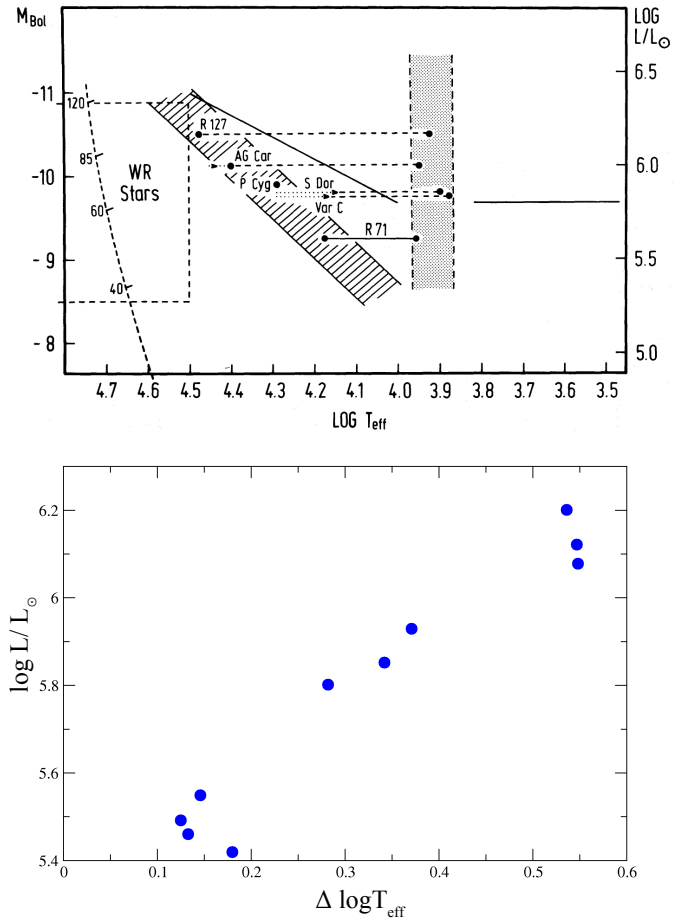

Figure 2. This figure shows the classical plot by Wolf [18] (left) and in a new version (right) we plotted the luminosity L and change in Temperature ΔT_{eff} for a new way to visualize the amplitude-luminosity-relation.

A more elaborate photometric classification, based on the duration of the S Dor cycle was made by van Genderen in 2001 [19]. He subdivided the phase and thereby objects into long S Dor (L-SD), here the cycle lasts $\leq$ 20 years and the short S Dor (S-SD) with the cycle being less than 10 yrs. Beside that he added a group he designated as ex-/dormant for those that currently (within the last 100 years) showed only a weak or no activity at all. Note that these variation are much larger as the microvariability which is common for supergiants in general [20].

In contrast to the more ordered S Dor variability (or eruption) LBVs can undergo more energetic events. In spontaneous *giant eruptions* the visible brightness increases spontaneously by several magnitudes [21]. The best known and well documented event is the giant eruption of the LBV η Carinae around 1843. During the eruption the star (or rather outburst) was with -1^{m} the second brightest star in the sky, surpassed only by Sirius with -1.46^{m} [21,22]. Other known and documented historic and present giant eruptions of LBVs are those of P Cygni around $\sim$1600 [23], SN1954J (=V12) in NGC 2403 ([21,24], and SN1961V in NGC 1058 ([25,26]). It is really important to distinguish between the "S Dor eruption" and a giant eruption. The latter being much more energetic and have changes of $\Delta \sim$ 5mag. With that different strength of the "eruptions" both are most likely caused by very different physical mechanism.

LBVs that showed a giant eruption are referred to as *giant eruption LBVs* or *η Car Variables*, to distinct them from LBVs that show only S Dor variations. Or more precisely for which we at least do not know if they have had a giant eruption, since we are limited to historic records of the last centuries, several giant eruption could have passed unnoticed. See the contribution by Kris Davidson in this volume for more details on giant eruption LBVs and there important distinction from LBVs with S Dor

variability only. Concerning these two very different variabilities it has so far not been observed and therefore is not clear if the S Dor variability and the giant eruptions occur separately or a LBV can show both variations.

Beside their variability LBVs stand out by having a rather high mass loss rate. In 1997 Leitherer [27] gave a first list for the mass loss rates of LBVs. They range from 7 10^{-7} to 6.6 10^{-4} with a typical values around 10^{-5} $M_{\odot}$ /yr^{-1}. Stahl et al. [28] used the H_{α} line to determined the mass loss rate the during one complete S Dor cycle of AG Car. They find that the derive mass-loss rates in the visual minimum is about a factor five higher as in the the visual maximum. More recent studies of the same object by Groh et al. [29] support and extend this study. The authors associate the changes with the bistability limit. Lamers et al. [30] first discussed that while evolving from hot to cool temperatures stars will pass the bistability limit at roughly 21000 K. At this limit a change in the stellar wind occurs. On the hot side the wind velocities are higher and the mass loss rates lower (see also [31]). The cool side of the bistability limit matches in the HRD to the region of LBVs in their cool state and causes a high mass loss in that phase. The closeness to the Eddington limit [32,33] of LBV in their cool phase also favors a high mass loss. This is even more so if the stars rotate fast and the modified Eddington limit the $\Omega\Gamma$ limit applies [33] lowering the gravitational force even further. And indeed AG Car [34] and HR Car [35] are fast rotating LBVs.

3. The evolutionary status of LBVs

LBVs are massive evolved stars. The LBV phase is in comparison to other phases massive stars will pass with roughly 25000 years rather short [36]. Originally, in the classical Conti scenario [37,38], only stars above roughly 50 $M_{\odot}$ were thought to turn into LBVs. Observations however identified LBVs that have a significantly lower mass. The position of LBVs in the HRD, see Figure 3 is associated with bright and generally blue stars (like AG Car, R 127, S 61, P Cyg, WRA 751), but an additional area is populated with LBVs that are fainter and somewhat cooler (HR Car, R 71, HD 160529). These maybe indeed hint for two subclasses the first group being massive LBVs and the latter less massive LBVs. Figure 3 shows the position of galactic and LMC LBVs and LBV candidates in the HRD. If known the position is given for both the cool (open circles) and the hot phase (filled circles).

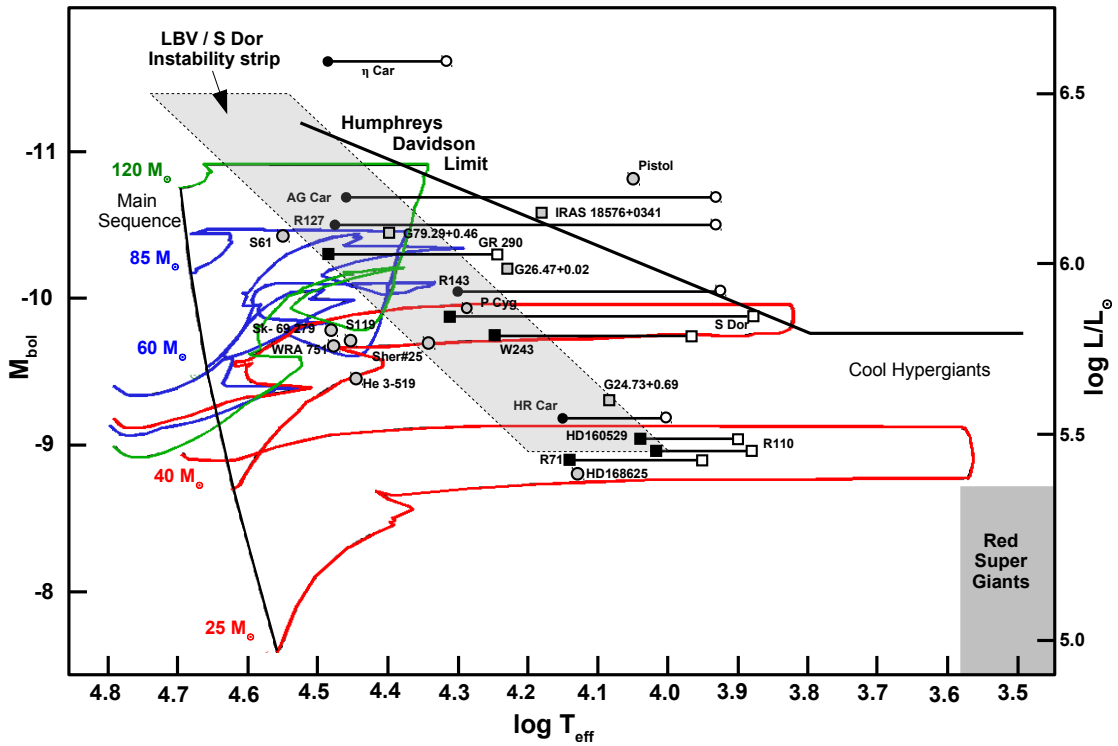

Figure 3. HRD with Galactic and LMC LBVs and LBV candidates. Circles are used for LBVs with an emission line (optical/NIR) nebulae, squares for all others. If an S Dor cycle has been observed both the cool (open symbol) and the hot phase (filled symbol) are marked. Otherwise an open grayish symbol is used. In color evolutionary tracks for different masses are added. The tracks are based on the data from the Geneva code for Z = 0.02 and v_{rot} = 300 km/s, colors code the generally three different evolutionary scenarios, see text for details.

Stellar evolution models by the Geneva group [39] that include rotation also shows the position of stars with lower mass matching both location of LBVs in the HRD Figure 3. Also plotted in this figure are tracks of the Geneva group, the Humphreys Davidson limit as well as the LBV/S Dor instability strip, the area of LBV in the hot phase.

The Geneva models [39] yield the following evolutionary scenarios:

least massive stars (red color code in Figure 3):

$M < M_{WR}$: O – BSG/RSG

intermediate massive stars (blue color code in Figure 3):

$M_{WR} < M < M_{OWR}$: O – LBV

or alternatively: O – RSG – eWNL – eWNE – WC/WO

most massive stars (green color code in Figure 3):

$M > M_{OWR}$: O – eWNL – eWNE – WC/WO

The authors define that mass limits as follows: "M_{OWR} is the minimum initial mass of a single star entering the WR phase during the MS phase...M_{WR} is the minimum initial mass of a single star entering the WR phase at any point in the course of its lifetime." Both limits M_{WR} and M_{OWR} depend on the rotation rate and metallicity. For a rotation rate of 300 km/s and solar metallicity $M_{WR} = 22\,M_{\odot}$ and $M_{OWR} = 45\,M_{\odot}$. Both values are higher for lower metallicity and lower for higher metallicity. This leads to a mass as low as $21\,M_{\odot}$ for LBVs at Z = 0.04. Depending on the mass and mass loss LBVs either evolve into Wolf-Rayet or directly turn supernovae. Figure 3 with the tracks and LBV positions also yield a clue to Wolfs amplitude-luminosity-relation: In their evolution the point in temperature (open circle) the stars start to turned back around towards hotter temperatures is relatively independent of the stars mass. The more massive, luminous stars start with a hotter temperature,

so for them the crossing in the HRD (or change in T_{eff}) to the turning point is larger. This cool limit is caused by the stars forming an "extended envelope" or pseudo-photosphere in an opaque stellar wind [40,41]. An analysis of this concept using NLTE expanding atmosphere models showed that the formation of a pseudo-photosphere due to strongly increased mass-loss alone does not explain large brightness excursions [42,43]. A later discussion in context of the bi-stability jump implied that the formation of a pseudo-photosphere might work for rotating, relatively low mass LBVs [44,45]. Still, the idea of pseudo-photospheres may explain the power-law shape of the variability spectrum at higher frequencies [46]. An promising alternative idea to explain S Dor variability is envelope inflation [47] potentially induced by changes of the stars rotation. A similar idea based on an instability induced by the lowering of the effective stellar mass by rotation was also suggested [35,48].

4. Nebulae around LBVs

4.1. Emission Line Nebulae

One consequence of the high mass loss rate that LBVs posses and if present giant eruption is the formation of circumstellar nebulae. Many, however apparently not all LBVs are surrounded by a small nebula. Nebulae form by wind wind interaction of faster and slower winds during a S Dor cycle, while giant eruption LBVs nebula are the result of mass ejection in the eruption.

LBV nebulae predominantly contain stellar material, noticeable by the presence of stronger [N II] emission lines as a result of CNO processed material that was mixed up into the wind and/or ejecta of the star. During one of the first conferences devoted to LBVs in 1988, Stahl [49] reviewed on what was known about the nebulae around LBVs. Our current knowledge of LBV nebula is however still restricted mainly to nebula in our own galaxy and the Magellanic Clouds, only these nebulae are are spatially resolved and can be studied in detail.

A more recent study by Weis [50] show that the morphologies of the nebula are manifold. A signification fraction (on average 60 %, 75% for galactic LBVs) show bipolarity. This bipolarity is either strong with a hourglass shape (i.e. η Car, HR Car, AG Car) or more weak in bipolar attachments, like Caps as seen in (i.e. WRA 751, R 127). Figure 4 shows one example of all so far known types of morphologies of either a galactic or LMC nebula. The true bipolar nature of the nebulae around AG Car has been identified by Weis [51]. Its hourglass structure is seen pol on and appears more spherical or rather boxy. Only by using high resolution Echelle spectra the kinematics revealed the true bipolar nature. Only one, the nebula around the LMC LBV R 143 is really irregular[52], this however is not surprising given the stars is situated in the middle of the 30 Doradus HII region. Spherical are S 61 and S 119 the latter showing signs of an outflow [53].

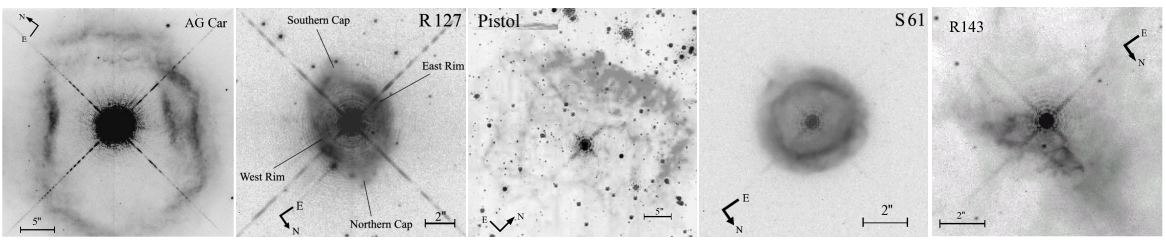

Figure 4. HST images of LBV nebulae sorted by morphology: hourglass AG Car [54] , R 127 with bipolar attachments, weakly bipolar He 3-519 [55], spherical S 61 [52] and last in row irregular R 143 [52].

The list with parameters in Table 1 reveals that LBV nebulae are with only a few parsec rather small. The largest is with a diameter of about 4.5 pc the nebula around Sk-69° 279 in the LMC, the nebula shows an 1.7 pc extension in one direction, enlarging the nebula size to a dimension of 4.5×6.2 pc [56].

The the smallest (detected so far) are the Homunculus around η Carinae (see chapter 4.4), the inner nebula around P Cygni (see chapter below) and the nebula around HD 168625 ([57], Weis et al

in prep) all with sizes of roughly 0.2 parsec. Note in that context that Weis [52] found for S Dor(LBV) nebula emission in the spectrum but it's physically to small to be spatially resolved (so far). The same is true for GR 290 in M 33 (see Maryeva this volume) and the galactic LBV W243 in Westerlund 1. They are therefore excluded from Table 1 and not marked bold for LBVs with nebulae in Table 2. The expansion velocities of LBV nebulae are a few km/s to 100 km/s [50,58,59] They are higher for η Car see chapter below.

Table 1. Parameters of Galactic and LMC LBVs and LBV candidates with an line emission (optical/NIR) nebulae. LBVs with dust nebulae only have been excluded here. In case the nebula has several spatially distinct parts (inner and outer regions) a slash is used for separation between them.

LBV	Host Galaxy	Maximum Size [pc]	v_{exp} [km/s]	Morphology	Reference
η Carinae	Milky Way	0.2/0.67	300/10 − 3200	bipolar	[58,60]
AG Carinae	Milky Way	1.4 × 2	25/43	bipolar	[61]
HD 168625	Milky Way	0.13 × 0.17	40	bipolar	[57]
He 3-519	Milky Way	2.1	61	spherical	[55]
HR Carinae	Milky Way	1.3 × 0.65	75	bipolar	[62]
P Cygni	Milky Way	0.2/0.8	110 − 150/185	spherical	see text
WRA 751	Milky Way	0.5	26	bipolar	[63]
Pistol star	Milky Way	0.8 × 1.2	60	spherical	[64]
Sher 25	Milky Way	0.4×1	20/83	bipolar	[65]
R 127	LMC	1.3	32	bipolar	[52]
R 143	LMC	1.2	24 (line split)	irregular	[52]
S 61	LMC	0.82	27	spherical	[52]
S 119	LMC	1.8	26	spherical plus outflow	[53]
Sk-69° 279	LMC	4.5×6.2	14	spherical plus outflow	[56]

4.2. Dust Nebulae

With the SPITZER MIPSGal survey more than 400 small ($\sim 1'$) single bubbles were detected in 24 μm emission [66,67]. An extended sample was even derived using citizen-science and machine-learning methods [68]. For most of these bubbles no optical counterpart is known, making them heavy obscured gas and/or pure dust bubbles. Some of the bubbles contain central, NIR bright stars (some even faintly visible in the optical), while others do not show central sources at all, not even in SPITZER IRAC images 3.6 & 4.5μm from the GLIMPSE surveys. The nature of these small bubbles were an enigma, until first classification spectra of some the bright central sources were taken [69,70]. Several of those turned out to be massive evolved stars, like blue supergiants, LBV candidates and Wolf-Rayet stars. Others were red supergiants and AGB stars. The nature and origin of the emission of the bubbles however remained uncertain. It could be hot dust, or MIR lines of ionized gas, or both. Taking SPITZER IRS spectra of several of the bubble revealed that all cases exist [71,72]: bubbles for which no central stars are detected seems to be dominated by line emission (mostly the high ionization [OIV] λ25.9μm line), and are therefore most likely planetary nebulae. Bubbles with NIR visible central stars that show dust dominated IRS spectra are even less frequent. Stellar NIR spectroscopic classification again prove that the central stars are dominated by evolved massive stars [73] of various types, with several Wolf-Rayet stars, e.g. [74,75], and a number of LBV candidates or related stars [76–78]. Two of these candidates can now be seen as established LBVs (see Table 2, WS1 [79] and MN48 [80]. Also, several previously known LBVs show MIR nebulae, e.g. MWC 930 [81] or HR Car [82].

Still there are some problems with interpreting the small MIR bubbles and especially the LBV candidate interpretation. Most of these bubbles are round/spherical, e.g. [69], and bipolar structures are rare among the 24μm bubbles. While this is consistent with the morphology of circumstellar

gas nebulae of Wolf-Rayet stars, it seems to contradict the results found for LBV nebulae [52] which have as reported above a preference for bipolar morphologies. From the 24 μm images alone it is not clear, whether the nebulae are a) dust only b) partly dust, partly gas, or c) dominated by ionized gas. The distribution and kinematics of the dust and gas are often different for circumstellar nebulae of massive stars, as e.g., shown for the nebula of the classical LBV AG Carinae [61]. Gail et al. [83] were among the first to investiage the problem of dust formation in an CNO precessed material like LBV envelops. Later hydrodynamical simulations of gas and dust nebulae, e.g. [84], show the small dust grains follow the gas quite well, but the larger grains show their own unique distribution. The morphologies problem may therefore be dominantly a wavelength bias. Last but not least one can speculate about the bubbles being signposts of a more general, previously overlooked short high mass-loss phase in the evolution of many massive stars. We are currently running a program with the LBT infrared spectrograph LUCI to classify more of the central stars using HK band spectroscopy.

4.3. P Cygni

As was mentioned above P Cygni is one of the classical giant eruption LBVs, with an eruption observed in 1600. In the Van Genderen classification it is currently a weakly active LBV. The nebula around P Cygni has at least, two distinct parts. One larger structure with a diameter of 0.8 to 0.9 pc named the outer shell or OS which is rather spherical and a much smaller and clumpy structure the inner shell or IS which is less than 0.2 pc across [85]. Beside the IS and OS Meaburn et al. [86] reported 1999 a giant lobe to associated with the stars. Its has a PA = 50° to the other nebulae and stretches to an extend of 7 arcminutes or up 3.6 pc. He finds expansion velocities around 110 to 140 km/s (depending on which line he uses) associate with the inner shell and structures as high 185 km/s in the outer shell.

With a diameter of only 0.2 pc the IS is in most images barely resolved. A new LBT/LUCI AO image (Figure 5) we made recently shows the large amount of fine structure and details of inner nebula for the very first time. With a resolution down to 85 AU size structures it is an improvement from the previously published LBT image by Arcidiacono et al. [87].

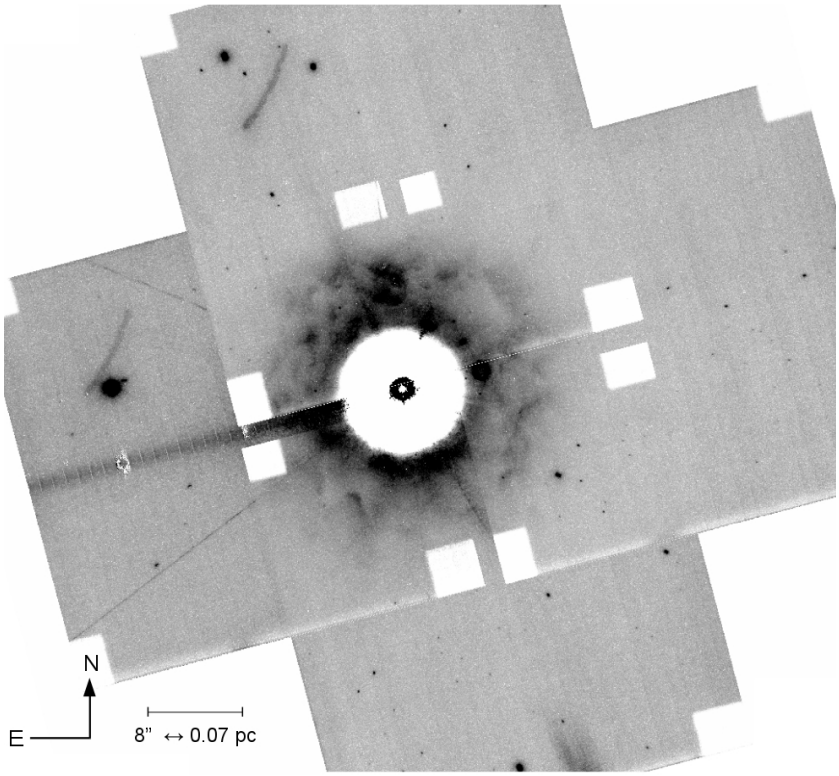

Figure 5. An LBT LUCI AO [FeII] image of the inner nebula (or inner shell) of P Cygni (Weis et al., in prep). The images has pixel scale of 0.015″/pixel and resolve scales down to 85 AU.

Mapping the nebulae with KPNO high resolution longslit Echelle Spectra we measured the expansion velocity of the inner nebula is 100–150 km/s, this is well in agreement to Meaburns values. This would assuming no larger acceleration or deceleration match to the inner shell having been ejected during the 1600 giant eruption. With the spectra we can also associate velocities to distinct clumps that appear in the spectra and can be identified on the image (Weis et al. in prep.).

4.4. η Carinae — the Most Peculiar LBV?

η Carinae used to be the most classical giant eruption LBV or η Carinae variable. With the discovery of many unique and unusual characteristics η Carinae or the η Carinae system is not the LBV par excellence anymore. A book devoted to η Carina and the Supernova impostors [88] can be consulted for all details on this object. Here a short summary of the characteristics:

- A giant eruption that took place in 1843
- A binary system with two massive components one with 60 $M_\odot$ the second with 30 $M_\odot$ [89]
- A nebula that has at least three section: *The little Homunculus*, *The Homunculus*, *The outer ejecta*.

The Homunculus was identified first and photographed in 1950 by Gaviola [90], the name of the nebula was motivated by the first images showing a man like morphology. The little Homunculus resides within the Homunculus and was revealed only using HST STIS long slit spectroscopy by Ishibashi et al. [91]. The outer ejecta as the name implies surrounds the Homunculus. It consists of a countless number of clumps and filaments. A first report and catalog with designation of several part of the outer ejecta was made 1976 by Walborn [92]. A summary of more recent optical, x-ray and kinematic studies of the outer ejecta is given by Weis [59]. Today we know that all three sections of the nebula are of bipolar morphology. The expansion velocities are with up to 3000 km/s faster than in any other LBV nebula. Shocks of these extremely fast structures in the outer ejecta create X-ray emission [93,94]. This emission is shown in the right section of Figure 6, here a a CHANDRA image is color coded and in indicates in red soft Xray emission of the outer ejecta is, in blue the more central emission results mark shocks of the central stellar system not the Homunculus nebula!

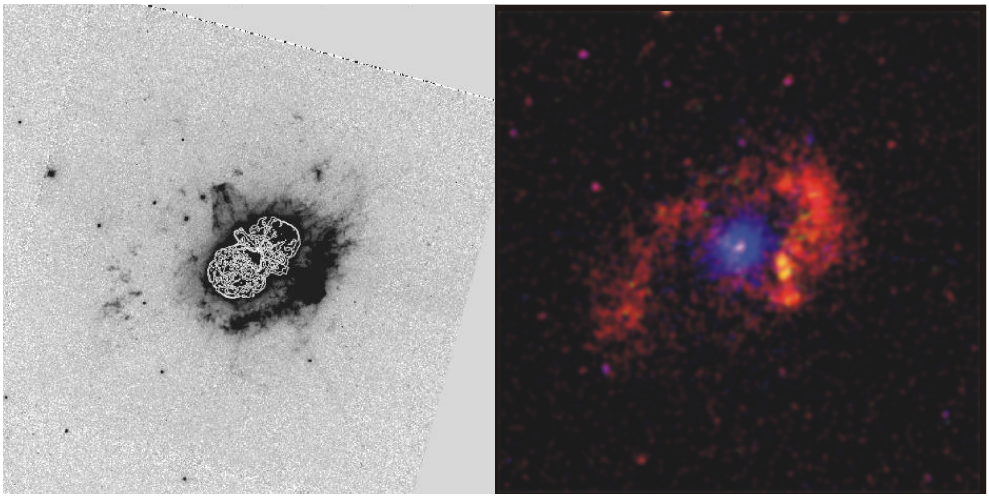

Figure 6. The nebula around η Carinae in the optical and X-ray. Left: An optical F658N HST image in greyscale, the Homunculus nebula additionally marked in contour to distinguish it from the outer ejecta, shown only in grey scale [58] Right: A CHANDRA Xray image with color coded energy regimes, green:0.2-0.6 keV, red: 0.6–1.2 keV and blue 1.2–12 keV color version of Figure 1 in [95].

5. Instabilities and the Origin of Variability

What are possible origins of the LBV variability. First we have to differentiate between the S Dor variability and giant eruptions. The latter are in need of much larger energy being released. Already in their 1994 paper Humphreys and Davidson [41] discussed what could cause the variabilities

and whether one or more mechanism are at work. They argue and cite several works showing that a classical κ-mechanism seems not to work. A more likely cause also discussed in that paper is the proximity of LBV to the Eddington, or in case of rotation $\Omega\Gamma$ limit. This limit indeed lies in the HRD in the same region as the Humphreys Davison limit, which also resembles the cool position of an LBV in the S Dor cycle. Clearly the properties of the stellar winds and their dependence of metallicity have to be a major contributor to the mechanisms creating the variability. For various more detailed theoretical works the reader is referred a review by Glatzel [96] a newer overviews by Vink [97] and Owocki [98]. Alternative models like non-radial gravity mode oscillations have been proposed by Guzik [99]. The potential importance of pulsations for the driving of the S Dor mechanism was discussed in [100]. The analysis of long, well sampled lightcurves may provide more information about the properties of the S Dor process [20,101]. Still, the link of low amplitude variability patterns with LBV nature is far from clear. Kalari et al. [101] showed that SMC blue supergiant AzV 261 exhibits variability patterns consistent with other LBVs in a 3 year time span and nearly nightly photometric observations, but their detailed analysis of high dispersion spectra showed no temperature changes typical for an S Dor cycle over a decade, precluding a classification as LBV.

Recently, new 3d radiation hydrodynamic simulations of 80 and 35 $M_\odot$ performed and the results point at variations of the He opacity as a possible cause of the S Dor variability and link the shorter time scale irregular oscillations to convection [102]. Other ideas for the origin of the S Dor variability were already discussed in chapter 3.

6. The LBV Wolf-Rayet Star Connection

In the last years it has been found that the masses of Wolf-Rayet stars in that state (not their initial mass) is much lower as can be explained by the stellar winds only. Furthermore the empirical mass loss rates for hot, massive stars have also been seriously questioned, mainly because of the effects of wind clumping [103,104]. Wind clumping will reduce the mass loss rate and leave us with even higher mass in evolved stars. Stellar evolution models use theoretical mass loss rates, generally lower that the empirical ones even without clumping. A phase of enhanced mass loss with a different mechanism may be needed [105].

The LBVs phase would just fit. It is passed right before the WR phase and is known for high mass loss as well as the formation of massive nebulae. A LBV phase therefore might be mandatory to explain at least some WR classes and the lower WR star masses. One might even speculate that WR nebula are only by fast WR winds blown up, enlarged former LBV nebulae. Indications for such a hypothesis are the somewhat larger size of WR nebulae in combination with a N enhancement. The latter being a well known attribute of LBV nebula. Most WR nebula are not found around WO or WC but WN type stars, the natural and direct predecessor of LBVs.

First hints for such a scenario have been shown for the Wolf-Rayet stars WR 124 with its nebula M1-67 and the LBV He 3-519 [55]. The M1-67 WR nebula is one of few if not the only one that has a bipolar morphology and a size of only 2pc. As described above these are very typical values for LBV nebula. One might picture WR 124 as an old LBV that has just left the LBV and entered the WR phase, matching well to its current WN 8 spectrum. The scenario for He 3-519 might be just reversed, the stars is an LBV that is turning into an WR right now. This would also explain why no S Dor variability is seen for that star. Its current spectra type is already that of a WN 11. The nebula is only weakly bipolar and with 2×2.5 pc rather large for an galactic LBV see HST image in Figure 4. It looks more like an old LBV nebula that by inflation via the strong WR stars wind has already increased its size. Doing so also caused bipolarity to fade o[55]. For a more general review about WR stars see the contribution by Kathryn Neugent and Philip Massey in this volume.

7. Links of SN Impostors and LBVs

In recent years several projects and monitoring surveys that search for supernovae found what has become known as *SN impostors*. These transients show spectra similar to core-collapse SN,

especially of the type SNIIn, but are generally significant fainter than core-collapse SN. SN impostors show lightcurves quite different from all core collapse SN, sometimes even showing strong fluctuations on short timescales some time after the initial eruption, see e.g. [106]. It is interesting to note, that the brightest impostors events even overlap in energy with the faint SN IIP, e.g. [107,108]. A very tempting and likely explanation is to identify at least a subset of these SN impostors with giant eruptions or even S Dor variabilities of LBVs [109] in distant galaxies. Note in this context that while a LBV giant eruption will look like a SN impostor, not all SN impostors might indeed be LBV giant eruptions!

With the current list of about 40 SN impostors [110], light curves and spectra during the eruption, and especially the pre- and post-eruption behavior imply at least two different object classes are summarized in the name Impostor: the transients with strong narrow emission lines and erratic lightcurves with secondary, smaller outbursts following the first eruption, and the transients, which are followed with less than a decade by a true supernova explosion, e.g. [111]. This diversity of the lightcurves and spectra of the transients denoted as SN impostor was also noted by Smith [112]. It is potentially important, that the rise of the eruptions can be very steep [106,110,113], putting interesting limits on the kinetic energy and size scales evolved.

SN impostors will be discussed in detail in this volume by Kris Davidson.

8. Multiplicity of LBVs

In recent years it became clear, that a significant part of massive stars are born in double (or multiple) systems. A detailed analysis of the results from the FLAMES-Tarantula survey lead Sana et al. [114] to the following percentages for massive stars: effective single (real single stars or wide binaries without significant interaction ∼29%, stellar merger ∼24%, accretion and spin up or common envelope evolution ∼14%, and envelope stripping ∼33% [114]. Therefore, about ∼71% are affected by binary interaction. Alternatively, if one sees the result of mergers as apparent single stars for most of their lifetime, then only ∼47% of the massive stars should show a companion. The same data also imply that the numbers of equal mass binaries are lower than unequal mass pairs. The ratio goes up to ∼50% at $M_2/M_1 = 0.3$, the lowest mass ratio probed by their data [114].

This immediately implies that a sizable number of LBVs should have binary companions. The idea, that binary star evolution is linked to the LBV phenomenon is quite old, see e.g. Gallagher (1989) [115]. More recently, the idea of mergers triggering giant eruptions (or being one path to SN impostors) gained some interest, e.g. [116]. Still, the observation of binary companions of LBVs are difficult, due to the large luminosity of the primary, and its strong stellar wind, which both limits spectroscopic searches. Direct imaging searches only cover relatively large separations, and only few LBVs are analyzed with stellar interferometers, yet. A search for X-ray only covers situations in which colliding winds can occur, and may be in part contaminated by the X-ray emission of circumstellar nebula.

The current state on observed stellar companions to LBVs is the following: As shown in chapter 4.4 η Carinae show strong signs of being a binary star with a massive, hot companion stars. HD 5980 was first reported as an exlipsing LBV Wolf-Rayet binary system that showed an LBV like eruption [117]. Koenigsberger et al. [118] report new analysis which is consistent with the system being more complex and multiple: a double binary scenario and manifests a quadruple system. The LBV candidate [KMN95] Star A (= 1806-20) showes double He lines [119] but single emission lines, implying a dense stellar wind for the primary, similar to the case of η Carinae. MCW 314 shows clear indications in its lightcurve and its radial velocity curve for having a lower luminosity supergiant companion [120]. If the wide companion candidate [121] is truly bound, than MWC 314 would be a hierarchical triple star. The LBV HR Car was observed with stellar interferometry and strong indications of a companion was found [122]. The companion star appears to be relatively low mass (below $\sim 15 M_\odot$).

A search for wide companions based on natural seeing, AO assisted imaging, and archival HST imaging of 7 galactic LBVs, LBV candidates, and some related objects yielded one star with potential companion (MWC 314) and no apparent bound companions for the 5 other LBVs and LBV candidates (the Pistol star, HD 168625, HD 168607, MWC 930, and [KMN95] Star A (= 1806-20)) [121]. The PSF

subtracted HST images used in the study of LBV nebulae in the LMC by Weis [52] also showed no apparent companion stars, but only relatively large projected orbital distances could be probed (>0.1 pc).

A X-ray archival survey (using XMM-Newton and CHANDRA X-ray satellites) of 31 LBVs, LBV candidates, and related objects was performed by Naze et al. [123]. X-ray emission may indicated colliding winds in a binary, but (softer) X-ray could also be created in a circumstellar nebula, see e.g. Weis [94] for the case of η Carinae. The survey of Naze et al. yielded 4 detection (η Carinae, W243 (= Westerlund 1 #243), MSX6C G026.4700+00.0207 (= GAL 026.47+00.02), and Schulte #12 (= Cyg OB2 #12). Two more are labeled doubtful candidates (GCIRS 34W, and GCIRS 33SE) by the authors. This result also implies a long list of 25 non-detections, which includes confirmed LBVs like P Cygni, the Pistol star, and FMM 362. While acknowledging their rather heterogenous data base, the authors suggest that their detection rate is consistent with a binary fraction between 26% and 69%, roughly consistent with that of other classes of hot, massive stars.

Given the very different methods used, and the therefore very different orbital radii and mass (and luminosity) ratios probed up to now, it is hard to derive a reliable result on the binary fraction for LBVs as a class. An additional problem are the very different LBV input lists used in the different searches. There are clearly several good cases for binary companions of LBV stars. Still, we regard the actual binary fraction of LBVs as currently very uncertain, but most likely around ∼20% for the confirmed LBVs. This would be somewhat lower than the binary fraction for other classes of massive stars like O supergiants or Wolf-Rayet stars. If this estimate of the binary fraction is correct, it may hold important clues for the evolutionary pathways leading to LBVs.

9. LBV and Their Neighborhood

Smith & Tombleson[124] analyzed the location of LBVs in comparison to their surrounding and concluded that LBVs in MW and LMC are isolated, and not spatially associated with young O-type stars. This would imply a complete change of the standard view of the evolution of LBVs, clearly a far reaching claim, which needed further investigation. Humphreys et al. [125] analyzed the location of a sample of LBVs in M 31, M 33, and the LMC in comparison too other massive main sequence and supergiant stars. With this large and more coherently selected sample,Humphreys et al. [125] concluded that LBVs are associated with supergiant stars and are neither isolated or preferentially run-away stars. Separating the more massive classical and the less luminous LBVs, the classical LBVs have a distribution similar to the late O-type stars, while the less luminous LBVs have a distribution like the red supergiants. Smith [126] questioned the results of this analysis and reiterated the results of his analysis. Davidson et al. [127] shortly after showed that the statistical analysis methods use in [126] are flawed. Independently, Aadland et al. [128] performed a very similar analysis and came to similar conclusions as Humphreys et al. [125], that the stellar environment of LBVs is the same as for supergiants. It is still be worth noting, that the Aadland et al. sample is not a clean LBV sample, but contains many B[e] supergiants. Note that this point was also pointed out by Kraus in her review paper on B[e] in this volume. In a recent paper Smith [129] gravitated to the interpretation by Humphreys et al. of LBV locations within (or near) their birth association. Just lately with an analysis of GAIA data [130], strong evidence was presented, that OB stars form not preferentially in bound clusters, but in a continuous distribution of gas densities, at many locations of the birth cloud. This view is also supported by recent simulations which also favor a hierarchical formation model for the formation of OB stars as a result of the fractal structure of the birth clouds, contrary to a monolithic collapse. In this picture many different stellar neighborhoods of massive stars would be natural, also consistent with our results.

10. The Population of LBVs

As mention above the first reports on Var 2 in M 33 was already in the 1920ties marks the first identification of an LBV-at that time without the knowledge that it is and what LBV are.

Since the Studies by Hubble & Sandage 1953 [1] and Sandage & Tamman 1974[4] we know that both M 31 and M 33, as well as NGC 2403 host several LBV and LBV candidates. S Dor added the LMC to the LBV host galaxies. The LMC has a remarkable population of LBVs [6,131]. Bernhard Wolf and his group in Heidelberg studied various LBVs and LBV candidates in several galaxies and with this first larger sample was able to identify the above mentioned amplitude luminosity relation. Beside that they found several LMC LBV candidates and confirmed many LBVs by observing their S Dor Cycles like R 127 [132], R 110 [133]. They also noticed an inverse P Cygni profile in the spectrum of S Dor [134]. and added HD 160529 to the galactic LBVs. Last but not least the group also identified with R 40 the very first LBV in the SMC [135,136] . Other LBV host galaxies now known are locally IC 10 and further out are the M 1 group members M 1, NGC 2366. LBV and LBV candidates are reported also in M 101, NGC 300, NGC 247, NGC 6822, NGC 4414, and IC 1613, just to name the most important galaxies.

In Table 2a list of known LBV and LBV candidates is given. True LBVs are those stars where the membership is clear since a complete S Dor cycle has been observed, this is not the case for the LBV candidates. For LBVs that had a giant eruption, those are classified separately and named giant eruption LBVs (or η Car Variables) to distinct them from LBVs with S Dor variability only.

Several more stars have for the one or other reason be classified as LBVs by one or more authors, but show no clear hints like S Dor cycle or giant eruption. For the Milky Way the objects HD 80077 and Schulte 12 the new GAIA parallax moves both to a closer distance and to a lower luminosity. Still, the GAIA parallaxes are at this time (GAIA DR2) prone to several systematics [137,138]. Therefore the distance of at least the Schulte 12 is still not settled yet [139]. According to Humphreys et al. [125] in the LMC R 66, R 74, R 123 are B[e], R 149 is an Of star, HD 269604 an A supergiant and HD 34664 as well as HD 38489 are B[e]sg. Neither are R 81, R 84, R 99, R 126 LBVs. The SMC object R 50 is a B[e]sg while R 4 is a spectroscopic binary system with one B[e]sg. Finally the activity HD 5980 is more like a giant eruption but this most likely due to a binary interaction, see chapter on Multiplicity of LBVs below. Therefore its seen as a giant eruption LBV candidate with the above caveat. Just recently Humphreys [140] report that the following objects are not LBVs: I 8 in M 81 is an F supergiant, furthermore V 52 in NGC 2403 and I 3 in M 81 are foreground objects and not even part of those galaxies! HD 168625, He 3-519, Pistol star, and Sher 25 are LBV candidates due to the fact that they posses a circumstellar nebula. They however might indeed be LBVs, as members of what van Genderen classified as a group ex/dormant LBVs, just currently not showing any variability. Besides the variability searches, there is also a consistent search of luminous emission line stars using two or more broad band colors, Hα as detection and [OIII] as veto filter, done as part of the NOAO Local Group Survey [141,142] and independently by our group [143]. Both searches covered M 31, M 33, NGC 6822, IC 10, Wolf-Lundmark-Melotte, Sextans A, and Sextans B and finding very few candidates in the dwarf galaxies.

We searched also NGC 3109, a low metallicity galaxy forming a subgroup with Sextans A and Sextans B at the fringes of the Local Group. We found one candidate [144], similar to the low candidate numbers for the low metallicity dwarfs in the Local Group. An earlier attempt with the same idea to detect very luminous stars, which are strong Hα line emitters (either from strong mass loss, or from a circumstellar nebula), which are faint or absent in [OIII] (no stellar emission line, and faint for circumstellar nebulae of CNO processed material) was done by the Heidelberg group [145] for M 33, M 81, NGC 2403, and M 101, but was not published. We used e.g. these data to complement our list of good candidates for spectroscopy in M 33 [146,147]. It is interesting to note here, that coordinated searches for variable stars (in particular not only analyzing the Cepheids) is done only for small number of massive local galaxies since the photographic plate area. A new effort is ongoing with the LBT and yielded already interesting results [140]. Our group is currently working on a search for LBV and related objects in several nearby galaxies.

Table 2. LBVs and LBV candidates in alphabetic order. Giant eruption LBVs are italic. Objects marked bold have (optical) emission LBV nebula. Except for the Milky Way and LMC which have a to large number of objects, references are given.

Galaxy	LBVs	LBV Candidates	References
Milky Way	**AG Car**, ***η Car***, FMM 362, [GKF2010] MN44, [GKM2012] WS1, HD 168607, HD 160529, HD 193237, **HR Car** , **LBV G0.120-0.048**, MWC 930, ***P Cygni***, V481 Sct, W243, **WRA 751**	BD+143887, BD-13 5061, B[B61] 2, G025.520+0.216, G79.29+0.46, GCIRS 16C, GCIRS 16NE, GCIRS 16NW, GCIRS 33SE, GCIRS 16SW, [GKF2010] MN58, [GKF2010] MN61, [GKF2010] MN76, [GKF2010] MN 80, [GKF2010] MN83, [GKF2010] MN96, [GKF2010] MN112, [GKF2010] WS2, **HD 168625**, HD 316285, HD 326823, **He 3-519**, IRAS16278-4808, IRAS19040+0817, J17082913-3925076, [KMN95] Star A, MSX6C G026.4700+00.0207, **Pistol star**, **Sher 25**, WR 102ka, WRAY 16-137, WRAY 16-232	
LMC	HD 269216,R 71, R 85, **R 127**, **R 143**, R 110, S Dor,	HDE 269582, **S 61**, **S 119**, **Sk-69° 279**	
SMC	R 40	(R 4), (R 50)	[148]
M 31	AE And, AF And, LAMOSTJ0037+4016, UCAC4 660-00311, Var A-1, Var 15	J003910.85+403622.4, J00441132+4132568, M 31-004425.18, M31-004051.59	[147,149] [150]
M 33	Var B, Var C, Var 2, Var 83,	GR 290, [HS80] B48, [HS80] B416 , [HS80] B517, J013228.99+302819.3, J013235.21+303017.4,J013317.01 + 305329.87, J013317.22+303201.6, J013334.11+304744.6, J013337.31336+303328.8, J013351.46+304057.0, J013354.85+303222.8, J01342475+3033061, J01342718+3045599, J013432.76+304717.2, J013459.36+304201.0, J01350971+3041565, M33C-5916, M33C-10788, M33C-15235, M33C-16364, M33C-21386, UIT 008	[147] [17]
NGC 2403	*SN 1954J=V12*, SN 2002kg=V37	V 22, V 35, V 38	[24] [140,151]
NGC 1058	*SN 1961V*		[25,26]
NGC 2366	NGC 2363 V1		[152]
M 101		J140220.98+542004.38, V 1, V 2, V 4, V 9, V 10	[153,154]
M 81		I 1, I 2	[140,155]
IC 10		unnamed	[156]
NGC 300		B 16	[157]
NGC 6822		unnamed	[158]
NGC 4414		unnamed	[159]
IC 1613		V 39, V1835, V2384, V3072, V3120, V0416, V0530,	[158] [160,161]
UGC 5340		unnamed	[162–164]
NGC 3109		unnamed	[144]

Another different approach was used by Khan et al. [165,166] to search for analogs of η Carinae. They applied SED fitting to HST and Spitzer IRAC data of resolved stars in nearby massive galaxies, and found 5 promising candidates (one each in M 51, M 101, NGC 6946, and two in M 83). Again, these are at best only candidate LBV, mainly due to the missing variability information.

11. LBVs in Low Metallicity Systems

The situation is even worse for LBVs in lower mass galaxies. Detections are rare as metal-poor also implies low mass and even in actively starforming dwarf galaxies the numbers of massive stars are more limited as in large, massive spirals. The SMC, for example, on has only one confirmed LBV, see Table 2. An interesting LBV candidate is V 39 in the low metallicity Local Group dwarf galaxy IC 1613. Detailed analysis of its spectrum shows some patterns similar to other LBVs, but is also consistent with that of a sgB[e] star [161].

Besides the aforementioned Local Group galaxies, there are only chance detections up to now, including the exceptional case of NGC 2366 V1. NGC 2366 V1 [152,167,168] is located in a dwarf galaxy with a metallicity below 1/10 solar. Its "outburst", with a change of only $\sim$ 3 mag [167] was probably not really a giant eruption). Neither did it follow the classical S Dor pattern since it turned bluer (not redder) with increasing brightness.

The transient in UGC 5340 (DDO 68) was again a chance detection [162]. The brightening is 1 mag, and here again a blueing during the bright state is visible [163,164]. The galaxy is a morphologically peculiar, low mass system, which has with $\sim$ 1/30 solar (log (O/H) = 7.12) one of the lowest gas-phase metalicities in the nearby universe (distance 12.6 Mpc [169]. The transient in PHL 293B (= SDSS J223036.79-000636.9) [170] is difficult to study mainly due to its distance of $\sim$25 Mpc. The host galaxy is a dwarf galaxy and more metal-poor than the SMC (log O/H = 7.72). The transient discovery spectrum shows clear P Cygni profiles, but no details on the temporal variability were known, only 2 spectra (one without and one with P Cygni profiles). An additional spectrum brought the time baseline to 8 years and proved temporal variations of the broad stellar lines [171]. While being an interesting object, which may acquire LBV candidate status with a longer term photometric and spectroscopic monitoring, but the currently limited data makes the label LBV for this object a bit premature. As similar problem is the transient in the galaxy SDSS J094332.35+332657.6 [172], an apparent stellar transient in an very low mass and extremely low metallicity (log (O/H) = 7.03) galaxy at a distance of $\sim$ 8 Mpc. Only a very limited historical record is available, and therefore the LBV nature of the transient is quite unclear. It may be interesting to note here that the LBV GR 290 (= Romano's star) in M 33 also shows spectra variability, but not consistent with an S Dor pattern, see Maryeva et al., this volume. The star is located in the outer regions of the disk of M 33 (r= 4.3 kpc from the center of M 33. The observed metallicity gradient [173] therefore implies a low metallicity of log (O/H) = 8.2 (roughly between LMC and SMC [174]) for the star. Note in that context that metallicity gradients are a common feature in spiral galaxies, e.g. [175,176], so large spiral galaxies do not have one fixed metallicity.

Another intriguing object was detected by as a point source with high velocity dispersion in Hα Fabry-Perot observations of the local (D$\sim$2.6 Mpc), low metallicity dwarf galaxy UGC 8508 [177]. An intermediate dispersion spectrum of the source shows a bright Hα line with broad wings, a relatively strong Fe II λ4924 line, but also a strong He II λ4686 line. The classification of the authors as a massive star with strong mass loss is convincing, but if it is indeed a good LBV candidate is more uncertain, given the high temperature (and/or hard radiation field) implied by the presence of the strong, narrow He II line.

We detected another unusual point source [178] in NGC 1705, a starburst dwarf galaxy at D$\sim$ 5 Mpc with a metallicity similar to the LMC. The spectrum shows several very strong (and split) forbidden emission lines, all showing an expansion velocity of 50 km s^{-1}, and an underlying spectrum of the source is that of an A supergiant. Again this is a massive star with an expanding circumstellar bubble, but its exact nature is not determined yet.

The starter for the question, how many galaxies do we know in the local universe (e.g. the Local Volume = D < 11 Mpc) based on the classic compilation of [179]. There is an obvious distance limit when using photometry from the ground, especially historic photographic plate material for long term light curves to identify LBV candidates. This limit is depending on seeing, size of the telescope used, and the detector. The limits for photographic plate work is about 7 Mpc (the distance of M 101) [24], and is for most telescopes more like $\sim$ 4 Mpc (the M 81 and IC 342 groups in the north, and Sculptor and Fornax groups in the south). Obviously with CCDs and good seeing this can be extended (and/or the quality of the photometry improved), but access of older CCD data is tricky, if the observatory does not run a well maintained archive. Clearly, HST and in the near future EUCLID and JWST, can go much farther out, but it gets hard beyond 20 Mpc (especially due to the crowding of stars).

Low metallicity LBVs are especially interesting, since the metallicity can influence opacity in the interior of the stars and in the wind. Metallicity also affects the path of the evolutionary tracks (at which mass stars still go RSG, return to the blue, or go through a LBV phase with S Dor-like variability and instability that caused these, etc...) Furthermore rotation rate, binary fraction, and potentially IMF as well as magnetic fields are important.

Several of this markers of LBV candidates are directly, or indirectly influenced by metallicity. Mass loss e.g. [180–182], emission lines of heavy elements (e.g. photospheric or wind emission lines of FeII, FeIII, [FeII], then HeI, and [NII] in a circumstellar nebula) [146,147], and variability due to the metallicity dependence of the instabilities involved (see above). It could be that at low enough metallicity, massive stars behave differently, e.g., not showing an typical S Dor variability pattern anymore. The cases of V1 in NGC 2366 [167] and the transient in UGC 5340 (DDO 68) [163,164] hints towards and seem to support such a scenario. No coordinated search for luminous variable sources in a sample of low metallicity dwarf galaxies outside the Local Group was done yet. A pilot search on a few selected very low metallicity galaxies was reported by [183] using HST archival data. While there are several interesting candidates of luminous stars with signs of variability and in some cases Hα emission, the data yield not enough proofs to claim LBV candidates. Figure 7 demonstrates one of the problem, very low metallicity galaxies are rare and spatial resolution poses severe problems for ground based studies beyond $\sim$5 Mpc, requiring HST time. This aspect may improve with the upcoming EUCLID mission and more in the future by WFIRST, and is alleviated somewhat by the improving image quality of the large survey instruments, link e.g. SUBARU SuprimeCAM, DECam, and hopefully LSST. Another problem is the metallicity-luminosity relation, which implies that low metallicity is in the local universe the exclusive regime of dwarf galaxies. Therefore, even in a burst of starformation the absolute number of massive stars produced is, during a short time frame only, still comparable to the production rate of a massive spiral galaxy. With the current data situation it is to early to speculated on trends of LBV numbers and LBV nature at low metalicities, but as noted above, it is intriguing to see so many LBVs and LBV candidates in the LMC. With at the same time nearly non in the SMC.

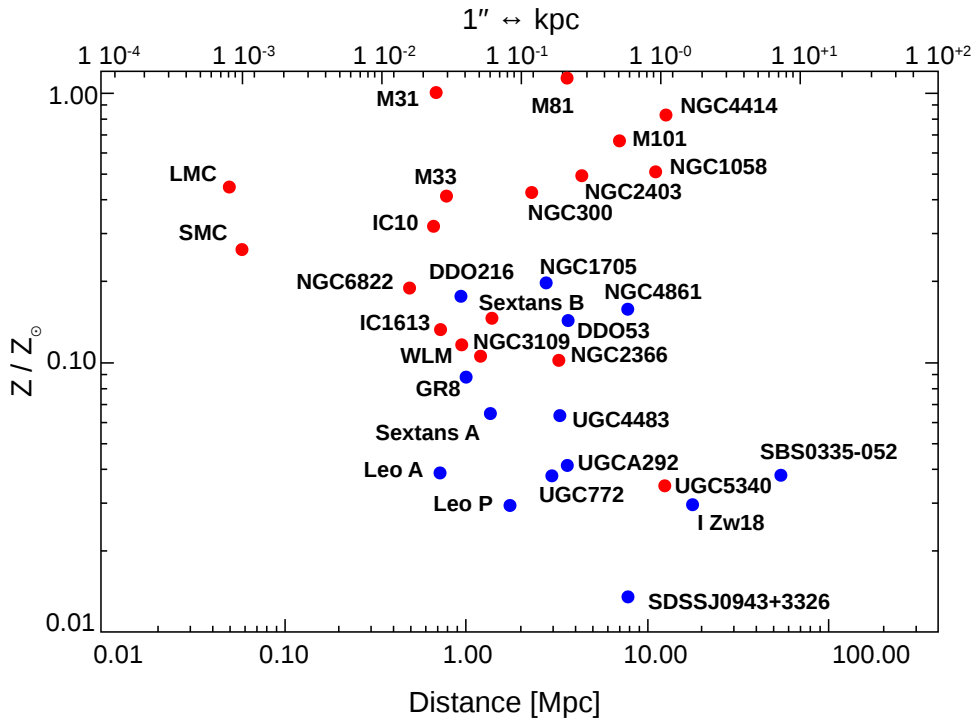

Figure 7. Plot of the gas-phase metallicity of nearby galaxies versus their distance and spatial resolution. Only a selection of the galaxies in the Local volume are plotted, but the sample is complete for the significantly starforming galaxies in the Local Group. Metalicities of the inner disk are chosen for the spiral galaxies with metallicity gradients, the metalicities of stars in the outer disk of these galaxies can be a a few faction of tens solar lower. Galaxies with LBVs and/or LBV candidates are plotted as red dots, the other galaxies are plotted as blue dots. Plot was adapted and updated from [163].

12. Summary and Conclusions

The Luminous Blue Variable phase is a short phase in the life of massive stars. It may be passed by stars with an initial mass as low as 21 $M_{\odot}$. LBVs have a specific variability the S Dor variable, can undergo giant eruption and have very high mass loss rate. The one and only way to pinpoint and truly classify LBVs is by the variability and/or giant eruption This asks for the detection of at least one S Dor cycle the star passes or to catch it in a giant eruption. These variabilities also subdivide the LBV class in classical (S Dor variable) LBVs and giant eruption LBVs. With the variability as the only clear classification method many LBVs in a quiescence state might be overlooked and not be identified as such. It is therefore not trivial to describe the LBV population in a galaxy. In that connection not knowing the true amount of LBVs and non-LBVs makes it hard to give an estimate for the real duration of the LBV phase. This again is directly linked to uncertainties of the total mass loss rate of massive stars. Even small changes of the phase length are linked to large changes in the mass total loss of the stars, given LBVs have very high mass loss rates. Last but not least that implies that the final mass of stars that pass a LBV phase could be much lower as thought so far. In that case this would even effect amounts and ratios of different SN types.

The path is therefore clear, to better characterize the LBV population and the underlying physics more long-term variability studies of nearby galaxies are needed. Spanning the parameter space especially towards lower metalicities will potentially clarify the importance of opacity effects and rotation for the S Dor variability. Also analyses of the long-term variability of massive stars in all the most metal-rich spiral galaxies in the Local Universe are not really done yet. First attempts are already ongoing, partly using data from well maintained archives, and the time-domain section of future large survey projects like LSST will be a major step forward. This will also be true for a better understanding of eruption LBVs. Another promising avenue will be the "archaeology" of the mass-loss

of LBVs and related stars using their circumstellar nebulae. In this way, information on energy, mass, and chemical composition of earlier mass-loss of the stars can be investigated, again providing clues about the underlying mechanism of instability and the evolutionary state of the stars. With the rise of integral field spectrographs, even with AO support (e.g. MUSE at the ESO/VLT), such analyses should be possible in all Local Group galaxies and the nearest galaxy groups. First such analyses are already appearing for galaxies in the Scultor group: NGC 300 [184] and NGC 7793 [185]. An unfortunate weakness in the currently available instrumentation are high-dispersion spectrographs fed by long-slits and IFUs, an important capability for kinematics/energetics of nebulae, which is becoming rare [186] at the intermediate and large telescopes. High-multiplex spectroscopic survey instruments at large telescopes, like e.g. Hectospec at the MMT, and soon MOONS and 4MOST at ESO telescopes, as well as WEAVE at the WHT, can be very useful tools to set LBVs in context to their massive star environment, as they are capable of providing good quality spectra for many photometrically selected LBV candidates (as well as other supergiants). This still requires that starforming, nearby galaxies will be targeted in the upcoming large surveys at these facilities.

Taking this all together, one can be optimistic, that in the coming years many more good quality observational data will be available to improve our understanding of the LBV phenomenon and its importance for the evolution of massive stars.

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Abbreviations

The following abbreviations are used in this manuscript:

BSG	Blue Supergiant
ESO	European Southern Observatory
HRD	Hertzsprung-Russell Diagram
HST	Hubble Space Telescope
JWST	James Webb Space Telescope
LBV	Luminous Blue Variable
LMC	Large Magellanic Cloud
LSST	Large Synoptic Survey Telescope
MMT	(converted) Multi Mirror Telescope
NOAO	National Optical Astronomy Observatory
RSG	Red Supergiant
SMC	Small Magellanic Cloud
SN	supernova
WFIRST	Wide Field Infrared Survey Telescope
WHT	William Herschel Telescope
WR	Wolf-Rayet star

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