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# The nebulae around LBVs: a multiwavelength approach

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**Abstract:** We present first results of our study of a sample of Galactic LBV, aimed to contribute to a better understanding of the LBV phenomenon, by recovering the mass-loss history of the central object from the analysis of its associated nebula. Mass-loss properties have been derived by a synergistic use of different techniques, at different wavelengths, to obtain high-resolution, multi-wavelength maps, tracing the different emitting components coexisting in the stellar ejecta: the ionized/neutral gas and the dust. Evidence for asymmetric mass-loss and observational evidence of possible mutual interaction between gas and dust components have been observed by the comparison of mid-IR (Spitzer/IRAC, VLT/VISIR) and radio (VLA) images of the nebulae, while important information on the gas and dust composition have been derived from Spitzer/IRS spectra.

## 1 Introduction

Luminous Blue Variables are luminous (intrinsically bright,  $L \sim 10^4 L_\odot$ ), which show different kinds of photometric and spectroscopic variabilities. They are massive ( $M \sim 22 - 120 M_\odot$ ), characterized by intense mass-loss rates ( $10^{-6} - 10^{-4} M_\odot \text{yr}^{-1}$ ), which can occur also in the form of eruptive events. LBVs are quite rare objects in our Galaxy. This is probably connected to their very short lifetime (some  $10^4 \text{yr}$ s). The most recent census of Galactic LBVs counts 12 effective members and 23 candidates (Clark et al. 2005) and a few LBV (and candidates) have been also reported in some nearby galaxies.

LBVs represent a crucial phase in massive star evolution during which a star loses enough mass to become a  $\sim 20 M_\odot$  WR star. To test evolutionary models, it is extremely important to quantify a key parameter: the total mass lost during the LBV phase, i.e. the gas (ionized, neutral, and molecular, if it exists) and the dust. Another important aspect of the study of circumstellar envelopes is to determine the mass-loss archeology of central star and in particular how the mass-loss behavior (multiple events, bursts) is related to the physical parameters of the central object.

## 2 The project

A good understanding of the physical conditions in LBV ejecta requires multi-wavelength observations, tracing the different emitting components coexisting in the stellar ejecta: the ionized/neutral gas and the dust. The study of both components provides two kinds of information: current mass-loss, via direct observations of stellar winds (the gas component), and mass loss history of the central star, by analysis of the dust component/s. The detailed knowledge of the gas and dust distribution allows us to evaluate the total (gas+dust) mass of the nebula, the presence of different shells related to different mass-loss episodes, and thus the total mass lost by the central object during this critical phase of its evolution. Moreover, it could provide evidence for gas and dust mutual interactions which are a possible cause of the quite complex morphologies often observed in the LBVNs.

In the last few years we have started a systematic study of a sample of Galactic LBVs and LBV candidates aimed at deriving their mass-loss properties for a better understanding of the LBV phenomenon in the wider context of massive star evolution. Our approach is based on a synergistic use of different techniques, at different wavelengths, that allows us to analyze the several emitting components coexisting in the nebula. In particular, we performed a detailed comparison of mid-IR and radio maps, with comparable spatial resolution, to sort out the spatial differences in the maps in order to detect particular features which can be associated with mass-loss during the LBV phase: asymmetric winds versus symmetric winds in asymmetric environments; single events versus multiple events. In the framework of our LBV project, we obtained Spitzer/IRAC observations aimed at detecting and resolving the faint dust shells ejected from the central stars, and Spitzer/IRS observations to characterize the dust content of the nebula via mid-IR spectra. The ionised fraction of the nebulae has been mapped via high-angular resolution radio (VLA) observations. For the more compact nebulae, images in the mid-IR have been obtained by using VLT/VISIR in the N and Q mid-IR bands.

## 3 Results

Many interesting results have been obtained from our imaging and spectroscopic program. In particular, extended dusty shells have been detected around some of our targets (see Fig. 1) and evidence for asymmetric mass-loss and of possible mutual interaction between gas and dust components is suggested by the comparison of VLT/VISIR and VLA images of the more compact nebulae. The analysis of the mid-IR spectra has provided information on the gas and dust composition, allowing identification of the mineral composition of LBV ejecta and to discriminate between crystalline or amorphous dust components. Moreover, the presence of low-excitation atomic fine structure lines points out the existence of a photodissociation region (PDR), an extra component of neutral/molecular gas that should be taken into account when one determines the total budget of mass lost by the star during its LBV phase. We present examples of our results in the following sections. More details can be found in a series of papers devoted to the project.

### 3.1 IRAS 18576+034

This is the object which shows the most extreme difference between the ionized gas component (traced by free-free emission) and the dust component (Fig. 2). High spatial resolution and high sensitivity images of IRAS 18576+0341 were obtained using the mid infrared imager VISIR at the Very Large Telescope and the Very Large Array interferometer (see Buemi et al., 2010 for details). The approximately circularly-symmetric, mid-IR nebula strongly contrasts with the asymmetry that characterizes the ionized component of the envelope, as seen in the radio and [Ne II] line images. Among possible scenarios for the cause of the observed asymmetry in the ionized gas morphology



Figure 1: IRAC composite image of Wray 17-96 with north up and east to the left,  $FOV = 5''$ . Emission from the central star is evident at  $3.6\mu m$  (Blue), while the warm dust is well traced by the  $8.5\mu m$  (Red)

are an unseen external ionizing source (either a companion or shocked gas) or holes in the dusty material. However, at the moment it is not possible to discriminate amongst them.

The detailed mid-IR maps allowed us to determine the size of the dusty nebula ( $R_{dust}=7''$ ), the dust temperature distribution, and the total dust mass. From the total dust mass (Buemi et al. 2010), assuming a gas to dust ratio of 100, a total nebular mass of  $\sim 0.5M_{\odot}$  is derived. If this material is expanding at  $70 km/sec$  (Clark et al. 2009), we derive an averaged mass-loss rate of  $\sim 1 \times 10^{-4}M_{\odot}yr^{-1}$  during the nebula formation. However, the dust distribution in the nebula is consistent with a strong mass-loss episode that occurred  $\sim 2000$  years ago (Buemi et al. 2010), indicating the mass-loss is not constant, with different quantity of mass released during episodes of different duration. This result is corroborated by the current-day mass loss rate of  $3.7 \times 10^{-5}M_{\odot}yr^{-1}$  from the central object as measured in the radio (Umana et al. 2005), which is smaller than the average value necessary to fill up the circumstellar nebula.

### 3.2 HR Car

HR Car is surrounded by a faint, low-excitation nebula which is difficult to observe because of the high luminosity of the central object. One of the most striking properties of the nebula is the difference between the large scale optical morphology and the inner, strongly asymmetric, radio nebula (see White 2000). Our spectroscopic Spitzer/IRS observations of the inner nebula reveal a rich mid-IR spectrum showing both solid state and atomic gas signatures (Umana et al. 2009). The characteristic broad feature at  $10\mu m$  indicates the presence of amorphous silicates, suggesting that dust formation occurred during the LBV outburst. This is in contrast with the detection of crystalline dust in other Galactic LBVs that are probably more evolved. The crystalline dust is similar to the dust observed in red supergiants that has been considered to be evidence of dust production during evolutionary phases prior to the outburst (Waters et al. 1998). Strong low-excitation atomic fine structure lines such as  $26.0\mu m$  [Fe II] and  $34.8\mu m$  [Si II] indicate, for the first time, the presence of a PDR around this object class. While the physics and chemistry of the low-excitation gas appears

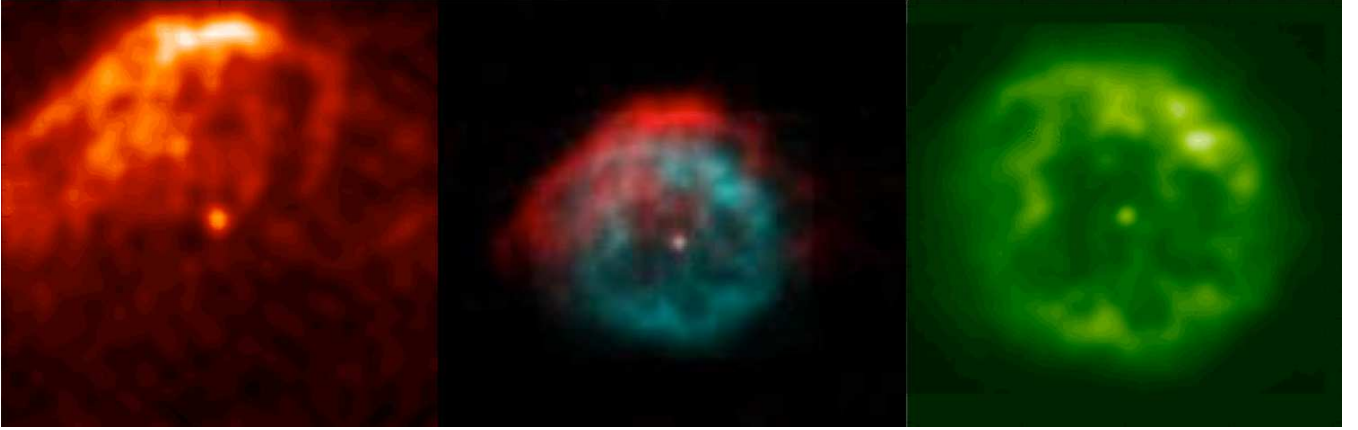


Figure 2: (center) Multi-configuration 6-*cm* VLA map (red) superimposed on the 11.26- $\mu\text{m}$  VISIR map (blue) of IRAS 18576+0341. Both maps have north up and east to the left. The center image is 20'' across. A zoomed (FOV 8'') of the VLA map (left) and of the VISIR map (right) are also shown (adapted from Buemi et al. 2010).

to be dominated by photodissociation, a possible contribution due to shocks can be inferred from the evidence of gas phase Fe abundance enhancement.

### 3.3 HD 168625

Our mid-IR spectroscopic observations (IRS) of this LBV candidate detected spectral features attributable to polycyclic aromatic hydrocarbons (PAHs), indicating the presence of a PDR around the ionized nebula. This result enlarges the number of LBV and LBV candidates where the presence of a PDR has been confirmed, implying the importance of such a component in the budget of total mass lost by the central object during this elusive phase of massive star evolution.

We have analyzed and compared the mid-IR and radio maps, and derive several results concerning the associated nebula (Umana et al. 2010). While the overall torus-like shape of the dust morphology is confirmed, the higher resolution and sensitivity of our images allow us to discern finer details of the dust distribution, most notably the highly structured texture of the nebula, and provide a better localization of the dust ring, with its north-west and south-east condensations (Fig. 3). There is also evidence for grain distribution variations across the nebula, with a predominant contribution from larger grains in the northern part of the nebula while PAH and smaller grains are more segregated in the southern part.

Besides via optical emission, the ionized part of the nebula can be traced by radio observations, without suffering of intrinsic extinction. We have obtained a 3.6-*cm* VLA map by using the interferometer in two configurations to determine the structure down to sub-arcsec scale without resolving out the more extended emission (Fig 4). The overall ionized nebula is reminiscent of the dust distribution, with one main difference: the brightest radio emission is located where there is a lack of thermal dust grains, corroborating the hypothesis of the presence of a shock in the southern portion of the nebula as consequence of the interaction of a fast outflow with the slower, expanding dusty nebula. Such a shock would be a viable means for PAH production as well as for changes in the grain size distribution. Finally, from the detection of a central radio component, very probably associated with the wind from the central massive supergiant, we derive a current mass-loss rate of  $\dot{M} = (1.46 \pm 0.15) \times 10^{-6} M_{\odot} \text{yr}^{-1}$ .

### 3.4 Future prospects

The study of the LBV phenomenon has been hampered by the lack of a significant sample of objects with associated nebulae. The presence of an extended, dusty circumstellar nebula can be identified by its IR/mid-IR fingerprints. Therefore, we can search among proposed candidates by assessing the presence of observational characteristics that define a LBV. A good possibility is offered by the more than 400 bubbles identified at  $24\mu m$  by Mizuno et al., 2010 in the Galactic Plane survey conducted with MIPS on the Spitzer Space telescope (MIPSGAL). These small ( $\leq 1'$ ) rings, bubbles, disks or shells are pervasive through the entire Galactic plane in the mid-infrared. Whatever the nature of these  $24\mu m$  sources, the implications of such a large number in the Galactic plane is remarkable and they provide a powerful "game reserve" for evolved massive stars as already pointed out by Wachter et al (these proceedings).

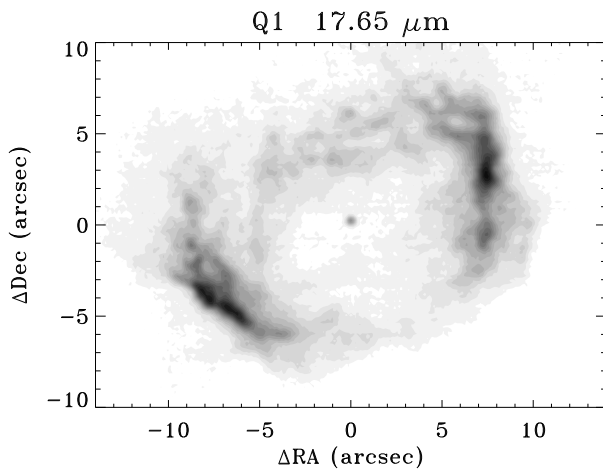


Figure 3: VISIR map of HD 168625 in the Q1 continuum filter. The brightness levels range from 0 to  $8.06 \text{ Jy arcsec}^{-2}$ .

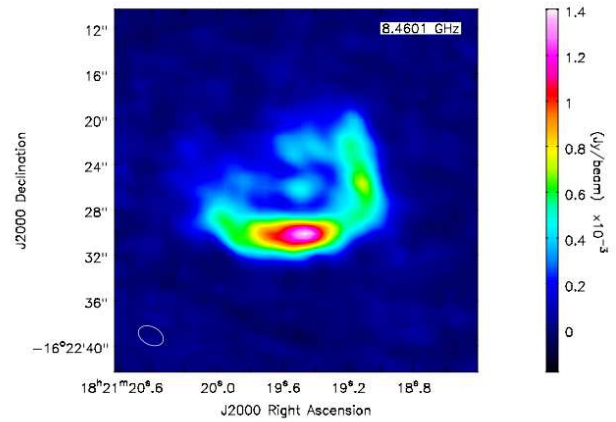


Figure 4: The multi-configuration 3.6-cm VLA map of HD168625. The point-like central source, whose coordinates coincides with that of the central object, is probably related to the current-day stellar wind of the LBV.

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