Central stars of mid-infrared nebulae discovered with Spitzer and WISE

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Abstract. Searches for compact mid-IR nebulae with the Spitzer Space Telescope and the Wide-field Infrared Survey Explorer (WISE), accompanied by spectroscopic observations of central stars of these nebulae led to the discovery of many dozens of massive stars at different evolutionary stages, of which the most numerous are candidate luminous blue variables (LBVs). In this paper, we give a census of candidate and confirmed Galactic LBVs revealed with Spitzer and WISE, and present some new results of spectroscopic observations of central stars of mid-IR nebulae.

1. Introduction

The majority of massive stars reside in binary systems (Sana et al. 2012) and can lose a significant fraction of their initial mass because of interaction with their companion stars through mass transfer, common envelope evolution or merger. In addition to binary interaction processes, the copious stellar winds of the most massive stars also significantly reduce their initial masses. The material lost by massive stars can, in principle, be detected as parsec-scale circumstellar nebulae. But since these stars form in star clusters and the majority of them end their lives there, the origin of coherent (observable) nebulae around stars residing in their parent clusters is hampered by the effect of stellar winds and ionizing emission from nearby massive stars. On the other hand, about 20% of OB stars escape from their birth places because of dynamical encounters with other massive stars or because of supernova explosions in binary systems (Blaauw 1961; Gies 1987). These so-called runaway stars are more suitable for producing observable circumstellar nebulae because they are not exposed to destructive influence of nearby massive stars. Indeed, the vast majority of known circumstellar nebulae are associated with stars located either in the field (e.g. nebulae around the bona fide LBVs AG Car and HR Car) or at the outskirts of their parent clusters (e.g. the Pistol Nebula).

Among stars of different evolutionary stages the circumstellar nebulae are very common for LBVs, of which more than 70% have associated nebulae (Kniazev, Gvara-
The circumstellar nebulae can also be found around late nitrogen sequence Wolf-Rayet stars and blue supergiants (BSGs), and less frequently around red supergiants, Be and B[e] stars. The detection of nebulae reminiscent of those associated with known massive stars serves as a strong indication that their central stars are massive as well. Indeed, follow-up spectroscopy of stars selected in this way has led to the discovery of many dozens of massive stars at various evolutionary stages (Clark 2003; Gvaramadze et al. 2009, 2010a,b, 2012, 2014a,b, 2015a; Gvaramadze, Kniazev, & Fabrika 2010c; Gvaramadze, Kniazev, & Berdnikov 2015b; Wachter et al. 2010, 2011; Mauerhan et al. 2010; Stringfellow et al. 2012a,b; Burgemeister et al. 2013; Flagey et al. 2014; Kniazev & Gvaramadze 2015; Kniazev et al. 2015, 2016). Given the high percentage of LBVs having circumstellar nebulae, it is not surprising that many of the newly identified massive stars show LBV-like spectra and therefore were classified as candidate LBVs (cLBVs). In this paper, we give a census of (c)LBVs revealed with Spitzer and WISE, and present some new results of spectroscopic observations of central stars of mid-infrared (mid-IR) nebulae.

2. Mid-IR nebulae discovered with Spitzer and WISE

Because of high visual extinction in the Galactic plane – close to which the majority of massive stars are concentrated – the most effective way for detection of circumstellar nebulae is through mid-IR observations. Using data from various Spitzer Legacy Programmes\(^1\) and the WISE all-sky survey (Wright et al. 2010), we detected about 250 nebulae with central stars. These nebulae have a wide range of morphologies, ranging from circular and ring-like to bipolar and more complex forms (see Fig. 2). 115 of them were discovered with Spitzer by 2010 and presented in Gvaramadze et al. (2010c), while others were detected later on with either Spitzer or WISE. Almost all of the nebulae were found in the Spitzer 24 µm or WISE 22 µm images. A two times lower angular resolution of the WISE data resulted in that the nebulae detected with this telescope have, in general, larger angular dimensions, which suggests that they are located at closer distances. This is supported by the fact that the percentage of WISE nebulae having optical counterparts is higher than that among the nebulae detected with Spitzer (see Fig. 4 for three examples of such WISE nebulae).

3. Central stars of mid-IR nebulae discovered with Spitzer and WISE

The majority of the central stars are either invisible or dim in the optical band. To determine their nature, one needs therefore to use IR telescopes or large (8–10-m class) optical ones. Fig. 1 (right panel) shows Spitzer 24 µm images of five nebulae, whose central stars are visible only in the IR and whose K-band spectra, taken with the ISAAC spectrograph on the ESO Very Large Telescope (VLT), are presented in the same figure (left panel). Interestingly, although all five nebulae look quite different, their spectra are very similar to each other and to those of known LBVs (see e.g. fig. 2 in Stringfellow et al. 2012b), which suggests a classification of these stars as cLBVs.

Optical and IR spectroscopy of other central stars, carried out by our and two other independent groups, led to the discovery of 40 cLBVs, which doubled the number of

\(^1\)http://sha.ipac.caltech.edu/applications/Spitzer/SHA/
known Galactic stars of this type (cf. Clark, Larionov, & Arkharov 2005). Moreover, follow-up spectroscopic and photometric monitoring of some of these cLBVs revealed significant changes in the spectra and brightness of four of them, Wray 16-137 (Gvaramadze et al. 2014b), WS1 (Kniazev et al. 2015), MN44 (Gvaramadze et al. 2015b) and MN48 (Kniazev et al. 2016), implying that these stars belong to the family of Galactic bona fide LBVs, which currently consists of 18 members (see table 2 of Kniazev & Gvaramadze 2015). In Table 1 we give a current census of candidate and bona fide LBVs discovered with Spitzer and WISE.

In Fig. 2 (left panel) we show images of nebulae around 36 cLBVs to further illustrate the variety of shapes inherent to these nebulae. In the same figure (right panel), we also show nebulae around 6 BSGs: from up to bottom, respectively, WS3 (or BD+60° 2668), MN18, WS29 (or ALS 19653), MN94, MN108 and MN113. One can see that the nebulae associated with both types of stars show a wide range of morphologies and that individual objects from one group of nebulae have close counterparts among nebulae from the other group. Possible implications of this similarity is that (i) some BSGs might be dormant LBVs, (ii) nebulae around some (c)LBVs might be formed during the preceding evolutionary stages and therefore their origin is not necessarily related to episodes of enhanced mass loss experienced by LBVs. Also, the variety of shapes inherent to nebulae around (c)LBVs and BSGs suggests that several mechanisms might be responsible for their formation and, perhaps, for triggering the LBV activity of massive stars.

Finally, in Figs 3 and 4 we present spectra and images at several wavelengths of two of the six BSGs shown in Fig. 2. Both these BSGs, WS3 and WS29, were discovered through detection of their circumstellar nebulae with WISE and both nebulae have optical counterparts, detected respectively in the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS; González-Solares et al. 2008) and the Digitized Sky Survey II (DSS-II; McLean et al. 2000). Note that the central star of WS3 consists of two components (separated by about 3 arcsec), which we classify as B0 Ib and B5-6 Ib.
Table 1. Candidate and bona fide LBVs discovered with Spitzer and WISE.

| cLBVs |   |   |   |   |   |
|-------|---|---|---|---|---|
| MN1<sup>a</sup> | Hen 3-729<sup>b</sup> | MN7<sup>b</sup> | MN8<sup>a</sup> | MN13<sup>c</sup> | MN30<sup>c</sup> |
| MN39<sup>c</sup> | IRAS 16115−5044<sup>b</sup> | MN41<sup>c</sup> | WMD14<sup>a</sup> | MN42<sup>c,d</sup> | MN45<sup>a</sup> |
| MN46<sup>e</sup> | MN47<sup>c</sup> | MN51<sup>a</sup> | MN53<sup>c</sup> | MN55<sup>a</sup> | MN56<sup>f</sup> |
| WS2<sup>g</sup> | MN58<sup>c,h</sup> | MN61<sup>c,h</sup> | MN64<sup>a</sup> | MN68<sup>a,c</sup> | MN76<sup>d</sup> |
| MN79<sup>c,i</sup> | MN80<sup>h</sup> | MN81<sup>i</sup> | MN83<sup>h</sup> | MN84<sup>a,h</sup> | MN87<sup>j</sup> |
| MN90<sup>c</sup> | IRAS 18433−0228<sup>i</sup> | MN96<sup>c,d</sup> | MN101<sup>c,d</sup> | MN107<sup>i</sup> | MN112<sup>k</sup> |
| LBVs: |   |   |   |   |   |
| WS1<sup>i</sup> | Wray 16-137<sup>m</sup> | MN44<sup>n</sup> | MN48<sup>o</sup> |

<sup>a</sup>Wacht et al. (2010); <sup>b</sup>Kniazev & Gvaramadze (2015); <sup>c</sup>Wacht et al. (2011); <sup>d</sup>Stringfellow et al. (2012a); <sup>e</sup>Gvaramadze et al. (2010c); <sup>f</sup>Gvaramadze et al. (2015a); <sup>g</sup>Gvaramadze et al. (2012); <sup>h</sup>Stringfellow et al. (2012b); <sup>i</sup>Flagey et al. (2014); <sup>j</sup>Ingallinera et al. (2016); <sup>k</sup>Gvaramadze et al. (2010b); <sup>l</sup>Kniazev et al. (2015); <sup>m</sup>Gvaramadze et al. (2014b); <sup>n</sup>Gvaramadze et al. (2015b); <sup>o</sup>Kniazev et al. (2016).

Note also that WS29 is indicated in the SIMBAD data base as a planetary nebula (PN), while our spectroscopy shows that it is a B0 Ib star.

Figure 2. Spitzer and WISE images of nebulae associated with 36 cLBVs (shown in the left panel in the same order as they appear in Table 1) and 6 BSGs (right panel). See text for details.

4. By-products

It should be noted that only two of the newly-discovered mid-IR nebulae with central stars, namely MN102 and WS31, turn out to be PNe, and both of them have optical counterparts. MN102 was discovered with Spitzer and its central star is of [WC] type
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Figure 3. Normalized spectra of WS29 (ALS 19653) and two components of WS3 (BD+60° 2668) obtained respectively with the Southern African Large Telescope and the 3.5-m telescope in the Observatory of Calar Alto (Spain).

Figure 4. Multi-wavelength images of three nebulae discovered with WISE. Upper rows show WISE 22 (left) and 12 µm images of each nebula. Left panels in the bottom rows are the 2MASS K-band images, while the right panels are the IPHAS Hα (WS3 and WS29) and the DSS-II red band (WS31) images. See text for details.

(Gvaramadze et al. 2010c; see also Flagey et al. 2014). WS31 was detected with WISE. In the 22 and 12 µm images it appears as a circular nebula without a central star (Fig. 4, right panel), which is also not visible in other WISE and all 2MASS (Two Micron All-Sky Survey; Skrutskie et al. 2006) wavebands. Surprisingly, we found that this nebula has an obvious, previously unknown, counterpart in the DSS-II red band image. We identified the central star of the nebula with a blue star at RA(J2000)=22h27m39.19 and Dec.(J2000)=+66°44′09″.6 (marked in the DSS-II image by a white circle). The Seventh Data Release of the Sloan Digital Sky Survey (Abazajian et al. 2009) provides for this star the following photometry: $u=21.116\pm0.115$ mag, $g=20.540\pm0.027$ mag,
$r = 20.087 \pm 0.025$ mag, $i = 19.846 \pm 0.028$ mag and $z = 19.706 \pm 0.090$ mag. To our knowledge, this is the first new PN detected with WISE.

5. Conclusions

- Mid-IR imaging provides a powerful tool for revealing LBVs and related stars.
- Spectroscopic and photometric observations of the newly-identified cLBVs continue, with discoveries of new bona fide LBVs anticipated.

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