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Massive Stars with Circumstellar Shells Discovered with the Spitzer Space Telescope

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Abstract: We report on our ongoing efforts to characterize the luminous central stars of circumstellar shell sources discovered with the Spitzer Space Telescope. The objects in our selection are highly symmetric, circular and elliptical shells, most prominent at 24μm, and the vast majority of the shells and central sources has never been studied previously. We obtained near-IR spectroscopic observations of the central stars and find the overwhelming number of these objects to be massive stars, including new Wolf Rayet stars and Luminous Blue Variable candidates.

1 Introduction

Massive stars play a key role in the chemical and mechanical evolution of the ISM in galaxies. These luminous stars with their strong winds and mass outflows are the dominating influence on their environment in terms of energetics and chemical modification of the ISM. Despite their importance, our knowledge about their formation and evolution is surprisingly limited. In particular, the post main sequence evolution of massive stars, where they shed most of their mass, is poorly understood. Observationally, this stage can be explored through the study of Wolf-Rayet stars (WRs), luminous blue variables (LBVs) and red supergiants.

Recently, a large population of obscured evolved massive stars has been revealed through their prominent circumstellar shells at 24 μm (Wachter et al. 2010, Mizuno et al. 2010, Gvaramadze et al. 2010) based on the data from the MIPSGAL legacy survey (Carey et al. 2009) conducted with the Spitzer Space Telescope. In Wachter et al. (2010), we selected a subsample of the 62 most well-defined, symmetrical shells with obvious central sources for an in depth follow-up study. A SIMBAD search within 2' of the shell locations revealed that most of these objects (90% of the shells, 80% of the central sources) had not been previously studied. The radii of our shells range from 0.14' - 2.4' with a formal average of 0.7'. Follow-up investigation utilizing the complementary data from the GLIMPSE Spitzer Legacy project (Benjamin et al. 2003), as well as 2MASS and the Digitized Sky Survey shows that about 60% of these shells are *only* detected at 24μm (the 8 and 24μm images of the shells are displayed in Wachter et al. 2010). This is somewhat unusual, as we generally expect a strong emission component due to polycyclic aromatic hydrocarbons (PAHs) at 8μm if we are simply observing warm dust continuum emission.

We report here on additional spectroscopic results for our sample of 24μm shell central sources.

2 Results

We summarize here the results of our newly acquired IR spectroscopy. Data were obtained on three nights in May 2010 on SOAR with OSIRIS, providing R $\sim$ 1200 JHK spectra, and on 19-20 June 2010 with Triplespec on the Palomar 200 inch telescope, with a slightly higher resolution of R $\sim$ 2700. In addition to the remaining targets from our sample detailed in Wachter et al. (2010), we also obtained data for the more asymmetric and/or bipolar shells included in the sample of Gvaramadze et al. (2010). A preliminary classification of all the newly observed central sources is presented in Table 1.

Table 1: Preliminary classification of newly observed shell central stars.

Name	Type		Name	Type
WMD 002	late type		MN 009	WN 8-9h
WMD 012	late type		MN 010	OB
WMD 015	B[e]/LBV		MN 013	B[e]/LBV
WMD 018*	B[e]/LBV		MN 018*	OB
WMD 019	B[e]/LBV		MN 031	OB
WMD 020*	Be		MN 039	B[e]/LBV
WMD 027	B[e]/LBV		MN 041*	B[e]/LBV
WMD 030	B[e]/LBV		MN 053	B[e]/LBV
WMD 032*	OB		MN 069	OB
WMD 035	OB		MN 079	B[e]/LBV
WMD 036*	B[e]/LBV		MN 092	OB
WMD 038	Be		MN 094	OB
WMD 039*	Be		MN 101	B[e]/LBV
WMD 041	WN 8-9h		MN 106	late type
WMD 042	B/A		MN 107	Be
WMD 047	WN 8-9h		MN 108*	OB
WMD 048	WN 8-9h		MN 109*	OB
WMD 050*	WN 3-4			
WMD 051	B[e]/LBV			
WMD 053	WN 9h			
WMD 054	B[e]/LBV/WN			
WMD 055	OB			
WMD 056	Be			

Targets labeled "WMD" correspond to the central stars of the shells of Wachter et al. (2010), targets designated as "MN" are from the sample of Gvaramadze et al. (2010). The * indicates sources which were already classified in Wachter et al. (2010) or Gvaramadze et al. (2010), but were reobserved to improve the S/N, search for variability, or cover a different wavelength range. A detailed comparison with existing data for these sources will be discussed in a future publication.

We discovered five new WR stars, namely the central sources of the shells WMD 041, 047, 048, 053, and MN 009. A detailed analysis for the twin WN stars at the center of the double shell complex WMD 047/048 is presented in Mauerhan et al. (2010), the remaining spectra of the WR sources are displayed in Figure 1. WMD 050 has previously been observed in the optical by Wachter et al. (2010). Curiously, the WR spectral type was determined to be WN6 from the optical spectrum, while

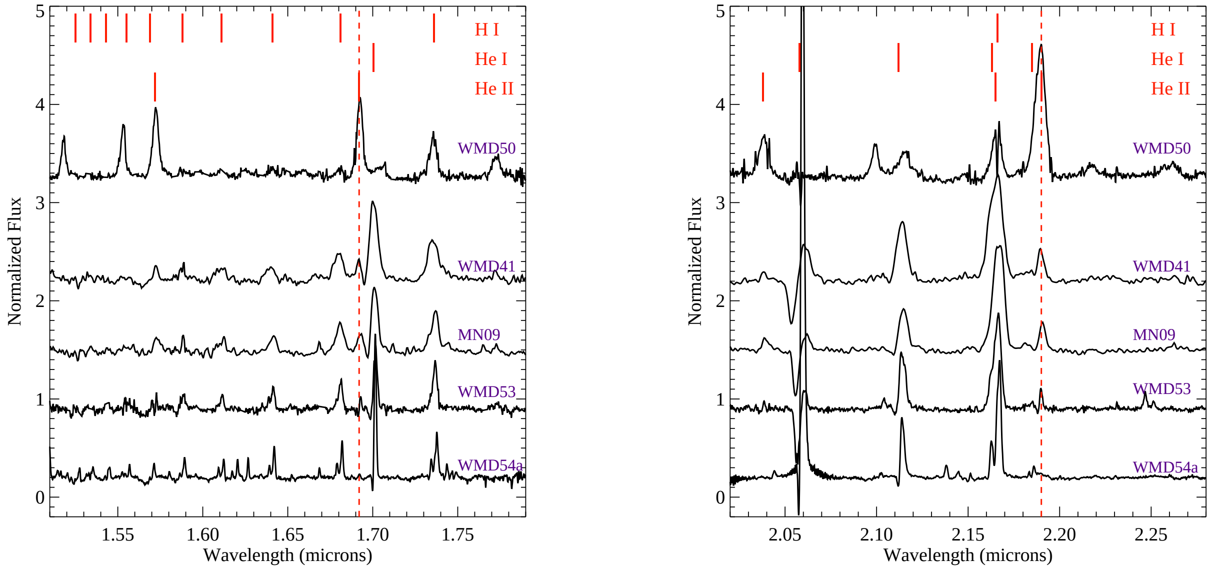

Figure 1: H and K band spectra of newly discovered WR stars.

the IR classification indicates an earlier type, WN3-4. We also find a treasure trove of potential LBV candidates, designated as B[e]/LBV in Table 1. An example of some of the spectra are shown in Figure 2. WMD 054 is an interesting source, as it exhibits emission features similar to both the WR and the B[e]/LBV group of sources (bottom spectrum of Figures 1 and 2), possibly even a hint of the He II 2.189μm line. Finally, we identify 11 OB type central stars, some of which are shown in Figure 3. More detailed analysis is needed to classify these stars in terms of luminosity class, but it is already apparent that OB central stars are preferentially located in shells with asymmetric or bipolar morphology.

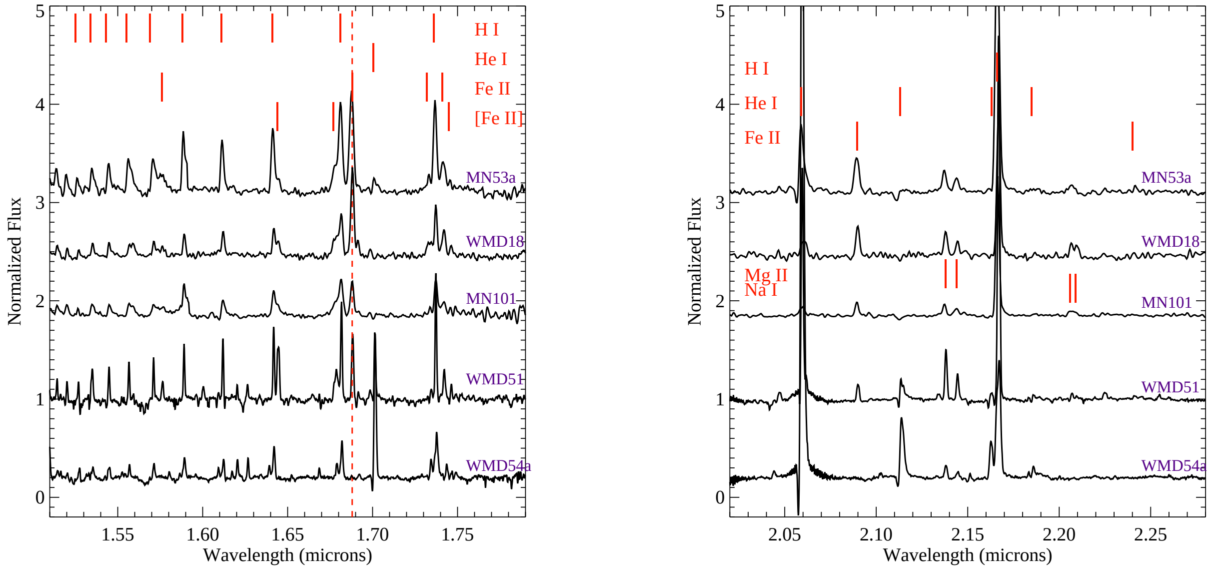

Figure 2: H and K band spectra of a subsample of the newly discovered B[e]/LBV type stars.

We assembled 2MASS and GLIMPSE photometry for each source and constructed a color-color diagram (Figure 4) following Mauerhan et al. (2009) and Hadfield et al. (2007). The various types of sources we have identified spectroscopically are indicated by different colors (see the caption of

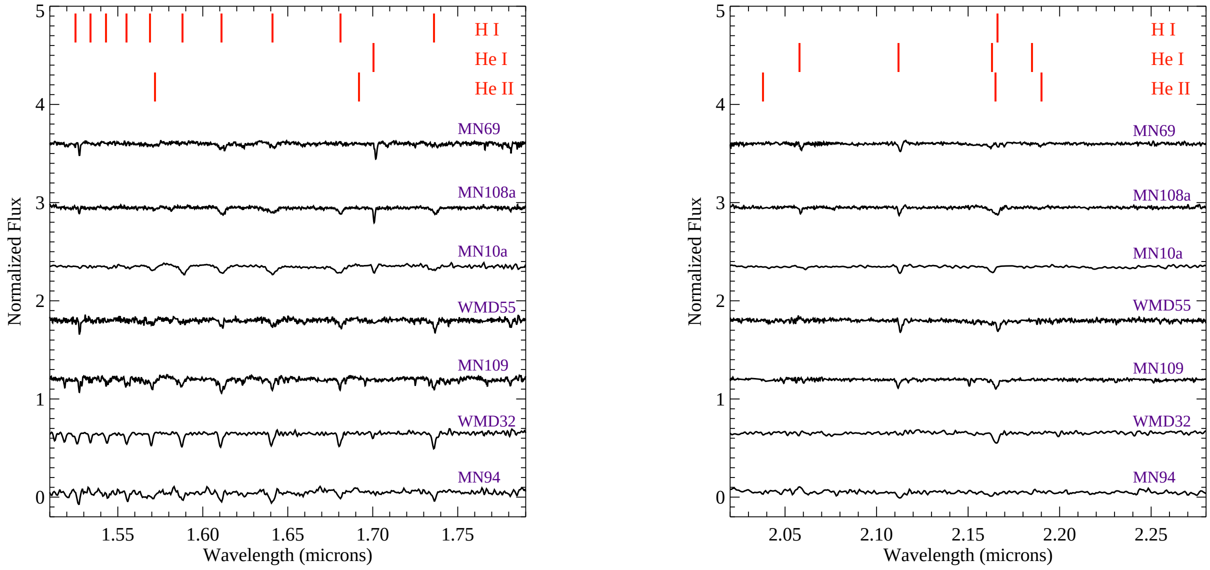

Figure 3: H and K band spectra of a subsample of the newly discovered OB type central stars.

Figure 4 for details). While there is clearly some overlap between the various types of sources, some general trends emerge. The WR stars (red points) in our sample separate quite cleanly from the main locus of field stars and form a surprisingly well-defined and tight sequence, roughly parallel to the reddening vector. The direction of the reddening vector at the locus of our WR stars is indicated by the dashed line. Compared to the analogous figure presented in Mauerhan et al. (2009), about half of our WR points have larger $J - Ks$ values, indicating a more heavily reddened population. B stars and LBV candidates appear to populate the locus in between the normal stars and the WR track. These photometric criteria can prove extremely useful in identifying additional transition stars *without* circumstellar nebulae in the vicinity of our shell sources. For example, we have spectroscopically identified a previously unknown WC and O7-8 star in the immediate environment of the double shell complex WMD 047/048 (Mauerhan et al. 2010) based on their position in the local color-color diagram. We are currently conducting similar searches around all the shell sources in our sample.

Overall, our sample of 62 sources contains 10 WR stars, eight of which are new identifications, as well as five OB type stars. Most strikingly, our study revealed a large number of new LBV candidates. Our sample of shells includes four known LBV type stars (one confirmed, three candidates) and we classified an additional twenty sources as LBV candidates based on the similarities between the spectra (we include both Be and B[e] stars in this group). We realize that the classification of a particular source as an LBV involves a host of criteria, including photometric and spectroscopic variability, that still need to be investigated for these new sources. However, given the small numbers of known LBVs, the presence of a shell combined with the spectroscopic characteristics make this relatively large sample of new candidates an exciting discovery.

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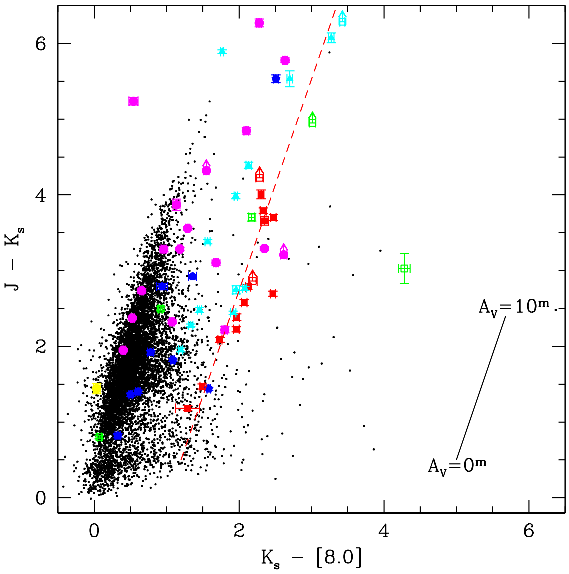

Figure 4: Color–color diagram for the sources in our sample. WR stars are indicated in red, LBVs / B[e]/LBV candidates in cyan, B stars in blue, planetary nebulae in yellow, and F-M stars in magenta. Green symbols indicate yet unclassified central sources. The comparison population of sources (black points) represents a 1 square degree "slice" of the Galactic plane from the GLIMPSE survey. The reddening vector was adapted from Indebetouw et al. (2005).

of data products from the 2 Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. It also utilized NASA's Astrophysics Data System Abstract Service and the SIMBAD database operated by CDS, Strasbourg, France.

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Discussion

D. Gies: Any evidence of more elliptical shapes among the Be star category?
S. Wachter: No. But the classification of the stars based only on IR spectra is difficult and I'm not sure these are truly classical Be stars. Also, the number of Be stars in our sample is quite small (most are B[e]/LBV types) so the statistics are not very meaningful.

S. Owocki: Why do you lump Be, B[e] and LBVs? The former should have a disk and asymmetric mass loss. The latter could well be mostly spherical.
S. Wachter: Be/B[e] and LBV stars exhibit very similar features in their IR spectra (as already noted by Morris et al. 1996). Based on their spectra (combined with the presence of a shell) we could classify all of the Be/B[e] stars in our sample as new LBV candidates. Of course we now have to study these sources in more detail to determine their luminosities, photometric + spectroscopic variability and the chemical composition and mass of their shells in order to explore this possibility further.

S. Dougherty: Were these objects picked out by eye since there seems to be a remarkable degree of symmetry in your sources - which suggests either a selection bias (by-eye detection) or that they are expanding symetrically into an evacuated medium?
S. Wachter: Yes, we assembled the original sample of > 200 shells by eye and then selected only the most symmetric shells (circular or slightly elliptical) for our in depth follow-up study presented here. So there is definitely a very strong selection bias for this sample. However, it is still a very interesting question of whether we find these circular shells in the first place because they happen to be in some preferred environment that doesn't destroy or impede the formation of the bubble.

N. Smith: Have you investigated what emission mechanism dominates the 24μm MIPS or IRAC filters? I.e. is it always dust continuum or line emission?
In cases where you have seen line emission, is it [O IV]?
S. Wachter: You can have both dust and/or line emission. We have a few spectra from Spitzer for a few of the shells. There are some with pure line emission and no sign of a dust continuum. In that case it is usually very strong [O IV] which makes the shell stand out at 24 μm. But there are also several that show a slowly rising dust continuum starting at $\sim 10\mu m$, sometimes with some emission lines (e.g. [Fe II]). These results should come out in Flagey et al. (2010) pretty soon.

M. Garcia: Do you have an estimate of the extinction caused by the dust structures?
S. Wachter: We only have an estimate of the combined extinction (interstellar and local) towards the central sources for which we can derive reliable spectral types (WR and late type stars). We don't have an estimate for the extinction in the shell structures.

W.-R. Hamann: You mentioned the need for spectroscopic data to establish the nature of the circumstellar nebulae around the WN star. I want to recall our work of the "Peony Nebula" (Barniske et al. 2008, A&A 486, 971) around WR102ka, for which we got a Spitzer spectrum in the mid-IR which revealed the whole combination of warm-dust emission, forbidden-line emission from an ionized nebula, and molecular hydrogen (H_2) emission from a photo-dissociation region (PDR).
S. Wachter: Absolutely, there are a few mid-IR spectra of known WRs and LBVs in the literature. However, I don't think we can simply assume that all of these newly discovered sources have the same SEDs and chemical composition, particularly given the differences in detection rate of the shells at $8\mu m$. All I'm saying is that it would be nice to get spectra of the shells to see if there are differences or common characteristics.