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Revealing evolved massive stars with *Spitzer*, *WISE* and SALT

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We present the results of optical spectroscopic observations of 55 candidate evolved massive stars revealed through the detection of mid-infrared nebulae of various shapes surrounding them with the *Spitzer Space Telescope* and *Wide-field Infrared Survey Explorer*. These observations, carried out with the Southern African Large Telescope (SALT) in 2010–2015, led to the discovery of about two dozens emission-line stars, of which 15 stars we classify as candidate luminous blue variables (cLBVs). Spectroscopic and photometric monitoring revealed significant changes in the spectra and brightness of four newly identified cLBVs, meaning that they are new members of the class of bona fide LBVs. We present an updated list of the Galactic bona fide LBVs. Currently, this list contains eighteen stars, of which more than 70 per cent are associated with circumstellar nebulae. We also discovered a very rare [WN] star – the central star of the planetary nebula Abell 48, and a WN3 star in a close, eccentric binary system with an O6 V star in the Large Magellanic Cloud – the first-ever extragalactic massive star identified via detection of a circular shell around it. Most of the remaining targets are tentatively classified as OB, A and M stars.

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1. Introduction

Stars more massive than $\geq 20\,M_\odot$ experience the short-lived luminous blue variable (LBV) stage [4], which among other evolutionary stages of massive stars is the most interesting in observational manifestations and perhaps the most important in the evolutionary sense [20, 25, 34, 8]. During this stage a massive star exhibits irregular spectroscopic and photometric variability on time-scales from years to decades or longer, which is reflected in changes of the stellar type from late O/early B supergiants to A/F-type ones (see e.g. [29, 7]) and changes in the brightness by several magnitudes. At the brightness maximum, LBVs could be confused with supernovae (e.g. [6, 35]), and it is believed that some LBVs could be the direct progenitors of supernovae (e.g. [24, 8]). The LBV stars experience episodes of enhanced, sometimes eruptive, mass loss, so that most of them (see [3, 22] and Table 2) are surrounded by compact ($\sim 0.1-1$ pc in diameter) shells with a wide range of morphologies (e.g. [27, 39, 12]).

The LBV phenomenon is still ill-understood, which is mostly because the LBV stars are very rare objects. The recent census of Galactic confirmed and candidate LBVs (cLBVs) presented in [36] lists only 13 and 25 stars, respectively. The discovery of additional LBVs would, therefore, be of great importance for understanding their evolutionary status and their connection to other massive transient stars, as well as for unveiling the driving mechanism(s) of the LBV phenomenon.

Detection of LBV-like shells can be considered as an indication that their associated stars are massive and evolved, and therefore could be used for the selection of candidate massive stars for follow-up spectroscopy. Because of the huge interstellar extinction in the Galactic plane, the most effective channel for the detection of circumstellar shells is through imaging with modern infrared (IR) telescopes. Application of this approach using the *Spitzer Space Telescope* and *Wide-field Infrared Survey Explorer* (*WISE*) resulted in the discovery of hundreds of such shells whose central stars could be LBVs or other types of evolved massive stars ([12, 37, 26, 13]). Indeed, follow-up optical and IR spectroscopy of these central stars led to the discovery of dozens of new cLBV, blue supergiant and Wolf-Rayet (WR) stars in the Milky Way ([9, 10, 11, 12, 37, 38, 14, 30, 31, 2, 5, 15, 16, 17, 22, 18, 19, 23]). Because of reddening many of the central stars are very dim in the optical, which makes inevitable the use of 8–10-m class telescopes like the Southern African Large Telescope (SALT). Here we report the results of optical spectroscopy with the SALT of 55 central stars of compact mid-IR nebulae discovered with *Spitzer* and *WISE*.

2. Observations

The SALT observations were carried out in 2010–2015 with the Robert Stobie Spectrograph (RSS; [1]) in the long-slit mode. In most cases, the spectra covered the range of 4200−7300 Å. The primary reduction of the data was done with SALT science pipeline. After that, the bias and gain corrected and mosaicked long-slit data were reduced in the way described in [21]. Examples of 1D finally reduced spectra of a dozen emission-line stars are shown in Figure 1, while Figure 2 presents the mid-IR images of circumstellar nebulae associated with these stars. The list of all observed targets is given in Table 1.

To search for possible spectroscopic and photometric variability of the newly identified cLBVs, we obtained additional spectra with the SALT and performed photometric monitoring of these stars

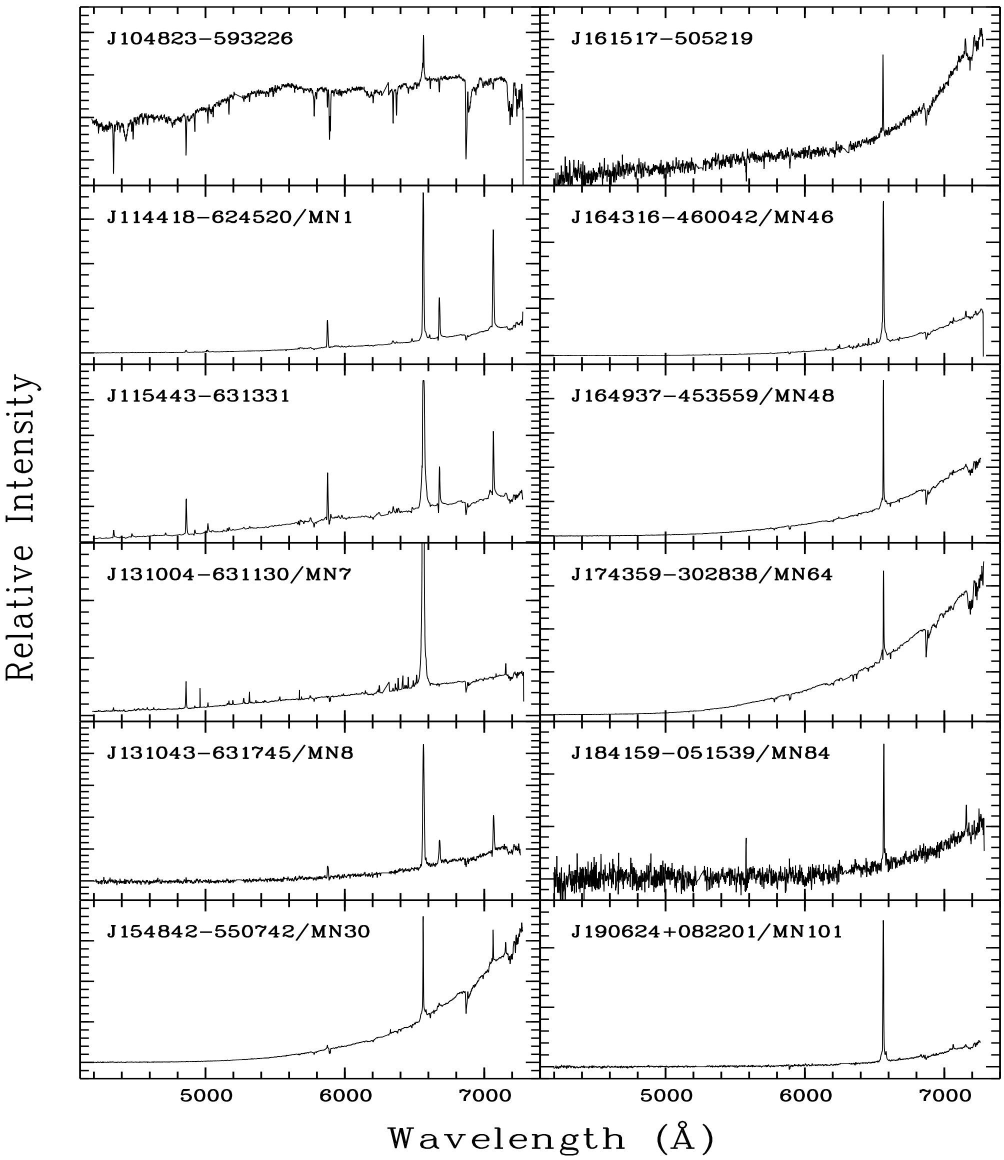

Figure 1: The observed SALT spectra of a dozen emission-line stars from our sample of candidate evolved massive stars revealed with *Spitzer* and *WISE*.

with the 76-cm telescope of the South African Astronomical Observatory.

3. Results

We carried out optical SALT spectroscopy of 55 candidate evolved massive stars. The first results of our observing program were presented in [14, 32, 16, 17, 18, 22, 19]. Table 1 summarizes the (mostly preliminary) spectral classification of the observed targets. We detected about two dozen of emission-line stars, of which 15 stars were classified as cLBVs. Subsequent spectroscopic

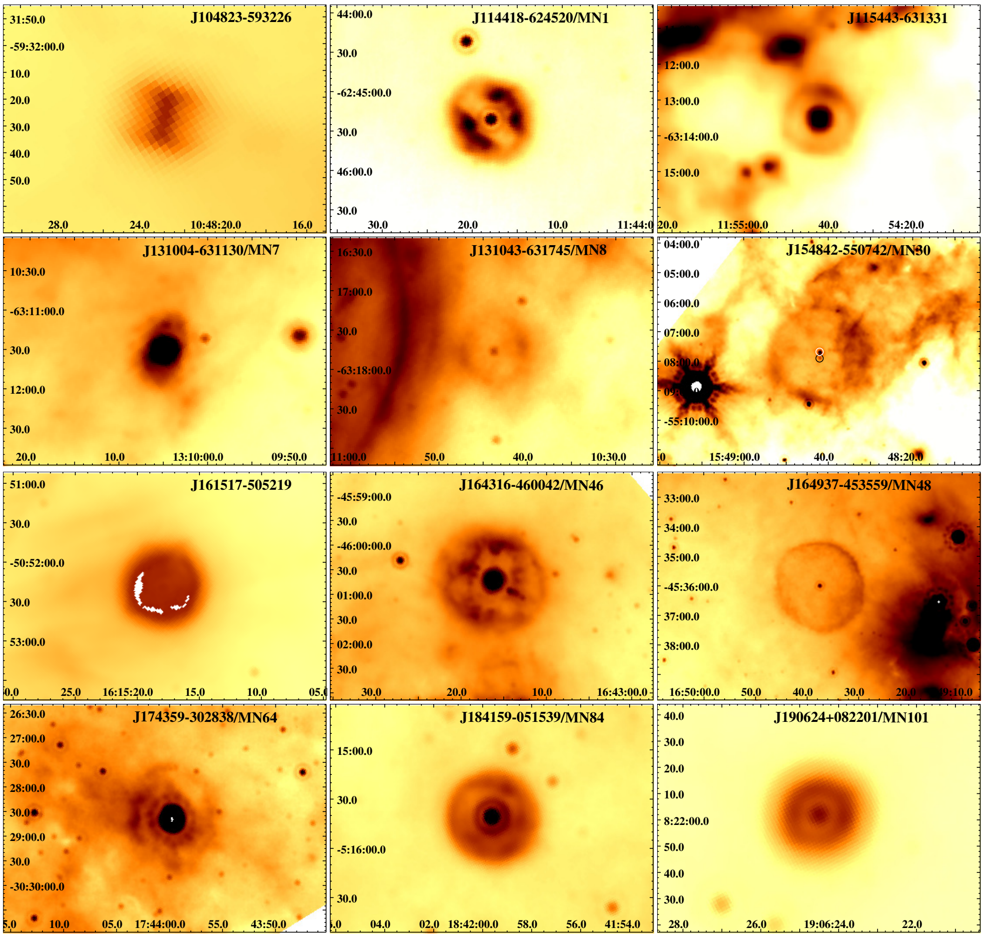

Figure 2: Mid-IR images of circumstellar nebulae around stars whose spectra are shown in Figure 1. All but one of these nebulae were discovered with *Spitzer* at 24 μm. The nebula around J115443-631331 was discovered with *WISE* at 22 μm. The nebula shown in the right panel of the second row contains two stars near the geometrical centre. One of them (marked by a white circle) is the cLBV J154842-550742/MN30. The second one (marked by a black circle) is the WC9 star J154842-550755. The coordinates are in units of RA(J2000) and Dec.(J2000) on the horizontal and vertical scales, respectively.

and photometric monitoring of these stars allowed us to confirm the LBV status of four of them (see Tables 1 and [17, 22, 19, 23]). Figure 3 shows the evolution of the spectrum of Wray 16-137 (one of the four newly identified Galactic bona fide LBVs) in 2011–2014. One can see that the He I emission lines have almost disappeared, while numerous Fe II emissions have become prominent. These changes along with significant brightness increase of the star (by about 1 mag during three years) indicate that currently Wray 16-137 experiences an S Dor-like outburst.

We also discovered a rare WN-type central star of a planetary nebula (Abell 48), which is the second known example of [WN] stars [32]. Thanks to the high angular resolution of *Spitzer* images (6 arcsec at 24 μm), we detected a new circular shell in the Large Magellanic Cloud. Follow up spectroscopy of its central star with SALT (and several other telescopes) resulted in the discovery of a new WR star in a close, eccentric binary system with an O6 V star [16]. The majority of the

Table 1: The observed central stars of mid-IR nebulae and their (mostly preliminary) spectral classification. The stars whose spectra and nebulae are presented in Figures 1 and 2 are starred.

Object (1)	Name (2)	Type (3)
J045304-692352	BAT99 3a	WN3b+O6 V[a]
J052848-705105		OB
J052412-683011	LHA 120 N	OB
J071810-265124	CD−26 4148	OB
J091714-495502		M
J100122-550046		OB
J103638-580012		Be
J104823-593226*	HD 93795	A
J110340-592559	HD 96042	OB
J111428-611820	Wray 15-780	OB
J114418-624520*	MN1	cLBV[b]
J115443-631331*		cLBV
J120058-631259	MN2	OB
J124626-632427	WRAY 17-56	PN[c]
J131004-631130*	MN7	cLBV
J131028-621331		OB
J131043-631745*	MN8	cLBV[d]
J131933-623844	MN10	OB[e]
J132647-615924		M
J133628-634538	WS1	LBV[f]
J133654-632552		OB
J135015-614855	Wray 16-137	LBV[g]
J140707-652934	CPD−64 2731	O
J143111-610202	MN14	OB
J145409-564817	TYC 8689-1568-1	Be
J151342-585318	MN17	OB
J151641-582226	MN18	B1 Ia[h]
J151959-572415	MN19	OB
J153856-563722	MN25	OB
J154527-535602	MN26	OB
J154842-550742*	MN30	cLBV[i]
J154842-550755		WC9[j]
J161132-512906	MN40	OB
J161517-505219*		cLBV[k]
J163239-494213	MN44	LBV[l]
J164316-460042*	MN46	cLBV[m]
J164937-453559*	MN48	LBV[n]
J170723-395651	MN50	M[o]
J171307-384734	CD−38 11646	OB
J172031-330949	WS2	cLBV[p]
J173753-302311		OB
J173918-312424	MN59	OB[q]
J174359-302838*	MN64	cLBV[r]
J174627-302001		OB
J180433-210326	HD 313642	A
J180612-211745	MN74	OB
J180823-221939	ALS 4684	OB
J182721-132209		OB
J183217-091614		OB[s]
J183528-064415		OB
J184159-051539*	MN84	cLBV[t]
J184246-031317		[WN5][u]
J185404+033544		M
J190421+060001	MN100	OB[v]
J190624+082201*	MN101	cLBV[w]

Notes: [a] [16]; [b] classified as an Oe/WN in [37]; [c] originally classified as a PN in [28]; [d] classified as an Oe/WN in [37]; [e] originally classified as an OB in [38]; [f] [14, 22]; [g] [17]; [h] [18]; [i] classified as a Be/B[e]/LBV in [38]; [j] originally classified as a WC9 in [38]; [k] classified as a star in transition from AGB to PN in [33]; [l] [19]; [m] [12]; [n] [23]; [o] classified as a M1 I in [37]; [p] [14]; [q] originally classified as an OB in [37]; [r] classified as a Be in [37] and as an OB in [38]; [s] classified as a BA in [38]; [t] classified as a Be/B[e]/LBV in [37] and as a cLBV in [31]; [u] originally classified as a WN6 in [37] and then re-classified as a [WN5] in [32]; [v] classified as a FG in [38]; [w] classified as B[e]/LBV in [38] and as a cLBV in [31].

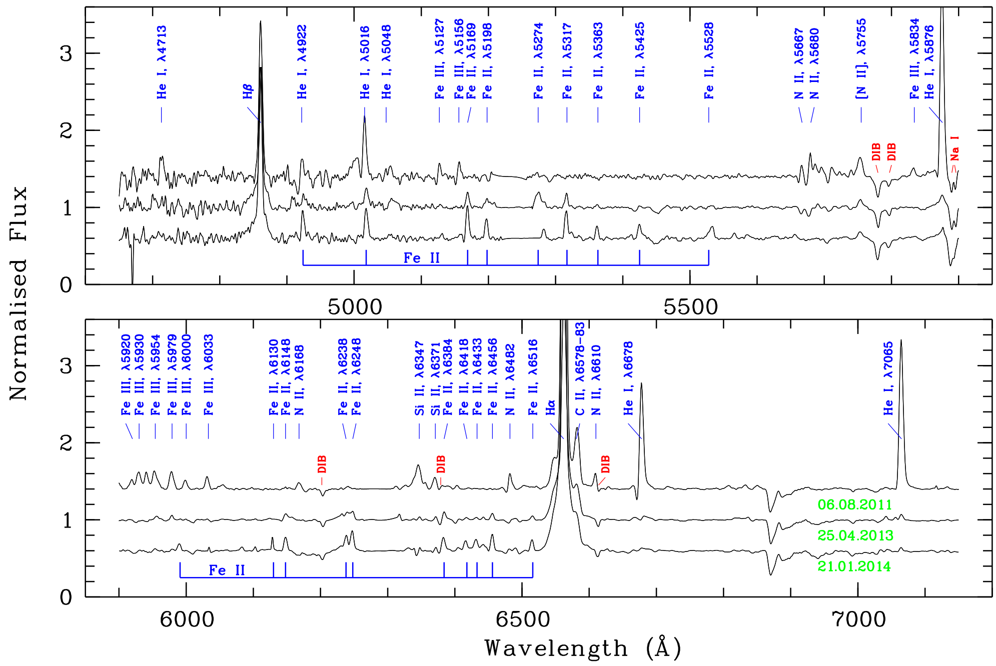

Figure 3: Evolution of the (normalized) spectrum of the new Galactic bona fide LBV Wray 16-137 in 2011–2014 (adopted from [17]).

Table 2: Current census of the Galactic bona fide LBVs. The objects with detected circumstellar nebulae are starred.

HR Car*	η Car*	AG Car*	Wray 15-751*
[GKM2012] WS1*	Wray 16-137*	[GKF2010] MN44*	Cl* Westerlund 1 W 243
[GKF2010] MN48*	HD 160529	GCIRS 34W	[MMC2010] LBV G0.120−0.048*
qF 362	HD 168607	MWC 930*	G24.73+0.69*
AFGL 2298*	P Cyg*		

remaining targets were tentatively classified as OB, A and M stars.

Finally, we present in Table 2 the current census of the Galactic bona fide LBVs (eighteen stars in total). The objects with detected circumstellar nebulae are starred. As follows from the table, 72 per cent of the Galactic confirmed LBVs are associated with nebulae. This provides further proof that the detection of compact mid-IR shells is a powerful tool for identifying (candidate) LBVs. Searches for new mid-IR nebulae continue, with further discoveries of LBVs and other related stars anticipated.

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