

Discovery of a new Galactic bona fide luminous blue variable with *Spitzer*[★]

V. V. Gvaramadze,^{1,2,3†} A. Y. Kniazev,^{1,4,5} L. N. Berdnikov,^{1,3,6} N. Langer,⁷
E. K. Grebel⁸ and J. M. Bestenlehner⁷

¹Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskij Pr. 13, Moscow 119992, Russia

²Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia

³Isaac Newton Institute of Chile, Moscow Branch, Universitetskij Pr. 13, Moscow 119992, Russia

⁴South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa

⁵Southern African Large Telescope Foundation, PO Box 9, 7935 Observatory, Cape Town, South Africa

⁶Astronomy and Astrophysics Research division, Entoto Observatory and Research Center, P.O.Box 8412, Addis Ababa, Ethiopia

⁷Argelander-Institut für Astronomie der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

⁸Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany

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ABSTRACT

We report the discovery of a circular mid-infrared shell around the emission-line star Wray 16-137 using archival data of the *Spitzer* Space Telescope. Follow-up optical spectroscopy of Wray 16-137 with the Southern African Large Telescope revealed a rich emission spectrum typical of the classical luminous blue variables (LBVs) like P Cygni. Subsequent spectroscopic and photometric observations showed drastic changes in the spectrum and brightness during the last three years, meaning that Wray 16-137 currently undergoes an S Dor-like outburst. Namely, we found that the star has brightened by ≈ 1 mag in the V and I_c bands, while its spectrum became dominated by Fe II lines. Taken together, our observations unambiguously show that Wray 16-137 is a new member of the family of Galactic bona fide LBVs.

Key words: line: identification – circumstellar matter – stars: emission-line, Be – stars: evolution – stars: individual: Wray 16-137 – stars: massive.

1 INTRODUCTION

During their life, some massive stars undergo a stage of drastic changes in spectral appearance and brightness, which are accompanied by episodes of enhanced mass-loss (Humphreys & Davidson 1994). In this, so-called luminous blue variable (LBV; Conti 1984), stage the stars change their visual brightness by one or more magnitudes on time-scales of years, while their spectral types vary between late O/early B and A/F supergiants. The nature of the LBV-type activity remains unclear (see Vink 2012 for a recent review), as well as whether the LBV stage is intermediate between the main sequence and Wolf-Rayet stages or is an immediate precursor of a supernova explosion (e.g. Langer et al. 1994; Stothers & Chin 1996; Groh, Meynet & Ekström 2013; Groh et al. 2014; Smith & Tombleson 2014). To some extent, this is because the number of bona fide and candidate LBVs (cLBVs) has remained quite sparse until recently (Clark, Larionov & Arkharov 2005).

The number of known cLBVs in the Milky Way has greatly increased with the advent of modern infrared telescopes [e.g. *Spitzer* Space Telescope, *Wide-field Infrared Survey Explorer* (WISE)], which resulted in the discovery of numerous compact shells – the

distinctive characteristic of LBV and some other evolved massive stars (Gvaramadze, Kniazev & Fabrika 2010b; Wachter et al. 2010). Follow-up spectroscopy of central stars of these shells nearly doubled the number of Galactic cLBVs (Gvaramadze et al. 2010a,b, 2012; Wachter et al. 2010, 2011; Stringfellow et al. 2012a,b; Flagey et al. 2014). This burst of discoveries conforms with the idea that LBVs could be the descendants of not only the most massive and therefore very rare stars (as it was generally believed), but also of the moderately massive ($\sim 20 M_\odot$) and much more numerous ones (Smith et al. 2011; Groh et al. 2013). However, none of the newly discovered cLBVs have reported spectral and photometric variability strong enough to call them bona fide LBVs (cf. Gvaramadze et al. 2010a, 2012). In this Letter, we present a first case of a new Galactic bona fide LBV discovered through detection of a ring-like nebula with *Spitzer* and follow-up spectroscopic and photometric observations of its central star.

2 INFRARED NEBULA AND ITS CENTRAL STAR WRAY 16-137

The new nebula was discovered in the 24 μ m archival data of the *Spitzer* Space Telescope obtained with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) within the framework of the 24 and 70 Micron Survey of the Inner Galactic Disk with

[★]Based on observations made with the Southern African Large Telescope.

[†]E-mail: vgvaram@mx.iki.rssi.ru

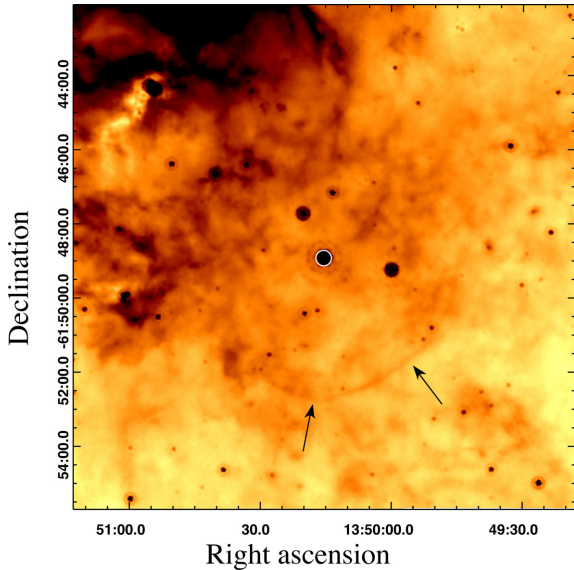


Figure 1. *Spitzer* MIPS 24 μm image of a ring-like nebula (indicated by arrows) around Wray 16-137 (marked by a white circle). A bright emission to the north-east of the nebula is the H II region GAL 309.91+00.37.

MIPS (Carey et al. 2009).¹ It appears as an incomplete ring-like shell (see Fig. 1) of radius of ≈ 1.8 arcmin, whose northeastern half is hidden by the bright emission associated with the H II region GAL 309.91+00.37 (Caswell & Haynes 1987). The nebula can also be discerned in the lower resolution *WISE* 22 μm image (Wright et al. 2010), but it is invisible in the other three *WISE* bands (3.4, 4.6 and 12 μm) and all (3.6, 4.5, 5.8 and 8.0 μm) images obtained with the *Spitzer* Infrared Array Camera (IRAC; Fazio et al. 2004) within the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (Benjamin et al. 2003).

The nebula is centred on a point-like source known as IRAS 13467–6134 ($\alpha_{2000} = 13^{\text{h}}50^{\text{m}}15^{\text{s}}.36$, $\delta_{J2000} = -61^{\circ}48'55''.2$). This source is visible in all IRAC and *WISE* bands. Its optical counterpart, named in the SIMBAD data base as Wray 16-137 and SS 252, was identified as an emission-line star by Wray (1966) and Stephenson & Sanduleak (1977), respectively. In what follows, we adopt the first of these two names. Wray 16-137 was suspected as an M supergiant with H α emission by MacConnell (1983).

The published optical photometry of Wray 16-137 is very uncertain. The SIMBAD data base quotes a visual magnitude of 15.5 without indication of the source of this value. The NOMAD catalogue (Zacharias et al. 2004) gives $B = 14.1$ mag and $V = 14.0$ mag, based on the unpublished data, while the Yale/San Juan Southern Proper Motion Catalog 4 (SPM4; Girard et al. 2011) lists $B = 19.4$ mag and $V = 16.0$ mag. The discordance in the optical photometry might be caused by the intrinsic variability of Wray 16-137 (see next section).

For the sake of completeness, we note that Wray 16-137 is a source of radio emission (Ricci et al. 2004).

3 WRAY 16-137: A BONA FIDE LBV

To clarify the nature of Wray 16-137, we obtained its spectrum with the Southern African Large Telescope (SALT; Buckley, Swart & Meiring 2006; O’Donoghue et al. 2006) on 2011 August 6, using the Robert Stobie Spectrograph (RSS; Burgh et al. 2003; Kobulnicky et al. 2003) in the long-slit mode with a 1.25 arcsec slit width. The PG900 grating was used to cover the spectral range of 4200–7300 $\text{\AA}$ with a final reciprocal dispersion of $0.97 \text{ \AA pixel}^{-1}$ and full width at half-maximum (FWHM) spectral resolution of $5.47 \pm 0.30 \text{ \AA}$. The RSS uses a mosaic of three 2048×4096 CCDs and the final spatial scale for observations was $0.253 \text{ arcsec pix}^{-1}$. Three 300 s spectra were taken. The seeing during this and subsequent (see below) observations was $\approx 2\text{--}3$ arcsec. A Xe lamp arc spectrum was taken immediately after the science frames. A spectrophotometric standard star was observed during twilight time for relative flux calibration.

The primary reduction of the data was done with the SALT science pipeline (Crawford et al. 2010). After that, the bias and gain corrected and mosaicked long-slit data were reduced in the way described in Kniazev et al. (2008).

The resulting normalized spectrum of Wray 16-137 is presented in Fig. 2 (see the upper curve). It is dominated by strong emission lines of H and He I and numerous Fe III emissions, some of which show P Cygni profiles. Further emission lines in the spectrum are permitted singly ionized lines of C, N and Si. No He II lines are present in the spectrum. The only forbidden line detected is the line of [N II] $\lambda 5755$. On the whole, the spectrum is very similar to those of the bona fide LBVs P Cygni (Stahl et al. 1993) and AG Car (near visual minimum; Groh et al. 2009) and several cLBVs discovered with *Spitzer* and *WISE* through detection of their associated mid-infrared shells (see figs 3–5 in Gvaramadze et al. 2012). This spectrum along with the presence of the circular shell around the star allows us to classify Wray 16-137 as a cLBV.

It is likely that most, if not all, LBVs go through the long (centuries or more) quiescent periods (Lamers 1986; Massey 2006), during which they do not show major spectrophotometric variability, and formally cannot be classified as genuine LBVs, even though they possess LBV-like spectra and shells. Nevertheless, if one is lucky enough, one can detect such variability without having to wait for too long. Fortunately, Wray 16-137 provided us with this opportunity.

To search for spectral variability of Wray 16-137, we obtained two additional spectra with the SALT using the same spectral setup. These spectra, taken on 2013 April 25 and 2014 January 21, are shown in Fig. 2 along with the first spectrum. The first look on them reveals that by 2014 January the He I emission lines had almost disappeared, which indicates that the stellar effective temperature decreased during the last three years. (A detailed spectral analysis of Wray 16-137 is currently underway and will be presented elsewhere.) This conclusion is reinforced by the disappearance of the Fe III emission lines, major changes in other temperature sensitive lines like C, N and Si, and the appearance of numerous singly ionized iron emission lines (some of which show P Cygni profiles).

The [N II] $\lambda 5755$ line also has changed significantly. The FWHM and heliocentric radial velocity of this line could be used as a measure of the stellar wind (Crowther, Hillier & Smith 1995) and systemic (Stahl et al. 2001) velocities, v_{∞} and v_{sys} , respectively. After correction for instrumental width, the FWHMs of $8.92 \pm 0.18 \text{ \AA}$ (2011), $7.46 \pm 0.31 \text{ \AA}$ (2013) and $7.73 \pm 0.30 \text{ \AA}$ (2014) correspond to v_{∞} of 367 ± 18 , 264 ± 22 and $285 \pm 22 \text{ km s}^{-1}$, respectively. As expected, v_{∞} decreased as

¹ The discovery was made serendipitously after our list of mid-IR nebulae detected with *Spitzer* was already published (Gvaramadze et al. 2010b). One can expect that thorough inspection of complex environments of star-forming regions – where the majority of massive stars are reside – will disclose more new shells (e.g. Gvaramadze et al. 2011).

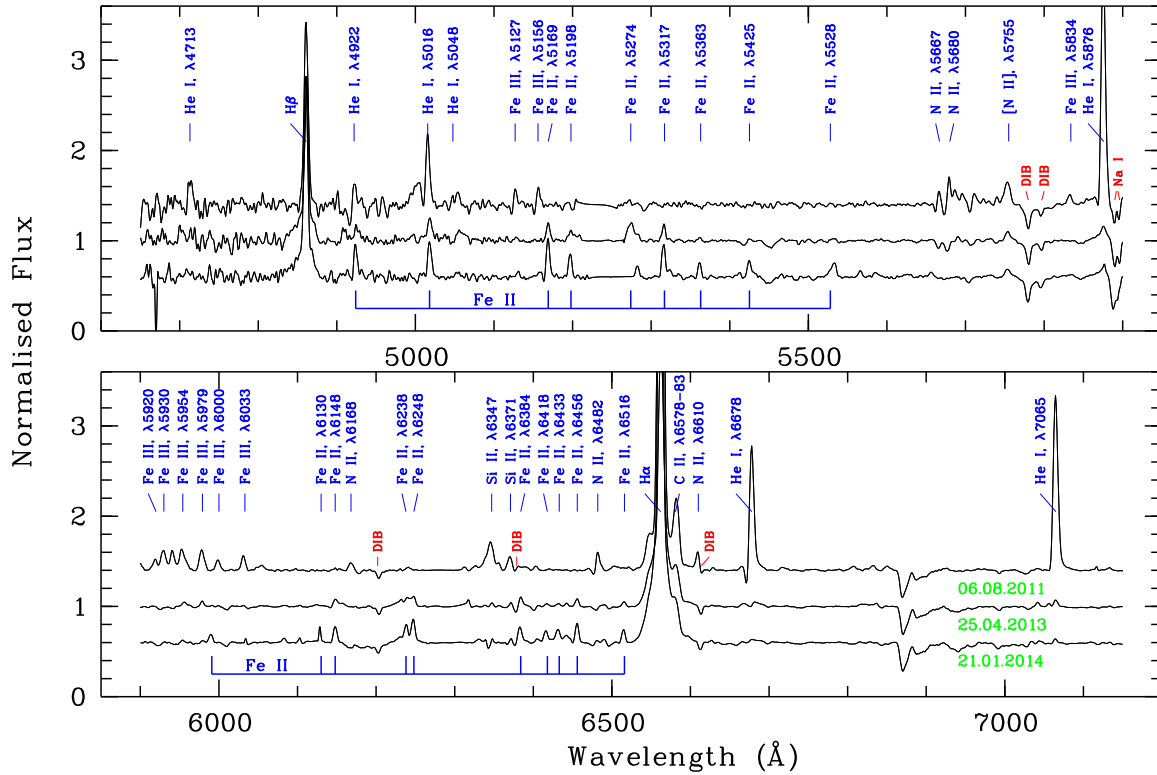


Figure 2. Evolution of the (normalized) spectrum of Wray 16-137 between 2011 August and 2014 January. The principal lines and most prominent DIBs are indicated. For clarity, the spectra are offset by 0.4 continuum flux unit.

Table 1. Photometry of Wray 16-137.

Date	<i>B</i>	<i>V</i>	<i>I_c</i>
2007 ^(a)	—	16.02 ± 0.04	—
2011 August 6 ^(b)	—	15.24 ± 0.03	—
2012 May 6 ^(c)	17.98 ± 0.10	15.05 ± 0.04	10.06 ± 0.01
2013 January 14 ^(c)	18.26 ± 0.10	14.88 ± 0.04	9.77 ± 0.01
2013 April 25 ^(b)	—	14.79 ± 0.03	—
2014 January 19 ^(c)	17.75 ± 0.10	14.36 ± 0.03	9.26 ± 0.01
2014 January 21 ^(b)	—	14.40 ± 0.03	—
2014 April 23 ^(c)	17.39 ± 0.15	14.18 ± 0.03	9.04 ± 0.03

Note: ^aSPM4; ^bSALT; ^c76-cm telescope.

the star became cooler. For v_{sys} , we derived a mean value of -33 ± 3 km s⁻¹ based on all three spectra.

To detect photometric variability of Wray 16-137, we determined its *B*, *V* and *I_c* magnitudes on CCD frames obtained with the 76-cm telescope of the South African Astronomical Observatory in 2012–2014. We used an SBIG ST-10XME CCD camera equipped with *BVI_c* filters of the Kron–Cousins system (see e.g. Berdnikov et al. 2012). Absolute flux calibration is not feasible with SALT because the unfilled entrance pupil of the telescope moves during the observations. However, we were able to calibrate our spectra and synthesize their *V* magnitudes (cf. Kniazev et al. 2005) using a foreground star on the slit as a secondary standard, whose photometry was determined from our CCD frames. The results are presented in Table 1. To this table we also added the *V* magnitude (measured on CCD frames in 2007) from the SPM4 catalogue (Girard et al.

2011).² One can see that Wray 16-137 monotonically brightened in the *V* and *I_c* bands during the last three years with the net increase of ≈ 1 mag. Changes in *B* are less secure because the weakness of the star in this band causes larger errors of measurements. The brightening in the *V* band would be even more spectacular (≈ 2 mag!) if one takes into account the SPM4 photometry.

Taken together, our observations unambiguously show that Wray 16-137 is a bona fide LBV, which now experiences an S Dor-type outburst and is on the way to visual maximum.

4 DISCUSSION AND CONCLUSION

To estimate the reddening towards Wray 16-137 and thereby to constrain its absolute visual magnitude, M_V , we matched the dereddened spectral slope of this star with those of stars of similar effective temperature, T_{eff} . Using the Stellar Spectral Flux Library by Pickles (1998) and assuming that T_{eff} of Wray 16-137 in the hot phase (i.e. in 2011 August) is similar to that of P Cygni (≈ 18 000 K; Najarro, Hillier & Stahl 1997), we found a colour excess of $E(B - V) \approx 3.7$ mag (this estimate only slightly depends on the assumed T_{eff} ; see Gvaramadze et al. 2012). With this $E(B - V)$ and the standard ratio of total to selective extinction $R_V = 3.1$, we obtained $A_V \approx 11.5$ mag and $DM + M_V \approx 3.8$ mag, where A_V is the *V*-band extinction and *DM* is the distance modulus.

To constrain *DM*, we note that the line of sight towards Wray 16-137 first crosses the Carina-Sagittarius arm at ~ 2 kpc and then

² The *B* magnitude of Wray 16-137 in this catalogue was extrapolated from the *JHK_s* photometry of the Two Micron All Sky Survey and therefore is less reliable.

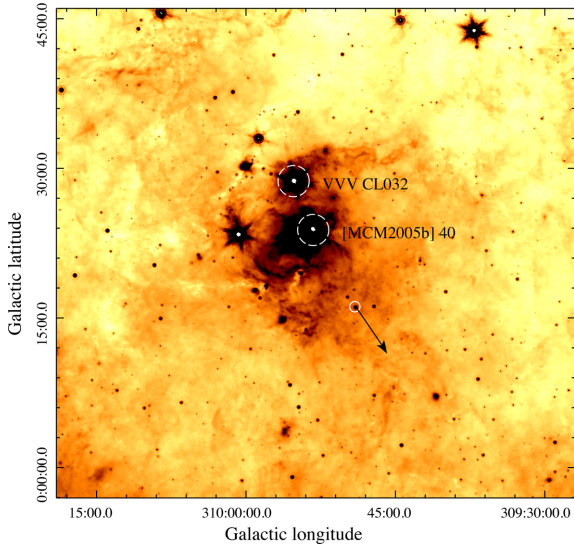


Figure 3. *Spitzer* MIPS 24 μm image of the H II region GAL 309.91+00.37 and two highly reddened clusters (marked by dashed circles). The arrow shows the direction of motion of Wray 16-137 (marked by a white circle), as suggested by the proper motion measurement for this star. See text for details. At the distance of 4 kpc, 1 arcmin corresponds to ≈ 1.15 pc.

Table 2. Peculiar transverse (in Galactic coordinates) and radial velocities, and the total space velocity of Wray 16-137 for two adopted distances (see text for details).

d (kpc)	v_l (km s^{-1})	v_b (km s^{-1})	v_r (km s^{-1})	v_* (km s^{-1})
2	-46 ± 47	-75 ± 50	-5 ± 3	88 ± 49
4	-107 ± 93	-157 ± 100	17 ± 3	191 ± 97

tangentially crosses the Crux–Scutum one at ≈ 4 –10 kpc. Placing Wray 16-137 in the first of these two arms ($\text{DM} \approx 11.5$ mag) would imply $M_V \approx -7.7$ mag, while in the next arm out ($\text{DM} \approx 13$ –15 mag) M_V would be between ≈ -9 and -11 mag. Correspondingly, the luminosity of Wray 16-137 would be $\log(L/L_\odot) \approx 5.6$ and 6.2–7.0; here, we assumed that the bolometric correction of Wray 16-137 is equal to that of P Cygni, -1.54 mag (Najarro, personal communication). In the first case, the luminosity of Wray 16-137 would be comparable to that of P Cigni of 5.7 (Najarro et al. 1997), while in the second one Wray 16-137 would be one of the most luminous Galactic LBVs.

The high A_V towards Wray 16-137 is suggestive of the longer distance. The longer distance should also be accepted if Wray 16-137 is associated with the H II region GAL 309.91+00.37 (see Figs 1 and 3), which is located in the Crux–Scutum arm (Caswell & Haynes 1987). Table 2 lists the components of the peculiar transverse velocity (in Galactic coordinates), v_l and v_b , the peculiar radial velocity, v_r , and the total space velocity, v_* , of Wray 16-137,³ derived from the proper motion measurement given in the SPM4 catalogue (Girard et al. 2011): $\mu_\alpha \cos \delta = -10.08 \pm 4.89 \text{ mas yr}^{-1}$, $\mu_\delta = -11.22 \pm 5.28 \text{ mas yr}^{-1}$. For the sake of illustration, we

³ To derive these velocities, we used the Galactic constants $R_0 = 8.0$ kpc and $\Theta_0 = 240 \text{ km s}^{-1}$ (Reid et al. 2009) and the solar peculiar motion ($U_\odot, V_\odot, W_\odot$) = (11.1, 12.2, 7.3) km s^{-1} (Schönrich, Binney & Dehnen 2010). For the error calculation, only the errors of the proper motion and the systemic velocity measurements were considered.

adopted two distances: 2 and 4 kpc. Taken at face value, the obtained velocities imply that Wray 16-137 is a runaway star moving away from the geometric centre of the H II region. Interestingly, the SIMBAD data base indicates two highly reddened clusters, [MCM2005b] 40 (Mercer et al. 2005) and VVV CL032 (Borissova et al. 2011), within the boundaries of GAL309.91+00.37. Although the distances to these clusters and their stellar contents are unknown, it is likely that they power the H II region and that one of them might be the parent cluster of Wray 16-137. Upcoming high-precision proper motion and parallax measurements with the space astrometry mission *Gaia* would allow us to derive the distance to Wray 16-137 and to prove whether it could be associated with GAL 309.91+00.37.

To conclude, further spectroscopic and photometric observations of this interesting star with better cadence and higher spectral resolution and coverage are very desirable.

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