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Modeling hydrogen-rich Wolf–Rayet stars in M33

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We present the results of a spectral variability study of two very luminous stars in the M33 galaxy – LBV V532 and late WN star (possibly, dormant LBV) FSZ35. We studied the spectral variability of V532, derived its atmosphere parameters and showed that the bolometric luminosity varied between the two states by a factor of ∼1.5. Using the non-LTE radiative transfer code CMFGEN, we determined the wind parameters for both objects. Since both stars are located at distances of about 100 pc from the nearest association, we supposed that they may be massive runaway stars with velocities of the order 100 km s^{-1}.

Keywords: Stars: Wolf–Rayet; Star: individual: Romano's star; Star: individual: FSZ35; Galaxies: individual: M33

1 Introduction

Luminous blue variables (LBVs) are rare objects of very high luminosity (∼10^6 $L_\odot$) and mass loss rates (10^{-5} to 10^{-4} $M_\odot\,\mathrm{yr}^{-1}$), exhibiting strong irregular photometric and spectral variability (Conti 1984; Humphreys & Davidson 1994). LBVs span quite a large range of magnitudes and variability types (Humphreys & Davidson 1994). Despite much research, there is still no consensus about the evolution of massive stars. In particular, there is no answer to the question whether all WN stars passed through the LBV stage. Contemporary evolutionary scenarios say that massive O-stars with mass 90 $M_\odot$ cross to WNL without going through the LBV phase (Maeder & Meynet 2010).

$M > 90\ M_\odot$: O → Of → WNL → (WNE) → WCL → WCE → SN
(hypernova at low Z?)

whereas if mass is 40–90 $M_\odot$, then

60–90 $M_\odot$: O → Of/WNL ⇔ LBV → WNL(H-poor) → (WNE)
→ WCL-E → SN(SNIIn?)

40–60 $M_\odot$: O → BSG → LBV ⇔ WNL → (WNE) → WCL-E → SN(SNIb)
or → WCL-E → WO SN(SNIc)

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Generally, LBV are believed to be a relatively short evolutionary stage in the life of massive stars. However, recent investigations of the light curves of a few supernovae (SN2006gy, 2006tf, SN2005gl) indicate that their progenitors underwent LBV-like eruptions (Smith & McCray 2007; Smith et al. 2008; Gal-Yam & Leonard 2009). These observations support the view that at least some luminous LBV stars are the end point of evolution but not a transition phase.

Therefore, a continuous spectral and photometric monitoring and numerical modeling of the atmospheres of these objects are very important for understanding the evolutionary relationship between WR and LBV stars, as well as the physical causes of LBV variability. Observations of Galactic LBV stars are inevitably connected with difficulties in determining the distance and interstellar extinction, which results in huge uncertainties in their bolometric luminosities. Thus, studies of these rare objects in nearby galaxies are potentially more prospective, though extragalactic objects are more distant and hence are more difficult targets for spectral observations.

FSZ35 and V532 (known as Romano's star) are stars with similar spectra and, probably, similar evolution, but different histories of research. The V532 star, known by its variability, is a famous object in M33 galaxy. Photometric observations have been carried out since 1961 (Romano 1978; Zharova et al. 2010), spectral observations – since 1992 (Szeifert 1996). Polcaro et al. (2003) classify V532 as an LBV. The spectrum of object changes from a B emission line supergiant in the optical maximum (Szeifert 1996), through Ofpe/WN (WN10,WN11) and WN9 toward a WN8-like spectrum in deep minima (Maryeva & Abolmasov 2010). Sholukhova et al. (1999) note a similarity between the spectra of Romano's star and FSZ35. The object FSZ35 is a little-studied WNL star in M33. Ivanov et al. (1993) were the first to obtain photometric data for this object (IFM-B 174, in their notation). The star is listed in the Hα emission-line object catalogue (Fabrika et al. 1997) as number 35. In Massey & Johnson (1998) the star is listed as object E1 and is classified as a Wolf–Rayet star of nitrogen sequence, WN8 subtype.

In this work we investigate the optical spectra of V532 and FSZ35 using the non-local thermodynamic equilibrium (non-LTE) radiative transfer code CMFGEN (Hillier & Miller 1998). We pay special attention to comparison between these two objects.

This paper is organized as follows. The observational data and data reduction process are described in the next section. In Section 3 and Section 4 we present and analyse the modeling results for V532 and FSZ35. In Section 5 we discuss the results.

2 Observations and Data Reduction

In this work, we use spectral data taken from the archive of the 6-m BTA telescope of Special Astrophysical Observatory (SAO) of Russian Academy of Sciences (RAS) (http://www.sao.ru) and from the SMOKA science archive (Baba et al. 2002) of SUBARU telescope (http://smoka.nao.ac.jp). The 6-m telescope data were obtained with the SCORPIO multi-mode focal reducer in the long-slit mode (Afanasiev & Moiseev 2005). One exposure V532 was obtained with the SUBARU telescope with the Faint Object Camera (FOCAS) (Kashikawa et al. 2002) in October 2007. Observational log information on the data used in this work is summarized in Table 1.

Table 1 Observational log for the spectral data used in the work. S/N is signal-to-noise ratio per resolution element.

Date	Exposure time, [s]	Grism	Spectral range, [Å]	$\delta\lambda$, [Å]	S/N	Seeing, [″]	Spectral standard star
			V532				
06.02.2005, SCORPIO	2×300	VPHG550G	3700–7200	10	8	1.7	G248
08.01.2008, SCORPIO	2×900	VPHG1200R	5700–7500	5	20	2.1	BD25d4655
08.10.2007, FOCAS	1200	VPHG450	3750–5250	1.7	30	0.53	BD40d4032
			FSZ35				
04.10.2007, SCORPIO	900+1200	VPHG1200G	4000–5700	5.5	19	1.2	G191B2B

All the SCORPIO spectra were reduced using the `ScoRe` package written in IDL language. The package includes all the standard stages of the long-slit data reduction process. FOCAS data were reduced in IDL development environment using procedures similar to those containing `ScoRe` but taking into account the specific features of FOCAS. We describe the observational data of V532 and FSZ35 in more detail in Maryeva & Abolmasov (2010) and in Maryeva & Abolmasov (2011a), respectively.

3 Romano's star

We investigate the optical spectra of Romano's star in two different states, the brightness minimum of 2008 ($B = 18.5 \pm 0.05$ mag) and a moderate brightening in 2005 ($B = 17.1 \pm 0.03$ mag). We refer to both states as hot and cool phases, respectively.

Figure 1 shows the observed spectra of V532 at different phases and the best-fit model spectra. Stellar parameters derived for both hot- and cool-phase models are given in Table 2. For comparison, the values of these parameters for some other stars are given. The table shows that V532 in the minimum of brightness is similar to a classical WN8 star, but the wind velocity is lower, characteristic rather of a WN9 star. The relative hydrogen abundance (H/He) for V532 is seen to be similar to that of WN8h stars. In February 2005, during the outburst, parameters of the star correspond to the spectral class WN11. The model spectrum is similar to the spectrum of P Cyg in 1998. V532 shows a WN11 spectrum in the maximum, while the classical LBVs like AG Car and P Cyg become WN11 only in deep minima and in the long-lasting quiet state, respectively. Note however that V532 had a strong maximum in 1993 ($0\overset{\mathrm{m}}{.}9$ brighter than in February 2005) and exhibited a B-supergiant spectrum. The two phases, hot and cool, are mainly distinguished by the photosphere radius. In the hot phase the radius is about three times larger than in the cool phase. Three basic parameters vary simultaneously and make measurable contributions to the observed inflation of the star. For the two states, $\dot{M}$ differ by a factor of 2.4, and the wind velocity is 1.8 times larger for the hot state. Our models favour correlation of hydrostatic radius with mass loss rate.

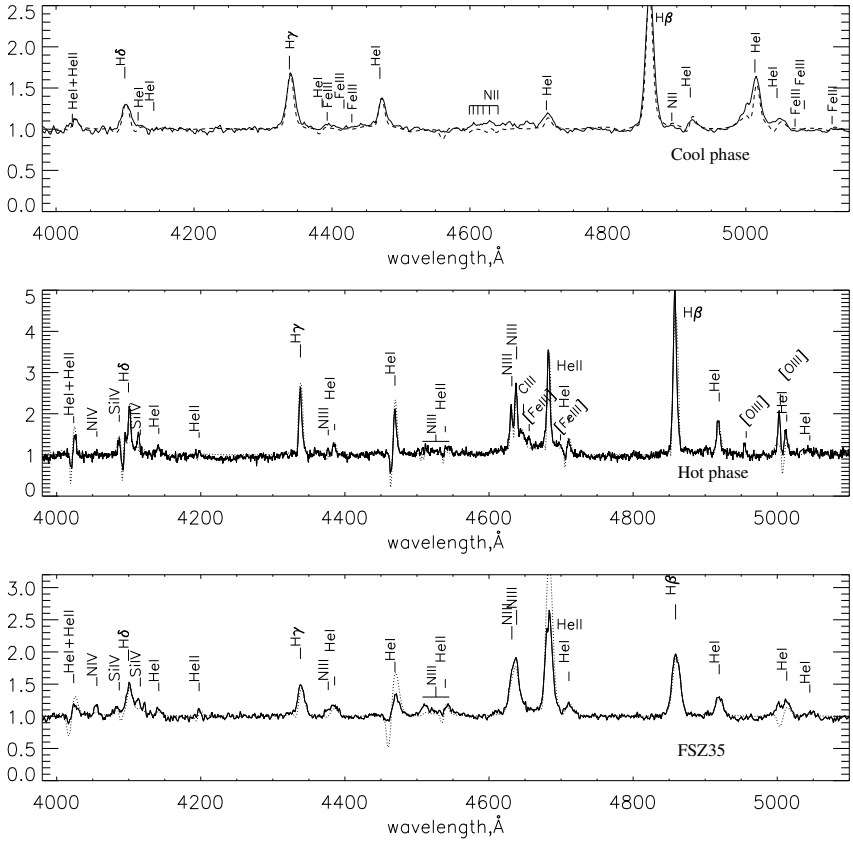


Figure 1 The normalized optical spectra (solid line) compared with the best-fit CMFGEN models (dashed line). Top panel: the spectrum obtained in February 2006 when V532 is $17^{\rm m}.27$ in V band. Middle: the spectrum obtained in October 2007, when V-band magnitude is $V = 18^{\rm m}.68$. Bottom: The spectrum of FSZ35 with the final model.

The luminosity of V532 in 2005 ($L_* = 7.7 \cdot 10^5 L_\odot$) is 1.5 times higher. Therefore, V532 should be considered one more LBV (after the objects mentioned by Koenigsberger (2004), Drissen et al. (2001), Clark et al. (2009)) that changes its luminosity during (even moderate amplitude) eruption. In this sense, V532 behaves similar to AG Car that has bolometric luminosity variations during its S Dor cycle (Groh et al. 2009).

4 FSZ35

We analyzed a spectrum of FSZ35 in the 4000–5500 Å wavelength range and identified about 40 spectral lines. The spectral appearance of FSZ35 shows strong similarities with V532. Therefore we classify FSZ35 as a WN8 as well. Besides this, the NIV λ4057

Table 2 Derived properties of V532 in the maximum and the minimum of brightness, and comparison with related stars in M33, LMC and Milky Way (MW) galaxies, including the LBVs P Cyg and AG Car in visual minima (Dec 1990). H/He denotes hydrogen number fraction relative to helium.

Star	Gal.	Sp. type	T_* [kK]	R_* [$R_\odot$]	$T_{\rm eff}$ [kK]	$R_{2/3}$ [$R_\odot$]	$\log L_*$ [$L_\odot$]	$\log \dot{M}_{\rm cl}$ [$M_\odot$ yr^{-1}]	f	v_∞ [km s^{-1}]	H/He
WR124[a]	MW	WN8h	32.7	18.0			5.53	–4.7	0.1	710	0.7
WR40[b]	MW	WN8h	45.0	10.6			5.61	–4.5	0.1	840	0.75
WR16[b]	MW	WN8h	41.7	12.3			5.68	–4.8	0.1	650	1.2
AG Car[c] Dec 1990	MW	WN11	24.64	67.4	21.5	88.5	6.17	–4.82	0.1	300	2.3
P Cyg[d]	MW	B1Ia^+			18.7	76.0	5.8	–4.63	0.5	185	2.5
FSZ35	M33	WN8h	36.5	19	35	20	5.76	–4.58	0.1	800	0.8
V532 hot-phase	M33	WN8h	34.0	20.8	31.7	23.9	5.7	–4.72	0.1	360*	1.9
V532 cool-phase	M33	WN11h	22.0	59.6	20.4	69.1	5.89	–4.4	0.5	200	1.4

*v_∞ was estimated using HeI lines (Maryeva & Abolmasov 2010)

[a]Crowther et al. (1999); [b]Herald et al. (2001); [c]Groh et al. (2009); [d]Najarro (2001)

line clearly seen in our spectrum is never present in WN9 spectra, thus excluding FSZ35 identification as a later-subclass object.

The best-fit parameters of the CMFGEN model are given in Table 2. Derived parameters of FSZ35 atmosphere correspond to a typical WN8 star. Because the mass fraction of hydrogen is 16.5% (H/He = 0.8) in the spectrum of FSZ35, we classify this object as an H-rich WN8 star.

5 Discussion

Figure 2 presents the positions of FSZ35 and V532 in different phases in the Hertzsprung–Russell (HR) diagram. Groh et al. (2009a) suggest that the LBV minimum instability strip is characterized by $\log(L_*/L_\odot) = 4.54 \cdot \log(T_{\rm eff}) - 13.61$. Groh et al. (2009a) suggest that the LBV minimum instability strip corresponds to the region where critical rotation is reached for LBVs with strong S-Dor-type variability. When LBVs are evolving toward a maximum, the star moves far from the LBV minimum instability strip (to the right in the HR diagram), and $v_{\rm rot}/v_{\rm crit}$ decreases considerably. The region in the HR diagram on the left side of the LBV minimum instability strip would be populated by unstable LBV stars with $v_{\rm rot}/v_{\rm crit} > 1$, which would make it a "forbidden region" for LBVs. Indeed, no confirmed strong-variable LBV is seen in this region (see Groh et al. (2009a) and references therein). V532 in the maximum of brightness ($V = 17\overset{\rm m}{.}$, Feb. 2005) lies on the LBV minimum instability strip. And it moves to the "forbidden region" in the minimum of brightness. Unlike V532, FSZ35 does not demonstrate any prominent spectral variability. The lack of photometrical variability may be ascribed to the more advanced evolutionary status of FSZ35.

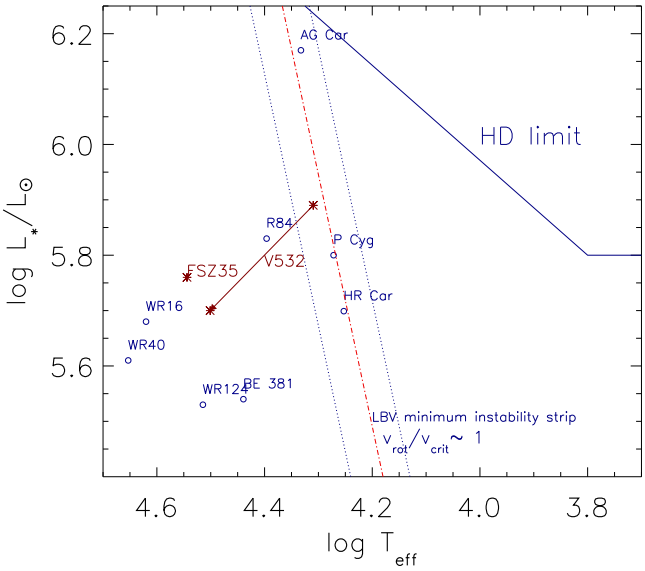


Figure 2 HR diagram showing the positions of V532 and FSZ35, according to the stellar parameters determined in this work. Position for the LBV minimum instability strip is provided (dashed line). The location of the Humphreys–Davidson limit (Humphreys and Davidson 1994) is shown (solid line). WN9 (BE381, R84), WN8 (WR124, WR16, WR40) and LBV (AG Car, HR Car, P Cyg) stars are shown for comparison. Data on these objects were taken from Crowther & Smith (1997), Crowther & Smith (1997), Crowther et al. (1999), Herald et al. (2001), Herald et al. (2001), Groh et al. (2009, 2009a), Najarro (2001), respectively.

According to modern theories, there is no mechanism of the formation of single stars. Stars are born in groups consisting of two and more components, entering into larger base units (complexes, clusters, etc.).

FSZ35 is located at a distance of about 35″ (∼115 pc) from the 128 association. Suppose that once FSZ35 was a member of 128 association and was ejected via slingshot-type dynamical interaction. If its peculiar velocity is ∼100 km s^{-1}, as for WR124 (Sirianni et al. 1998; Marchenko et al. 2010), it could have been expelled from the parent cluster about a million years ago.

Offset positions with respect to the probable parent associations (at distances ∼100 pc) and unexpectedly large peculiar velocities (of the order ∼100 km s^{-1}) seem to be common for very luminous and massive stars like V532, FSZ35 and Galactic late WN stars like WR20a and WR124. A scenario was proposed by Gvaramazde & Gualandris (2011) that applies three-body dynamical interaction in the cores of young massive clusters and star-forming regions (similar to 30 Doradus) to reproduce the observed population of massive runaways. This scenario has the disadvantage of relying heavily on the formation of massive stars in the cores of massive young clusters that are, in contrast with LMC, absent in M33, where massive stars are rather formed in dispersed stellar associations. Instead we would rather propose that very massive stars are formed in dense groups containing several stars each. This is confirmed, for

example, by the increasing multiplicity with stellar mass (Zinnecker & Yorke 2007) simultaneously in young star clusters and in associations. Reasonably, the higher the fraction of massive binaries the higher the accompanying fraction of massive multiple systems.

The characteristic peculiar velocities ($\sim$100 km s^{-1}) of these "childhood runaways" may be reproduced if the initial spatial sizes of the systems are $\sim 10^{14}$ cm.

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