Modeling Hydrogen-Rich Wolf-Rayet Stars in M33

OLGA MARYEVA

Stavropol State University, Stavropol, Russia; olga.maryeva@gmail.com

ABSTRACT

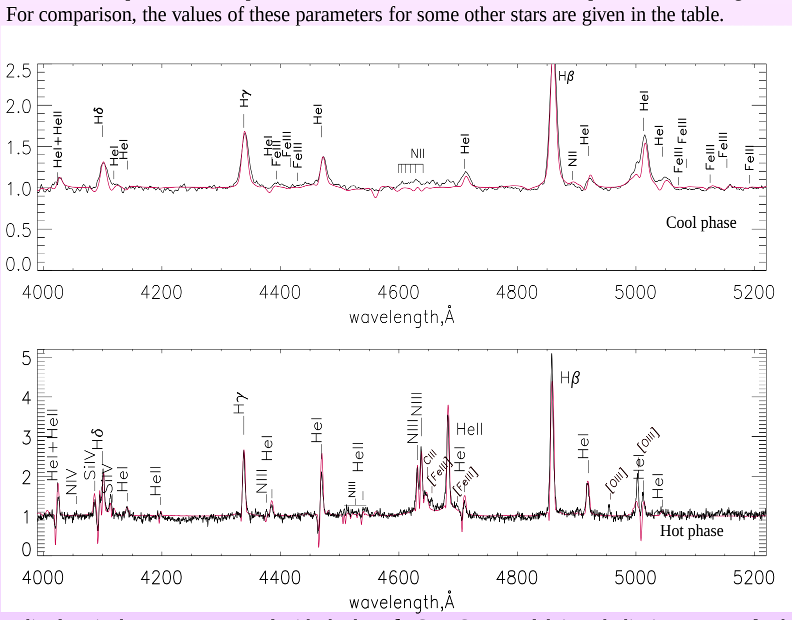
Most massive stars spend a short time as a Luminous Blue Variables (LBVs) before becoming WN stars. Detailed relations between LBV, WN and hydrogen-rich WN (WNH) stars are poorly known. Studying WNH demonstrating spectral variability and strong mass loss is very important for understanding stellar evolution. 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 spectral variability of V532, derived its atmosphere parameters and show that the bolometric luminosity of V532 varies during the eruption in 2005 by a factor of $\sim$1.5. Using the non-LTE radiative transfer code CMFGEN, we determined 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.

Romano's star

V532, known as Romano's star, is an interesting variable star located in the M33 galaxy. As it demonstrates pronounced photometrical and spectral variability (Kurtev et al., 2001; Polcaro et al., 2003), V532 is classified as an LBV. The 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).

We investigate the optical spectra of V532 in two different states, the brightness minimum of 2008 (*hot phase*) and a moderate brightening in 2005 (*cool phase*), using the non-LTE radiative transfer code CMFGEN (Hillier & Miller, 1998). In Figure 1 we show 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 1. For comparison, the values of these parameters for some other stars are given in the table.

Fig. 1



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

Table 1 shows that V532 in the minimum of brightness is similar to a classical WN8 star, but the wind velocity is lower, characteristic rather for a WN9 star. We see that relative hydrogen abundance (H/He) for V532 is 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 ($0^{\rm m}.9$ brighter than in February 2005) and exhibited a B-supergiant spectrum.

Table 1 *Derived properties of V532 in the maximum and the minimum of brightness and FSZ35, and comparison with WN8h stars and LBV P Cyg.* X_H *is mass fraction of hydrogen. Our results are highlighted.*

Star	Sp. type	T_* [kK]	$R_{2/3}$ [R$_\odot$]	log L_* [L$_\odot$]	log $\dot{M}_{cl}$ [M$_\odot$ yr^{-1}]	f	v_∞ [km s^{-1}]	X_H [%]	Ref
WR40	WN8h	45.0	10.6	5.61	-4.5	0.1	840	15	[1]
WR16	WN8h	41.7	12.3	5.68	-4.8	0.1	650	23	[1]
FSZ35	WN8	36.5	20	5.76	-4.58	0.1	800	17	[3]
V532 hot-phase	WN8	34.0	20.8	5.7	-4.75	0.1	360	24	[4]
V532 cool-phase	WN11	22.0	59.6	5.89	-4.4	0.5	200	24	[4]
P Cyg	B1Ia$^+$			5.8	-4.63	0.5	185		[2]

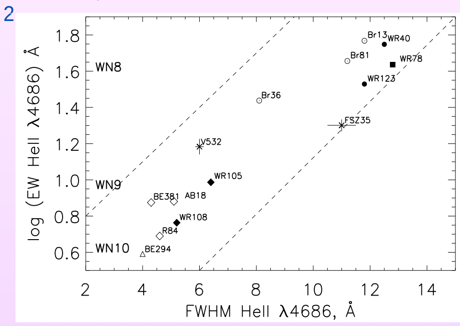
[1]- Herald et al. (2001), [2]- Najarro (2001), [3]- Maryeva & Abolmasov (2011a), [4]- Maryeva & Abolmasov (2011b)

The two phases, hot and cool, are mainly distinguished by the (pseudo-)photosphere radius, that is about three times larger in the cool phase. For the two states, $\dot{M}$ differ by a factor 2.8, and the wind velocity is 1.8 times larger for the hot state. Bolometric luminosities of V532 were different in 2005 and 2008. 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 similarly to AG Car that has bolometric luminosity variations during its S Dor cycle (Maryeva & Abolmasov, 2011b).

FSZ35

The object FSZ35 is little-studied WNL star in M33. We analyzed a spectrum of FSZ35 in the $4000 \div 5500$Å [a] 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 line clearly seen in our spectrum is never present in WN9 spectra, thus excluding FSZ35 identification as a later-subclass object.

Fig. 2

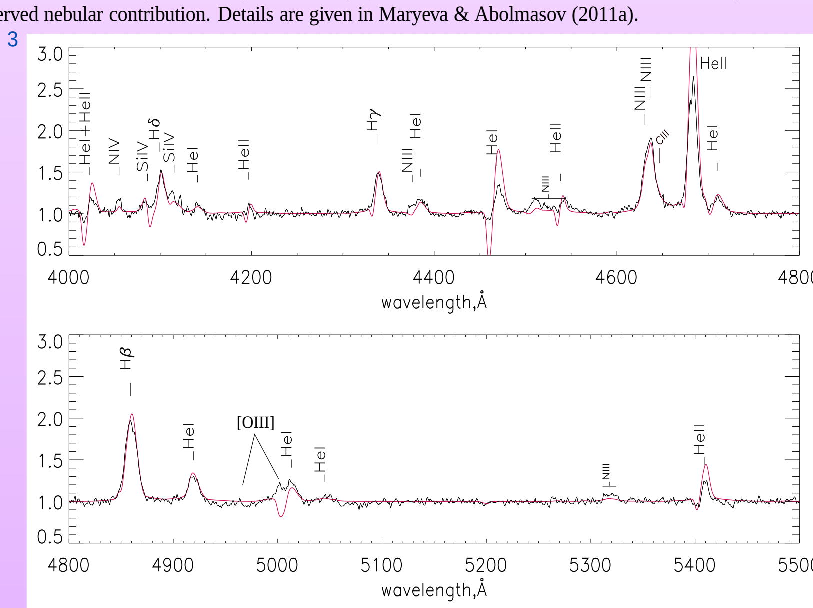


We used a quantitative chemistry-independent criterion based on the FWHM of HeII 4686 line for alternative spectral classification. In Fig. 2 we show the location of V532 and FSZ35 on the diagram of EW of HeII 4686 versus the FWHM of this line. Position of the object on this diagram is consistent with our identification FSZ35 as a WN8 star. Using non-LTE code CMFGEN we estimate the parameters of FSZ35.

The best-fit parameters of the CMFGEN model are: luminosity $L = 5.8 \cdot 10^5 L_\odot$, mass loss rate $2.6 \cdot 10^{-5} M_\odot$/year, nitrogen abundance N/He =11(N/He)$_\odot$, effective temperature at hydrostatic radius $T_* = 36.5$K ($R_* = 19 R_\odot$) and at the Rosseland photosphere $T_{tau=2/3} = 35.0$K (Table 1). Derived parameters of FSZ35 atmosphere correspond to a typical WN8 star. Because mass fraction of hydrogen is 16.5% (H/He=0.8) in the spectrum of FSZ35 we classify this object as H-rich WN8 star.

We find that FSZ35 has a surrounding nebula, possibly of low excitation and deficient in oxygen, that decreases its detectability. Modeling with Cloudy (Ferland et al., 1988) version 08.00 allows reproduce the observed nebular contribution. Details are given in Maryeva & Abolmasov (2011a).

Fig. 3



The spectrum of FSZ35 (black line) compared with the best-fit CMFGEN model (purple line).

[a] The spectrum was taken from the archive of Special Astrophysical Observatory (SAO) of Russian Academy of Sciences

Results and Conclusions

Using comoving frame numerical radiative transfer with the CMFGEN code, we estimate the physical parameters of the photosphere of Romano's star coming to the two principal conclusions. Firstly, in this object, variability is caused by correlated changes in mass loss rate, wind velocity and possibly hydrostatic radius. Elementary abundances do not change significantly, in both states we find similar helium and nitrogen overabundance characteristic for hydrogen-rich WNL stars, H/He$\simeq 1.3 \div 1.5$ and N/He$\simeq (3 \div 5) \times 10^{-3}$. We find that the bolometric luminosity of this object was higher during the eruption in 2005 by a factor of $\sim$1.5, that makes V532 one more example of an LBV that changes its luminosity. Its behaviour indicates that even moderate amplitude LBV outbursts are accompanied by changes in bolometric luminosity.

We analyzed the optical spectrum of WNL star FSZ35 in M33. We classify FSZ35 as a WN8 star, confirming the result of Massey & Johnson (1998). Using CMFGEN we estimate the parameters of FSZ35 (bolometric luminosity, stellar radius, mass loss rate, wind velocity, elementary abundances) and compare them to the corresponding parameters of other WN8 stars including the LBV star V532 during the minimum of brightness. FSZ35 is a H-rich WN8 star where the mass fraction of hydrogen is 16.5% (H/He=0.8). Position of FSZ35 at the outskirts of association 128 OB suggests that it was expelled from this association about a million years ago at a velocity of $\sim$ 100km s^{-1}.

FSZ35 is located at a distance of about $35''$ ($\sim$ 115 pc) from the OB 128 association (Humphreys & Sandage, 1980). Probably, once FSZ35 was a member of OB 128 and was ejected via slingshot-type dynamical interaction. Offset positions with respect to the probable parent associations (at distances $\sim$ 100pc) and unexpectedly large peculiar velocities (of the order $\sim$ 100km s^{-1}) seem to be common for very luminous and massive stars like V532, FSZ35 and Galactic late WN stars like WR20a and WR124. We propose that very massive stars are formed in dense groups containing several stars each. This is confirmed, for example, by the multiplicity increasing with stellar mass (Zinnecker & Yorke, 2007) both in young star clusters and associations. It is reasonable that higher fraction of massive binaries will be accompanied by a higher fraction of massive multiple systems. When formed, such systems are often unstable (Kiseleva et al., 1998) and dynamic interaction between its components should both produce a larger fraction of runaways at these masses ($\sim$ 100M$_\odot$) and a larger fraction of binaries. The characteristic peculiar velocities ($\sim$ 100km s^{-1}) of these "childhood runaways" may be reproduced if the initial spatial sizes of the systems are $\lesssim 10^{14}$cm (Maryeva & Abolmasov, 2011a).

References

Herald, J.E, Hillier, D.J. Schulte-Ladbeck, R.E. 2001, ApJ, 548, 932
Hillier, D.J., Miller, D.L. 1998, ApJ, 496, 407
Humphreys, R.M., Sandage, A. 1980, ApJS, 44, 319
Clark J.S., Crowther P.A., Larionov V.M., Steele I.A., Ritchie B.W., Arkharov A.A., 2009, A&A, 507, 1555
Drissen L., Crowther P. A., Smith, L. J., Carmelle R., Roy, J.-R., Hillier D. J., 2001 ApJ, 546, 484
Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., Verner, E. M. 1998, PASP, 110, 749
Kiseleva, L. G., Colin, J., Dauphole, B., & Eggleton, P. 1998, MNRAS, 301, 759
Koenigsberger G. 2004, Rev.Mex. AA, 40, 107
Kurtev R., Sholukhova O., Borrisova J., Georgiev L. 2001, Rev.Mex. AA, 37, 57
Maryeva, O., Abolmasov, P. 2010, Rev.Mex. AA, 46, 279
Maryeva, O., Abolmasov, P. *"Spectral Study of the WNL Star FSZ35 in the M33 Galaxy"*, MNRAS, submitted
Maryeva, O., Abolmasov, P. *"Modeling the optical spectrum of Romano's star"*, MNRAS, submitted
Massey, P., Johnson, O. 1998, ApJ, 505, 793
Najarro F. 2001, ASPC, 233, 133
Polcaro V.F.,Gualandi R., Norci L. 2003, A&A, 411, 193
Szeifert T. 1996, In: *Wolf-Rayet Stars in the Framework of Stellar Evolution* Eds. J.M.Vreux, A.Detal, D.Fraipont-Caro, E.Gosset and G.Rauw. 33rd Liege Institute Astroph. Coll., Liege, 459
Zinnecker, H., Yorke, H. W. 2007, ARA&A, 45, 481