Discovery of a new WNL star in Cygnus with Spitzer

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Abstract

We report the discovery of a ring nebula around a candidate Wolf-Rayet (WR) star, HBHA 4202-22, in Cygnus using the *Spitzer Space Telescope* archival data. Our spectroscopic follow-up observations confirmed the WR nature of this star (we named it WR 138a) and showed that it belongs to the WN8-9h subtype. We thereby add a new example to the known sample of late WN (WNL) stars with circumstellar nebulae. We analyzed the spectrum of WR 138a by using the Potsdam Wolf-Rayet (PoWR) model atmospheres, obtaining a stellar temperature of 40 kK. The stellar wind composition is dominated by helium with 20 % of hydrogen. The stellar spectrum is highly reddened and absorbed (A_V = 7.4 mag). Adopting a stellar luminosity of log $L/L_\odot$= 5.3, the star has a mass-loss rate of $10^{-4.7}$ $M_\odot$ yr^{-1}, and resides in a distance of 4.2 kpc. We measured the proper motion for WR 138a and found that it is a runaway star with a peculiar velocity of ~ 50 km s^{-1}. Implications of the runaway nature of WR 138a for constraining the mass of its progenitor star are discussed.

1. A new ring nebula and its central star

The nebula, which is the subject of this poster, was discovered in the archival data of the *Spitzer Space Telescope*, obtained with the IRAC and MIPS instruments (Werner et al. 2004) within the framework of the Cygnus-X Spitzer Legacy Survey*. Fig. 1. shows the MIPS 24 μm image of the nebula and its central star.

The optical counterpart to the central star was identified by Dolidze (1971) as a possible WR star due to the presence in its spectrum of an emission band around λ6750 A. This star was included in the Catalogue of H-alpha emission stars in the Northern Milky Way (Kohoutek & Wehmeyer 1999) as a candidate WR star (named in the SIMBAD database as [KW97] 44-47 or HBHA 4202-22), but was not listed in the VIIth Catalogue of Galactic WR Stars (van der Hucht 2001) nor in the annex to this catalogue (van der Hucht 2006).

*http://www.cfa.harvard.edu/cygnusX/index.html

2. Observations

2.1 Spectroscopy

To verify the nature of HBHA 4202-22, we had performed spectroscopic observations with the Russian 6-m telescope using the SCORPIO focal reducer (Afanasiev & Moiseev 2005) in a long-slit mode with a slit width of 1', providing a spectral resolution of 5 A. The spectra were taken on two occasions: October 10, 2008 (spectral range λλ4000-5700 A and November 11, 2008 (spectral ranges λλ4000-5700 A , and λλ5700-7500 A).

2.2 Photometry

We measured HBHA 4202-22 using POSS-O plate taken in the epoch of 1954.57, CCD frames taken with 6-m BTA telescope in 2008.90 and CCD frames taken with SAO 1-m Zeiss telescope in 2009. The results are given in Table 1. They show that the star is variable with amplitudes between 0.04 and 0.07 in different filters in the time scale of a month. A total variability range in B filter between 1955 and 2009 is 0.19 mag.

2.3 Proper motion

We measured the proper motion for HBHA 4202-22 using four epochs in the POSS-1 and POSS-2 Digitized Sky Surveys and the epoch of our BTA/SCORPIO frames. The full epoch range is 54.3 years. The result is μ_α = - 4.9±1.2 mas yr^{-1}, μ_δ = -4.7±1.2 mas yr^{-1}.

To convert the observed proper motion into the true tangential velocity of the star, we use the Galactic constants R_0=8 kpc and Θ=200 km s^{-1} (e.g. Reid 1993) and the solar peculiar motion ($U_\odot$,$V_\odot$,$W_\odot$) = (10.00, 5.25,7.17) km s^{-1} (Dehnen & Binney 1998), and adopt a distance *d*=4.2 kpc (see Section 5). We found that the star is moving in the west-southwest direction with a peculiar (transverse) velocity of ≈50±24 km s^{-1}.

The details of HBHA 4202-22 are summarized in Table 2.

Table 1. Photometry of HBHA 4202-22 (WR 138a)

JD	B	V	R_C	Source
2434951	17.15±0.06	--	--	POSS-1
2454796	17.25±0.01	15.44±0.01	--	BTA
2454981	17.34±0.02	15.57±0.02	13.90±0.02	1-m Zeiss
2455008	17.27±0.02	15.53±0.02	13.85±0.02	1-m Zeiss

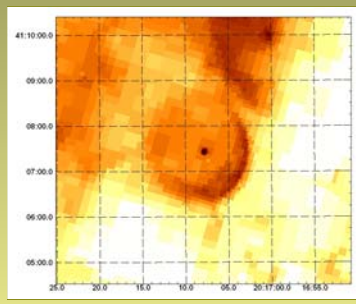

Fig. 1. *Spitzer* MIPS 24 μm image of a new ring nebula in Cygnus and its central star HBHA 4202-22 (WR 138a).

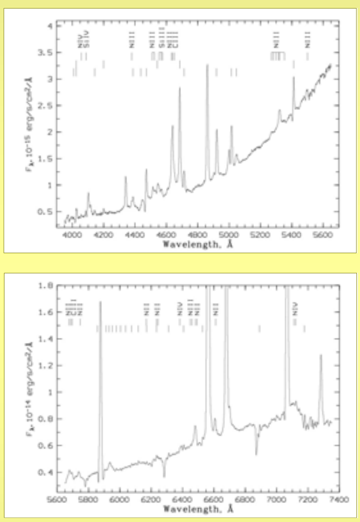

Fig. 2. Blue (top) and red (bottom) spectra of HBHA 4202-22 (WR 138a) with some lines indicated (upper row). In the blue spectrum, the bottom row of vertical bars marks numerous He II lines while the middle one marks He I lines. In the red spectrum, the vertical bars mark He II lines, whereas very strong He I lines are not marked. H I emissions are not marked on both spectra as well. CCD fringes are noticeable at wavelengths longer than ~ 6900 A.

3. Spectral type

In Fig 2 we present the spectrum of HBHA 4202-22 in the blue and red regions. The spectrum shows strong emission lines of hydrogen, He I and He II. We detect emissions of N II, N III, C III, N IV, Si IV. No forbidden lines can be seen in the spectrum. Many of the weaker lines in the spectrum show P Cygni profiles, while the strongest lines are entirely in emission. The strong absorptions visible in the red spectrum are telluric. Numerous diffuse interstellar bands (DIBs) are observed, in the blue region they are λλ4428, 4726, 4762, in the red the strongest one is at 6280 A.

The dominance of helium and nitrogen emission lines indicates that HBHA 4202-22 belongs to the nitrogen (WN) sequence of WR stars. The presence of hydrogen emission lines is typical for WNL subtypes (Hamann et al. 1991). We named this star WR 138a, in accordance with the numbering system of the VIIth Catalogue of Galactic WR Stars by van der Hucht (2001). To determine the subtype of WR 138a more precisely, we used the classification scheme proposed by Smith (1968) and updated for WNL stars by Crowther, Hillier & Smith (1995) and Smith, Shara & Moffat (1996). We found that WR 138a belongs to the WN8-9 subtype. Following the three-dimensional classification for WN stars by Smith et al. (1996), we add a `h' suffix to WN8-9 to indicate the presence of hydrogen emission lines, so that WR 138a is a WN8-9h star.

Table 2. Details of HBHA 4202-22 (WR 138a)

RA(J2000)	20^h 17^m 08.12^s
Dec.(J2000)	41^o 07' 27.0"
l,b	78.3203, 3.1536
B (mag)	17.25±0.01
V (mag)	15.44±0.01
J (mag)	10.15±0.02
H (mag)	9.27±0.02
K_S (mag)	8.65±0.02
[3.6] (mJy)	168.0±5.0
[5.8] (mJy)	154.0±4.6
[24] (mJy)	45.7±1.4
[70] (mJy)	< 28.1

4. Spectral analysis and stellar parameters

To analyze the stellar spectrum and to derive the fundamental parameters of WR 138a, we use the Potsdam Wolf-Rayet (PoWR) models for expanding stellar atmospheres. These models account for complex model atoms including iron-line blanketing in non-LTE (for a detailed description see Hamann & Grafener 2004). For abundances of trace elements we adopt values which are typical for Galactic WN stars -- N: 0.015, C: 0.0001, Fe: 0.0014 (Hamann &Grafener 2004).

The basic stellar parameters T_* and R_t are determined from fitting the lines in the normalized spectrum (see Fig. 3). A first orientation about the proper choice of these parameters can be obtained by comparing the observed spectrum to the published grids of WN models (Hamann & Grafener 2004). For a detailed fit, we calculate individual models for this star with the adequate terminal wind velocity, which is v_∞= 700 km s^{-1} as inferred from fitting the width of the emission line profiles.

The stellar temperature is adjusted such that the balance between the lines from He I versus He II is reproduced. At the same time, R_t is adjusted, which influences the strength of the emission lines in general. The parameters of the best-fitting model are compiled in Table 3.

Fig. 3 shows that the Balmer lines of hydrogen dominate their blend with lines of the He II Pickering series. These blends are nicely matched by models with a hydrogen mass fraction of 20 %, leaving about 80 % of the mass for helium which is a typical composition for WNL stars.

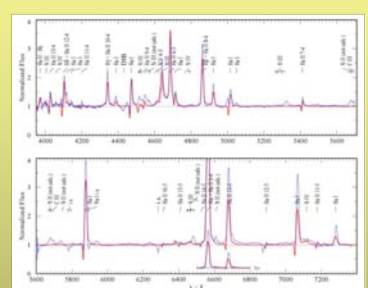

Fig.3. Observed optical spectrum (blue line) of WR 138a, compared with the best fitting model (red line) with the parameters as given in Table 2. The absolutely calibrated observation had been divided by the reddened model continuum for normalization.

Table 3. Stellar parameters for WR 138a

Spectral type	WN8-9h
T_*[kK]	40
log R_t [$R_\odot$]	0.9
v_∞ [km s^{-1}]	700
log L [$L_\odot$]	5.3
R_*[$R_\odot$]	9.4
log $\dot{M}$ [$M_\odot$ yr^{-1}]	-4.7
E_{B-V} [mag]	2.4
d [kpc]	4.2

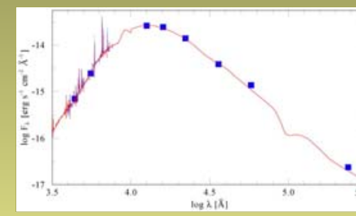

Fig. 4. Observed flux distribution of WR 138a (blue) in absolute units, including the calibrated spectrum and the photometric measurements compiled in Table 2, compared to the emergent flux of the model continuum (red line), in the optical also shown with lines. The model flux has been reddened and scaled to the distance according to the parameters given in Table 3.

5. Luminosity and distance of WR 138a

The lowest plausible luminosity for a massive WNL star is about log $L/L_\odot$= 5.3 (Hamann, Grafener & Liermann 2006). Let us adopt this value for a moment. This choice implies the values for the stellar radius and mass-loss rate as given in Table 3.

To estimate the corresponding distance to WR 138a, we now fit its observed spectral energy distribution (SED) with the model SED (Fig. 4). Two parameters can be adjusted for the fit, the distance *d* and the reddening E_{B-V}. The reddening law we adopt from Seaton (1979) in the optical and from Moneti et al. (2001) in the IR. A perfect fit to the whole SED is achieved with E_{B-V} = 2.4 mag, implying an extinction in the visual of A_V = 7.4 mag and *d*=4.2 kpc. The strong interstellar absorption also shows up in the observed spectrum by pronounced DIBs (see Fig. 3).

The line-of-sight towards WR 138a is nearly tangential to the local (Orion) spiral arm, whose extent in this direction is ~ 4--6 kpc (e.g. Russeil 2003). A distance of about 4 kpc would imply that this star is located at the far end of the Orion arm, which is compatible with the high reddening.

6. WR 138a as a runaway star

Our proper-motion measurements for WR 138a (Sect.2.3) showed that the star is moving in the west-southwest direction (i.e. away from the Galactic plane) with a peculiar (transverse) velocity of ~ 50 km s^{-1} (for d=4.2 kpc), which is typical of runaway stars. In the Galactic coordinates, the components of the peculiar velocity are almost equal to each other: v_l ≈ -36 km s^{-1}, v_b ≈ 34 km s^{-1}.

Assuming that the progenitor star of WR 138a was born near the Galactic plane and ejected from the parent star cluster soon after the birth, one has that the time it needs to reach the present height above the Galactic plane, $t_* \approx d \sin b / v_b$, should be ≤ t_H, where t_H is the H-burning lifetime of the star. Adopting the minimum plausible luminosity for WNL stars of log ($L/L_\odot$)=5.3, one finds the current mass of WR 138a of ~ 13 $M_\odot$, which in turn implies the initial mass of the star of ~30 $M_\odot$ and t_H ~ 6.0--7.0 Myr (e.g. Meynet & Maeder 2003). Thus, one has that t_* (~ 6.7 Myr) ≤ t_H, so that the star had enough time to reach its present location.

Placing WR 138a at, for example, *d*=6 kpc would result in a twofold increase of the stellar luminosity and in a increase of the present and initial mass of the star to, respectively, ~ 17 $M_\odot$ and ~ 40 $M_\odot$. In this case, t_* ~ 7.0 Myr > t_H ~ 4.5-5.5 Myr. Further increase of *d* makes the discrepancy between t_* and t_H more severe. The discrepancy would be even more sever if the star spent several Myr in the parent cluster before it was ejected (Gvaramadze & Bomans 2008; Gvaramadze, Gualandris & Portegies Zwart 2008). From this follows that the most likely initial mass of the progenitor star of WR 138a was ~ 25-30 $M_\odot$. One cannot however exclude a possibility that the progenitor star was a blue straggler formed via merging of two less massive stars in the course of close binary-binary encounter, resulting in ejection of the merger product from the parent cluster (e.g. Gvaramadze & Bomans 2008). In this case, the distance to and the mass of WR 138a could be larger.