The Discovery of a Twelfth Wolf-Rayet Star in the Small Magellanic Cloud

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ABSTRACT

We report the discovery of a relatively faint ($V = 15.5$) early-type WN star in the SMC. The line strength and width of He II $\lambda4686$ emission is similar to that of the other SMC WNs, and the presense of N V $\lambda4603, 19$ emission (coupled with the lack of N III) suggests this star is of spectral type WN3-4.5, and thus is similar in type to the other SMC WRs. Also like the other SMC WN stars, an early-type absorption spectrum is weakly present. The absolute magnitude is comparable to that of other (single) Galactic early-type WNs. The star is located in the Hodge 53 OB association, which is also the home of two other SMC WNs. This star, which we designate SMC-WR12, was actually detected at a high significance level in an earlier interference-filter survey, but the wrong star was observed as part of a spectroscopic followup, and this case of mistaken identity resulted in its Wolf-Rayet nature not being recognized until now.

Subject headings: Magellanic Clouds – galaxies: stellar content – stars: Wolf-Rayet

1. Introduction

Wolf-Rayet stars (WRs) are the evolved, He-burning descendents of the most massive stars, and their strong emission lines allow them to serve as an important tracer of the massive star content of nearby galaxies (see Massey 2003 for a recent review). Massey & Duffy (2001) recently completed a survey for Wolf-Rayet stars in the SMC, discovering two previously unknown ones, bringing the total to 11 known. Their study confirmed that there is not a significant population of WR stars still to be found in the SMC, although they expected that a few remained to be discovered. As they note, the number of WRs is thus a factor of 3-4 lower in the SMC than in the LMC (normalized per unit luminosity) despite the fact that the SMC and LMC have a comparable star-formation rate for massive stars. This is in accord with the suggestion that at the lower metallicity of the SMC only the highest mass massive stars possess sufficient stellar winds to evolve to the Wolf-Rayet phase. Studies of coeval regions in the SMC, LMC, and Milky Way seem to confirm this, as the turn-off masses in clusters containing WRs suggest that only stars with masses greater than $65\mathcal{M}_\odot$ may become WRs in the SMC, while the lowest progenitor mass for a WR in the LMC may be 30 $\mathcal{M}_\odot$ and $20\mathcal{M}_\odot$ in the Milky Way (Massey, Waterhouse, & DeGioia-Eastwood 2000; Massey, DeGioia-Eastwood, & Waterhouse 2001).

The authors and several additional collaborators are engaged in a spectroscopic survey of hot, massive stars in the Magellanic Clouds using the CTIO 4-m. During a recent run, we chanced across another previously unknown WR in the SMC. Here we describe this interesting object.

2. Observations and Reductions

The data were taken on the CTIO 4-m Blanco telescope during a four night observing run 18-21 December 2002 using the Hydra multi-object fiber position (Barden & Ingerson 1998). The instrument consists of 138 fibers (300μm, which equals 2.0-arcsec in diameter) which can be positioned within a 40 arcmin diameter field of view. The fibers "feed" a bench-mounted spectrograph, where we used grating KPGLD in second-order and a BG-39 blocking filter and a 400-mm focal length camera, behind which was a SITe 2096×4096 (15μm pixels) CCD. The chip was binned by 2 in the dispersion direction, resulting in a dispersion of 0.45Å pixel^{-1} and a spectral resolution of 3.5 pixels (1.6Å). Our wavelength coverage extended from 3900Å to 4950Å. The fiber-to-fiber sensitivity was removed by a combination of exposures of the illuminated "great white spot" each afternoon/morning along with projector flat exposures taken at each telescope position and fiber configuration. The pixel-to-pixel variations of the CCD were removed by means of a “milk flat”, an exposure through a diffuser screen of the illuminated fiber ends. Wavelength calibration was by means of a long He-Ne-Ar lamp exposure taken each afternoon, supplemented by shorter exposures taken at each field.

The data for the WR star was obtained on the second night of the run (19 Dec 2002). A sequence of four exposures, each of 1200 s, was taken of this field. The data were combined after extraction and processing. The seeing conditions were described in the observing log as “rotten”. At the time the Tololo seeing monitor was reporting the seeing as 2.4 arcsec, eventually improving to 1.2 arcsec near the end of the exposures.

3. Discussion: SMC-WR12

The spectrum of one of the targets in this field showed the characteristic broad, strong emission features of a Wolf-Rayet star of the WN sequence (Fig. 1). He II $\lambda4686$ is visible with an equivalent width (EW) of -22Å and a full-width at half-maximum of 21Å. The strength of He II $\lambda4686$ argues that this star must be a WN-type Wolf-Rayet rather than an Of-type star, as even the most extreme Of-type stars known have EWs > -10Å (Conti & Leep 1974), although some SMC WNs stars do have EWs that overlap with Of stars (see Conti, Garmany, & Massey 1989 and Conti & Massey 1989). The weak presence of N V $\lambda4603, 19$ emission also precludes the possibility that the star is an Of supergiant. The lack of N III $\lambda4634, 42$ emission then makes the spectral class of type WN3-4.5. Unfortunately our spectrum is too noisy in the far blue to tell if NIV$\lambda4058$ is present or not, leading to the uncertainity in the subtype (Smith 1968, van der Hucht et al. 1981). In any event the spectral type of this WN is “early”, similar to most of the other SMC WNs. Absorption is clearly visible at He II $\lambda4542$, although there is no sign of He I $\lambda4471$ in our somewhat noisy spectrum. We would thus describe the absorption spectrum as O3-O4. Although in general WRs do not show any absorption features, nearly all of the SMC WNs do, and the absorption features are mostly of the same O3-4 class (i.e., He II). Massey & Duffy (2001) argue that the presence of absorption spectra in the SMC WRs is still not well-understood: either it is due to the fact that the stellar winds are weak (and hence one sees photospheric absorption) or it suggests that most of the SMC WRs are binaries. Recent radial velocity studies by Foellmi, Moffat, & Guerrero (2003) suggest that the binary fraction of WRs is normal in the SMC.

We compare the spectral characteristics and photometry to that of the other SMC WRs in Table 1. The values for this newly found WR star (which we are designating SMC-WR12 for consistency; see Massey & Duffy 2001) are in fact in keeping with those of the other SMC stars. The most notable thing about this WR star is how similar it is to the others in terms of all of its properties, although it is on the faint end of the luminosity distribution of WRs in the SMC. However, the absolute visual magnitude (inferred by adopting $(B-V)_o = -0.32$, following Pyper 1966 and assuming a true distance modulus to the SMC of 18.9, following van den Bergh 2000) is quite normal for a (single) early-type WN in the Milky Way (Conti & Vacca 1990).

SMC-WR12 was previously cataloged in the *UBVR* photometry of Massey (2002) as SMC-054730. A finding chart is given in Fig. 2. The star is located in the Hodge 53 OB association (Hodge 1985), which is also home to two of the other SMC WRs. Thus one-quarter of the known SMC WRs are found in this one rich association. An investigation of the *unevolved* stars in Hodge 53 was carried out by Massey et al. (2000), who found that the most massive H-burning stars had (initial) masses in the range of 50-80$\mathcal{M}_\odot$. This would suggest that the progenitors of the Hodge 53 Wolf-Rayet stars had masses of comparable or slightly higher values, although the coevality of the region was considered "questionable" as there were also evolved stars of 10-20$\mathcal{M}_\odot$ present.

We were naturally curious as to why this star was not detected on earlier surveys. The star is rather faint ($V = 15.5$) to have been detected by the objective prism search of Azzopardi & Breysacher (1979), who cataloged the first eight WRs in Table 1. (Some had been known previous to their survey.) In addition, the star's location in a relatively crowded region would create confusion for objective prism studies. Inspection of the working notes for the Massey & Duffy (2001) interference-filter imaging survey reveals that SMC-WR12 *was* detected at a very high significance level (7σ), with a magnitude difference (0.36 mag) consistent with real WRs. The star was observed spectroscopically as part of that program, but the spectrum was that of a (foreground) G-type dwarf, and the first author incorrectly concluded that there had been something wrong with the interference-filter photometry: our notes say "2 stars", indicated we thought that crowding had compromised the photometry. In retrospect, the wrong star must have been observed spectroscopically. A careful comparison of the telescope coordinates for the old (October 2000) observations with that expected suggests that a star about 5-10 arcsec south was observed instead, likely the star 7 arcsec to the SW shown on the finding chart. This is unfortunate, but consistent with Massey & Duffy's caution that they "cannot preclude a WR star or two [from] having been overlooked in our survey, particularly in crowded regions."

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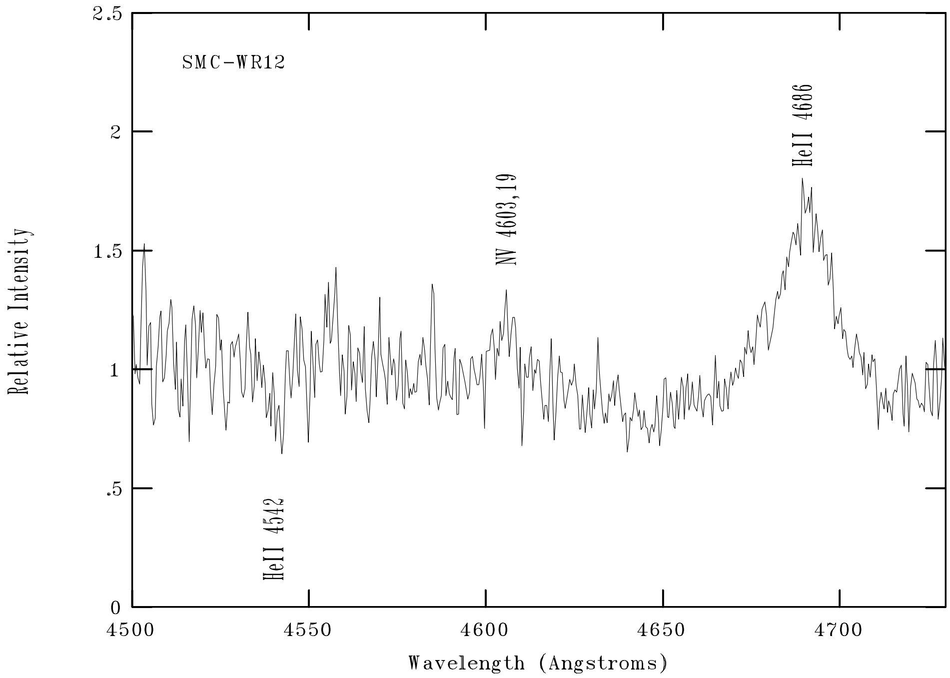

Fig. 1.— The spectrum of SMC WR-12 is shown. Strong, broad emission lines of He II $\lambda4686$ and N V $\lambda4603, 19$ are visible, as well as absorption at He II $\lambda4542$.

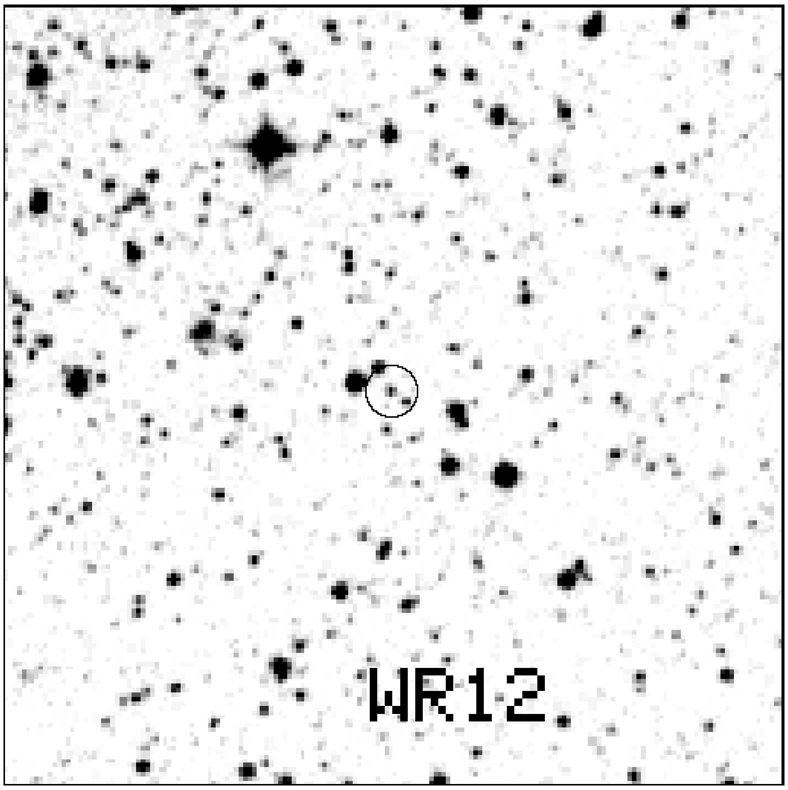

Fig. 2.— Findging chart for SMC WR-12. The chart is 5 arcmin on a side and was made from the Digitized Sky Survey; the circle marking the WR star is 20 arcsec in diameter. North is up, and east is to the left. Similar finding charts for the other SMC WRs may be found in Massey & Duffy (2001).

Table 1. Wolf-Rayet Stars in the SMC[a]

Star	Other ID	α_{2000}	δ_{2000}	OB/HII[b]	Spectral Type	Abs.	V	$B-V$	M_V	He II or C III[c] EW (Å)	He II or C III[c] FWHM(Å)	Comment
SMC-WR1	AV 2a	00 43 42.23	−73 28 54.9	no	WN3+abs	O3-4	15.14	−0.04	−4.6	−28	21	Weak abs.
SMC-WR2	AV 39a	00 48 30.81	−73 15 45.1	near h15	WN4.5+abs	O5:	14.23	−0.15	−5.2	−15	12	
SMC-WR3	AV 60a	00 49 59.33	−73 22 13.6	near h17	WN3+abs	···	14.48	−0.10	−5.1	−53	26	Very weak abs.
SMC-WR4	AV 81, Sk 41	00 50 43.41	−73 27 05.1	h21	WN6p	···	13.35	−0.16	−6.2	−45	15	N V abs?
SMC-WR5	HD 5980	00 59 26.60	−72 09 53.5	NGC 346=h45	WN5	···	11.08	+0.03	−8.9	−85	18	
SMC-WR6	AV 332, Sk 108	01 03 25.20	−72 06 43.6	NGC 371(e76)=h53	WN3+abs	O7	12.30	−0.15	−7.1	−8	28	
SMC-WR7	AV 336a	01 03 35.94	−72 03 21.5	NGC 371(e76)=h53	WN2+abs	O6	12.93	− 0.05	−6.8	−16	27	
SMC-WR8	Sk 188	01 31 04.22	−73 25 03.9	NGC 602c=h69	WO4+abs	O4 V	12.81	−0.14	−6.6	−76	71	
SMC-WR9	Morgan et al.	00 54 32.17	−72 44 35.6	no	WN3+abs	O3-4	15.23	−0.13	−4.3	−22	24	
SMC-WR10		00 45 28.78	−73 04 45.2	NGC 249(e12)	WN3+abs	O3-4	15.76:	−0.08:	−3.6	−24	23	Strong neb.
SMC-WR11		00 52 07.36	−72 35 37.4	no	WN3+abs	O3-4	14.97	+0.18	−5.5	−14	25	
SMC-WR12	SMC-054730	01 02 52.07	−72 06 52.6	NGC 371(e76)=h53	WN3-4.5+abs	O3-4	15.46	−0.15	−4.0	−22	21	

[a]This table is an updated version of Table I in Massey & Duffy 2001.

[b]OB associations designation (h) are from Hodge (1985), and emission-line regions are from the Hodge & Wright (1977) atlas.

[c]The equivalent width (EW) and full-width-at-half-maximum (FWHM) of He II $\lambda4686$ is given for the WNs; that of C III $\lambda4650$ is given for the WO4 star.