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A NEW WOLF-RAYET EJECTA SHELL IN THE LMC

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RESUMEN

Presentamos observaciones espectroscópicas de dos nebulosas de cascarón recientemente descubiertas alrededor de estrellas Wolf-Rayet en la Nube Mayor de Magallanes (NMM). Uno de estos cascarones, alrededor de la estrella brillante Br 13, muestra líneas de [N II] y de He I mucho más intensas que las de regiones H II de la NMM de similar excitación, lo que es evidencia de que el cascarón contiene nitrógeno y helio recién sintetizado y arrojado desde el interior de la progenitora de la W-R. Estimamos que N y He están excedidos al menos por un factor de dos sobre las abundancias interestelares en el NMM. El segundo cascarón, asociado con la estrella WN1 Br 2 muestra abundancias interestelares normales, y es probablemente una estructura formada por la acción del viento y dominada por la materia interestelar. El espectro se caracteriza por la emisión muy intensa de [O III] y He II, indicadores que Br 2 es una estrella W-R particularmente brillante.

ABSTRACT

We present spectroscopic observations of two recently discovered shell nebulae around Wolf-Rayet stars in the Large Magellanic Cloud (LMC). One of these shells, around the WN4 star Br 13, shows much stronger [N II] and He I lines than in LMC H II regions having similar excitation, strong evidence that the shell contains freshly synthesized and ejected nitrogen and helium from the interior of the W-R progenitor. We estimate that N and He are enhanced by at least a factor of two over their average interstellar abundances in the LMC. The second shell, associated with the WN1 star Br 2, shows normal LMC interstellar abundances, and is more likely a wind-blown structure which is dominated by interstellar material. The spectrum is characterized by unusually strong [O III] and He II emission, indicative that Br 2 is an unusually hot W-R star.

Key words: **CIRCUMSTELLAR SHELLS — ISM: ABUNDANCES — MAGELLANIC CLOUDS — STARS: WOLF-RAYET**

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1. INTRODUCTION

The most recent stellar evolution models incorporating stellar winds (Maeder 1992 and references therein) indicate that mass loss from massive stars has a profound effect on the evolution of those stars. In particular, Maeder finds that the theoretical yield of helium is strongly affected by mass loss; the stripping of the stellar envelope can remove significant amounts of helium which would otherwise be converted (in the hydrostatic case) into carbon and heavier elements. Since mass loss through radiatively driven winds is expected to vary with stellar metallicity, we should then expect that the yield for helium should also vary with metallicity. Unfortunately, stellar mass loss rates are still rather poorly known, so the effect is not well determined quantitatively yet.

One possibly useful way of approaching the problem is to measure abundances in the Wolf-Rayet stars and any associated circumstellar ejecta shells, comparing objects in regions having widely different metallicities. The Milky Way and the Magellanic Clouds are ideal hunting grounds for such a study, since the LMC and SMC have significantly lower heavy element abundances than the solar neighborhood. Several Galactic W-R stars are known to have shell nebulae which show the products of stellar nucleosynthesis, such as NGC 6888 (Kwitter 1981, Esteban & Vílchez 1992). However, until recently no comparable objects had been found in the Magellanic Clouds. Heydari-Malayeri, Melnick, & Van Drom (1990) found a nitrogen-rich nebula around a WC 9 star in the LMC; more recently, Dopita *et al.* (1993) completed a narrow-band imaging survey of all known W-R stars in the Magellanic Clouds, uncovering several good candidates for circumstellar shells. We report spectroscopic observations for two of these candidates.

2. OBSERVATIONS AND ANALYSIS

We have obtained long-slit spectroscopic observations of the circumstellar shells associated with the WN4 star Br 13 and the WN1 star Br 2 (Breysacher 1981), using the 4-m reflector and R-C spectrograph at CTIO. We covered the spectral range 3350-8000 Å in two segments; 3350-5500 Å at 4 Å spectral resolution and 4250-8000 Å at 8 Å resolution. The observed and reddening-corrected line strengths for both shells are listed in Table 1.

Table 1. Line Intensities for LMC Wolf-Rayet Shells.[a]

Line	Br 13 shell		Br 2 shell	
	I_o	I_c	I_o	I_c
[O II] λ3727	0.70 (0.11)	0.88 (0.16)	0.99 (0.07)	1.14 (0.09)
[Ne III] λ3869	0.18 (0.05)	0.22 (0.06)	0.53 (0.04)	0.60 (0.05)
Hδ	0.24 (0.05)	0.28 (0.07)	0.23 (0.02)	0.26 (0.03)
Hγ	0.40 (0.04)	0.45 (0.05)	0.43 (0.03)	0.47 (0.04)
[O III] λ4363	0.07 (0.03)	0.08 (0.03)	0.11 (0.01)	0.12 (0.02)
He I λ4471	0.09 (0.02)	0.10 (0.02)	0.015 (0.011)	0.016 (0.011)
He II λ4686	···	···	0.58 (0.04)	0.59 (0.04)
Hβ	1.00	1.00	1.00	1.00
[O III] λ4959	1.14 (0.18)	1.12 (0.18)	2.13 (0.16)	2.10 (0.16)
[O III] λ5007	3.26 (0.43)	3.17 (0.42)	6.41 (0.49)	6.30 (0.48)
He I λ5876	0.22 (0.07)	0.19 (0.06)	0.056 (0.004)	0.050 (0.004)
Hα	3.61 (0.44)	2.81 (0.34)	3.26 (0.11)	2.80 (0.13)
[N II] λ6583	0.61 (0.11)	0.48 (0.09)	0.11 (0.02)	0.10 (0.02)
[S II] λ6717	< 0.11	< 0.11	0.22 (0.01)	0.18 (0.01)
[S II] λ6731	< 0.08	< 0.08	0.15 (0.01)	0.12 (0.01)
c(Hβ)	0.35 (0.05)		0.22 (0.05)	

[a]Line strengths relative to Hβ, with 1σ uncertainties given in parentheses.

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We derive an upper limit of $n_e < 250cm^{-3}$ for the electron density in the Br 2 shell, from both [S II] and [Ar IV] line ratios. For the Br 13 shell, we were unable to detect the [S II] lines, and so could not determine n_e directly. From the Hβ flux, we estimate the rms density $(n_e^2\epsilon)^{1/2} \approx 10cm^{-3}$, which implies that the local densities are too low to significantly affect the derived abundances. We adopted $n_e = 100cm^{-3}$ for the remainder of the analysis.

Electron temperatures T_e were determined from measurements of the [O III] 4363 Å and 5007 Å lines in both shells. The ratios of these two lines yielded T_e = 17,200 (+4200, −2000) K for the Br 13 shell, and T_e = 14,000 (+1600, −1000) K for the Br 2 shell.

We determined the ionic abundance ratios O^+/H^+, O^{+2}/H^+, N^+/H^+, He^+/H^+, and He^{+2}/H^+ from the emission line strengths and theoretical emissivities. The forbidden line emissivities were computed using a five level atom approximation, while the He and H recombination line emissivities were taken from tables in Osterbrock (1989). The He and O ion ratios were then summed to obtain the total helium and oxygen abundances (for the high-ionization Br 2 shell, we accounted for unobserved O^{+3} by assuming $O^{+3}/O = He^{+2}/He$). We also assumed $N/O = N^+/O^+$ to estimate the nitrogen abundance. The calculated ionic and elemental abundances so derived are listed in Table 2.

3. DISCUSSION

A comparison of the W-R shell abundances with the average LMC interstellar values in Table 2 indicates that the Br 13 shell does show evidence for synthesized He and N; we derive He/H and N/H in the shell approximately a factor of two higher than the LMC average. Thus, the Br 13 shell is only the second such object associated with a massive W-R star in the LMC, besides N82 (Heydari-Malayeri *et al.* 1990). There is a problem in that the derived O/H is much lower than would be expected from the increased N/H. We suspect the electron temperature may be too high. One possibility is that we may be observing an "incomplete" shock arising from the interaction of the fast stellar wind with photoionized material, along with the photoionized ejecta. This phenomenon has been seen in shells around Galactic W-R stars by Dufour and collaborators (Dufour 1989); they have observed filaments with very high [O III]/Hβ ratios and electron temperatures indicative of shock-heated gas, but weak or absent emission from singly-ionized and neutral metals. The presence of such

Table 2. Abundances in the Br 13 and Br 2 Shells.

Quantity	Br 13 shell	Br 2 shell	LMC average[a]
T_e	17,200 $^{+4200}_{-2000}$ K	14,000 $^{+1600}_{-1000}$ K	
He^+/H^+	0.19±0.05	0.041±0.007	
He^{+2}/H^+	...	0.051±0.004	
ICF	1.00	1.00	
He/H	0.19±0.05	0.092±0.008	0.088
O^+/H^+	(5.1±2.7)x10^{-6}	(12.3±3.7)x10^{-6}	
O^{+2}/H^+	(25.0±10.5)x10^{-6}	(85.3±19.5)x10^{-6}	
ICF	1.00	2.24	
O/H	(3.0±1.1)x10^{-5}	(2.19±0.44)x10^{-4}	2.5x10^{-4}
N^+/H^+	(2.9±1.0)x10^{-6}	(0.86±0.24)x10^{-6}	
ICF	5.88	14.4	
N/H	(1.7±0.6)x10^{-5}	(1.2±0.3)x10^{-5}	1.0x10^{-5}
N/O	0.57±0.18	0.070±0.015	0.042

[a]Average of Dufour (1984) and Russell & Dopita (1990).

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gas in the region covered by our slit could cause us to derive too high a temperature. This does not affect our conclusion that the Br 13 shell contains enriched gas, however: the He/H derivation is almost independent of T_e, while a lower T_e would yield an even *higher* N/H, strengthening our conclusion. High resolution imaging and velocity mapping could help to separate any shocked material from the photoionized ejecta and provide a better measurement of the abundances.

Meanwhile, the Br 2 shell shows no signs of abundance enhancements; both the He and N abundances are identical to the LMC interstellar values to within the uncertainties. It is likely the W-R star is extremely young and has not yet evaporated enough material to have significant enriched the local ISM. The nebula is remarkable, however, for its high degree of ionization. Pakull (1990) has already noted the remarkable strength of He II 4686 in this nebula, indicating that Br 2 is an unusually hot W-R star. Further analysis of the spectrum of this object is under way to study the extreme ultraviolet spectrum of this star.

These observations clearly demonstrate that we are now finding the true analogs to the Galactic W-R shells in the Magellanic Clouds. Earlier studies based on low-resolution Schmidt plates (Chu & Lasker 1980, Rosado 1986) were unable to discern these objects, even in deep images - the low surface brightness of the nebulae did not allow them to be distinguished from the wings of the stellar profile. Now, with deeper analysis of the nebulae and with complementary studies of the W-R stars as well, we may be able to study W-R stars at high and low metallicities to better understand how mass loss affects the evolution of massive stars.

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