Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Neon abundances in three Wolf-Rayet stars observed with the ISO Short Wavelength Spectrometer

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1. Introduction

We are motivated to study the Ne/He abundance ratio at the surfaces of Wolf-Rayet stars by evolutionary models, which have predicted enhancements by more than an order of magnitude over cosmic levels during the WC stage (*e.g.*, Maeder 1991). This should occur early in the WC phase, as core-hydrogen is exhausted and the CNO bi-cycle gives way to the following chain of reactions for the Galactic stars:

$$^{14}\mathrm{N}(\alpha,\gamma) \longrightarrow {}^{18}\mathrm{F}(\beta^+,\nu) \longrightarrow {}^{18}\mathrm{O}(\alpha,\gamma) \longrightarrow {}^{22}\mathrm{Ne}(\alpha,n) \longrightarrow {}^{25}\mathrm{Mg}$$

The latest evolutionary models, which include the effects of interior mixing due to stellar rotation, indicate that the enhancement may be somewhat more gradual, but that the Ne/He ratio is essentially unchanged in its peak value, coinciding with complete H-depletion (*e.g.*, Meynet, these Proceedings).

2. Latest ISO results

The first WC star to be studied in detail, γ^2 Vel (WR 11, WC8+O8.5III), showed only a minor enhancement of Ne/He (Barlow *et al.* 1988). This was the only WC star for which an *IRAS*-LRS spectrum was available to measure the [NeIII] 15.55 μm line emission. With *ISO*, γ^2 Vel and several other WR stars have been observed using the Short Wavelength Spectrometer (SWS). The reader is referred to Figure 4 in the review by A. Willis (these Proceedings) for a montage of several WR star spectra over the 12–17 μm range that would include the lines of [NeII] 12.81μm, [NeV] 14.32μm, and [NeIII] 15.55μm.

The SWS and ground-based spectrum of WR 146 (WC6+O) has been studied by Willis *et al.* (1997), who found Ne/He to be much closer to the evolutionary

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predictions. Subsequently, Morris *et al.* (1998) presented preliminary results for WR 135 (WC8) and WR 147 (WN8(h)+B0.5V), and re-assessed the results for γ^2 Vel in light of the new distance established by *Hipparcos* (van der Hucht *et al.* 1997) and the mass-loss rate estimates by St-Louis *et al.* (1988) and Stevens *et al.* (1996).

2.1. WR 135 (WC8)

The Ne/He ratio of WR 135 is roughly a factor four higher than expected for an environment where H/He = 0.0 and C/He = 0.13, but this is not as much as the evolutionary models predict. There is some hint of [MgV] 13.54 μm emission, which could indicate that α capture by ^{22}Ne has occured. We do not notice magnetic dipole transtions of [MgV] 5.608 μm or [MgIV] 4.488 μm.

2.2. WR 11 (WC8+O8.5III)

The Ne-line fluxes at 12.81 μm and 15.55 μm are in good agreement with the values quoted by Barlow *et al.* (1988), but the stellar distance is now known to be nearly a factor of two closer based on *Hipparcos* observations. This by itself does not influence the results much, since the ion fraction γ_i scales as $d^2/\dot{M}^{3/2}$, and $\dot{M}$ scales as $d^{3/2}$. However, much lower mass-loss rates are given by polarimetery studies by St-Louis *et al.* (1988) and X-ray observations by Stevens *et al.* (1996), roughly three times lower than estimated by Barlow *et al.* (1988) from the radio free-free continuum. Using an average $\dot{M} = 1.3 \times 10^{-4}\ \mathrm{M_{\odot} yr^{-1}}$ and C/He = 0.14 from recombination analysis of the SWS lines, a lower value of Ne/He $\geq 6.3 \times 10^{-3}$ is obtained, a factor of ~10 higher than a cosmic environment where H/He = 0.0 and C/He = 0.14.

2.3. WR 147 (WN8(h)+B0.5V)

The SWS spectrum of WR 147 shows very strong [NeIII] 15.55 μm emission, and no [NeII] 12.81 μm line (*e.g.*, Morris *et al.* 1998). Nonetheless, Ne in the ratio with He should be normal, since no net Ne production occurs during the CNO bi-cycle. To check Ne/He, we relied on the mass-loss rate estimated by Hamann *et al.* (1995) from optical spectroscopy. Their value was re-scaled to the distance and interstellar reddening given by Churchwell *et al.* (1992), using $\mathrm{M}_v = v - \mathrm{DM} - A_v$, $A_v = 4.1\, E_{b-v}$, and equations (4) and (5) in Hamann *et al.* (1993). This leads to a lower limit of Ne/He $\geq 1.0 \times 10^{-3}$, which is a factor of 2 or 3 higher than expected for an environement where H/He is somewhere between 0.0 and 0.4. With respect to levels predicted for WC stars, the enhancement is hardly that, but it is significant for a WN star, and may indicate some exposure of core-processed material via rotational mixing, as predicted to occur in WR stars (Meynet, these Proceedings).

3. The $\dot{M}$ problem

As mentioned, the Ne-ion fraction scales as $\dot{M}^{-3/2}$ in the two-level atom, mass-loss normalizing method by Barlow *et al.* (1988). Among published results using spherical, homogeneous wind models, differences by a factor of three in the value of $\dot{M}$ are not unusual due to distance and (to a lesser extent) reddening uncertainties, and the inclusion of line-blanketing by metals. More important may be the assumptions on geometry and homegeneity of the wind. It is known that clumping may lower the mass-loss rate by factors of two to three, which would serve to increase the ion fractions *in the clumps*, according to the inverse scaling with $\dot{M}$. This is emphasized by the case of WR 11, and might rectify the low Ne/He abundance ratio in WR 135. It would normally, however, exacerbate an already unexpected (albeit minor at the moment) over-abundance in the WN8 star of WR 147. But the system is highly reddened at $A_V \simeq 11.5$ mag (Churchwell *et al.* 1992), and the foreground extinction properties are probably anomylous, contributing to the difficulty in arriving at a clean spectroscopic solution for the physical parameters of the system. These issues are addressed in papers in preparation, where we will present the *ISO*-SWS spectra of WR 11, WR 135, and WR 147 in detail.

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