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:

\[ ^{14}\text{N}(\alpha, \gamma) \rightarrow ^{18}\text{F}(\beta^+, \nu) \rightarrow ^{18}\text{O}(\alpha, \gamma) \rightarrow ^{22}\text{Ne}(\alpha, n) \rightarrow ^{25}\text{Mg} \]

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, $\gamma^2$ Vel (WR11, 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 $\mu$m line emission. With ISO, $\gamma^2$ 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 $\mu$m range that would include the lines of [NeII] 12.81 $\mu$m, [NeV] 14.32 $\mu$m, and [NeIII] 15.55 $\mu$m.

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 γ² 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 [Mg vi] 13.54 μm emission, which could indicate that α capture by \(^{22}\)Ne has occurred. We do not notice magnetic dipole transitions of [Mg vii] 5.608 μm or [Mg iv] 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 \(\gamma_i\) 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 polarimetry 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 \(\dot{M} = 1.3 \times 10^{-4} M_\odot \text{yr}^{-1}\) and C/He = 0.14 from recombination analysis of the sws lines, a lower value of Ne/He ≥ 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 [Ne iii] 15.55 μm emission, and no [Ne ii] 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 bicycle. 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 \(M_v = v - DM - A_v, A_v = 4.1 E_{B-v}\), and equations (4) and (5) in Hamann et al. (1993). This leads to a lower limit of Ne/He ≥ 1.0 \times 10^{-3}, which is a factor of 2 or 3 higher than expected for an environment 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 homogeneity 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 $M$. 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 $A_V \approx 11.5\text{ mag}$ (Churchwell et al. 1992), and the foreground extinction properties are probably anomalous, 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.

References


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