WARMERS

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ABSTRACT. We present direct observational evidence showing that early type WR stars, and WO stars in particular, are exceedingly hot, and that their ionizing radiation is not fully trapped by their extended atmospheres. We show that extreme WR stars, or *Warmers,* are found in metal poor as well as in metal rich regions in accordance with theory. Images of HeIII regions around Galactic and Magellanic Cloud *Warmers* are shown.

1. INTRODUCTION

The latest stages in the evolution of massive stars are identified with Wolf-Rayet (WR) stars of the carbon sequence. Evolutionary models show that mass loss will remove the outer envelopes of these stars exposing their extremely hot helium burning cores. The models predict that the effective temperatures of these early type WC and WO stars can exceed 100,000K (Maeder and Meynet, 1989). The emergence of these hot stars in young starburst clusters results in a dramatic hardening of integrated ionizing spectra of these clusters, and this effect led Terlevich and Melnick (1985) to introduce the term *Warmers* to refer to massive stars whose effective temperatures are higher than their original ZAMS value. Terlevich and Melnick showed that, not surprisingly, the emission line spectra of model HII regions ionized by clusters with *Warmers* match extremely well the observed spectra of narrow line Seyfert galaxies.

A fundamental uncertainty about these *Warmer* models, however, is whether or not the winds of WR stars are optically thick to ionizing radiation, and in particular, to radiation harder than the HeII limit at 4 Rydbergs.

In this contribution we present observational evidence showing that the hard ionizing radiation from the hottest WR stars is not completely absorbed by their winds. This evidence comes from observations of nebular HeII emission in the integrated spectra of luminous emission-line galaxies, and in nebulae associated with individual WR stars in the Galaxy and the Magellanic Clouds.

2. HII GALAXIES

HII galaxies are gas rich dwarf irregular galaxies whose observable properties are dominated by one or several extremely young giant HII region components (Melnick, 1987). The starburst clusters

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in HII galaxies may contain hundreds to thousands of very young massive stars, so HII galaxies are excellent objects to test evolutionary theories of metal poor massive stars. Figure 1 presents the run of the electronic temperature of the nebular gas (Te) as a function of oxygen abundance (O/H). The lines show the predictions of photoionization models using the isochrones of Maeder and Meynet (1989) and Mihalas' (1972) model atmospheres for different effective temperatures. The effect of changing the ionization parameter is illustrated in this Figure by models computed using two extreme values of this parameter which span the range observed in HII galaxies (Melnick and Terlevich, 1987).

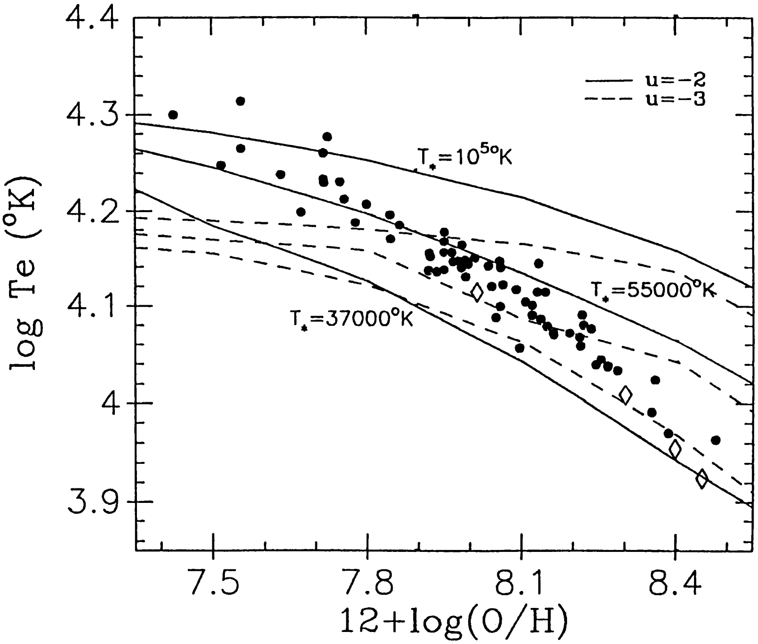

FIGURE 1: Relation between electron temperature and oxygen abundance for the best observed HII galaxies. Typical errors are ~ 10% in O/H and ~ 5% in Te. The lines show photoionization models using Mihalas' (1972) NLTE atmospheres for two extreme values of the ionization parameter *u*. More details about the models are given in Melnick and Terlevich (1987).

Models using other stellar atmospheres are not significantly different from the curves presented in Figure 1 (Melnick and Terlevich,1987). The feature of this diagram which is relevant in the present context is that the electron temperatures of the most metal poor HII galaxies can only be explained if their ionizing clusters contain exceedingly hot stars. Notice that models plotted in the figure are for *single* stars.

The models of Maeder (1990) predict that *Warmers* should appear either in very metal poor, or in very metal rich, systems. This is because the evolutionary time scales decrease with abundance while the mass loss rates increase. Thus, for metal poor stars winds peel off the envelopes at a very advanced stage of evolution. As a consequence, only the most massive stars arrive to the *Warmer* phase and essentially all the WC stars in metal poor clusters should be WOs. For SMC abundances the minimum mass of stars that reach the WC phase is close to 65 $M_\odot$ (Maeder, 1990).

A further strong evidence for the presence of such stars in metal poor HII galaxies is the observation of *nebular* HeIIλ4686 lines in the spectra of these galaxies. Three examples of HII galaxies with nebular HeII lines are presented in Figure 2.

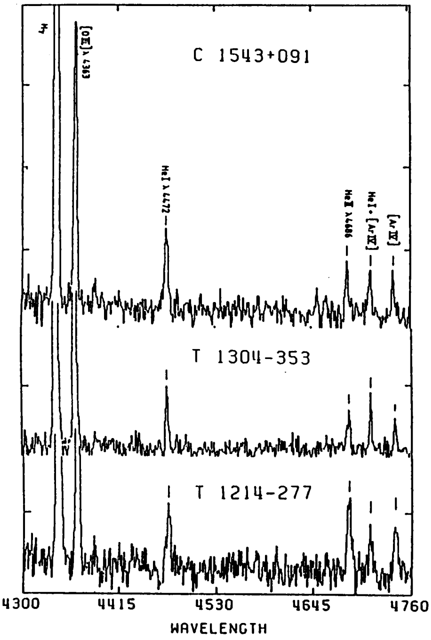

FIGURE 2: Nebular HeII lines in the spectra of three extreme HII galaxies. Notice the strength of the temperature sensitive [OIII]λ4363 lines.

3. INDIVIDUAL WARMERS

At least in principle, a direct determination of the hardness of the ionizing radiation emitted by WO stars could be simply obtained from the analysis of the nebular spectrum of HII regions ionized by these stars. In practice, however, this is made difficult by the fact that the strong winds from WR stars very effectively sweep out the interstellar medium surrounding them and thus prevent the formation of bright HII regions.

As a backup programme for cloudy nights, we have undertaken a search for HeIII regions around hot WR stars in the Galaxy and the Magellanic clouds. Our prime candidates for this search were, of course, the 4 known WO stars with massive progenitors (Sanduleak, 1971). We have obtained images of 3 of these stars: Sand 1=Sk 188 in the SMC, Sand 2=Br93 (Breysacher, 1981), and Sand 4=WR102 (van der Hucht *et al.* , 1981). Sand 1 is a member of the young SMC cluster NGC602c, and shows extremely weak [OIII] emission and no HeII in our images. Br93 is embedded in a bright HII region with a very complex structure in [OIII], but our HeII image is of insufficient quality to reveal any HeII emission.

Sand 4 = WR102 is a galactic WO star associated with the ring nebula G2.4+1.4 (van der Hucht *et al.* , 1981) where Johnson (1975) reported the detection of strong HeII lines. Figure 3 presents a narrow band HeII CCD image of this nebula obtained with the 3.6m telescope on La Silla which shows the presence of a filamentary HeIII region around the star.

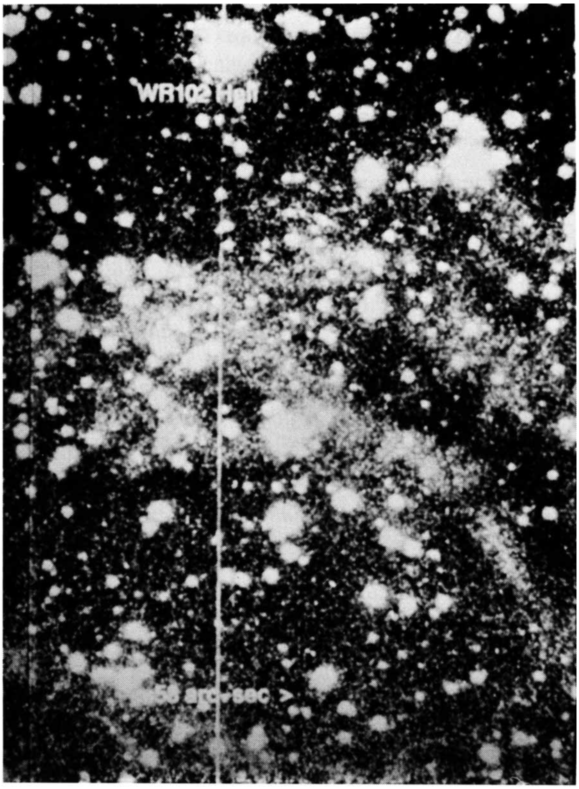

FIGURE 3: Narrow band CCD image of the nebula associated with the WO star WR102 obtained through a 60 Å wide filter centered at the wavelength of the HeIIλ4686 line. The image was exposed for 45 minuted with EFOSC at the 3.6m telescope on La Silla

Johnson (1975) suggested that G2.4+1.4 was a supernova remnant (SNR) and therefore that the HeII lines could be excited collisionally, but this conclusion was disputed by Green and Downes (1987) who, on the basis of VLA data, conclude that the nebula is most likely a stellar wind blown bubble. This is supported by Dopita *et al.* (1989) and by our own observation that show that G2.4+1.4 is a wind blown bubble ionised by the WO star.

We have obtained a long slit spectrum of the nebula using EFOSC and the 3.6m telescope on La Silla on a partially cloudy night on June, 16, 1989. Tracings of the spectrum at several positions of the HeIII filaments are presented in figure 4. Table 1 summarizes the relevant line ratios derived from this spectrum.

TABLE 1
WR102: nebular line intensities

Line	Relative intensity
[OII]λ3727	0.5:
[OIII]λ4363	<0.01
HeIIλ4686	0.77
Hβ	1.00
[OIII]λ5007	5.20
C(Hβ) = 2.1	
E(B-V) = 1.5	

From the HeII/Hβ ratio we derive a black-body Zanstra temperature of ~ 10^5 °K for the star. The weakness of the temperature sensitive [OIII]λ4363 line implies that the nebula must be metal rich. We estimate an oxygen abundance of ~1.5 times solar on the basis of rough photoionization models. This value is consistent with the galactocentric distance of the nebula derived using the absolute magnitude of WR102 and the reddening derived from the Balmer decrement.

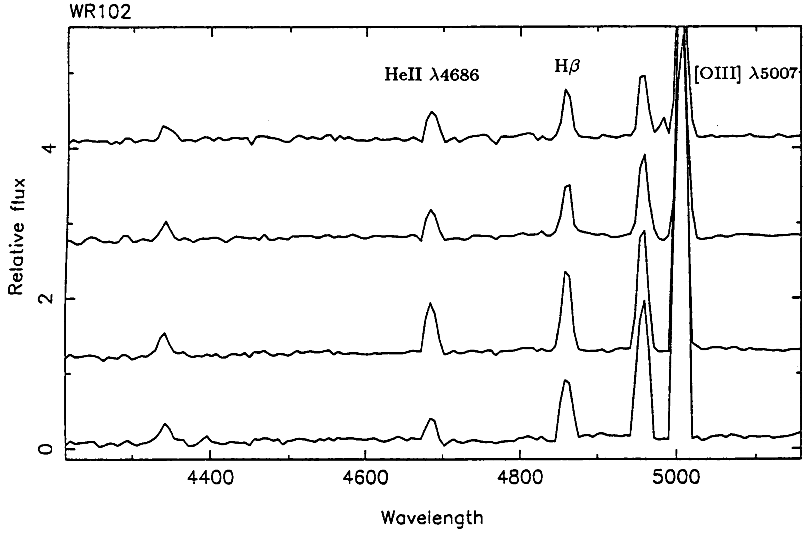

FIGURE 4: Intensity calibrated tracings of the spectrum of the nebula around WR102 for several filaments. The strength of the HeIIλ4686 line relative to Hβ throughout the HeIII regions is clearly seen

Dopita *et al.* (1990) determined line ratios for G2.4+1.4 which are largely consistent with our values, but they derive a much higher temperature for the star, and also a much higher oxygen abundance. We have not attempted to run very detailed photoionization models because of the uncertainties in the geometry of the nebula, and its abundance. An illustration of these uncertainties is the difficulty encountered both in our models and those of Dopita *et al.* to match the strength of the [OII]λ3727 doublet. We believe, therefore, that the difference between our values for Teff and O/H and those of Dopita *et al.* reflect the range of possible values and not a fundamental difference in the photoionization models.

The observations of WR102 clearly show, however, that WO stars are very hot and that the hard ionizing radiation is not trapped by their extended atmospheres.

Figure 5 presents narrow band HeII images of HeIII regions around WR stars in the Magellanic Clouds. The first panel shows an image of the SMC star AB7 (WN3p+OB) whose HeIII region has been discussed in detail by Pakull and Motch (1989). The second panel shows an image of the HeIII nebula around the LMC star Br2 (WN4) recently discovered by Pakull (1990).

We have also photographed a number of other early type WR stars in the LMC using a narrow band filter centered at the wavelength of HeIIλ4686, without much success. Figure 5 shows a possible candidate around the star Br7 (WC4). The [OIII] image shows that the star appears embedded in a bright HII region. The HeII image suggests the presence of a faint HeIII region near the star, but spectroscopy is required for confirmation.

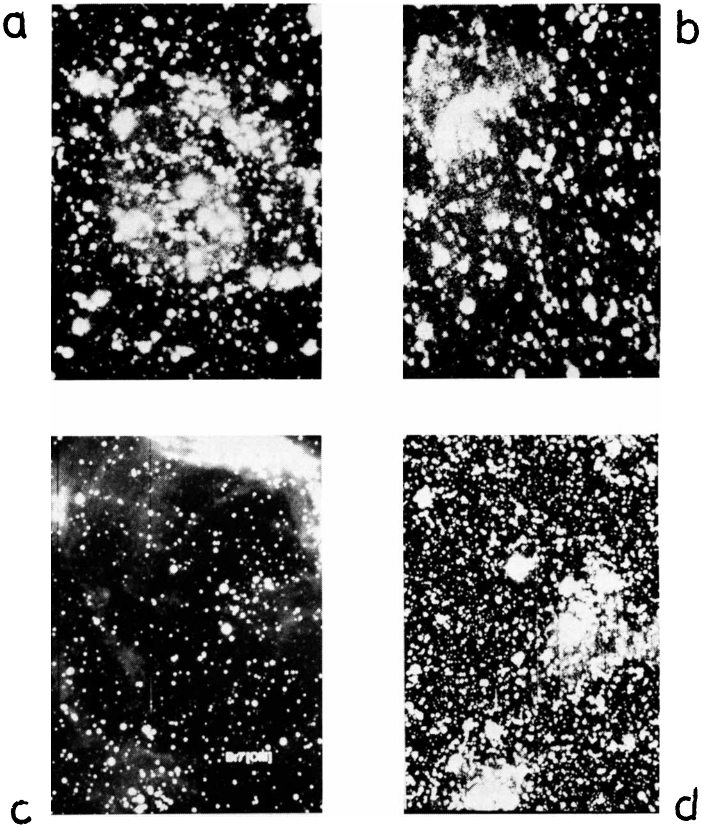

FIGURE 5: Examples of HeIII nebulae around hot stars in the Magellanic Clouds. a) HeII image of AB7 obtained with the Danish 1.5m telescope on La Silla. b) HeII image of Br2 obtained during the commissioning phase of the NTT. c) [OIII] image of Br7, d) HeII image of Br7, both taken with the 3.6m telescope on La Silla.

These observations provide direct evidence for the existence of *Warmers* in low abundance regions while WR102 is an example of a *Warmer* in a metal rich region in the direction to the Galactic centre. Thus, in agreement with the theory, *Warmers* are found both in metal poor as well as in metal rich systems.

Pakull and Motch (1989) comment that, in at least one of their cases, the nebular HeII emission appears significantly weaker than the broad HeII line from the WR star. This leads them to question whether the integrated spectrum of a cluster containing a population of *Warmers* would show nebular HeII lines. Because of the effects of stellar winds, however, the HII regions associated with the individual *Warmers* discussed above are density bounded and therefore the nebular emission lines are weak. In starburst clusters, on the other hand, most of the original gas has not been dispersed by star formation and the HII regions are ionization bounded. Therefore, the stellar lines are diluted by the clusters, while the nebular lines are very strong.

4. CONCLUDING REMARKS

We have showed that the *Warmer* model for nuclear activity in galaxies stands on a solid observational basis in what regards the existence of *Warmers* as hot WR stars that produce copious amounts of hard ionizing radiation.

We also find a substantial agreement between theory and observations regarding the formation of *Warmers* in metal poor systems. As a further test to the theory, it is of crucial importance to determine abundances of the gas in the immediate vicinity of the WR stars.

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DISCUSSION

Langer: If you need many (*i.e.*, more than one or two) warmers to account for some kind of galactic activity you may be in trouble: theory predicts $T_{eff} > 10^5 K$ only for a very brief evolutionary time ($< 10^4$ yr), and observationally very hot WR stars are also very rare ($\sim 1\%$).

Filippenko: A crucial assumption of the Terlevich-Melnick hypothesis is that Warmers form *much* more easily in metal-rich environments than in metal-poor environments. However, from your talk, and especially from Pakull's talk yesterday, I do not see any *observational* evidence for this in studies of individual Warmers.
Heydari-Malayeri: In this work we have concentrated on the Magellanic Clouds, which are metal-poor galaxies. We also show the presence of a Warmer in a metal-rich region of the Galaxy. On the other hand, we do not know at all how the atmospheres of WR stars react to hard UV photons when metallicity is high.

Kunth: Have you attempted to detect *HeIII* regions around known O-LMC stars?
Heydari-Malayeri: O stars are not hot enough to produce *HeIII* regions.
Niemela: With Heathcote and Weller we have observed *HII* regions around O3 stars in LMC, and we did not see any nebular *HeII* in these *HII* regions.

Lortet: From Westerlund's BV photometry (1964), there is a red supergiant candidate ($v \approx 14?$) in NGC 602c, the cluster containing the WO4 star of the SMC. Is there any spectrum of this star?
Heydari-Malayeri: We have no spectrum of that star.

Virpi Niemela