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SPECTROPHOTOMETRY OF MASSIVE STAR FORMING REGIONS WITH THE GTC

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RESUMEN

En estos últimos años, la detección de estrellas Wolf–Rayet (WR) en regiones H II gigantes ha levantado ciertos interrogantes sobre nuestros conocimientos de la evolución de estrellas masivas y sus atmósferas extensas, la edad de la población ionizante y su impacto sobre las propiedades físicas de dichas regiones. En este artículo, presentamos observaciones espectrofotométricas de cuatro regiones H II extragalácticas gigantes que muestran rasgos debidos a estrellas WR en sus espectros de emisión. Nuestro objetivo consiste en reproducir de forma simultánea tanto las propiedades de las estrellas WR observadas, como el espectro de líneas de emisión del gas, con la ayuda de modelos de síntesis de poblaciones. Finalmente, señalamos las principales ventajas que proporcionará el GTC para nuestro mejor entendimiento de regiones de formación de estrellas masivas.

ABSTRACT

In the last few years, the detection of Wolf–Rayet (WR) stars in Giant H II Regions (GHRs) has yielded several questions about our current understanding of massive stars evolution and hot expanding atmospheres, the age of the ionizing populations, and their impact on the physical properties of GHRs. Here, we present spectrophotometric observations of four extragalactic GHRs which show WR features in their spectra. Our goal is to reproduce simultaneously the observed WR properties and the emission line spectra with the help of current evolutionary synthesis models. Finally, we address the main advantages that the GTC will provide to our better understanding of massive star forming regions.

Key Words: **ISM: H II REGIONS — ISM: INDIVIDUAL: NGC 628 AND NGC 1232 — STARS: WOLF–RAYET**

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1. INTRODUCTION

Wolf–Rayet (WR) stars are evolved descendants of massive O stars, and hence, they represent one of the latest stages of massive star evolution. These stars experiment powerful winds, which can lead to a complete loss of their outer envelopes. Let us summarize the main topics associated with the presence of WR stars in giant H II regions (GHRs). Stellar evolution predicts mass loss rates to be more prominent at high metallicity ($Z \geq Z_{\odot}$), and that, therefore, O stars can enter the WR phase at a lower cut-off mass (Meynet 1995). This leads to both higher WR/O star ratios and stronger recombination lines formed in the wind. However, few detections at high metallicity have been made at the moment (Castellanos, Díaz, & Terlevich 2002, hereafter Paper I; Bresolin & Kennicutt 2002) to shed some light on this matter. On the other hand, a high metal content implies an increase in the opacity of the stellar material. This effect would lower the effective temperature of massive stars in regions of high metal content. There is a general agreement on the hardening of the ionizing radiation in regions of low metal content (Campbell, Terlevich, & Melnick 1986). However, the softening of the ionizing radiation in regions of high metal content is difficult to quantify since the functional parameters in these regions cannot be parameterized in a trivial way (see Díaz et al. 1991). Stellar evolution can also predict the WR/O star ratio from the elemental surface abundances and should therefore be able to reproduce adequately the WR population properties (mass loss rates and line strengths). Again, the detailed observation of GHRs with embedded WR

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stars is compulsory in order to constrain the stellar evolution assumptions. Finally, taking apart the metal content of the regions, the sole presence of WR stars is supposed to raise drastically the number of ionizing photons at energies higher than $\sim$40 eV (Pérez 1997). Hence, one might expect the ionization structure to change inside GHRs. In order to analyze these topics, we have studied four GHRs in NGC 628 (H13) and NGC 1232 (CDT1, CDT3, and CDT4) showing WR features in their spectra (Castellanos, Díaz & Terlevich 2002, hereafter Paper II).

2. WR POPULATIONS

Schaerer & Vacca (1998, hereafter SV98) have presented very detailed models of the WR population in young star clusters, at different metallicities from $Z = 0.001$ ($1/20Z_\odot$) to $Z = 0.04$ ($2Z_\odot$). Their clusters are formed according to a Salpeter IMF with upper and lower mass limits of 120 $M_\odot$ and 0.8 $M_\odot$, respectively. They use the stellar evolution models by Meynet et al. (1994), which assume a mild overshooting and enhanced mass loss rate. These models have been shown to reproduce the observed WR/O star ratios in a variety of regions (Maeder & Meynet 1994). Regarding the energy output of main sequence stars they use the CoStar models (Schaerer & de Koter 1997), which include non-LTE effects, line blanketing and stellar winds, for stars with initial masses larger than 20 $M_\odot$ and Kurucz (1992) plane–paralel LTE models, including line blanketing effects, for less massive stars. The atmospheres of evolved stars in the WR phase correspond to the spherically expanding, non-LTE, unblanketed models by Schmutz, Leitherer, & Gruenwald (1992).

SV98 provide accurate predictions, as a function of the cluster age, for the total number of WR stars and their subtype distribution, the broad stellar emission lines and the luminosities and equivalent widths of the two "WR bumps" at λ 4650 Å and λ 5808 Å . We have used these models to derive the age of the ionizing population which contains WR stars and whose metallicity has been previously derived from the calculated ionic temperatures (see Paper I).

Figure 1 shows that the predicted emission line intensities and equivalent widths of the WR blue "bump" for different metallicities ($0.2Z_\odot$; $0.4Z_\odot$ and $Z_\odot$), together with the observed values in the four regions. Solid symbols correspond to the observed data. It can be seen that in three of the analyzed regions, observations and predictions are in excellent agreement for a single instantaneous burst. The derived ages for the WR population range between 3.1 Myr (CDT3) and 4.1 Myr (H13 and CDT4). In fact, for regions CDT3 and CDT4 observations and predictions are nearly identical for the respective clusters and therefore only one symbol is shown. In the case of region CDT1, two open symbols are shown, one corresponding to the predictions for a single ionizing cluster of 2.4 Myr, and another one including the contribution to the Hβ and continuum luminosity of a cluster not containing WR stars (around 7 Myr). This latter is able to reproduce the observed WR features and the Hβ equivalent width.

3. MODELING THE EMISSION LINE SPECTRA

Regarding the integrated spectral energy distribution (SED) from the ionizing cluster, the recent models from Leitherer et al. (1999, hereafter STARBURST99) provide an almost self-consistent frame to be used in combination with the above WR models. In fact, they use the same stellar evolution models with enhanced mass loss rate, the same atmosphere models to describe the stars in the WR phase, and cover the range of metallicities and IMF used by SV98. The only appreciable difference between both sets of models concerns the atmospheres of the main sequence stars with initial masses greater than 20 $M_\odot$, which in STARBURST99 are represented by the plane–paralel Kurucz models implemented by Lejeune, Cuisiner, & Buser (1997). We have therefore used the STARBUST99 models in order to fit the emission line spectra for our analyzed regions. Hence, as the WR emission features have been used to date the ionizing star clusters, these should reproduce the observed gas emission line intensities if the other parameters controlling the emission line spectra, namely elemental abundances, particle density, and ionization parameter, are known. Our four observed GHRs meet all these requirements.

Therefore, since both SV98 and STARBURST99 models make use of the same stellar evolution prescriptions, we have assumed that a STARBURST99 model of a cluster of a given metallicity that contains the same WR/O star ratio as SV98 (corresponding to a given age), must provide the spectral energy distribution of the ionizing radiation. In the case of region H13 in NGC 628, this model (corresponding to an age of 4.1 Myr from the previous analysis of the WR features), however, provides an [O III]λ 5007 Å line emission that is higher than observed by a factor of about 4. On the other hand, our best photoionization model corresponds to an age of 4.7 Myr producing an Hβ equivalent width of 108 Å, to be compared with the observed one of 140 Å. The rest of

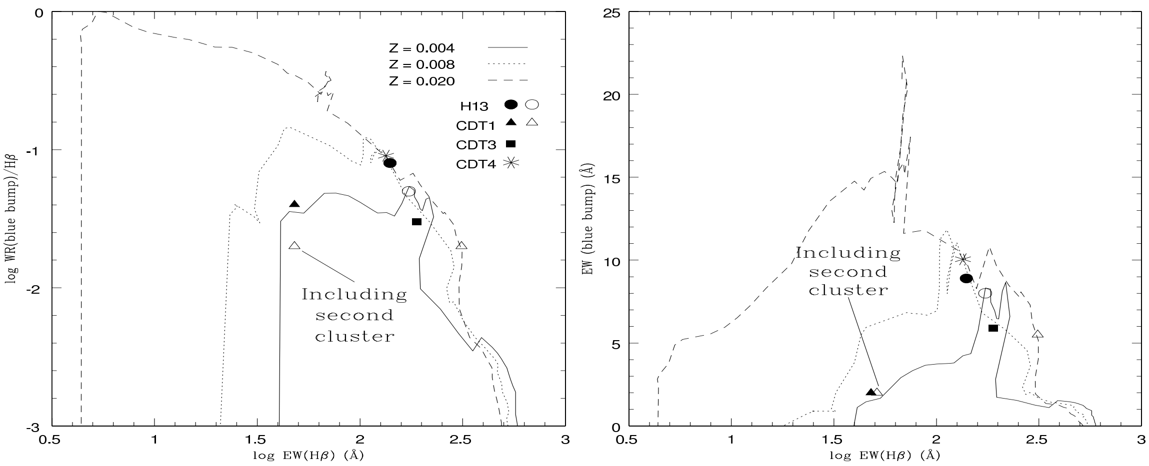

Fig. 1. Relative intensity (left) and equivalent width (right) of the WR blue 'bump' versus Hβ equivalent width for SV98 models of three different metallicities as labeled. The data are shown as solid and open symbols, as explained in the text.

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the spectrum is reproduced remarkably well taking into account the uncertainties in both the observed values and model computations. We can conclude that a single star cluster with age between 4.0 and 4.7 Myr fit all the observations adequately.

For region CDT1, given that a young 2.4 Myr cluster is successful in reproducing both the WR blue "bump" luminosity and equivalent width (although it overpredicts the equivalent width of Hβ by a factor of 7), a composite population with at least two clusters must be invoked. We have therefore run a model using as ionizing source the combination of the spectral energy distributions of two ionizing clusters of ages 2.4 and 7.1 Myr, calculated with the STARBURST99 code, in which the younger of the two provides 10 times the number of ionizing photons emitted by the older. This cluster contains the same WR/O star ratio as the SV98 model reproducing the observed WR features. The computed photoionization model is able to reproduce all the observables.

For the other two GHRs in NGC 1232, CDT3 and CDT4, STARBURST99 model clusters with the same WR/O ratio as those given by SV98 provide [O III] λ5007 Å line emission higher than observed by factors of about 5 and 3, respectively. Clusters slightly older, also reproducing the observed WR features within the errors, have larger WR/O number star ratios (up to 8.3×10^{-2}) and, therefore, their spectral energy distributions are even harder. Alternatively, it is possible to find a combination of ionizing clusters that reproduces well the emission line spectrum, but predicts WR feature luminosities and equivalent widths well below the observed values.

4. DISCUSSION AND CONCLUSIONS

That the WR features are adequately reproduced by SV98 models seems to imply that the evolutionary tracks are able to predict the right relative numbers of WR/O stars and their different subtypes at the derived abundances. These relative numbers, combined with the observed emission line luminosities of the individual WR stars and the predicted continuum energy distribution of the ionizing population, predict emission line intensities and equivalent widths of the WR stars in excellent agreement with observations. On the other hand, in two of the analyzed regions (CDT3 and CDT4 in NGC 1232), it is not possible to fit the emission line spectrum since the population containing WR stars produces a spectral energy distribution that is too hard to explain the emission of the gas. The same sort of effect has been found by Díaz et al. (2000a) for region 74C in NGC 4258 and Esteban et al. (1993) for the galactic WR nebula M1-67. These latter authors, from stellar and nebular spectroscopic analyses, concluded that lower temperatures were required from the photoionization models for late type WN (WNL) stars. They used the unblanketed WR models of Schmutz et al. (1992). A subsequent reanalysis of this region has been made by Crowther et al. (1999) using blanketed model atmospheres. In this case the resulting ionizing spectrum is much softer and better reproduces the observations, although some discrepancies still remain. For the high metallicity GHR CDT1 in NGC 1232, a composite population can explain adequately both the WR features and the emission line spectrum. Composite populations for H II regions have been found in previous works by Mayya

& Prabhu (1996) and by Díaz et al. (2000b) for disk and circumnuclear objects respectively from broad band and Hα photometry.

In the case of region H13 in NGC 628, a single instantaneous burst between 4.0 and 4.7 Myr, is able to reproduce all the observables within the errors. This result seems to indicate that line blanketing effects at low metallicity ($0.2Z_{\odot}$) could be less severe for the correct interpretation of the emission line spectra.

Our observations indicate no appreciable change in the ionization structure of the analyzed H II regions, despite the presence of WR stars. Line blanketing in WR atmospheres would point again in the right direction. It should be kept in mind that all our analysis is based on ionization-bounded models. An approach of the emission line spectra of H II region with WR features on the basis of matter-bounded models has been presented in Castellanos, Díaz & Tenorio-Tagle (2002). Models of this kind have been found to provide excellent fittings to the observations of H13 in NGC 628, CDT3 in NGC 1232, and 74C in NGC 4258 using both SV98 and STARBURST99 models. These models would point to an important leakage of ionizing photons depending on both the metallicity and evolutionary state of the region. There are still several caveats about our understanding of emission line spectra of GHRs with WR stars. The controversial observation of main sequence hydrogen-rich WNL-like stars (de Koter, Heap & Hubeny 1997; Crowther & Dessart 1998), not predicted by current stellar evolution calculations at ages less than 2 Myr at low metallicity, and the observation of dust envelopes around WC stars (Marchenko et al. 2002) may, of course, also have important consequences in interpreting correctly the ionization structure in GHRs, closely related to the impact of WR stars in the surrounding medium. GTC + OSIRIS spectroscopy would allow shorter-exposure observation of WR features in low excitation H II regions (high metallicity regions generally). The detection of He II at 4686 Å with tunable filters is a promising tool for the GTC. Clearly, the GTC would allow us to solve some of the problems mentioned above.

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