The Astrophysical Journal, 565:L79–L82, 2002 February 1

ON THE LARGE ESCAPE OF IONIZING RADIATION FROM GIANT EXTRAGALACTIC H II REGIONS

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Received 2001 October 15; accepted 2001 December 18; published 2002 January 11

ABSTRACT

A thorough analysis of well-studied disk giant H II regions, for which we know the ionizing stellar population, gas metallicity, and Wolf-Rayet population, leads to photoionization models that can only match all observed line intensity ratios ([O III], [O II], [N II], [S II], and [S III] with respect to the intensity of Hβ), as well as the Hβ luminosity and equivalent width if one allows for an important escape of energetic ionizing radiation. For the three regions presented here, the fractions of escaping Lyman continuum photons amount to 10%–73%, and in all cases, the larger fraction of escaping photons has energies of between 13.6 and 24.4 eV. These escaping photons clearly must have an important impact as sources of ionization of the diffuse ionized gas found surrounding many galaxies, as well as of the intergalactic medium.

Subject headings: galaxies: individual (NGC 628, NGC 1232, NGC 4258) — galaxies: ISM — H II regions — intergalactic medium — stars: Wolf-Rayet

1. INTRODUCTION

The issue of whether or not ionizing star clusters are the sources of radiation responsible for the diffuse ionized gas (DIG) and, moreover, for the background radiation at low redshift (Heckman et al. 2001) is still controversial. Ultraviolet observations of four nearby starburst galaxies (Leitherer et al. 1995; Hurwitz, Jelinsky, & Van Dyke Dixon 1997) showed that more than 10% of the ionizing photons could escape from these galaxies. On the other hand, Dove, Shull, & Ferrara (2000) obtained from theoretical arguments that 7% of photons produced by OB associations would have to escape into the DIG to sustain it, which could also be consistent with the estimated flux required to photoionize the Magellanic Stream (Weiner & Williams 1996; Bland-Hawthorn & Maloney 1999). All these aspects at low redshift are undoubtedly important to establish whether massive stars in starburst galaxies can rival quasars as sources of the metagalactic background radiation at high redshifts ($z > 3$; see Ricotti & Shull 2000). Furthermore, an estimate of the escape fraction at low redshift is to provide an upper limit to the expected escape fraction at high redshift, when the universe was much denser. Beckman et al. (2000) presented evidence, based on the analysis of the Hα luminosity function of H II region populations in nearby spiral galaxies, that luminous H II regions may be matter bounded. This would imply that these regions are an important source of photons to the DIG. Here we report strong evidence indicating that giant extragalactic H II regions (GEHRs) are matter bounded and thus are an important source of ionization at large distances from their exciting stars. Our conclusions are based on evolutionary synthesis models (Leitherer et al. 1999) applied to previously analyzed GEHRs with observed Wolf-Rayet (W-R) features (Díaz et al. 2000; Castellanos, Díaz, & Terlevich 2002, hereafter Paper I). The observed parameters inside these regions, i.e., the fluxes and equivalent widths of the W-R features, the emission-line intensities of [O II] λ3727, [O III] λ5007, [N II] λ6584, [S II] λ6717, and [S III] λ9069 relative to Hβ, and the observed Hβ luminosity and equivalent width cannot be fitted simultaneously unless an important fraction of the ionizing radiation escapes from these regions.

2. MODELS AND RESULTS

The analyzed GEHRs are regions H13 in NGC 628, CDT3 in NGC 1232, and 74C in NGC 4258. The three regions, particularly 74C and H13, show spectral signatures of prominent W-R features. The presence of these stars allows us to constrain the age of the ionizing clusters to between 3 and 6 Myr. These values depend on the stellar mass loss rates and, consequently, on the stellar metallicity that ultimately controls when massive O stars enter the W-R phase (Meynet 1995). This metallicity has been assumed to be similar to that found through the analysis of the emission-line spectrum (see Paper I). Once the age and metallicity are known, a unique spectral energy distribution (SED) can be provided by evolutionary synthesis models.

To estimate the age of the ionizing stellar clusters from the measured strength and equivalent widths (EWs) of the observed W-R features, we used the models of Schaerer & Vacca (1998). Ages of between 4 and 4.5 Myr, 3 and 3.5 Myr, and 3.5 and 4 Myr are found for regions H13, CDT3, and 74C with oxygen abundances of 0.2, 0.4, and 0.5 solar, respectively. We then used the Leitherer et al. (1999) models to predict the SEDs of the ionizing clusters. These models assume the same stellar tracks as those used by Schaerer & Vacca (1998), and at the metallicities considered here, they represent a good approach to the ionizing spectra (see Stasińska, Schaerer, & Leitherer 2001).

The predicted SEDs were then used as input to the latest version of CLOUDY (Ferland 1999). The models also require an electron density (assumed to be constant throughout the nebula), the derived gas metallicity (see Paper I), and an ionization parameter, $U = Q(\mathrm{H})/(4\pi R^2 n_e c)$, where $Q(\mathrm{H})$ is the total flux of ionizing photons emitted by the cluster per second, R the distance from the ionizing source to the illuminated face of the cloud, n_e the electron density, and c the speed of light.

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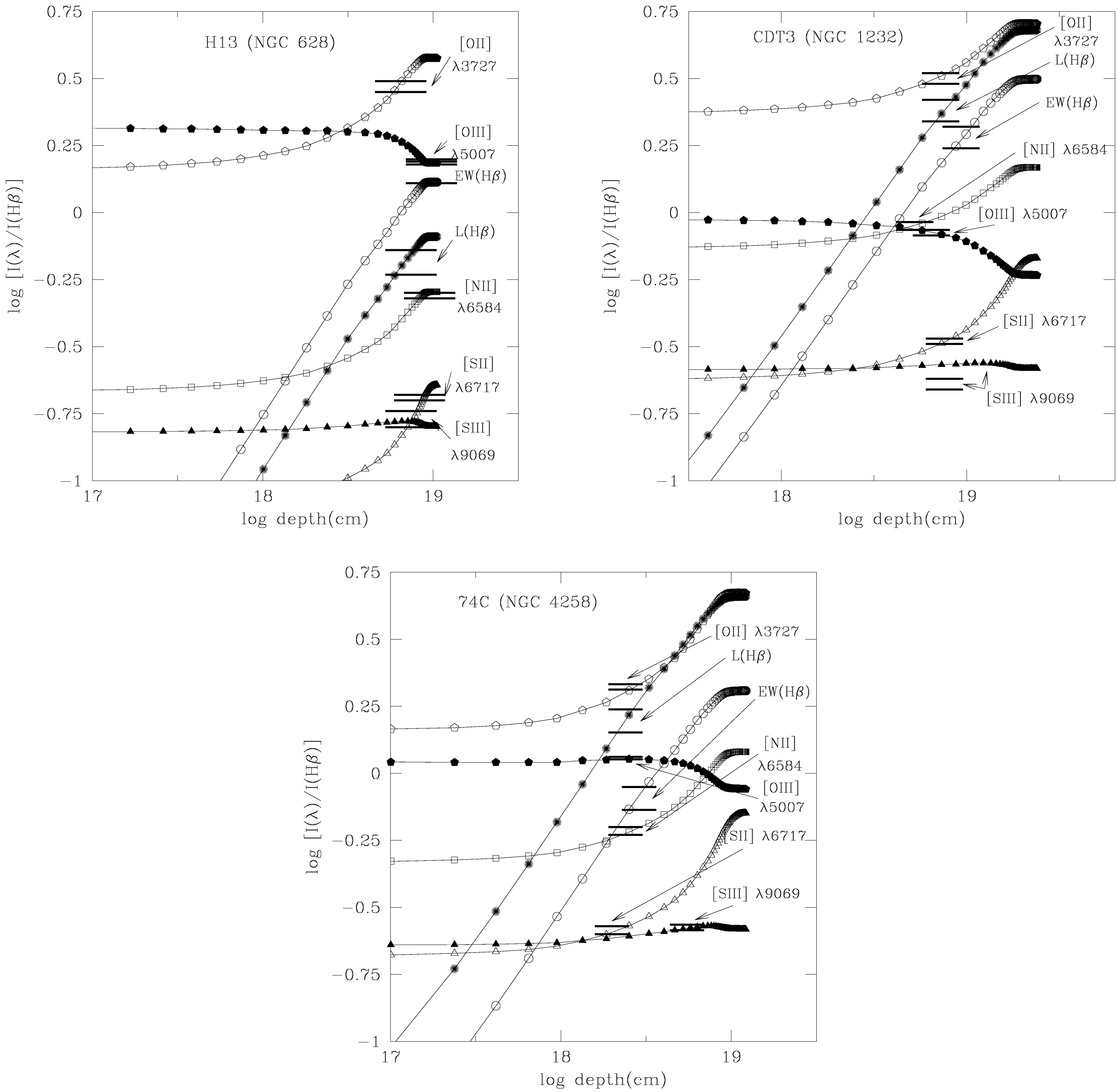

FIG. 1.—Run of different line intensity ratios ([O II] λ3727, [O III] λ5007, [N II] λ6584, [S II] λ6717, and [S III] λ9069 relative to Hβ), as well as the Hβ equivalent width and Hβ luminosity (both scaled by a constant factor), as a function of ionized gas shell thickness in the three nebulae considered here. The models were derived from the ionization parameter range given in Table 1 and extend until all photons are used up. Horizontal bars across each predicted quantity trend indicate the observed values and their errors (see Paper I).

In spherical geometry, the average U is proportional to $[Q(\mathrm{H}) n_e \epsilon^2]^{1/3}$, where ϵ is the gas filling factor. In the case of ionization bounded regions, Q(H) must equal—in the absence of dust—the number of ionizing photons derived from Hα recombinations. Our models have considered ionization parameter values in the range $-4.0 < \log U < -2.0$ through the span of the W-R phase, which combined with the observed numbers of ionizing photons [Q(H)] imply R values on the order of 10^{20}–10^{21} cm (≈30–300 pc). The thickness of the ionized gas shell is on the order of 10^{19}, less than 10% of the total dimensions of the region, which results in a plane-parallel geometry.

Figure 1 shows the run of the emission-line intensities relative to Hβ and the Hβ equivalent width and luminosity as a function of the ionized gas shell thickness. The figure also compares the model predictions in each case with the observed values (*horizontal bars*).

Figure 1 clearly shows that a consistent fit to all observed quantities can be found only if the regions are considered to be matter bounded, i.e., only if there is an important escape of ionizing radiation from the nebulae. Models in which all photons are absorbed (most right-hand points in Fig. 1) lead to large departures from all observed values. However, if one assumes the nebulae to be matter bounded, a satisfactory agree-

TABLE 1
Model Results

Region	$Z/Z_{\odot}$[a]	t[b] (Myr)	log U	log Q_{esc}[c] (13.6–24.6 eV)	log Q_{esc}[c] (24.6–54.4 eV)	log Q_{esc}[c] (≥54.4 eV)	log Q_{esc}[c] (Total)
H13 (NGC 628) ………	0.2	4–4.5	−3.00 ± 0.05	49.68 (8.5), 50.17 (26)	49.15 (25), 49.41 (45)	43.51 (0.1), 43.70 (0.3)	49.80 (10), 50.24 (28)
CDT3 (NGC 1232) ……	0.4	3–3.5	−3.35 ± 0.05	51.30 (41), 51.38 (48)	50.70 (63), 50.74 (68)	45.72 (4), 45.76 (5)	51.40 (43), 51.47 (51)
74C (NGC 4258) ………	0.5	3.5–4	−3.25 ± 0.05	51.13 (51), 51.42 (71)	50.52 (72), 50.74 (84)	47.08 (11), 47.60 (26)	51.23 (54), 51.51 (73)

[a] Gas metallicity relative to solar.
[b] Derived age from W-R population models.
[c] Lower and upper values for the number of escaping ionizing photons in the three energy bins and the total one. Parentheses in each column provide the ratios of escaping to incident radiation in units of percent in each energy bin and for the total one.

ment between all predicted quantities and the observations is found at a common distance to the ionizing cluster for each case. Clearly, for these models we have also demanded consistency with the observed Hα luminosity, which has been found through an iterative process. Successful models have hydrogen column densities on the order of 10^{19} cm^{-2}, while ionization-bounded models reach column densities of close to 10^{20} cm^{-2}.

The fraction of escaping photons depends on both their energy and the gas column density. Table 1 gives the main physical conditions of the observed regions. The first three columns identify the GEHRs and list the observed metallicity and resultant age of the best-fitting models for the ionizing clusters. The fourth column indicates the range in ionization parameter used, and the fifth, sixth, and seventh columns indicate both the absolute and relative values of the photon flux escaping in three different energy bins (13.6–24.5 eV, 24.5–54.4 eV, and ≥54.4 eV). The log of the total values of photons escaping the nebulae are in the range of $49.80 < \log Q_{esc}(H) < 51.51$, which implies an escape fraction of between 10% (for region H13) and 73% (for region 74C).

3. DISCUSSION AND CONCLUSIONS

The observed emission lines of GEHRs have been widely used to derive the properties of the ionizing radiation and to link them to those of the stellar populations generating this latter one, but always under the assumption that the ionized region is ionization bounded. In the absence of an independent constraint on the age of this stellar population, such as the presence of W-R stars, successful fits to the emission-line spectra of most GEHRs have been found within a narrow range of ages: between 2 and 2.5 Myr (Bresolin, Kennicutt, & Garnett 1999; Dopita et al. 2000). In fact, if similar methods of analysis were applied to the regions modeled here, we would obtain a similar result. For these regions, however, we have accurate determinations of the gas metallicities and their ages, provided by the analysis of the W-R spectral features, and therefore we can synthesize the corresponding SEDs. However, the derived SEDs are unable to reproduce the observed emission-line spectra unless the GEHRs are density bounded. In such a case, we have shown here that satisfactory fits can be found in the three analyzed cases.

Our results suggest that the leaking of ionizing photons does depend on the evolutionary stage of the region. Regions 74C and CDT3 show the highest escape fractions, consistent with the prominent observed W-R features in the former spectrum and the high excitation lines ([Fe II], [Fe III]) in the latter one. However, region H13, which also shows a prominent W-R feature, shows a far lower escape fraction, which can be understood from its lower metallicity (0.2 versus 0.5 solar in 74C and CDT3, respectively), affecting the W-R phase strength. It is plausible that large photon escaping fractions might be expected in those regions that experience a hard W-R phase, this one depending on both the age and metallicity.

An important implication of the escape of ionizing photons concerns the EW(Hβ)-age relation, which does not hold for matter-bounded regions. It is a well-known fact that few H II regions show EW(Hβ) values as large as those predicted from evolutionary synthesis models (e.g., Melnick, Terlevich, & Eggleton, 1985; Mas-Hesse & Kunth 1998). The leak of Lyman continuum radiation provides a natural explanation in the correct direction.

A close analysis of the energy distribution of the escaping radiation (see Table 1) shows that the largest fraction has energies of between 13.6 and 24.4 eV (up to 80% in the case of 74C). However, if escaping to incident fractions is considered, helium-ionizing photons are clearly dominant (e.g., up to 84% of the incident photons with energies of between 24.4 and 54.4 eV escape from region 74C). This would explain why the observed emission-line spectrum is so similar to that produced by a star cluster without W-R stars.

Furthermore, the derived large amounts of escaping ionizing photons indicate that GEHRs and stellar OB associations may significantly contribute to the ionization of the diffuse gas layers observed above the disks of spiral galaxies. Although to our knowledge no measurements of the DIG are available for NGC 628, NGC 1232, and NGC 4258, recent studies by Ferguson et al. (1996), Oey & Kennicutt (1997), and Zurita, Rozas, & Beckman (2000) stress the fact that the integrated escaping flux from disk galaxies can attain up to 10^{41} ergs s^{-1}, enough to account for the diffuse Hα flux and fully compatible with our derived values for single GEHRs.

In our models, the lower energy photons emitted by the central star cluster are more effectively absorbed by the H II region gas, while a large fraction of the photons with energy of between 1.8 and 4 Ryd escape the nebula. Therefore, the resulting SED of the escaping photons is slightly harder than that of the ionizing star cluster. For the three studied regions, the Q(He)/Q(H) ratios of the escaping photons are 0.22, 0.20, and 0.19, which should be compared to 0.10, 0.14, and 0.15 for the respective ionizing clusters.

One still unsolved problem for the interpretation of observations of the DIG above the galactic disk is the apparently low value of the He I λ5876/Hβ (Reynolds & Tufte 1995), which would be in contradiction with our derived Q(He)/Q(H) ratios. Our studied regions, however, are not representative of galactic H II regions ionized by a single star but of high-luminosity GEHRs on the disks of spiral galaxies, such as, for example, NGC 891. For the DIG in this galaxy, the average value of He I λ5876/Hβ is 0.1 (Rand 1997). According to Bresolin et al. (1999), the value of this ratio for stellar effective temperatures between 40,000 and 50,000 K is highly dependent on metallicity and reaches the value of 0.1 for a metallicity of about $\frac{1}{4}$ solar. In fact, most H II galaxies show He I λ5876/Hβ values of around 0.10 (Izotov & Thuan 1998 and references therein).

In summary, by applying evolutionary synthesis models to well-studied GEHRs with observed W-R features, we find that these regions need to be matter bounded in order to reconcile model predictions with observations. The amount of escaping ionizing photons per unit time from these regions is in the rage of $49.80 < \log Q_{\rm esc}(\rm H) < 51.51$, which implies an escape fraction of between 10% and 73% of the available incident photons. These fractions seem to increase with both the strength of the W-R phase and the metallicity of the interstellar medium (ISM). The implication is thus that the mass of the ionizing clusters is larger than the value derived in a straight manner from the observed Hα luminosity. It is also clear that the ISM is highly nonuniform and that the matter swept-up in the shells produced by the mechanical energy deposited by the W-R sources and other massive stars is not sufficient to trap the ionization fronts. This is also the result obtained from numerical calculations that consider both the mechanical energy of massive stellar clusters as well as their ionizing luminosity. Tenorio-Tagle et al. (1999) have shown how once the shell of swept up matter becomes Rayleigh-Taylor unstable and fragments, as it evolves out of a galaxy disk into the halo (the blowout phenomenon), it then allows not only for the venting of the hot (wind and supernovae) matter into the halo, but also for the leakage of a large fraction of the ionizing radiation. The latter soon establishes a giant conical H II region in the low-density halo. The low densities in the halo lead to a long recombination time and thus to a large leakage of photons into the intergalactic medium. The situation later changes once the shock is able to sweep enough halo matter, enhancing locally the number of recombinations in the expanding shell. This leads eventually to the trapping of the ionization front. Consequently, depending on the stage of the evolution, a large fraction of the ionizing flux escapes the nebulae and is freely available to impact upon the gas at large distances from the host galaxy plane (Collins & Rand 2001), and it is also likely to escape the galaxy and cause an important ionization of the intergalactic medium. Clearly, further analysis of this kind must be done to infer whether or not our derived escape fractions are typical of other GEHRs.

We thank the anonymous referee for many comments and suggestions that significantly improved the content of this Letter. G. T.-T. is grateful to an IBERDROLA Visiting Professorship to the Universidad Autónoma de Madrid, during which part of this work was completed. This work has been partially supported by DGICYT project AYA-2000-0973.

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