The Light Elements and Their Evolution
IAU Symposium, Vol. 198, *2000*
L. da Silva, M. Spite, J. R. de Medeiros, eds.

Inhomogeneous H II Regions and the Helium Abundance

S. M. Viegas and R. Gruenwald

IAG-USP; Av. Miguel Stefano, 4200; 04301-904 São Paulo, SP, Brazil

Abstract. When calculating the helium (^{4}He) abundance in low metallicity H II regions, the ionization correction factor (*icf*) for unseen neutral helium (and hydrogen) is usually assumed to be unity. In this paper, we explore this factor for H II regions ionized by young stellar clusters. Our main result is that *icf* < 1 for homogeneous H II regions and, that the effect of density condensations in the H II regions is to further *reduce* the *icf*. For *icf* < 1, the primordial helium abundance inferred from observations of low-metallicity, extragalactic H II regions is *decreased.*

1. Introduction

The importance of the primordial helium abundance as a key test of the standard hot big bang model and the necessity of determining an accurate value are discussed in another paper in this volume (Steigman 2000). The usual method to derive the primordial ^{4}He abundance from very low-metallicity H II regions has achieved very small statistical uncertainties ($\sim$ 1%) for Y_P, the primordial helium mass fraction (Olive & Steigman 1995, Olive, Skillman & Steigman 1997, Izotov, Thuan & Lipovetsky 1994, 1997 (ITL), Izotov & Thuan 1998 (IT)). However, the derived value may be contaminated by unrecognized systematic uncertainties (Davidson & Kinman 1985, Pagel et al. 1992, Skillman et al. 1994, ITL, IT, Skillman, Terlevich & Terlevich 1998). Here we discuss one potential source of systematic error – the ionization correction for unseen neutral hydrogen and/or helium, both for homogeneous and inhomogeneous H II regions.

The empirical method usually used to derive the chemical abundances from the observed emission-line intensities from an assumed homogeneous nebula was first proposed by Peimbert & Costero (1969). The fractional abundances of the ions present in the gas which produce observable emission-lines are obtained and combined to obtain the element abundances. In order to account for the unseen ions and neutral atoms, an ionization correction factor (*icf*), derived from considerations of the ionization potential or from photoionization models (Peimbert & Torres-Peimbert 1977, Stasinska, 1980, 1982, Mathis 1982, Peña 1986) is used. However, these ionization correction factors were obtained while assuming a homogenous nebula. In contrast, recent HST imaging reveals that real H II regions are far from homogeneous, showing many different features such as condensations, filaments and voids. Thus, the true *icf* may differ from calculated values, introducing a systematic error in the calculation of the element abundances. In particular, an error in the helium abundance determination will reflect directly on the inferred primordial helium abundance. $\equiv$ valleys) as shown

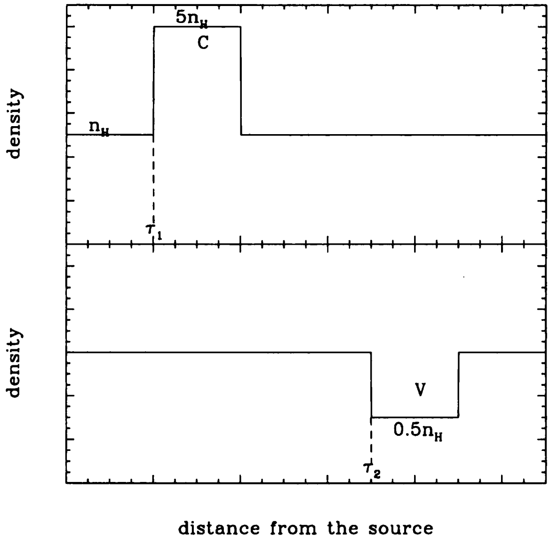

Figure 1. Illustration of an enhancement (C) and a deficit (V) of the density, where n_H is the density of the corresponding homogeneous model. In our models, the density increases by a factor of 5, or decreases by a factor of 2 from the homogeneous case extending over a distance which is 10% of the thickness of the H II region for the corresponding homogeneous model. The position of the condensation (C) or valley (V) is fixed by the choice of the optical depth (τ_1, τ_2) at that location.

in Figure 1. The location of the condensations and valleys are chosen by fixing the corresponding optical depth at the Lyman limit, τ_H, in the homogeneous model (H); the following values were chosen: $\tau_H = 0.02$, 0.03, 0.04, 0.10, and 0.40. Using a Monte Carlo method on a variety of H, C and V models, we mimic the physical conditions in more realistic H II regions.

2. Simulating an Inhomogeneous H II Region

The available 1-D photoionization codes have been widely used to analyse observed emission-line spectra and several of them have been intercompared showing good agreement (Péquignot 1986, Ferland et al. 1995). The input parameters are the ionizing radiation spectrum, the gas density and the chemical abundances in the gas, in addition to the assumption of spherical or plane-parallel symmetry in order to account for the diffuse radiation.

Here, in this analysis, the photoionization code AANGABA is used to build spherically symmetric homogeneous models. Further, in order to mimic the presence of condensations and voids revealed by H II region imaging, several models with different choices of the input parameters are combined. The ionizing radiation of a young stellar cluster (Cid-Fernandes et al. 1992) is adopted for two evolutionary phases of the stellar cluster: the initial phase (t = 0), when the spectrum is dominated by the hottest, most massive stars (appropriate for low-metallicity, high-excitation H II regions), and a later phase (t= 2.5 Myr), when the massive stars have evolved and there are fewer He^+ ionizing photons. The stellar cluster is characterized by the number of ionizing photons above the hydrogen Lyman limit, Q_H, which, along with a choice of the gas density defines the H II region model. Regarding the ionization parameter U, commonly used to define photoionization models, for a given density our models correspond to a fixed value of $UR_i{}^2$ (where R_i is the inner radius of the H II region). More details on this point can be found in Viegas, Gruenwald & Steigman (2000). Because we are interested in low-metallicity H II regions, 0.1 solar composition is chosen.

Based on the homogeneous models described above, models mimicking condensations and voids are built with spatially bounded density enhancements (C $\equiv$ condensations) and density deficits (V

3. The Helium Correction Factor and the Helium Abundance

Pagel et al. (1992) proposed a method to estimate the ionization correction factor *icf*, based on the "radiation softness parameter" $\eta = (O^+/S^+)(S^{++}/O^{++})$ defined by Vilchez & Pagel (1988). Comparing with photoionization models, they concluded that $icf = 1$ for $\log \eta < 0.9$, corresponding to models with effective temperature higher than 37 000 K, while for $\log \eta > 0.9$ the *icf* may differ from unity. In the following we will analyse the behaviour of *icf* as a function of η from H II region models using the stellar cluster radiation spectra at t = 0 and t = 2.5 Myr.

In order to account for the presence of unseen He^{++}, and H^0, the *icf* is defined as

$$icf = [1 + \frac{(n(He^0) + n(He^{++}))}{n(He^+)}]/[1 + \frac{n(H^0)}{n(H^+)}]. \qquad (1)$$

The results for the *icf* are shown in Figure 2. For the homogeneous models we fixed the density at $n_H = 10$ cm^{-3} and varied Q_H by nine orders of magnitude from 7.5×10^{44} s^{-1} to 7.5×10^{53} s^{-1}. All the models were calculated assuming a filling factor equal to unity, although the results obtained with a lower filling factor all lie along the same curves (trading Q_H for filling factor).

Models with the radiation spectrum of a young (t = 0) stellar cluster predict $icf \leq 1$, indicating that neutral hydrogen is present where the helium is still ionized. On the other hand, a different result is obtained with an evolved stellar cluster (t = 2.5 Myr). In this case, because the ionizing radiation lacks photons beyond the He^+ Lyman limit, there is neutral He inside the H^+ zone and the ionization correction factor exceeds unity.

Regarding the inhomogeneous models, the results for "valleys" are indistinguishable from the corresponding homogeneous models, while those for condensations tend to lead to a bigger downward correction (reduction in the predicted *icf*) than for the homogeneous cases, with the greatest deviation occurring in models where the condensation is located at $\tau = 0.04$. Since a real H II region must be a mix of H, C and V regions located at different τ, a single composite model can be created assuming that the weighted contribution of each region to the composite H II region is proportional to the solid angle occupied by the H, C or V model. The solid angles are chosen randomly, with the constraint that their sum is 4π. The Monte Carlo method is used for different choices of Q_H

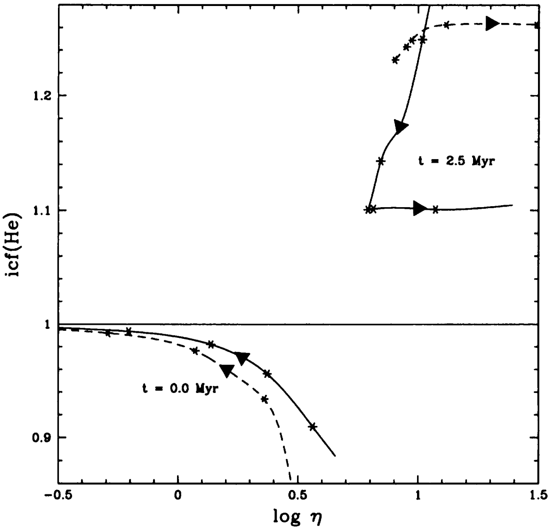

Figure 2. The *icf* – log η relation for H II regions ionized by a young (t = 0, left bottom curves) and an evolved (t = 2.5 Myr, top right curves) stellar cluster. The solid lines correspond to homogeneous models, and the dashed lines to models with condensation located at τ = 0.04. The tickmarks correspond to models with $n_H = 10$ cm^{-3}, ϵ = 1., and $Q_H/(7.5\times\ 10^{45}$ = 1., 10^2, 10^4, 10^6, 10^8. Arrows indicate the effect of increasing values of Q_H.

and n. As expected, the results for these composite models lie between those for the homogenous and the "extreme" condensation models.

Another kind of composite model has been investigated by Dinerstein & Shields (1986), who considered the case where the spectrum of an H II region ionized by a young stellar cluster could be contaminated by emission from a region powered by an older cluster lying along the same line of sight. As seen in Figure 2, the log η values for models with young and old stellar clusters are very different. Thus, for most combinations of the two cases, the resulting H II region would show the log η and *icf* characteristic of the dominant H II region (*i.e.*, the one with the largest Q_H). However, models with similar Q_H would generally result in log η larger than 1, and would not be appropriate to describe the H II regions used for deriving the primordial helium abundance which are selected to have log η less than unity. However, the combination of an H II region powered by a young stellar cluster and low Q_H, with an older cluster with high Q_H, could result in a log $\eta \leq 0.8$ but with *icf* larger than unity. In fact, combining the results of the model where t = 0 and $Q_H = 7.5 \times 10^{47}$ s^{-1}, for which log η = 0.37, with the models for t = 2.5 Myr and $Q_H = 7.5 \times 10^{49}$ s^{-1}, 7.5×10^{51} s^{-1}, and 7.5×10^{53} s^{-1}, for which log $\eta \approx 0.8$, we obtain log $\eta \approx 0.4$ and *icf* $\approx$ 1.04. However, for these models the emission-line ratios differ noticeably from the case of a single H II region with the same value of log η as can be seen for the key line ratios which are shown in Table 1, where the results for a young, less luminous H II region are compared to those in the composite models described above (characterized by the Q_H value of the older H II region).

Table 1. Table1 - Emission-line intensities relative to Hβ

Emission-line	t = 0	Composite model		
	7.5E47	7.5E59	7.5E51	7.5E53
[O II]3727	2.65	1.76	0.86	0.48
[Ne III]3868+	0.43	0.39	0.53	0.63
[O III]5007+	3.88	5.48	7.58	8.81
He I 5876	0.11	0.099	0.098	0.098
[N II]6584+	0.68	0.41	0.20	0.11
[S II]6717+	0.32	0.13	0.041	0.011

4. Concluding Remarks

As described above, the helium ionization correction factor for homogeneous H II regions ionized by a young stellar cluster is ≤ 1. The *icf* may be further reduced by the presence of condensations, which are likely to be present in real H II regions as indicated by HST imaging. Composite models which combine the results of a young (t = 0), less luminous stellar cluster with an evolved (t = 2.5 Myr), more luminous stellar cluster, may mimic a single H II region with log η $\approx$ 0.4, but having *icf* larger than unity. Since the composite models will have different emission-line intensities, relative to Hβ, only by comparison to all the observational data can composite H II regions mimicking a single H II region be unmasked, allowing us to choose the appropriate *icf*.

Finally, in order to quantify our results we used the data from a sample of low-metallicity H II regions observed by Izotov & Thuan (1998) in a Monte Carlo simulation (see Viegas, Gruenwald & Steigman 2000 for details), to calculate the systematic error in the inferred primordial helium abundance due to realistic values of the *icf*. The results indicate that the systematic error in the mass fraction, Y_P, could be as large as -0.004, which is significant when compared to the quoted statistical errors on Y_P. Recent observations of Magellanic Cloud H II regions, which may be less affected by systematic errors than the distant low-metallicity H II regions, provide independent support for this conclusion by also indicating a lower value for the primordial helium abundance (Peimbert 2000, this volume).

Acknowledgments. We are indebted to G. Steigman for many fruitful discussions. This work has been partially supported by FAPESP, CNPq and PRONEX/Finep.

References

Cid-Fernandes, R., Dottori, H., Gruenwald, R., & Viegas, S.M. 1992, MNRAS, 255, 165

Davidson, K., & Kinman, T.D. 1985, ApJS, 58, 321

Dinerstein, H.L., & Shields, G.A. 1986, ApJ, 311, 45

Ferland et al. 1995, in The Analysis of Emission Lines, STScI Symp. Ser. 8,ed. R.E. Williams & M. Livio (Cambridge: Cambridge University Press), 143

Izotov, Y.I., Thuan, T.X., & Lipovetsky, V.A. 1994, ApJ, 435, 647

Izotov, Y.I., Thuan, T.X., & Lipovetsky, V.A. 1997, ApJS, 108, 1

Izotov, Y.I. & Thuan, T.X. 1998, ApJ, 500, 188

Mathis, J.S. 1982, ApJ, 261, 195

Olive, K.A., Skillman, E., & Steigman, G. 1997, ApJ, 483, 788

Olive, K. A., &, Steigman, G. 1995, ApJS, 97, 49

Pagel, B.E.J., Somonson, E.A., Terlevich, R.J. & Edmunds, M. 1992, MNRAS, 255, 325

Peimbert, M. & Costero, R. 1969, Bol. Obs. Tonantziltla y Tacubaya, 5, 3

Peimbert, M. & Torres-Peimbert, S. 1977, MNRAS, 179, 217

Pena, M. 1986, PASP, 98, 1061

Pequignot 1986, Workshop on Model Nebulae, ed. D. Pequignot (Meudon, Observatoire de Paris-Meudon)

Skillman, E., Terlevich, R.J., Kennicutt, R.C., Garnett, D.R., & Terlevich, E. 1994, ApJ, 431, 172

Skillman, E., Terlevich, E., & Terlevich, R.J. 1998, Sp. Sci. Rev, 84, 105

Stasinska, G. 1980, A&A, 84, 320

Stasinska, G. 1982, A&AS., 41, 513

Viegas, S.M., Gruenwald, R., & Steigman, G. 2000, ApJ (in press)

Vilchez, J.M. & Pagel, B.E.J. 1988, MNRAS, 231, 257