IONIZATION CORRECTIONS FOR LOW-METALLICITY H II REGIONS AND THE PRIMORDIAL HELIUM ABUNDANCE

SUELI M. VIEGAS1, RUTH GRUENWALD1, AND GARY STEIGMAN2

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ABSTRACT

Helium and hydrogen recombination lines observed in low-metallicity, extragalactic H II regions provide the data used to infer the primordial helium mass fraction, $Y_p$. The ionization corrections for unseen neutral helium (or hydrogen) are usually assumed to be absent; i.e., the ionization correction factor (ICF) is taken to be unity (ICF = 1). In this paper we revisit the question of the ICF for H II regions ionized by clusters of young, hot, metal-poor stars. Our key result is that for the H II regions used in the determination of $Y_p$, there is a “reverse” ionization correction: ICF < 1. We explore the effect on the ICF of more realistic inhomogeneous H II region models and find that for those regions ionized by young stars, with “hard” radiation spectra, the ICF is reduced further below unity. In Monte Carlo using H II region data from the literature (Izotov & Thuan) we estimate a reduction in the published value of $Y_p$ of order 0.003, which is roughly twice as large as the quoted statistical error in the $Y_p$ determination.

Subject headings: cosmology: observations — H II regions — ISM: abundances

1. INTRODUCTION

The primordial abundance of $^4$He is key to testing the consistency of the standard hot big bang model of cosmology and to using primordial nucleosynthesis as a probe of cosmology and particle physics (for a recent review, see Olive, Steigman, & Walker 1999). Since stars burn hydrogen to helium in the course of their evolution contaminating any primordial helium in the interstellar gas with their debris, it is the availability of large numbers of carefully observed, very low-metallicity extragalactic H II regions that has permitted estimates of the primordial helium mass fraction, $Y_p$, whose statistical uncertainties are very small, $\approx 1\%$ (e.g., see Olive & Steigman 1995, hereafter OS; Olive, Skillman, & Steigman 1997, hereafter OSS; Izotov, Thuan & Lipovetsky 1994, 1997, hereafter ITL; Izotov & Thuan 1998, hereafter IT). However, along the path from the observational data to the derived abundances, contamination by unknown systematic uncertainties may bias the inferred value of $Y_p$. Observers have identified many potential sources of systematic error (Davidson & Kinman 1985; Pagel et al. 1992, hereafter PSTE; Skillman et al. 1994; Peimbert 1996; ITL; IT; Skillman, Terlevich, & Terlevich 1998) and, where possible, have designed their observing programs to minimize and/or to account for them. In a previous paper (Steigman, Viegas, & Gruenwald 1997) we have explored the magnitude of the contribution to systematic error in $Y_p$ from possible temperature fluctuations in the extragalactic H II regions, concluding that they may have a significant effect on the determination of the primordial abundance of helium, comparable to or even greater than the statistical uncertainties. Here we turn our attention to another potential source of systematic error: the ionization correction for unseen neutral hydrogen and/or helium in H II regions.

Following Peimbert & Costero (1969), an empirical method is usually employed to derive the abundances from the observed emission-line intensities. The electron density and temperature of the gas are obtained from various emission-line intensity ratios, and they are then used to calculate the appropriate line emissivities, which, along with the observed emission-line intensities, provide the fractional abundances of the various ions that are finally combined to obtain the element abundances (see, e.g., Osterbrock 1989). Since not all the ions present in the gas actually produce observable lines, an ionization correction must be applied to account for the “missing” ionization states. Historically, the ionization correction factor (ICF) has been derived for H, He, and many of the heavier elements from considerations of the ionization potentials or from numerical photoionization models (Peimbert & Torres-Peimbert 1977; Statinska 1980, 1982; Mathis 1982; Peña 1986). In the quest for $Y_p$ a key concern has been that owing to its higher ionization potential, unseen neutral helium may lurk in those parts of the H II regions where the hydrogen is still fully ionized (ICF > 1). As the metallicity of the stellar population responsible for creating the H II region decreases, the stars providing the ionizing radiation are expected to be hotter, with “harder” spectra. If so, the helium and hydrogen ionization zones should be more nearly coincident and the ionization correction minimized (i.e., the ICF should be closer to unity).

Some years ago, Pagel et al. (PSTE) proposed a method for estimating the helium ICF based on the “radiation softness parameter” $\eta \equiv \langle (O^+ / S^+) - (S^+ / O^++ ) \rangle$ of Vílegas & Pagel (1988). Comparing with photoionization models, they concluded that the ICF will differ negligibly from unity for $\log \eta < 0.9$, corresponding to models with effective stellar temperatures higher than 37,000 K. When using a sample of H II regions to derive $Y_p$, PSTE impose this $\eta$ condition to discard from their data set those H II regions for which the ICF may differ from unity ($\log \eta > 0.9$), and they adopt ICF = 1 for all those H II regions with $\log \eta < 0.9$. In fact, as we shall see, for the sufficiently “hard” radiation field provided by a population of young, hot stars, the ionization
correction may actually be reversed with neutral hydrogen present in those parts of the H II regions where the helium is still ionized (ICF $< 1$) (Stasinska 1980, 1982; Peña 1986; Dinerstein & Shields 1986). In either case, a potentially serious hidden assumption is that of homogeneity for the H II regions (see, e.g., Dinerstein & Shields 1986). Recent HST imaging reveals that these regions are far from homogeneous, showing many different features such as pillars, globules, and even voids. As a result the true ICF may differ significantly (on the scale of the statistical errors) from the values calculated in simplified models of homogeneous regions, introducing a systematic error in the calculation of the primordial abundance of $^4$He. For example, for $Y_p \approx 0.24$, if the ICF should differ from unity by 1\%–2\%, the change in $Y_p$ will be of order 0.002–0.004, comparable to the statistical uncertainties in $Y_p$ suggested by the analyses of OS, OSS, and IT. Furthermore, if indeed the ICF is less than unity for sufficiently young and metal-poor H II regions, then even the seemingly conservative assumption of PSTE to adopt ICF = 1 may lead to a (metallicity-dependent) bias which systematically overestimates $Y_p$.

Another common simplification of the photoionization models used to estimate the ICF is the assumption that the ionizing radiation is provided by stars of a single stellar temperature. In contrast, real H II regions are ionized by clusters of stars of differing masses and temperatures whose ionizing radiation spectra differ from that of a single blackbody. In the following we adopt the (time-dependent) spectrum of a starburst (Cid-Fernandes et al. 1992) appropriate to low-metallicity stars and employ a numerical photoionization code (AANGABA; Gruenwald & Viegas 1992) that allows us to account for inhomogeneity. The models are described in § 2. The ICF results are discussed in § 3 and are applied to an H II region sample taken from the literature in § 4. Our concluding remarks appear in § 5.

2. PHOTOIONIZATION MODELS

Many independent one-dimensional photoionization codes have been developed over the last 30 years or so. Comparison among several of them for some standard test cases of H II regions, planetary nebulae, and active galactic nuclei reveals very good agreement (Peña 1986; Ferland et al. 1995). These codes are in wide use analyzing observed emission-line spectra. For such codes the usual input parameters are the ionizing radiation spectrum, the gas density, and the relative chemical abundances. In most of the codes spherical or plane-parallel symmetry is assumed and the diffuse radiation is treated in the outward-only approximation. Usually a constant density is assumed, or a specific functional form for the variation of density with distance is adopted. However, these simplifying choices may not reflect the true structure of real H II regions as revealed by HST imaging. One way to approach the problem of more realistic modeling is to mimic the presence of condensations or voids by combining models for several different choices of input parameters.

In our analysis the AANGABA photoionization code is used to model the gas whose distribution is taken to be spherically symmetric. Later, in constructing more general inhomogeneous models, this restriction to spherical symmetry is relaxed. Because we are specifically interested in the helium/hydrogen ICF with the goal of analyzing its effect on the helium abundances derived from the low-metallicity H II regions, a metal-poor chemical composition (0.1 solar) is chosen. The stellar cluster ionizing radiation spectrum from Cid-Fernandes et al. (1992) is adopted and models are built for two evolutionary phases of the star cluster: the initial phase ($t = 0$), when the spectrum is dominated by the hottest, most massive stars, and a later phase ($t = 2.5$ Myr), when the hot stars have evolved and there are fewer He $^+$ ionizing photons. In order to explore a variety of different physical conditions, the radiation intensity is characterized by the number of ionizing photons above the Lyman limit, $Q_H$. $Q_H$ is directly related to the mass and IMF of the stellar cluster and, along with the gas density, defines the H II regions. In terms of the population parameter, $U$, for a given density each of our models corresponds to a fixed value of $UR_H^2$, which is proportional to $Q_H (R_i$ is the inner radius of the H II region). As a result, our constant density models should reproduce the ICF-$n$ behavior found in PSTE (their Fig. 6). Since the ionization parameter is proportional to $Q_H/n$, a grid of models at a given density and characterized by the value of the ionization parameter, corresponds to different values of $Q_H$. It is true that those combinations of $Q_H$, $n$, and $R_i$ that keep $U$ constant lead to the same ionization structure of the gas. However, when looking for models to represent the observations of a specific H II region, ionized by a given number of stars, any conclusions should be based on a grid with $Q_H$ constant. Thus, in the following we show the results of a series of models with different values of $U$, satisfying the condition $Q_H = constant$. First, for each choice of $Q_H$, a homogeneous (H) constant density model is constructed.

The above homogeneous models form the basis for the inhomogeneous models we create next: models with spatially limited density enhancements which will mimic density condensations (C) and those with density deficits for “valleys” (V). These alternate models all start with the same input parameters as the corresponding homogeneous model. We set the location of the condensations or valleys by specifying the corresponding optical depths at the Lyman limit, $\tau$, in the homogeneous model. In our analysis we placed the condensations/valleys at the following locations: $\tau = 0.02, 0.03, 0.04, 0.10$, and 0.40. At each of these radii the density (in a spherical shell) is either increased by a factor of 5 (condensation) or decreased by a factor of 2 (valley), extending over a distance that is 10\% of the thickness of the H II region for the corresponding homogeneous model. To avoid numerical problems, the increase/decrease of the density followed a smooth analytical form. Notice, however, that the size of this transition zone is always much smaller than the size of the condensation or the valley. Aside from the condensation/valley, the density throughout the rest of the region is the same as in the corresponding homogeneous model. We explored many other choices of these parameters, but the ones adopted here provide a fair sample of the variations of the ionization correction factor (see the next section) in all the models we constructed. By constructing inhomogeneous H II regions using as building blocks a variety of the $H$, $C$, and $V$ models, we can mimic the physical conditions in realistic H II regions using the Monte Carlo method.

Examples of a different sort of composite model are those of Dinerstein & Shields (1986) and of Peña (1986) in which they account for the contributions from superposed H II regions with high and low stellar temperatures (“hard” and “soft” radiation fields). In our analysis we can do the same, combining models for H II regions using the stellar cluster
ionizing radiation spectra at $t = 0$ and at $t = 2.5$ Myr. In the following we pursue both kinds of inhomogeneous models.

3. The Helium Ionization Correction Factor

In H II regions often only lines from the recombination of He$^+$ are observed, although occasionally those from the recombination of He$^{++}$ are also seen. In order to account for the possible presence of any unseen He$^{++}$ and He$^0$, and also of H$^0$, we define the ICF so that the He/H abundance ratio is given by $\text{He}/\text{H} \equiv \text{ICF} \times \left[ n(\text{He}^+) / n(\text{H}^+) \right]$ so that

$$\text{ICF} = \frac{1 + \left[ n(\text{He}^0) + n(\text{He}^{++}) \right]}{1 + \left[ n(\text{He}^+) / n(\text{H}^+) \right]}. \quad (1)$$

In addition, following Vilchez & Pagel (1988), the radiation "softness" parameter is defined as

$$\eta = \frac{n(\text{O}^+)/n(\text{S}^+))}{n(\text{S}^+)/n(\text{O}^+)} \quad (2)$$

Both the ICF and $\eta$ are obtained from the models described in the previous section.

3.1. Radiation Softness Parameter

The use of the radiation softness parameter has been challenged by Skillman (1989). Using photoionization models characterized by the value of the ionization parameter, he found that "for $T_{\text{eff}} \geq 45,000$ K, $\eta$ shows a strong dependence on $U$." This conclusion could invalidate the use of $\eta$ to obtain the helium ionization correction factor. Skillman’s models for different H II regions are characterized by different values of the ionization parameter. We note that Skillman uses the Dinerstein & Shields (1986) ionization parameter, which is defined as the ratio of the ionizing photon density and the gas density evaluated at the Strömgren radius when the inner radius is fixed at 10% of the Strömgren radius ($R_*/R_s = 0.10$). Each choice of Skillman’s ionization parameter corresponds to a different H II region, irradiated by a different number of ionizing photons $Q_H$, leading to a different ionization structure. It is, therefore, not surprising that when Skillman varies the ionization parameter he finds variations in the radiation softness parameter. We have explored Skillman’s claim using our homogeneous models and varying $U$ (and $R_s$) while keeping $Q_H$ fixed. We recall that, as described in §2, each of our H II region models is defined by fixed values of $Q_H$ for given choices of the gas density and filling factor and the ionization parameter ($U$) is defined as the ratio of the ionizing photon density to the gas density, evaluated at the inner radius. We emphasize that the $Q_H$ range covered by our models is the same as that of Skillman’s models. In all cases we find that the models with fixed $Q_H$ but different $U$ yield $\eta$ values that differ by less than 10% and ICFs that differ by less than 0.02%. Exceptions do occur if the $U$ value is too low, corresponding to a very large value of $R_*/R_s$. These latter cases correspond to unrealistic models in that the geometrical width of the ionized region is much smaller than the inner radius($R_s - R_*/R_s \ll R_s$). Nevertheless, even for these cases (low $U$, fixed $Q_H$) the ICF differs from that of the higher $U$ models by less than 0.5%. Thus, if $U$ is varied while keeping $Q_H$ (and the density) fixed, the radiation softness parameter $\eta$ is virtually unchanged, and there is a well-defined relation between the ionization correction factor and the Vilchez & Pagel (1988) radiation softness parameter.

3.2. Homogeneous Models

First consider our results for the homogeneous models (Fig. 1, solid lines). For our fiducial models we fixed the density at $n_H = 10$ cm$^{-3}$ and varied $Q_H$ from $7.5 \times 10^{44}$ s$^{-1}$ to $7.5 \times 10^{53}$ s$^{-1}$. The lower bound on $Q_H$ is set by the requirement that the H II region be bright enough to be observable. The arrows on the solid lines indicate the effect of increasing $Q_H$. By varying our choice of the $Q_H$ and the H II region density we found that the solid (and dashed) lines are actually the loci of constant values of the combination $n^2 Q_H$. In addition, although our fiducial models assume a filling factor of unity ($\epsilon = 1$), we experimented with several choices of filling factor ($\epsilon < 1$) and verified that these models also lie along the lines in Figure 1, with a decrease in $\epsilon$ corresponding to an increase in $n^2 Q_H$. As noted in §3.1 above, the range in $Q_H$ covered by our models explores the same ionization parameter range that Skillman (1989) covered in his investigation.

As anticipated for the case where the nebula is ionized by a young starburst with hot stars providing a hard radiation spectrum, the H II region models predict a "reverse" ionization correction (ICF \leq 1); i.e., neutral hydrogen is present where the helium is still ionized. As $n^2 Q_H$ increases (and/or the filling factor decreases), $\eta$ decreases (from $\eta \leq 0.7$) and the He$^+$ and H$^+$ regions more nearly coincide (ICF \rightarrow 1) with the ICF-$\eta$ relation being traced out by the solid line in the lower left-hand corner of Figure 1.

In contrast to the young starburst case, the softer spectrum of the ionizing radiation present 2.5 Myr after the...
initial burst leads to very different behavior (see the upper right-hand corner of Fig. 1). In these cases neutral helium is present in the hydrogen ionized zone (ICF \( \geq 1 \)). At first, as \( Q_H \) increases, \( \eta \) barely changes, decreasing only very slightly, while the ICF decreases noticeably (in contrast to the young starburst case). However, after turning the corner at the “elbow” located at \( \log \eta \approx 0.8 \), \( \eta \) then increases with increasing \( Q_H \) while now the ICF remains relatively constant.

These distinct behaviors of H II regions ionized by hard and by soft spectra were also found by Peña (1986), by Dinerstein & Shields (1986), and by PSTE. Note in particular that for regions ionized by the soft spectra of “old” starbursts, the radiation softness parameter, \( \eta \), is bounded from below (\( \log \eta \gtrsim 0.8 \)). Since H II regions with such large values of \( \eta \) are normally excluded from analyses whose goal is the determination of the primordial abundance of helium, such old starbursts cannot dominate the ionizing radiation of the regions employed in such analyses. Nonetheless, as noted by Dinerstein & Shields (1986), some contamination from regions ionized by such soft spectra could effect the overall ionization correction. We explore this possibility below in \( \S \) 3.4.

### 3.3. Inhomogeneous Models

Now consider the noncomposite inhomogeneous models \((C/V)\) whose construction was described in \( \S \). Since the results of the inhomogeneous “valley” models are virtually indistinguishable from those of the corresponding homogeneous models, we have not shown them in Figure 1. For the “condensation” models we found that the greatest deviation from the corresponding homogeneous case occurs when the condensation is located at a radius equivalent to an optical depth of \( \tau = 0.04 \). At this distance the radiation field is still sufficiently strong to have been only partially absorbed by the high density gas and the regions shadowed by the condensation are still partially ionized, with the amounts of H II (for the high-temperature cluster) and He II (for the low-temperature cluster) determining the ICF value. It is these cases (\( \tau = 0.04 \)) that are shown by the dashed lines in Figure 1. Thus, all of our models, the noncomposite \( C/V \) models as well as the composite models described below, lie between the homogeneous cases (solid lines) and these “extreme” inhomogeneous models (dashed lines).

For our Monte Carlos we used the \( H/V/C \) models as building blocks in the construction of a suite of composite inhomogeneous models. First, we fix the number of ionizing photons, \( Q_H \), and the density, \( n \), and archive the results of a set of corresponding \( H/V/C \) models with the valleys and condensations located at the different optical depths \( \tau_i \) (see \( \S \)). A single composite inhomogeneous model is created by assigning a weight proportional to the solid angle, \( \Omega_i \), occupied by each \( H/V/C \) model and summing the weighted contributions of each model. The \( \Omega_i \) are chosen randomly, subject to the constraint that their sum is 4\( \pi \). This procedure is then repeated 10,000 times, and the Monte Carlos are run for different choices of \( Q_H \) and \( n \).

Not surprisingly, the results of our Monte Carlos (for the young starburst case) all lie in the shaded region in Figure 1, between the ICF-\( \eta \) relation for the homogeneous models (solid curve) and that for the “extreme” condensation (\( \tau = 0.04 \)) models (dashed curve). Although the behavior for the case of the old starburst is more complicated, it is clear that these composite inhomogeneous models will always have “large” values for the radiation softness parameter and cannot, by themselves, describe the H II regions selected for probing the primordial helium abundance.

### 3.4. Contamination by “Old” H II Regions

As we have seen, H II regions ionized by young starbursts with hard spectra always have a “reverse” ionization correction (ICF \( < 1 \)) and are limited to relatively low values of the radiation softness parameter (\( \log \eta \lesssim 0.7 \)). In contrast, regions ionized by a softer spectrum will have ICF \( > 1 \), but also \( \log \eta \gtrsim 0.8 \). Although the latter would normally be eliminated from consideration by an \( \eta \) cut, it is possible that a contribution from such regions could contaminate the helium abundances derived from observations (Dinerstein & Shields 1986). To test this possibility it would be necessary to construct models of superposed H II regions for each observed H II region and to constrain the parameters of the mixture by demanding that these composite models reproduce all the observed line strengths. As an illustrative example, Dinerstein & Shields (1986) have done something simpler. For NGC 4861 they superposed a “hot” region (\( T_* = 55,000 \) K) and a “cool” region (\( T_* = 35,000 \) K), fixing the ionization parameter for each region by the arbitrary requirement that each component reproduce the observed \((I/6300)/(I(H\beta))\) ratio. The relative weights of each component were then fixed by the requirement that the resulting \((I/3372)/(I(H\beta))\) ratio have the observed value. In this case they found that the low-\( T_* \) component contributes 12% of the observed H\( \beta \) luminosity. For this composite model they found ICF = 1.09 (and \( \log \eta = 0.39 \)) in contrast to the value ICF = 0.99 (and \( \log \eta = 0.47 \)) for their simple, noncomposite model, and they noted that “low observed values of He I/He II cannot be interpreted as low He/H with complete confidence.” However, it should be remarked that neither of their models is consistent with all their observed line ratios. For example, neither their one-component nor their two-component model reproduces the observed value of the radiation softness parameter: \( \log N_{\text{obs}} = -0.07 \). Notice from Figure 1 that for our one-component homogeneous and inhomogeneous models, the ICF \( \approx 0.99 \) for \( \log \eta \approx -0.07 \).

As suggested by the failure of Dinerstein & Shields (1986) to account for all the observed line ratios, it may not be so easy to confuse a composite “young/old” H II region with a single (albeit inhomogeneous) H II region. Various line ratios can be the key to distinguishing between the two possibilities. Using our young (\( t = 0 \)) and old (\( t = 2.5 \) Myr) H II region models we have constructed a suite of composite models whose results are easy to understand with reference to Figure 1. For almost all combinations one or the other region will dominate and the ICF-\( \eta \) results will lie close to those of the dominant case (i.e., the one with the largest \( Q_H \)). Given the separation in \( \log \eta \) between the young and old regions, it is unlikely that an observed H II region will be confused by a composite region dominated by a component with the “wrong” value of \( \log \eta \). Since virtually all of the H II regions selected for determination of the primordial helium abundance have low values of \( \log \eta \) (see the data utilized in the next section), this suggests that most of the viable composite models will have ICFs similar to those for our \( t = 0 \) case (i.e., ICF \( \lesssim 1 \)). Only when the number of ionizing photons (\( Q_H \)) for each of the two regions (\( t = 0 \) and \( t = 2.5 \) Myr) are comparable may it be possible for a composite region to masquerade as a single region. We have
we find that the individual ion ratios O\(^{++}/O^+\) and S\(^{++}/S^+\) differ by factors of 6–7 between the simple and the composite models. To explore this further, we compared the ratios of the intensities of various emission lines to that of H\(\beta\) for the simple model (\(t = 0, Q_H = 7.5 \times 10^{47} \, \text{s}^{-1}\)) with those for a series of composite models with \(Q_H\) varying from 7.5 \(\times\) \(10^{49}\) \(\text{s}^{-1}\) to 7.5 \(\times\) \(10^{53}\) \(\text{s}^{-1}\). All of these composite models have \(\log \eta \approx 0.4\) and ICF \(\approx 1.04\). In the composite models the \([\text{O} \ II]\) (\(\lambda 3727\)) to H\(\beta\) ratio varies from 18% to 66% of that in the simple model, the \([\text{N} \ II]\) (\(\lambda 6584 + 6548\)) to H\(\beta\) ratio is 16% to 60% of that in the simple model, and the \([\text{S} \ II]\) (\(\lambda 6717 + 6731\)) to H\(\beta\) ratio is 3% to 41% of that in the simple model. In contrast, the \([\text{O} \ II]\) (\(\lambda 37007 + 4959\)) to H\(\beta\) line ratios in the composite models exceed those in the simple model by factors of 1.4–2.3. From our analysis it seems clear that these crucial line ratios can be key to unmasking composite H\(\ II\) regions masquerading as simple H\(\ II\) regions (see, also, Peña 1986).

4. CORRECTIONS TO THE HELIUM ABUNDANCE FOR OBSERVED H\(\ II\) REGIONS

As we have done in our previous analysis of the effect of temperature inhomogeneities on the primordial helium abundance inferred from the observational data (Steigman et al. 1997), we quantify the effect on \(Y_p\) of an ICF which differs from unity using a sample of H\(\ II\) regions from the literature. The data of Izotov & Thuan (IT) are especially well suited to our task. For 41 of the 45 H\(\ II\) regions presented by IT, they provide helium abundances and data from which we may estimate the radiation softness parameter \(\eta\). Although one of their H\(\ II\) regions, UM 311, is not really in the category of “metal-poor,” we have verified that whether or not we include it in our analysis has no significant effect on the difference in the derived value of \(Y_p\) using our calculated ICF as compared to the IT choice ICF = 1 for all regions. For the IT sample, \(-0.25 \leq \log \eta \leq 0.37\) suggesting (see Fig. 1) an “average” ICF \(\approx 0.96 \pm 0.02\) and a potentially large reduction in \(Y_p, \Delta Y_p \approx -0.0072 \pm 0.0036\). To quantify this reduction we have run a series of Monte Carlos using the IT data set and our computed ICF-\(\eta\) relations shown in Figure 1.

For each H\(\ II\) region in the IT sample, we have \(\eta\), the oxygen abundance O/H, and \(Y\) for ICF = 1. For this fiducial data set we find the best linear fit to \(Y\) versus O/H in order to derive \(Y_p\). We have also experimented with using averages of \(Y\) for the 15–20 lowest oxygen abundance regions to bound \(Y_p\) and find the difference in our derived \(\Delta Y_p\) to be negligible compared to that found using the linear fit. We emphasize that here we are not interested in the actual value of \(Y_p\) per se. Rather, we want to find the reduction in \(Y_p\) due to ICF \(\leq 1\). In the Monte Carlos, for each of the observed regions we use the value of log \(\eta\) from the data to randomly choose an ICF between the minimum value for a condensation located at \(t = 0.04\) (“extreme” inhomogeneous case) and the ICF for the homogeneous case. In choosing between these two extremes we have experimented with three probability distributions: equal probability for the ICF to lie between the two extremes and decreasing/increasing probability for the extreme inhomogeneity. For each of the (41) IT regions we correct their value of \(\text{He}^+ /\text{H}^+\) with the randomly chosen ICF and compute the ICF-corrected \(\text{He}^+ /\text{H}^+\) ratio which we use to find the ICF-corrected \(Y\). This new set of (41) \(Y, \text{O/H}\) pairs is used to find the corresponding \(Y_p\) from the linear \(Y\) versus

![Figure 2](image-url)  

**Fig. 2.**—Distribution of the offsets in the primordial helium mass fraction, \(Y_p\), inferred from Monte Carlos using the IT data and our ICF-\(\eta\) results for three different probability distributions that interpolate between the homogeneous and “extreme” inhomogeneous models (see the text). From top to bottom, the probability distributions favor the homogeneous models, are neutral, and favor the inhomogeneous models.

Therefore concentrated on such “democratic” composite models and found that they occupy a region in the ICF–log \(\eta\) plane with log \(\eta \geq 0.4\) and ICF \(\leq 1.04\). For the IT data that we use in our quantitative analysis in the next section, log \(\eta \leq 0.37\) and interloping regions are unlikely to have played a major role. Nonetheless, we have pursued the question of whether such composite regions could contaminate the ICF inferred for H\(\ II\) regions that are observed to have log \(\eta \geq 0.4\).

As a first step we have compared the results of the \(t = 0, Q_H = 7.5 \times 10^{47} \, \text{s}^{-1}\) model (\(n = 10 \, \text{cm}^{-3}\) and \(\epsilon = 1\)) for which log \(\eta = 0.37\) and ICF = 0.956 with those for a composite model of two regions (\(t = 0\) and \(t = 2.5\) Myr) each with \(Q_H = 7.5 \times 10^{51} \, \text{s}^{-1}\) (\(n = 10 \, \text{cm}^{-3}\), \(\epsilon = 1\)) for which log \(\eta = 0.42\) and ICF = 1.036. Notice that if \(\epsilon < 1\), similar \(\eta\) and ICF values are obtained with higher \(n^2 Q_H\). Although the \(\eta\)'s of the single and composite regions are very similar,
O/H fit. For each choice of ICF probability distribution we redid this 10,000 times. Our results appear as histograms for the distributions of $\Delta Y_p$ in Figure 2. It is clear from Figure 2 that our principal conclusion, $- \Delta Y_p \approx 0.003-0.004$, does not depend on the choice of ICF probability distribution. Our Monte Carlo results suggest that by ignoring the correction for He-H ionization, IT have overestimated the primordial helium mass fraction by 0.0034 ± 0.0003. For their sample, IT derive (see their Table 7) $Y_p(\text{IT}) = 0.2443 ± 0.0015$ (or 0.244 ± 0.002). Including our estimate of the true ICF we suggest their value of $Y_p$ should be reduced to $Y_p(\text{VGS}) = 0.241 ± 0.002$. We note that ICF ≈ 1 has also been assumed for the H II regions in the data sets used by OS and OSS, so their estimates of $Y_p$ should likely be reduced by a similar amount to that which we have found for the IT sample.

5. CONCLUSIONS

Relatively accurate helium abundance determinations are currently available for nearly 100 low-metallicity extragalactic H II regions (see, e.g., OS; OSS; IT). These data enable estimates of the primordial abundance of helium to unprecedented statistical accuracy. For example, IT quote $\Delta Y_p = ±0.0015$ (or ±0.002) for the regions they have observed and analyzed. At this level of uncertainty unanticipated systematic errors may overwhelm the statistical uncertainties (see, e.g., Davidson & Kinman 1985; PSTE; Skillman et al. 1994; ITL; Peimbert 1996; Steigman et al. 1997; Skillman et al. 1998; IT). In this paper we have revisited the question of the helium ionization correction and its contribution to estimates of $Y_p$. Virtually all the low-metallicity H II regions employed in the quest for $Y_p$ have “hard” spectra (low $\eta$), and almost always the ionization correction has been ignored or, rather, assumed to be unity (no correction). We have seen, as have others before us (e.g., Peña 1986; Dinerstein & Shields 1986; PSTE), that there is a reverse ionization correction (ICF < 1) for regions ionized by such hard spectra. Inhomogeneities, surely present in these regions, serve only to exacerbate this correction (i.e., to reduce the ICF). In our comparison with real data (IT), we suggest that their estimate of $Y_p = 0.244 ± 0.002$, should be reduced to $Y_p = 0.241 ± 0.002$, a correction larger than the quoted statistical error. Of course, this latter estimate still ignores other possible sources of systematic error such as temperature fluctuations (Peimbert 1971; Steigman et al. 1997) and underlying stellar absorption (see ITL; Skillman et al. 1998; IT).

In the current precision era of cosmology, predictions and observations are achieving unprecedented levels of statistical accuracy. This is certainly the case for primordial nucleosynthesis in the standard (isotropic, homogeneous, three flavors of light neutrinos, etc.) hot big bang cosmological model (BBN). For example, at a fixed value of the baryon density (or, equivalently, the baryon-to-photon ratio) the uncertainty in the predicted primordial abundance of helium is at the level of ±0.0005 (Hata et al. 1996; Burles et al. 1999; Olive et al. 1999; Lopez & Turner 1999). Furthermore, the variation of $Y_p(\text{BBN})$ with baryon density is very slow so that if deuterium is used as a baryometer to constrain the baryon density, $\Delta Y_p(\text{BBN}) \approx 0.006(\Delta y_2/y_2)$, where $y_2 \equiv (\text{D}/\text{H})_p$. The uncertainty in the BBN-predicted primordial deuterium abundance is of order 8% (Hata et al. 1996) or less (Burles et al. 1999), a level comparable to that claimed for the uncertainty in the value inferred from observations of deuterium along the lines of sight to two high-redshift, low-metallicity (hence, very nearly primordial) QSO absorption-line systems (Burles & Tytler 1998a, 1998b): $y_2(\text{obs}) = 3.4 ± 0.25 \times 10^{-3}$. The BBN helium abundance which corresponds to this deuterium abundance is $Y_p(\text{BBN}) = 0.247 ± 0.0011$. Notice that while this expected abundance is consistent with the IT-determined value (0.244 ± 0.002) it is higher than our IT-corrected estimate (0.241 ± 0.002) by some 3 $\sigma$.

Strictly speaking, our quantitative estimate of the reduction in $Y_p$ associated with the ionization correction factor applies only to the data of IT. Nonetheless, it is anticipated that $Y_p$ inferred from the data assembled by OS should be similarly reduced. Since the OS estimate of $Y_p$ (excluding the northwest region of I Zw 18, which is suspected of being contaminated by underlying stellar absorption) is even lower than that of IT [$Y_p(\text{OS}) = 0.234 ± 0.003$] the discrepancy between theory and data is even larger. Of course it could be that the Burles & Tytler (1998a, 1998b) estimate of the primordial deuterium abundance is too low (see, e.g., Webb et al. 1997; Levshakov, Kegel, & Takahara 1998a, 1998b, 1999). Nonetheless, this example provides an object lesson highlighting the importance of careful estimates of systematic errors in the current era of precision cosmology.

In deriving the helium abundance from observations of H II regions, it is necessary to correct the emission-line data for various effects (e.g., collisional excitation). In this paper we have explored the correction for unseen hydrogen and/or helium using detailed photoionization models of H II regions ionized by realistic radiation spectra from different (young/hot and old/cool) stellar clusters. For regions ionized by young, hot stars the radiation softness parameter is small ($\log \eta < 0.7$) and there is a systematic, reverse ionization correction (ICF < 1). In contrast, for regions ionized by an older stellar population with fewer hot stars the radiation softness parameter is large ($\log \eta > 0.8$) and ICF > 1. Thus, the correction for ionization is systematically correlated with the magnitude of the radiation softness parameter. Of course, if this correction were very small, it would have a negligible effect on the helium abundance determination and could be neglected. Our results suggest this is not the case. For the H II regions in the IT data set, there are reductions in individual Y values that could be as large as 0.01 or even larger. These reductions, which are comparable to (or, even larger than) typical statistical errors in Y for individual H II regions (see, e.g., OS, OSS, and IT), should be compared to the theoretical (SBBN) uncertainty which is more than one order of magnitude smaller (e.g., Olive et al. 1999). For the IT data set we find the reduction in the inferred primordial mass fraction is comparable to (or, even somewhat larger than) the quoted statistical error in $Y_p$. The importance of including the ionization correction may be illustrated by the corresponding bound on $N_e$, the “effective” number of light neutrino species, which provides a measure of any deviation from the standard model energy density at the epoch of BBN (Steigman, Schramm, & Gunn 1977). For SBBN, $N_e > 3$, while the presence of “new,” light particles (beyond the standard model of particle physics) would permit $N_e > 3$. In a recent analysis utilizing the IT determination of $Y_p$ and the Burles & Tytler (1998a, 1998b) deuterium, Burles et al. (1999) find a 2 $\sigma$ upper bound of $N_e \leq 3.2$ (see, also, Olive et al. 1999). Incorporating the reduction in $Y_p$ from the ionization correction will reduce
this bound to $N_e \leq 2.9$, posing a potential challenge to SBBN. While there undoubtedly remain other, as yet unquantified, systematic errors whose magnitude may be larger than the ionization correction, it seems clear that the systematic reduction for ionization cannot be ignored.

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