THE CHEMICAL COMPOSITION OF THE SMALL MAGELLANIC CLOUD H II REGION NGC 346 AND THE PRIMORDIAL HELIUM ABUNDANCE

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ABSTRACT

Spectrophotometry in the \(\lambda\lambda 3400–7400\) range is presented for 13 areas of the brightest H II region in the SMC: NGC 346. The observations were obtained at CTIO with the 4 m telescope. Based on these observations, its chemical composition is derived. The helium and oxygen abundances by mass are given by \(Y(\text{SMC}) = 0.2405 \pm 0.0018\) and \(O(\text{SMC}) = 0.00171 \pm 0.00025\). From models and observations of irregular and blue compact galaxies it is found that \(\Delta Y/\Delta O = 3.5 \pm 0.9\) and, consequently, that the primordial helium abundance by mass is given by \(Y_p = 0.2345 \pm 0.0026\) (1 \(\sigma\)). This result is compared with values derived from big bang nucleosynthesis and with other determinations of \(Y_p\).

Subject headings: galaxies: abundances — galaxies: individual (Small Magellanic Cloud) — galaxies: ISM — H II regions — ISM: abundances — Magellanic Clouds

1. INTRODUCTION

The determination of \(Y_p\) based on the Small Magellanic Cloud can have at least four significant advantages and one disadvantage with respect to those based on distant H II region complexes: (1) no underlying absorption correction for the helium lines is needed because the ionizing stars can be excluded from the observing slit; (2) the determination of the helium ionization correction factor can be estimated by observing different lines of sight of a given H II region; (3) the accuracy of the determination can be estimated by comparing the results derived from different points in a given H II region; (4) the electron temperature is generally smaller than those of metal poorer H II regions reducing the effect of collisional excitation from the metastable \(^2\)S level of He \(\epsilon\); and (5) the disadvantage is that the correction due to the chemical evolution of the SMC is in general larger than for the other systems.

The determination of the pregalactic, or primordial, helium abundance by mass \(Y_p\) is paramount for the study of cosmology, the physics of elementary particles, and the chemical evolution of galaxies (e.g., Fields & Olive 1998; Izotov et al. 1999; Peimbert & Torres-Peimbert 1999, and references therein). In this paper we present a new determination of \(Y_p\) based on observations of the SMC. This determination is compared with those carried out earlier based on extremely metal-poor extragalactic H II regions.

2. OBSERVATIONS

Long-slit spectra were obtained at CTIO during two observing runs, in 1990 August and September, with the 4m telescope equipped with the R-C Spectrograph and a coated GEC CCD detector. Using three different gratings (at first order), the spectral ranges between \(\lambda\lambda 3440–5110\), 4220–7360, and 5800–7370 were covered. The slit, oriented east-west, was 4.7 long and 1.6 wide; the scale along the dispersion axis was 0.73 pixel\(^{-1}\). The resolution was 7 Å for the blue and red wavelength ranges and 14 Å for the intermediate one. The slit was placed at two different positions of the nebula, five extraction windows were defined in one slit position (regions 1–5) and eight in the other (regions 11–18), four of the extraction windows included the brightest ionizing stars (\(m \sim 14\)), while the other nine positions avoided stars brighter than \(m = 17\) to minimize the stellar contamination of the nebular spectra. Table 1 presents the positions and sizes of the extraction windows.

In Table 1 we also present the observed \(H\beta\) fluxes, \(F(H\beta)\), before correction for extinction. Massey, Parker, & Garmany (1989) present excellent pictures of the stellar cluster of NGC 346 in which the ionizing stars included in Table 1 are indicated and the observed regions can be located. Ye, Turtle, & Kennicutt (1991) also present excellent pictures of NGC 346 in which the filamentary structure of the nebula can be appreciated. Also in Table 1 we define regions A and B. Region A is the sum of regions 2, 3, 5, 12, 13, 17, and 18. Region A was defined to minimize the errors of the emission lines and the effect of stellar underlying absorption; the main results of this paper will be based on it. Regions 1 and 11 were not included in region A because they are fainter than the others (see Table 1) and the equivalent widths of their emission lines are also smaller (see the last paragraph of this section), both effects could increase the systematic errors. Region B is the sum of all observed regions and will be used to show the effect of the underlying absorption on the measured line intensities.

To flux-calibrate the spectra, five or six spectrophotometric standards, from Stone & Baldwin (1983), were observed each night with the slit widened to 6'4. A He-Ne-Ar lamp was used to perform the wavelength calibration. Dome-flats and sky-flats were obtained to flatten the red frames while a quartz lamp flat and a sky flat were used for the blue range frames. Several bias frames were taken each night. Data reduction was performed using the IRAF reduction package. Sky subtraction was made from observations taken one degree away from the nebula before and

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after each nebular observation. Short exposure frames at each position were used to remove cosmic rays and to measure fluxes of strong lines saturated in the longer exposures.

In Figures 1, 2, and 3 we show spectra of region A at different wavelength ranges. In Figure 4 we compare regions A and B near the Balmer limit to show the effect of the underlying absorption on the Balmer lines and on $\lambda$4026 of $\text{He I}$.

In Tables 2, 3, and 4 we present the intrinsic line intensities, $I(\lambda)$, given by

$$\log \left[ \frac{I(\lambda)}{I(HB)} \right] = \log \left[ \frac{F(\lambda)}{F(HB)} \right] + C(HB)f(\lambda),$$

where $F(\lambda)$ is the observed line flux-corrected for atmospheric extinction, $C(HB)$ is the logarithmic reddening correction at $HB$, and $f(\lambda)$ is the reddening function. For $f(\lambda)$ we adopted the normal extinction law (Whitford 1958). $C(HB)$ was obtained by fitting the observed Balmer decrement with

| POSITION* | X  | Y  | LENGTH b | $F(HB)$ (erg cm$^{-2}$ s$^{-1}$) | STAR c | SPECTRAL TYPE |
|-----------|----|----|----------|-----------------|--------|---------------|
| 1         | 102.2 W | 0.0 | 34.1     | 6.23-14         |        |               |
| 2         | 58.0 W  | 0.0 | 22.4     | 1.14-13         |        |               |
| 3         | 24.9 W  | 0.0 | 13.6     | 1.63-13         |        |               |
| 4         | 2.1 E   | 0.0 | 18.6     | 2.37-13         | 355    | O3V (f*)      |
| 5         | 86.4 E  | 0.0 | 43.6     | 2.54-13         |        |               |
| 11        | 123.9 W | 5.5 S | 24.8     | 4.33-14         |        |               |
| 12        | 77.6 W  | 5.5 S | 32.9     | 9.48-14         |        |               |
| 13        | 42.5 W  | 5.5 S | 25.8     | 2.52-13         |        |               |
| 14        | 15.5 W  | 5.5 S | 5.6      | 4.51-14         | 324    | O4V(f)        |
| 15        | 7.8 E   | 5.5 S | 9.0      | 1.08-13         | 396    | O7V           |
| 16        | 22.6 E  | 5.5 S | 9.3      | 1.39-13         | 470+476 | O8-O8.5III + |
| 17        | 66.9 E  | 5.5 S | 29.2     | 2.22-13         |        |               |
| 18        | 92.4 E  | 5.5 S | 13.1     | 5.70-14         |        |               |
| A         | ...    | ... | ...      | ...             | 11.6-13 |               |
| B         | ...    | ... | ...      | 17.9-13         |        |               |

* Relative to star 355: $x = 00^h57^m19.82^s$; $y = -72^\circ26'40.4''$ (1950).

b Slit is 1/6 wide and is oriented east-west.

c Star numbers and spectral types from Massey, Parker, & Garmany 1989.

d Region A is the sum of Regions 2, 3, 5, 12, 13, 17, 18.

e Region B is the sum of Regions 1 to 5 and 11 to 18.

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**Fig. 1.**—Blue spectrum for region A

**Fig. 2.**—Red spectrum for region A

**Fig. 3.**—Spectrum of region A near Hα that shows [N II], [S II], and $\text{He I}$ lines.
that computed by Brocklehurst (1971) for $T_e = 12,000$ K, and $N_e = 100$ cm$^{-3}$; the Balmer decrement is almost insensitive to the expected variations in $T_e$ and $N_e$ over the observed volumes. Table 2 presents the line intensities for regions A and B that were obtained after adding the spectra of all their components, while Tables 3 and 4 present the observed volumes. Table 2 presents the line intensities for regions 1–5 and 11–18, respectively.

The $C(H\beta)$ value for region A amounts to 0.15 ± 0.01, a value in good agreement with the values derived from the stellar data of the cluster by Niemela, Marraco, & Cabanne (1986) and Massey, Parker, & Garmany (1989) that amount to 0.20 and 0.18 respectively. We have adopted the $C(H\beta)$ value of region A for all the observed regions. The differences between the adopted $f(\lambda)$ and the reddening function in the visual region in the direction of NGC 346 are small; moreover, their effect on the determination of the line-intensity ratios is negligible because with the adopted $C(H\beta)$ value we have recovered the theoretical Balmer decrement of the four brightest lines that are not expected to be affected by underlying absorption.

The SMC reddening law in the UV is very different from the normal Galactic one, but fortunately in the visual both laws are similar (Bouchet et al. 1985); according to Bouchet et al. (1985) $R = A_B/E(B-V)$ amounts to 2.7 ± 0.2 for the SMC. From the use of various reddening laws with $R$ in the 3.0–3.2 range (Whittard 1958; Nandy et al. 1975; Seaton 1979) we estimate that the error introduced by the adopted reddening law is about 0.002 dex for all line ratios and smaller than 0.001 dex for ratios of lines closer than 500 Å.

In Tables 2, 3, and 4, 1 σ errors are included, and the errors were estimated by comparing the results derived from the two different observing seasons. The total number of photons received by each of the He I lines of region A is in the $3 \times 10^4$ to $6 \times 10^5$ range; therefore the errors presented in Table 2 are about a factor of 5 larger than those given by photon statistics. The errors presented for region A are larger because they include other sources of error present in the reduction procedure.

The line intensities in Tables 2, 3, and 4 were not corrected for underlying stellar absorption, with the exception of the Hα lines of regions B, 4, 14, 15, and 16, where we adopted an underlying absorption of 2 Å; for these regions we adopted the theoretical $I(H\alpha)/I(H\beta)$ value to normalize all the lines to Hα, notice that Hβ has an intensity smaller than unity because it has not been corrected for underlying absorption.

The $\lambda 3727$ line intensity was corrected for the contribution due to H13 and H14 and to $\lambda 3724$ of [S II], and these contributions were estimated from the other Balmer lines and from the $\lambda 6312$ of [S II]; $I(4711)$ of [Ar IV] was obtained after subtracting the expected contribution of $\lambda 4713$ of He I based on the work by Smits (1996); and $I(3889)$ of He I was obtained after subtracting the expected contribution of H8 based on the work by Brocklehurst (1971).

In Table 5 we present the H I and He I equivalent widths for all the observed regions. The equivalent widths of regions B, 4, 14, 15, and 16 are strongly affected by the stellar underlying absorption. No correction due to underlying absorption has been made for any line in this table. After correcting region A for extinction, based on the four brightest Balmer lines, it is found that the weaker Balmer lines (H9 to H12) are not affected by stellar underlying absorption (see Fig. 4); therefore the He lines are not expected to be affected by underlying absorption. From similar arguments we expect each of the regions included in region A (2, 3, 5, 12, 13, 17, and 18) to be unaffected by underlying absorption.

### 3. Temperatures and Densities

We derived the temperatures and densities presented in Tables 6 and 7 based on the program of Shaw & Dufour (1995) for forbidden lines. $T$([O III]), $T$([O II]), and $N_e($[S II]) values were derived from the 4363/5007, 3727/7325, and 6716/6731 ratios, respectively; to derive $T$([O II]) we considered the contribution by recombination to the $\lambda 7320,7330$ line intensities (Liu et al. 2000). We will define another temperature given by

$$T([O II] + [O III]) = \frac{N([O I])T([O II]) + N([O II])T([O III])}{N(O)}$$

where $N([O I])$ and $N([O II])$ are obtained in §4 (see Table 7).

To derive the root mean square density, $N_e$(rms), we adopted the following equation

$$N_e^2$(rms) = $\left(\frac{3d^2}{r^3}\right) \frac{I(H\alpha)\gamma(H\alpha)}{a(H\alpha)\gamma(H\alpha)} \times \left[ 1 + \frac{N(He^+)}{N(H^+)} + 2 \frac{N(He^{++})}{N(H^+)} \right],$$

where $a(H\alpha)$ is the effective recombination coefficient (e.g., Brocklehurst 1971), $d$ is the distance to the SMC (64 kpc Reid 1999, and references therein), and $r$ is the radius of the adopted homogeneous sphere (150”). From the He$^+/H^+$ and He$^{++}/H^+$ values for region A presented in the next section, the $a(H\alpha)$ value for $T = 11,950$ K, and the $I(H\alpha)$ measured by Kennicutt & Hodge (1986), we find that $N_e$(rms) = 14 cm$^{-3}$ (see Table 7). It can be shown that, in the presence of density fluctuations (which is always the case), $N_e$(rms) provides us with a lower limit for the local density, $N_e$(local). To derive the abundance ratios we need to use $N_e$(local) values; in the presence of density fluctuations $N_e^2$(rms) = $\epsilon N_e^2$(local), where $\epsilon$ is the filling factor. From our $N_e$(rms) value and the $N_e$(He I)$_{SC}$ present in Table 7 (defined in the last paragraph of this section) it follows that 0.01 is a representative value for $\epsilon$. 

### Figure 4

Spectra of NGC 346 with and without underlying absorption. The vertical scale is for the lower spectrum (region A). The flux of the upper spectrum (region B) was normalized to the Hα emission-line flux for the lower spectrum.
From the ratio of the Balmer continuum flux to a Balmer line flux it is possible to derive the temperature $T_{\text{r}}(\text{Bac})$, from the Balmer line emissivities (Storey & Hummer 1995; Hummer & Storey 1987; Brocklehurst 1971) and the continuum emissivities for the He I and H I continuum (Brown & Mathews 1970) we find the $T_{\text{r}}(\text{Bac})$ value presented in Table 7.

By combining $T_{\text{r}}(\text{Bac})$, $T(\text{O} \text{ ii})$, and $T(\text{O} \text{ iii})$, together with $N(\text{O} \text{ i})$ and $N(\text{O} \text{ ii})$ (see § 4), and assuming that $t^2(\text{O} \text{ iii}) = t^2(\text{O} \text{ ii})$, it is possible to determine the mean square temperature variation $t^2(\text{H} \text{ ii}) \equiv t^2$, the average temperature $T_0(\text{H} \text{ ii}) \equiv T_0$, and $t^2(\text{O} \text{ iii})$ over the observed volume since (Peimbert 1967)

$$T_0(\text{X}^+) = \frac{\int T_e N_e N(X^+)dV}{\int N_e N(X^+)dV}$$

$$t^2(\text{X}^+) = \frac{\left[ T_0 - T_0(\text{X}^+) \right]^2 \int N_e N(X^+)dV}{T_0(\text{X}^+)^2}$$

$T_0(\text{Bac}) = T_0(1 - 0.1677)$

$$T(\text{O} \text{ ii}) = T_0(\text{O} \text{ ii}) \left[ 1 + \left[ \frac{90.800}{T_0(\text{O} \text{ ii})} - 3 \right] \frac{t^2(\text{O} \text{ ii})}{2} \right]$$

$$T(\text{O} \text{ iii}) = T_0(\text{O} \text{ iii}) \left[ 1 + \left[ \frac{97.300}{T_0(\text{O} \text{ iii})} - 3 \right] \frac{t^2(\text{O} \text{ iii})}{2} \right]$$

$$T_0 = \frac{N(\text{O})}{N(\text{O} \text{ ii}) + N(\text{O} \text{ ii}) + N(\text{O} \text{ iii})}$$

In region A, $T(\text{O} \text{ ii}) < T(\text{O} \text{ iii})$; therefore, $T_0(\text{O} \text{ ii}) \neq T_0(\text{O} \text{ iii})$, and from equation (5) it follows that $t^2 > t^2(\text{O} \text{ iii})$. In Table 7, we present the $t^2(\text{Bac, O ii + O iii})$ value for region A.
that the emissivities of the helium and hydrogen lines are proportional to powers of the temperature and, consequently, that \( T_e(\text{He} \, \text{II}) \) is given by (Peimbert 1967)

\[
T_e(\text{He} \, \text{II}) = T_0[1 + (\langle \alpha \rangle + \beta - 1) - \epsilon/2],
\]

where \( \langle \alpha \rangle \) is the average value of the power of the temperature for the helium lines and \( \beta \) for H\( \beta \). The \( \alpha \) powers in the low-density limit for the [\( 3889, 4026, 4388, 4471, 4922, 5876, 6678, 7065, \) and 7281 lines are \(-0.72, -0.49, -0.00, -1.02, -1.04, -1.12, -1.14, -0.55, \) and \(-0.60, \) respectively (Smits 1996), and \( \beta = -0.89 \) (e.g., Brocklehurst 1971).

In the low-density limit and weighted according to the observational errors we obtain \( \langle \alpha \rangle = -0.96 \); for \( N_e(\text{He} \, \text{II}) = 143 \, \text{cm}^{-3} \) we obtain \( \langle \alpha \rangle = -0.89 \). From \( t^2(\text{Bac}, \text{O} \, \text{II} + \text{O} \, \text{III}) \) and \( T_e(\text{Bac}, \text{O} \, \text{II} + \text{O} \, \text{III}) \) derived from equations (6)–(9) together with equation (10), we obtain \( T_e(\text{He} \, \text{II})_{\text{bac}} = 11890, \) which is a representative temperature for the H\( \epsilon \) lines.

Based on nine emission-line ratios, in the next section we derive \( N(\text{He}^+) / N(\text{H}^+) \), \( T_e(\text{He} \, \text{II}) \) and \( N_e(\text{He} \, \text{II}) \) self-consistently, hereafter \( N_e(\text{He} \, \text{II})_{\text{bac}} \) and \( T_e(\text{He} \, \text{II})_{\text{bac}} \) (which are presented in Table 7). In Table 7 we also include \( t^2(\text{He} \, \text{II}, \text{O} \, \text{II} + \text{O} \, \text{III}) \) derived from equations (7), (8), (9), and (10); and \( t^2(\text{Bac}, \text{He} \, \text{II}, \text{O} \, \text{II} + \text{O} \, \text{III}) \), an average of the two \( t^2 \) determinations; \( T_e(\langle \text{He} \, \text{II} \rangle) \) which is the average of \( T_e(\text{He} \, \text{II}) \)_{\text{bac}} and \( T_e(\text{He} \, \text{II})_{\text{bac}} ; \) and \( N_e(\langle \text{He} \, \text{II} \rangle) \), which is the density that corresponds to \( T_e(\langle \text{He} \, \text{II} \rangle) \).

From this discussion and the values in Table 7 we conclude that \( t^2 = t^2(\text{He} \, \text{II}) = 0.22 \pm 0.008 \) and that to a very good approximation \( t^2(\text{O} \, \text{III}) = t^2(\text{H} \, \text{II}) \).

### 4. IONIC CHEMICAL ABUNDANCES

To determine the abundances from collisionally excited lines many authors adopt a two-temperature scheme, with \( T(\text{O} \, \text{III}) \) for the high degree of ionization zones and \( T(\text{O} \, \text{II}) \) or \( T(\text{N} \, \text{II}) \) for the low degree of ionization zones. Therefore to compare with the abundances determined from collisionally excited lines by other authors we will assume also that the temperature within the O\( \, \text{II} \) and O\( \, \text{III} \) zones is constant, that is, \( t^2(\text{O} \, \text{II}) = t^2(\text{O} \, \text{III}) = 0.000 \). Two points should be stated here: (1) under the assumption that \( t^2(\text{O} \, \text{II}) = t^2(\text{O} \, \text{III}) = 0.000 \) and since \( T(\text{O} \, \text{II}) \neq T(\text{O} \, \text{III}) \), from equation (5), it follows that \( t^2 \neq 0.000 \); from the \( T(\text{O} \, \text{III}) \) and \( T(\text{O} \, \text{II}) \) values for region A (see Table 6) and equations (5) and (9), we find that \( t^2 = 0.0013 \); (2) the \( t^2 = 0.0013 \) abundances are a lower limit to the real abundances since the assumption that \( t^2(\text{O} \, \text{II}) = t^2(\text{O} \, \text{III}) = 0.000 \) would imply constant temperature within the O\( \, \text{II} \) and O\( \, \text{III} \) zones, which is not the case (see § 3). The total abundances for \( t^2(\text{H} \, \text{II}) = 0.022 \), our preferred \( t^2 \) value, will be discussed in § 5.

Therefore we have determined the ionic abundances of...
| $\lambda$   | 11     | 12     | 13     | 14$^b$ | 15$^b$ | 16$^b$ | 17     | 18     |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 3726 + 3729 | 0.129 ± 0.010 | 0.231 ± 0.007 | 0.167 ± 0.006 | -0.115 ± 0.020 | -0.051 ± 0.012 | -0.328 ± 0.008 | -0.224 ± 0.008 | -0.430 ± 0.020 |
| 3835        | -1.174 ± 0.040 | -1.155 ± 0.030 | -1.163 ± 0.015 | ...      | ...      | -1.155 ± 0.015 | -1.116 ± 0.040 | ...     |
| 3869        | -0.488 ± 0.012 | -0.453 ± 0.008 | -0.422 ± 0.005 | -0.354 ± 0.020 | -0.494 ± 0.012 | -0.485 ± 0.012 | -0.326 ± 0.005 | -0.319 ± 0.012 |
| 3893        | -0.106 ± 0.030 | -1.043 ± 0.020 | -1.037 ± 0.012 | ...      | ...      | ...      | -0.688 ± 0.010 | -0.698 ± 0.020 |
| 3967 + 3970 | -0.609 ± 0.015 | -0.555 ± 0.010 | -0.573 ± 0.006 | ...      | ...      | ...      | -0.539 ± 0.006 | -0.537 ± 0.015 |
| 4069 + 4076 | ...     | -1.930 ± 0.080 | -1.988 ± 0.040 | ...      | ...      | ...      | -2.131 ± 0.060 | ...     |
| 4102        | -0.597 ± 0.015 | -0.593 ± 0.012 | -0.595 ± 0.006 | ...      | -0.982 ± 0.025 | -0.953 ± 0.025 | -0.589 ± 0.007 | -0.583 ± 0.015 |
| 4340        | -0.323 ± 0.008 | -0.332 ± 0.005 | -0.329 ± 0.003 | -0.509 ± 0.015 | -0.496 ± 0.009 | -0.405 ± 0.007 | -0.328 ± 0.003 | -0.325 ± 0.006 |
| 4363        | -1.259 ± 0.025 | -1.264 ± 0.015 | -1.237 ± 0.010 | -1.141 ± 0.040 | -1.250 ± 0.025 | -1.272 ± 0.025 | -1.085 ± 0.010 | -1.022 ± 0.020 |
| 4711        | ...      | -1.410 ± 0.020 | -1.419 ± 0.012 | ...      | ...      | ...      | -1.415 ± 0.015 | -1.428 ± 0.035 |
| 4896        | < -2.181$^d$ | < -2.662$^d$ | < -2.815$^d$ | < -2.343$^d$ | < -2.609$^d$ | < -2.609$^d$ | ...     | ...     |
| 4711 + 4713 | ...     | -2.152 ± 0.035 | ...      | ...      | ...      | ...      | -1.847 ± 0.025 | -1.694 ± 0.050 |
| 4711        | ...     | -2.637 ± 0.050 | ...      | ...      | ...      | ...      | -2.023 ± 0.035 | -1.810 ± 0.060 |
| 4740        | ...     | ...      | ...      | ...      | ...      | ...      | -2.239 ± 0.040 | -1.965 ± 0.070 |
| 4861        | 0.000 ± 0.000 | 0.000 ± 0.000 | 0.000 ± 0.000 | ...      | ...      | ...      | 0.000 ± 0.000 | 0.000 ± 0.000 |
| 4922        | ...     | -1.995 ± 0.025 | -1.982 ± 0.012 | ...      | ...      | ...      | -2.023 ± 0.020 | ...     |
| 4959        | +0.205 ± 0.004 | +0.188 ± 0.003 | +0.210 ± 0.002 | +0.282 ± 0.008 | +0.151 ± 0.005 | +0.135 ± 0.004 | +0.294 ± 0.002 | +0.332 ± 0.004 |
| 5007        | +0.672 ± 0.004 | +0.660 ± 0.003 | +0.683 ± 0.002 | +0.757 ± 0.008 | +0.628 ± 0.005 | +0.597 ± 0.004 | +0.767 ± 0.002 | +0.804 ± 0.004 |
| 5876        | -0.977 ± 0.020 | -0.988 ± 0.012 | -0.987 ± 0.008 | -1.074 ± 0.040 | -1.047 ± 0.020 | -1.205 ± 0.020 | -0.983 ± 0.008 | -0.981 ± 0.015 |
| 6312        | -1.623 ± 0.040 | -1.672 ± 0.035 | -1.761 ± 0.015 | -1.953 ± 0.100 | -1.931 ± 0.060 | -1.961 ± 0.070 | -1.869 ± 0.025 | -1.980 ± 0.040 |
| 6563        | +0.445 ± 0.004 | +0.446 ± 0.003 | +0.446 ± 0.002 | +0.451 ± 0.000$^a$ | +0.451 ± 0.000$^a$ | +0.451 ± 0.000$^a$ | +0.451 ± 0.000$^a$ | +0.451 ± 0.000$^a$ |
| 6584        | -1.381 ± 0.020 | -1.228 ± 0.012 | -1.273 ± 0.008 | -1.546 ± 0.040 | -1.379 ± 0.020 | -1.137 ± 0.012 | -1.732 ± 0.015 | -1.769 ± 0.025 |
| 6716        | -1.118 ± 0.012 | -0.966 ± 0.006 | -1.041 ± 0.004 | -1.396 ± 0.030 | -1.140 ± 0.012 | -0.985 ± 0.008 | -1.246 ± 0.005 | -1.512 ± 0.020 |
| 6731        | -1.306 ± 0.015 | -1.124 ± 0.007 | -1.184 ± 0.005 | -1.548 ± 0.035 | -1.251 ± 0.015 | -1.075 ± 0.009 | -1.389 ± 0.006 | -1.677 ± 0.020 |
| 7065        | -1.627 ± 0.025 | -1.690 ± 0.015 | -1.687 ± 0.010 | -1.815 ± 0.050 | -1.759 ± 0.025 | -1.907 ± 0.030 | -1.669 ± 0.010 | -1.679 ± 0.020 |
| 7136        | -1.097 ± 0.012 | -1.098 ± 0.007 | -1.096 ± 0.004 | -1.168 ± 0.020 | -1.174 ± 0.012 | -1.175 ± 0.010 | -1.145 ± 0.005 | -1.202 ± 0.012 |
| 7320 + 7330 | -1.585 ± 0.025 | -1.385 ± 0.015 | -1.406 ± 0.012 | -1.645 ± 0.040 | -1.486 ± 0.020 | -1.189 ± 0.020 | -1.864 ± 0.015 | -1.945 ± 0.030 |

$^a$ Given in log $I(\lambda)/I(H\beta)$.
$^b$ Given in log $I(\lambda)/I(H\alpha)+0.51$ (see text).
$^c$ Corrected for underlying absorption.
$^d$ 1σ upper limit.
the heavy elements for all the regions observed using $r^2 = 0.0013$, and the abundances are presented in Table 8. The abundances were computed with the program presented by Shaw & Dufour (1995). To determine the O$^{++}$, Ne$^{++}$, S$^{++}$, Ar$^{++}$, and Ar$^{+++}$ abundances we used $T(O\,\text{iii})$, while for N$^+$, O$^+$, and S$^+$ we used $T(O\,\text{ii})$. For $T(O\,\text{iii})$ we adopted the value derived for each region (see Table 6). On the other hand, it can be seen in Table 6 that the $T(O\,\text{ii})$ temperatures are systematically higher for those regions that include bright stars and have relatively smaller EW(H$\beta$) values (regions 4, 14, 15, 16, and B) than for the regions that have larger EW(H$\beta$) values; however, this effect is not real and has to do with the difficulty of establishing a proper continuum baseline owing to the presence of underlying Balmer lines in absorption in the 3700–3750 Å region, where the $\lambda$3727 lines originate. This effect, together with large $T(O\,\text{ii})$ errors presented in Table 6, which are due to other causes, led us to assume for all regions that $T(O\,\text{ii}) = 0.9036 T(O\,\text{iii})$, the value determined for region A.

To estimate the H$\beta$ emissivity we adopted

$$I(H\beta) = I([H\beta(O^+)] + I([H\beta(O^{++} + )]),$$

$$I([H\beta(O^+))] = \frac{T(O\,\text{ii})^{-0.89} N(O^+)}{\frac{T(O\,\text{iii})^{-0.89} N(O^{++})}{N(O^{++})}},$$

where $I([H\beta(O^+)]$ and $I([H\beta(O^{++} + )])$ are the intensities of H$\beta$ in the O$^+$ and O$^{++}$ regions, respectively. We consider our procedure adequate since the total O abundances derived for all the regions show a small dispersion despite their different ionization degree (compare for example the total O abundances of regions 16 and 18, which are practically the same).

To obtain He$^+$/H$^+$ values we need a set of effective recombination coefficients for the He and H lines, the contribution due to collisional excitation to the helium line intensities, and an estimate of the optical depth effects for

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**TABLE 5**

| Region | Hx | H$\beta$ | Hy | H$\delta$ | H$\theta$ | 4471 | 4922 | 5876 | 6678 | 7065 |
|--------|----|---------|----|---------|---------|------|------|------|------|------|
| 1 ...... | 520 | 85      | 25 | 11      | 2.2     | 2.5  | 0.9  | 18   | 7.0  | 6.5  |
| 2 ...... | 720 | 190     | 75 | 38      | 10      | 5.5  | 2.0  | 28   | 9.5  | 8.5  |
| 3 ...... | 1650| 380     | 140| 65      | 17      | 12   | 4.5  | 60   | 20   | 16   |
| 4 ...... | 115 | 19      | 5.0| 1.5     | -0.65b | 0.55 | 0.35 | 2.8  | 1.2  | 1.1  |
| 5 ...... | 785 | 210     | 90 | 45      | 11      | 7.5  | 2.2  | 28   | 8.5  | 7.0  |
| 11 ...... | 580| 140     | 60 | 30      | 7.5    | 5.0  | ...  | 22   | 7.0  | 5.5  |
| 12 ...... | 790| 200     | 75 | 38      | 9.5    | 7.2  | 1.4  | 33   | 8.5  | 7.0  |
| 13 ...... | 1760| 350    | 115| 60      | 13     | 11   | 4.0  | 65   | 21   | 16   |
| 14 ...... | 55 | 7.0   | 2.0 | ...     | ...    | 1.4  | 0.80 | 0.45 |
| 15 ...... | 200 | 22     | 4.8 | ...     | ...    | 4.5  | 2.0  | 1.9  |
| 16 ...... | 69  | 8.0   | 2.5 | ...     | -0.85b | 1.0  | 0.29 | 0.16 |
| 17 ...... | 1950| 340   | 120| 55      | 14     | 10   | 3.5  | 70   | 21   | 19   |
| 18 ...... | 1800| 300   | 100| 60      | 13     | 9.5  | 4.0  | 65   | 20   | 18   |
| A ...... | 1250| 250   | 99 | 44      | 12.5   | 8.5  | 2.5  | 46   | 14.7 | 11.2 |
| B ...... | 230 | 35    | 11.1| 4.7     | 0.43   | 0.7  | 0.18 | 2.7  | 2.2  |

a In angstroms.
b EW in absorption.

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**TABLE 6**

| Region | $T(O\,\text{ii})$ | $T(O\,\text{iii})$ | $N_{\alpha}$/S$\text{n}$ |
|--------|------------------|-------------------|------------------------|
| 1 ...... | 13,730 ± 250     | 11,650 ± 450      | 40 ± 35                |
| 2 ...... | 13,350 ± 190     | 11,150 ± 400      | 50 ± 25                |
| 3 ...... | 12,500 ± 130     | 12,600 ± 350      | 55 ± 45                |
| 4 ...... | 12,840 ± 130     | 13,600 ± 350      | 15 ± 20                |
| 5 ...... | 13,540 ± 100     | 10,950 ± 250      | 55 ± 20                |
| 11 ...... | 12,230 ± 250     | 10,500 ± 600      | 14± ± 50               |
| 12 ...... | 12,320 ± 170     | 12,100 ± 250      | 15 ± 25                |
| 13 ...... | 12,360 ± 130     | 12,600 ± 300      | 50 ± 20                |
| 14 ...... | 12,580 ± 390     | 13,550 ± 1150     | 25 ± 150               |
| 15 ...... | 12,800 ± 270     | 12,550 ± 250      | 80 ± 150               |
| 16 ...... | 12,890 ± 310     | 12,550 ± 600      | 220 ± 45               |
| 17 ...... | 13,120 ± 140     | 11,100 ± 300      | 55 ± 20                |
| 18 ...... | 13,440 ± 280     | 13,500 ± 950      | 14 ± 65                |
| A ...... | 13,070 ± 50      | 11,810 ± 160      | 50 ± 15                |
| B ...... | 12,755 ± 90      | 12,360 ± 220      | 85 ± 20                |

* Low-density limit.

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**TABLE 7**

| Region | $T_e$ (K) | $r^2$ | $N_e^+$ (cm$^{-3}$) |
|--------|----------|------|---------------------|
| (O iii)=13,070 ± 100 ............. | ... | (rms) = 14 ± 3 |
| (O ii)=11,810 ± 300 ............. | ... | (S n) = 50 ± 15 |
| (O iii+O iii)=12,860 ± 100 ........ | ... | (Bac) = 11,800 ± 500 |
| (Bac)=11,800 ± 500 ................... | (Bac, O iii+O iii)=0.023 ± 0.011 | (He n)_{bac}=11,890 ± 500 |
| (He n)_{bac}=11,890 ± 500 ........ | ... | (He n)=11,950 ± 500 |
| (He n)=11,920 ± 370 ............. | (Bac, He n, O iii+O iii)=0.022 ± 0.008 | (He n)=146 ± 50 |
| $\langle He n \rangle$=11,920 ± 370 | ... | (Bac, He n, O iii+O iii)=0.022 ± 0.008 | (He n)=146 ± 50 |
the helium lines. The recombination coefficients that we used were those by Storey & Hummer (1995) for H and those by Smits (1996) for He. The collisional contribution was estimated from Kingdon & Ferland (1995) and Benjamin, Skillman, & Smits (1999). From the intensity of the 38614 and the computations of Robbins & Bernat (1973) it was found that the He I singlet lines were produced under case B. The optical depth effects in the triplet lines were estimated from the computations by Robbins (1968).

To derive the He$^+$/H$^+$ value of region A, in addition to the Balmer lines, we made use of nine He I lines, $\lambda\lambda3889, 4026, 4387, 4471, 4922, 5876, 6678, 7065,$ and 7281 to determine $N_e$(He II) and $T_e$(He II) self-consistently. Each of the nine H/He I line ratios depends on $T_e$, $N_e$, $N$(He$^+$)/$N$(H$^+$), and the optical depth of 3889 ($\tau_{3889}$), and each dependence is unique. Therefore we have a system of nine equations and four unknowns. We decided to obtain the best value for the four unknowns by minimizing $\chi^2$. The $\chi^2$ value is given by

$$\chi^2 = \sum_{i=1}^{9} \left\{ \frac{1 - \langle N(\text{He}^+) \rangle / N[\text{He}^+(\lambda_i, T_e, N_e, \tau_{3889})]}{\sigma(\lambda_i)/I(\lambda_i)} \right\}^2,$$

(13)

where $\sigma(\lambda_i)$ is the absolute error in the measurement that can be obtained from Table 2, and $N[\text{He}^+(\lambda_i, T_e, N_e, \tau_{3889})]/N$(H$^+$) is the abundance derived from each line for those parameters. The best $\tau_{3889}$ value is slightly negative which is unphysical, moreover from Cloudy models (Peimbert, Peimbert, & Luridana) it is found that $\tau_{3889}$ is close to zero, therefore we decided to adopt $\tau_{3889} = 0.0$ and to use equation (13) to derive $T_e$, $N_e$, and $N$(He$^+)/N$(H$^+$) self-consistently. For a system with nine independent determinations and three unknowns we have 6 degrees of freedom and we expect the minimum $\chi^2$ to be in the range 1.64 < $\chi^2_{\text{min}}$ < 12.59 at the 90% confidence level. The value of $\chi^2_{\text{min}} = 6.53$ found in Table 9 is in excellent agreement with this range. In Table 10 we present He$^+$/H$^+$ values for different temperatures and densities; the temperatures were selected to include T(O III), T(Bac), T(He II)$_{\text{SC}}$, and two representative temperatures; the densities were selected to include the minimum $\chi^2$ at each one of the five temperatures. The temperature with the minimum $\chi^2$ is the self-consistent $T$(He II) and amounts to 11950 ± 560 K; this temperature is in excellent agreement with the temperature derived from the Balmer continuum that amounts to 11800 ± 500 K, alternatively $T$(O III) amounts to 13070 ± 100 K. Notice that the $\chi^2$ test requires a higher density for a lower temperature, increasing the dependence on the temperature of the He$^+$/H$^+$ ratio. As mentioned above, the values in Table 9 correspond to the case where $\tau_{3889}$ equals zero; for higher values of $\tau_{3889}$ the $\chi^2$ values increase. In Table 9 we present He$^+$/H$^+$ and $\chi^2$ values for a set of temperatures and densities.

From Table 9 we obtain that $T_e$(He II)$_{\text{SC}}$ = 11,950 K and $N_e$(He II)$_{\text{SC}}$ = 143 cm$^{-3}$, which correspond to He$^+$/H$^+$ = 0.0793.

### Table 8

| Region | O$^+$ | O$^{++}$ | N$^+$ | Ne$^{++}$ | S$^+$ | S$^{++}$ | Ar$^{++}$ | Ar$^{+++}$ |
|--------|------|--------|------|----------|------|--------|---------|---------|
| 1 ...... | 7.44 | 7.19 | 5.87 | 6.95 | 5.42 | 6.11 | 5.52 | ... |
| 2 ...... | 7.47 | 7.86 | 5.91 | 7.04 | 5.44 | 6.19 | 5.61 | ... |
| 3 ...... | 7.10 | 7.99 | 5.45 | 7.15 | 4.93 | 6.16 | 5.64 | 4.65 |
| 4 ...... | 7.27 | 7.93 | 5.67 | 7.12 | 5.15 | 5.95 | 5.57 | ... |
| 5 ...... | 7.01 | 7.94 | 5.53 | 7.11 | 5.21 | 5.89 | 5.49 | 4.98 |
| 6 ...... | 7.51 | 7.96 | 5.81 | 7.10 | 5.35 | 6.40 | 5.68 | ... |
| 7 ...... | 7.60 | 7.94 | 5.96 | 7.12 | 5.50 | 6.34 | 5.67 | ... |
| 8 ...... | 7.53 | 7.95 | 5.91 | 7.15 | 5.42 | 6.25 | 5.66 | 4.56 |
| 9 ...... | 7.22 | 8.01 | 5.62 | 7.19 | 5.05 | 6.02 | 5.58 | ... |
| 10 ...... | 7.38 | 7.86 | 5.77 | 7.03 | 5.32 | 6.02 | 5.56 | ... |
| 11 ...... | 7.65 | 7.82 | 6.01 | 7.03 | 5.49 | 5.98 | 5.55 | ... |
| 12 ...... | 7.06 | 7.97 | 5.40 | 7.16 | 5.17 | 6.05 | 5.56 | 4.81 |
| 13 ...... | 6.83 | 7.97 | 5.34 | 7.13 | 4.88 | 5.90 | 5.49 | 5.07 |
| 14 ...... | 7.28 | 7.94 | 5.69 | 7.13 | 5.27 | 6.15 | 5.59 | 4.81 |
| 15 ...... | 7.41 | 7.97 | 5.81 | 7.17 | 5.33 | 6.11 | 5.63 | 4.64 |

* Given by log N(N)/N(He$^+$) + 12.
* We have adopted a two temperature model with T(O III) and T(He II), inside the O$^+$ and O$^{++}$ zones the temperature is uniform ($t^2 = 0.000$), but the $t^2$ over the entire model turns out to be 0.0013. Notice that our preferred $t^2$ value is 0.022, see Tables 7 and 11.

### Table 9

| Region | $N$(He$^+$/N(H$^+$)) and $\chi^2$ for Region A |
|--------|-----------------------------------------------|
| $T_e$ (K) | 53 | 100 | 143 | 162 | 247 |
| 11200 ...... | 805 | 798 | 793 | 799 | 781 |
| (83.2) | (47.7) | (26.4) | (20.0) | (8.24)$^b$ |
| 11800 ...... | 806 | 799 | 793 | 799 | 780 |
| (38.6) | (15.9) | (7.37) | (6.39)$^b$ | (20.4) |
| 11950 ...... | 806 | 799 | 793 | 799 | 779 |
| (30.8) | (11.7) | (6.35)$^b$ | (7.25) | (27.7) |
| 12400 ...... | 807 | 799 | 793 | 799 | 778 |
| (15.0) | (7.17)$^b$ | (12.5) | (17.9) | (58.6) |
| 13000 ...... | 809 | 800 | 793 | 799 | 777 |
| (9.72)$^b$ | (18.2) | (38.4) | (50.2) | (118) |

* Given in units of $10^{-4}$. $\chi^2$ values in parenthesis.
* The minimum $\chi^2$ value at a given temperature is presented in italics.
* The smallest $\chi^2$ value for all temperatures and densities, thus defining $T_e$(He II) and $N_e$(He II).
From the surface of $T_e$, $N_e$ and $\text{He}^+/\text{H}^+$ values defined by the condition $\chi^2 = \chi^2_{\text{min}} + 1$ the 1 $\sigma$ errors presented in Table 7 were computed.

In Table 10 we present the $\text{He}^+/\text{H}^+$ values for all the observed regions without underlying stellar absorption. We have adopted the $N_e(\text{He} \text{II})$ and $T_e(\text{He} \text{II})$ values of region A to determine the $\text{He}^+/\text{H}^+$ values for all the other regions in Table 10 because their observational errors are higher than for region A and do not permit to obtain $N_e(\text{He} \text{II})$ and $T_e(\text{He} \text{II})$ self-consistently for each region.

5. TOTAL ABUNDANCES

In Table 11 we present the total abundances of region A for $t^2(\text{O} \text{II}) = t^2(\text{O} \text{III}) = 0.000$ and $t^2 = 0.0013$. The gaseous abundances were obtained from the following equations (Peimbert & Costero 1969)

$$N(\text{O}) = \frac{N(\text{O}) + N(\text{O}^+)}{N(\text{H})},$$

$$N(\text{N}) = \frac{N(\text{N}) + N(\text{N}^+)}{N(\text{H})},$$

$$N(\text{Ne}) = \frac{N(\text{Ne}) + N(\text{Ne}^+)}{N(\text{H})}.$$ (14)

The abundances derived for all the other regions based on these equations agree within the errors with those derived from region A, which indicates the reliability of the equations. To obtain the total O abundances we assumed a correction of 0.04 dex due to the fraction of O tied up in dust grains, this fraction was estimated from the Si/O values derived for the Orion nebula (Esteban et al. 1998) and for H II regions in irregular galaxies (Garnett et al. 1995).

To obtain the total S abundance we adopted the following equation:

$$\frac{N(\text{S})}{N(\text{H})} = \frac{ICF(\text{S}) N(\text{S}^+) + N(\text{S}^+)}{N(\text{H})};$$ (17)

from Table 8 it can be seen that the higher the O ionization degree the lower the $[N(\text{S}^+) + N(S^{+3})]/N(\text{H}^+)$ ratio indicating, as expected, the increase of S$^{++}$ with the O ionization degree. Therefore to obtain the S abundance we decided to take regions 11 and 12 as representative of NGC 346 since they are expected to have the smallest ionization correction factor (ICF(S)) values. Therefore, from the ICF(S) values computed by Garnett (1989), the data for regions 11 and 12 in Table 8, and equation (17), we derived the value presented in Table 11.

To obtain the total Ar abundance we adopted the following equation:

$$\frac{N(\text{Ar})}{N(\text{H})} = \frac{ICF(\text{Ar}) N(\text{Ar}^{++}) + N(\text{Ar}^{3+})}{N(\text{H}^+)};$$ (18)

where ICF(Ar) includes the Ar$^+/\text{H}^+$ contribution and according to Liu et al. (2000) can be approximated by

$$ICF(\text{Ar}) = \left(1 - \frac{N(\text{O})}{N(\text{O})}\right)^{-1}.$$ (19)

Based on the $T_e$ values presented in Table 7 we also include in Table 11 the total abundances for $t^2 = 0.022$, our preferred $t^2$ value, following the procedure outlined by Peimbert & Costero (1969). The relevant equations are

$$\frac{N(X^+)}{N(\text{H}^+)} = \frac{T[H/\lambda(X^+)]}{T(\lambda/\lambda', X^+)} \times \exp \left[ \frac{\Delta E}{kT(\lambda, X^+)} - \frac{\Delta E}{kT(\lambda', X^+)} \right] \times \frac{N(\text{X}^+)}{N(\text{H}^+)}_{\lambda/\lambda'}.$$ (20)
where $\Delta E$ is the energy difference between the ground and the excited levels, $\lambda$ is the wavelength of the nebular line (5007 Å for O III), $\lambda'$ is the wavelength of the auroral line (4363 for O III), and $T[H\beta(X^+)]$ is the $T[H\beta]$ value in the region where the $X^+$ ion is present and is given by

$$T[H\beta(X^+)] = T_0(X^+)[1 - 0.945t^2(X^+)] ;$$

(21)

$T(\lambda, X^+)$ is the representative temperature of the nebular line which can be obtained from

$$T(\lambda, X^+) = T_0(X^+) \times \left[1 + \left\{\frac{[\Delta E/kT_0(X^+)][3\Delta E/kT_0(X^+) + 3/4]}{\Delta E/kT_0(X^+) - 1/2}\right\} \times \frac{t^2(X^+)}{2}\right];$$

(22)

and $[N(X^+)/N(H^+)]_{\lambda/\lambda'}$ is the abundance derived from $T(\lambda/\lambda')(T[\text{O III}]$ for O III).

It is possible to derive the abundances for other $t^2$ values by interpolating or extrapolating the abundances presented in Table 11.

In Table 11 we compare the abundances of NGC 346 with an average of the H II regions in the SMC derived by Dufour (1984) and those of the Sun and M17. Notice that the abundances derived by Dufour should be compared with those for $t^2 = 0.0013$ and that no correction for the fraction of O tied up in dust grains was included by Dufour. Alternatively, the M17 values are for $t^2 = 0.037$ and 0.08 dex has been added to the O abundance to correct for the fraction of this element tied up in dust grains, and consequently the M17 values can be compared directly with the NGC 346 values for $t^2 = 0.022$.

The total He/H value is given by

$$\frac{N(\text{He})}{N(H)} = \frac{N(\text{He}^0) + N(\text{He}^+) + N(\text{He}^{++})}{N(H^0) + N(H^+)} = \text{ICF(He)} \times \frac{N(\text{He}^+) + N(\text{He}^{++})}{N(H^+)} ,$$

(23)

The $\text{He}^{++}/H^+$ ratio can be obtained directly from the 4686/H$\beta$ intensity ratio. In objects of low degree of ionization the presence of neutral helium inside the H II region is important and ICF(He) becomes larger than 1. The ICF(He) can be estimated by observing a given nebula at different lines of sight since He$^0$ is expected to be located in the outer regions. Another way to deal with this problem is to observe H II regions with a high degree of ionization, where the He$^0$ amount is expected to be negligible.

Vilchez & Pagel (1988; see also Pagel et al. 1992) defined a radiation softness parameter given by

$$\xi = \frac{N(O^+)N(S^{++})}{N(S^{+})N(O^{++})} ;$$

(24)

for large values of $\xi$ the amount of neutral helium is significant, while for low values of $\xi$ it is negligible, where the critical value is around 8. In Table 10 we present the $\xi$ values for all the observed regions, and these values indicate that the amount of He$^0$ inside the H$^+$ region is negligible.

On the other hand, for ionization bounded objects with a very high degree of ionization the amount of H$^0$ inside the He$^+$ Strömgren sphere becomes significant and the ICF(He) can become smaller than 1. This possibility was firstly mentioned by Shields (1974) and studied extensively by Armour et al. (1999), Viegas, Gruenwald, & Steigman (2000), and Ballantyne, Ferland, & Martin (2000).

To study this possibility we have estimated the ICF(He) from three different methods. (1) We have divided the regions in Table 10 in three groups: H (regions 5, 17, and 18), I (regions 1, 2, 3, and 13), and L (regions 11 and 12), where H, I, and L stand for regions with high, intermediate, and low degrees of ionization; within the errors the three groups yield the same He/H ratio, indicating that the ICF(He) is very close to unity. (2) Ballantyne et al. (2000) have defined the following cutoff:

$$[\text{O III}]\lambda 5007/H\beta_{\text{cutoff}} = (1.139 \pm 0.306) + (2.5 \pm 0.4)O/H \times 10^4 .$$

(25)

For observed values higher than the cutoff ICF(He) is very close to unity; from Table 11, and without considering the fraction of O embedded in dust grains, we have that log $N(\text{O})/N(\text{H}) + 12 = 8.11$ and, consequently, a cutoff of $4.36 \pm 0.60$. Alternatively the observed value is $5.43 \pm 0.03$. (3) Ballantyne et al. (2000) also find that for [O III] 5007/ [O I] 6300 $\geq 300$, the ICF(He) becomes very close to unity; from Table 2 it is found that $I(5007)/I(6300) > 600$. (It should be noted that the [O I] lines present in Figure 2 are blends of telluric and nebular lines even though we subtracted the sky contribution. Unfortunately the [O I] line intensities in the sky varied in a scale of minutes, leaving a telluric remnant present, which becomes apparent because the centroids of the [O I] lines are blueshifted by about 3 Å from the centroid of the other lines.) From these three methods we conclude that the amount of H$^0$ inside the He$^+$ Strömgren sphere is negligible and in what follows we will adopt an ICF(He) = 1.000.

In Table 12 we present the helium abundance by mass $Y$(SMC), derived from region A. The $Y$(SMC) values were derived from Table 9, the He$^{++}/H^+$ value (that amounts to $2.2 \times 10^{-4}$ for $T_e$ range present in Table 12), and the $Z$-values presented in Table 13. The $Y$(SMC) error presented in Table 13 is based only on the results of the self-consistent method; by considering the $T_e$(Bac) measurement the $Y$(SMC) error diminishes from 0.0018 to 0.0013 (and $Y$(SMC) diminishes by 0.0001).

In Table 13 we present the helium, heavy elements, and oxygen abundance by mass of NGC 346. The estimated error for $O$ amounts to 0.06 dex. The $Z$-value was obtained by assuming that $O$ comprises 54% of the heavy elements by mass, this fraction was estimated by Carigi et al. (1995)

### Table 12

| $T_e$ (K) | NGC 11200 | 118000 | 119500 | 124000 | 130000 |
|----------|-----------|--------|--------|--------|--------|
| 53       | 0.2431    | 0.2416 | 0.2404 | 0.2399 | 0.2377 |
| 100      | 0.2435    | 0.2419 | 0.2405 | 0.2399*| 0.2375 |
| 143      | 0.2436    | 0.2420 | 0.2405*| 0.2399 | 0.2374 |
| 162      | 0.2439    | 0.2421*| 0.2406 | 0.2399 | 0.2372 |
| 247      | 0.2443*   | 0.2423 | 0.2407 | 0.2400 | 0.2370 |

* Entries that correspond to minimum $\chi^2$ values (see Table 9).
from a group of ten irregular galaxies that includes the SMC. The estimated error for the Z-value amounts to 0.08 dex.

6. THE PRIMORDIAL HELIUM ABUNDANCE

To determine the $Y_p$ value from the SMC it is necessary to estimate the fraction of helium present in the interstellar medium produced by galactic chemical evolution. We will assume that

$$Y_p = Y(\text{SMC}) - O(\text{SMC}) \frac{\Delta Y}{\Delta O}. \quad (26)$$

### TABLE 13

**CHEMICAL COMPOSITION**

| ELEMENT | $t^2 = 0.0013$ | $t^2 = 0.0220$ | M17$^{\text{ab}}$ |
|---------|---------------|---------------|----------------|
| Y ......... | 0.2445 | 0.24050 ± 0.00180 | 0.2797 ± 0.0060 |
| Z .......... | 0.00263 | 0.00315 ± 0.00063 | 0.0212 ± 0.0030 |
| O .......... | 0.00142 | 0.00171 ± 0.00025 | 0.0083 ± 0.0012 |
| $\Delta Y/\Delta Z$ ...... | ... | 1.9 ± 0.5 | 2.13 ± 0.5 |
| $\Delta Y/\Delta O$ ...... | ... | 3.5 ± 0.9 | 5.45 ± 1.1 |

$^a$ Given by mass.
$^b$ This paper.
$^c$ Peimbert et al. 1992; Esteban et al. 1999.

In a recent review Peimbert & Peimbert (2000) derive $Y_p$ for the SMC from a similar discussion but using Z instead of O in equation (26); since the error in the O determination is smaller than in the Z determination (see Table 13) it is better to use O to determine $Y_p$.

To estimate $\Delta Y/\Delta O$ we will consider three observational determinations and a few determinations predicted by chemical evolution models.

Peimbert, Torres-Peimbert, & Ruiz (1992) and Esteban et al. (1999) found that $Y = 0.2797 ± 0.0060$ and $O = 0.0083 ± 0.0012$ for the Galactic H II region M17, where we have added 0.08 dex to the oxygen gaseous abundance to take into account the fraction of these elements embedded in dust grains (Esteban et al. 1998). By comparing the $Y$ and O values of M17 with those of region A we obtain $\Delta Y/\Delta O = 5.45 ± 1.10$. M17 is the best H II region to determine the helium abundance because among the brightest galactic H II regions it is the one with the highest degree of ionization and consequently with the smallest correction for the presence of He$^+$ [i.e., ICF (He) is very close to unity; see e.g., Deharveng et al. 2000]. It can be argued that the M17 $\Delta Y/\Delta O$ value is not representative of irregular galaxies, because the yields are heavy element dependent and the O-value is considerably higher than that of the SMC.

From a group of 10 irregular and blue compact galaxies, that includes the LMC and the SMC, Carigi et al. (1995) found $\Delta Y/\Delta O = 4.48 ± 1.02$, where they added 0.2 dex to the O/H abundance ratios derived from the nebular data to take into account the temperature structure of the H II regions and the fraction of O embedded in dust; moreover they also estimated that O constitutes 54% of the Z-value. Izotov & Thuan (1998) from a group of 45 supergiant H II regions of low metallicity derived a $\Delta Y/\Delta Z = 2.3 ± 1.0$; we find from their data that $\Delta Y/\Delta Z = 1.46 ± 0.60$ by adding 0.2 dex to the O abundances to take into account the temperature structure of the H II regions and the fraction of O embedded in dust; furthermore from their data we also find that $\Delta Y/\Delta O = 2.7 ± 1.2$ by assuming that O constitutes 54% of the Z-value.

Based on their two-infall model for the chemical evolution of the Galaxy, Chiappini, Matteucci, & Gratton (1997) find $\Delta Y/\Delta O = 3.15$ for the solar vicinity. Carigi (2000) computed chemical evolution models for the Galactic disk, under an inside-out formation scenario, based on different combinations of seven sets of stellar yields by different authors; the $\Delta Y/\Delta O$ spread predicted by her models is in the 2.9 to 4.6 range for the Galactocentric distance of M17 (5.9 kpc).

Carigi et al. (1995), based on yields by Maeder (1992), computed closed box models adequate for irregular galaxies, like the SMC, and obtained $\Delta Y/\Delta O = 2.95$. They also computed models with galactic outflows of well-mixed material, that yielded $\Delta Y/\Delta O$ values similar to those of the closed box models, and models with galactic outflows of O-rich material that yielded values higher than 2.95. The maximum $\Delta Y/\Delta O$ value that can be obtained with models of O-rich outflows, without entering into contradiction with the C/O and $(Z - C - O)/O$ observational constraints, amounts to 3.5.

Carigi, Colin, & Peimbert (1999), based on yields by Woosley, Langer, & Weaver (1993) and Woosley & Weaver (1995), computed chemical evolution models for irregular galaxies also, like the SMC, and found very similar values for closed box models with bursting star formation and
constant star formation rates that amounted to $\Delta Y/\Delta O = 4.2$. The models with O-rich outflows can increase $\Delta Y/\Delta O$, but they predict higher C/O ratios than observed.

From the previous discussion it follows that $\Delta Y/\Delta O = 3.5 \pm 0.9$ is a representative value for models and observations of irregular galaxies.

The $Y_p$ values in Table 14 were computed by adopting $\Delta Y/\Delta O = 3.5 \pm 0.9$. The differences between Tables 12 and 14 depend on $T_e$ because the lower the $T_e$ value the higher the $O$-value for the SMC. In Figure 5 we present our $Y_p$ value as well as the theoretical $Y_e$ value derived from big bang nucleosynthesis computations by Copi, Schramm, & Turner (1995) for three neutrino species as a function of $\eta$, the baryon to photon ratio.

7. CONCLUSIONS

The $Y_p$ value derived by us is significantly smaller than the value derived by Izotov & Thuan (1998) from the $Y$ versus O/H linear regression for a sample of 45 blue compact galaxies, and by Izotov et al. (1999) from the average for the two most metal deficient galaxies known (I Zw 18 and SBS 0335−052), that amount to 0.2443 ± 0.0015 and 0.2452 ± 0.0015 respectively (see Fig. 5).

The difference could be due to systematic effects in the abundance determinations. There are two systematic effects not considered by Izotov and collaborators that we did take into account, the possible presence of $H^0$ inside the $He^+$ region and the use of a lower temperature than that provided by the [O III] lines. We consider the first effect to be a minor one and the second to be a mayor one but both should be estimated for each object. For further discussion of the first effect see the papers by Viegas, Gruenwald, & Steigman (2000) and Ballantyne et al. (2000). The second effect was first mentioned by Peimbert & Costero (1969; see also Peimbert 1995).

From constant density chemically homogeneous models computed with Cloudy (Ferland 1996; Ferland et al. 1998) we estimate that the maximum temperature that should be used to determine the helium abundance should be 5% smaller than $T_e$(O III). Moreover, if in addition to photoionization there is additional energy injected to the H II region $T_e$(He II) should be even smaller.

Luridiana, Peimbert, & Leitherer (1999) produced a detailed photoionized model of NGC 2363. For the slit used by Izotov, Thuan, & Lipovetsky (1997) they find an ICF(He) = 0.993; moreover they also find that the $T_e$(O III) predicted by the model is considerably smaller than observed. From the data of Izotov, Thuan, & Lipovetsky (1997) for NGC 2363, adopting a $T_e$(He II) 10% smaller than $T_e$(O III) and $\Delta Y/\Delta O = 3.5 \pm 0.9$, we find that $Y_p = 0.234 \pm 0.006$.

Similarly, Stasinska, & Schaerer (1999) produced a detailed model of I Zw 18 and find that the photoionized model predicts a $T_e$(O III) value 15% smaller than observed; on the other hand their model predicts an ICF(He) = 100. From the observations of $\lambda \lambda 5876$ and 6768 by Izotov et al. (1999) of I Zw 18, and adopting a $T_e$(He II) 10% smaller than $T_e$(O III), we obtain $Y_p = 0.237 \pm 0.007$; for a $T_e$(He II) 15% smaller than $T_e$(O III) we obtain $Y_p = 0.234 \pm 0.007$, both results in good agreement with our determination based on the SMC. Further discussion of these issues is presented elsewhere (Peimbert, Peimbert, & Luridana 2000).

The primordial helium abundance by mass of $0.2345 \pm 0.0026(\sigma)$—based on the SMC—combined with the big bang nucleosynthesis computations by Copi et al. (1995) for three light neutrino species implies that, at the 1 $\sigma$ confidence level, $\Omega_\chi h^2$ is in the 0.0065−0.0091 range. For $h = 0.65$ the $Y_p$ value corresponds to 0.015 $< \Omega_\chi < 0.022$, a value considerably smaller than that derived from the pre-galactic deuterium abundance, $D_p$ determined by Burles & Tytler (1998) that corresponds to 0.041 $< \Omega_\chi < 0.047(1\sigma)$ for $h = 0.65$. Our $\Omega_\chi$ value is in very good agreement with the low-redshift estimate of the global budget of baryons by Fukugita, Hogan, & Peebles (1998) who find 0.015 $< \Omega_\chi < 0.030(1\sigma)$ for $h = 0.65$ and is consistent with their minimum to maximum range for redshift $z = 3$ that amounts to 0.012 $< \Omega_\chi < 0.070$. The discrepancy between $Y_p$ and $D_p$ needs to be studied further.

In addition to the relevance for cosmology an accurate $Y_p$ value permits to determine $\Delta Y/\Delta O$, ratio that provides a strong constraint for the models of chemical evolution of galaxies (see, for example, Carigi et al. 1995, 1999).

To increase the accuracy of the $Y_p$ determinations we need observations of very high quality of as many He I lines as possible to derive $T_e$(He II), $N_e$(He II), $\tau_{5899}$, and $N_e$(He I)/$N_e$(H I) self-consistently. We also need observations with high spatial resolution to estimate the ICF(He) along different lines of sight.

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