THE PRIMORDIAL HELIUM-4 ABUNDANCE DETERMINATION: SYSTEMATIC EFFECTS

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Abstract.
By extrapolating to O/H = N/H = 0 the empirical correlations \( Y \equiv \text{O/H} \) and \( Y \equiv \text{N/H} \) defined by a relatively large sample of \( \sim 45 \) Blue Compact Dwarfs (BCDs), we have obtained a primordial helium mass fraction \( Y_p = 0.2443 \pm 0.0015 \) with \( \frac{dY}{dZ} = 2.4 \pm 1.0 \). This result is in excellent agreement with the average \( Y_p = 0.2452 \pm 0.0015 \) determined in the two most metal-deficient BCDs known, I Zw 18 (\( Z_{\odot}/50 \)) and SBS 0335–052 (\( Z_{\odot}/41 \)), where the correction for He production is smallest. The quoted error (1\( \sigma \)) of \( \lesssim 1\% \) is statistical and does not include systematic effects. We examine various systematic effects including collisional excitation of Hydrogen lines, ionization structure and temperature fluctuation effects, and underlying stellar He I absorption, and conclude that combining all systematic effects, our \( Y_p \) may be underestimated by \( \sim 2–4\% \). Taken at face value, our \( Y_p \) implies a baryon-to-photon number ratio \( \eta = (4.7^{+1.0}_{-0.8}) \times 10^{-10} \) and a baryon mass fraction \( \Omega_b h_100^2 = 0.017 \pm 0.005 \) (2\( \sigma \)), consistent with the values obtained from deuterium and Cosmic Microwave Background measurements. Correcting \( Y_p \) upward by 2–4\% would make the agreement even better.

Key words: Helium-4, cosmic abundance, H II region, chemical evolution, dwarf galaxies

1. Standard big bang nucleosynthesis

The standard hot big bang model of nucleosynthesis (SBBN) is one of the key quantitative tests of big bang cosmology, along with the Hubble expansion and the cosmic microwave background radiation. In the SBBN, four light isotopes, D, \(^3\)He, \(^4\)He and \(^7\)Li, were produced by nuclear reactions a few minutes after the birth of the Universe. Given the number of relativistic neutrino species and the neutron lifetime, the abundances of these light elements depend on one cosmological parameter only, the baryon-to-photon ratio \( \eta \), which in turn is directly related to the density of ordinary baryonic matter \( \Omega_b \). The ratio of any two primordial abundances, for example that of D to H gives \( \eta \), and accurate measurements of the other three light elements, for example \(^4\)He/H, tests SBBN.

Of all light elements, the abundance of deuterium (D) is the most sensitive to the baryonic density. The primordial D abundance can be measured directly in low-metallicity absorption line systems in the spectra of high-redshift quasars. The quasar is used as a background light source, and the nearly primordial gas doing the absorbing is in the outer regions of intervening galaxies or in the intergalactic medium (the so-called Lyman \( \alpha \) clouds). Tytler and his group (see Tytler et al. 2000 for a review) have vigorously pursued this type of measurements. They have
now obtained D/H measurements in the line of sight towards 4 quasars. Combining all measurements, they found all their data are consistent with a single primordial value of the D/H ratio: \((D/H)_{p} = 3.0 \pm 0.4 \times 10^{-5}\) (O'Meara et al. 2001). This latest value is about 10% lower than their previous value \((D/H)_{p} = 3.39 \pm 0.25 \times 10^{-5}\) (Burles & Tytler 1998).

The primordial abundance of \(^3\)He is also quite sensitive to the baryon density, though less than the D abundance. It has not been yet measured, mainly because low-mass stars make a lot of \(^3\)He, increasing its value in the interstellar medium of the Milky Way well above the primordial value. Furthermore, the amount of \(^3\)He destroyed in stars is unknown. Bania, Rood & Balser (2000) have measured an average \(^3\)He/H = 1.5\(\pm\)0.6\(\times\)10\(^{-5}\) in Galactic H II regions. This value represents the average in the interstellar medium of the Milky Way, but there exists no good way to extrapolate the \(^3\)He abundance to the primordial value.

Old halo stars that formed from nearly pristine gas with very low iron abundances during the gravitational collapse of the Milky Way show approximately constant \(^7\)Li/H (the so called “Spite plateau”, Spite & Spite 1982), implying that their \(^7\)Li is nearly primordial. Creation or depletion of \(^7\)Li may make the \(^7\)Li abundances of halo stars deviate from the primordial value. Creation of \(^7\)Li in the interstellar medium by cosmic ray spallation prior to the formation of the Milky Way has to be less than 10–20%, so as not to produce more Be than is observed (Ryan, Norris & Beers 1999). There is still considerable debate concerning the possible depletion of \(^7\)Li at the surface of stars. Depletion mechanisms that have been proposed include mixing due to rotation or gravity waves, mass loss in stellar winds and gravitational settling. Depending on the exact depletion mechanism, the primordial lithium abundance varies from \((^{7}\text{Li}/H)_{p} = (1.73\pm0.21) \times 10^{-10}\) (Bonifacio & Molaro 1997) to \((2.24\pm0.57) \times 10^{-10}\) (Vauclair & Charbonnel 1998), to \((3.9\pm0.85) \times 10^{-10}\) (Pinsonneault et al. 1999).

Because of the relatively large uncertainties in the determination of the primordial abundances of \(^3\)He and \(^7\)Li, the primordial abundance of \(^4\)He plays a key role for deriving \(\Omega_b\) independently of D measurements, and is crucial for checking the consistency of SBBN. We discuss next how the primordial \(^4\)He mass fraction \(Y_p\) is determined, and the uncertainties which enter in such a determination.

### 2. The primordial \(^4\)He abundance as derived from blue compact dwarf galaxies

Because of the relative insensitivity of \(^4\)He production to the baryonic density of matter, \(Y_p\) needs to be determined to a precision of about one percent to provide useful cosmological constraints. This precision can in principle be achieved by obtaining high signal-to-noise ratio spectra of a class of star-forming dwarf galaxies called Blue Compact Dwarf (BCD) galaxies. These are low-luminosity (\(M_B \geq -18\)) systems undergoing an intense burst of star formation in a very compact
THE PRIMORDIAL ABUNDANCE OF $^4$HELIUM

region (less than 1 kpc) which dominates the light of the galaxy and which shows blue colors and a H II region-like emission-line optical spectrum (Thuan & Izotov 1998a). BCDs are ideal laboratories in which to measure the primordial $^4$He abundance because, with an oxygen abundance O/H ranging between 1/50 and 1/3 that of the Sun, BCDs are among the most metal-deficient gas-rich galaxies known. Their gas has not been processed through many generations of stars, and thus best approximates the pristine primordial gas. Izotov & Thuan (1999) have argued that BCDs with O/H less than $\sim 1/20$ that of the Sun may be genuine young galaxies, with ages less than several 100 Myr. Thus $Y_p$ can be derived accurately in very metal-deficient BCDs with only a small correction for Helium made in stars. Moreover, the theory of nebular emission is well understood enough to allow to convert He emission-line strengths into abundances with the desired accuracy.

Figure 1. MMT spectra of the NW (top) and SE (bottom) regions of I Zw 18. It is evident that underlying He I stellar absorption is much more important in the NW than in the SE component. All marked He I lines in the spectrum of the SE component are in emission, while the He I 4026 and 4921 lines are in absorption and the He I 4471 emission line is barely seen in the spectrum of the NW component.

$Y_p$ is generally determined by linear extrapolation of the correlations $Y$–O/H and $Y$–N/H to O/H = N/H = 0 as first proposed by Peimbert & Torres-Peimbert (1974), where $Y$, N/H and O/H are respectively the $^4$He mass fraction, the Oxygen and Nitrogen abundances relative to Hydrogen of a sample of dwarf irregular and BCD galaxies. Based on a relatively large sample of $\sim 45$ BCDs, we (Izotov, Thuan & Lipovetsky 1994, 1997, hereafter ITL94, ITL 97; Izotov & Thuan 1998, hereafter IT98) have obtained $Y_p = 0.2443 \pm 0.0015$ with $dY/dZ = 2.4 \pm 1.0$ (see Thuan & Izotov 1998b, 2000 for reviews). This result is quite robust as it is in excellent agreement with the average $Y_p = 0.2452 \pm 0.0015$ (Izotov et al. 1999) determined in
the two most metal-deficient BCDs known, I Zw 18 ($Z_{\odot}/50$) and SBS 0335–052 ($Z_{\odot}/41$), where the correction for He production is smallest. The quoted statistical error ($1\sigma$) is $\lesssim 1\%$ because of the high quality of the spectra and the large size of the sample.

Our derived value of $Y_p$ is significantly higher than those of $0.228\pm 0.005$ by Pagel et al. (1992), of $0.234\pm 0.002$ obtained by Olive, Steigman & Skillman (1997), of $0.2345\pm 0.0026$ by Peimbert, Peimbert & Ruiz (2000) and of $0.2384\pm 0.0025$ by Peimbert, Peimbert & Luridiana (2001). These values are lower than ours by several times the quoted statistical error and lead to very different cosmological consequences. This implies that systematic effects in the determination of $Y_p$ play an important role and need to be considered carefully to achieve the desired accuracy. We discuss the most important systematic effects below, specifically in the two most metal-deficient BCDs known, I Zw 18 and SBS 0335–052. Because different systematic effects are at play in these two objects, they allow to illustrate the relative importance of each nicely.

3. Systematic effects

3.1. Reddening

One possible systematic effect may be due to the adopted interstellar extinction curve. We use the Galactic extinction curve by Whitford (1958). There is evidence that the extinction curve does change when metallicity decreases, being steeper at short wavelengths (e.g. Rocca-Volmerange et al. 1981), but the changes are mainly in the ultraviolet and are small in the optical range. Relying mainly on the three Balmer line ratios $H\alpha/H\beta$, $H\gamma/H\beta$ and $H\delta/H\beta$, we have adopted an iterative procedure to derive simultaneously both the extinction and the absorption equivalent width for the hydrogen lines assumed to be the same for all lines (ITL94). Since the derived extinction correction is applied to the He i lines, any uncertainty in it will propagate in the derivation of the final He abundance. A stringent observational check for the adequacy of the extinction curve is the good agreement between the corrected intensities of the Balmer hydrogen emission lines and the theoretical values for hydrogen recombination line intensities. Using Monte-Carlo simulations of the hydrogen Balmer ratios, Olive & Skillman (2001) estimate the uncertainties in the reddening corrections to be about $1–2\%$ for the blue He lines and $3–4\%$ for the red ones. However, the uncertainties for the red lines can be substantially less if the corrected $H\alpha/H\beta$ ratio matches the theoretical ratio.

3.2. Underlying stellar absorption in He i lines

Underlying stellar absorption in He i lines caused by hot stars can decrease the intensities of nebular He i lines. Model calculations of synthetic absorption line
strengths in star forming regions by Olofsson (1995) show that the equivalent widths of He I absorption lines decrease as the starburst ages. Furthermore, the dependence of He I equivalent widths on metallicity is small, and the equivalent width of the He I 4471 absorption line can be as high as 0.35 Å. Unfortunately, similar calculations for other important lines used in the determination of $Y_p$ such as He I 5876, 6678 and 7065 are not yet available. The effect of underlying He I stellar absorption is most important for the emission lines with the smallest equivalent widths. Therefore, the He I 5876 emission line which has the largest equivalent width is the least affected by such absorption, while the He I 4471 emission line is the most affected because of its low equivalent width, the effect of underlying absorption being 5–10 times larger for it than for the 5876 line.

Figure 1 shows the spectra of the 2 brightest centers of star formation in I Zw 18, the NW and SE components, with the He I lines marked. It is clear that the NW component suffers far more stellar absorption than the SE one: all marked He I lines of the SE component are in emission while the two He I 4026 and 4921 lines are in absorption and the He I 4471 line is hardly detected in the NW component, its intensity being decreased by a factor of $\sim 2$ (Izotov et al. 1999). However, the strong He I absorption in the NW component of I Zw 18 constitutes the exception rather than the rule. It is relatively less important in other very metal-deficient BCDs, such as SBS 0335–052, because the equivalent widths of their He I emission lines are considerably larger than those of the NW component of I Zw 18. This can be seen in Figure 2 which compares the spatial distributions of the He I nebular emission line equivalent widths ($EW$) in I Zw 18 and SBS 0335–052. While the maximum $EW$s of the He I emission lines in the SE component of I Zw 18 are
close to those in the central brightest part of SBS 0335–052, the He I line \(EW\)'s in the NW component of I Zw 18 are several times smaller. The largest ratio of minimum values of equivalent widths in I Zw 18 as compared to in SBS 0335–052 is \(\sim 14\) for the 4471 line. The effect of underlying stellar absorption is smaller for the other He I lines because of their higher equivalent widths. Thus for the 6678 line, Izotov et al. (1999) estimate it to be \(\sim 5\%\) in the NW component of I Zw 18, but to be less than 1\% in its SE component and in SBS 0335–052. As for the 5876 line, it is less than 0.4\% in SBS 0335–052 (it is contaminated by the Galactic Na I 5890 line in I Zw 18, so is unusable). It was mainly because the importance of underlying He I stellar absorption was insufficiently recognized in the NW component of I Zw 18 that led to the low \(Y_p\) values of Pagel et al. (1992) and Olive et al. (1997).

![Figure 3](image)

Figure 3. The spatial distributions of the helium mass fractions in SBS 0335–052 derived from the He I 4471, 5876 and 6678 emission line intensities. The intensities of the He I emission lines in a) are corrected for fluorescent and collisional enhancement with an electron number density \(N_e(\text{He II})\) and an optical depth \(\tau(3889)\) derived self-consistently from the observed He I 3889, 4471, 5876, 6678 and 7065 emission line intensities. The points for the 4471 line are below the points for the other lines because of underlying He I stellar absorption. For comparison, the intensities of the He I emission lines in b) are corrected only for collisional enhancement, with an electron number density \(N_e(\text{S II})\). The points for the different lines do not agree anymore. The 1\(\sigma\) error bars are shown only for the He mass fraction derived from the He I \(\lambda 5876\) emission line. They are larger in b) because of the large uncertainties in the determination of \(N_e(\text{S II})\).

In our work thus far, we have not corrected self-consistently for underlying He I self-absorption. We have simply not used regions where underlying absorption is important (such as the NW component in I Zw 18), or not averaged in lines that give a \(Y\) clearly deviant from the \(Y\)'s from other lines. Thus, in the case of SBS 0335–052, Figure 3a shows that the \(Y\) obtained from He I 4471 line is systematically below the values from the He I 5876 and 6678 lines. It is affected by underlying absorption and is not included. In the future, we plan to solve for He I absorption (assumed to be the same for all He I lines) self-consistently, as we did for the H I lines (see below).
3.3. **HE I AND H I EMISSIVITIES**

Line ratios corrected for reddening and absorption are converted to He/H abundance ratios by using theoretical emissivities calculated from recombination and radiative cascade theory. We use the H I emissivities of Brocklehurst (1971) which are in excellent agreement with the more recent ones by Hummer & Storey (1987) for the range of temperatures and densities in metal-deficient BCDs, and the He I emissivities of Smits (1996). Benjamin, Skillman & Smits (1999) have estimated that uncertainties in the theoretical He I emissivities can be as large as 1.5%, ~ 3 times worse than the accuracy expected from comparing Brocklehurst (1972) and Smits (1996) emissivities.

3.4. **ELECTRON DENSITY DETERMINATION**

To determine element abundances, we adopt a two-zone photoionized H II region model (ITL94, ITL97, IT98): a high-ionization zone with temperature $T_e$(O III), where the O III, Ne III and Ar IV lines originate, and a low-ionization zone with temperature $T_e$(O II), where the O II, N II, S II and Fe III lines originate. As for the Ar III and S III lines they originate in the intermediate zone between the high and low-ionization regions. The [S II] $\lambda 6717/\lambda 6731$ line ratio is used to determine the electron density $N_e$(S II) according to five-level atom calculations.

Previous authors have set $N_e$(He II) = $N_e$(S II). However, this is not appropriate as $N_e$(S II) measures the density in the low-ionization zone, while He II is produced in the high-ionization zone. Furthermore, the [S II] ratio is fairly insensitive for densities below 100 cm$^{-3}$. Thus it is much better to determine $N_e$(He II) directly from the He I lines themselves, in a self-consistent manner, which we have done. Because the electron density enters linearly in the calculation of the correction for collisional enhancement of the He I emission lines (see below), its different estimate by us and previous authors is also responsible for the difference between our $Y_p$ and theirs.

3.5. **THE COLLISIONAL EXCITATION OF HYDROGEN LINES**

It is also generally assumed that case B recombination theory holds, i.e that the line photons (usually resonance lines of abundant ions) are scattered so many times that their downward radiative transitions can effectively be neglected. In other words, the H II regions are considered to be optically thick in the Lyman transitions but optically thin in the other transitions of both hydrogen and helium atoms. (The opposite assumption, case A, where all emitted photons escape without absorption and there is no radiative transfer problem, does not apply to nebulae with large enough amounts of gas and optical depths to be seen). However, there are known physical effects that make the helium lines deviate from case B. One such effect is the collisional excitation of the Balmer hydrogen lines by thermal electrons.
This process and its effect on the determination of $Y_p$ was first discussed by Davidson and Kinman (1985). Low-metallicity H II regions have high enough electron temperatures so that the observed fluxes of lines like H$\alpha$ may be overestimated by this effect, leading to an underestimate of $Y_p$. Davidson & Kinman (1985) estimated crudely this effect to be $\sim 2\%$ for I Zw 18. Sasselov & Goldwirth (1995) examined this effect with detailed radiative transfer calculations and also found it to cause an increase of $\sim 2\%$ in the $Y$ of I Zw 18 and up to $3\%$ for other metal-deficient BCDs. Stasińska & Izotov (2001) used a grid of photoionization models to show that the effect of collisional excitation on the H$\alpha$/H$\beta$ ratio can be as high as $8\%$, resulting in an upward correction in $Y$ of up to $5\%$ in objects like SBS 0335–052. Thus this effect can be one of the most important sources of systematics in the determination of $Y_p$.

### 3.6. The Collisional and Fluorescent Enhancements of He I Lines

In the high range of electron temperatures found in metal-deficient BCDs (10000–20000 K), collisional excitation from the metastable level $2\,3S$ level of He I can be important in populating the higher levels and making the He I line intensities deviate from pure recombination values. Another effect that also leads to deviation from pure recombination values is self-absorption in some optically thick emission lines which populates the upper levels of He I, a mechanism called fluorescence. The emission lines most sensitive to fluorescence in the optical range are the He I 3889 and 7065 lines. The He I 7065 also plays an important role because it is particularly density sensitive. In contrast to collisional excitation, which increases the line intensities of all He I lines, the fluorescent mechanism decreases the intensity...
of the He I 3889 line as its optical depth increases, while increasing the intensities of the He I 4471, 5876, 6678, and 7065 lines.

Figure 5. Keck spectrum of the BCD SBS 0335–052 with labeled He I emission lines.

How do these two effects play out in I Zw 18 and SBS 0335–052? They are less important in I Zw 18 than in SBS 0335–052 because the physical conditions in the two BCDs are quite different. While in I Zw 18 the electron number density is small \( N_e(S\,\text{II}) \leq 100 \, \text{cm}^{-3} \) and collisional enhancement has a minor effect on the derived helium abundance, the electron number density in SBS 0335–052 is considerably higher \( N_e(S\,\text{II}) \approx 500 \, \text{cm}^{-3} \) in the central part of the H II region. Additionally, the linear size of the H II region in SBS 0335–052 is \( \sim 5 \) times larger than in I Zw 18, making it optically thick for some He I transitions. Therefore, both collisional and fluorescent enhancements of He I emission lines play a significant role in this galaxy (Izotov et al. 1999). Figure 4 shows that the spatial distribution of He I emission line intensities in SBS 0335–052 is very different from that in I Zw 18. The increase of He I 5876 and He I 7065 emission line strengths by \( \sim 20\% \) and \( \sim 75\% \) respectively in the central part of SBS 0335–052 within a radius \( \sim 2'' \) is caused by collisional and fluorescent enhancement. The increase of the He I \( \lambda 6678 \) emission line intensity is only \( \leq 4\% \). The combined effect of collisional enhancement and underlying stellar absorption results in a small depression in the He I 4471 intensity in the central region. As for I Zw 18, the main effect is underlying He I stellar absorption causing the dip in the He I emission line intensities at the location of the NW component.

To correct the He I line intensities for collisional enhancement, we use the correction factors calculated by Kingdon & Ferland (1995) based on collisional rates by Sawey & Berrington (1993). To correct the He I line intensities for fluorescent enhancement, we have fitted the Robbins (1968) correction factors with polynomials as given in IT98. Since the collisional enhancement factor of the He I lines depend exponentially on the electron temperature and linearly on the electron density \( N_e (\text{He II}) \), we correct for these two effects and determine \( N_e (\text{He II}) \) at the same time, in a self-consistent way so that the He I 5876/4471, 6678/4471, and 7065/4471 line ratios have their recombination values, after correction for both collisional and fluorescent enhancement.
3.7. The non-coincidence of the H\(^+\) and He\(^+\) Strömgren spheres

Depending on the hardness of the ionizing radiation, the radius of the He\(^+\) sphere can be smaller or larger than the radius of the H\(^+\) sphere. When the ionizing radiation is soft, the first case prevails, it is necessary to consider the presence of unseen neutral helium in the H\(^+\) zone and a correction needs to be made, resulting in a higher He abundance. On the other hand, if the ionizing radiation is hard, the second case holds, there is neutral hydrogen in the He\(^+\) zone, which results in a downward correction of the He abundance. The correction in \(Y\) can be as high as several percent, either upward or downward (e.g. Steigman, Viegas & Gruenwald 1997, Peimbert, Peimbert & Ruiz 2000, Sauer & Jedamzik 2001). The hardness of the radiation is usually characterized by the “radiation softness parameter” \(\eta\) defined by Vilchez & Pagel (1988) as \(\eta = \frac{O^+ + S}{O^{++}}\), and the ionization parameter \(U\). For both I Zw 18 and SBS 0335–052, the ionizing radiation is hard, and the correction to \(Y\) is downward. Using the extensive grid of correction factors as functions of \(\eta\) and \(U\), calculated by Sauer & Jedamzik (2001) using photoionized H II region models, we found the downward correction to be less than 1% for both BCDs.

3.8. Temperature structure

To convert the He I line intensities into abundances, we have set the electron temperature \(T_e(\text{He II})\) to be equal to \(T_e(\text{O III})\) as obtained from the [O III] 4363 / (4959+5007) ratio. However as emphasized by Peimbert, Peimbert & Ruiz (2000), detailed modeling of BCDs like I Zw 18 (Stasińska & Schaerer 1999) and examination of photoionization models (Stasińska 1990) suggest that \(T_e(\text{He II})\) is smaller than \(T_e(\text{O III})\) by at least 5% in this type of object (deviations from a constant temperature are sometime called “temperature fluctuations”). Peimbert, Peimbert & Luridiana (2001) found that this leads to a downward correction of \(Y\) of about 3%. However, examination of the correction factors for temperature effects derived by Sauer & Jedamzik (2001) using photoionization models give downward corrections of \(Y\) that are considerably smaller for I Zw 18 and SBS 0335–052, less than 1%.

4. Cosmological implications

In summary, the important systematic effects that may affect our determination of \(Y_p\) from spectra of the two most metal-deficient BCDs known, I Zw 18 (the SE component) and SBS 0335–052, and that have not been taken into account by our self-consistent procedure are: 1) the collisional excitation of Hydrogen lines that can increase \(Y_p\) by up to 5%; 2) the non-coincidence of the H\(^+\) and He\(^+\) zones that may decrease \(Y_p\) by \(\sim 1\%\); 3) the temperature fluctuations that may decrease it by \(\sim 1 \text{ to } 3\%\); and 4) underlying stellar He I absorption that may increase it by \(\sim 1\%\).
Thus, combining all those systematic effects, our $Y_p$ value may be underestimated by as much as $\sim 2–4\%$.

Taken at face value, our $Y_p = 0.2452 \pm 0.0015$ implies a baryon-to-photon number ratio $\eta = (4.7^{+1.0}_{-0.8}) \times 10^{-10}$. This translates to a baryon mass fraction $\Omega_b h^2_{100} = 0.017 \pm 0.005$ ($2\sigma$) where $h_{100}$ is the Hubble constant in units of 100 km s$^{-1}$Mpc$^{-1}$. This value is consistent with the one of $0.020 \pm 0.002$ ($2\sigma$) derived from the primordial deuterium abundance measured in high-redshift hydrogen clouds backlit by distant quasars (O’Meara et al. 2001), vindicating SBBN. It is also consistent with the baryon mass fraction $\Omega_b h^2_{100} = 0.022 \pm 0.003$ ($1\sigma$) inferred from measurements of the angular power spectrum of the Cosmic Microwave Background (CMB, Netterfield et al. 2001). Note that correcting upward $Y_p$ by 2–4% would bring it into even better agreement with the deuterium and CMB measurements.

5. Future work

It is clear from the previous discussion that, to decrease or eliminate the main systematic effects in the determination of $Y_p$, it is best to determine all the four following quantities – the electron density $N_e$ (He II) and temperature $T_e$ (He II) of the He II zone, the optical depth $\tau$ (3889) in the He I 3889 line, and the equivalent width for underlying He I absorption – in a totally self-consistent manner. ITL94, ITL97 and IT98 have used the five He I 3889, 4471, 5876, 6678 and 7065 lines to solve self-consistently for $N_e$ (He II) and $\tau$ (3889). We plan to add the He I 4026, 4438 and 4922 lines, giving a total of 8 lines, to solve self-consistently for all four quantities. The last three lines are particularly sensitive to underlying He I stellar absorption. However their intensities are less than 1/10 that of the 5876 line, and very high signal-to-noise ratio spectra are needed to determine their intensities precisely. Such a spectrum obtained with the Keck telescope and where all 8 He I lines are marked is shown in Figure 4 for the BCD SBS 0335–052.

Future work to improve on the determination of $Y_p$ will consist of: 1) obtaining deep spectra for the most metal-deficient BCDs known, to determine $Y_p$ using a self-consistent method based on 8 lines; 2) detailed modeling of BCDs such as done for I Zw 18 by Stasińska & Schaerer (1999). It was found that a simple photoionization model is insufficient to account for the high [O III] 4363/5007 ratio in I Zw 18 and that an additional heating mechanism such as shock heating is necessary. Such a modeling will also help to quantify potential temperature fluctuations; and 3) searching for more extremely metal-deficient BCDs such as I Zw 18 and SBS 0335–052, to increase the number of objects where we can determine $Y_p$ without a large correction for He production by stars.

We thank Dr. Johannes Geiss for a careful reading of the manuscript. This work has been supported by National Science Foundation grant AST-9616863.
References

Bania, T.M., Rood, R.T, & Balser, D.S. 2000, in The Light Elements and Their Evolution, ed. L.D. Silva, M. Spite & J.R. de Medeiros (San Francisco:ASP), 214
Benjamin, R.A., Skillman, E.D., & Smits, D.P. 1999, Astrophysical Journal, 514, 307
Bonifacio, P., & Molaro, P. 1997, Monthly Notices of the RAS, 285, 847
Brocklehurst, M. 1971, Monthly Notices of the RAS, 153, 471
Brocklehurst, M. 1972, Monthly Notices of the RAS, 157, 211
Burles, S., & Tytler, D. 1998, ApJ, 507, 732
Davidson, K., & Kinman, T. D. 1985, Astrophysical Journal, Supplement Series, 58, 321
Hummer, D.G, & Storey, P.J. 1992, Monthly Notices of the RAS, 254, 277
Izotov, Y.I., Chaffee, F.H., Foltz, C.B., Green, R.F., Guseva, N.G., & Thuan, T.X. 1999, Astrophysical Journal, 527, 757
Izotov, Y.I., Thuan, T.X., & Lipovetsky, V.A. 1993, Astrophysical Journal, 435, 647 (ITL94)
Izotov, Y.I., Thuan, T.X., & Lipovetsky, V.A. 1997, Astrophysical Journal, Supplement Series, 108, 1 (ITL97)
Izotov, Y.I., & Thuan, T.X. 1998, Astrophysical Journal, 500, 188 (IT98)
Izotov, Y.I., & Thuan, T.X. 1999, Astrophysical Journal, 511, 639
Kingdon, J, & Ferland, G. J. 1995, Astrophysical Journal, 442, 714
Netterfield, C.B., et al. 2001, Astrophysical Journal, in press (astro-ph/0104460)
Oliver, K., Skillman, E.D., & Steigman, G. 1997, Astrophysical Journal, 483, 788
Oliver, K., & Skillman, E.D. 2001, New Astronomy, 6, 119
Olofsson, K. 1995, Astronomy and Astrophysics, Supplement Series, 111, 57
O’Meara, J.M, Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J.X., Lubin, D., & Wolfe, A.M. 2001, Astrophysical Journal, 552, 718
Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. G. 1992, Monthly Notices of the RAS, 255, 325
Peimbert, A., Peimbert, M., & Luridiana, V. 2001, Astrophysical Journal, in press (astro-ph/0107183)
Peimbert, M., Peimbert, A., & Ruiz, M.T. 2000, Astrophysical Journal, 541, 688
Peimbert, M., & Torres-Peimbert, S. 1974, Astrophysical Journal, 193, 327
Prinsonneault, M.H., Walker, T.P., Steigman, G., & Narayanan, V.K. 1999, Astrophysical Journal, 527, 180
Robbins, R.R. 1968, Astrophysical Journal, 151, 497
Rocca-Volmerange, B., Prévot, L., Ferlet, R., Lequeux, J., & Prévot-Burnichon, M.L. 1981, Astronomy and Astrophysics, 99, L5
Ryan, S.G, Norris, J.E., & Beers, T.C. 1999, Astrophysical Journal, 523, 654
Sasselov, D., & Goldwirth, D. 1995, Astrophysical Journal, 444, 5
Sauer, D., & Jedamzik, K. 2001, Astronomy and Astrophysics, in press (astro-ph/0104392)
Sawey, P.M.J., & Berrington, K.A. 1993, At. Data Nucl..Data Tables, 55, 81
Smits, D. P. 1996, Monthly Notices of the RAS, 278, 683
Spite, F., & Spite, M. 1982, Astronomy and Astrophysics, 115, 357
Stasinska, G. 1990, Astronomy and Astrophysics, Supplement Series, 83, 501
Stasinska, G., & Izotov, Y.I. 2001, Astronomy and Astrophysics, in press
Stasinska, G., & Schaerer, D. 1999, Astronomy and Astrophysics, 351, 72
Steigman, G., Viegas, S.M., & Gruenwald, R. 1997, Astrophysical Journal, 490, 187
Thuan, T.X., & Izotov, Y.I. 1998a, in The Birth of Galaxies, ed. B. Guiderdoni, F.R. Bouchet, T.X.
Thuan & J.T.T. Van (Hanoi: The Gioi Publishers), 39
Thuan, T.X., & Izotov, Y.I. 1998b, Space Sci. Rev., 84, 83
Thuan, T.X., & Izotov, Y.I. 2000, in The Light Elements and Their Evolution, ed. L.D. Silva, M. Spite & J.R. de Medeiros (San Francisco:ASP), 176
Tytler, D., O’Meara, J.M, Suzuki, N., & Lubin, D. 2000, Physica Scripta, 85, 12
Vauclair, S., & Charbonnel, C. 1998, Astrophysical Journal, 502, 372
Vilchez, J.M., & Pagel, B.E.J. 1988, Monthly Notices of the RAS, 231, 257
Whitford, A.E., 1958, Astronomical Journal, 63, 201