Big Bang nucleosynthesis and the baryonic content of the universe

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Abstract

A review of the latest measurements of the primordial abundances of the light nuclei D, ^{3}He, ^{4}He and ^{7}Li is given. We discuss in particular the primordial abundance $Y_{\rm p}$ of ^{4}He as measured in blue compact dwarf galaxies. We argue that the best measurements now give a "high" value of $Y_{\rm p}$ along with a "low" value of D/H, and that the two independent measurements are consistent within the framework of standard Big Bang nucleosynthesis with a number of light neutrino species N_ν = 3.0±0.3 (2σ).

1 Introduction

The Big Bang theory which says that the universe began its existence from an inimaginably small, hot and dense state is supported by four main key observations: 1) the expansion of the universe, 2) the Planck blackbody spectrum of the Cosmic Microwave Background (CMB), 3) the tiny density fluctuations in the CMB and the resulting large-scale distribution of galaxies, and 4) the chemical make-up of the stars and galaxies, with which we will be concerned here. In the Standard Big Bang Nucleosynthesis (SBBN) model, light nuclei H, 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 light neutrino species $N_\nu = 3$ and the neutron lifetime, the abundances of these light elements depend on one cosmological parameter only, the baryon-to-photon ratio η, which in turn is directly related to the density of ordinary baryonic matter $\Omega_{\rm b}$. The ratio of any two primordial abundances, for example that of ^{4}He to H gives η, and accurate measurements of the other three light elements tests SSBN.

η is determined during baryogenesis which occurs when three conditions are fulfilled in the early universe, as pointed out by Sakharov (1967): 1) a symmetry violation leading to different interactions for matter and anti-matter (such as CP violation), 2) interactions which modify the baryon number and 3) departure from thermodynamic equilibrium. It is not known when the last condition occurs, but if it occurs in a first order phase transition, at the electroweak scale, then it may be hoped that future experiments will allow to predict η. On the other hand, if it occurs at the GUT or inflation scale, which is not accessible to experimentation in the near-future, predicting η will be very difficult.

The main physical processes in SBBN are the following (Kolb & Turner 1990, Tytler et al. 2000): at early times, for times less than about 1 second, weak reactions maintain the n/p ratio close to the Boltzman value. As the universe expands and the temperature drops, n/p decreases until about 1 second ($T \sim 1$MeV), when the weak reaction rate becomes slower than the expansion rate. At that time, the n/p ratio freezes at the value of about 1/6. n and p start to combine to make D, but photodissociation is rapid and no significant build-up of light nuclei occurs until about 100 seconds, when the universe has cooled down to about 0.1 MeV, well below the binding energies of the light nuclei. About 20% of the free neutrons have decayed before being included in nuclei. The remaining neutrons go into the building of ^{4}He nuclei. The primordial helium mass fraction Y_p of ^{4}He depends relatively weakly on η as the n/p ratio depends on weak reactions between nucleons and leptons and not on pairs of nucleons. If η is larger, Y_p increases because nucleosynthesis starts earlier and more nucleons end up in ^{4}He nuclei, and less in D and ^{3}He. As for ^{7}Li, two channels contribute to manufacture it in the η range of interest, so that a given ^{7}Li abundance corresponds to two different values of η.

Section 2 discusses our latest measurements of the primordial ^{4}He abundance as derived from observations of blue compact dwarf galaxies. Section 3 reviews the measurements of the primordial abundances of other light elements. Section 4 discusses whether these independent measurements are consistent with each other within the framework of SSBN, and gives the derived cosmological baryon density. Section 5 discusses the number of light neutrino species as derived from the most consistent set of primordial element abundances.

2 The primordial ^{4}He abundance as derived from blue compact dwarf galaxies

Blue compact dwarf galaxies (BCD) are low-luminosity ($M_B \geq -18$) systems which are undergoing an intense burst of star formation in a very compact region (less than 1 kpc) which dominates the light of the galaxy (Figure 1) and which shows blue colors and a HII region-like emission-line optical spectrum (Figure 2). BCDs are ideal laboratories in which to measure the primordial ^{4}Helium abundance because of several reasons:

1) 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 stars not older than ~ 100 Myr. Thus the primordial Helium mass fraction Y_p can be derived accurately in very metal-deficient BCDs with only a small correction for Helium made in stars.

2) Because of the relative insensitivity of ^{4}He production to the baryonic density of matter, Y_p needs to be determined to a precision better than 5% to provide useful cosmological constraints. This precision can in principle be achieved by using BCDs because their optical spectra show several He I recombination emission lines and very high signal-to-noise ratio emission-line spectra with moderate spectral resolution of BCDs can be obtained at large telescopes (4 m class or larger) coupled with efficient and linear CCD detectors with a relatively

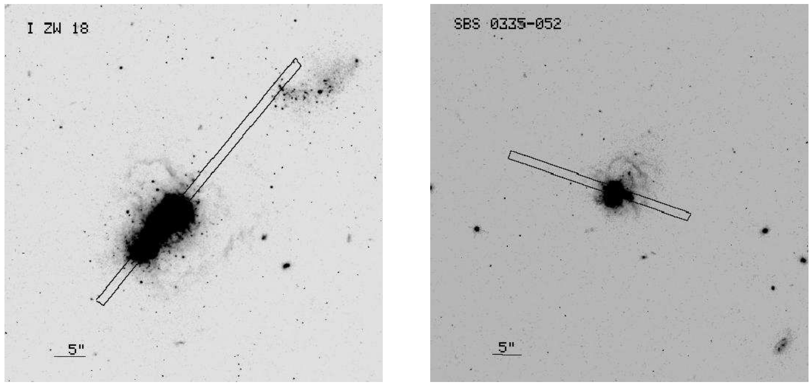


Figure 1: Hubble Space Telescope V images of of the two most metal-deficient blue compact dwarf galaxies known: I Zw 18 (1/50 solar) and SBS 0335–052 (1/41 solar). The spatial scale is 1 arcsec = 49 pc in the case of I Zw 18 and is 1 arcsec = 257 pc in the case of SBS 0335–052.

modest investment of telescope time. The theory of nebular emission is well understood and the theoretical He I recombination coefficients are well known enough to allow to convert He emission-line strengths into abundances with the desired accuracy.

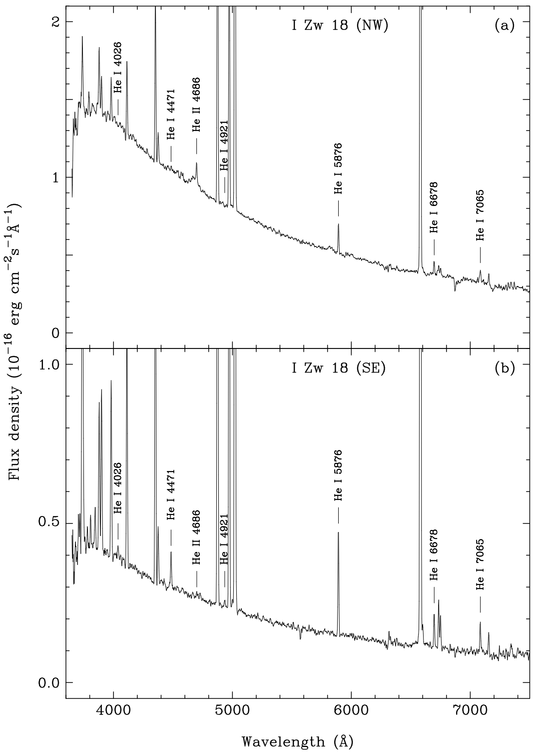
$Y_{\rm p}$ is generally determined by linear extrapolation of the correlations Y–O/H and Y–N/H to O/H = N/H = 0 (Peimbert & Torres-Peimbert 1974, Pagel, Terlevich & Melnick 1986), where Y, N/H and O/H are respectively the ^{4}He mass fraction, the Oxygen and Nitrogen abundances relative to Hydrogen of a sample of dwarf irregular and BCD galaxies. Izotov, Thuan & Lipovetsky (1994, 1997), Izotov & Thuan (1998) and Izotov et al. (1999) have obtained high signal-to-noise ratio spectra for a relatively large sample of $\sim$ 45 BCDs (see Thuan & Izotov 2000 for a review).

We obtain $Y_{\rm p}$= 0.2443±0.0015 with dY/dZ = 2.4±1.0 (Figure 3). Our $Y_{\rm p}$ is considerably higher than those derived in previous work by other groups which range from 0.228±0.005 (Pagel et al. 1992) to 0.234±0.002 (Olive et al. 1997). At the same time, our derived slope is significantly smaller than those of other authors, dY/dZ = 6.7±2.3 for Pagel et al. (1992) and dY/dZ = 6.9±1.5 for Olive et al. This shallower slope is in good agreement with the value derived from stellar data for the Milky Way's disk and with simple models of galactic evolution of BCGs with well-mixed homogeneous outflows.

We believe our $Y_{\rm p}$ value to be more reliable because we have taken into account several systematic effects that were not considered in previous work. In order of decreasing importance, these effects are:

1) Stellar HeI absorption lines underlying HeI emission lines. When these are not recognized and corrected for, the derived $Y_{\rm p}$ is too low. Underlying stellar absorption is particularly important in the BCD I Zw 18 (compare in Figure 2 the He I line intensities in the NW component where underlying stellar absorption is important and in the SE component where that effect is less important). Because this BCD has the lowest metallicity known, it plays a particularly important role in determining the intercept and slope of the Y versus O/H and Y versus N/H regression lines and hence $Y_{\rm p}$.

2) To derive the He mass fraction, the emission He I line fluxes (Figure 2) need to be corrected for several mechanisms which enhance the line emission. Previous authors usually use only the single 6678 He I line and correct only for electron collisional enhancement. This correction is usually carried out adopting the electron density derived from the [S II] 6717/6731 emission-line ratio. They neglect fluorescent enhancement which can also be important. We use the five brightest He I lines in the optical range, which allows us to correct for both collisional and fluorescent enhancements and calculate the electron density N_e(He II) in a self-consistent



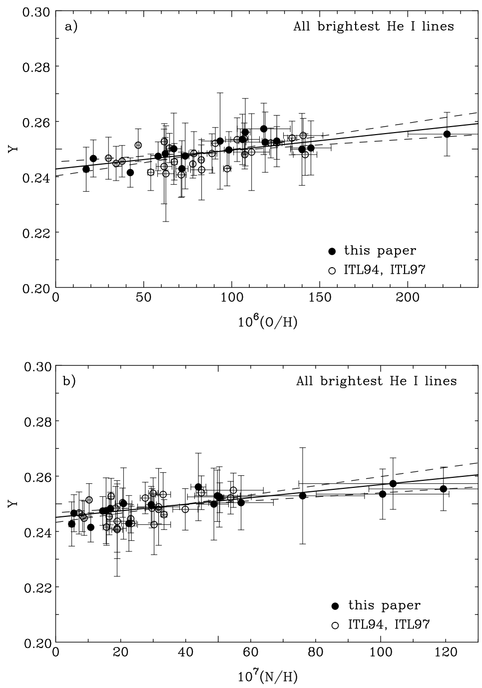


Figure 2: Spectra of the brightest parts of the NW and the SE components of I Zw 18. The positions of He I lines used for ^{4}He abundance determination are marked. Note the effect of underlying stellar absorption is much larger in the NW than in the SE component: all marked He I lines in the spectrum of the SE component are in emission while the two He I λ4026 and λ4921 lines are in absorption and the He I λ4471 emission line is barely detected in the spectrum of the NW component.

Figure 3: Linear regressions of (a) the helium mass fraction Y vs. oxygen abundance O/H and (b) the helium mass fraction Y vs. nitrogen abundance for our sample of 45 H II regions. The Ys are derived self-consistently by using the 5 brightest He I emission lines in the optical range. Collisional and fluorescent enhancements, underlying He I stellar absorption and Galactic Na I interstellar absorption are taken into account.

manner. Setting N_e(He II) equal to N_e(S II) is not physically reasonable as the S^+ and He^+ regions are not expected to coincide, given the large difference in the S I and He I ionization potentials.

3) We have observed all the galaxies in our sample with the same telescopes and instrumental set up, and the data were all reduced in a homogeneous way. This is in contrast to more heterogeneous BCD samples used by previous investigators. A uniform sample is essential to minimize as much as possible the artificial scatter introduced by assembling different data sets reduced in different ways.

Instead of the statistical approach described above, we can also derive the primordial He abundance from accurate measurements of the He abundance in a few objects selected to have very low O/H to minimize the amount of He manufactured in stars. Izotov et al. (1999) have carried out such a study for the two most metal-deficient BCDs known. I Zw 18 (1/50 of solar metallicity) and SBS 0335–052 (1/41 of solar metallicity) provide a study in contrast concerning the different physical mechanisms which may modify the He I emission-line intensities. While in I Zw 18, the electron number density is small ($N_e \leq 100$ cm^{-3}) and collisional enhancement has a minor effect on the derived helium abundance, N_e is much higher in SBS 0335–052 ($N_e \sim 500$ 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, suggesting that it may be optically thick for some He I transitions. In fact, both collisional and fluorescent enhancements of He I emission lines play an important role in this galaxy. By contrast, underlying stellar He I absorption is $\sim$ 5 times smaller in SBS 0335–052 than in I Zw 18. Izotov et al. (1999) derive $Y = 0.243 \pm 0.007$ for I Zw 18 , and $Y = 0.2463 \pm 0.0015$ for SBS 0335–052. The weighted mean is then $Y = 0.2462 \pm 0.0015$. Using $\mathrm{d}Y/\mathrm{d}Z = 2.4$ from the regression lines above, the stellar He contribution is 0.0010, giving a primordial value $Y_{\mathrm{p}} = 0.2452 \pm 0.0015$, in excellent agreement with the value 0.2443 ± 0.0015 derived from extrapolation of the Y—O/H and Y—N/H regression lines for our large BCD sample.

3 Primordial abundances of Deuterium, Lithium and ^{3}Helium

3.1 Deuterium

Of all light elements, the abundance of deuterium (D) is the most sensitive to the baryonic mass. Stars do not make significant D but D is easily destroyed because of its fragility, so that D/H measured in the interstellar medium of the Milky Way or the Solar System constitute only lower limits to the primordial D abundance. The latter 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 α 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: $(\mathrm{D/H})_{\mathrm{p}}$ $3.0 \pm 0.4 \times 10^{-5}$ (O'Meara et al. 2000). This latest value is about 10% lower than their previous value $(\mathrm{D/H})_{\mathrm{p}} = 3.39 \pm 0.25 \times 10^{-5}$ (Burles & Tytler 1998). During the period 1994 to 1996, there were reports in the literature of D/H varying over a factor of 10 along different quasar line of sights. Songaila et al. (1994) reported $(\mathrm{D/H})_{\mathrm{p}}$ $= 24 \pm 4 \times 10^{-5}$ in one system. However, later observations showed the absorption near D to be at the wrong velocity and being too wide. The high value is now generally attributed to contamination from another HI cloud with a velocity near that of D along the line of sight. Tytler et al. (2000) argue convincingly that all available data are consistent with a single low value of $(\mathrm{D/H})_{\mathrm{p}}$, and that quasar spectra that give high $(\mathrm{D/H})_{\mathrm{p}}$ values can be readily interpreted as contamination by HI clouds along the line of the sight to the quasars and having a velocity near that of D.

3.2 Lithium

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 since the latter is also enhanced in this process (Ryan et al. 1999).

There is still considerable debate concerning the possible depletion of ^{7}Li inside stars. Depletion mechanisms that have been proposed include mixing due to rotation or gravity waves, mass loss in stellar winds and gravitational settling. If depletion is present, then the primordial

^{7}Li abundance is higher than the value $(^7\mathrm{Li/H})_\mathrm{p} = (1.73\pm0.21)\times10^{-10}$ obtained by Bonifacio & Molaro (1997). Vauclair & Charbonnel (1998) have shown that the depletion of ^{7}Li in Population II stars may be as high as 30%. They give for the primordial lithium abundance $(^7\mathrm{Li/H})_\mathrm{p}$ $= (2.24\pm0.57)\times10^{-10}$. Ryan et al. (1999) also find that the small scatter in their data limits the mean depletion of ^{7}Li to be less than 30%. Pinsonneault et al. (1998) have analyzed ^{7}Li depletion in rotating stars. They found that the depletion factor can be as high as 1.5 – 3 times, larger than the value obtained by Vauclair & Charbonnel (1998). Pinsonneault et al. (1999) give a primordial lithium abundance $(^7\mathrm{Li/H})_\mathrm{p} = (3.9\pm0.85)\times10^{-10}$. In summary, it is likely that the ^{7}Li abundance measured in halo stars on the Spite plateau is not the primordial value and needs to be corrected upwards by a factor probably less than 2.

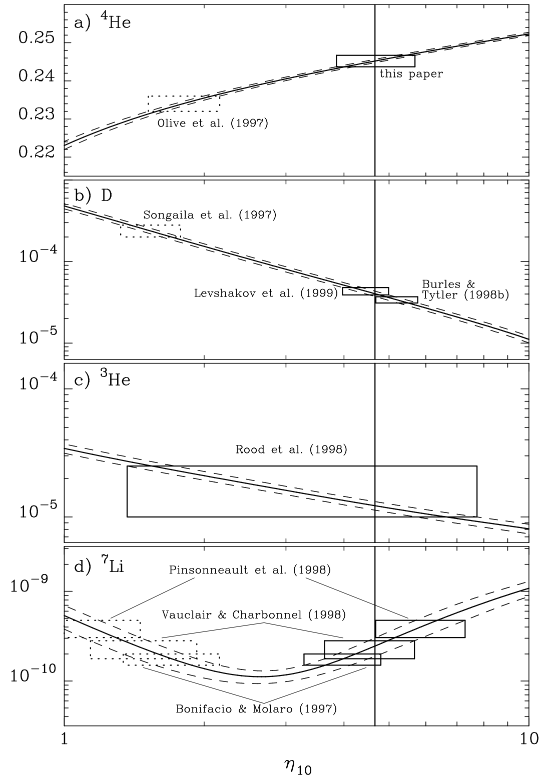
3.3 ^{3}Helium

Although the primordial abundance of ^{3}He is nearly as sensitive to the baryon density as D, 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. Rood et al. (1998) have measured an average $^3\mathrm{He/H} = 1.6\pm0.5\times10^{-5}$ in Galactic H II regions. This value represents the average in the interstellar medium of the Milky Way, but it is not known how to use it to derive the primordial abundance of ^{3}He.

4 The consistency of Big Bang nucleosynthesis and the baryonic content of the Universe

In Figure 4, solid lines show the primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li predicted by standard big bang nucleosynthesis theory as a function of the baryon-to-photon number ratio η. The dashed lines are 1σ uncertainties in model calculations. The analytical fits are taken from Fiorentini et al. (1998). The solid boxes show the 1σ predictions of η as inferred from the measured primordial abundances of ^{4}He (Izotov & Thuan 1998, Izotov et al. 1999), D (Burles & Tytler 1998), ^{3}He (Rood et al. 1998) and ^{7}Li (Bonifacio & Molaro 1997; Vauclair & Charbonnel 1998; Pinsonneault et al. 1998). For D, we have also shown the value of Levshakov et al. (1999). These authors have used the data of Tytler et al. together with kinematic models with correlated turbulent motions for absorbing Lyα clouds instead of microturbulent models to derive $(\mathrm{D/H})_\mathrm{p} = (4.35\pm0.43)\times10^{-5}$, slightly higher than the value of Burles & Tytler (1998). All these determinations are consistent to within 1σ with a baryon-to-photon number ratio η $= (4.7^{+1.0}_{-0.8})\times10^{-10}$, corresponding to the primordial Helium mass fraction $Y_\mathrm{p} = 0.245\pm0.002$ value determined by Izotov & Thuan (1998). This baryon-to-photon number ratio translates to a baryon mass fraction $\Omega_b h_{50}^2 = 0.068^{+0.015}_{-0.012}$ where h_{50} is the Hubble constant in units of 50 km s^{-1}Mpc^{-1}.

For comparison, we have also shown with dotted boxes the 1σ predictions of η inferred from the "low" primordial abundance of ^{4}He derived by Olive et al. (1997), and the "high' D/H value of Songaila et al. (1994), along with the values of ^{7}Li (Bonifacio & Molaro 1997; Vauclair & Charbonnel 1998; Pinsonneault et al. 1998). This second data set has, however, several problems: 1) Olive et al. (1997) have not taken into account underlying stellar absorption and fluorescent enhancement, which results in an artificially low helium mass fraction; and 2) the high primordial D abundance reported by Songaila et al. (1994) is probably caused by H contamination.



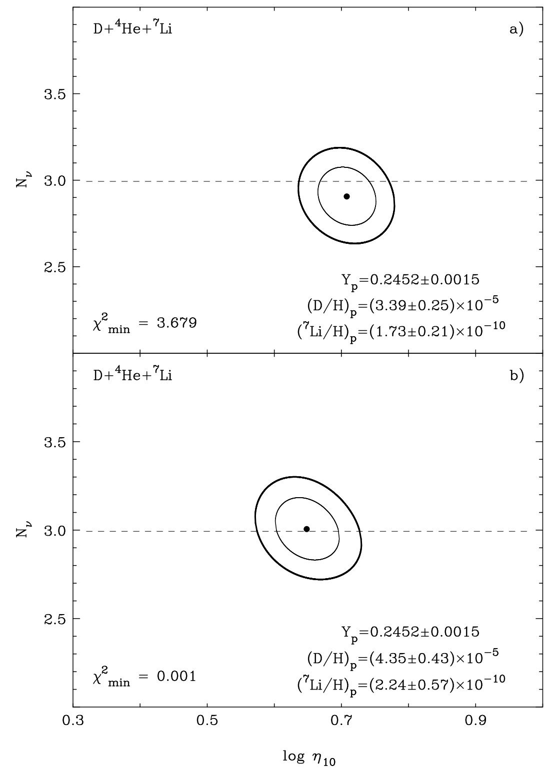


Figure 4: The abundance of (a) ^{4}He, (b) D, (c) ^{3}He and (d) ^{7}Li as a function of $\eta_{10} \equiv 10^{10}\,\eta$, where η is the baryon-to-photon number ratio, as given by the standard hot big bang nucleosynthesis model. The abundances of D, ^{3}He and ^{7}Li are number ratios relative to H. For ^{4}He, the mass fraction Y is shown. The value of Izotov & Thuan (1998) and Izotov et al. (1999) $Y_{\rm p}$ = 0.245±0.002 gives $\eta = (4.7^{+1.0}_{-0.8})\times10^{-10}$ as shown by the solid vertical line. We show other data with 1σ boxes.

Figure 5: Joint fits to the baryon-to-photon number ratio, log η_{10}, and the equivalent number of light neutrino species N_ν using a χ^2 analysis with the code developed by Fiorentini et al. (1998) and Lisi et al. (1999) (a) for primordial abundance values $Y_{\rm p}$ (Izotov & Thuan 1998), (D/H)$_{\rm p}$ (Burles & Tytler 1998) and (^{7}Li/H)$_{\rm p}$ (Bonifacio & Molaro 1997) and (b) same as in (a) except (D/H)$_{\rm p}$ from Levshakov et al. (1999). The experimental value is shown by the dashed line.

5 The number of light neutrino species

We use the statistical χ^2 technique with the code described by Fiorentini et al. (1998) and Lisi et al. (1999) to analyze the consistency of different sets of primordial ^{4}He, D and ^{7}Li abundances, varying both η and the equivalent number of light neutrino species N_ν. The lowest $\chi^2_{\rm min} = 0.001$ results when $\eta = 4.45\times10^{-10}$ and $N_\nu = 3.0\pm0.3$ (2σ) for the set of primordial abundances with $Y_{\rm p}$ = 0.245±0.002 (Izotov & Thuan 1998, Izotov et al. 1999), (D/H)$_{\rm p}$ = $(4.35\pm0.43)\times10^{-5}$ (Levshakov et al. 1999) and (^{7}Li/H)$_{\rm p}$ = $(2.24\pm0.57)\times10^{-10}$ (Vauclair & Charbonnel 1998). If instead, we use the D/H of Burles & Tytler (1998), then $\chi^2_{min} = 3.7$ and $N_\nu = 2.9\pm0.3$. The joint fits of η and N_ν to both data sets are shown in Figure 5a and 5b, respectively. The 1σ ($\chi^2 - \chi^2_{min} = 2.3$) and 2σ ($\chi^2 - \chi^2_{min} = 6.2$) deviations are shown respectively by thin and thick solid lines. Both values of N_ν are consistent with the experimental value of 2.993±0.011 (Caso et al. 1998) shown by the dashed line. Therefore, we conclude that both data sets of primordial abundances of light elements are in good agreement with predictions of standard big bang nucleosynthesis theory.

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References

[1] Bonifacio, P. & Molaro, P. 1997, MNRAS, 285, 847

[2] Burles, S., & Tytler, D. 1998, ApJ, 507, 732

[3] Caso, C. et al. (Particle Data Group). 1998, Eur.J.Phys.C, 3,1

[4] Fiorentini, G., Lisi, E., Sarkar, S., & Villante, F. L. 1998, Phys. Rev. D, 58, 063506

[5] Izotov, Y.I. & Thuan, T.X. 1998, ApJ, 497, 227

[6] Izotov, Y.I. & Thuan, T.X. 1999, ApJ, 511, 639

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

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

[9] Izotov, Y. I., Chaffee, F. H., Foltz, C. B., Green, R. F., Guseva, N. G., Thuan, T. X. 1999, ApJ, 527, 757

[10] Kolb, E.W. & Turner, M.S. 1990, The Early Universe, (New York: Addison-Wesley)

[11] Levshakov, S. A., Kegel, W. H., & Takahara, F. 1998, MNRAS, 302, 707

[12] Lisi, E., Sarkar, S., & Villante, F.L. 1999, Phys. Rev. D, 59, 123520

[13] Olive, K. A., Skillman, E. D., & Steigman, G. 1997, ApJ, 483, 788

[14] O'Meara, J.M., Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J.X., Lubin, D. & Wolfe, A.M. 2000, astro-ph 0011179

[15] Pagel, B. E. J., Terlevich, R. J., & Melnick, J. 1986, PASP, 98, 1005

[16] Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. G. 1992, MNRAS, 255, 325

[17] Peimbert, M., & Torres-Peimbert, S. 1974, ApJ, 193, 327

[18] Pinsonneault, M. H., Walker, T. P., Steigman, G., & Naranyanan, V. K. 1999, ApJ, 527, 180

[19] Rood, R. T., Bania, T. M., Balser, D. S., & Wilson, T. L. 1998, Space Sci. Rev., 84, 185

[20] Ryan, S.G., Norris, J.E. & Beers, T.C. 1999, ApJ, 523, 654

[21] Sakharov, A.D. 1967, JETP Letters, 91 B, 24

[22] Songaila, A., Cowie, L. L., Hogan, C.J., & Rugers, M. 1994, Nature, 368, 599

[23] Spite, F. & Spite, M. 1982, A&A, 115, 357

[24] Thuan, T.X. & Izotov, Y.I. 2000, in IAU Symp. 198, The light elements and their evolution, eds. L. da Silva, M. Spite & J.R. de Medeiros (San Francisco: ASP), 176

[25] Tytler, D., O'Meara, J.M., Suzuki, N. & Lubin, D. 2000, Physica Scripta, 85, 12

[26] Vauclair, S., & Charbonnel, C. 1998, ApJ, 502, 372