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Primordial abundances of ^{4}He and other light elements

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Abstract. The primordial abundances of light elements and their isotopes D, ^{3}He, ^{4}He and ^{7}Li provide an important consistency check of cosmological models. They also played an important role in formation and evolution of primordial stars. Therefore, the use of accurate chemical composition of the primordial gas could improve the predicted properties of the first generation stars. The most recent determination of the primordial D, ^{3}He, ^{4}He and ^{7}Li abundances are discussed.

Key words. Galaxies: abundances – Galaxies: irregular – ISM: abundances – Cosmology: observations

1. Introduction

Standard Big Bang nucleosynthesis (SBBN) model predicts that light elements and isotopes D, ^{3}He, ^{4}He, and ^{7}Li were formed during 0.1 – 10^4 s after Big Bang. The SBBN abundances of these species depend on a single cosmological parameter, baryon mass fraction Ω_b. Recent space missions WMAP and Planck for measuring microwave background radiation temperature fluctuations showed the validity of the SBBN and greatly improved the determination of a number of cosmological parameters. In particular, the SBBN light element abundances inferred from Planck measurements are $Y_p(^4\mathrm{He})$ = 0.2477±0.0001 (Planck Collaboration 2013), D/H = $(2.67\pm0.09)\times10^{-5}$, ^{3}He/H = $(1.05\pm0.03)\times10^{-5}$, and ^{7}Li/H = $(4.89\pm0.40)\times10^{-10}$ (Coc et al. 2013).

In spite of these achievements, the primordial abundances of light elements derived by differing methods in various astrophysical objects are highly important for the consistency check of SBBN.

Furthermore, light elements played an important role in thermal processes of the primordial gas and formation of first stars. H_2 molecules were a main contributor to zero-metal gas cooling at temperatures below 10^4K. On the other hand, at lower temperatures <100K, cooling by HD and, possibly, LiH molecules could compete with that by H_2 molecules (Galli & Palla 1998, 2013; Coppola et al. 2011, 2013).

The results of the light element primordial abundance determinations were summarised during two recent meetings, IAU Symp. No. 268 “Light Elements in the Universe” (2009, Geneva, Switzerland) and Workshop “Lithium in the Cosmos” (2012, Paris, France). In addition, detailed reviews on BBN were appeared recently (Steigman 2007, 2012; Jedamzik & Pospelov 2009; Pospelov & Pradler 2010; Iocco et al. 2009).

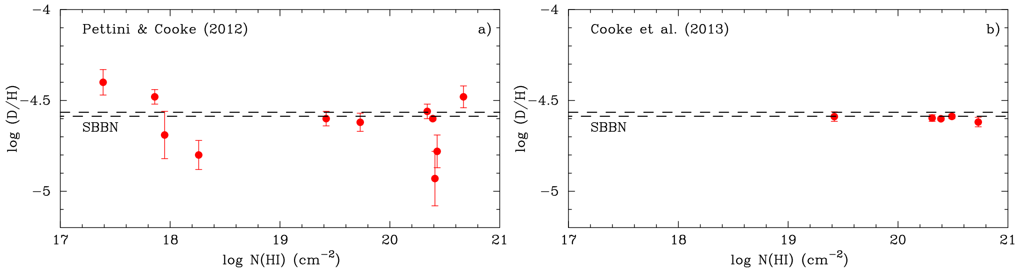

Fig. 1. (a) Dependence of deuterium abundance D/H on H I column density N(H I) for DLAs from the Pettini & Cooke (2012) sample. (b) Same as in (a) but for DLAs from the Cooke et al. (2013) sample. The range of SBBN D/H values predicted by Planck mission (Planck Collaboration 2013) is shown by two dashed lines.

Therefore, I will concentrate mainly on the most recent results of light element primordial abundance determinations obtained in 2012-2013,

2. D abundance

Deuterium is served as a best "baryometer" because of strong dependence of its primordial abundance on the baryon mass fraction Ω_b. Since deuterium is only destroyed after the Big Bang, the best objects for its determination are high-redshift damped Lyα absorption (DLA) systems. Because DLAs are metal-poor systems, deuterium experienced a little astration and its observed abundance is very close to the primordial one.

Special requirements for DLAs are needed to be suitable for the D/H determination (Cooke et al. 2013, Cooke, these proceedings):

1) H I column density should be high enough to allow its determination from the damping wings of the Lyα absorption line;
2) D lines should not be saturated to allow the determination of N(D I);
3) velocity structure of H I and D I lines should be simple, and no contamination from other absorbing H I systems should be present.

Recently, Pettini & Cooke (2012) derived the primordial D abundance for a sample of 11 metal-poor DLAs. Their average value D/H = $(2.6\pm0.1)\times 10^{-5}$ is in very good agreement with the SBBN values inferred from WMAP and Planck measurements. In Fig. 1a are shown D/H abundances in these DLAs in function of N(H I). Despite very good agreement of the mean D/H with the SBBN value, the data in Fig. 1a show large scatter, which is higher than the quoted D/H errors in individual systems.

Cooke et al. (2013) reanalysed this sample. They, adding one more DLA, were restricted by the sample of five DLAs with the best derived D/H (Fig. 1b) which shows small scatter with a mean D/H value very close to the SBBN one. Such a small scatter strongly supports SBBN leaving a little room for non-standard BBN scenarios. However, larger samples of DLAs are needed to strengthen Cooke et al. (2013) findings. More details of this study can be found in the Ryan Cooke talk (these Proceedings).

3. ^{3}He abundance

Fragile ^{3}He isotope, at variance with D, could not only be destroyed after the Big Bang but also be produced in low-mass main-sequence stars. Unfortunately, there are no low-metallicity astrophysical objects where ^{3}He abundance can presently be measured.

The abundance of ^{3}He was measured in high-metallicity Solar system objects (Geiss & Gloeckler 1998) or Milky Way H II regions (Bania et al. 2002). Therefore, it hardly can be considered as a primordial abundance.

According to standard chemical evolution model, ^{3}He/H should grow with 1) time, 2) metallicity and 3) decreasing of galactocentric distance. Contrary to that, no dependence

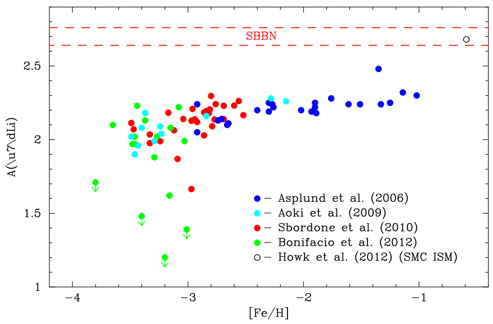

Fig. 2. ^{7}Li abundances $A(^7\mathrm{Li})\equiv 12+\log(^7\mathrm{Li/H})$ as a function of metallicity [Fe/H] in halo turn-off stars (blue, red, green and cyan filled circles). The ^{7}Li abundance in the Small Magellanic Cloud ISM by Howk et al. (2012) is shown by black open circle. The range of the SBBN primordial ^{7}Li abundance from the data of Planck mission (Planck Collaboration 2013) is shown by dashed lines.

on metallicity and galactocentric distance is found for Milky Way H II regions (Bania et al. 2002, 2010). Furthermore, similar ^{3}He/H measured in H II regions and in the Solar system implies that ^{3}He abundance did not vary with time during last ∼ 5 Gyr. The disagreement between observations and models suggests that low-mass stars fail to enrich the ISM with ^{3}He produced during main-sequence stage (Bania et al. 2010). Apparently, some unaccounted mechanisms of ^{3}He depletion in low-mass stars should be present. In particular, an extra-mixing in the red-giant-branch (RGB) stage is proposed which could strongly reduce ^{3}He yields (Bania et al. 2010).

Bania et al. (2002) adopted an upper limit on the primordial ^{3}He/H abundance of $(1.1\pm0.2)\times10^{-5}$ based on a single H II region S209 with the lowest metallicity and largest galactocentric distance in their sample. However, in spite of complexity of ^{3}He production and depletion in stars and the absence of bright nearby low-metallicity H II regions for ^{3}He abundance determination it is difficult to consider this isotope as good one for constraining cosmological models. However, ^{3}He abundances in the Milky Way objects could shed light on evolution of low-mass stars.

4. ^{7}Li abundance

Spite & Spite (1982) found that the ^{7}Li abundance derived from the Li I λ6707Å doublet in spectra of warm ($T_{\rm eff}$ > 5900K) halo turn-off stars with metallicity [Fe/H] ∼ −1 - −2.5 does not depend on metallicity. It was suggested that the existence of this "Li plateau" with small dispersion is due to the fact that ^{7}Li in stars studied by Spite & Spite (1982) was synthesised during BBN.

It was found in more recent studies (e.g., Asplund et al. 2006) that the mean ^{7}Li abundance in "Li plateau" is of $A(^7\mathrm{Li}) \equiv 12 + \log(^7\mathrm{Li/H}) = 2.2$. On the other hand, the SBBN value of ^{7}Li abundance, inferred from the WMAP and Planck measurements of microwave background radiation, is ∼ 3 times higher, corresponding to $A(^7\mathrm{Li}) = 2.7$. Two different explanations of this difference were proposed (and summarized, e.g., in Iocco et al. 2009; Pospelov & Pradler 2010): 1) unaccounted stellar processes do exist, which deplete ^{7}Li; 2) the BBN was non-standard.

However, recent observations by, e.g., Aoki et al. (2009), Sbordone et al. (2010), Bonifacio et al. (2012) demonstrated the "meltdown" of the "Li plateau": the dispersion of ^{7}Li abundance in halo turn-off stars at metallicities [Fe/H] < −2.5 is highly increased (Fig. 2). Upper values of $A(^7\mathrm{Li})$ in these stars are consistent with the "plateau" value, but there are many stars with very low ^{7}Li abundance. These findings strengthen the point of view that the ^{7}Li "plateau" abundance is not primordial and ^{7}Li in halo turn-off stars is depleted by stellar processes.

Spite et al. (2012) discussed different mechanisms inside stars which would result in ^{7}Li depletion. However, for the moment, no mechanisms were found, which explain altogether the very small dispersion of the "plateau" abundances and its strong increase at lower metallicities. Iocco (2012) analysed some exotic BBN models with injection of high-energy, non-thermal particles during BBN, which can modify primordial abundances. However, no compelling evidence was found in favour of these models. Depletion of ^{7}Li in these models is associated with in-

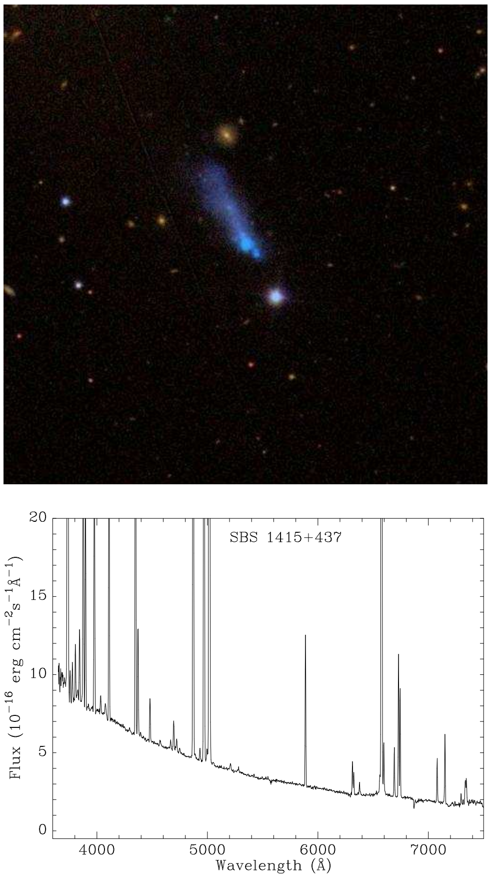

Fig. 3. SDSS *gri* composite image (top) and MMT spectrum (bottom) of cometary BCD SBS 1415+437.

creasing of D abundance. In spite of the very good agreement between observationally inferred and SBBN predicted D/H ratios, this possibility seems to be unlikely.

It is to note the first determination of ^{7}Li abundance in the Small Magellanic Cloud (SMC) ISM by Howk et al. (2012), which is consistent with SBBN abundance (black symbol in Fig. 2). However, the metallicity of the ISM in SMC is high. Therefore, it is not clear, how ^{7}Li abundance in such processed material with high level of astration is linked to the primordial abundance.

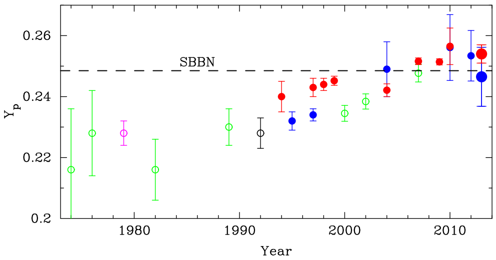

Fig. 4. History of the primordial ^{4}He mass fraction Y_p determination. Magenta open circle is from Legueux et al. (1979), black open circle is from Pagel et al. (1992), green open circles are from Peimbert & Torres-Peimbert (1974, 1976), Rayo et al. (1982), Torres-Peimbert et al. (1989), and Peimbert et al. (2000, 2002, 2007), blue filled circles are from Olive & Steigman (1995), Olive et al. (1997), Olive & Skillman (2004), and Aver et al. (2010, 2012, 2013), red filled circles are from Izotov et al. (1994, 1997, 1999, 2007, 2013), and Izotov & Thuan (1998, 2004, 2010). Two most recent Y_p values by Izotov et al. (2013) and Aver et al. (2013) are shown by large symbols. The SBBN value is shown by dashed line.

5. ^{6}Li/^{7}Li isotope ratio

The ^{6}Li/^{7}Li isotope ratio in halo turn-off has been considered as the consistency test of the SBBN (e.g., Jedamzik & Pospelov 2009; Iocco et al. 2009). SBBN predicts very low ^{6}Li abundance, $\sim 10^4$ times lower than that of ^{7}Li. Subsequent cosmic-ray spallation processes can significantly increase the ^{6}Li/^{7}Li isotope ratio, but at metallicities [Fe/H] < -2 these processes would result in ^{6}Li/^{7}Li less than 1% (Prantzos 2012).

Since ^{6}Li and ^{7}Li lines are blended in spectra of stars, the ^{6}Li/^{7}Li ratio can be derived from asymmetry of Li I λ6707Å line in high-quality spectra with SNR $\gtrsim$ 1000.

The detection of ^{6}Li isotope with the ^{6}Li/^{7}Li ratio of $\sim$ 5 - 10% was announced in several papers (e.g., Smith et al. 1993, 1998; Asplund et al. 2006). However, asymmetric Li I λ6707Å profiles can be not only due to the high ^{6}Li abundance but also due to convection, which is present in turn-off halo stars. Therefore, the simplifying assumptions of the hydrostatic equilibrium in one-dimensional models with local thermodynamic

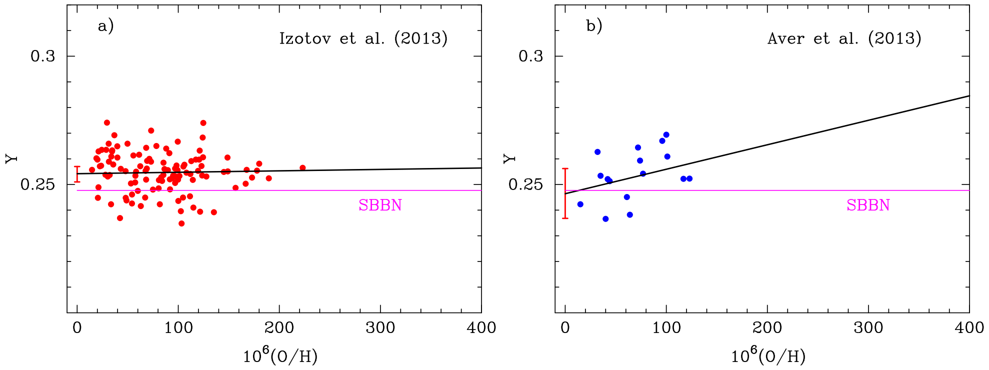

Fig. 5. (a) Y - O/H for the sample of 111 H II regions with the Hβ emission-line equivalent width EW(Hβ)≥150Å, with the excitation parameter x=O^{2+}/O ≥0.8 and with 1σ error in $Y \leq$ 3% (Izotov et al. 2013). The continuous black line represents the linear regression. The SBBN value is indicated by magenta solid line. (b) Same as in (a) but for Aver et al. (2013) sample of 16 BCDs.

equilibrium (LTE) would result in incorrect high values of ^{6}Li abundance (Cayrel et al. 2007).

This was demonstrated by Lind et al. (2013) who considered NLTE line formation and three-dimensional hydrodynamical model atmospheres. They found no detection of ^{6}Li at 2σ level (^{6}Li/^{7}Li < 1%) in their sample stars. This result weakens the possibility of non-standard BBN ^{6}Li production.

6. ^{4}He abundance

^{4}He is the most abundant element produced during the BBN. At variance with other light elements, its primordial abundance measured in terms of mass fraction $Y_{\rm p}$ is most sensitive to the expansion rate of the Universe. Therefore, $Y_{\rm p}$ can be used to constrain the existence of additional relativistic particles during the BBN epoch, such as sterile neutrinos.

The best objects for the determination of the primordial ^{4}He abundance are low-metallicity blue compact dwarf (BCD) galaxies, which show in their spectra strong emission lines (Fig. 3), allowing reliable determination of the electron temperature $T_{\rm e}$, the electron number density $N_{\rm e}$, and element abundances. ^{4}He mass fraction Y in BCDs is derived from recombination intensity ratios of several helium and hydrogen lines. The relation Y – O/H for a sample of BCDs proposed by Peimbert & Torres-Peimbert (1974, 1976) is frequently used to derive the primordial mass fraction $Y_{\rm p}$ extrapolating the relation to O/H = 0.

However, because $Y_{\rm p}$ only logarithmically depends on $\Omega_{\rm b}$, it should be derived with accuracy better than 1% to put useful cosmological constraints.

First, observational data have to be of good quality and should constitute a large sample to reduce statistical uncertainties. Second, most recent and accurate He I and H line emissivities should be used.

Third, to reduce systematic uncertainties, different effects and corrections for them should be taken into account. These are

1) interstellar reddening;
2) underlying stellar absorption in the H and He I emission lines;
3) collisional excitation of the He I emission lines;
4) fluorescence of the He I lines;
5) collisional excitation and fluorescence of the hydrogen lines;
6) possible departures from case B in the emissivities of H and He I lines;
7) the temperature structure of the H II region;
8) the ionization structure of the H II region;
9) shocks.

All these effects were considered, e.g., in Izotov et al. (2013) (see also references therein).

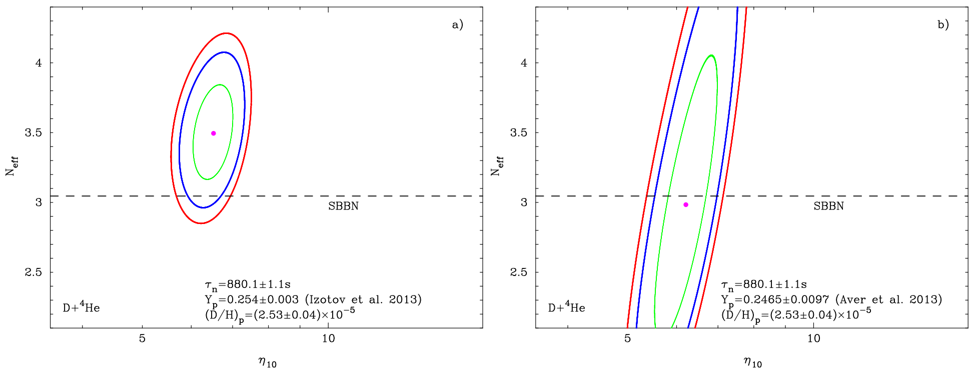

Fig. 6. (a) Joint fits to the baryon-to-photon number ratio, $\eta_{10} = 10^{10}\,\eta$, and the equivalent number of light neutrino species $N_{\rm eff}$, using a χ^2 analysis with the code developed by Fiorentini et al. (1998) and Lisi et al. (1999). The value of the primordial ^{4}He abundance has been set to $Y_{\rm p}$ = 0.254±0.003 (Izotov et al. 2013) and that of (D/H)$_p$ is taken from Cooke et al. (2013). The filled circle corresponds to $\chi^2 = \chi^2_{min} = 0$. Solid lines from the inside out correspond to confidence levels of 68.3%, 95.4%, and 99.0%, respectively. The SBBN value $N_{\rm eff}$ = 3.046 is shown with a dashed line. (b) Same as in (a), but the value of the primordial ^{4}He abundance has been set to $Y_{\rm p}$ = 0.2465±0.0097 (Aver et al. 2013).

History of $Y_{\rm p}$ determinations since 70th is shown in Fig. 4. The tendency of $Y_{\rm p}$ increase is caused by the use of more realistic He I line emissivities and more accurate corrections for different systematic effects. Two most recent $Y_{\rm p}$'s by Izotov et al. (2013) and Aver et al. (2013) derived with the use of the latest He I emissivities by Porter et al. (2013) are shown by large symbols. They differ by ∼3% but both at 2σ level are consistent with the SBBN value of 0.2477±0.0001 (Planck Collaboration 2013).

Linear regressions Y – O/H in these two most recent studies are compared in Fig. 5. Izotov et al. (2013) used a sample of 111 BCDs with the most accurate Y determinations and derived $Y_{\rm p}$ = 0.254±0.003. On the other hand, Aver et al. (2013) considered only 16 BCDs from the Izotov and collaborators sample and obtained $Y_{\rm p}$ = 0.2465±0.0097. The difference in $Y_{\rm p}$ values is caused mainly by the difference in slopes of linear regressions, which in the case of small sample by Aver et al. (2013) is highly uncertain. Despite of this difference, both samples are very similar. In particular, the average Y in samples by Izotov et al. (2013) and Aver et al. (2013) are ∼ 0.255 and ∼ 0.254, respectively, and they agree with $Y_{\rm p}$ derived by Izotov et al. (2013). More than ∼75% of BCDs in both samples have Y's above the SBBN value. This analysis indicates that the use of average Y for $Y_{\rm p}$ determination could be more preferable as compared to linear regressions for small samples because of highly uncertain slope of regression (e.g., Steigman 2006).

I use both values of $Y_{\rm p}$ together with the primordial deuterium abundance by Cooke et al. (2013) to produce joints fits to baryon-to-photon number ratio η and the equivalent number of light neutrino species $N_{\rm eff}$ (Fig. 6). The joint fit with $Y_{\rm p}$ = 0.254±0.003 from Izotov et al. (2013) is resulted in $N_{\rm eff}$ = 3.5±0.3, which is compared well to the Planck value of $N_{\rm eff}$ = 3.3±0.3 (Planck Collaboration 2013), but it by ∼2σ is above the SBBN value. On the other hand, $N_{\rm eff}$ = 3.0±1.1 inferred from $Y_{\rm p}$ = 0.2465±0.0097 by Aver et al. (2013), although formally consistent with the SBBN value, puts very weak cosmological constraints because of the large errors.

In perspective, the primordial ^{4}He abundance value could be improved. First, the discovery of new low-metallicity emission-line galaxies with high-excitation H II regions is highly important. Unfortunately, this is not easy task. Izotov et al. (2012) presented a list of most metal-deficient galaxies with 12 + log O/H < 7.35, including those found in

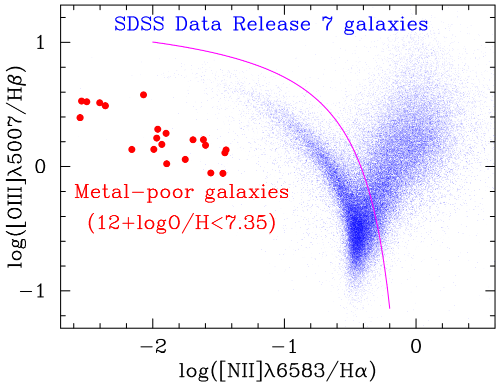

Fig. 7. The Baldwin-Phillips-Terlevich diagram (Baldwin et al. 1981) for emission-line galaxies. The most-metal-deficient star-forming galaxies known (Izotov et al. 2012) are shown by red filled circles. Also, plotted are the 100 000 emission-line galaxies from SDSS DR7 (cloud of blue dots). The magenta solid line from Kauffmann et al. (2003) separates star-forming galaxies from active galactic nuclei. The latter lie in the right wing of the "butterfly".

a huge SDSS data base. All of them are located in the very scarcely populated regions on the diagnostic diagram [O III] 5007Å/Hβ vs [N II] 6583Å/Hα (Fig. 7) implying that they are extremely rare. Only few of them are suitable for the ^{4}He abundance determination. These are I Zw 18 (Searle & Sargent 1972), SBS 0335−052E (Izotov et al. 1990), SBS 0335−052W (Pustilnik et al. 1997), DDO 68 (Pustilnik et al. 2005), J2104−0035 (Izotov et al. 2006), and Leo P (Skillman et al. 2013). The remaining most metal-deficient galaxies have low-excitation H II regions, which are not suitable for reliable determination of the ^{4}He abundance.

Second, multiple observations by different investigators of the same galaxy would be important for decreasing statistical errors.

Third, the inclusion of the near-infrared strongest He I λ10830Å emission line (Izotov & Thuan 2011) could greatly improve the Y_p determination because this line is very sensitive to the collisional excitation and it can allow to much better constrain the electron temperature T_e and the electron number density N_e.

7. Conclusions

Recent determinations of light element abundances can be summarised as follows.

Primordial D and ^{4}He abundances are consistent with the SBBN, although there is a hint to the larger effective number N_eff of neutrino species as compared to SBBN predictions. Larger high-quality datasets are needed to improve D/H and Y_p and to put more stringent constraints on the non-SBBN models.

New results on the ^{7}Li and ^{6}Li abundance determinations weakened the possibility for the non-standard BBN depletion of ^{7}Li and production of ^{6}Li. Furthermore, present-day ^{3}He and ^{7}Li abundances are unlikely to be considered for constraining cosmological models. However, they are highly important for understanding evolution of low-mass stars.

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