IS PRIMORDIAL $^4$He TRULY FROM BIG BANG?

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ABSTRACT

Population III stars are now believed to contribute to the observed Near Infrared Background (NIRB) and heavy element pollution of the intergalactic medium. Here we show that a Pop III contribution to the primordial $^4$He abundance consistent with NIRB constraints, might mask a lower value for the Big Bang Nucleosynthesis (BBN) $^4$He abundance.

Key words: galaxies: formation - intergalactic medium - black holes - cosmology: theory

As observations start to explore cosmic epochs close to the formation of the first, so-called Population III (Pop III) stars, theoretical models provide increasingly detailed predictions on the properties and evolution of these objects. Bond, Carr & Arnett (1983) and Carr (1994), discussed a possible contribution of Pop III stars to the primordial $^4$He mass fraction ($Y_p$). The observational data at that time did not allow to check the validity of their hypothesis. Current experiments are able to determine $Y_p$ with a precision $\lesssim 1\%$ allowing further investigations of the problem. Such experiments are based on high signal-to-noise ratio spectra of a class of star-forming galaxies called Blue Compact Dwarf (BCD) galaxies. These are low-luminosity ($M_B \geq -18$) systems undergoing an intense burst of star formation occurring in a very compact region (less than 1 kpc) characterized by a blue color and a HII region-like emission-line optical spectrum, which dominates the galactic light. BCDs are among the most metal-deficient gas-rich galaxies known. Their gas has not
been processed through many generation of stars, and thus best approximates the pristine primordial composition. Thus, $Y_p$ can be derived accurately with only a small correction for helium produced in stars. Moreover, the theory of nebular emission is understood well enough to convert $^4$He emission-line strengths into abundances with the desired accuracy. $Y_p$ is generally determined (Peimbert & Torres-Peimbert 1974) by linear extrapolation of the $Y$– $O/H$ correlation to $O/H=0$, where $Y$ and $O/H$, are respectively the $^4$He mass fraction and the oxygen abundance relative to hydrogen of a sample of dwarf irregular and BCD galaxies. Based on a relatively large sample of 45 BCDs, Izotov & Thuan (1998) found $Y_{p,IT} = 0.2443 \pm 0.0015$ and a scaling $dY/d(O/H) = 4.5 \pm 1.9$.

The Pop III star comoving density as a function of redshift, $\rho_*(z)$, is given by

$$\rho_*(z) = f_* \frac{\Omega_b}{\Omega_M} \int_{M_{min}(z)}^{\infty} n(M_h, z) M_h dM_h,$$

where $n(M_h, z)$ is the comoving number density of dark matter halos of mass $M_h$ at redshift $z$ given by the Press & Schechter formalism (Press & Schechter 1974); the integral gives the dark matter mass per unit volume contained in dark matter halos with mass greater than $M_{min}(z)$, where $M_{min}$ (computed by Fuller & Couchman (2000)) is a cutoff mass below which halos cannot form stars due to the lack of cooling. $\Omega_M$ and $\Omega_b$ are the total matter and baryon density* in units of the critical density $\rho_c = 3H_0^2/8\pi G$. The ratio $\Omega_b/\Omega_M$ converts the integral into baryonic mass which is then turned into stars with an efficiency $f_*$. The latter is constrained by the contribution of the redshifted light of Pop III stars to the NIRB. The observational data in the NIR (see e.g. Hauser & Dwek (2001) and references therein) are well fitted by a model in which the contribution from Pop III stars is added to the “normal” galaxy background light (Salvaterra & Ferrara 2002), where the Pop III contribution is given by

$$I(\nu_0, z_0) = \frac{1}{4\pi} \int_{z_0}^{\infty} l_\nu(z, \phi) \rho_*(z) e^{-\tau_{eff}(\nu_0, z_0, z)} \frac{dl}{dz} dz,$$

with $l_\nu(z, \phi)$ being the specific luminosity of the population at redshift $z$, computed using the spectra for metal-free stars obtained by Schaerer (2002), $\phi$ is the initial mass function (IMF), $\nu = \nu_0(1+z)/(1+z_0)$, $\tau_{eff}(\nu_0, z_0, z)$ is the effective optical depth at $\nu_0$ of the IGM between redshift $z_0$ and $z$, and $dl/dz$ is the proper line element. The Pop III star formation efficiency required to account for the observed NIRB depends essentially only on IMF for

* We adopt the ‘concordance’ model values for the cosmological parameters: $h = 0.7$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.038$, $\sigma_8 = 0.9$, and $\Gamma = 0.21$, where $h$ is the dimensionless Hubble constant, $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$.
those objects, the redshift $z_{\text{end}}$ at which the formation of Pop III stars ends being constrained to be $z_{\text{end}} \approx 8.8$ by the J band data (Salvaterra & Ferrara 2002). In addition to the NIRB, an early star formation may contribute to the metal enrichment of the intergalactic medium (IGM). Although the enrichment history of the IGM at high redshift is very uncertain, mainly depending on the metal escape fraction from galaxies and their actual spatial distribution, it sounds reasonable to adopt the mean Ly$\alpha$ forest metallicity as a ‘reliable’ first-order estimate of the mean IGM metallicity. Ly$\alpha$ forest QSO absorption line experiments indicate a mean IGM metallicity of $\log(Z_{\text{IGM}}/Z_\odot) = -2.5 \pm 0.5$ at $z \sim 3$ (Davé et al. 1998, Telfer et al. 2002). Salvaterra & Ferrara (2002) have shown that this constraint is not exceeded by first stars if either [i] their primordial Initial Mass Function is a Salpeter one ($\phi(M) \propto M^{-2.35}$), in which pair instability supernovae (SN$\gamma\gamma$, i.e. progenitor stars with mass in the range 130-260 $M_\odot$ (Heger & Woosley 2002)) are the dominant sources of heavy elements, or [ii] only stars with masses in excess of 260 $M_\odot$ are formed, that lock their nucleosynthetic products into a very massive black hole (VMBH) remnant (Schneider et al. 2002). In the first case, the NIRB is well fitted with $f_* = 0.534$ and $z_{\text{end}} = 8.788$. For the second case, although the model seems to overproduce the VMBH density to respect of the estimate density of super massive black hole (SMBH) (Merritt & Ferrarese 2001), at the moment there is no strong reason to reject this model, since the connection between VMBHs and SMBHs is not clear. We adopted here $\phi(M) = \delta(1000 \ M_\odot)$ and the NIR data are reproduced with $f_* = 0.043$ and $z_{\text{end}} = 8.830$; we will use these $z_{\text{end}}$ values in the following. Note that, as stars more massive than about 300$M_\odot$ have virtually the same spectrum, the $\delta$-function distribution does not represent an unrealistic assumption (Bromm, Kudritzki & Loeb 2001). These two best fit models to the NIRB data are shown in Figure 1. Obviously, the NIRB fraction accounted for by PopIII stars is directly proportional to $f_*$; as a consequence the same linear dependence is found for $\Delta Y_p$, as it is clear from eq. 3 below and eq. 1.

The constraints on the IMF obtained from this fit can then be used to estimate the contribution of Pop III stars to $^4$He primordial abundance. This is given by

$$\Delta Y_p(\phi, z) = f_{He}(\phi) \Omega_*(\phi, z)/\Omega_b$$

(3)

where $\Omega_*(z) = \rho_*/\rho_c$; $f_{He}$ is the $^4$He fraction of the stellar mass ejected via supernova explosions and/or through mass-loss in a radiatively-driven wind (although Kudritzki (2002), has hinted that winds might not be effective at $Z = 0$, recent results show that winds can take place even in metal-free stars; Lentz, Hauschildt, Aufdenberg & Baron, in preparation);
its value depends on the adopted IMF, $\phi$. The $^4$He produced by SN$_{\gamma\gamma}$ explosions of Pop III stars has been computed by Heger & Woosley (2002). Stars with mass above 260 $M_\odot$ are likely to end up in VMBHs without $^4$He ejection. On the other hand, according to very recent calculations (Marigo, Chiosi & Kudritzki 2002), wind mass-loss is significant only for very massive objects (750-1000 $M_\odot$). For a 1000 $M_\odot$ non rotating star, 17.33% (0.03%) of the initial mass is ejected via mass-loss as helium (oxygen) during the stellar lifetime. A small amount of carbon and nitrogen is ejected as well. If rotation is taken into account the percentages are 16.97% (He) and 0.15% (O). Pulsational instabilities may not have sufficient time to drive appreciable mass-loss in metal free stars (Baraffe, Heger & Woosley 2001).

We calculate the contribution of Pop III stars to the $^4$He abundance according to eq. (3) down to redshift $z_{\text{end}}$ at which the formation of Pop III stars ends. For the Salpeter IMF (case [i] above) $\Delta Y_p$ is quite small, $\approx 2 \times 10^{-6}$ if mass-loss is not considered. This value doubles if one accounts for He ejected from 750-1000 $M_\odot$ stars via wind losses; inclusion of rotation does not change these conclusions. In case [ii] there is no contribution from SN$_{\gamma\gamma}$, since 1000 $M_\odot$ stars fall above the SN$_{\gamma\gamma}$ progenitor range; as already mentioned, mass-loss in a wind is instead quite efficient at ejecting $^4$He. The resulting contribution is $\Delta Y_p = 3.191 \times 10^{-3}$ (3.258$\times 10^{-3}$) in the rotating (non-rotating) case. Moreover, the gas is also enriched in oxygen\footnote{Following common notation, we use square brackets to express values in units of solar abundance, [O/H]=log(O/H) – log(O/H)$_\odot$, and use (O/H)$_\odot = 5 \times 10^{-4}$, where (O/H) is the abundance ratio of the two species by number.} to [O/H]=$-2.33$ (-3.02), leading to a mean IGM metallicity of log($Z/Z_\odot$) = $-2.52$ (-3.15). In Figure 2 we show the $^4$He data points from the Izotov & Thuan sample (Izotov & Thuan 1998) from which we have subtracted the best fit primordial value, $Y_{p,IT}$. Our results for the non-rotating and rotating cases are also indicated in the Figure by the square and triangle points. Both points fall beyond the 1$\sigma$ error line (and the non-rotating one beyond 2$\sigma$). Hence the conclusion is that a measure of the $^4$He primordial abundance extrapolated to zero metallicity from the values of currently sampled [O/H]$\gtrsim -1.6$ would include the contribution from the very first generation of stars and therefore overestimate the amount of ‘truly’ primordial, BBN $^4$He. As a result, a correct determination of BBN $^4$He can only be made by sampling a strictly metal-free gas: any metal-enriched gas will already bear the signature of the $^4$He production of Pop III stars. A similar conclusion, although based on totally different arguments, has been suggested in the past (Mathews, Boyd & Fuller 1993). We note that the exact horizontal position of the theoretical points
is affected by the systematic uncertainty introduced by the implicit assumption made of a homogeneous distribution of the stellar nucleosynthetic products; such error is difficult to estimate. In general, as observations are pushed to lower metallicity gas, we expect the scattering in the data to increase as a result of the inhomogeneous distribution of oxygen, which is presumably enhanced close to the most actively star forming regions of the universe.

We reiterate that the value for $\Delta Y_p$ here inferred has to be considered as an upper limit, since a broader IMF in the range $300$-$1000$ $M_\odot$ leads to a lower contribution.

The inferred value of $\Delta Y_p$ gives us a measure of the accuracy with which $Y_p$ can be measured though current observations of this type. In the most extreme case we can expect $Y_p = Y_{p,\text{IT}} - \Delta Y_p = 0.2443 - 3.258 \times 10^{-3} = 0.241$. Is this low value at odd with BBN theory? It is well known that there is a tension between theoretical BBN predictions and observed abundances, in the sense that the latter typically fall short, particularly for $^4$He and $^7$Li. The further decrease of $^4$He abundance suggested here would aggravate the discrepancy, a fact which should lead us to consider even more seriously non-standard BBN models. Similar arguments apply if one considers D and $^4$He data simultaneously: observations of high-$z$ QSO absorbers seem to suggest a low primordial deuterium abundance, implying high nucleon-to-baryon ratio and $Y_p$ values. The contribution from Pop III stars will instead tend to decrease $Y_p$, a problem which would be exacerbated if we are to believe lower (with respect to the IT one) determinations of such quantity, $Y_p = 0.234\pm0.003$, obtained by other groups (Olive, Skillman & Steigman 1997). A lower $Y_p$ value would require a slower expansion of the radiation-dominated universe. This behavior is predicted by a class of so-called “extended quintessence” models, as a result of a decrease of the effective gravitational constant $G$.

Obviously, there is a lot that we can learn from BBN element abundance measurements.

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REFERENCES

Figure 1 Caption

Best fit results of the NIRB data (Salvaterra & Ferrara 2002). Dotted line: Salpeter IMF $z_{end} = 8.788$, $f_* = 0.534$. Solid line: $\phi = \delta(1000 \, M_\odot) \, z_{end} = 8.83 \, f_* = 0.043$. The small filled circles are the NIRS data (Matsumoto et al. 2000). The open symbols are the DIRBE results: squares for Wright (2001), diamonds for Cambrésy et al. (2001), and circles for Gorjian et al. (2000). The big filled circle is the Kiso star count measurement. The errors are at 1$\sigma$ and for all the data the Kelsall’s model (Kelsall et al. 1998) for the zodiacal light is applied. The “normal” galaxy contribution is estimated from the Subaru Deep Field (Totani et al. 2001). For $\lambda > 2.2 \, \mu m$ a zero contribution from normal galaxies to the NIRB is assumed.
Figure 2 Caption

Effect of Pop III stars on the $^4$He primordial abundance determination. The plot shows the $^4$He abundance, $Y$, to which the estimate by Izotov & Thuan, $Y_{p,IT}$ (Izotov & Thuan 1998) has been subtracted, as a function of the oxygen content of the galaxy. The triangle (square) represents the $^4$He abundance obtained taking into account the helium ejected via mass-loss from rotating (non-rotating) Pop III stars. The black dots are the data of the sample of Izotov & Thuan (1998). The solid line is the best fit relation $Y - O/H$ and the dashed lines represent the corresponding $1\sigma$ errors (Izotov & Thuan 1998).