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Big-bang nucleosynthesis: A probe of the early Universe

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ABSTRACT

Primordial nucleosynthesis is one of the three observational evidences for the Big-Bang model. Even though they span a range of nine orders of magnitude, there is indeed a good overall agreement between primordial abundances of ^{4}He, D, ^{3}He and ^{7}He either deduced from observation or primordial nucleosynthesis. This comparison was used for the determination of the baryonic density of the Universe. For this purpose, it is now superseded by the analysis of the Cosmic Microwave Background radiation anisotropies. Big-Bang nucleosynthesis remains, nevertheless, a valuable tool to probe the physics of the early Universe.

1. Introduction

There are presently three observational evidences for the Big-Bang model: the universal expansion, the Cosmic Microwave Background (CMB) radiation and Primordial or Big-Bang Nucleosynthesis (BBN).

The Hubble law states that the recession velocity of a galaxy is proportional to its distance: $V_{\rm rec} = H_0 \times D$ where H_0 is the Hubble constant. (It is usual to parametrize H_0 as $H_0 = h \times 100\,{\rm km/s/Mpc}$ with $h \approx 73$ [1].) It is a direct consequence of the expansion of the Universe assuming that spatial dimensions are all proportional to a scale factor $a(t)$ that increases with time. Wavelengths are also affected by the expansion, $\lambda \propto a(t)$, so that the *redshift* z is given by

$$z \equiv \lambda_0/\lambda - 1 = a_0/a - 1 \qquad (1)$$

where a (λ) and a_0 (λ_0) are the scale factors (wavelengths), respectively at emission and present times.[1]

Recombination of the free electrons with protons occurs when the temperature drops below 3000 K. Space, now filled with neutral atoms, becomes transparent for the first time and thermalized photons are free to roam the Universe. Because of the expansion, photons are affected by redshift so that their present temperature has now dropped to ≈ 2.725 K bringing this radiation into the microwave domain.

The third evidence for a hot Big-Bang comes from the primordial abundances of the "light elements": ^{4}He, D, ^{3}He and ^{7}He. They are produced during the first ≈ 20 min of the Universe when it was dense and hot enough for nuclear reactions to take place. These primordial abundances can, in principle, be deduced from astronomical observations of objects that were formed shortly after the Big-Bang. When compared with BBN calculations, the overall agreement spans nine orders of magnitudes.

BBN used to be the only method to determine the baryonic content of the Universe. The number of free parameters entering Standard BBN have decreased with time. The number of light neutrino families is known from the measurement of the Z^0 width by LEP experiments at CERN: $N_\nu = 2.9840 \pm 0.0082$ [2]. The lifetime of the neutron (entering in weak reaction rate calculations) and the nuclear reaction rates have been measured in nuclear physics laboratories. The last parameter to have been independently determined is the baryonic density of the Universe which is now deduced from the observations of the anisotropies of the CMB radiation. When considering density components of the Universe, it is convenient to refer to the *critical density* which corresponds to a flat 3D-space. It is given by

$$\rho_{0,{\rm C}} = \frac{3H_0^2}{8\pi G} = 1.88h^2 \times 10^{-29}\,{\rm g/cm^3} \qquad (2)$$

where G is the gravitational constant. It corresponds to a density of a few hydrogen atoms per cubic meter or one typical galaxy per cubic megaparsec. Densities are now given relative to $\rho_{0,{\rm C}}$ with the notation $\Omega \equiv \rho/\rho_{0,{\rm C}}$.

Table 1 gives the principal components to the density of the Universe. The total density is very close to the critical density but is dominated by vacuum energy and dark matter contributions. The baryonic matter only amounts to $\approx 4\%$ of the total density or 17% of the total matter content. What we observe with our telescopes corresponds to only $\sim 10^{-3}$ of the total. Is is usual to introduce η, the number of photons per baryon which remains constant during the expansion and is directly related to $\Omega_{\rm b}$ by $\Omega_{\rm b} \cdot h^2 = 3.65 \times 10^7 \eta$ with $\Omega_{\rm b} \cdot h^2 = 0.02230^{+0.00075}_{-0.00073}$ ("WMAP only" [3]).

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[1] Present values are usually labeled with index 0.

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Table 1
Density components of the Universe, adapted from Ref. [1].

Radiation (CMB) energy	$\Omega_{R(CMB)}$	$\approx 5 \times 10^{-5}$
Visible matter	Ω_L	≈ 0.003
Baryonic matter	Ω_b	≈ 0.04
Matter (dark+baryonic)	Ω_M	≈ 0.3
Vacuum energy	Ω_Λ	≈ 0.7
Total	Ω_T	≈ 1

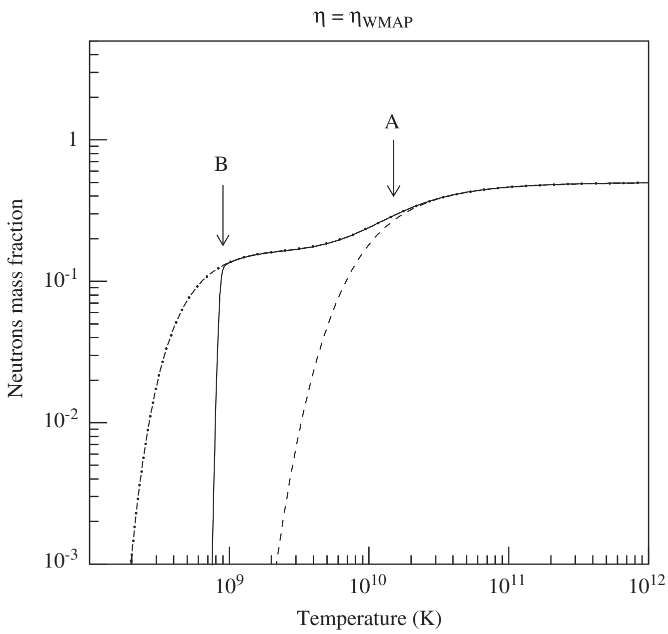

Fig. 1. Neutron mass fraction as a function of temperature. The curves represent the $n \leftrightarrow p$ equilibrium (dashed line), the free neutron decay (dash-dotted line) and the full network calculation (solid line).

2. Physics of the expanding Universe in the BBN era

At temperatures slightly above 10^{10} K, the particles present are: photons, electrons, positrons, the three families of neutrinos and antineutrinos, plus a few neutrons and protons. All these particles are in thermal equilibrium so that the numbers of neutrons and protons are simply related (Fig. 1) by $N_n/N_p = \exp(-Q_{np}/k_B T)$ where $Q_{np} = 1.29$ MeV is the neutron–proton mass difference. This holds until $T \approx 10^{10}$ K, when the $n \leftrightarrow p$ reactions ($\nu_e + n \leftrightarrow e^- + p$ and $\bar{\nu}_e + p \leftrightarrow e^+ + n$) become slower than the rate of expansion $H(t)$ (label "A" in Fig. 1). Afterwards, the ratio at *freezeout* $N_n/N_p \approx 0.2$ slightly decreases due to free neutron beta decay until the temperature is low enough ($T \approx 10^9$ K) for the first nuclear reaction $n + p \rightarrow D + \gamma$ to become faster than the reverse photodisintegration ($D + \gamma \rightarrow n + p$) that up to now prevented the production of heavier nuclei (label "B" in Fig. 1). From that point on, the remaining neutrons almost entirely end up bound in ^{4}He while only traces of D, ^{3}He and ^{7}Li are produced.

The ^{4}He yield is directly related to the N_n/N_p ratio at freezeout occurring if the expansion rate $H(t)$ is comparable to the weak rates. $H(t)$ is obtained from the Einstein equation that links the curvature and energy–momentum tensors. The first one is derived from the metrics (Friedmann–Lemaître–Robertson–Walker),

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin\theta d\phi^2)\right) \quad (3)$$

which represents the *Cosmological Principle*: homogeneity and isotropy of the Universe. $a(t)$ is the above-mentioned scale factor and $k = 0$ or ± 1 marks the absence or sign of space curvature. In an appropriate (free falling) referential, the energy–momentum tensor has only non-zero diagonal elements: (ρ, p, p, p) where ρ and p are the energy density and pressure of the fluid. It leads to the Friedmann equation that links the rate of expansion to the energy density ρ:

$$H(z) \equiv \frac{1}{a}\frac{da}{dt} = \sqrt{\frac{8\pi G\rho}{3}} = H_0 \Omega^{1/2}(z) \quad (4)$$

with (Eq. (2)),

$$\Omega(z) \equiv \Omega_M(z+1)^3 + \Omega_R(z+1)^4 + \Omega_\Lambda + (1-\Omega_T)(z+1)^2 \quad (5)$$

Given the values from Table 1, at BBN when $z \sim 10^8$, the dominant term is the "radiation" term, Ω_R. This corresponds to all the relativistic particles whose energies also scale as a^{-1} in addition to the a^{-3} number density factor. The important consequence is that during BBN, $H(t)$ is only governed by relativistic particles while the baryons, cold dark matter, cosmological constant or curvature terms play no role (Eq. (5)). The radiation density for species i, $\rho_{R;i}$, is given by the Stefan–Boltzmann law:

$$\rho_{R;i} = g_i \frac{k_B^2 \pi^2}{30\hbar^3} T_i^4 \equiv \frac{g_i}{2} a_R T_i^4 \quad \text{(bosons)} \quad (6)$$

where g_i is the spin factor and a_R the radiation constant. For fermions (e.g. electrons), an additional factor of $\frac{7}{8}$ must be inserted. In the radiation dominated era, in particular during BBN, the expansion rate is hence simply given by

$$H = \sqrt{\frac{8\pi G a_R g_{eff}(T)}{6}} \times T^2. \quad (7)$$

The effective spin factor $g_{eff}(T)$ includes contributions from photons ($g_\gamma \equiv 2$), neutrinos ($g_\nu = 2 \times N_\nu \frac{7}{8}(T_\nu/T_\gamma)^4$ as $T_\nu \neq T_\gamma \equiv T$, with $N_\nu = 3$ the number of neutrino families) and electrons/positrons (from $2 \times 2 \times \frac{7}{8}$ for $T \gg m_e$ to 0 for $T \ll m_e$). When particles annihilate the released energy is shared among the other particles they were in equilibrium with. As neutrinos decouple from other particles *before* electron–positron annihilation they do not take advantage of the corresponding reheating.

3. Primordial abundances

During the evolution of the Galaxy, nucleosynthesis takes place mainly in massive stars which release matter enriched in heavy elements into the interstellar medium when they explode as supernovae. Accordingly, the abundance of heavy elements in the gas, at the origin of star formation, increases with time. The observed abundance of *metals*[2] is hence an indication of its age: the older the lower the *metallicity*. Primordial abundances are hence extracted from observations of objects which are thought to be the most primitive followed by an extrapolation to zero metallicity.

Fig. 2 shows observations of lithium, beryllium and boron at the surface of low metallicity stars found in the halo of our galaxy. The abundances of beryllium and boron increase with metallicity (i.e. with time) confirming that these elements are continuously

[2] In astrophysics, *metals* means all elements with $Z > 2$ and the abundance of metals is called *metallicity*. Logarithm of metallicity relative to solar ($\odot$) is often used with the notation $[X/H] = \log(X/H) - \log(X_\odot/H_\odot)$ where X is usually Fe. Hence, for instance, $[Fe/H] = 0$ or -3 correspond to a solar, or 10^{-3} solar metallicity.