INTERSTELLAR ABUNDANCES OF THE LIGHT ELEMENTS

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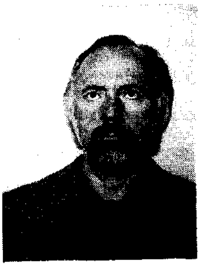

ABSTRACT

Primordial nucleosynthesis is considered as a pillar of the Big Bang theory. The predicted abundances of the light elements deuterium, helium 3 and 4 and lithium 7 cover a range of about 10 decades and nevertheless generally agree with observational data. We briefly review the current status of observations and derived abundances in different interstellar media. From the healthy confrontation of theory with observations, limits on the baryonic density of the Universe are outlined, as well as some potential problems with galactic evolution.

INTRODUCTION

The expansion of the Universe is governed by its density ρ. In the framework of the General Relativity and assuming the Universe to be homogeneous and isotrope and the cosmological constant zero, one can define a critical density $\rho_c \equiv 3H_o^2/8\pi G$, in which H_o is the Hubble constant, still poorly known within a factor of ~ 2, and G the gravitation constant; ρ_c is of the order of few protons per m^3. If $\rho < \rho_c$, then the Universe will expand forever; if $\rho > \rho_c$, it will recollapse; if $\rho = \rho_c$, the Universe is flat and asymptotically expanding. This latter case corresponds to the closure density: $\Omega = \rho/\rho_c = 1$. A major problem is therefore to derive the density parameter Ω.

This expanding Universe is today filled with a black body radiation at a temperature measured for instance with the COBE satellite to be $T_\gamma = 2.726$ K, which corresponds to a number of photons $n_\gamma = 411$ cm^{-3}. The hot, dense, early Universe was therefore once a primordial nuclear reactor. During the first hundreds seconds or so, when thermal energies were around 0.1 Mev, the light elements deuterium, helium 3 and 4 and lithium 7 were synthesized in astrophysically interesting quantities. The Big Bang Nucleosynthesis theory (BBN) thus predicts these abundances and inferes a baryon density parameter $\Omega_B \sim 1.5 \times 10^8\ \eta\ h_{50}^{-2}$, where $h_{50} = H_o/50$ km/s/Mpc, which depends on the one astrophysical parameter of the BBN[1,2) the baryons to photons ratio $\eta = n_B/n_\gamma$.

Is there a range of values of η such that all the predicted abundances are consistent with the inferred primordial abundances derived from the observational data? Furthermore, how the deduced Ω_B – based on processes which occured about 15 Gyr ago – compares with the observed Universe at present?

In the next sections, we will very briefly highlight successively each of the light elements, from an observational point of view. Because the BBN abundance of D shows a steep dependence on η, it represents a crucial baryometer that deserves a more thorough discussion. Very recent data on Li and D are presented, and finally the above questions are discussed.

HELIUM 4

The path from observations to the primordial ^{4}He abundance is not straightforward. In stellar interiors, hydrogen is burned producing ^{4}He from generations to generations of stars. To minimize this enhancement, the most valuable observational sites are extragalactic H II regions with the lowest metallicities. It is the visual emission lines from the recombination of $^4He^+$ and $^4He^{++}$ as well as H^+ which are analyzed. By using only the hottest, highest excitation regions, the correction for the unobserved neutral helium is thought to be negligible. The best, most coherent data sets include a few dozen H II regions with oxygen and/or nitrogen abundances down to about 1% of solar. The extrapolation to zero metallicity yields:

$$Y_P = 0.228 \pm 0.005^{3)}$$

$$Y_P = 0.232 \pm 0.003^{4)}$$

where the error bars are 1σ statistical uncertainty.

It is worthwhile to recall that the BBN predictions for ^{4}He depend on the number of neutrino flavors. The overall comparison with the inferred Y_P implied only three ν flavors. It was a great success and a proof of maturity of the BBN theory when particle physics experiments with LEP at CERN beautifully confirmed in 1989 that indeed only three flavors do exist.

HELIUM 3

Whenever deuterium is cycled through stars it is burned to ^{3}He, some of it surviving in the cooler, outer stellar layers. Furthermore, low mass stars ($1 - 3\ M_\odot$) are net sources of ^{3}He. Thus, the primordial ^{3}He abundance is expected to increase with time. From observations of the hyperfine radio transition emission line of $^3He^+$ as well as radio recombination line of H^+ for about a dozen galactic H II regions, interstellar abundances are deduced through a detailed modeling of the emissive regions and lie in the range[5,6]:

$$^3\mathrm{He/H} = (0.9 - 5.4)\times 10^{-5}.$$

These abundance differences are claimed to be real[7] and moreover, it seems that an inverse galactocentric gradient might be present (lower abundances toward the Galactic center); both facts are difficult to understand with standard chemical evolution models.

From lunar experiments of direct exposure to the solar wind and from meteorites, a presolar $^3\mathrm{He/H} = (1.5 \pm 0.3)\times 10^{-5}$ is derived[8], definitively not lower than some of the present day interstellar values and as all these ones, much lower than the calculated values with evolutionary models. The problem with ^{3}He seems to be galactic instead of cosmological[9].

DEUTERIUM

BBN is the only known source of astrophysical deuterium. D is easily destroyed in stars, even during pre-main sequence evolution, so that its primordial abundance is predicted to be larger than that observed anywhere in the Universe, by a factor of $\sim$2 according to early classical astration models. It follows that the D+^{3}He primordial abundance should increase with time.

Prior to 1972, D was only measured on Earth in oceans; then, it has been observed in the solar system, in massive stars photospheres, and in the interstellar medium (ISM) through deuterated molecules, its hyperfine radio transition or Lyman absorption lines. A reanalysis of the solar system data yields the presolar values[8]:

$$D/H = (2.6 \pm 1)\times 10^{-5}$$
$$(D+{}^3He)/H = (4.1 \pm 1)\times 10^{-5}.$$

The more accurate deuterium abundance determinations are made in the diffuse ISM through the observations in the far UV of the Lyman line series of both H I and D I in absorption toward early type fast rotating stars or toward cool nearby stars superposed against the stellar emission line[10]. This was one of the major accomplishments of the Copernicus satellite from 1972 to 1980 which operated at a spectral resolution of 15 km/s, then followed by IUE but at a lower resolution and for Lyman–α only. One has to stress here the importance of the instrumental resolving power in order to resolve the different interstellar absorption components present in most of the lines of sight, even the shortest ones[11]. It is also worthwhile to recall the uncertainties possibly associated with the Doppler parameter of the lines in the common case with saturation effects. From a careful analysis (including discussion of potential stellar effects which could pollute the measurements) of about two dozens sight-lines (both toward early type and cool stars), one finds[10] a mean value:

$$(D/H)_{ISM} \sim (1. \pm 0.5)\times 10^{-5} \text{ by mass,}$$

along with evidences of possible significant variations of this ratio from one line of sight to the other, even on small scales.

Thanks to the high resolution ($\sim$ 3 km/s) of the Hubble Space Telescope, newer, beautiful data are available. Unfortunately however, only the very strong Lyman α line is observable with HST in the Galactic ISM, requiring thus nearby lines of sight for which the D I absorption is not blended with the H I one (the relative shift is $\sim$ 82 km/s). A very precise measurement toward the cool star Capella gives[12]:

$$(D/H)_{ISM} = 1.60 \pm 0.09(\text{random } 2\sigma \text{ error})\ [+0.05,-0.10 \text{ systematic error}]\times 10^{-5}$$

still compatible with the previous mean value, while toward Procyon, a delicate analysis related to the stellar profile does not permit to conclude that the D/H ratio is constant in the local ISM. It also follows that the presolar $(D+{}^3He)/H$ appears possibly larger than the corresponding ISM value, contrary to expectations but reflecting the ^{3}He problem mentionned above. Concerning the primordial D/H ratio, a hard lower limit is therefore:

$$(D/H)_P \geq 1.41\times 10^{-5},$$

independently of the poorly known Galactic chemical evolution models, and still compatible with the presolar value.

In order to get rid of the unknown stellar emission profile of cool stars, another approach is to use white dwarves as background sources. A first attempt with HST toward G191-B2B[13] has been unconclusive because of the multiple velocity structure of this sight-line, but nevertheless seems to indicate different D/H ratios from one cloud to another confirming thus the possible uncertainty on a meaningful mean ISM value.

Finally, HST has been used to derive again the deuterium abundance in Jupiter, thought to be representative of the proto-solar nebula. From modeling the Lyman α emission at the limb of the planet, D/H = $(6 \pm 1)\times10^{-5}$ is obtained[14], surprisingly higher than the current belief[15]. If confirmed, it would imply a presolar (D+^{3}He)/H value in even more contradiction with the ISM value and would favor a very high primordial $(D/H)_P$ ratio.

Beside continuing these observations, a major challenge is to look for deuterium in astrophysical sites closer to the early Universe, in terms of metallicities. In 1994, two independant groups reported the first detection of a deuterium Lyman–α line in an absorption system toward the same quasar, in a so-called "primordial" cloud at high redshift (z_{abs}=3.32) and low metallicity ($Z < 10^{-3}$ solar). One with the 10 m Keck Telescope at Hawaii[16] and the other with a 4 m telescope at Kitt Peak[17], both groups used about the same resolving power ($\sim$ 30000) and agreed on D/H $\approx$ $(19 - 25)\times10^{-5}$. If this surprisingly high value is really the deuterium abundance at $z = 3.32$, then the standard models of Galactic chemical evolution are very wrong! These indeed predict a deuterium astration factor in the range 2 to about 7, while at least a factor 12 would be required to reach the present local interstellar value[18]. Furthermore, such a high value implies a presolar ^{3}He abundance much larger than observed, again suggesting a problem with our understanding of the stellar and galactic evolution of ^{3}He.

More recently, a third group announced[19] a new D/H determination toward a second quasar. Also using the HIRES echelle spectrograph at the Keck Telescope, they claimed D/H $\sim 2\times10^{-5}$ in an absorption system at $z = 3.57$ with a somewhat higher Z than for the first QSO, which is then in agreement with current models. These two determinations toward QSOs are in complete disagreement; either one (or both) does not reflect the real primordial D/H ratio, or primordial nucleosynthesis was dramatically inhomogeneous. As a matter of fact, it is possible that the observed features are not due to deuterium at all but, rather, to a hydrogen line blueshifted by the right amount, thus mimicking the deuterium line and wrongly increasing the derived D/H ratio. The probability for such an accidental coincidence is not negligeable ($\sim$ 15%)[17]. Also, evidently in one case[19] there are two absorption components at the redshift of the observed system, perhaps leading to large error bars on the derived column-densities. Only a statistical study will resolve these points. Ground-based and HST observations are eargerly needed.

LITHIUM

Lithium 7 originates in the BBN with a primordial abundance ^{7}Li/H$\simeq 10^{-10}$, in excellent agreement with the observed uniformity of the Li abundance in very metal deficient Pop II stars[20]. During the Galactic evolution, both Li isotopes are created by spallation reactions of Galactic cosmic rays (GCR) interacting with the ISM that yield[21] ^{7}Li/H$\simeq 2 \times 10^{-10}$ in 10 Gyrs, with a ratio $(^7\mathrm{Li}/^6\mathrm{Li})_{GCR}$=1.4. The major problem is then to explain the observed Pop I Li abundance, $(^7\mathrm{Li/H})_{PopI} \sim 10^{-9}$, of which only 30% is accounted for by BBN and GCR spallation, as well as the high ^{7}Li/^{6}Li ratio measured in meteorites, representative of the solar system formation epoch 4.6 Gyrs ago, $(^7\mathrm{Li}/^6\mathrm{Li})_{\odot}$=12.3, whereas the above mechanisms predict a ratio around 2.

The existence of an extra stellar source of Li has been suggested, AGB C and S stars being the best candidates. GCR spallation alone tends to decrease the ^{7}Li/^{6}Li ratio with time, and one should observe today an interstellar ratio $\simeq$5–6 without production of Li in stars, or $\gtrsim$6 with a stellar production[22]. Measuring this ISM ratio thus provides a key test for the models of lithium evolution. If it is found to be $\lesssim$5, then another scenario would have to be considered. One way out would be to start with a primordial abundance ^{7}Li/H $\geq 10^{-9}$, together with some form of internal mixing that could very well reproduce the plateau observed for Pop II stars[23] and some rotational mechanisms to reproduce ^{7}Li abundances in stars of different metallicities[24]. However, there is no obvious way of yielding such a high primordial abundance since the inhomogeneous nucleosynthesis models still advocated few years ago to do so no longer work[21].

The only accessible resonance lines are those of the ^{7}Li I doublet around 670.78 nm, and a similar one for ^{6}Li I redshifted by 7.2 km/s. Due to the nearly complete ionisation to Li II in the ISM, the strongest equivalent widths expected are of the order of a few tenths of pm. Moreover, several interstellar components separated by few km/s are often present so that the resulting Li I absorption profile may be very complex. The only line of ^{6}Li that one may hope to resolve is the weaker one. Once again, it emphasizes the need for very high spectral resolution and signal to noise ratios. The first actual detection of ^{6}Li has been reported in 1993 toward ρ Oph[25], then followed by ζ Per and ζ Oph[26,27]. These last data[27] shows a S/N=7500 per pixel, and from a sophisticated analysis, it appears that two components are present with:

$(^7\mathrm{Li}/^6\mathrm{Li})_A$=8.6 $\pm$ 0.8 (random 2σ error) [$\pm$1.4 systematic error] and

$(^7\mathrm{Li}/^6\mathrm{Li})_B$=1.4 $^{+1.2}_{-0.5}$ (random 2σ error) [$\pm$0.6 systematic error].

Similar results are also found toward ρ Oph[28]. The higher ratio evidences a stellar source of ^{7}Li, while the lower one is extremely atypical.

The only standard way to reproduce a ratio as low as $\sim$2 in the ISM comes through a massive interaction of the GCR with the material of cloud B, a scenario which seems unrealistic as for now. Recently, a very elegant explanation has been suggested[29] which involves a SNII explosion inside an IS cloud, a new spallation process indeed able to produce a ratio $\simeq 3$. Just as for the D/H ratio on QSO lines of sight, obtaining a representative value of the interstellar ^{7}Li/^{6}Li ratio is no longer a matter of a few measurements but is a matter of statistics at a long term.

CONCLUSION

Until 1994, it seemed largely accepted that the predicted light element abundances were generally consistent with the inferred primordial abundances derived from the observational data if $\eta_{10} = 10^{10}\eta$ was taken in the fairly narrow range ~3–4 which corresponds to $0.04 \leq \Omega_B h_{50}^2 \leq 0.06$. Assuming $40 \leq H_o \leq 100$ km/s/Mpc, one gets for the present baryonic density of the Universe: $0.011 \leq \Omega_B \leq 0.093$, significantly lower than the closure density. Since the luminous matter density parameter Ω_L appears quite firmly established to lie in the range $(3–7)10^{-3}$, the existence of at least some baryonic dark matter in the Universe seems therefore inevitable. Also, the upper bound 0.09 strongly suggests the existence of non-baryonic dark matter when compared to Ω derived through different dynamical studies at different scales[30].

However, if one believes the very high D/H ratio $(19 - 25)\times 10^{-5}$ found in one quasar[16,17], it implies $\Omega_B \sim 0.009$ if one adopts a high value (~80 km/s/Mpc) for the Hubble constant as it is favored by recent observations of Cepheids in the Virgo cluster[31]. In this case, there is almost no more room for baryonic dark matter. Nevertheless, if H_o is indeed lower, then dark baryons are again viable. On the contrary, assuming the other QSO value[19] as more representative of $(D/H)_P$ induces no "dramatical" consequences. It is worthwhile to recall here the first preliminary results of the on-going microlensing experiments searching for baryonic dark matter in the form of brown dwarves in the halo of our Galaxy, which indicate that their mass fraction is less than ~20%[30].

The standard models for galactic evolution do not explain a very high $(D/H)_P$. From presolar and interstellar data on D (excluding the high, recent evaluation in Jupiter[14]) and ^{3}He, they lead to $Y_P \geq 0.241$. In contrast, we have seen that observations indicates $Y_P \leq 0.238$ at 2σ. This potential crisis is resolved[32] by accounting for possible systematic uncertainties in ^{4}He abundance determinations. Nevertheless, it has to be noted that a very high $(D/H)_P$ ($\sim 2\times 10^{-4}$) implies $Y_P \sim 0.23$ and $^7\mathrm{Li/H} \simeq 2 \times 10^{-10}$, in excellent agreement with the observations. This in turn would require much more efficient stellar destruction of ^{3}He and again questions our understanding of its evolution. Observations will hopefully decide.

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