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Nucleosynthesis [and Discussion]

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Nucleosynthesis

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Both Big-Bang and stellar nucleosynthesis have outcomes related to the density of baryonic matter, but whereas in the first case there is a standard model that makes very precise predictions of light element abundances as a function of the mean density of baryons in the Universe, in the second case various uncertainties permit only very limited conclusions to be drawn.

As far as Big-Bang synthesis and the light elements are concerned, existing results on D, ^{3}He and ^{7}Li indicate a value of $\Omega_N h_0^2$ greater than 0.01 and less than 0.025, where Ω_N is the ratio of baryonic density to the closure density and h_0 is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}; probably $0.5 \leqslant h_0 \leqslant 1$. New results on the primordial helium abundance give a still tighter upper limit to Ω_N, $\Omega_N h_0^2 < 0.013$, which when compared with redshift surveys giving $\Omega > 0.05$ implies that the observed matter can all be baryonic only if the various uncertainties are stretched to their limits.

1. INTRODUCTION

Nucleosynthesis, whether in the Big Bang or in stars, is by its nature related to baryonic matter, be it bright or dark. In the case of Big-Bang nucleosynthesis this relation is both intimate and universal, because all baryonic matter was involved and because the microwave background gives an indication that the Universe was once in a state of thermal equilibrium which enables very precise predictions to be made on the basis of a standard set of assumptions. These assumptions can be tested by observing the abundances of the light elements D, ^{3}He, ^{4}He and ^{7}Li, extrapolating them back as well as we can to their primordial or pregalactic values and seeing if they are consistent. If they are, which is what most people believe, the results give upper and lower limits to the average density of baryons, with the well-known result that there are too few baryons to close the Universe by a factor of at least five (Yang *et al.* 1984), probably ten.

Nucleosynthesis in stars also relates to the amount and distribution of baryonic matter, but the information we can derive is necessarily more parochial, because it refers to individual galaxies or parts of galaxies, and more uncertain, because there are still many unknown factors in the birth and evolution of stars and the way they exchange matter with the interstellar medium. In what follows I shall first discuss briefly what can and cannot be deduced about the distribution of matter from considerations of stellar nucleosynthesis and then return to the Big Bang and primordial abundances of the light elements, presenting some preliminary new results on helium and discussing their implications.

2. STELLAR NUCLEOSYNTHESIS

When stellar nucleosynthesis occurs in gas-rich disc systems like the solar neighbourhood and irregular galaxies, the resulting heavy-element content of the gas is related to its fractional mass chiefly through a single parameter called the yield, which is the ratio of heavy elements newly synthesized and ejected by a generation of stars to the mass locked up either in small stars with lifetimes longer than the age of the Universe or in compact remnants from the bigger stars which die leaving white dwarfs, neutron stars or black holes. Knowing the yield, one can then predict the heavy-element abundance or 'metallicity' as a function of the fractional mass of the system that is still in the form of gas. However, there are various reasons for mistrusting theoretical calculations of the yield, even when the mass spectrum of the stars is known, because we do not know which stars explode or how many brown dwarfs and Jupiters there are, the effect of close binaries is very uncertain, and the situation can be complicated by inflows and outflows of material to and from the system under consideration. It seems wiser, therefore, just to regard the yield as an empirical parameter.

What, then, can we say from nucleosynthesis arguments about the nature of dark matter? Larson (1986) examines the consequences of bimodal star formation, with a high-mass mode and a low-mass mode that occur in varying proportions. The high-mass mode dominates in the inner parts of large galaxies, accounting for radial abundance gradients, for the properties of starburst galaxies like M82 and NGC253, and for the correlation between mass, mass:light ratio and metallicity among elliptical galaxies, where the mass is dominated by compact remnants from old massive stars. In the solar neighbourhood, the high-mass mode dominated more in the past, leaving remnants in the form of cool white dwarfs, which provide the dark mass found by Bahcall (1984, 1986, this symposium), and the halo is dominated by black holes resulting from still more massive stars as first suggested by Truran & Cameron (1971). Hegyi & Olive (1986) and Hegyi *et al.* (1986) have given arguments to rule out various baryonic candidates for dark matter in the halo and disc, but the only one of their arguments that might invalidate Larson's picture is based on assumptions about the yield and the resulting metallicity, and this argument is unsound for reasons given above.

3. BIG-BANG NUCLEOSYNTHESIS AND THE ABUNDANCES OF THE LIGHT ELEMENTS

We now return to nucleosynthesis in the Big Bang according to the standard model, which has been very thoroughly reviewed by Yang *et al.* (1984), who also give a comprehensive discussion of the relevant observational data (see also Pagel 1982; Shaver *et al.* 1983; Boesgaard & Steigman 1985). Assuming the standard model with three light neutrino species, the predicted abundances of D, ^{3}He, ^{4}He and ^{7}Li depend on a single parameter η, the ratio of baryons to photons which was established after positron–electron annihilation one second after the Big Bang and has remained constant, at a value of the order of 10^{-10}, through the five minutes or so of nucleosynthesis and up to the present day (figure 1). Therefore η is related to the present density in the Universe through the known temperature $T = 2.7$ K of the microwave background and this in turn can be expressed in terms of the closure density required to give a flat Universe by the relation

$$\Omega_{\mathrm{N}} = 3.53 \times 10^7\, \eta h_0^{-2} (T/2.7\ \mathrm{K})^3, \tag{1}$$

where Ω_N is the fraction of the closure density provided by baryons and h_0 (believed to be between 0.5 and 1) is the Hubble constant in units of 100 km s^{-1} $Mpc^{-1} = (10^{10}\ a)^{-1}$.

Ω_N and hence η is also related to the mass:light ratio in galaxies that can be attributed to baryons, through the average luminosity density in the Universe. The visual luminosity density in solar luminosities per cubic megaparsec is

$$L = 2.3 \times 10^8\, h_0\, l \tag{2}$$

(Kirshner *et al.* 1983), where l is a dimensionless uncertainty factor of order unity ($0.75 \leqslant l \leqslant 1.25$) and the corresponding mass density, in units of the critical density, is

$$\Omega_{\mathrm{Gal}} = 8.3 \times 10^{-4}\, l\, h_0^{-1} \langle M/L \rangle = l \langle M/L \rangle / 1200\, h_0, \tag{3}$$

where $\langle M/L \rangle$ is the average mass:light ratio in galaxies. 1200 h_0 is thus a critical mass:light ratio that would just suffice to close the Universe. Equating Ω_{Gal} to Ω_N from (1), we find that

$$\langle M/L \rangle_N = 1200\, \Omega_N\, h_0 / l = 4.2 \times 10^{10}\, (\eta / l\, h_0)(T/2.7\ \mathrm{K})^3 \tag{4}$$

is the average mass:light ratio attributable to baryons.

We now look at the constraints placed on η, Ω_N and $\langle M/L \rangle_N$ by measurements of the abundances of the light elements, which are subject to various uncertainties, and their extrapolation back to pregalactic values, which involves yet more uncertainties.

Possibly the simplest case is that of ^{7}Li, which was discovered by Spite & Spite (1982) to be present in the atmospheres of subdwarf stars. These stars are very deficient in carbon and heavier elements (by factors of up to 1000 relative to the Sun), but the hotter subdwarfs have a very uniform content of ^{7}Li amounting to a tenth of that in the present-day interstellar medium (Spite *et al.* 1984); cooler subdwarfs (and also the Sun) have less ^{7}Li because they have convective envelopes mixing the atmosphere with deeper layers where lithium is destroyed. It is therefore plausible to follow Spite & Spite in their conclusion that the observed ^{7}Li abundance in subdwarfs is primordial and so directly comparable with the Big-Bang predictions. Allowing for a factor of two uncertainty in those predictions (Yang *et al.* 1984) and a 30% uncertainty in the abundance, one obtains the limits (see figure 1).

$$1.2 < 10^{10}\, \eta < 6.3, \quad 0.004 < \Omega_N\, h_0^2 < 0.022, \quad 5.0 < \langle M/L \rangle_N\, l\, h_0 < 26. \tag{5}$$

The cases of deuterium and ^{3}He are more complicated. Deuterium is observed in the interstellar medium both in atomic and in molecular form and its abundance has been deduced from *Copernicus* observations of atomic lines from diffuse clouds in several lines of sight. There is a large scatter with values of D:H ranging from 5×10^{-6} to 2.5×10^{-5} that has been attributed by Vidal-Madjar *et al.* (1983) to the existence of spurious signals from atomic hydrogen coming out of some of the target stars with a speed of 80 km s^{-1} that just mimics the isotopic shift and they accordingly adopt the lower limit. Dalgarno & Lepp (1984) have deduced an average value for D:H of about 1×10^{-5} from observations of DCO^+ and HCO^+ in seven molecular clouds after making a quantitative allowance for fractionation, but again the range of values obtained is quite wide and we do not have a good figure for the deuterium abundance in the interstellar medium.

^{3}He is also detectable in the interstellar medium by way of the hyperfine transition of $^3He^+$ at 3.46 cm which is emitted from ionized hydrogen (H II) regions, but here the situation is even

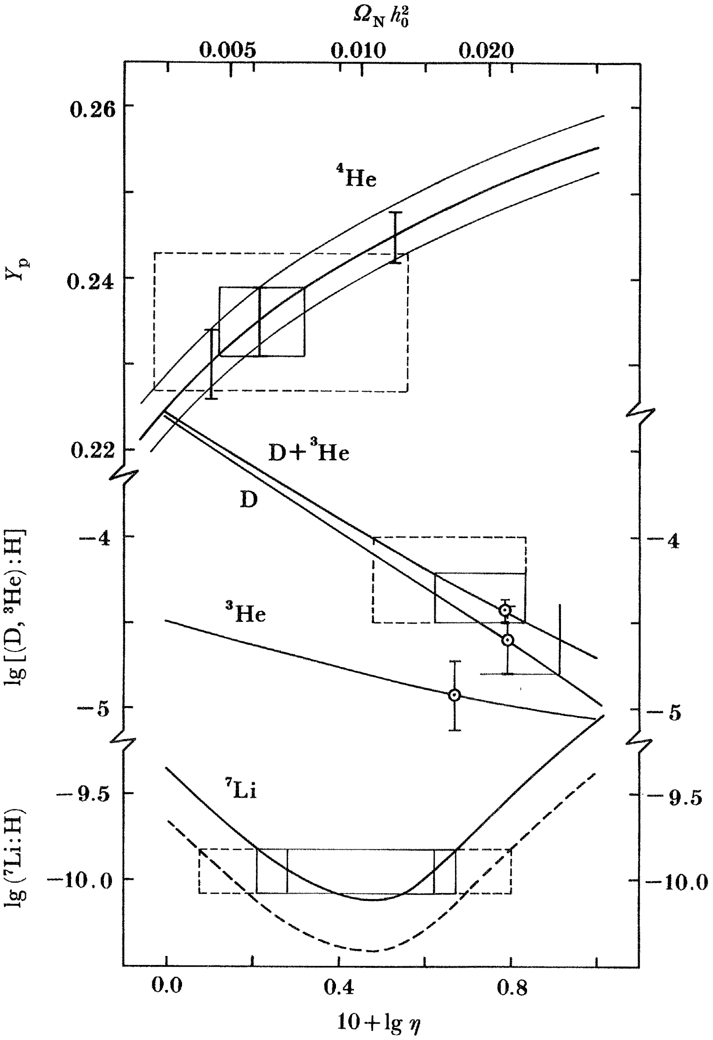

FIGURE 1. Predicted primordial abundances of light elements as a function of η, after Yang *et al.* (1984), assuming the standard model with three light neutrino flavours. Uncertainty limits are shown for ^{4}He (neutron halflife between 10.4 and 10.8 min) and for ^{7}Li (factor of two uncertainty; to aid clarity the upper limit is not shown). Observational data are shown with $\pm 1\sigma$ error bars for ^{4}He and ^{7}Li. 'Sun' symbols refer to protosolar values, the others to primordial values. Solid-line boxes show plausibly expected limits of error; broken-line boxes show estimated maximum errors.

more confusing because the observed ^{3}He:H ratios range from a very high value of 4×10^{-4} in one case to mere upper limits of as little as 2×10^{-5} (Rood *et al.* 1984).

It therefore seems advisable not to rely on the interstellar medium as a source of abundance estimates for D and ^{3}He and instead use only the data derived for the Solar System. The solar wind contains ^{3}He which is a result of both ^{3}He that was present at the Sun's birth and D that was present at the Sun's birth and later burned into ^{3}He, so that solar-wind ^{3}He gives a fairly precise estimate of the sum of presolar ^{3}He+D for which Yang *et al.* (1984) adopt

$$y_{23} \equiv (\mathrm{D}+{}^3\mathrm{He}):\mathrm{H\ presolar} = (3.7 \pm 0.3) \times 10^{-5}. \qquad (6)$$

The two components can be separated by heating carbonaceous chondrite meteorites to release older solar wind that contains only the presolar ^{3}He and subtracting this to get the deuterium, but the uncertainties then are greater although the order of magnitude ($D{:}H \approx 2.5 \times 10^{-5}$) is supported by observations of deuterated molecules in the atmosphere of Jupiter.

The main trouble with deuterium is that the amount observed either in the interstellar medium or in the proto-Solar System is only a lower limit to the primordial abundance, which is higher by an unknown factor owing to astration, that is the destruction of all deuterium in that part of the interstellar gas that has been recycled through stars. One day it may be possible to observe primordial deuterium in the 'Lyman-α' forest of absorption lines in the spectra of quasars (Sargent *et al.* 1980), or at least place interesting upper limits thereon but, so far, no significant results have yet been published.

To overcome the problem with deuterium, Yang *et al.* (1984) consider the evolution of the sum of $D+{}^3He$, on the grounds that when astration occurs, ^3He is destroyed only in the more massive stars, whereas in less massive stars ^3He survives and may even be enhanced. Consequently, a certain fraction of ^3He survives astration, and this fraction is estimated to be at least 0.25 and more likely higher, about 0.5, depending on the details of the stellar mass spectrum, chemical composition and rate of mass loss (Dearborn *et al.* 1986). In a simple one-cycle approximation, an upper limit to the primordial $D+{}^3He$ abundance y_{23p} is given by

$$y_{23p} \leqslant y_{23} + (1/g - 1)\, y_3, \tag{7}$$

where y_{23} is the sum of presolar D abundance y_2 and ^3He abundance y_3, and g is the fraction of ^3He that survives stellar processing. With the upper limits $y_{23} = 4 \times 10^{-5}, y_3 = 1.9 \times 10^{-5}$, (7) gives

$$y_{23p} \leqslant 5.9 \times 10^{-5} \quad \text{if} \quad g = 0.5, \tag{8}$$

$$y_{23p} \leqslant 9.7 \times 10^{-5} \quad \text{if} \quad g = 0.25. \tag{9}$$

These limits are shown in figure 1 as solid and broken-line error boxes respectively. The evolution of deuterium and ^3He has also been considered by Delbourgo-Salvador *et al.* (1985) with quite similar results. The result (9) places a lower limit on η leading with (5) to

$$3.0 < 10^{10}\,\eta < 6.3, \quad 0.011 < \Omega_N h_0^2 < 0.022, \quad 12.6 < \langle M/L\rangle_N\, l\, h_0 < 26. \tag{10}$$

4. Primordial helium abundance

Thus far the discussion of light-element abundances has followed that of Yang *et al.* (1984) quite closely, but the results have certain implications regarding helium and I am going to present some preliminary new data on helium that make the situation look somewhat different from the way it appeared in their discussion. It can be seen from figure 1 that the lower limit on η derived from $D+{}^3He$, in the context of the standard Big Bang model with three light neutrino species, requires that the primordial helium abundance should be

$$Y_p > 0.24 \tag{11}$$

and I intend to cast some doubt on whether this is actually the case.

Estimates of Y_p have been made by a variety of methods that have been extensively discussed and reviewed (Pagel 1982; Shaver *et al.* 1983; Yang *et al.* 1984; Pagel 1985; Boesgaard & Steigman 1985). The methods include studies of the Sun, Jupiter, hot stars, globular clusters, H II regions and planetary nebulae, and they almost all agree on a value somewhere between 0.20 and 0.25, which is encouraging as far as it goes, but the problem is to sharpen up this range of values into something that will be accurate to better than five per cent, bearing in mind that the actual helium abundance observed in most objects has been augmented above the primordial value by a few percentage units owing to synthesis of helium by stars.

Probably the most accurate method of getting the primordial helium abundance is from the study of optical emission lines in the spectra of extragalactic H II regions with differing oxygen abundances. This method was first suggested and applied to the Magellanic Clouds by Peimbert & Torres-Peimbert (1974, 1976), who correct for the stellar contribution to helium by assuming it to be proportional to the metallicity, or effectively to the oxygen abundance, which can be readily measured from the spectra, so that the observed helium abundance Y is given by

$$Y = Y_p + Z\,dY/dZ, \tag{12}$$

where Z is the heavy-element mass fraction and dY/dZ is a constant of order unity to be determined primarily from the observations themselves although there are theoretical predictions with which it can be compared. Strong points of this method are that the hydrogen and helium line intensities depend on recombination coefficients that are accurately known, and that there are some objects, like the compact galaxy IZw18 that have very low oxygen abundance, down to $\frac{1}{50}$ solar. There are also problems with the method (Davidson & Kinman 1985): ionization correction factors are often needed to allow for neutral helium in the ionized hydrogen zone and these are model-dependent; the yellow helium line, $\lambda = 5876$, which is the strongest, is subject to absorption at certain redshifts by galactic sodium, particularly in the case of IIZw40 which has been a popular object in such studies; and the weaker lines may be affected by underlying stellar absorption lines if the continuum is strong.

The most significant estimates of Y_p and dY/dZ by this method are those of Lequeux *et al.* (1979), who found that

$$Y_p = 0.230 \pm 0.004, \quad dY/dZ \simeq 3, \tag{13}$$

and Kunth & Sargent (1983) who found that

$$Y_p = 0.245 \pm 0.003, \quad dY/dZ \simeq 0, \tag{14}$$

so that one has a choice between a low value of Y_p that is discrepant with the limits on η found by Yang *et al.* and a higher value that is reasonably consistent with them. The average helium abundances in their samples are closely similar, but they differ seriously in the slope and hence in the extrapolation to zero metallicity by (12).

Both of these investigations are open to criticism because too many of their objects have significant (and therefore uncertain) ionization corrections, both included IIZw40 and together they cover a fairly limited sample of about 20 objects. Consequently more work is needed, and I have taken advantage of the existence of an extensive spectral survey by R. Terlevich and J. Melnick of blue compact emission-line galaxies taken largely from the Cambridge & Tololo objective prism surveys to pick out a series of objects with accurate line intensity measurements and with such a high degree of excitation that the ionization corrections should be negligible. I have also used the most highly ionized objects observed by Lequeux *et al.* and by Kunth & Sargent, for which again the ionization corrections should be negligible. The resulting plot of Y against Z is shown in figure 2, with a least-squares solution and 1σ error limits. Our preliminary result from these data is

$$Y_p = 0.235 \pm 0.004, \quad dY/dZ = 3.5 \pm 1.2 \tag{15}$$

giving a primordial helium abundance that is, satisfyingly, between the two previous results, but a dY/dZ slope that essentially agrees with that of Lequeux *et al.*

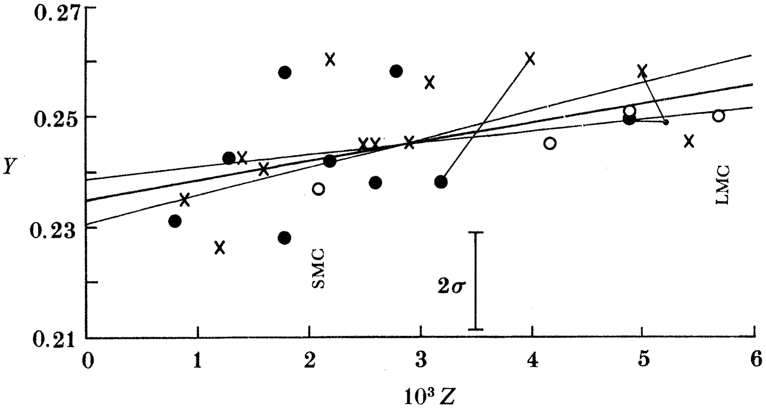

FIGURE 2. Plot of helium mass fraction Y against heavy-element mass fraction Z, resulting from new observations (RGO) and selected data from the literature (○, Lequeux *et al.* 1979; ●, Kunth & Sargent 1983; ×, RGO). Points joined by lines refer to the same object. The thick line is the least-squares regression and the thin lines are $\pm 1\sigma$ error limits.

Figure 1 shows that there is a marked discrepancy between the preferred ranges of η (solid error boxes) following from our result for helium and Yang *et al.*'s result from $D + {}^3He$. The discrepancy is just barely bridged by taking extreme error limits (broken-line error boxes) corresponding to 2σ for the helium and $y_{23p} = 10^{-4}$. This suggests that there might be something wrong with the standard Big-Bang model and three light neutrino species or alternatively that there has been more destruction of ${}^3He$ than is allowed for in standard models, which could be the case if the first generation of stars had been very massive. In this case the Lyman-α forest clouds should have quite a large deuterium abundance, $D:H > 10^{-4}$.

If, in spite of everything, we decide to stand by the standard model and adopt the broken-line error boxes, then the restrictions on η become very tight:

$$3.0 < 10^{10}\,\eta < 3.6, \quad 0.011 < \Omega_N h_0^2 < 0.013, \quad 12.6 < \langle M/L \rangle_N\, l\, h_0 < 15.1. \tag{16}$$

A consequence of this is that, for $h_0 > 0.5, \Omega_N < 0.05$, which is very much at the lower end of the possible values of Ω for matter distributed like galaxies derived from redshift surveys of field galaxies (Bean *et al.* 1983), superclusters (Ford *et al.* 1981) and the Virgocentric flow (Aaronson *et al.* 1982). It is still possible that baryons account for all this matter, but only just.

5. CONCLUSION

The assertion that light-element abundances are consistent with standard Big-Bang nucleosynthesis theory assuming three light neutrino flavours (Yang *et al.* 1984) is still tenable if all uncertainties are stretched to their limits, but the new evidence for a low primordial helium abundance makes the position now look somewhat uncomfortable unless there has been more destruction of deuterium and ^{3}He than is usually assumed. This makes it important to make more searches for deuterium in the Lyman-α forest systems as well as extending the data base for helium in objects with suitably high ionization.

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Discussion

R. J. TAYLER (*Astronomy Centre, University of Sussex*). How small a value of Y would one have to measure in a single object before it was decided that the standard model of the hot Big Bang was untenable?

B. E. J. PAGEL. A value below 0.22 would lead to a need for a radical reassessment, either of the standard hot Big-Bang model or of current ideas on the origin and evolution of the light elements.