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LIGHT ELEMENTS: FROM BIG BANG TO STARS

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Invited review at Third Intl. Symp. Nuclei in the Cosmos,
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Light Elements: from Big Bang to Stars¹

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Abstract. Primordial abundances inferred by extrapolation of astrophysical and cosmochemical measurements continue to support the so-called “Standard” Big Bang nucleosynthesis model, but raise many unanswered questions concerning galactic chemical evolution.

Key words: beryllium, Big Bang, boron, deuterium, helium-3, helium-4, lithium-6, lithium-7, nucleosynthesis

1. INTRODUCTION

The light elements up to ^{11}B are of special interest because they are created in whole or in part by different processes than the others, namely Big Bang and cosmic-ray spallation or $\alpha - \alpha$ fusion (see, e.g., Reeves 1994a). Intensive activity in their study in the past decade has been largely stimulated by cosmology, but results from the last few years have also raised interesting questions about galactic chemical evolution (GCE), e.g. why is there so much beryllium and boron in metal-weak stars and how to explain the ^3He abundance (or lack of it) and the $^6\text{Li}/^7\text{Li}$ ratio in the interstellar medium (ISM)? “Standard” Big Bang nucleosynthesis theory (SBBN) still seems to be in good shape, but when we consider the growth of any one of the light elements due to subsequent GCE, we open a whole can of worms. In this review, I shall briefly summarize the inferences made a few years ago by comparing observational data with SBBN theory, and then comment on more recent developments.

2. EXISTING INFERENCE FROM SBBN

Fig. 1 shows what has been inferred over the last few years about baryonic density from a comparison of SBBN predictions with primordial abundances deduced by extrapolating astrophysical and cosmochemical measurements, and the resulting implications for baryonic and non-baryonic dark matter. The most restrictive upper limit to baryonic density comes from ^4He and the most restrictive lower limit from $\text{D} + ^3\text{He}$, resulting in a narrow region of concordance. Recent developments concerning each of the relevant elements are presented in the succeeding sections.

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Fig. 1 — Light-element abundances vs. baryon-photon ratio for ^4He (top); $\text{D} + ^3\text{He}$, D and ^3He (middle) and ^7Li (bottom) predicted as a function of baryon:photon ratio and with lower and upper limits deduced from various observations, after Walker *et al.* (1991) and M.S. Smith *et al.* (1993). The cross shows an estimate of primordial ^3He by Balser *et al.* (1994). Implications for existence of baryonic and non-baryonic dark matter are shown at the top.

3. DEUTERIUM AND HELIUM-3

Protosolar ($\text{D} + ^3\text{He}/\text{H} \equiv y_{\text{p}}(\odot)$, $^3\text{He}/\text{H} \equiv y_{\text{H}}(\odot)$ and $\text{D}/\text{H} \equiv y_{\text{D}}(\odot)$) are deduced from meteoritic and solar wind measurements to be 4.1 ± 1.0 , 1.5 ± 0.3 and 2.6 ± 1.0 respectively, all in units of 10^{-5} (Geiss 1993), from which by the well known arguments about survival of ^3He (Yang *et al.* 1984; Stogman & Tosi 1992; Vangioni-Flam *et al.* 1994) one infers $y_{\text{p}} < 10^{-4}$ and $y_{\text{H}} < 8 \times 10^{-5}$. HST measurements of interstellar deuterium towards Capella give $10^5 y_{\text{D}} = 1.65 \pm 0.15$ (Linsky *et al.* 1993; Linsky 1994), which may be representative of the results of older *COPERNICUS* observations along lines of sight towards more distant OB stars as well (McCallough 1992), but Lemoine (1994a) suspects some variations in local clouds towards a white dwarf observed with HST.

Much more sensational is the observation of a putative D by- α line with a red-shift of 3.32 in a Lyman forest cloud towards the QSO Q0014+813 giving

a nominal D/H ratio of $(2.5 \pm 0.6) \times 10^{-4}$ (Songaila *et al.* 1994; Carswell *et al.* 1994). If this is a correct identification, the arguments about ^3He must be invalid for some reason (*cf.* Vangioni-Flam & Cassé 1994), evidence for baryonic and non-baryonic dark matter becomes weaker and stronger, respectively, and the upper limit to primordial helium abundance allows one additional neutrino type. However, as both groups of authors point out, one cannot exclude the possibility of interference from a rogue hydrogen cloud, especially as Carswell *et al.* find that quite a number of clouds with different velocities are needed anyway to get a satisfactory fit to the data and express some scepticism as to whether the result is more than just an upper limit. More data on other systems will be needed before a firm conclusion can be drawn.

At the same time, there are also problems with ^3He . Balser *et al.* (1994) are making considerable progress in their long-term programme to measure $^3\text{He}/\text{H}$ in Galactic HII regions from the H δ line at 3.46 μm and (assuming homogeneous HII region models) they find values ranging from 0.7 to 6×10^{-3} with no clear correlation with galactocentric distance that might give a clue to the chemical evolution. Their suggestion is that there is an underlying ^3He abundance of about 1.1×10^{-5} , unchanged since the Big Bang (*cf.* Fig. 1), on which are superposed local variations due to pollution by winds from massive stars, for which there is some evidence in the form of helium variations across W3 (Roelfsema *et al.* 1992) and some optical extragalactic HII regions (see below). That explanation fits in quite nicely with the old arguments about D+ ^3He , but only on the assumption that there has been little net production of ^3He in the Galaxy by stellar processes, whereas substantial production of a long been predicted with $^3\text{He}/\text{H} \simeq 10^{-3}$ (Rood *et al.* 1992). Since AGB stars planetary nebula with $^3\text{He}/\text{H} \simeq 10^{-3}$ (Rood *et al.* 1992). Since AGB stars with typically an order-of-magnitude enhancement of s-process elements are plausibly sufficient to account for the presence of those elements in the Solar System, it is implausible that the presence of an enhancement of ^3He by nearly 2 orders of magnitude should not have led to a substantial increase in the course of GCE. Thus the arguments about D+ ^3He look somewhat unsafe, whatever one thinks about the observations at high red-shift.

4. HELIUM-4

The position about 10 years ago is well described in the ESO Workshop on "Primordial Helium" (Shaver *et al.* 1983; *cf.* also Boesgaard & Steigman 1985 and Pagel 1993, 1994a). Helium is robust and abundant and accordingly there is an abundance of data from various sources; but the accuracy of a few per cent or better that is needed in order to constrain cosmology and astrophysics significantly is difficult to achieve. By the mid-70's it had become clear that it has a universal "floor", as required by SBBN, both from stellar observations (including members of globular clusters and other metal-deficient stars) and from emission lines in ionized nebulae, which are capable of greater accuracy. After the seminal observations of the two Zwicky blue compact

galaxies IZw18 and IZw40 by Searle & Sargent (1972), which showed them to be dominated by giant HII regions with low oxygen but near-normal helium abundance (IZw18 still holds the record among HII regions with about 1/50 solar oxygen abundance), Peimbert & Torres-Peimbert (1974) initiated a programme to determine the primordial mass fraction Y_p and the astrophysically important quantity dY/dZ from observations of the Magellanic Clouds and other irregular and blue compact galaxies by plotting regressions of helium against oxygen abundance, culminating in the papers by Lequeux *et al.* (1979) who found $Y_p = 0.230$ and $dY/dZ = 3.5$, and by Kunth & Sargent (1983) who with generally better data (but some bias due to high weighting of $\lambda 5876$ in IZw40 which is absorbed by Galactic sodium), detected no dY/dZ slope and could only conclude that $Y_p < 0.243$.

The spectrophotometric survey of HII galaxies by Roberto Terlevich and colleagues (Campbell, Terlevich & Melnick 1986; Terlevich *et al.* 1991) seemed to me to provide a good opportunity to improve the situation by combining new observations with a careful re-evaluation of existing data. Davidson & Kinman (1985) had given a formidable survey of the difficulties involved, but I thought I had answers to most of them. Pagel, Terlevich & Melnick (1986) noted that there seemed to be real scatter in helium at a given oxygen abundance; we attributed this to local pollution by winds of hydrogen-burned material from embedded Wolf-Rayet stars that sometimes show up in the form of broad H α $\lambda 686$ emission and accordingly introduced the idea of plotting a regression against nitrogen as well as oxygen, in the vain hope that this effect would cancel out to first order. Later we added new data taken with the INT and AAT, some (not enough) of unprecedentedly good quality; the results are described in Simonson (1990) and Pagel *et al.* (1992) and they are illustrated in Fig. 2.

The main problems in our work are remaining imperfections in the data and certain problems of interpretation, notably

- (i) Theoretical recombination coefficients. As usual, we used those of Brocklehurst (1972), but noted that new calculations by Smits (1991ab) gave slightly smaller values for $\lambda 5876$ and $\lambda 6678$. Improved calculations (Smits 1994) confirm Brocklehurst's values for these lines, but substantially change the one for $\lambda 7065$ which is sensitive to collisional and radiative transfer effects.
- (ii) Collisional excitation, which we estimated using formulae by Clegg (1987) with electron densities deduced from the [SII] line ratio. Since these came out very small, uncertainties in the theory did not seem important.
- (iii) Cosmic scatter in the He,O or He,N relation. In NGC 5253, Campbell *et al.* found a central peak in Y associated with a highly localized WR feature, and subsequent observations revealed variations across the extended HII region in N/O and probably He/H as well, while in other objects there is just marginal evidence that high He and N abundances may be associated with the WR feature. To eliminate systematic effects from the existence of such a correlation (which may or may not be real) without introducing a statistical bias, we decided to exclude from our regression lines all objects in which the WR feature had been definitely identified; these are shown by filled circles in Fig. 2.

Fig. 2.— Regressions of helium against oxygen and nitrogen in HII galaxies (Pagel *et al.* 1992). Filled circles show objects with definite WIR features, open circles others. Maximum likelihood regression lines are shown with equivalent $\pm 1\sigma$ limits; the short line in the lower panel is the regression finally preferred for nitrogen. Triangles show later results from Skillman & Kennicutt (1993), Skillman *et al.* (1994a) and Izotov *et al.* (1994); stars are from a rediscussion of observations of SBS 0355-052 (Melnick *et al.* 1992).

The results from this were $Y_p = 0.228 \pm 0.005$ (s.e.) or, assuming a systematic error of up to 0.005, $Y_p < 0.242$ with 95 per cent confidence, and $dY/dZ = 4 \pm 1$ for $O/H \leq 2.4 \times 10^{-4}$ or 0.3 solar oxygen abundance, not significantly different from the results of Lequeux *et al.* (1979). We derived the same Y_p from the regression against nitrogen, taking into account the contribution of “secondary” nitrogen production, which led to some discussion but no serious subsequent change (Pagel & Kazlauskas 1993; Balbes *et al.* 1993). The large dY/dZ , already implicit in earlier work (Paulker 1967; Perrin *et al.* 1977; Lequeux *et al.* 1979), and supported by studies of planetary nebulae (Chiappini & Maciel 1994), has led to much discussion, since it is about twice the value expected from conventional stellar nucleosynthesis, and basically three different hypotheses have been put forward:-

(i) A low upper limit ($\approx 25M_\odot$) to the initial mass of stars undergoing supernova explosions rather than going into black holes (Maeder 1992, 1993; Brown & Behr 1994). Apart from questions about the initial mass function and resulting absolute yields assumed by Maeder, objections have been raised by Prantzos (1994) on grounds of overproduction of carbon.

(ii) Preferential loss of oxygen and other components of Z by selective galactic winds following bursts of star formation in dwarf galaxies (Pilyugin 1993; Marconi *et al.* 1994). Pilyugin also includes temporary increases in both

Y and Z by self-pollution in HII regions, for which there is some independent evidence in the case of I Zw 18 from HST observations giving a still much lower oxygen abundance in the neutral gas (Kunth *et al.* 1994). Such differences could cast doubt on the whole principle of plotting regression lines, but they cannot be a major factor in objects like the Magellanic Clouds and the Galaxy, where no HII regions are found to be overabundant compared to stars or neutral gas, and the scatter in helium abundance that they are supposed to explain only marginally exceeds experimental errors.

(iii) Our oxygen abundances are overestimated because we neglected fluctuations in electron temperature. This is a controversial question, but there is some evidence now that fluctuations are significant and could result in our having underestimated O/H by up to a factor 2 in some cases (González Delgado *et al.* 1995). For Galactic HII regions, with temperature fluctuations included, Peimbert (1993) has derived $\Delta Y/\Delta Z$ values close to 3. An upper IMF slope of 1.7 and an upper mass limit of $50M_\odot$ for SN progenitors gives $\Delta Y/\Delta Z = 3$ (Maeder 1992), so this may be the solution.

At present, efforts are being made towards still further refinements of helium abundance by discovering more low-metallicity systems (which reside in low-luminosity galaxies), better signal:noise and resolution using various telescopes and data reduction systems and improvements in atomic data. Skillman & Kennicutt (1993) have re-observed I Zw 18 and Skillman *et al.* (1994a) have studied NGC 4483 with results shown in Fig. 2. Further results from this group (Skillman *et al.* 1994b) have been exhaustively analysed together with our data (Pagel *et al.* 1992) by Olive & Steigman (1994); from various subsets of the data, mostly including the definite WIR objects which we had rejected, they find $Y_p = 0.232 \pm 0.003$ and $Y_p^{2\sigma} + \sigma_{\text{sys}} \leq 0.243$. Izotov *et al.* (1994) have observed ten HII galaxies from the Second Byurakan Survey including NGC 4483 and analyzed them with various combinations of Broeklehurst and Smits recombination coefficients. The right combination is presumably Smits (1994) giving the same dY/dZ as Pagel *et al.* (1992), but a higher $Y_p = 0.239 \pm 0.007$. The Y_p value given by Olive & Steigman looks like the best compromise, but radiative transfer effects not previously taken into account could raise the upper limit, perhaps by as much as 0.01 (Saslov & Goldwirth 1994).

5. LITHIUM, BERYLLIUM AND BORON

The discovery of lithium in metal-deficient stars (Spite & Spite 1982) was a confirmation of SBBN, whereas the discoveries of beryllium (Gilmore *et al.* 1991) and boron (Duncan *et al.* 1992), though stimulated by ideas on inhomogeneous Big-Bang nucleosynthesis, are now thought to have little or no cosmological significance, although they raise plenty of problems about (X/Y) .

A useful compilation of I_i/I_1 vs. $[Fe/H]$ by Rebolo, Molero & Beekman (1988) shows the main outline of the trends observed: Below $[Fe/H] = -1.5$ or so (and for stars that are not too cool or evolved; cf. Pilachowski *et al.* 1993), one has the Spite plateau with $12 + \log(I_i/I_1) \approx 2.2$, while at higher

metallicities there is a vast scatter due to depletion in stellar atmospheres, but with a fairly well defined upper envelope rising to somewhere near the meteoritic abundance of 3.3 at solar and higher metallicity. This is usually ascribed to a contribution from some sort of stellar production, and the upper envelope is fairly well fitted by adding to the primordial abundance another component that evolves *pari passu* with iron (Pagel 1991), or maybe a little more slowly (D'Antona & Matteucci 1991). There is a vast literature on processes leading to the depletion of lithium in stellar atmospheres, which are not well understood, although it seems that with new opacities and other developments some progress is being made (Swenson *et al.* 1994). The best evidence that depletion is not very great along the lithium plateau is the detection of ^6Li in the warm subdwarf HD 84937 (V. Smith *et al.* 1993).

Despite this, some evidence is emerging that the lithium plateau is not a true plateau, but has a gentle rise as a function of metallicity. This comes out from careful analyses of subdwarf lithium abundances as a function of effective temperature, showing a small but significant decrease with decreasing temperature consistent with the predictions of Pinsonneault *et al.* (1992) for non-rotating stellar models (Thorburn 1994; Norris *et al.* 1994). Analysis of the residual scatter around this temperature dependence leads to a noticeable increase of lithium (corrected to a standard effective temperature) with metallicity, implying a primordial lithium abundance possibly as low as $12 + \log(\text{Li}/\text{H}) = 2.0$ and an increase by maybe 0.1 of solar-system Li for only 0.01 of solar-system iron. This suggests significant ^7Li production by cosmic-ray $\alpha - \alpha$ fusion in the early Galaxy, which is not entirely unexpected in view of the abundance of ^6Li and those of beryllium and boron, discussed below.

Further evidence against the usual view that ^7Li comes mainly from stellar production on top of the Big Bang comes from measurements of the $^7\text{Li}/^6\text{Li}$ ratio in the interstellar medium which give about 12 (like the Solar System) or lower, and variation between clouds (Meyer *et al.* 1993; Lemoine *et al.* 1993), in one case being as low as 2 (Lemoine 1994b). An increase in $^6\text{Li}/^7\text{Li}$ since formation of the Solar System is not easy to understand if ^7Li comes from stellar production and ^6Li from cosmic-ray spallation and fusion (*cf.* Steigman 1993), and so there are arguments for reinvestigating the role of a low-energy component of cosmic rays (Beckman 1994)—as previously postulated to explain the $^{11}\text{B}/^{10}\text{B}$ ratio (Reeves 1994b)—particularly in view of recent evidence for a high flux of low-energy cosmic rays in Orion (Bloemen *et al.* 1994).

There is now quite a lot of data on beryllium in low-metallicity stars (Ryan *et al.* 1992; Gilmore *et al.* 1992; Boesgaard & King 1993) which indicates that there is no plateau at the abundance levels observed, but that beryllium evolves with a nearly constant ratio to iron or oxygen, which is unexpected in view of the need to have CNO elements present for spallation so that (for unchanged cosmic-ray flux relative to supernova rates and oxygen production) one expects it to behave like a “secondary” element rising approximately as the square of primary elements. At the same time, IIST observations of HD 140283, with $[\text{Fe}/\text{H}] \simeq -2.6$, analyzed with the aid of non-LTE model atmosphere

calculations, indicate a B/Be ratio of about 17 (Edvardsson *et al.* 1994), similar to the prediction for conventional cosmic-ray spallation (Walker *et al.* 1985), although ^{11}B could also have a primary source from neutrino processes in supernovae (Olive *et al.* 1994).

Several ideas have been put forward to explain the mysterious “primary” behaviour of beryllium and boron at low metallicities. Such behaviour is natural if they result from the accelerated component and if ancient cosmic rays had the same CNO abundance as now (Duncan *et al.* 1992) or if spallation took place mainly in the near-supernova environment before the dilution of synthesis products (Feltzing & Gustafsson 1994). Ryan *et al.* pointed out that, if the Galactic halo lost most of its material in an intense Galactic wind (Hartwick 1976), the resulting reduction in star formation rate would lead to a flattening of the initially quadratic dependence of Be on Fe or O, giving a crude fit to the data, and Prantzos *et al.* (1993) provided physical motivation for such a model by postulating a strengthening of the cosmic ray flux and hardening of its spectrum by a large grammage due to the great extent of the early halo. Spectral hardening had the desirable effect of reducing any lithium production from $\alpha - \alpha$ fusion associated with the large CR flux, as well as explaining a low B/Be ratio that was thought to hold at the time, two aspects that deserve re-examination in the light of the results reported above for both lithium and boron. Pagel (1994b) considered an inhomogeneous “chemo-dynamical” toy model and showed that in this case the cosmic-ray boost required could be considerably reduced, but he was no more successful than Ryan *et al.* or Prantzos *et al.* in producing a linear Be, O relation at the lowest metallicities observed, and the fit to the data is crude rather than convincing. However, the assumptions made in all these papers about cosmic rays are very simplistic, and the answer could lie there (*cf.* Fields *et al.* 1994).

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