COSMOLOGICAL SIGNATURES IN HIGH S:N SPECTRA

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ABSTRACT. We review briefly the observational status of abundance determinations for those elements produced in the first seconds of a "standard" Big Bang Universe, showing that although [^{4}He] and [D] appear not to be mutually compatible there is still room for reconciliation via astration of D, for values consistent with estimated [^{7}Li]. New limits to production cross-sections for ^{7}Li appear to limit N_ν (the number of light neutrino types) to no more than 3. Non-standard models with fluctuations are briefly considered; they are attractive because they use $\Omega=1$ and may also yield early C, N, O in significant quantities. The true value of ^{7}Li [10^{-9} or 10^{-10}w.r.t. H] is the critical test here. We show where spectra of improved S:N are needed to progress in constraining cosmological models.

1. INTRODUCTION

One triumph of hot Big Bang model universes is their ability to account for the observed set of abundances of light elements, notably ^{2}H and ^{4}He, but also ^{7}Li and ^{3}He, over a range of nine orders of magnitude (^{4}He:^{7}Li). Global agreement is felt to be satisfactory enough to use the "standard" model (see Yang et al., 1984) to derive the universal photon:baryon ratio and to limit N_ν , the number of light neutrino types more stringently (see e.g. Rebolo et al., 1988) than the limits from the experimental "width" of the Z measured at CERN.

Referring the reader to the recent review by Boesgaard and Steigman (1985) here we concentrate on only two topics: possible discrepancies between the standard model and observations, and those cases where S:N ratio, rather than interpretation, limits our progress in grasping the physics.

2. ARE THE OBSERVED ABUNDANCES CONSISTENT WITH THE STANDARD MODEL?

(a) ^{4}He. For details of the derivation of the primordial ^{4}He abundance we refer the reader to the recent review by Pagel (1987) and the proceedings of the ESO workshop (Shaver et al., 1983). The method favoured by Pagel uses

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emission from HII regions of external galaxies (e.g. Vilchez et al., 1987) in the λ4417 Å and λ5876 Å He recombination lines. Limitations are the interpretation of observed fluxes to give relative abundances, and the required extrapolation to low metallicity. Recent work (Pagel et al., 1986) has stressed the reliability of the use of nitrogen (rather than only oxygen) as a measure of a nuclide produced in primary processes against which ^{4}He can be extrapolated to zero metallicity. The most recent observed value for Y_p is 23.2 (±0.4)% by number. For ^{4}He the primordial abundance depends on η, and also on N_ν and the neutron half-life τ_n. Using a reasonable modern estimate for τ_n of 10.5 (±0.1) min, we find, from ^{4}He alone (see Yang et al., 1984):

$$N_\nu=4: \; 0.8 \times 10^{-10} \leq \eta \leq 1.3 \times 10^{-10}; \quad 10^{-10} \leq \eta \leq 3 \times 10^{-10} : N_\nu = 3$$

$$2.5 \times 10^{-10} \leq \eta \leq 10 \times 10^{-10} : N_\nu = 2$$

We will see below when discussing Li that a value of N_ν =4 appears to be excluded, and $N_\nu > 4$ is certainly rule out.

(b) D+ ^{3}He. It is difficult to use primordial D directly as a check on η, because D is so readily destroyed by astration.

Interstellar determinations, using the Ly series of deuterium, or from molecules give $5\times10^{-6} < [D] < 2\times10^{-5}$, but even 2×10^{-5} must be taken as a lower limit, because D is so fragile that no production, only destruction is expected within stars. Using $[D] = 2\times10^{-5}$, these standard models (Yang et al., 1984) gives $\eta = 4\times10^{-10}$, which is incompatible with the ^{4}He data and 3 light neutrino types. Either N_ν =2 (the neutrino would have mass), or the standard model fails or the true [D] is larger. A value for [D] of 2×10^{-4} is needed for agreement with ^{4}He and ^{7}Li estimates. Direct determination of primordial D via the Lyα forest in QSO's offers a solution but is at present balked by inadequate S:N (Carswell et al., 1986).

An indirect method for D is to subtract the pre-solar ^{3}He abundance measured in carbonaceous chondrites: 1.5×10^{-5} (Eberhardt, 1978) from the ^{3}He abundance in the solar wind: 4×10^{-5} (Black, 1972), or in a prominence: 4×10^{-5} (Hall, 1975). The difference is supposedly attributable to D burning to ^{3}He in the sun, and yield $[D]_{protosolar} = 2.5\times10^{-5}$, agreeing with proto-solar D in planetary atmospheres (Encrenaz and Combes, 1982). The problem is that $[D]_{protosolar}/[D]_{primordial}$ could be as high as 40 (Pagel, 1986; Larson, 1086) depending on galactic chemical evolution.

To improve reliability, Yang et al. (1984) suggested [D+^{3}He] instead of [D] as a test abundance, assuming that all astrated D becomes ^{3}He, a fraction, g, of which survives astration. Assuming g=0.25, Delbourgo-Salvador et al. (1985) using a specific galactic model, obtain $[D]_p < 8.6\times10^{-5}$. This is still incompatible with the range permitted by ^{4}He (unless N_ν=2), but the gap is small, and with present errors in observations, and uncertainties in chemical evolution, does not at this point rule out the standard model. Observational estimate of Y have tended to decrease, thus widening the gap between (^{4}He) and (D+^{3}He), but the total light element picture can still accommodate the standard model, as we consider below.

(c) ^{7}Li. The sound use of ^{7}Li as a primordial probe dates from the elegant work by the Spites (1982) on subdwarfs. Their original value log $N(Li)_p$2.08 has been confirmed. although slightly raised to 2.20 by more recent observations (Beckman et al., 1986; Rebolo et al., 1987 a; Hobbs and Duncan, 1987). Three arguments support this value as primordial. (a) The uniformity of log N(Li) with Teff between Teff=6300 K and 5700 K; (b) the uniformity of log N(Li) with metallicity over the wide range $-1.5 > [Fe/H] > -3.5$, and (c) the uniformity of log N(Li) for halo dwarfs with sites of origin separated by up to several kpc.

Nevertheless two question marks can be placed on the use of log N(Li)= 2.2 as a primordial value: (a) was ^{7}Li produced in a significant quantity between the Big Bang and the formation of Pop II ? and (b) have Pop II subdwarfs suffered significant ^{7}Li depletion? In a recent article Rebolo et al. (1987 b) give negative answers to both questions. Against extra ^{7}Li prior to Pop II they point out: (i) observational limits of ^{6}Li (Maurice et al., 1984) and to ^{9}Be (Rebolo et al., 1987 c) in these stars, excluding virtually all non-primordial sources of ^{7}Li; (ii) the uniformity of ^{7}Li over a hundred-fold metallicity range below [Fe/H] =1.5 showing no tendency for much ^{7}Li to be produced in this early phase of chemical galactic evolution. Observations expecially of ^{9}Be and ^{6}Li, at higher S:N are needed to clinch these arguments. Against depletion, Rebolo et al. (1987 b) compare the log N(Li) v. Teff curves for "EMD" stars (with [Fe/H] $\leq$1.5) with those of open clusters, showing that non-diffusive depletion could not have occurred in the EMD group. Diffusive depletion is not ruled out, but the observed "plateau" in log N(Li) v. Teff between 6300 K and 5700 K in EMD stars does not conform to any theoretical accounts of diffusion effects (Michaud, 1984). Taking a value for log N(Li) of 2.2 we find, with observational (Rebolo et al., 1987) and theoretical (Kawano, 1987) uncertainties accounted for:

$$1.5 \times 10^{-10} \leq \eta \leq 6.5 \times 10^{-10}$$

Comparing this range with the ranges infered from ^{4}He we see that the maximum number of light neutrino types permitted in a standard model is 3.

3. NON-STANDARD MODELS

Cosmological models have recently been produced in order to fit the inflationary premise that Ω_0 =1 with a purely baryonic density. these either invoke ad hoc baryon density fluctuations (Applegate et al., 1987) or fluctuations arising from the quark-hadron phase transition (Alcock et al., 1987). Although these variants are able to reconcile the apparent ^{4}He-D discrepancy, they "overproduce" ^{7}Li by at least a factor 10. This is one reason for perhaps wishing to reconsider whether the arguments of those who prefer to identify the present-day Pop I ^{7}Li abundance of log $N(Li)_p \sim 3$ with the primordial value may be justified. The evidence cited above, plus the trend of ^{7}Li to rise in measured stellar abundance linearly with metallicity (Rebolo et al., 1987 a) points towards log $N(Li)_p \sim 2$, but the question is still open. It is unlikely that higher S:N spectra of ^{7}Li or ^{4}He will help to decide whether non-standard models are required. The key datum is now primordial [D] and hence the Ly-α forest observations mentioned above.

Table 1
Light element abundances with cosmological signatures: requirements of high S:N spectra

Nuclide	Measurement	S:N (and spectral resolution) required	Significance
D	D/H in Ly-αforest (QSO forest)	>100 $(\lambda/\Delta\lambda \gtrsim 10.000)$	Direct non-astrated chemistry free primordial D.
^{3}He	Subdwarfs; emission at 10830 equivalent of ^{3}He.	>150 $(\lambda/\Delta\lambda > 50.000)$	Nearest data to primordial ^{3}He (very difficult measurement.
^{6}Li	Subdwarfs	>200 $(\lambda/\Delta\lambda > 30.000)$	Limits non-primordial sources of ^{7}Li.
	ISM	>300 $(\lambda/\Delta\lambda > 50.000)$	Examine formation rate of ^{6}Li in galaxy (^{7}Li data will emerge automatically).
^{9}Be	Subdwarfs	$\gtrsim$200 $(\lambda/\Delta\lambda > 50.000)$	Limit non-primordial ^{7}Li. Explore early galactic evolution.
^{10}B	Subdwarfs	>200 $(\lambda/\Delta\lambda > 20.000)$	Limit non-primordial ^{7}Li.
O C N	Subdwarfs	>200 $(\lambda/\Delta\lambda > 20.000)$	Test of possible light metal production in Big Bang; early galactic evolution.

A further feature of the fluctuation models is that they can yield quantities of C, N, O which approach measurability limits. Since the finite metallicities of the earliest stars are a puzzle, this feature may prove attractive, but there is no prima facie evidence (Cayrel , 1986) that any phenomenon other than a "normal" massive early stellar population is required. High S:N data on early chemical evolution i.e. of weak C N O in Pop II would certainly be useful in this context.

4. CONCLUSIONS

Table 1 lists the requirements of spectral resolution and S:N for nuclides relevant to constraining cosmological models, where improved S:N is important. The isotopes ^{6}Li, ^{9}Be and ^{10}B constrain early galactic ^{7}Li production and high S:N is necessary because of their low abundances (similarly for very early C, N, O). However imprecision of the neutron half-life, ulterior knowledge of the number of neutrino types, understanding of D astration and Li depletion and model-dependent abundance determinations are at present the principal impediments to further advance.

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