A case for nucleosynthesis in slowly evolving models

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Abstract

We present a case for Cosmological Nucleosynthesis in an FRW universe in which the scale factor expands linearly with time: $a(t) \sim t$. It is demonstrated that adequate amount of $^4$He requires a baryon density that saturates mass bounds from galactic clusters. There is a collateral metallicity production that is quite close to the lowest metallicity observed in metal poor Pop II stars and clouds. On the other hand, sites for incipient low metallicity (Pop II) star formation can support environments conducive to Deuterium production up to levels observed in the universe. A profile of a revised “Standard Cosmology” is outlined.

1 Introduction:

Early universe (standard big-bang) nucleosynthesis [SBBN] is regarded as a major success for the Standard Big Bang [SBB] Model. As presented, SBBN results look rather good indeed. The observed light element abundances are taken to severely constrain cosmological and particle physics parameters. Deuterium, in particular, is regarded as an ideal “baryometer” for determining the baryon content of the universe [1]. This follows from the fact that deuterium is burned away whenever it is cycled through stars, and a

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belief, that there are no astrophysical sites (other than SBBN), capable of producing it in its observed abundance [2]. The purpose of this article is to admit caution in adhering to this belief and to explore nucleosynthesis in an environment radically different from the Standard.

What would be the point of such an exercise?

Indeed, at the outset, drastic variations from SBBN may sound preposterous at this time. Confidence in SBBN stems primarily from $^4\text{He}$, $^7\text{Li}$ and $^4\text{He}$ measurements. $D$ abundance is measured in the solar wind, in interstellar clouds and, more recently, in the inter-galactic medium [3, 4]. The belief that no realistic astrophysical process other than the Big Bang can produce sufficient $D$ lends support to its primordial origin. Further, $^7\text{Li}$ measurement [$^7\text{Li}/\text{H} \sim 10^{-10}$] in Pop II stars [5] and the consensus [6] over the primordial value for the $^4\text{He}$ ratio $Y_p \geq 23.4\%$ (by mass) suggest that light element abundances are consistent with SBBN over nine orders of magnitude. This is achieved by adjusting just one parameter, the baryon entropy ratio $\eta$. Alternative mechanisms for $^7\text{Li}$ production that are accompanied by a co-production of $^6\text{Li}$ with a later depletion of $^7\text{Li}$ have fallen out of favour.

The debate on depletion of $^7\text{Li}$ has been put to rest by the observation of $^6\text{Li}$ in a Pop II star [7]. Any depletion of $^7\text{Li}$ would have to be accompanied by a complete destruction of the much more fragile $^6\text{Li}$. Within the SBBN scenario therefore, one seeks to account for the abundances of $^4\text{He}$, $D$, $^3\text{He}$ and $^7\text{Li}$ cosmologically, while $^{12}\text{C}$, $B$ and $^6\text{Li}$ are generated by spallation processes [8].

These results, however, do meet with occasional skepticism [see eg. [25] for problems with BBN]. Observation of $^6\text{Li}$, for example, requires unreasonable suppression of astrophysical destruction of $^7\text{Li}$. On the other hand, the production of $^6\text{Li}$ would be accompanied by a simultaneous production of $^7\text{Li}$ comparable to observed levels [9]. This raises doubts about using observed $^7\text{Li}$ levels as a benchmark to evaluate SBBN.

Further the best value of $^4\text{He}$ mass fraction, statistically averaged and extrapolated to zero heavy element abundances, hovers around $0.216 \pm 0.006$ for Pop II objects [10]. Such low $^4\text{He}$ levels have also been reported in several metal poor HII galaxies [11]. For example for SBS 0335-052 the reported value is $Y_p = 0.21 \pm 0.01$ [12]. Such small values for $^4\text{He}$ would not lead to any concordant value for $\eta$ consistent with bounds on $^7\text{Li}$ and $D$. Of course, one could still explore a multi-parameter non-minimal SBBN instead of the minimal model that just uses $\eta$ for a single parameter fit. Non-vanishing neutrino chemical potentials have been proposed to be “natural” parameters for
such a venture. These conclusions have been criticized in \cite{6,12} on grounds of reliance on statistical over-emphasis on a few metal-poor objects with a high enough $^4\text{He}$ abundance to save minimal SBBN. On the other hand, there are objects reported with abysmally low $^4\text{He}$ levels. This is alarming for minimal SBBN. For example, levels of $^4\text{He}$ inferred for $\mu$ Cassiopeiae A \cite{12} and from the emission lines of several quasars \cite{13} are as low as 5% and 10 - 15% respectively. Such low levels would most definitely rule out SBBN. At present one excludes such objects from SBBN considerations on grounds of “our lack of understanding” of the environments local to these objects. As a matter of fact, one has to resort to specially contrived explanations to account for low $Y_p$ values in quasars. Considering that a host of mechanisms for light element synthesis are discarded on grounds of requirement of special “unnatural” circumstances \cite{2}, it does not augur to have to resort to special explanations to contend with low $^4\text{He}$ emission spectra. This comment ought to be considered in the light of much emphasis that is laid on emission lines from nebulae with low metal content \cite{6}. Quasars most certainly qualify for such candidates. Instead, one merely seems to concentrate on classes of Pop II objects and HII galaxies that would oblige SBBN. Until the dependence of light element abundance on sample and statistics is gotten rid of and / or fully understood, one must not close one’s eyes to alternatives.

We end our overview of the status of SBBN with a few comments. Firstly the low metallicity that one sees in type II stars and interstellar clouds poses a problem in SBBN. There is no object in the universe that has low abundance [metallicity] of heavier elements as is produced in SBB. One relies on some kind of re-processing, much later in the history of the universe, to get the low observed metallicity in, for example, old clusters and inter-stellar clouds. This could be in the form of a generation of very short-lived type III stars. Such a generation of stars may also be necessary to ionize the intergalactic medium. The extrapolation of $^4\text{He}$ abundance in type II objects and low metal (HII) galaxies, to its zero heavy metal abundance limit, presupposes that reprocessing and production of heavy elements in type III stars is not accompanied by a significant change in the $^4\text{He}$ levels. A violation of this assumption, i.e. a minute increase in $^4\text{He}$ during reprocessing (even as low as 1 - 2 %) would rule out the minimal SBBN. As a matter of fact, it is possible to account for the entire pre-galactic $^4\text{He}$ by such objects \cite{14}.

Finally, of late \cite{15}, the need for a careful scrutiny and a possible revision of the status of SBBN has also been suggested from the reported high abundance of $D$ in several $Ly_\alpha$ systems. It may be difficult to accommo-
date such high abundances within the minimal SBBN. Though the status of these observations is still a matter of debate, and (assuming their confirmation) attempts to reconcile the cosmological abundance of deuterium and the number of neutrino generations within the framework of SBB are still on, a reconsideration of alternate routes to deuterium in a slow expanding universe as described in this article could well be worth the effort. This is specially in consideration of the stranglehold that Deuterium has on SBB in constraining the baryon density upper limit to not more than some 3 to 4 %. This constraint has been used in SBB to make out a strong case for non-baryonic dark matter to make up the mass estimates at galactic and cluster scales. Relying on Deuterium that is so local environment sensitive, to predict the nature of CDM runs the risk of “building a colossus on a few feet of clay” [16].

This article reports our study of nucleosynthesis in a universe in which the scale factor evolves linearly with time independent of the equation of state of matter. A strictly linear evolution of the cosmological scale factor is surprisingly an excellent fit to a host of cosmological observations. Any model that can support such a coasting presents itself as a falsifiable model as far as classical cosmological tests are concerned as it exhibits distinguishable and verifiable features.

Large scale homogeneity and isotropy observed in the universe is incorporated in the Friedman-Robertson-Walker (FRW) metric:

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

Here $K = \pm 1, 0$ is the curvature constant. In the following section, we summarize the concordance of observations in a $K = -1$ FRW cosmology in which the scale factor evolves linearly with time: $a(t) \propto t$, right from the creation event itself. The motivation for such an endeavor has been discussed at length in a series of earlier articles [31, 23]. For the purpose of this article, we shall take as a conjecture that a strictly homogeneous background FRW model coasts linearly with time. This can be achieved in a large class of non-minimally coupled theories of gravity. However, perturbations around the homogeneous background are assumed to satisfy the perturbed Einstein equations. Section 3 describes concordant nucleosynthesis in such a model.
2 Concordance of a linear coasting cosmology:

Classical Cosmology tests

- **n(z), a(z):** Data on Galaxy number counts as a function of red-shift along with data angular diameter distance as a function of red-shift do not rule out a linearly coasting cosmology [28]. However, as these tests are marred by evolutionary effects (and mergers), they have fallen into disfavour as reliable tests of a viable model.

- **Hubble Diagram:** With the discovery of Supernovae type Ia [SNe Ia] as reliable standard candles, the status of the Hubble test has been elevated to that of a precision measurement. The Hubble plot relates the magnitude of a standard candle to its redshift in an expanding FRW universe. In [31] we demonstrated how linear coasting is as accommodating for high red-shift objects as the standard non–minimal model with a small cosmological constant. The concordance of linear coasting with SNe1a data finds a passing mention in the analysis of Perlmutter [26] who noted that the Hubble plot for \( \Omega_\Lambda = \Omega_M = 0 \) (for which the scale factor would have a linear evolution in standard cosmology) is “practically identical to the bestfit plot for an unconstrained cosmology”. The concordance of this Hubble plot continues even for the more recent data on SNe1a with redshifts \( z \geq 1 \). The plot almost coincides with the Hubble plot for \( \Omega_\Lambda \approx 0.72, \, \Omega_M = 0.28 \).

- **Age of the Universe** The age estimate of an \( (a(t) \propto t) \) universe, deduced from a measurement of the Hubble parameter, is given by \( t_o = (H_o)^{-1} \). The low red-shift SNe1a give the best value of 65 km sec\(^{-1}\) Mpc\(^{-1}\) for the Hubble parameter. The age of the universe turns out to be \( 15 \times 10^9 \) years. Such an age estimate is comfortably concordant with age estimates of old clusters.

- **Lensing Statistics:** Consistency and concordance of linear coasting with gravitational lensing statistics was reported in [32].

- **Density Perturbations**
In [27] we explored a conjecture that the background universe coasts linearly with perturbations around this background being described by

\[-8\pi G\delta T^M_{\mu\nu} = \delta G_{\mu\nu}\]  

(2)

It turns out that small perturbations can evolve to a non-linear regime and therefore be expected to lead to structures at large scales. This can be seen by expressing the metric as \(g_{\mu\nu} = (\eta)(g_{\mu\nu} + \delta g_{\mu\nu})\), the \(\delta g_{\mu\nu}\) being the perturbations. Scalar perturbations can be decomposed in terms of eigenmodes of the laplacian on the constant \(\eta\) surface (here \(d\eta = a^{-1}dt\)) with eigenvalues \(-k^2\) In terms of matter gauge invariant variable \(D_g\) (see eg. [29, 30]) and a density parameter

\[C \equiv 4\pi G\rho_0^2 = \frac{3}{2}\rho_0 = \frac{3}{2}\Omega_b\]

the density perturbation equation simply reduces to [27]:

\[[k^2 + 3]D_g + [(k^2 + 3)e^\eta/C + 2]D_g - D_gk^2 = 0.\]  

(3)

\(k = 1\) corresponds to the Hubble scale which is the same as the curvature scale in this model. At a redshift \(\approx 1000\), a sphere of Hubble radius subtends an angle roughly .25 degrees. Using constraints from microwave background anisotropy at these angles gives \(D_g \approx 10^{-5}\) at these scales at the last scattering surface. It is easy to see that modes \(k \leq 1\) do not grow. At smaller angular scales \((k >> 1)\), the observed anisotropy is expected to fall to much lower values [34]. Photon diffusion dampens anisotropies at angular scales smaller than about one minute. However, for such large values of \(k\), \(D_g\) has rapidly growing solutions. The perturbation equation becomes

\[\ddot{D}_g + \dot{D}_g - Ce^{-\eta}D_g = 0\]  

(4)

This has exact solutions in terms of modified first and second type bessel functions \(I_1, K_1:\)

\[D_g = C_1(\eta)\dot{I}_1((4C\eta)^{\frac{1}{2}}) + C_2(\eta)\dot{K}_1((4C\eta)^{\frac{1}{2}})\]  

(5)

For large arguments, these functions have their asymptotic forms:

\[I_1 \rightarrow \frac{(C\eta)^{-\frac{1}{2}}}{2\sqrt{\pi}}exp[2(C\eta)^{\frac{1}{2}}]; \quad K_1 \rightarrow \frac{(C\eta)^{-\frac{1}{2}}}{2\sqrt{\pi}}exp[-2(C\eta)^{\frac{1}{2}}]\]  

(6)
Even if diffusion damping were to reduce the baryon density contrast to values as low as some $10^{-15}$, a straightforward numerical integration of eqn(4) demonstrates that for $k \geq 3000$ the density contrast becomes non-linear around redshift of the order 50.

In contrast to the above, in the radiation dominated epoch, the adiabatic approximation perturbation equations imply [27]:

$$[(k^2 + 3) \frac{3}{4k^2} + \frac{3\dot{C}}{2k^2e^{2\eta}}] \ddot{D}_g + \frac{3\dot{C}}{k^2e^{2\eta}} \dot{D}_g + \left[\frac{k^3 + 3}{8} - \frac{\dot{C}}{2e^{2\eta}}\right]D_g = 0 \quad (7)$$

For $\eta$ large and negative, small $k$ perturbation equation reduces to

$$3\ddot{D}_g + 6\dot{D}_g - k^2D_g = 0 \quad (8)$$

Eqns(7-8) imply that perturbations bounded for large negative $\eta$ damp out for small $k$ while large $k$ modes are oscillatory.

We conclude that fluctuations do not grow in the radiation dominated era, small $k$ (large scale) fluctuations do not grow in the matter dominated era as well. However, even tiny residual baryonic fluctuations $O(10^{-15})$ at the last scattering surface for large values of $k \geq 3000$ in the matter dominated era, grow to the non-linear regime. Such a growth would be a necessary condition for structure formation and is not satisfied in the standard model. In the standard model, cold dark matter is absolutely essential for structure formation.

- **The recombination epoch**

Salient features of the plasma era in a linear coasting cosmology have been described in [36, 33, 34]. Here we reproduce some of the peculiarities of the recombination epoch. These are deduced by making a simplifying assumption of thermodynamic equilibrium just before recombination.

The probability that a photon was last scattered in the interval $(z, z + dz)$ can be expressed in terms of optical depth, and turns out to be:

$$P(z) = e^{-\tau_g} \frac{d\tau_g}{dz} \approx 7.85 \times 10^{-3} \left(\frac{z}{1000}\right)^{13.25} \exp[-0.55\left(\frac{z}{1000}\right)^{14.25}] \quad (9)$$

This $P(z)$ is sharply peaked and well fitted by a gaussian of mean redshift $z \approx 1037$ and standard deviation in redshift $\Delta z \approx 67.88$. Thus
in a linearly coasting cosmology, the last scattering surface locates at redshift \( z^* = 1037 \) with thickness \( \Delta z \approx 68 \). Corresponding values in standard cosmology are \( z = 1065 \) and \( \Delta z \approx 80 \).

An important scale that determines the nature of CMBR anisotropy is the Hubble scale which is the same as the curvature scale for linear coasting. The angle subtended today, by a sphere of Hubble radius at \( z^* = 1037 \), turns out to be \( \theta_H \approx 15.5 \) minutes. The Hubble length determines the scale over which physical processes can occur coherently. Thus one expects all acoustic signals to be contained within an angle \( \theta_H \approx 15.5 \) minutes.

We expect the nature of CMB anisotropy to follow from the above results. The details are still under study and shall be reported separately.

**Summary**

In spite of a significantly different evolution, a linear coasting cosmology can not be ruled out by all the tests we have subjected it to so far. Linear coasting being extremely falsifiable, it is encouraging to observe its concordance !! In standard cosmology, falsifiability has taken a backstage - one just constrains the values of cosmological parameters subjecting the data to Bayesian statistics. Ideally, one would have been very content with a cosmology based on physics tested in the laboratory. Clearly, standard cosmology does not pass such a test. One needs a mixture of hot and cold dark matter, together with (now) some form of dark energy to act as a cosmological constant, to find any concordance with observations. In other words, one uses observations to parametrize theory in Standard Cosmology. In contrast, a universe that is born and evolves as a curvature dominated model has a tremendous concordance, it does not need any form of dark matter and there are sufficient grounds to explore models that support such a coasting.

3 **The Nucleosynthesis Constraint:**

What makes linear coasting particularly appealing is a straightforward adaptation of standard nucleosynthesis codes to demonstrate that primordial nucleosynthesis is not an impediment for a linear coasting cosmology [22][23].
A linear evolution of the scale factor radically effects nucleosynthesis in the early universe. With the present age of the universe some $15 \times 10^9$ years and the effective CMB temperature 2.73 K, the universe turns out to be some 45 years old at $10^9$ K. With the universe expanding at such low rates, weak interactions remain in equilibrium for temperature as low as $\approx 10^8$ K. The neutron to proton ratio is determined by the n-p mass difference and is approximately $n/p \sim \exp[-15/T_9]$. This falls to abysmally low values at temperatures below $10^9$ K. Significant nucleosynthesis leading to helium formation commences only near temperatures below $5 \times 10^9$ K. The low n/p ratio is not an impediment to adequate helium production. This is because once nucleosynthesis commences, inverse beta decay replenishes neutrons by converting protons into neutrons and pumping them into the nucleosynthesis network. For baryon entropy ratio $\eta \approx 7.8 \times 10^{-9}$, the standard nucleosynthesis network can be modified for linear coasting and gives $\approx 23.9\%$ Helium. The temperatures are high enough to cause helium to burn. Even in SBBN the temperatures are high enough for helium to burn. However, the universe expands very rapidly in SBBN. In comparison, the linear evolution gives enough time for successive burning of helium, carbon and oxygen. The metallicity yield is some $10^8$ times the metallicity produced in the early universe in the SBBN. The metallicity is expected to get distributed amongst nuclei with maximum binding energies per nucleon. These are nuclei with atomic masses between 50 and 60. This metallicity is close to that seen in lowest metallicity objects. Figure(1) & (2) describe nucleosynthesis as a function of the Baryon entropy ratio. The metallicity concommitantly produced with $\approx 23.9\%$ Helium is roughly $10^{-5}$ solar.

The only problem that one has to contend with is the significantly low residual deuterium in such an evolution. The desired amount would have to be produced by the spallation processes much later in the history of the universe as described below.

Interestingly, the baryon entropy ratio required for the right amount of helium corresponds to $\Omega_b \equiv \rho_b/\rho_c = 8\pi G \rho_b/3 H_o^2 \approx 0.69$. This closes dynamic mass estimates of large galaxies and clusters [see eg [35]]. In standard cosmology this closure is sought by taking recourse to non-baryonic cold dark matter. There is hardly any budget for non-baryonic CDM in linear coasting cosmology.

**Deuterium Production:**

To get the observed abundances of light elements besides $^4He$, we recall spallation mechanisms that were explored in the pre - 1976 days [2].
Deuterium can indeed be produced by the following spallation reactions:

\[ p + ^4 He \rightarrow D + ^3 He; \quad 2p \rightarrow D + \pi^+; \]
\[ 2p \rightarrow 2p + \pi^0, \quad \pi^0 \rightarrow 2\gamma; \quad \gamma + ^4 He \rightarrow 2D. \]

There is no problem in producing Deuterium all the way to observed levels. The trouble is that under most conditions there is a concomitant over-production of Li nuclei and γ rays at unacceptable levels. Any later destruction of lithium in turn completely destroys D. As described in [2], figure (3) exhibits relative production of \(^7\)Li and D by spallation. It is apparent that the production of these nuclei to observed levels and without a collateral gamma ray flux is possible only if the incident (cosmic ray or any other) beam is energized to an almost mono energetic value of around 400 MeV. A model that requires nearly mono energetic particles would be rightly considered \textit{ad hoc} and would be hard to physically justify.

However, lithium production occurs by spallation of protons over heavy nuclei as well as spallation of helium over helium:

\[ p, \alpha + C, N, O \rightarrow Li + X; \quad p, \alpha + Mg, Si, Fe \rightarrow Li + X; \]
\[ 2\alpha \rightarrow ^7 Li + p; \quad \alpha + D \rightarrow p + ^6 Li; \]
\[ ^7 Be + \gamma \rightarrow p + ^6 Li; \quad ^9 Be + p \rightarrow \alpha + ^6 Li. \]

The absence or deficiency of heavy nuclei in a target cloud and deficiency of alpha particles in the incident beam would clearly suppress lithium production. Such conditions could well have existed in the environments of incipient Pop II stars.

Essential aspects of evolution of a collapsing cloud to form a low mass Pop II star is believed to be fairly well understood [17, 18]. The formation and early evolution of such stars can be discussed in terms of gravitational and hydrodynamical processes. A protostar would emerge from the collapse of a molecular cloud core and would be surrounded by high angular momentum material forming a circumstellar accretion disk with bipolar outflows. Such a star contracts slowly while the magnetic fields play a very important role in regulating collapse of the accretion disk and transferring the disk orbital angular motion to collimated outflows. A substantial fraction of the accreting matter is ejected out to contribute to the interstellar medium.

Empirical studies of star forming regions over the last twenty years have now provided direct and ample evidence for MeV particles produced within
protostellar and T Tauri systems [19, 20]. The source of such accelerated particle beaming is understood to be violent magnetohydrodynamic (MHD) reconnection events. These are analogous to solar magnetic flaring but elevated by factors of $10^1$ to $10^6$ above levels seen on the contemporary sun besides being up to some 100 times more frequent. Accounting for characteristics in the meteoritic record of solar nebula from integrated effects of particle irradiation of the incipient sun’s flaring has assumed the status of an industry. Protons are the primary component of particles beaming out from the sun in gradual flares while $^4\text{He}$ are suppressed by factors of ten in rapid flares to factors of a hundred in gradual flares [19, 20]. Models of young sun visualizes it as a much larger protostar with a cooler surface temperature and with a very highly elevated level of magnetic activity in comparison to the contemporary sun. It is reasonable to suppose that magnetic reconnection events would lead to abundant release of MeV nuclei and strong shocks that propagate into the circumstellar matter. Considerable evidence for such processes in the early solar nebula has been found in the meteoric record. It would be fair to say that the hydrodynamical paradigms for understanding the earliest stages of stellar evolution is still not complete. However, it seems reasonable to conjecture that several features of collapse of a central core and its subsequent growth from acrating material would hold for low metallicity Pop II stars. Strong magnetic fields may well provide for a link between a central star, its circumstellar envelope and the acrating disk. Acceleration of jets of charged particles from the surface of such stars could well have suppressed levels of $^4\text{He}$. Such a suppression could be naturally expected if the particles are picked up from an environment cool enough to suppress ionized $^4\text{He}$ in comparison to ionized hydrogen. Ionized helium to hydrogen number ratio in a cool sunspot temperature of $\approx 3000$ K can be calculated by the Saha’s ionization formula and the ionization energies of helium and hydrogen. This turns out to be $\approx exp(-40)$ and increases rapidly with temperature. Any electrodynamic process that accelerates charged particles from such a cool environment would yield a beam deficient in alpha particles. With $^4\text{He}$ content in an accelerated particle beam suppressed in the incident beam and with the incipient cloud forming a Pop II star having low metallicity in the target, the “no - go” concern of (Epstein et.al. [2]) is effectively circumvented. The “no-go” used $Y_\alpha/Y_p \approx .07$ in both the energetic particle flux as well as the ambient medium besides the canonical solar heavy element mass fraction. Incipient Pop II environments may typically have heavy element fraction suppressed by more than five orders of magni-
tude while, as described above, magnetic field acceleration could accelerate beams of particles deficient in $^4$He.

One can thus have a broad energy band - all the way from a few MeV up to some 500 MeV per nucleon as described in the Figure (3), in which acceptable levels of deuterium could be “naturally” produced. The higher energy end of the band may also not be an impediment. There are several astrophysical processes associated with gamma ray bursts that could produce $D$ at high beam energies with the surplus gamma ray flux a natural by product.

Circumventing the “no-go” concern of Epstein et al would be of interest for any cosmology having an early universe expansion rate significantly lower than corresponding rates for the same temperatures in early universe SBB.

**Conclusions:**

Our understanding of star formation has considerably evolved since 1976. SBBN constraints need to be reconsidered in view of empirical evidence from young star forming regions. These models clearly imply that spallation mechanism can lead to viable and natural production of Deuterium and Lithium in the incipient environment of Pop II stars. One can conceive of cosmological models in which early universe nucleosynthesis produces the desired primordial levels of $^4$He but virtually no $D$. Such a situation can arise in SBBN itself with a high baryon entropy ratio $\eta$. In such a universe, in principle, Deuterium and Lithium can be synthesized up to acceptable levels in the environment of incipient Pop II stars.

In SBB, hardly any metallicity is produced in the very early universe. Metal enrichment is supposed to be facilitated by a generation of Pop III stars. Pop III star formation from a pristine material is not well understood till date in spite of a lot of effort that has been expanded to that effect recently [21]. It is believed that with metallicity below a critical transition metallicity ($Z_{cr} \approx 10^{-4}Z_\odot$), masses of Pop III stars would be biased towards very high masses. Metal content higher than $Z_{cr}$ facilitates cooling and a formation of lower mass Pop II stars. In SBB, the route to Deuterium by spallation discussed in this article would have to follow a low metal contamination by a generation of Pop III stars.

Deuterium production by spallation discussed in this article would be good news for a host of slowly evolving cosmological models [22, 23]. An FRW model with a linearly evolving scale factor enjoys concordance with constraints on age of the universe and with the Hubble data on SNe1A. Such a linear coasting is consistent with the right amount of helium observed in the universe and metallicity yields close to the lowest observed metallicities. The
only problem that one has to contend with is the significantly low yields of deuterium in such a cosmology. In such a model, the first generation of stars would be the low mass Pop II stars and the above analysis would facilitate the desired deuterium yields.

In SBB, large-scale production and recycling of metals through exploding early generation Pop III stars leads to verifiable observational constraints. Such stars would be visible as 27 - 29 magnitude stars appearing any time in every square arc-minute of the sky. Serious doubts have been expressed on the existence and detection of such signals [24]. The linear coasting cosmology would do away with the requirement of such Pop III stars altogether.
Fig1(a). The figure shows abundance of He4 as a function of temperature for \( \eta \approx 7.8 \times 10^{-9} \). The final abundance of He4 is approximately 23 %. It reaches this value around \( T \approx T_9 \) and stays same thereafter.

Fig1(b). The figure shows metallicity as a function of temperature for \( \eta \approx 7.8 \times 10^{-9} \). The metallicity for a linear coasting model is nearly equal to \( 10^{-5} \) times solar metallicity.
Fig2(a). The figure shows He4 abundance as a function of $\eta$.

Fig2(b). The figure shows metallicity as a function of $\eta$. 
Fig 3. The rates at which abundances approach their present values as a function of the energy per nucleon of the incident particle. 

[Diagram showing the rates of abundance formation over energy per nucleon, with curves for different elements like Li and γ.]

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16
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