Light element synthesis in baryon isocurvature models

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Abstract

The prejudice against baryon isocurvature models is primarily because of their inconsistency with early universe light element nucleosynthesis results. We propose that incipient low metallicity (Pop II) star forming regions can be expected to have environments conducive to Deuterium production by spallation, up to levels observed in the universe.

1 Introduction:

Early universe (standard big-bang) nucleosynthesis [SBBN] is widely 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 the 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 from a belief, that there are no astrophysical sites (other than SBBN), capable of producing it in its observed abundance [2].

Primary Isocurvature Baryon models [PIB] are characterised by a baryon density that saturates dynamic mass bounds from galactic clusters. These

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models can provide concordance with CMB anisotropy [4] and offer a plausible account for structure formation in the universe [5]. The model does away with the need for non-baryonic dark matter. One could consider a PIB model with $\Omega_b \approx 0.2$ to 0.3 and comply with the theoretical prejudice in favour of a flat model by adding a cosmological constant $\Omega_\Lambda = 1 - \Omega_b$. The problem with such a model is that the high baryon content gives low yields for Deuterium in a primordial nucleosynthesis scenario.

There have been suggestions that an early generation of massive black holes may form just after recombination in the PIB models. These could be sites on which accreting gas would emit radiation that could generate $D$ and $^3He$ by photo disintegration of $^4He$. The purpose of this article is to show that the environment of incipient Pop II stars are sufficient to produce these elements by spallation reactions. One thus does not need to invoke black holes for this purpose at all.

Confidence in SBBN stems primarily from $D$, $^7Li$ and $^4He$ measurements. $D$ abundance is measured in solar wind, in interstellar clouds and, more recently, in the inter-galactic medium [6, 7]. The belief that no realistic astrophysical process other than the Big Bang can produce sufficient $D$ lends support to its primordial origin. Further, $^7Li$ measurement [$^7Li/H \sim 10^{-10}$] in Pop II stars [8] and the consensus [9] over the primordial value for the $^4He$ 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 $^7Li$ production that are accompanied by a co-production of $^6Li$ with a later depletion of $^7Li$ have fallen out of favour. The debate on depletion of $^7Li$ has been put to rest by the observation of $^6Li$ in a Pop II star [10]. Any depletion of $^7Li$ would have to be accompanied by a complete destruction of the much more fragile $^6Li$. Within the SBBN scenario therefore, one seeks to account for the abundances of $^4He$, $D$, $^3He$ and $^7Li$ cosmologically, while $Be$, $B$ and $^6Li$ are generated by spallation processes [11].

These results do meet with occasional scepticism [see eg. [12] for problems with BBN]. Observation of $^6Li$, for example, requires unreasonable suppression of astrophysical destruction of $^7Li$. On the other hand, the production of $^6Li$ would be accompanied by a simultaneous production of $^7Li$ comparable to observed levels [13]. This raises doubts about using observed $^7Li$ levels as a benchmark to evaluate SBBN.

Further the best value of $^4He$ mass fraction, statistically averaged and
extrapolated to zero heavy element abundances, hovers around $0.216 \pm 0.006$ for Pop II objects [14]. Such low $^4\text{He}$ levels have also been reported in several metal poor HII galaxies [15]. For example for SBS 0335-052 the reported value is $Y_p = 0.21 \pm 0.01$ [16]. 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, on the one hand, to be “natural” parameters for such a venture. Adherents of minimal SBBN have criticised these conclusions in [9, 16] on grounds of reliance on statistical over-emphasis on a few metal-poor objects with a high enough $^4\text{He}$ abundance. 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 $\mu$ Cassiopeia A [16] and from the emission lines of several quasars [17] 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 local environments of 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 special “unnatural” circumstances [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 [9]. 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 dependence of light element abundance on sample and statistics is dispensed with and / or more fully understood, we should not close our eyes to alternative solutions.

We end this 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 reprocessing could take place in a generation of very short-lived type III stars conceived for this purpose. Such a generation of stars may also be necessary to ionise 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 [18].

Finally, of late [19], 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 \(^2\text{H}\) in several \(\text{Ly}_\alpha\) systems. It may be difficult to accommodate 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 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 close the dynamic mass estimates at galactic and cluster scales. Making out a case for CDM from observed (local environment sensitive) estimates of Deuterium runs the risk of “building a colossus on a few feet of clay”[20].

2 Deuterium Production

For a high baryon density model like the PIB model to clear the observed Deuterium constraints, the desired amount of Deuterium would have to be produced much later in the history of the universe. To this effect, we recall spallation mechanisms that were explored in the pre - 1976 days [2]. Deuterium can indeed be produced by the following spallation reactions:

\[ p + ^4\text{He} \rightarrow D + ^3\text{He}; \hspace{1cm} 2p \rightarrow D + \pi^+; \]

\[ 2p \rightarrow 2p + \pi^0, \hspace{1cm} \pi^0 \rightarrow 2\gamma, \hspace{1cm} \gamma + ^4\text{He} \rightarrow 2D. \]

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 \(\gamma\) rays to unacceptable levels. Any later destruction
of lithium in turn completely destroys \( D \). As described in [2], figure (1) exhibits relative production of \( ^7\text{Li} \) 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 energised 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. This presents a “no-go” result. There is no way to produce \( D \) without overproducing \( \text{Li} \).

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

\[
p, \alpha + C, N, O \rightarrow \text{Li} + X; \quad p, \alpha + Mg, Si, Fe \rightarrow \text{Li} + X;
\]

\[
2\alpha \rightarrow ^7\text{Li} + p; \quad \alpha + D \rightarrow p + ^6\text{Li};
\]

\[
^7\text{Be} + \gamma \rightarrow p + ^6\text{Li}; \quad ^9\text{Be} + p \rightarrow \alpha + ^6\text{Li}.
\]

Essentially, the “no-go” argument of Epstein et al [2] used \( Y_\alpha/Y_p \approx 0.07 \) (\( \approx 28\% \) by weight) in both the incident particle flux as well as the ambient medium, besides the canonical solar heavy element mass fraction in the target cloud. 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 [21, 22]. 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 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 [23, 24]. 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 $^4\text{He}$ levels are suppressed by factors of ten in rapid flares to factors of a hundred in gradual flares\cite{23,24}. Models of young sun visualises 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 are still not complete. However, it seems reasonable to conjecture that several features of collapse of a central core and its subsequent growth from accreting 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 accreting disk. Acceleration of jets of charged particles from the surface of such stars would have suppressed levels of $^4\text{He}$. Such a suppression could be naturally expected if the particles are picked up by magnetic reconnection events from an environment cool enough to suppress ionised $^4\text{He}$ in comparison to ionised hydrogen. Ionised helium to hydrogen number ratio in a cool sunspot temperature can be calculated by the Saha’s ionization formula and the ionization energies of helium and hydrogen. This could be as low as $\approx \exp(-40)$ 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. \cite{2}) is effectively circumvented. As stated before, the “no-go” result used $Y_\alpha/Y_\rho \approx .07$ in both the energetic incident particle flux as well as in the ambient medium besides the canonical solar heavy element abundance in the target cloud. Incipient Pop II environments may typically have heavy element fraction suppressed by more than five orders of magnitude while, as described above, magnetic field acceleration could accelerate beams of particles deficient in $^4\text{He}$.

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 (1), 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.

3 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 consider a baryon dominated PIB cosmological model in which early universe nucleosynthesis produces the desired primordial levels of \( ^4He \) but very little \( D \). In such a universe, in principle, spallation mechanism can lead to Deuterium and Lithium synthesis 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 \[25\]. 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.
Figure(1): The ratio of formation of abundances to their present values as a function of the energy per nucleon of the incident particle. Below $\approx 400$ MeV, the observed levels of $D$ are accompanied by an over production of Li isotopes while slightly above this energy a large gamma ray flux is produced.
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