Deuterium and $^7$Li Concordance in Inhomogeneous Big Bang Nucleosynthesis Models

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Abstract

Recent observational constraints on primordial deuterium and $^7$Li correspond to different values of the baryon-to-photon ratio when applied to the Standard Big Bang Nucleosynthesis (SBBN) model. In this article these constraints are applied to baryon Inhomogeneous (IBBN) models. A depletion factor of 3.4 applied to the $^7$Li constraints will bring $^7$Li, deuterium and $^4$He constraints in concordance for both the SBBN and IBBN models. A depletion factor of 6.1 will bring concordance for the IBBN model alone.

1. Introduction: SBBN Models

In Big Bang Nucleosynthesis free neutrons and protons fuse to form gradually heavier nuclei via nuclear and weak reactions. In the Standard BBN model the universe is homogeneous and isotropic. The baryon-to-photon ratio $\eta$ is a variable in the SBBN model.

Figure (1) shows the mass fraction of $^4$He and the log of the abundance ratios of deuterium to hydrogen and $^7$Li to hydrogen for the SBBN case, wherein they are functions of $\eta$. These results can be compared with observations of primordial abundances. The $^4$He mass fraction has been measured as low as 0.228 [5] and as high as 0.248 [1]. Kirkman et al [4] have measured $[d/H] = 2.78^{+0.44}_{-0.38} \times 10^{-5}$ while Ryan et al [6] have measured $[^7\text{Li}/H] = 1.23^{+0.68}_{-0.32} \times 10^{-10}$. $[d/H]$ corresponds to $\eta = (5.6 - 6.6) \times 10^{-10}$ while $[^7\text{Li}/H]$ to a different range, $\eta = (1.6 - 4.1) \times 10^{-10}$.

2. Methods: IBBN Models

Certain theories of baryogenesis [3] lead to inhomogeneous baryon distributions at the time of BBN. As an example, this article uses a model with a low density cylindrical core and a high density cylindrical outer shell. At temperatures $T > 13$ GK weak reactions gradually convert neutrons to protons. At some
time depending on the model size neutrons diffuse into the low density core until they are homogeneously distributed. The outer shell may maintain a high proton density at $T = 0.9$ GK, when BBN occurs. BBN will occur earlier in the outer shell, depleting neutrons there. Neutrons then back diffuse to the outer shell and BBN occurs primarily in the high density shell.

Along with $\eta$, IBBN models will depend on $r_i$, the size of the model, $R_\rho$, the initial ratio of high to low density, $f_v$, the volume fraction of the high density region, and the geometry of the model. To simplify the model only neutrons can diffuse.

### 3. Results and Discussion

Figure (2) is an abundance contour map for the cylindrical shell model. $r_i$ is the size of the model at $T = 100$ GK. A region of concordance between $[\text{d/H}]$ and the $^4\text{He}$ constraints is shown in yellow. The region marked by the $[^7\text{Li/H}]$ constraints is shown in light green.

The effect of inhomogeneity to the isotope abundances is comparable to a shift in the value of $\eta$ in the standard model. Abundance contours tend to run parallel to another, and the region marked out by the Ryan et al. constraints on
Fig. 2. \(^4\)He, [d/H], and \(^7\)Li/H constraints in the cylindrical shell model, as functions of \(\eta\) and \(r_i\).

\(^7\)Li never coincides with the [d/H]-\(^4\)He region of concordance for any value of \(r_i\). The \(^7\)Li constraints with a depletion factor of 3.4 are shown in moderate green. With this depletion factor the constraints agree the [d/H] and \(^4\)He constraints for the SBBN case. The constraints agree for this IBBN model as well for \(r_i\) up to 20000 cm, and for a region where \(r_i = [150000, 500000]\) cm.

As \(r_i\) increases neutron diffusion occurs at later times. The baryon density of the outer shell at the time of BBN increases. For any set value of of \(\eta\) \(^4\)He increases while deuterium production decreases, and the contours of \(^4\)He and [d/H] shift to lower \(\eta\). Production of \(^7\)Be, which decays into \(^7\)Li, increases with increasing \(r_i\) more quickly though than the change in the other light isotopes. For \(r_i = [20000, 150000]\) cm the \(^7\)Li constraints need a depletion factor of 6.1, shown in dark green, to be in concordance with the other isotope constraints.

At \(r_i = 600000\) cm neutron diffusion starts to occur late enough to coincide with BBN. Neutron diffusion to the low density core competes with back diffusion due to earlier BBN in the high density outer shell. In this case the model produces both large amounts of \(^4\)He and deuterium. The region of concordance between \(^4\)He and [d/H] reaches its maximum value of \(r_i\) for this case.

Contour maps were made for spherical shell, condensed sphere, and condensed cylinder geometries as well as cylindrical shell geometry. In these maps the shapes of the contour lines become more exaggerated if the volume fraction is decreased. But the contour lines maintain the same basic appearance. In all ge-
ometries a thin region of concordance existed between $[d/H]$ and $^4\text{He}$ constraints but not with $^7\text{Li}$ without the depletion factors mentioned above.

4. Conclusions

The existence of a region of concordance between $[d/H]$ and $^4\text{He}$ constraints in IBBN models is independent of the geometry of the model. In IBBN models the $^7\text{Li}$ constraints still need a depletion factor in order to be in concordance with the other constraints. A factor of 3.4 can bring all the constraints in concordance for both SBBN and small size IBBN models. Larger size IBBN models alone can satisfy the constraints with a factor of 6.1.

A future article will discuss the influence of neutron diffusion on final abundances in much greater detail. The cases where $^7\text{Be}$ production is greatly increased and when neutron diffusion and BBN coincide will be discussed as those cases determine the sizes of the concordance regions. The influence of other details such as proton and isotope diffusion and neutrino degeneracy \cite{2} also needs to determined. Models for $^7\text{Li}$ depletion will be kept in mind to compare with the depletion factors determined in this article.

5. List of Symbols/Nomenclature

\begin{itemize}
\item $T$ = Temperature, GK
\item $\eta$ = baryon to photon ratio
\item $r_i$ = size of the IBBN model at $T = 100$ GK, cm
\item $R_\rho$ = initial ratio of high to low baryon density
\item $f_v$ = fraction of volume that has high density.
\item $[d/H]$ = abundance ratio of deuterium to free protons
\item $[^7\text{Li}/H]$ = abundance ratio of $^7\text{Li}$ to free protons
\end{itemize}

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