

New Determination Method of Primordial Li Abundance

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Abstract. We discuss the primordial nucleosynthesis in lepton asymmetric Universe models. In order to better estimate the universal baryon-mass density parameter Ω_b , we try to remove the uncertainty from the theoretical prediction of primordial ${}^7\text{Li}$ abundance. We propose a new method to determine the primordial ${}^7\text{Li}$ by the use of isotopic abundance ratio ${}^7\text{Li}/{}^6\text{Li}$ in the interstellar medium which exhibits the minimum effects of the stellar processes.

1. Introduction

Recent spectral and photometric observations of Type Ia supernovae at high redshifts (Riess et al. 1998; Perlmutter et al. 1999) have raised a possibility that the cosmic expansion is accelerated. For a flat cosmology these data have χ^2 -minimum around $\Omega_0 \approx 0.3$ and $\Omega_\Lambda \approx 0.7$, allowing Hubble time $\sim 15\text{Gyr}$ which is not inconsistent with the age of the Milky Way constrained from the observations of the oldest globular clusters.

Cosmological model for primordial nucleosynthesis provides independent method to determine Ω_0 . The Big-Bang nucleosynthesis model (Copi et al. 1995) predicts $0.04 \leq \Omega_b h_{50}^2 \leq 0.08$. Combining this value with X-ray observations of rich clusters that indicate $0.3h_{50}^{-3/2} \approx \Omega_b/\Omega_0$ (Bahcall et al. 1995; White et al. 1993), total Ω_0 turns out to be $\Omega_0 h_{50}^{1/2} \approx 0.1\sim 0.3$, which is consistent with flat cosmology.

However, in the determination of Ω_b , a difficulty has been imposed by recent detections of a low deuterium abundance, $2.9 \times 10^{-5} \leq \text{D}/\text{H} \leq 4.0 \times 10^{-5}$, in Lyman- α clouds along the line of sight to high red-shift quasars (Burles & Tytler 1998ab). Primordial abundance of ${}^7\text{Li}$ is constrained from the observed "Spite plateau", $0.91 \times 10^{-10} \leq {}^7\text{Li}/\text{H} \leq 1.91 \times 10^{-10}$ (Ryan et al. 2000a), and the ${}^4\text{He}$ abundance by mass, $0.226 \leq Y_p \leq 0.247$ (Olive et al. 1999), from the observations in the HII regions. In order to satisfy these abundance constraints by single Ω_b value, one has to assume an appreciable depletion in the observed abundance of ${}^7\text{Li}$, which is still controversial both theoretically and observationally. We are now forced to critically study the uncertainty. An independent method to determine the primordial ${}^7\text{Li}$ is also desirable.

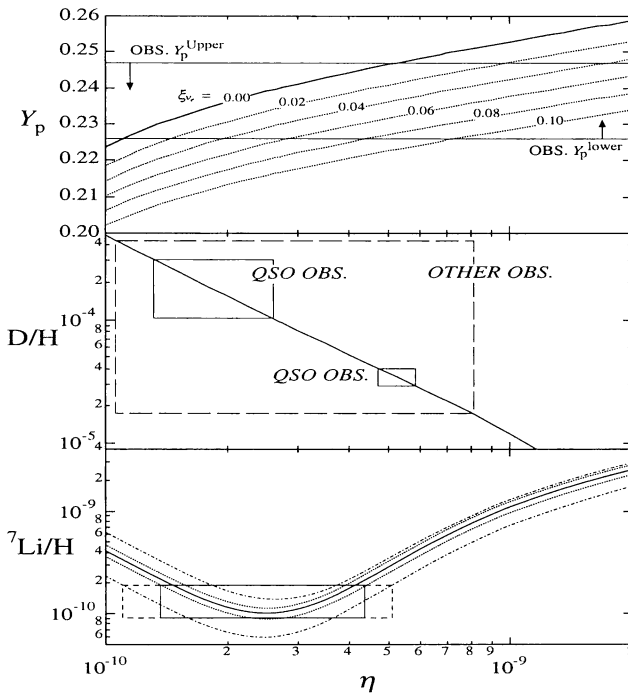


Figure 1. Y_p , D/H and ${}^7\text{Li}/H$ vs. η for various neutrino degeneracy parameters ξ_{ν_e} . Observed constraints on D/H are from Rugers & Hogan (1996) (upper) and Burles & Tytler (1998ab) (lower). Theoretical curves for ${}^7\text{Li}/H$ show the 2σ uncertainties based on two different error estimates of the reaction rates. See text for details.

2. Primordial Nucleosynthesis

2.1. ${}^4\text{He}$ vs. D and Neutrino Degeneracy

Shown in Fig. 1 is the comparison between the observed abundance constraints on ${}^4\text{He}$, D/H , and ${}^7\text{Li}/H$ and the calculated curves in the homogeneous Big-Bang model as a function of η , where $\eta = n_B/n_\gamma$ and $\Omega_b h_{50}^2 = \eta \cdot 1.464 \times 10^8$. Solid curves display the theoretical prediction of primordial abundances in the standard particle model for neutrino, which preserves the lepton symmetry $L_\nu=0$.

There is now a good collection of abundance information on the ${}^4\text{He}$ mass fraction, Y_p , in over 50 extragalactic HII regions, from which the upper limit on primordial abundance, $Y_p \leq 0.240$, and a systematic error, $\Delta Y_{sys}=0.005$, were extracted. Unfortunately, for this upper limit one cannot find Ω_b to satisfy both abundance constraints on ${}^4\text{He}$ and D/H . (See the solid curves in Fig. 1.)

It has been recognized that ΔY_{sys} may even be larger (Izatov et al. 1994; Thuan 2000), making the upper limit as large as $Y_p \leq 0.247$. If this upper limit is adopted, the Universe model with $\eta \approx 5 \times 10^{-10}$ is marginally consistent with both abundance constraints. However, since even smaller value, $Y_p=0.235 \pm 0.003$,

in low-metallicity extragalactic HII regions has been reported by Peimbert & Peimbert (2000), this potential conflict is to be studied more carefully.

One possible solution is to introduce a lepton asymmetry. Theoretically, it is natural to assume that both baryon and lepton symmetries are simultaneously broken, $B \neq 0$ and $L_\nu \neq 0$, due to the CP violation in baryogenesis. $L_\nu \neq 0$ is fulfilled by neutrino degeneracy with non-zero ξ_{ν_e} , where $\xi_{\nu_e} = \mu_{\nu_e}/kT_\nu$ and μ_{ν_e} is the chemical potential of electron neutrino. Since neutrinos had energy density comparable to the densities due to photons and charged leptons in the early Universe, even a small degeneracy $0 < \xi_{\nu_e} \ll 1$ leads to an appreciable decrease in the neutron-to-proton number ratio, slightly faster acceleration of the Universal expansion, and a small increase of the weak-decoupling temperature. As a net result, ${}^4\text{He}$ abundance decreases with increasing ξ_{ν_e} , as shown in Fig. 1, while keeping D/H and ${}^7\text{Li}/\text{H}$ almost unchanged in logarithmic scale (Kajino & Orito 1998). Since the abundance constraint on primordial ${}^4\text{He}$ is more accurate than the other light elements, this helps determine the most likely ξ_{ν_e} . $\xi_{\nu_e} \sim 0.05$ can best fit the ${}^4\text{He}$ abundance as well as low deuterium abundance $\text{D}/\text{H} \sim 10^{-5}$, leaving inevitable requirement that the observed abundance level of Spite plateau, ${}^7\text{Li}/\text{H} \sim 10^{-10}$, should be the result of depleted primordial abundance.

2.2. ${}^7\text{Li}$ vs. D

There are several input parameters in the primordial nucleosynthesis calculation. As the number of light neutrino families $N_\nu = 3$ and the neutron lifetime $\tau_n = 886.7 \pm 1.9$ s are known, the remaining major uncertainty arises from input nuclear reaction data. We did not take account of the effects of sterile neutrino which is a hypothetical particle for interpreting flavor mixing.

Laboratory cross section measurements ever done provide rather precise thermonuclear reaction rates for the production of D, T, ${}^3\text{He}$, and ${}^4\text{He}$. It however was claimed in literature (Smith et al. 1993) that the ${}^7\text{Li}$ abundance is strongly subject to large error bars associated with the measured cross sections for ${}^4\text{He}({}^3\text{H}, \gamma){}^7\text{Li}$ at $\eta \lesssim 2 \times 10^{-10}$ and ${}^4\text{He}({}^3\text{He}, \gamma){}^7\text{Be}$ at $3 \times 10^{-10} \lesssim \eta$. There are in fact several inconsistent data with one another, leading to large uncertainty in the primordial ${}^7\text{Li}$, as displayed by long-dash-dotted curves in Fig. 1.

We studied these two reactions very carefully and concluded that the proper 2σ error bars could be $1/4 \sim 1/3$ of the previous ones (Kajino et al. 2000). This improvement owes mostly to, first, the new precise measurement (Brune et al. 1994) of the cross sections for ${}^4\text{He}({}^3\text{H}, \gamma){}^7\text{Li}$ and, second, the systematic theoretical studies of both reaction dynamics and quantum nuclear structures of ${}^7\text{Li}$ and ${}^7\text{Be}$, whose validity is critically tested by electromagnetic form factors measured by high-energy electron scattering experiments.

When our recommended error estimate is applied to the determination of Ω_b in Fig. 1, we lose Ω_b value to explain both D/H and ${}^7\text{Li}/\text{H}$ simultaneously. If we allow for larger primordial ${}^7\text{Li}$ abundance in Population II halo stars because of possible lithium depletion for diffusion or rotation-induced mixing of matter (Deliyannis et al. 1998 ; Pinsonneault et al. 1992) or some systematic uncertainty in the model atmospheres (Kurucz 1995), we can recover the concordance. Taking depletion factor ≈ 2.5 , $\Omega_b h_{50}^2 \approx 0.075$ best fits all abundance constraints in the homogeneous Big-Bang model. Note that larger $\Omega_b h_{50}^2 \approx 0.2$ is allowed in the inhomogeneous Big-Bang model (Kajino & Orito 1998).

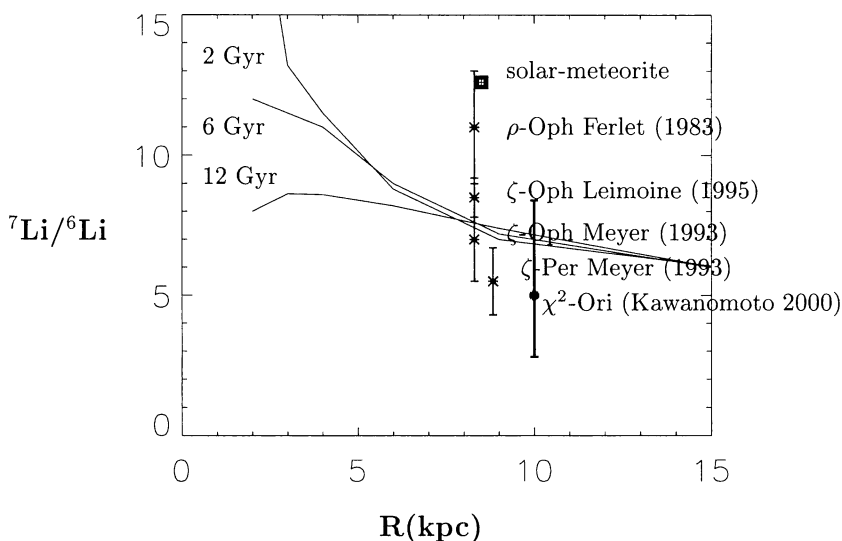


Figure 2. Calculated isotopic abundance ratios ${}^7\text{Li}/{}^6\text{Li}$ at various times as a function of the Galactocentric distance R , compared with observed data.

3. ${}^7\text{Li}/{}^6\text{Li}$ Ratio in the Interstellar Medium (ISM)

The lithium in the ISM is almost free from the complicated stellar processes. A diffuse cloud along the line of sight to ζOph was observed to show the lithium abundance depleted by 1.58dex from the meteoritic solar-system value 12.3. This is due to dust grain formation (Savage & Sembach 1996). The isotopic ratio is free from such condensation effects and represents the real ratio of chemical compositions in the gas phase. The D/H (Wannier 1980) and ${}^3\text{He}/\text{H}$ (Rood et al. 1995) abundance ratios in the ISMs have been observed over wide Galactocentric distance range $0 \leq R \leq 12\text{kpc}$ and used to constrain the primordial abundance of D/H (Dearborn et al. 1996), but the distribution of ${}^7\text{Li}/{}^6\text{Li}$ was poorly known.

3.1. Observation

Observations of isotopic abundance ratio, ${}^7\text{Li}/{}^6\text{Li}$, have been performed by several groups (Ferlet & Dennefeld 1983, Lemoine et al. 1993, 1995, Meyer et al. 1993) only for the ISMs in our solar neighborhood. The observed ratio is less than 12.3 and larger than 2.1 which is a predicted GCR abundance ratio.

Using the Coude spectrograph of the 74-inch telescope at Okayama Astrophysical Observatory, Japan, we have succeeded for the first time in the determination of ${}^7\text{Li}/{}^6\text{Li}$ in the diffuse cloud along the line of sight to $\chi^2\text{Ori}$, which is a member of OB association Gem-OB1, being located at $R = 10\text{kpc}$ (Kawanomoto et al. 2000). The telescope performance was $R=43,000$ (with slit width of $100\ \mu\text{m}$), $\text{exp}=50\text{hours}$, and $S/N=2,800$.

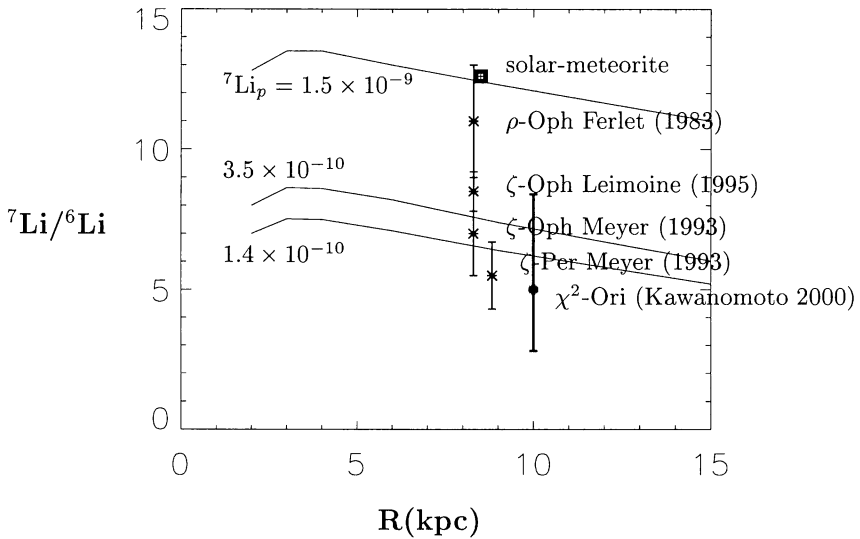


Figure 3. Calculated isotopic abundance ratios ${}^7\text{Li}/{}^6\text{Li}$ at the present time, $t_G = 12\text{Gyr}$, for various primordial abundances, ${}^7\text{Li}_p \equiv {}^7\text{Li}/\text{H}(\text{primordial})$, as a function of the Galactocentric distance R , compared with observed data.

We found a decreasing gradient of ${}^7\text{Li}/{}^6\text{Li}$, as shown in Figs. 2 & 3. It is interpreted as a result of gradual extinction of the stellar production of ${}^7\text{Li}$.

3.2. A New Method to Determine Primordial ${}^7\text{Li}$

In order to study the sensitivity to the primordial lithium abundance, we have calculated Galactic chemical evolution (GCE) of lithium (Kawanomoto 2000). We adopted a hybrid model (Ryan et al. 2000b) of the inhomogeneous GCE model (Suzuki et al. 1999), which was constructed for the early evolution of metal-deficient stars, being smoothly connected with a simple one-zone GCE model for later evolution. Five different sources of lithium production are included in this model: Primordial nucleosynthesis, GCR interactions with ISM, ν -induced nucleosynthesis in Type II SNe, AGB star nucleosynthesis, and nova nucleosynthesis. We took an approximation that each ring having different Galactocentric distance evolves independently so that the observed present day star-formation-rate and the gas fraction are reproduced very well.

The calculated time variation of ${}^7\text{Li}/{}^6\text{Li}$ is shown as a function of R in Fig. 2. Remarkable decrease of ${}^7\text{Li}/{}^6\text{Li}$ in the inner region is caused by faster gas consumption for the star formation. It is discussed in literature that the meteoritic chemical compositions are peculiar and different from those of ISM because they were possibly polluted by nearby AGB star. One might speculate another possibility that the solar-system might ever have moved outward over hundreds of turns of the Galactic disc, keeping high ${}^7\text{Li}/{}^6\text{Li} = 12.3$ as it was

in the original position when the solar system was isolated from viscous gas component at $t_G \approx 2 \sim 6$ Gyr.

Figure 3 displays sensitivity of the ${}^7\text{Li}/{}^6\text{Li}$ ratio at the present time $t_G=12$ Gyr to the primordial abundance of ${}^7\text{Li}$. It is very sensitive to ${}^7\text{Li}_p$. Except for old data point at ρ -Oph (Ferlet & Dennefeld 1983), which has the largest error bar among all data for the solar neighborhood, the observed ratios look more consistent with ${}^7\text{Li}_p = (1.4 \sim 3.5) \times 10^{-10}$ than ${}^7\text{Li}_p = 1.5 \times 10^{-9}$. More data with smaller error bars are highly desirable in order to convince the gradient of the ${}^7\text{Li}/{}^6\text{Li}$ ratio and to determine the primordial abundance of ${}^7\text{Li}$ in this method.

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