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Initial Li Abundances in the Proto-Galaxy and Globular Clusters Based upon the Chemical Separation and Hierarchical Structure Formation

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Abstract

The chemical separation of Li^+ ions induced by a magnetic field during the hierarchical structure formation can reduce initial Li abundances in cosmic structures. It is shown that the cosmological reionization of neutral Li atoms is completed as soon as the first star is formed. Because almost all Li is singly ionized during the main course of structure formation, it can efficiently separate from gravitationally collapsing neutral gas. The separation is more efficient in smaller structures that had formed earlier. In the framework of the hierarchical structure formation, extremely metal-poor (EMP) stars can have smaller Li abundances because of their earlier formation. It is found that the chemical separation by a magnetic field thus provides a reason why Li abundances in EMP stars are lower than the Spite plateau and have a large dispersion as well as an explanation of the Spite plateau itself. In addition, the chemical separation scenario can explain Li abundances in NGC 6397, which are higher than the Spite plateau. Thus, Li abundances in metal-poor stars possibly retain information on the primordial magnetic field and the structure formation history.

Key words: atomic processes – dark ages, reionization, first stars – Galaxy: halo – globular clusters: general – magnetic fields – stars: abundances

1. Introduction

It has been suggested that the primordial magnetic field (PMF) induced a chemical separation of neutral gas and ionized plasma during the structure formation in the early universe (Kusakabe & Kawasaki 2015, hereafter KK15). For specific values of the comoving field amplitude ($\mathcal{O}(0.1)$ nG) and the coherence length corresponding to structures with mass ($10^6\,M_\odot$), the chemical separation effectively works. In addition, even when a field amplitude does not initially have a gradient, a gradient is generated during the gravitational contraction of the structure. Therefore, the chemical separation likely occurred if a PMF of sub-nG existed during the cosmological structure formation, independent of its inhomogeneity.

At redshifts $z \gtrsim 10$ of the structure formation, the cosmological recombination of Li^+ ion is frozen out before completion. Because of a small electron abundance after H recombination (Galli & Palla 1998) and a nonthermal radiation field from a late time recombination of free protons (Switzer & Hirata 2005), the relic abundance of Li^+ is much larger than that of neutral Li. These abundant Li^+ ions, as well as protons and electrons, can be separated from neutral gas by the magnetic field effect, and escape from structure formation (KK15). In this case, the total lithium abundance relative to hydrogen abundance, i.e., Li/H, in the formed structures can be significantly smaller than the cosmological average value determined at the primordial nucleosynthesis. When the structure formation proceeds without magnetic field effects, abundances of chemical species heavier than ^{1}H are slightly enhanced by a diffusion in thermal structures by less than 1% depending on species, structure mass, formation stages, and reionization history (Medvedev et al. 2016). The reduction of Li abundance is then much more significant in the case with a magnetic field.

In this Letter we improve this scenario of chemical separation, taking into account the cosmological reionization of Li atoms. Becker et al. (2001) found that cosmological reionization of hydrogen via photoionization (e.g., Weymann 1967; Couchman 1985) occurred in the intergalactic medium (IGM) at the redshift $z \gtrsim 6$ based on the existence of a trough in a spectrum of a high-z quasi-stellar object (QSO; Gunn & Peterson 1965). In Section 2, it is shown that the reionization of Li occurs immediately at the formation of the first star in a volume including the Galactic mass. Because this Li reionization occurs in the beginning of the structure formation, the Li exists in the singly ionized state in the major course of structure formation. As a result, the chemical separation of Li^+ ion more effectively reduces the Li abundance in early structures.

Observations of warm dwarf metal-poor halo stars (MPHSs) show a plateau abundance of lithium (e.g., Spite & Spite 1982; Ryan et al. 2000; Shi et al. 2007; Sbordone et al. 2010) called the Spite plateau, which can be interpreted as the primordial abundance (Spite & Spite 1982). However, this observed abundance at $A(\mathrm{Li}) = 2.199 \pm 0.086$[4] (Sbordone et al. 2010) is about three times smaller than the abundance derived in the standard big bang nucleosynthesis (BBN) model (Cyburt et al. 2016). In addition, recent observations of extremely metal-poor (EMP; $[\mathrm{Fe/H}] < -3$)[5] stars show lithium abundances with a large dispersion and an average value below the Spite plateau (e.g., Bonifacio et al. 2007; Aoki et al. 2009; Sbordone et al. 2010; Matsuno et al. 2017b). Furthermore, stellar Li

[4] $A(\mathrm{Li}) = \log(N_{\mathrm{Li}}/N_{\mathrm{H}}) + 12$. with N_i the particle number of element i.

[5] $[\mathrm{A/B}] = \log(N_{\mathrm{A}}/N_{\mathrm{B}}) - \log(N_{\mathrm{A}}/N_{\mathrm{B}})_\odot$ where the subscript $\odot$ means the solar value.

abundances have also been measured in metal-poor globular clusters (MPGCs; e.g., Molaro & Pasquini 1994; Thévenin et al. 2001; Bonifacio et al. 2002; Korn et al. 2006; González Hernández et al. 2009 for NGC 6397; Deliyannis et al. 1995 for M92; Pasquini & Molaro 1997; Bonifacio et al. 2007 for 47 Tucanae; Pasquini et al. 2005 for NGC 6752; Monaco et al. 2010 for ω Centauri; and Monaco et al. 2012 for M4). Although those abundances are similar to the Spite plateau abundance, the Li abundance in NGC 6397, i.e., $A(\mathrm{Li}) = 2.37 \pm 0.01$ for subgiants (González Hernández et al. 2009), is slightly larger than the plateau. These observations indicate that some physical process operated and changed the stellar Li abundance during or after the BBN. In Section 3, we give an interpretation of those observations based upon the chemical separation effect caused by the cosmological magnetic field.[6] Our brief conclusion then follows in Section 4.

In this Letter we adopt the natural units for the reduced Planck constant, the Boltzmann constant, and the light speed, i.e., $\hbar = k_{\mathrm{B}} = c = 1$.

2. Li Reionization

2.1. Survival of Photons with $E_\gamma < E_{\mathrm{H}}^{\mathrm{ion}}$

Before the cosmological reionization of hydrogen atoms, photons with energies lower than the ionization potential of H, i.e., $E_\gamma < E_{\mathrm{H}}^{\mathrm{ion}}$, emitted from early astronomical objects such as Population III stars and QSOs, were not significantly absorbed in the interstellar medium or IGM. Those photons were strongly scattered only in narrow energy ranges at Lyman series transitions of hydrogen, e.g., $E_\alpha = 10.20$ eV corresponding to the Lyα transition. The baryonic matter was mainly composed of hydrogen ($\sim$75% in mass) and helium ($\sim$25%; Cyburt et al. 2016), and they were in the atomic ground states. The ground states of H and He can only absorb continuum photons with energies greater than $E_{\mathrm{H}}^{\mathrm{ion}} = 13.60$ and $E_{\mathrm{He}}^{\mathrm{ion}} = 24.59$ eV, respectively. Therefore, photons with energies $E_\gamma < E_{\mathrm{H}}^{\mathrm{ion}}$ can escape from the star-forming region easily without absorption by H and He, while those with $E_\gamma \geqslant E_{\mathrm{H}}^{\mathrm{ion}}$ are destroyed via the photoionization of H (and He). The ionization front of Li around the first star then propagated with the light speed for a long time, while those of H and He propagated slower than that (see Kusakabe & Kawasaki 2012, Appendix).

Abundances of all elements other than H and He are negligible in terms of absorption of ionizing photons because they are smaller than the H abundance by more than 9 orders of magnitude (Coc et al. 2012). As a result, Li-ionizing photons with $E_\gamma < E_{\mathrm{H}}^{\mathrm{ion}}$ can be efficiently used for the Li reionization at the first light from the astronomical object that formed via the structure formation. Although those photons are scattered by relic-free electrons in the universe, the optical depth is very small.

The destruction rate of ultraviolet photons via Compton scattering before the reionization of H is given by

$$\begin{aligned}\Gamma_\gamma^{\mathrm{Com}} &= n_e(z)\sigma_{\mathrm{Th}} = X n_{\mathrm{b}}(z)\chi_{\mathrm{H}^+}\sigma_{\mathrm{Th}}\\ &= \eta X n_\gamma(z)\chi_{\mathrm{H}^+}\sigma_{\mathrm{Th}}\\ &= 1.0 \times 10^{-5}\ \mathrm{Gyr}^{-1}\left(\frac{\eta}{6.0 \times 10^{-10}}\right)\left(\frac{X}{0.75}\right)\\ &\times \left(\frac{T_0}{2.7255\ \mathrm{K}}\right)^3\left(\frac{1+z}{11}\right)^3\left(\frac{\chi_{\mathrm{H}^+}}{6.5 \times 10^{-5}}\right), \end{aligned} \quad (1)$$

where n_e, n_{b}, and n_{H^+} are the number densities of free electrons, baryons, and protons, respectively, X is the primordial mass fraction of hydrogen, $n_\gamma = 2\zeta(3)T^3/\pi^2$ is the number density of background radiation with $\zeta(3) = 1.20206$ the zeta function of three and $T = T_0(1+z)$ the photon temperature with $T_0 = 2.7255$ K the present photon temperature (Fixsen 2009), $\eta = n_{\mathrm{b}}/n_\gamma$ is the baryon to photon ratio (Planck Collaboration et al. 2014), χ_{H^+} is the ratio of the number density of H^+ to the total H density (Vonlanthen et al. 2009), and $\sigma_{\mathrm{Th}} = 6.65 \times 10^{-25}\ \mathrm{cm}^2$ is the Thomson scattering cross section. At the first line, we used $n_e = n_{\mathrm{H}^+}$ from the charge neutrality of the universe, noting that the relic He^+ abundance is very small (Vonlanthen et al. 2009). The scatterings of photons emitted from Population III stars with cosmic background electrons are thus very rare, and can be negligible.

The fact that photons with wavelengths longer than the Lyman limit have no important absorber is apparently supported by observed spectra of QSOs (Lynds 1971, 1972; Rauch 1998). Ultraviolet (UV) continua from QSOs have been observed in which multiple absorption lines corresponding to Lyα wavelength of hydrogen in absorbers are identified. Except for dense clouds that show absorptions by H and metal lines, the UV photons with $E_\gamma < E_{\mathrm{H}}^{\mathrm{ion}}$ do not have detectable absorptions during the cosmological Li reionization.

We note that at the Li reionization, the recombination of Li^+ in the IGM has already frozen out. Before the formation of astrophysical sources for heating IGM begins in the structure formation, the baryonic and electron matter has cooled adiabatically, and the baryonic temperature scales as $T_{\mathrm{g}} = 2.3\ \mathrm{K}[(1+z)/10]^2$ (Loeb & Zaldarriaga 2004). For example, at the redshift $z = 10$ the gas temperature is $T_{\mathrm{g}} = 2.8$ K. The recombination rate of Li^+ ions[7] is given by

$$\begin{aligned}\Gamma_{\mathrm{Li}^+}^{\mathrm{rec}} &= n_e(z)\langle\sigma v\rangle_{\mathrm{rec}}\\ &= 0.033\ \mathrm{Gyr}^{-1}, \end{aligned} \quad (2)$$

where $\langle\sigma v\rangle_{\mathrm{rec}} \approx 1.0 \times 10^{-11}\ \mathrm{cm}^3\ \mathrm{s}^{-1}[T_{\mathrm{g}}/(107.7\ \mathrm{K})]^{-1/2}$ is the thermal recombination rate (Galli & Palla 1998). This recombination rate is significantly smaller than the Hubble

[6] It is expected that both isotopes of $^{6,7}\mathrm{Li}^+$ ions separate similarly, although only the $^7\mathrm{Li}^+$ ion was treated in KK15. The radiative recombination rates and ionization rates of $^{6,7}\mathrm{Li}^+$ are almost the same due to the nearly equal electric multipole moments in the systems. The frictions on Li^+ ions from electrons (Equation (63) in KK15) are similar and those from neutral hydrogen (see Krstić and Schultz 2009) are expected to change slightly only within a reduced mass factor. Therefore, the chemical separation effectively operates and $^6\mathrm{Li}^+$ ions move in a strong coupling with electrons. If primordial ^{6}Li abundance will be found in observations of MPHSs, it can test the current chemical separation model. However, it is hard to determine the primordial ^{6}Li abundance because the abundance in the standard BBN model, i.e., $^6\mathrm{Li/H} = 1.23 \times 10^{-14}$ (Coc et al. 2012), is much lower than the present upper limit at $^6\mathrm{Li/H} = \mathcal{O}(10^{-12})$ (Lind et al. 2013) and ^{6}Li nuclei are depleted in both pre-main sequence and main sequence phases.

[7] Here the rate of $\mathrm{Li}^+ + e^-$ reaction only is included. Although the reactions, $\mathrm{Li}^+ + \mathrm{H} \rightarrow \mathrm{Li} + \mathrm{H}^+$ and $\mathrm{Li}^+ + \mathrm{H}^- \rightarrow \mathrm{Li} + \mathrm{H}$, also produce the neutral Li, both of the rates are negligibly small. For the former reaction, the detailed balance relation and the forward reaction rate for the final state of the H ground state (Kimura et al. 1994, 1995) lead to the thermal reaction rate of $\langle\sigma v\rangle_{\mathrm{Li}^+ + \mathrm{H}} = \mathcal{O}(10^{-20})\ \mathrm{cm}^3\ \mathrm{s}^{-1}\ \exp(-9.52 \times 10^4\ \mathrm{K}/T_{\mathrm{g}})$ for $T_{\mathrm{g}} = \mathcal{O}(100)$ K. The latter reaction rate (Galli & Palla 1998) is large, i.e., $\langle\sigma v\rangle_{\mathrm{Li}^+ + \mathrm{H}^-} = 6.3 \times 10^{-6}(T_{\mathrm{g}}/\mathrm{K})^{-0.5}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$. However, the recombination rate of Li^+ ions is negligibly small because of the tiny abundance of H^-, $\chi_{\mathrm{H}^-} \sim 10^{-13}$ at $z = 10$.

expansion rate at $z = 10$,

$$H \approx \sqrt{8\pi G\rho_{\rm m}(z)/3} = 1.4\ {\rm Gyr}^{-1}\left(\frac{\Omega_{\rm m}h^2}{0.14}\right)^{1/2}\left(\frac{1+z}{11}\right)^{3/2}, \quad (3)$$

where G is the Newton constant, $\rho_{\rm m}$ is the matter density, $\Omega_{\rm m}$ is the matter density parameter, and $h = H_0/(100\ {\rm km\ s^{-1}\ Mpc^{-1}})$ is defined with H_0 the Hubble constant.

2.2. Quick Cosmological Reionization of Li

We show that only one massive Population III star is enough to reionize primordial Li atoms within a volume including Galactic baryon mass.

Long after the BBN, the first star formed and nucleosynthesis restarted inside the star. It is believed that the initial mass function of early stars was top-heavy; that is, the formation rate of massive stars in the early universe was larger relative to less-massive stars. The upper limit on the first star mass is $\lesssim 100\ M_\odot$ (Bromm 2013).

For example, it is assumed that the first massive star had a mass $M_* = 100\ M_\odot$, an Eddington limit luminosity $L_*/L_\odot = 3.3 \times 10^4 M_*/M_\odot$, a blackbody spectrum with the effective temperature $T_* = 10^5$ K, and the lifetime $\Delta t_* = \eta M_*/L_* = 3.2$ Myr with $\eta = 0.00717$ (Wang et al. 2017), the energy conversion efficiency for nuclear energy via the hydrogen burning (Dwek et al. 2005). The solar mass and luminosity are $M_\odot = 1.1 \times 10^{57}$ GeV and $L_\odot = 3.90 \times 10^{33}$ erg s^{-1}, respectively.

The number of ionizing photons for Li emitted from a star is given by

$$N_\gamma^{\rm Li} = \int_{E_{\rm Li}^{\rm ion}}^{E_{\rm H}^{\rm ion}} dE_\gamma \frac{L_*(E_\gamma)}{E_\gamma}\Delta t_* = \frac{120}{\pi^2}\frac{L_*\Delta t_*}{T_*^4}\int_{E_{\rm Li}^{\rm ion}}^{E_{\rm H}^{\rm ion}} dE_\gamma \frac{E_\gamma^2}{\exp(E_\gamma/T_*) - 1} = 6.3 \times 10^{65}, \quad (4)$$

where $L_*(E_\gamma) = dL_*/dE_\gamma$, and $E_{\rm Li}^{\rm ion} = 5.39172$ eV is the ionization potential of Li.

The number of Li atoms in a sphere of the comoving radius L in the universe is given by

$$N({\rm Li}) = \chi_7 X n_{\rm b}(4\pi L^3/3) = 1.1 \times 10^{58}\left(\frac{\chi_7}{5.0 \times 10^{-10}}\right)\left(\frac{X}{0.75}\right) \times \left(\frac{\eta}{6.0 \times 10^{-10}}\right)\left(\frac{T_0}{2.7255\ {\rm K}}\right)^3\left(\frac{L}{\rm Mpc}\right)^3, \quad (5)$$

where χ_7 is the number ratio of Li and hydrogen.[8]

[8] The value in brackets corresponds to the total ratio of Li species that is fixed at the BBN. The actual ratio of neutral Li, however, is much lower than that because of a nonthermal UV field from the late-time H recombination (Switzer & Hirata 2005).

The number of Li atoms in a baryonic material of the mass $M_{\rm b}$ in the universe is given by

$$N({\rm Li}) \approx \chi_7 X M_{\rm b}/m_{\rm H} = 4.5 \times 10^{59}\left(\frac{\chi_7}{5.0 \times 10^{-10}}\right)\left(\frac{X}{0.75}\right)\left(\frac{M_{\rm b}}{1.0 \times 10^{12}\ M_\odot}\right), \quad (6)$$

where $m_{\rm H} = 938.783$ MeV is the mass of hydrogen. It is seen that only one star is enough to induce the reionization of Li in a volume much larger than that of the present Galaxy, i.e., $N_\gamma^{\rm Li} \gg N({\rm Li})$.

2.3. Cosmological Chemical Separation of Li$^+$ Ions

The rapid reionization of Li$^+$ occurs at the dawn of the dark age of the universe. Although the ionized degree of Li is expected to be very close to unity even before the reionization (Switzer & Hirata 2005; Galli & Palla 2013), UV photons produced in the first star would have inevitably realized the full ionization independently of any possible deviations in background radiation spectrum and baryonic temperature from those in the standard cosmology. Therefore, during the main part of the structure formation, Li existed in the singly ionized state. If there is a coherent magnetic field with $B = \mathcal{O}(0.1)$ nG over the scale corresponding to $10^6\ M_\odot$ at the structure formation, Li$^+$ ions, as well as protons and electrons, can effectively separate from neutral gas, which gravitationally collapses (KK15).

The effects of Li reionization improve our understanding of the chemical separation. In KK15, the initial abundances of Li and Li$^+$ were adopted from a chemical reaction network calculation for a homogeneous universe (Vonlanthen et al. 2009), in which the reionization was not included. The ratio of adopted abundances is Li$^+$/Li ≈ 1. Then, a significant fraction of Li$^+$ ions that could escape from a collapsing structure while neutral Li atoms joined the gravitational contraction. The authors suggested that the Li elemental abundance in early structures can be smaller than the cosmological average, i.e., the primordial abundance fixed at BBN, by a factor of two at most. However, when the enhanced reionization rate by the late-time H recombination (Switzer & Hirata 2005) and the reionization by the first star are taken into account, the efficiency of the Li reduction doubles as the ionization degree of Li is not a half but unity.

For example, the chemical separation has been simulated (Case 1 in KK15) for a structure with a mass $M_{\rm str} = 10^6\ M_\odot$ and a coherent magnetic field $B \sim 0.3$ nG and its gradient over the comoving length $L_0 = 10.4$ kpc, which completes the gravitational collapse at $z = 10$. In that model, about three-quarters of the initial Li$^+$ ions escaped from the structure formation, and the final average Li abundance in the structure is about five-eighths of the primordial Li abundance. If the Li is singly ionized initially,[9] however, the average Li abundance in the structure in this model would be one-fourth. This solves the

[9] The Li reionization by the first star occurred in the early stage of structure formation. The first star formed at $z \sim$ 20–30 (Bromm 2013). For example, we take $z = 30$, i.e., the cosmic time $t = 0.10$ Gyr, which is the early phase of gravitational contraction of structures (see Case 1 in KK15). Li-ionizing photons with $E_\gamma < E_{\rm H}^{\rm ion}$ quickly propagate to the comoving distance L_0 in a time $\Delta t(L_0, z) \approx 0.11$ Myr $(L_0/1\ {\rm Mpc})/[(1+z)/31]$, which is much shorter than the cosmic expansion time.

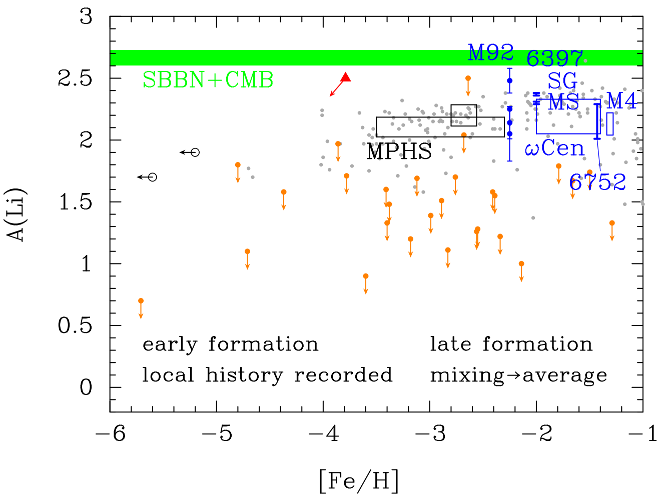

Figure 1. Li abundances as a function of metallicity taken from Matsuno et al. (2017a, and references therein), Bonifacio et al. (2018), Starkenburg et al. (2018), and Frebel et al. (2019). Symbols correspond to stars with detections of Li and Fe abundances (dots), only upper limits on Li abundances (solid circles), only upper limits on Fe abundances (open circles), and upper limits on both Li and Fe abundances (a triangle), respectively. Boxes show the Spite plateau of MPHSs (Ryan et al. 2000 (the wider one) and Sbordone et al. 2010 (the narrower one)), and abundances of ω Centauri (Monaco et al. 2010) and M4 (Monaco et al. 2012), while dots with error bars show abundances of M92 (Deliyannis et al. 1995), NGC 6397 (the main sequence and subgiants; González Hernández et al. 2009) and NGC 6752 (Pasquini et al. 2005), as labeled. The horizontal band is located at the standard BBN prediction of primordial Li abundance (Cyburt et al. 2016).

Li problem related to the Spite plateau and the primordial abundance.

3. Explanation of Li Abundances in Metal-poor Stars

The following three facts have been confirmed from spectroscopic observations for Li in metal-poor stars (MPSs) in the Galaxy on which initial Li abundance is preserved: (1) such MPSs have the same Li abundance, known as the Spite plateau, with a small dispersion, (2) EMP stars have Li abundances with an average that is lower than the Spite plateau and a dispersion of which is much larger than that of the Spite plateau, and (3) Li abundances in the MPGC NGC 6397 are higher than the Spite plateau.

These facts can be consistently explained by the chemical separation of Li^+ ions during a hierarchical structure formation as follows.

3.1. Li Abundances in Early Structures

Initial Li abundances are lower in smaller structures that formed earlier. First, the chemical separation of Li during the gravitational contraction of a structure is more effective for larger magnetic field intensities and/or its gradient (KK15). Because the PMF is diluted by the cosmic expansion as $B(z) \propto (1 + z)^2$, the chemical separation is stronger in the early universe. Second, the chemical separation is only effective for the structure mass of $M_{\rm str} \sim 10^6\,M_\odot$ (KK15). This specific mass comes from the condition for a successful contraction of neutral matter and a separation of charged matter from the neutral matter. Thus, as a result of the chemical separation, initial Li abundances are smaller in smaller structures that formed earlier.

In the course of hierarchical structure formation (e.g., Katz & White 1993; Navarro & White 1993), structures of a given mass can form at different times depending upon the initial degrees of density fluctuation. As a result of continuous structure formation, in the early time there are many structures with various masses and various formation times. In those structures, Li abundances are different due to different efficiencies of the separation of ^{7}Li ions from the structure. However, through collisions and mergers of early cosmological structures, gases from different structures mixed. The Li abundances in stars that form in structures then gradually approaches to the average value. The Spite plateau abundance is interpreted as this asymptotic Li abundance in a late epoch of structure formation.

In the standard cosmic and Galactic chemical evolution theory, metallicity increases as a function of time reflecting local metal injections from supernovae. Therefore, it is expected that EMP stars tend to form in an early stage of the structure formation, before the metallicity increases sufficiently. In such an early time, there existed small structures that formed early. Therefore, the Li abundance can be very small because of strong chemical separation at early times. In addition, the gas mixing via the collisions and mergers of small-scale structures has not yet occurred. Therefore, if MPSs formed in this early epoch, their Li abundances would have had a large dispersion and they would have been, on average, smaller than the Spite plateau abundance.

3.2. Formations of MPHSs and MPGCs

In the theory proposed in this Letter, differences in Li abundances in MPHSs and MPGCs are also explained by times of star formations and histories of formations of their parent bodies. How the Galaxy formed is still not known in detail. Consequently, the formations of MPHSs and MPGCs remain uncertain.

A simple scenario is that the MPHSs are formed in small structures that are the building blocks of the Galaxies. After the stars formed, those building blocks were engulfed in the proto-Galaxy. The stars survive in the Galaxy and are observed today as MPHSs, while gases later form a Galactic disk where disk stars could form. In such a scenario, MPHSs form before the mergers of their parent bodies with the proto-Galaxy.

On the other hand, although the formation of MPGCs is still uncertain, there are possible scenarios. They include: (1) production in small structures at star bursts before their mergers to the proto-Galaxy (e.g., Bekki 2012; Pfeffer et al. 2014), and (2) production at the mergers from a mixture of gases (Searle & Zinn 1978; Ashman & Zepf 1992; see Saitoh et al. 2009 for simulations of star formations at galaxy mergers).

In case (1), Li abundances of MPGCs are determined by the histories of the host structures of MPGCs. If those stars formed at relatively late times of the structure formation, the parent body would have a large Li abundance because of the less-effective chemical separation.

In case (2), globular clusters could possibly form at the mergers of small structures in the proto-Galaxy after a mixing of gases from the merging structures and the proto-Galaxy. Galactic gas is relatively Li-rich, excepting small structures inside the Galaxy because the chemical separation of Li is effective only in small structures (KK15). Therefore, the mixing of gases of the small structures and the proto-Galaxy could have resulted in a large Li abundance in mixed gas, even if the Li abundances in the merging small structures are small.

In these two cases, the Li abundances in MPGCs can be both higher than the Spite plateau as observed in NGC 6397 and similar to the plateau, depending on the origin of the MPGCs.

Figure 1 shows stellar Li abundances as a function of [Fe/H]. In the current scenario, MPHSs with very low [Fe/H] values form early and have low Li abundances because of the effective chemical separation. In addition, a large dispersion in the Li abundances is expected as the mixing of gases originating from different structures is incomplete and an inhomogeneity in the abundances remains. Stellar Li abundances approach an average value as the structure formation proceeds and the [Fe/H] increases.

4. Conclusions

The efficiency of the chemical separation of Li^+ ions by a postulated PMF with comoving intensities of ∼nG is enhanced in the early epoch of the structure formation. As soon as the first star begins to emit light, neutral Li atoms in the volume including the Galaxy mass are easily reionized. As a result, almost all Li nuclei can join the chemical separation, and Li abundances inside collapsing structures can be significantly smaller than the primordial abundance. This explains why Li abundances in MPSs are smaller than the primordial abundance.

Lithium abundances in EMP stars have an average value that is lower than the Spite plateau and a dispersion that is larger than that of the plateau. This trend is possibly explained by the fact that the chemical separation works more effectively in the early epoch, when the amplitude of PMF is larger. Through collisions and mergers during the hierarchical structure formation, gases with different Li abundances mix and an asymptotic abundance is expected to be realized. That asymptotic abundance corresponds to the Spite plateau. Thus, MPSs with $[Fe/H] \gtrsim -3$ have a similar Li abundance because they formed in a later epoch of structure formation.

The Li abundances in NGC 6397 are higher than the Spite plateau. In the current model, this indicates that the parent body of NGC 6397 is not affected by the chemical separation very much. The high Li abundance is possible if the formation of the parent body effectively progressed late or the PMF penetrating the body was initially weaker than the average value in the Galactic volume.

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