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Chemical separation of Li^+ ions by primordial magnetic field before the Galaxy formation

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Abstract. Spectroscopic observations of metal-poor stars (MPSs) show the Spite plateau for the Li abundance, a large dispersion of the abundances at low [Fe/H], and different Li abundances between halo stars and globular clusters. As a simultaneous explanation of those observations, a chemical separation of charged particles from neutral particles by the primordial magnetic field (PMF) is investigated. During the structure formation, this chemical separation occurs depending on the field amplitude and its gradient. A gradient of the PMF in a direction perpendicular to the field direction generates the Lorentz force on the charged species. Charged species can then move differently from neutral species, which collapses gravitationally. We calculate fluid motions of charged and neutral species, and show that charged fluid can significantly decouple from the neutral fluid. Therefore, the charged species can escape from the gravitationally-collapsing structure, which is a small building block contributing to the Galaxy formation later. The chemical separation results in inhomogeneous Li abundances in the universe. Since Li species are kept ionized before and during the structure formation, the chemical separation maximally operates on Li species. In the context of the hierarchical structure formation, Li abundances become smaller in smaller structures which formed earlier. Along with a growth of structure mass, Li abundance is expected to increase because of the less efficient separation in larger structures. If extremely MPSs formed early, smaller Li abundances and the large dispersion are naturally interpreted. This possibility of the chemical separation points to a possible relation of the Li abundances in MPSs to the PMF, the structure formation history, and physical environments at the formation of observed stars in Galactic halo and globular clusters.

Key words. Stars: abundances – Stars: Population II – Galaxy: globular clusters – Galaxies: magnetic fields – Plasmas – Cosmology: large-scale structure of Universe

1. Introduction

Lithium abundances in warm metal-poor stars (MPSs) indicates a plateau abundance, so called the Spite plateau (e.g. Spite & Spite 1982; Ryan et al. 2000; Shi et al. 2007). Recent observations also revealed that extremely metal-poor (EMP: [Fe/H]< -3) stars have Li 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. 2017). It has been also pointed out that stars in NGC 6397 have Li abundances slightly above the plateau (González Hernández et al. 2009). See contributions in this volume for the current status of Li observations. The standard big bang nucleosynthesis (BBN) model predicts a primordial Li abundance that is higher than the Spite plateau by a factor of $\sim$ 3 (Pitrou et al., this volume). This is the so-called cosmological Li problem. In the standard BBN (SBBN) model, the final abundance of ^{7}Be is larger than that of ^{7}Li by about one order of magnitude. Therefore, if the Li problem has been caused by nonstandard nuclear processes during the BBN, those processes need to reduce the ^{7}Be abundance. There is, however, the strongest constraint from D and ^{4}He abundances on such non-SBBN solutions to the Li problem (Fields et al., this volume). For example, modifications of cosmic expansion rate via the primordial magnetic field (PMF), effective neutrino number, or modified gravities result in an increase of D/H always along with a decrease of ^{7}Be/H, or the primordial Li abundance (e.g. Kawasaki, & Kusakabe 2012). Therefore, a selective ^{7}Be destruction mechanism is needed to solve the Li problem in non-SBBN models, instead of mechanisms of changing all reaction rates universally. In models including long-lived strongly interacting massive particles (SIMPs) or negatively charged massive particles (CHAMPs), selective ^{7}Be destructions are possible. Since heavier nuclei have larger binding energies of SIMPs and CHAMPs, their bound state formations become relevant earlier and the formation rates are larger. The selective destruction is then realized naturally. If the potential between SIMPs (X's) and nucleons are similar to that between two nucleons, heavy nuclei are formed through the bond state formation, and primordial ^{9}Be and B abundances increase (Kusakabe et al. 2009). If the potential is significantly smaller than that between two nucleons, ^{7}Be production is possible via the reaction $^7\mathrm{Be}+X \rightarrow {}^4\mathrm{He}_X+{}^3\mathrm{He}$, where $^4\mathrm{He}_X$ is the bound state of ^{4}He and X. If CHAMPs (X^-'s) exist, it can bind to ^{7}Be and help to destroy ^{7}Be via $^7\mathrm{Be}_X + p \rightarrow {}^8\mathrm{B}_X + \gamma$ (Bird et al. 2008; Kusakabe et al. 2007). The PMF is considered to be a seed of Galactic magnetic field of $O(1)\mu$G. It directly affects motions of charged fluid including protons, electrons and $^7\mathrm{Li}^+$ ions in the early universe, and also affects those of neutron fluid via scatterings with charged particles. Since most of ^{7}Li species are singly ionized (Switzer & Hirata 2005; Kusakabe & Kawasaki 2019), while H, D, ^{3,4}He, and ^{7}Be are neutral during the structure formation (Vonlanthen et al. 2009), the PMF selectively reduce the Li abundance in astronomical structures without changing other elemental abundances. In this paper, we briefly describe that the chemical separation can explain the three facts related to the Li abundances in MPSs.

2. Chemical separation in the early universe

A magnetic field influences the evolution of chemical compositions in star formation from molecular clouds (Ciolek & Mouschovias 1993, 1994). It has been suggested that charged grains deplete in the molecular clouds since the magnetic field retards the gravitational collapse of charged grains.

The chemical separation by the PMF considered here is similar to that at the star formation. However, the cosmic fluid during the early structure formation is composed of H and He mainly and trace amounts of p^+ and e^-. Although the primordial abundance of Li is tiny, i.e., $^7\mathrm{Li/H}\sim 5\times10^{-10}$, the Li abundances in structures are most strongly affected by PMF. Therefore, the Li^+ ion is also taken into account. The mechanism for the separation of Li^+ ions and a summary of Kusakabe & Kawasaki (2015) are described as follows.

2.1. Mechanism

We suppose that parallel PMF lines are piercing through a collapsing structure with a specific overdensity in the universe. We set the z-axis to the the field direction, and introduce a cylindrical coordinate system (r,ϕ,z). The structure has an axial symmetry with the z-

axis, and a gradient $\partial B_z/\partial r < 0$ exists initially. In this case, there is an electric current in the ϕ direction, and the Lorentz force operates on charged fluid in the r direction. Therefore, the charged fluid moves outward relative to the neutral fluid. In this way, protons, electrons, $^7\mathrm{Li}^+$ and other ions effectively escape from the structures during their gravitational collapse.

As another case, we suppose a uniform PMF in the z direction with $\partial B_z/\partial r = 0$. In this case, since the Lorentz force is initially zero, the charged fluid collapses in the same way as the neutral fluid. As the gravitational contraction proceeds, a density gradient at the boundary of the structure is enhanced. Since the magnetic field is frozen into the charged fluid, a field gradient $\partial B_z/\partial r < 0$ is also generated at the boundary. As a result, charged particles escapes from the boundary. In this way, the reduction of $^7\mathrm{Li}^+$ abundance is possible in the both cases. A nonuniform PMF leads to a reduction or an enhancement of Li abundance in structures, while a uniform PMF leads to a reduction generally.

2.2. Estimates

In the standard cosmology, i.e., the ΛCDM model, there is a condition for the nonuniform parallel PMF to realize a chemical separation of charged fluid without significantly counteracting the gravitational contraction of a structure. This condition is satisfied in a narrow parameter space of the structure mass and comoving Lorentz force, $(M_{\mathrm{str}}, B_{z0}^2/L_{B0})$, where B_{z0} and L_{B0} are the comoving values of amplitude and coherent length, respectively, of the PMF. For example, under the condition that structures form by the redshift $z = 10$, the Lorentz force should be $B_{z0}^2/L_{B0} \sim 10^{-20}$ G^2 kpc^{-1}. In general, the chemical separation is more effective in smaller structures for a given value of B_{z0}^2/L_{B0}. The chemical separation significantly operates only for $M_{\mathrm{str}} \lesssim O(10^8) M_\odot$ in the case of the formation redshift $z = 10$.

Suppose a structure with mass $M_{\mathrm{str}} = 10^6 M_\odot$ which completes the gravitational collapse at $z = 10$. At the turnround defining the time of transition from an expansion to a contraction, the comoving size of this structure is 10.4 kpc. In the hierarchical structure formation theory, small structures form early, and large structure gradually form via collisions and mergers. Therefore, separations of ions and electrons occurs in small structures first in the universe. For the small structure with $M_{\mathrm{str}} = 10^6 M_\odot$, the comoving PMF strength required for the separation is $O(1)$ nG.

3. inhomogeneous Li abundance from the structure formation

The efficiency of the reduction of Li abundance is maximal because of a large ionization degree. Interpretations of observed Li abundances of MPSs are provided in the context of the chemical separation during a hierarchical structure formation (Kusakabe & Kawasaki 2019). These are speculative and based on a very simplified consideration, and we need evaluate this solution to the Li problem more in detail both theoretically and observationally in the future.

3.1. Ionization degree of Li

When the universe expands to the redshift $z \gtrsim 1100$, the H (as well as D) recombination proceeds and trace amounts of relic protons and electrons remains (Vonlanthen et al. 2009). Because of the small first ionization potential of Li, i.e., 5.3917 eV, Li species are still fully ionized at this temperature of cosmological recombination. Thereafter, the recombination of relic protons and electrons continues to supply nonthermal photons via the Lyα transition and two-photon decay of the 2S state. These less energetic photons cannot ionize H and He, but easily ionize Li. Therefore, the ionization degree of Li is kept high even after the H recombination (Switzer & Hirata 2005).

Although a small fraction of Li species remain as neutral atoms, once the first star forms it emits enough ultraviolet photons to completely reionize relic Li atoms. For example, suppose that the first star has a mass $M_* = 100 M_\odot$, an Eddington limit luminosity, and surface temperature 10^5 K. This star can emit 6.3×10^{65} ionizing photons for Li, which is larger than the number of all Li species in the present Galactic volume by several orders of magnitudes (Kusakabe & Kawasaki 2019).

Therefore, in the structure formation epoch, we can safely assume that almost all Li species exist in ionized states. Among light elements produced in BBN, only the Li abundance is significantly affected by the chemical separation, and inhomogeneous abundances are reasonably realized.

3.2. Interpretations of observations

In the magnetized cosmological model considered here, small structures can have small Li abundances (Kusakabe & Kawasaki 2015). Those structures are gradually involved in larger structures with time. The larger structures may have larger Li abundances because of a less efficient chemical separation. Let us suppose that EMP stars typically formed early in relatively small structures or not early but in unevolved small structures. Then, the small Li abundances of some EMP stars can be explained by the chemical separation. We note that the Fe abundance indicates the age of the structure. Therefore, the assumption that EMP stars formed at a relatively early stage of structure formation is reasonable.

Through the structure formation, many small structures that formed at various times contribute to larger structures. As a result, in the later epoch the Li abundance would approach the average value which is below the primordial abundance. This average value corresponds to the Spite plateau in this scenario.

Formation histories of parent bodies for halo stars and globular clusters are different. The histories determine Li abundances in those parent bodies. Therefore, the difference of Li abundance in NGC 6397 from the Spite plateau is possibly attributed to the different formation histories. See Kusakabe & Kawasaki (2019) for comments on a few possibilities.

4. Conclusions

Consistent interpretations of observations for Li abundances in MPSs are derived taking into account the chemical separation of $^7Li^+$ ions by hypothetical PMF. Possibly the Spite plateau abundance is determined via non-SBBN physics or processes after the star formation (e.g. Fu et al. 2015; Korn et al. 2006). Even in that case, the PMF effects can appear as the existence of Li-poor warm EMP stars and the absence of such stars with high [Fe/H].

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