Chemical Abundances in the Universe: Connecting First Stars to Planets
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An overall picture of EMP stars using the stellar abundances for galactic archaeology (SAGA) database

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Abstract. We explore the general characteristics of extremely metal-poor (EMP) stars in the Galaxy using the Stellar Abundances for Galactic Archaeology (SAGA) database (Suda *et al.* 2008, PASJ, 60, 1159). The overall trend of EMP stars suggests that there are at least two types of extra mixing to change the surface abundances of EMP stars. One is to deplete lithium abundance during the early phase of giant branch and another is to decrease C/N ratio by one order of magnitude during the red giant branch or AGB phase. On the other hand, these mixing processes are different from those suggested in the Galactic globular clusters because of the different relations between O, Na, Mg, and Al abundances.

Keywords. stars: evolution, stars: abundances, stars: Population II, astronomical data bases: miscellaneous

1. Introduction

Extremely metal-poor (EMP) stars are the useful probes for the star formation history in the very early Universe. These stars were born in iron-poor or perhaps the primordial gas cloud produced soon after the Big Bang and considered to retain the information on the early epoch of the universe. Thanks to the detailed abundance analyses of large-scale surveys of metal-poor stars (e.g., Aoki *et al.* 2007), we have thousands of data of EMP candidates with element abundances of many species known.

One of the important characteristics in observed EMP stars is an abundance anomalies and star to star variations among stars at $[Fe/H] \lesssim -2$. In order to understand comprehensively the origins of elements and star formation history of our Galaxy, we developed the database of observed EMP stars by compiling observed abundances and related information from the literature (The SAGA database which is available online at http://saga.sci.hokudai.ac.jp, Suda *et al.* 2008). The SAGA database contains more than 20,000 records of abundance data for more than 1,300 unique stars.

In this paper, we compare the stellar evolution models with the observed EMP abundances using the SAGA database. The present paper explores the possible extra mixing in EMP stars by considering the dredge-up by surface convection of low-mass and low-metallicity stars. We focus on the lithium depletion in EMP stars in the next section and discuss the possible extra mixing in red giants in §3.

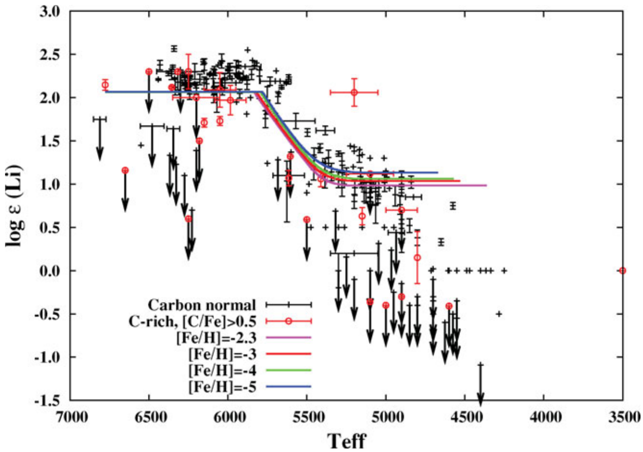

Figure 1. Lithium abundance as a function of effective temperature. Lines represent the expected lithium abundance using stellar models by assuming that the lithium are completely burnt at $T \geqslant 2.5 \times 10^6$ K. Sample stars are divided into carbon-rich and carbon-normal subgroups depending on whether a star has [C/Fe] $\geqslant 0.5$ or not.

2. Lithium Depletion in EMP Stars

It is well known that the ^{7}Li abundance in EMP dwarfs can be used for finding the effect of mass transfer in binaries. In Figure 1, we can see the dependence of lithium abundance on evolutionary status. We excluded one stars below 6000 K that are not a subgiant but a dwarf well below the turn-off point. In this figure, we also superposed the expected value of lithium abundance due to the dilution by the surface convection. We assume that lithium are completely burnt in the shell where the temperature is above 2.5×10^6 K. Stellar models are taken from $0.8 M_\odot$ and [Fe/H] $= -2.3, -3, -4,$ and -5 in Suda & Fujimoto (2009). We deduce the depleted lithium abundance as $\log \epsilon(\mathrm{Li}) = 2.10 - \log(M_{crit}/M_{conv})$ where M_{crit} is the shell of $T = 2.5 \times 10^6$ K and M_{conv} the mass of surface convection.

Each evolutionary line begins from the turn off point and ends at the tip of the red giant branch. The maximum depletion of lithium abundance corresponds to the maximum depth of surface convection soon after the core contraction during subgiant branch. This can be a sort of lithium isochrone for subgiants and giants as discussed in Deliyannis *et al.* (1990). It should be noted that the temperature at the bottom of surface convection attains at only $\sim 5 \times 10^5$ K during the red giant branch phase. This means that lithium cannot be burnt in the surface convection and are diluted in the entire convection on the red giant branch. As far as giants with [Fe/H] $\lesssim -2.5$ for which lithium abundance is determined, many of them are nearly on the lithium isochrone. On the other hand, we have ≈ 30 stars with only upper limits available whose values are well below the lithium isochrone. In order to explain such large depletion of lithium in the surface, it requires further mixing below the convective envelope. One possibility of explaining these lithium-depleted stars will be other mechanism of deep mixing such as diffusion or extra mixing. Another possible scenario will be the binary scenario that the outer shell of the main sequence star was almost or totally devoid of lithium in the consequence of binary mass transfer. However, this scenario may be inconsistent with observations because the fraction of lithium-depleted stars are much smaller in dwarfs than in giants.

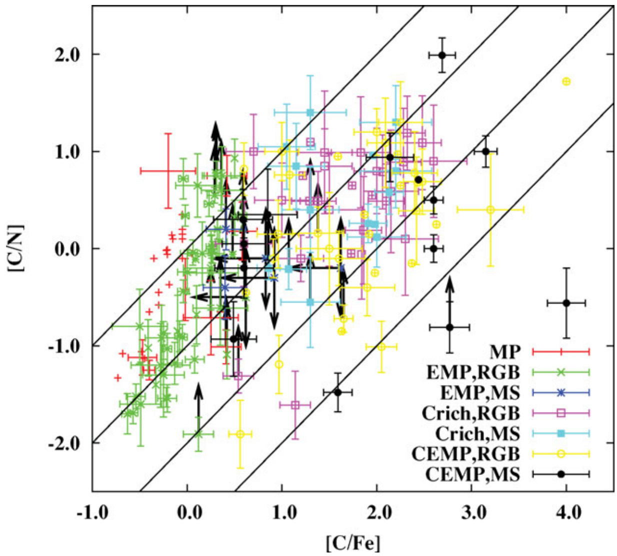

Figure 2. Abundance relation between [C/N] and [C/Fe] for 172 stars taken from the SAGA database. Sample stars are divided into seven subgroups by metallicity (boundary is [Fe/H] = −2.5), carbon abundance as in Fig. 1, and evolutionary status (red giants or dwarf). The notations of the symbols are the same as in Suda *et al.* (2008). Solid lines denote constant values of [N/Fe] $= 0, 1, 2$ and 3 from left to right.

3. Possible Mixing in EMP Giants

Carbon and nitrogen abundances play an important role in constraining the site of nucleosynthesis in stars. Figure 2 shows the ratio [C/N] as a function of [C/Fe] for 172 stars taken from the SAGA database. Most of carbon-enhanced EMP stars (CEMP stars, located in top right corner of the figure) are thought to be the result of binary mass transfer from the former AGB stars. For [Fe/H] > -2.5, carbon-enhanced stars (labeled by "Crich") can be explained by canonical AGB evolution. On the other hand, the CEMP stars with [C/N] $\gtrsim 0$ can be explained by the helium-flash driven deep mixing operated at [Fe/H] $\lesssim -2.5$ (Fujimoto *et al.* 2000, Suda *et al.* 2004, Komiya *et al.* 2007, Nishimura *et al.* 2009, and Suda & Fujimoto 2009 and also references therein).

However, the evidence of the CN cycles in the hydrogen burning shell is also observed in EMP stars. These so called "mixed" stars can be seen in EMP giants (see, e.g., Spite *et al.* 2005) (located in the bottom left corner of Fig. 2). If we try to explain the low C/N ratio by the CN cycles in observed stars, they require extended mixing below the surface convection over several times the pressure scale height as shown in Figure 3. Here we choose the ratio of pressure $P_{\rm shell}$ at the shell to the pressure $P_{\rm conv}$ at the bottom of surface convection instead of the local pressure scale height. In order to reach the shell having the abundance of mixed stars during the RGB evolution, it requires that the surface convective zone extends by at least 4 to 10 times the pressure scale height. The corresponding mass to be mixed amounts to $\geqslant 0.06 M_\odot$ at [Fe/H] $= -3$. Note that the required depth of mixing will be much larger unless the matter in the envelope continues to be mixed until it attains the same abundances as in the burning shell because the values of [C/N] in Fig. 3 represent those in the shells not at the surface. On the other hand, there is no supporting evidence of O-Na and Mg-Al anti-correlation in EMP stars differently from globular cluster stars (see, e.g., Gratton *et al.* 2000 and Suda *et al.* 2009, in prep.). Therefore, observed "mixed stars" require fine-tuned mixing deep enough to

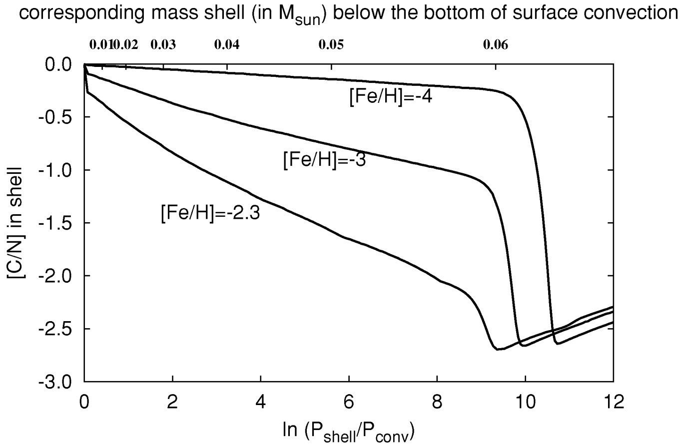

Figure 3. Abundance profile of $0.8M_{\odot}$ model for various metallicities as a function of the pressure normalized by the pressure at the bottom of the surface convection. The corresponding amount of mixed mass for the case of [Fe/H] $= -3$ is labeled on the top of panel. Models are taken at the maximum depth of surface convection during the first ascent on the giant branch. Each line denotes the [C/N] in the shell (metallicity is labeled next to the line).

dredge-up the layers with active CN cycles, but not deep enough to dredge-up the layers where ON cycles and NeNa cycles are active. This is also the case for AGB models.

At present, it is difficult to reproduce both the lithium depletion and C/N ratio from the standard stellar evolution models. It seems that at least two different types of mixing have been operated in metal-poor halo stars. The stellar models that satisfy all the requirements from observed abundance pattern are desired, which will be explored in the future works.

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References

Aoki, W., Beers T. C., Christlieb N., Norris J. E., Ryan S. G., & Tsangarides S., 2007, *ApJ*, 655, 492

Deliyannis, C. P., Demarque, P., & Kawaler, S. D. 1990, *ApJS*, 73, 21

Fujimoto, M. Y., Ikeda, Y., & Iben Jr., I. 2000, *ApJ*, 529, L25

Gratton, R. G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, *A&A*, 354, 169

Komiya, Y., Suda, T., Minaguchi, H., Shigeyama, T., Aoki, W., & Fujimoto, M. Y. 2007, *ApJ*, 658, 367

Nishimura, T., Aikawa, M., Suda, T., & Fujimoto, M. Y. 2009, *PASJ*, 61, 909

Spite, M., Cayrel, R., Plez, B., Hill, V., Spite, F., Depagne, E., François, P., Bonifacio, P., Barbuy, B., Beers, T., Andersen, J., Molaro, P., Nordström, B., & Primas, F. 2005, *A&A*, 430, 655

Suda, T., Aikawa, M., Machida, M. N., Fujimoto, M. Y., & Iben Jr., I. 2004, *ApJ*, 611, 476

Suda, T. & Fujimoto, M. Y. 2009, *MNRAS*, accepted, ArXiv 1002, 0863

Suda, T., Katsuta, Y., Yamada, S., Suwa, T., Ishizuka, C., Komiya, Y., Sorai, K., Aikawa, M., & Fujimoto, M. Y. 2008, *PASJ*, 60, 1159