Chemical Abundances in the Universe:
Connecting First Stars to Planets
Proceedings IAU Symposium No. 265, 2009
K. Cunha, M. Spite & B. Barbuy, eds.

doi:10.1017/S1743921310000311

Carbon-Enhanced Metal-Poor (CEMP) stars

Wako Aoki[1]

[1]National Astronomical Observatory
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
email: `aoki.wako@nao.ac.jp`

Abstract. A significant fraction of metal-poor stars have large over-abundances of carbon, and are called Carbon-Enhanced Metal-Poor (CEMP) stars. Most of CEMP stars also show excesses of heavy neutron-capture elements like Ba, indicating that their origin is the nucleosynthesis in AGB stars. Remaining CEMP stars that have Ba abundances as low as non-carbon-rich stars appear in the lowest metallicity range ([Fe/H]$\lesssim -2.5$), and connections with the two most iron-deficient stars (so-called Hyper Metal-Poor stars) are suggested. Although the origins of the carbon-excesses in these objects have not been well identified, some objects suggest contributions of faint supernovae. Remaining problems on CEMP stars, such as the binary fraction, excess of r-process elements, are discussed.

Keywords. stars:abundances, stars:AGB and post-AGB, stars:carbon, supernovae

1. Introduction

Carbon-Enhanced Metal-Poor stars (CEMP stars) in the Galactic halo have been known as CH stars (Keenan 1942) or subgiant CH stars (Bond 1974) that show strong CH absorption bands compared to other stars having similar temperatures. A number of stars showing strong CH bands have been identified by the HK survey (Beers *et al.* 1992), suggesting that the fraction of carbon-enhanced stars is much higher in the halo (the metal-poor range) than that in the disk (the metal-rich range). The recent estimates of the fraction of carbon-rich stars have confirmed this, although the derived values distribute rather wide range (10–25%; e.g. Cohen *et al.* 2006; Marsteller *et al.* 2006; Frebel *et al.* 2006).

The importance of CEMP stars was widely recognized by the discoveries of Hyper Metal-Poor (HMP) stars HE 0107–5240 and HE 1327–2326 by Christlieb *et al.* (2002) and Frebel *et al.* (2005), respectively. These stars are called "most metal-poor" because of their low iron abundances ([Fe/H]< -5), but their carbon abundance ratios are extremely high ([C/Fe]$\sim +4$). Although the estimate of carbon abundance ratios are sensitive to the 3D effects in stellar atmospheres, the large overabundance of carbon in these objects is clear, and the origin of this peculiar abundance pattern is considered as a key to understanding the nucleosynthesis of first generations of stars (Beers & Christlieb 2005).

In more general, CEMP stars are believed to contain useful information to understand the nucleosynthesis in the early Galaxy. The criterion of the carbon abundance ratio in the definition of "carbon-enhanced" objects is dependent on the authors of previous studies: some assume [C/Fe]$= 1.0$ but others do 0.5 or 0.7, and some study takes the evolutionary stage of the object into consideration. However, as seen in Figure 1, the distributions of carbon abundance ratios clearly split into two groups, and the estimate of the fraction of carbon-enhanced stars is not significantly changed by the criterion. Here we simply define CEMP stars as those having [C/Fe]$> +1.0$.

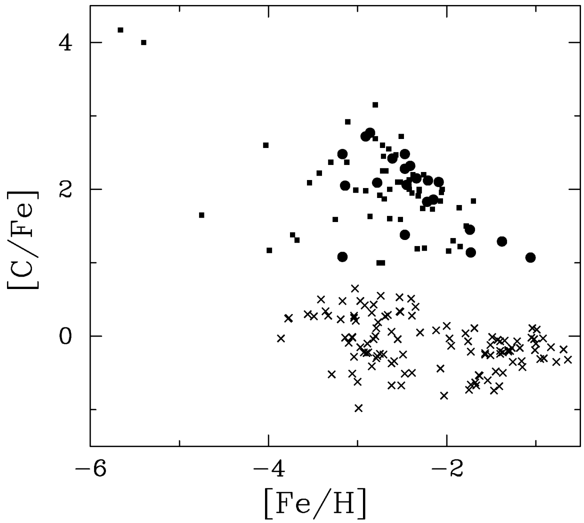

Figure 1. [C/Fe] as a function of [Fe/H]. [C/Fe] = +1.0 is adopted as a the criterion to define CEMP stars (filled symbols) in this paper. This figure is based on Fig. 3 of Aoki *et al.* (2007) with additional data from recent literature.

2. Origins of carbon-excesses

For understanding the origins of the carbon over-abundances, the neutron-capture element Ba is a key element. This element is efficiently produced by the s-process in thermally pulsing AGB stars, which are also a major source of carbon. Singly ionized Ba has strong resonance doublet lines as well as other weaker lines in the optical range, that makes it possible to detect this element for a wide abundance range.

Figure 2 (left) shows the Ba abundance ratio ([Ba/Fe]) as a function of [Fe/H]. A majority ($\sim$ 80%) of CEMP stars show large over-abundances of carbon. A correlation between [C/Fe] and [Ba/Fe] are seen in Figure 2 (right) for these Ba-enhanced stars. This means that the carbon-excesses of most of CEMP stars are attributed to AGB stars in which Ba are also synthesized by the s-process. These stars are called as CEMP-s stars (Beers & Christlieb 2005). It should be noted that the Ba-excess in some CEMP stars is possibly due to the r-process rather than the s-process. Measurements of other neutron-capture elements (e.g. Eu) are necessary to separate the two possibilities. However, among more than 10 CEMP stars for which detailed abundance measurements have been made, only one object (CS 22892–052) is known to have a large Ba-excess that is attributed to the r-process.

On the other hand, there are a small fraction of CEMP stars that have Ba abundances as low as other non-carbon-enhanced stars. These stars are called "CEMP-no" stars (Beers & Christlieb 2005). Although the Ba abundances have not been determined for the two HMP stars, the low upper limits suggest that these two stars are likely belong to the class of CEMP-no stars.

It is clear in Figure 2 (left) that CEMP-no stars appear in the lowest metallicity range ([Fe/H]< -2.5), while CEMP-s stars are seen in [Fe/H]$\gtrsim -3$. The difference of the metallicity distribution between the two classes is evident in Figure 3 (left) that shows the histogram of [Fe/H] for CEMP-s and CEMP-no stars. We note that CEMP stars for which Ba is not detected are not included in the histogram for CEMP-no stars. These objects have [Fe/H]< -3, including the two HMP stars. The difference of the metallicity distribution is more remarkable if these stars are included in the comparison.

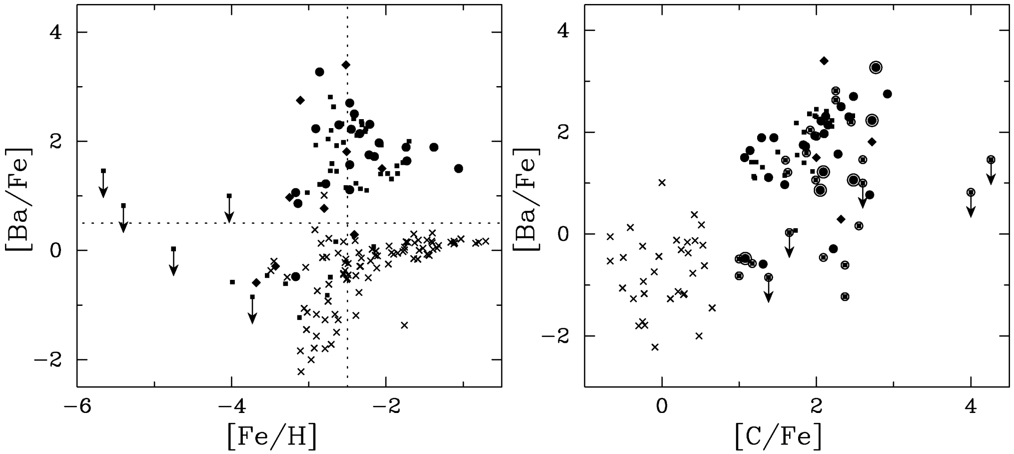

Figure 2. *left*: [Ba/Fe] as a function of [Fe/H] for CEMP stars (filled circles and squares) and carbon-normal stars (crosses). For some extremely metal-poor stars, including the two HMP stars, only upper limits of Ba abundance are determined. *right*: Same as the left panel, but for [Ba/Fe] as a function of [C/Fe].

Another difference between CEMP-s and CEMP-no stars is found in the carbon abundance distribution. Figure 3 (right) shows the histograms of [C/H]. The [C/H] distribution of CEMP-s stars has a peak at $[C/H] = -0.5 \sim 0.0$ and a cut-off at $[C/H] \sim 0$. This cut-off probably indicates the carbon abundance produced by AGB stars, which is not significantly dependent on metallicity (Ventura et al. 2002). The tail found in the lower [C/H] side can be interpreted as the result of dilution of the carbon-rich material produced by an AGB star in the stellar envelope after the mass transfer from the companion AGB star.

By contrast, the [C/H] values of CEMP-no stars distribute a wide range, suggesting the origins of the carbon-excess of these stars are different from that of CEMP-s stars. This is a problem probably related to the origins of HMP stars. To explain the carbon-excesses of HMP stars, several models have been proposed, including "faint supernovae" (see below), rotating massive stars from which significant amount of carbon is ejected (Maynet *et al.* 2006), and AGB stars that produce carbon but do not yield heavy elements. These models might also be applied to CEMP-no stars.

Among CEMP-no stars, the two extremely metal-poor stars CS 22949–037 and CS 29498–043 have large over-abundances of α elements as well as C, N and O (McWilliam *et al.* 1995; Aoki *et al.* 2002). α elements are usually considered to be products of core-collapse supernovae. Hence, the progenitors of these two stars are most likely massive stars that exploded as faint supernovae, explosions producing only small amount of Fe. Such supernovae are proposed to explain the abundance patterns of HMP stars, and successfully explain also these α-enhanced stars (e.g., Umeda & Nomoto 2003).

Another example that is well explained by the faint supernova models is recently discovered. That is the bright CEMP-no subgiant BD+44°493 that has extremely low [Fe/H] ($= -3.7$) and moderately high [C/H]($= +1.3$). The high O/C ratio as well as low Ba abundance of this object are not explained by AGB nucleosynthesis models, while the low N abundance does not support the rotating massive star scenario. The details of this object is reported by Ito *et al.* (in this volume) as well as by Ito *et al.* (2009).

Our conclusion here is that we have at least some evidence for the contribution of faint supernovae to some carbon-enhanced, extremely metal-poor stars having low Ba abundances. However, other possibilities are not excluded for other CEMP-no stars. Indeed,

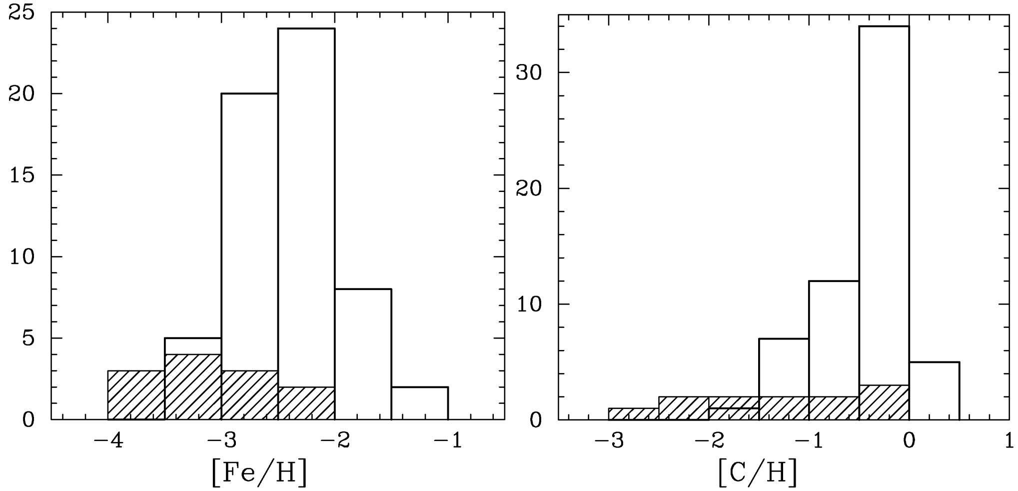

Figure 3. Histograms of [Fe/H] (left) and [C/H] (right) for CEMP-no stars (hatched) and CEMP-s stars (blank with solid lines).

the wide [C/H] distribution and the variety of α-elements abundance ratios suggest that the origins of carbon-excesses in these objects are not unique. Further investigations of these objects are clearly desired to understand the origins of CEMP stars and HMP stars.

3. Problems on CEMP stars

Continuous studies of CEMP-s and CEMP-no stars in the past several years have been revealing the origins of their carbon-excesses as discussed above. Here we review other problems on CEMP stars to be solved by further detailed studies.

3.1. *Binarity of CEMP-s and CEMP-no stars*

The enhancements of C and heavy neutron-capture elements in CEMP-s stars are explained by the mass transfer from the companion AGB star across a binary system. The binarity of these stars has been studied by monitoring radial velocity variation (e.g. McClure *et al.* 1984, Preston & Sneden 2001). Lucatello *et al.* (2006) investigated the binarity for 19 CEMP-s stars, concluding statistically that all CEMP-s stars can belong to binary systems. Further monitoring is required to investigate the orbital parameters of these binary systems.

By contrast, radial velocity studies for CEMP-no stars suggest that the binary fraction is much lower than for CEMP-s stars. However, the sample is still small and long-term monitoring is particularly important for these stars.

3.2. *Moderate excesses of Ba in very metal-poor CEMP stars*

The discussion in Section 2 is based on the classification of Ba-rich and Ba-normal stars. Ba abundances of most of CEMP stars are well separated into the two classes. However, as found in Figure 2 (left), there are several stars that have moderate over-abundances of Ba ([Ba/Fe]$\sim +0.5$). These stars are found at low metallicity ([Fe/H]~ -3). Some of them show (only) moderate excess of carbon as well, and would be affected by dilution inside the object itself after mass transfer from an AGB star. However, some others show very large over-abundances of C though the Ba excess is moderate (the right panel of Figure 2). This suggests that the s-process nature at such low metallicity is somewhat different from that at higher metallicity. These objects are recently discussed by Masseron *et al.* (2009) as "CEMP-low-s" stars, and further observational studies are desired.

3.3. *CEMP-rs stars*

A significant fraction of Ba-enhanced CEMP stars also show large over-abundance of Eu compared to the value expected from the Ba and La abundances assuming s-process nucleosynthesis. Such stars are called CEMP-rs stars, as both s- and r-process elements seem to be enhanced. A simple interpretation is that these are CEMP-s stars, but are also affected by the r-process before or after the star formation. However, the fraction of CEMP-rs stars among Ba-enhanced CEMP stars is high, while r-process-enhanced stars with normal carbon abundance are quite rare in metal-poor stars. This class of objects has also been discussed by Masseron *et al.* (2009) as well as other studies referred in the paper.

3.4. *Li abundances in some CEMP-s stars*

Li abundances of CEMP-s stars are usually low even in turn-off and subgiant stars. This is interpreted as the result of mass accretion from an AGB star in which Li is depleted. However, at least two CEMP-s stars (LP 706-7 and CS 22898-027) have Li abundance as high as the Spite plateau value. One possibility is that Li is enriched in the AGB star that provides carbon and heavy elements. The model calculation of Iwamoto *et al.* (2004) suggests production of Li in metal-poor AGB stars. However, the reason for the fact that the Li abundance becomes similar to the Spite plateau value is not clear (Ryan *et al.* 2005). More detailed studies of Li abundances in CEMP stars, e.g., more accurate determination of the abundance, are required to understand the origin of Li in these stars.

4. Summary

CEMP stars are related to many topics discussed in the symposium. A majority of CEMP stars show large over-abundances of Ba, and the origin of carbon-excesses is explained by AGB nucleosynthesis. However, some problems (e.g. large enhancement of r-process elements or high Li abundance in some objects) remain to be solved, and further studies of these stars will shed new light on AGB models. Although the formation mechanism of CEMP-no stars is still unclear, we found some evidence for the scenario that faint supernovae are a source of carbon-enhanced material in the very early Galaxy. Since the sample of CEMP-no stars is quite small, further searches for these objects, most of which have very low metallicity, and detailed follow-up studies are indispensable.

References

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

Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., & Ando, H. 2002, *ApJ*, 576, L141

Beers, T. C. & Christlieb, N. 2005, *ARAA*, 43, 531

Beers, T. C., Preston, G. W., & Shectman, S. A. 1992, *AJ*, 103, 1987

Bond, H. E. 1974, *ApJ*, 194, 95

Christlieb, N., *et al.* 2002, *Nature*, 419, 904

Cohen, J. G., *et al.* 2006, *AJ*, 132, 137

Keenan, P. C. 1942, *ApJ*, 96, 101

Frebel, A., *et al.* 2005, *Nature*, 434, 871

Frebel, A., *et al.* 2006, *ApJ*, 652, 1585

Ito, H., Aoki, W., Honda, S., & Beers, T. C. 2009, *ApJ*, 698, L37

Iwamoto, N., Kajino, T., Mathews, G. J., Fujimoto, M. Y., & Aoki, W. 2004, *ApJ*, 602, 377

Lucatello, S., Beers, T. C., Christlieb, N., Barklem, P. S., Rossi, S., Marsteller, B., Sivarani, T., & Lee, Y., *ApJ*, 625, 825

Marsteller, B. E., Beers, T. C., Sivarani, T., Rossi, S., Knapp, J., Plez, B., Johnson, J., & Masseron, T. 2006, Bulletin of the American Astronomical Society, 38, 1229

Masseron, T., Johnson, J. A., Plez, B., Van Eck, S., Primas, F., Goriely, S., & Jorissen, A. 2009, arXiv:0901.4737

McClure, R. D. 1984, *ApJ*, 280, L31

McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, *AJ*, 109, 2757

Meynet, G., Ekström, S., & Maeder, A. 2006, *A&A*, 447, 623

Preston, G. W. & Sneden, C. 2001, *AJ*, 122, 1545

Ryan, S. G., Aoki, W., Norris, J. E., & Beers, T. C. 2005, *ApJ*, 635, 349

Umeda, H. & Nomoto, K. 2003, *ApJ*, 422, 871

Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, *A&A*, 393, 215