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Carbon-enhanced metal-poor stars: probes of nucleosynthesis from the first generation of stars in the Universe

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Abstract. CEMP-no stars are a subclass of very metal-poor (VMP; [Fe/H] < -2.0) and extremely metal-poor (EMP; [Fe/H] < -3.0) stars in the Milky Way (including the most iron-deficient stars known) with no strong enhancements of s-process elements (which might be attributed to mass transfer from a binary companion). In addition to C, these stars exhibit enhancements of N, O, and other light elements such as Na, Mg, Al, and Si, a pattern that may be uniquely produced by the first-generation stars in the early Universe. These stars have also been recently linked to the observed abundance pattern in a high redshift ($z = 3.1$), EMP damped Lyman-α cloud. I discuss the discovery of CEMP-no stars, connections with their progenitors in the outer-halo component of the Galaxy, new surveys that are expanding their numbers, and planned future spectroscopic exploration of these fascinating objects.

Key words. Stars: abundances – Stars: Population III – Stars: carbon-enhanced stars – Galaxy: abundances

1. Introduction

First-generation stars of high mass (tens to hundreds of solar masses) presumably formed from metal-free gas, lived short main-sequence lifetimes (measured in Myrs, not Gyrs), exploded, and distributed their nuclosynthesis products (from pre- and/or post-explosion) into the gas in their immediate surroundings.

Next-generation stars formed from the gas polluted by these first-generation objects. A wider range of masses were now allowed (due to the existence of additional cooling channels), perhaps including stars with main-sequence lifetimes that exceed a Hubble time (M $<$ 0.8 M$_{\odot}$). Further star formation (Pop. II stars) contributed additional nucleosynthetic material, and diluted the signatures of first/next-generation stars.

Thus, in order to explore the chemistry of the Universe in the era of the first/next-generation stars, we should look for a characteristic set of abundance signatures that are *only* found among the lowest metallicity stars. Although a number of alternatives have been suggested in the past (e.g., the "sawtooth" odd/even pattern of elemental abundances thought to be associated with pair-instability SNe), here I advocate for the likely connection between the enhancement of C,N,O, and other light elements among stars with [Fe/H] < -3.0, with the products of first-generation stars.

2. The CEMP stars

Although carbon-enhanced stars of various sorts have been recognized as a class of objects for over a century, the identification of very metal-poor (VMP; [Fe/H] < −2.0) stars with enhanced carbon as a class was made by Beers et al. (1992), based on some tens of such objects found in the HK survey. The so-called CH stars, identified in previous decades, generally have higher metallicities, −2.0 < [Fe/H] < −1.0.

Some two decades later, follow-up medium-resolution spectroscopy by various survey efforts has expanded the list of known carbon-enhanced metal-poor (CEMP) stars from hundreds (Hamburg/ESO Survey – HES; Christlieb et al. 2008) to many thousands (SDSS/SEGUE; Lee et al. 2013a). Beers & Christlieb (2005) provided a quantitative set of definitions for the CEMP stars, and their subclasses, which include the CEMP-*s*, CEMP-*r*/*s*, CEMP-*r*, and CEMP-no stars, indicating different patterns in the abundances of neutron-capture elements revealed from high-resolution spectroscopic analyses.

Several observational results in recent years strongly suggest that at least a subset of the CEMP stars *are* the long-sought next-generation stars, hence they can provide direct information on the nucleosynthesis processes that occured in first-generation stars. Among these results:

- CEMP stars occur with dramatically increasing frequency with declining [Fe/H] (Beers et al. 1992; Rossi et al. 2005; Carollo et al. 2012; Lee et al. 2013; Norris et al. 2013). The most recent compilation of CEMP frequencies, based on over 240,000 stars from SDSS/SEGUE is provided by Lee et al. (2013), and includes some 5,000 CEMP stars.
- The frequency of CEMP stars increases with distance above the Galactic plane (Frebel et al. 2006; Carollo et al. 2012).
- The majority (80%) of CEMP stars are of the classification CEMP-*s* (or CEMP-*r*/*s*), indicating that they also exhibit overabundances of *s*-process elements (Aoki et al. 2007). These have been shown to be essentially all binaries, and are likely to have originated from material processed by a former AGB companion (Lucatello et al. 2005).
- The CEMP-no stars, which exhibit no overabundances of neutron-capture elements, represent about 20% of all CEMP stars, and are primarily found at lower metallicities than the CEMP-*s* stars (Aoki et al. 2007). High-resolution radial velocity spectroscopic follow-up by T. Hansen et al. (in preparation) demonstrates that the CEMP-no stars have no greater a binary fraction than other low-metallicity giants. See also the discussion by Norris et al. (2013).
- Carollo et al. (2012) have demonstrated that the fraction of CEMP stars kinematically assigned to the outer-halo population *in a given low-metallicity interval* is roughly twice the fraction assigned to the inner-halo population. This immediately suggests that the outer-halo progenitors include additional sources of carbon enhancement other than AGB stars, and likely associated with nucleosynthesis by the first-generation stars.
- The pattern of elemental abundances, in particular for C, N, O, and other light elements, found for numerous CEMP-no stars, including the 9th magnitude [Fe/H] = −3.8 star BD+44:493 (Ito et al. 2009, 2013), as well as the first two hyper metal-poor (HMP; [Fe/H] < −5.0) stars reported by Christlieb et al. (2002) and Frebel et al. (2005), can be accounted for by at least two possible classes of progenitors. These include massive, rapidly rotating, mega metal-poor (MMP; [Fe/H] < −6.0) stars, which produce large amounts of C, N, and O due to distinctive internal burning and mixing episodes (Meynet et al. 2006, 2010), and faint supernovae explosions associated with the first generations of stars, which experience extensive mixing and fallback during their explosions, and eject large amounts of C and O, but not iron-peak elements (Umeda & Nomoto 2003, 2005; Tominaga et al. 2007; Ito et al. 2013). See Figure 1.

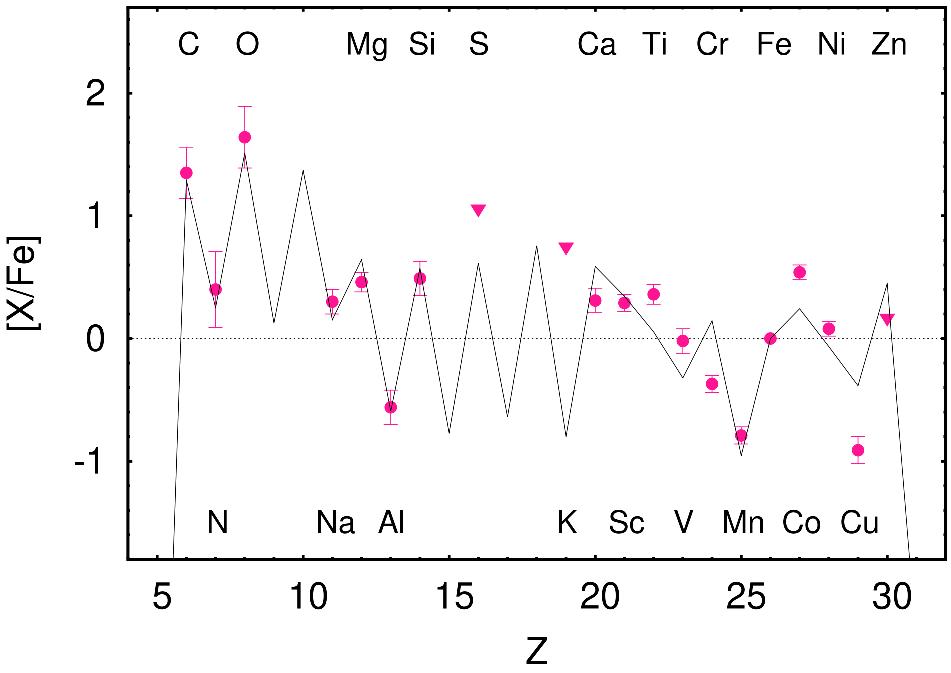

Fig. 1. Comparison between the observed elemental-abundance pattern of BD+44:493 (filled circles) and theoretical individual supernova yields, based on a mixing and fallback model (solid lines). The upper limits on the abundances for several elements set by the observation are shown by triangles. Figure from Ito et al. (2013) reproduced by permission of the AAS.

- Carollo et al. (2013) have demonstrated that the frequency of CEMP-no stars that are kinematically associated with the outer-halo population is roughly twice that of the CEMP-*s* stars (the reverse holds true for the inner-halo population), strengthening the case for additional carbon sources in the early Galaxy.
- Lee et al. (2014) have compared the observed frequencies of CEMP stars from SDSS/SEGUE with predictions of alternative initial mass functions (IMFs), and find that the IMF shifted from high-mass to low-mass dominated in the early history of the Milky Way, at a "chemical time" between [Fe/H] ~ -2.5 and [Fe/H] ~ -1.5, supporting the previous assertion that one or more additional mechanisms, not associated to AGB stars, are required for the production of carbon-rich material below [Fe/H] $= -3.0$.
- Other evidence for the large production of carbon at early times comes from the discovery by Cooke et al. (2011) of an EMP ([Fe/H] ~ -3.0) damped Lyman-α (DLA) system at $z = 2.3$ that exhibits an enhanced carbon abundance ratio ([C/Fe]= +1.5) and other elemental-abundance signatures similar to the CEMP-no class of stars. Matsuoka et al. (2011) also reported evidence for strong carbon production in the early Universe, based on their analysis of the optical spectrum of the most distant known radio galaxy, with $z = 5.1$.

3. New surveys for CEMP stars

Although medium-resolution follow-up of HK and HES candidate metal-poor stars has continued at a modest level over the past decade, recently a resurgence has emerged from the use of previously unobserved candidates (and

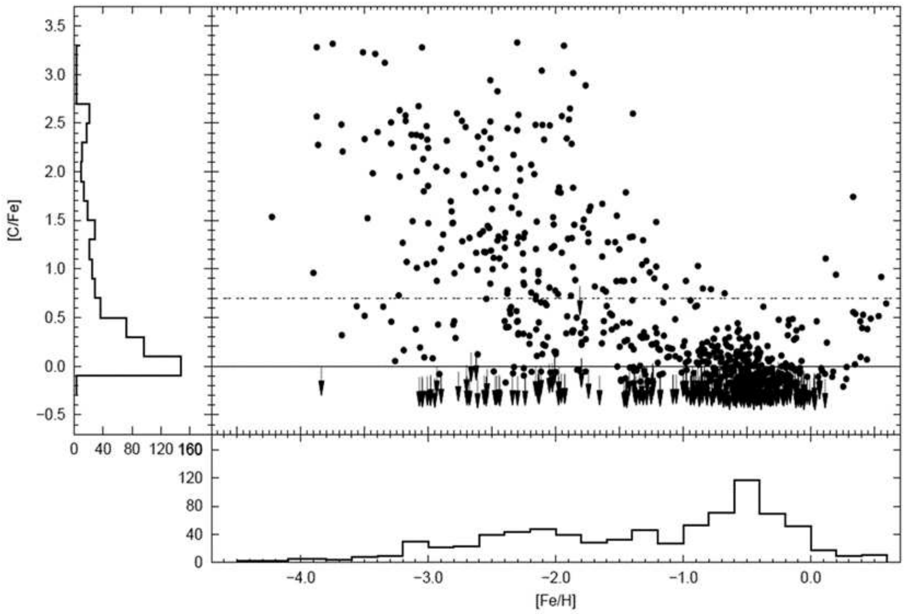

Fig. 2. [C/Fe] as a function of [Fe/H] for a sample of over 500 metal-poor candidates from the HES, observed with Gemini-S, Gemini-N, SOAR, and the ESO NTT, picked out on the basis of their strong CH G-bands (for their color) on the original prism spectra. The marginal plots show the distributions of [C/Fe] and [Fe/H] individually. Upper limits are indicated by downward arrows. The dashed line indicates [C/Fe] = +0.7, the line above which stars are considered CEMP. From Placco et al. (2013), based on application of the a modified version of the SEGUE Stellar Parameter Pipeline (SSPP), described by Lee et al. (2013), and references therein.

newly selected HES candidates) as filler objects for queue-mode observations with GMOS on the Gemini-S and Gemini-N telescopes, in particular during poor weather/seeing conditions. These candidates are very well suited for this observational approach, as they are reasonably bright, and located at most all right ascensions in both the northern and southern hemispheres. As a result, over 800 hours of time has been devoted to this effort over the past two years. Although many thousands of CEMP stars have already been identified in SDSS/SEGUE, most of them are fainter than 16th magnitude, and hence are more challenging to obtain the high-resolution follow-up spectroscopy that is required to assign them to the CEMP-*s* or CEMP-no subclasses.

It appears that many additional EMP stars are being discovered among stars selected from the HES on the basis of their strong CH *G*-bands, rather than exclusively on the basis of their weak CaII K lines. An example of the distribution of [C/Fe] as a function of [Fe/H] for the HES candidates is shown in Figure 2. Note many of these candidates were not previously selected by the HES criteria, hence they will boost the strength of the tail of the MDF that was found for HES stars (Schörck et al. 2009; Li et al. 2010), and may indeed account for its reported sharp cutoff. For more details, see (Placco et al. 2010, 2011, 2013).

4. Future observations of CEMP stars

The LAMOST Experiment for Galactic Understanding and Exploration (LEGUE) is now underway, with the expectation that as many as 5-10 million spectra for Milky Way stars at similar resolution and wavelength coverage as the SDSS/SEGUE spectra will be obtained over the course of the next four years (Deng et al. 2012). One can obviously expect large numbers of CEMP stars to be discovered, improving our ability to examine the "fine structure" of the distribution of CEMP frequencies as a function of [Fe/H] for various stellar populations.

Even though a substantial number of CEMP stars have already been identified, additional future observations are required in order to explore these stars in more detail. These include:

- High-resolution spectroscopy is required in order to assign a given CEMP star to its appropriate subclass. This is of particular importance in order to identify the CEMP-no stars that provide information on the nature of early-Universe nucleosynthesis.
- High-resolution follow-up is also needed in order to measure the abundances of Li and Be for the CEMP-no stars, as well as their N, O, and $^{12}C/^{13}C$ ratios, which constrain the nature of their progenitor objects.
- Long-term radial-velocity monitoring, which again requires high-resolution spectroscopy, is needed for samples of CEMP-no and CEMP-*s* stars, in order to strengthen the claim of a significant difference in their binary fractions, as well as to provide the information necessary to compare the nature of any given detected binary with its detailed chemical-abundance pattern.

5. Conclusions

Since their discovery over 20 years ago, during the course of the HK survey, the importance of CEMP stars for understanding the nature of nucleosynthesis in the early Universe, for demonstrating the apparent evolution of the IMF, and for placing constraints on the likely progenitors of the inner- and outer-halo populations of the Milky Way has only increased with time. The next several years of ongoing medium-resolution surveys and dedicated high-resolution spectroscopic follow-up of the CEMP stars will no doubt prove illuminating.

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