Carbon-Enhanced Metal-Poor Stars in the Early Galaxy

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Very metal-deficient stars that exhibit enhancements of their carbon abundances are of crucial importance for understanding a number of issues – the nature of stellar evolution among the first generations of stars, the shape of the Initial Mass Function, and the relationship between carbon enhancement and neutron-capture processes, in particular the astrophysical s-process. One recent discovery from objective-prism surveys dedicated to the discovery of metal-deficient stars is that the frequency of Carbon-Enhanced Metal-Poor (CEMP) stars increases with declining metallicity, reaching roughly 25% for [Fe/H] < −2.5.

In order to explore this phenomenon in greater detail we have obtained medium-resolution (2 Å) spectroscopy for about 350 of the 413 objects in the Christlieb et al. catalog of carbon-rich stars, selected from the Hamburg/ESO objective prism survey on the basis of their carbon-enhancement, rather than metal deficiency. Based on these spectra, and near-IR JHK photometry from the 2MASS Point Source Catalog, we obtain estimates of [Fe/H] and [C/Fe] for most of the stars in this sample, along with reasonably accurate determinations of their radial velocities. Of particular importance, we find that the upper envelope of carbon enhancement observed for these stars is nearly constant, at [C/H] ∼ −1.0, over the metallicity range −4.0 < [Fe/H] < −2.0; this same level of [C/H] applies to the most iron-deficient star yet discovered, HE 0107-5240, at [Fe/H] = -5.3.

1. Introduction

In recent studies of the most metal-poor stars known, an interesting trend has been discovered regarding the abundance of carbon. Several authors have noted that roughly 25% of the most metal-poor stars studied exhibit strong enhancements of carbon, as reflected in the unusual strength of their CH G-band features. These Carbon-Enhanced Metal-Poor (CEMP) stars occur with such a large frequency that one is forced to consider
the implications on the nature of possible production mechanisms of carbon in the early universe.

Over the metallicity range $-4.0 < [\text{Fe/H}] < -2.0$, there exists an upper limit to the level of carbon enhancement amongst CEMP stars at $[\text{C/H}] \sim -1.0$ \cite{1}. This immediately suggests that at some early time in the universe a significant amount of carbon was produced, in all likelihood by one of the following sources: (1) a \emph{primordial} mechanism from massive stellar progenitors, (2) \emph{intrinsic} internal production by low-mass stars of extremely low [Fe/H], or (3) \emph{extrinsic} production of carbon by stars of intermediate mass, which can be prodigious manufacturers of carbon during their AGB stages, followed by mass transfer to a surviving lower-mass companion. Indeed, it remains possible that all three sources might play a role.

The first alternative, in which the observed levels of carbon in at least some of the CEMP stars is primordial, or close to primordial, and was produced in the first generations of (presumably quite massive) stars, receives some support from models of element production in zero metal abundance stars in the mass range $18 - 30 M_\odot$ \cite{2}. In this scenario a large amount of carbon was produced early on, and then not as prodigiously after that.

The second possibility is that, early in the universe, when there were few heavy elements present, unusually effective mixing episodes triggered at the time of helium core flash dredges up internally produced carbon and deposits it on the surfaces of low-mass stars \cite{3}.

The final alternative is that intermediate-mass stars (e.g., $2 \leq M_\odot \leq 8$) in binary pairs with lower-mass companions, quickly evolved, producing large amounts of carbon during their AGB evolution. Then, a significant amount of this carbon-rich material was transferred to the long-lived companion, via roche-lobe overflow or a wind. The lower-mass companion is presently observed to be carbon-rich, while the higher-mass carbon-producing star is now a faint white dwarf (see, e.g., \cite{4}). In this scenario, one would expect to be able to detect the presence of the binary system, either directly through high-angular-resolution observations, or indirectly by detecting the tell-tale wobble in the orbit of the visible companion.

2. Further Investigations

In order to investigate these different scenarios, new medium-resolution spectroscopic data has been gathered, with a variety of 2m-4m class telescopes, for over 350 stars in the large sample of carbon-rich stars reported by Christlieb et al. \cite{5}. It should be kept in mind that this sample of stars was selected based, not on metallicity, but rather, on the apparent level of carbon enhancement revealed in low-resolution objective-prism spectra. As a result, only those metal-poor stars which exhibited enhancement of carbon were selected, resulting in a determination of the upper limit of carbon enhancement, without restricting the metallicity range.

These data allow for the determination of reasonably accurate estimates of carbon abundances (and [Fe/H]) for the Christlieb et al. carbon-rich stars, using techniques described by Rossi et al. \cite{6}. The calibration of Rossi et al., based on the KP and GP indices described by Beers et al. \cite{7}, in combination with de-reddened $J - K$ colors
obtained from the 2MASS survey \([8]\), achieves accuracies of \(\sigma = 0.25\) dex for \([\text{Fe/H}]\) and \(\sigma = 0.30\) dex for \([\text{C/Fe}]\), respectively.

Figure 1 shows the derived abundances that have been obtained to date for a subset of the Christlieb et al. carbon-rich stars. Roughly 50% of the carbon-enhanced candidates proved to be very metal-deficient stars with \([\text{Fe/H}] \leq -2.0\), in other words, they are CEMP stars. The remainder appear to be stars of higher metallicity, up to and including solar. These latter stars may be examples of intermediate-mass intrinsic AGB stars, whose presence in the halo of the Galaxy might well be accounted for by stripping from dwarf galaxies such as Sagittarius \([9]\).

Figure 1. Note the strong trend of increasing \([\text{C/Fe}]\) with declining \([\text{Fe/H}]\). These stars were selected as carbon-enhanced, independent of metallicity. The upper envelope of abundances correspond to \([\text{C/H}] = -1.0\). Note that abundances have not yet been determined for stars more metal-rich that \([\text{Fe/H}] = -1.0\).

In addition to elemental abundances, radial velocities have been obtained for most of these candidates. Around half of these stars have velocities consistent with membership of the general halo population. The remainders are a mix of high- and low-velocity stars, some of which are likely members of the metal-weak thick disk \([10]\), while others are possibly associated with the Sagittarius stream.

High-resolution spectroscopy of the most interesting stars from this sample are presently being obtained with a variety of 4m-8m telescopes, and will be reported on in due course.

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