

Carbon-Rich, Extremely Metal-Poor Population II Stars

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Abstract.

A significant fraction of very metal-poor stars have unexpectedly high carbon abundances. I recap on their discovery, describe the results of high-resolution spectroscopic studies of their composition, and consider possible origins. It is now clear that at least two, and possibly three different explanations are needed for their general characteristics.

1. Introduction

Beers, Preston & Shectman (1985,1992) conducted an objective-prism survey to search for low-metallicity stars. The spectral range, defined by an interference filter, spanned 150 Å near 3950 Å. This included the Ca H and K lines (3933 Å, 3968 Å), the latter blended with H ϵ , but did not extend to the CH bands around 4310 and 4324 Å, and had no significant sensitivity to the CN band at 3883 Å. From these spectra, Beers et al. selected a weak-lined stars for further study.

Subsequent slit spectroscopy at 1 Å resolution identified an unusually high proportion of objects having very strong CH bands. In a sample of 1044 stars, Beers et al. (1992) identified 50 with anomalously strong CH bands “characteristic of the subgiant CH stars discussed by Bond”. They noted that the proportion of C-rich objects increased at lower metallicity, being 6 out of 70 at $[\text{Fe}/\text{H}] < -3$. From that sampling, it appeared that 10% of their most metal-poor stars had substantial carbon excesses. Other objects in their sample might also have carbon excesses but at more moderate levels.

2. Element Abundances in C-rich Stars

High-resolution studies of C-rich stars in the Beers et al. survey (and its successors) have found diverse chemical properties. Sneden et al. (1994) identified a strong excess of r-process elements in the C-rich star CS 22892-052. In contrast, Norris, Ryan & Beers (1997a) and Barbuy et al. (1997) identified stars with carbon-to-iron ratios up to 100 times the solar value in objects with $[\text{Fe}/\text{H}] \simeq -2.7$, but with strong s-process signatures. This supported the suggestion by Beers et al. that their C-rich objects were related to Bond’s (1974) CH subgiants, which are believed to be contaminated by C- and s-process-rich material from a now-extinct AGB companion. The r-process enhancement in CS 22892-052, far from being typical, now appears anomalous.

Is an s-process enhancement the norm? Apparently not. C-rich stars without anomalous abundances amongst the neutron-capture elements have also been found (e.g. Norris et al. 1997b). So have stars with only mild C-enhancements and no neutron capture anomalies. The situation is summarised by Aoki et al. (2002, their Figure 8). Clearly, different processes are required to explain the s-process-rich and s-process-normal objects, and yet another process is required to explain the r-process-rich object, CS 22892-052. Three other r-enhanced objects are known, but they are not C-rich. The fractions of r-enhanced objects in the C-rich and C-normal classes are difficult to determine reliably with such small statistics, but there is no evidence that these fractions differ greatly. Aoki et al. (2002) have proposed that the r-process enhancement in CS 22892-052 may have no causal link to its C enhancement.

3. Degrees of Carbon Enrichment

Published evidence concerning the degree of C enhancements must be drawn either from the highly-selected objects for which detailed abundance calculations have been made (citations above), or from the low-resolution results of Rossi, Beers & Sneden (1999, their Figure 2). The data of Rossi et al. are in agreement with the levels of enhancement from detailed measurements, but cover a wider range of metallicities. Curiously, the data are suggestive of an upper envelope to the C enrichment, corresponding to a fixed C/H ratio at $[C/H] \simeq -1$. If such a maximum does exist, it may begin to explain why the C-rich stars become more noticeable at lower metallicity, since there the abundance of other metals becomes insignificant in comparison.

Christlieb et al. (2002) have identified a star, HE0107-5240, with an unprecedented iron deficiency, $[Fe/H] = -5.3 \pm 0.2$. More curiously, this object has an extremely high C abundance, quite out of keeping with the normal ratios for its other elements. Nevertheless, its $[C/H]$ value is -1.3 ± 0.3 , which places it close to the extrapolation of the envelope described above (see Figure 1).

4. Orbital Characteristics

One prediction of the CH subgiant explanation for the C-rich, s-rich stars is that the presence of the extinct AGB companion should be detectable via radial velocity variations. The orbital periods of such systems had to be short enough, and hence the stars' separations small enough, to facilitate accretion of material onto the lower-mass star. However, the stars must also have sufficiently large separations that they avoided transferring matter during the donor's first-ascent of the giant-branch, rather than surviving until the AGB when it attained an even greater radius (Wallerstein et al. 1997). These trade-offs suggest periods of 1-10 yr (Han et al. 1995; Jorissen & Boffin 1992).

In some cases, radial velocity variations on this timescale have been observed. For example, LP 625-44 has an orbital period of order 13 yr (Tsan-garides, Ryan & Beers 2003). In contrast, the chemically-similar star LP 706-7 has revealed no radial velocity variations over a ten year period. This object is on the early subgiant branch, cooling from the main-sequence turnoff. Other main-sequence turnoff stars that are C-rich have also been found not to exhibit

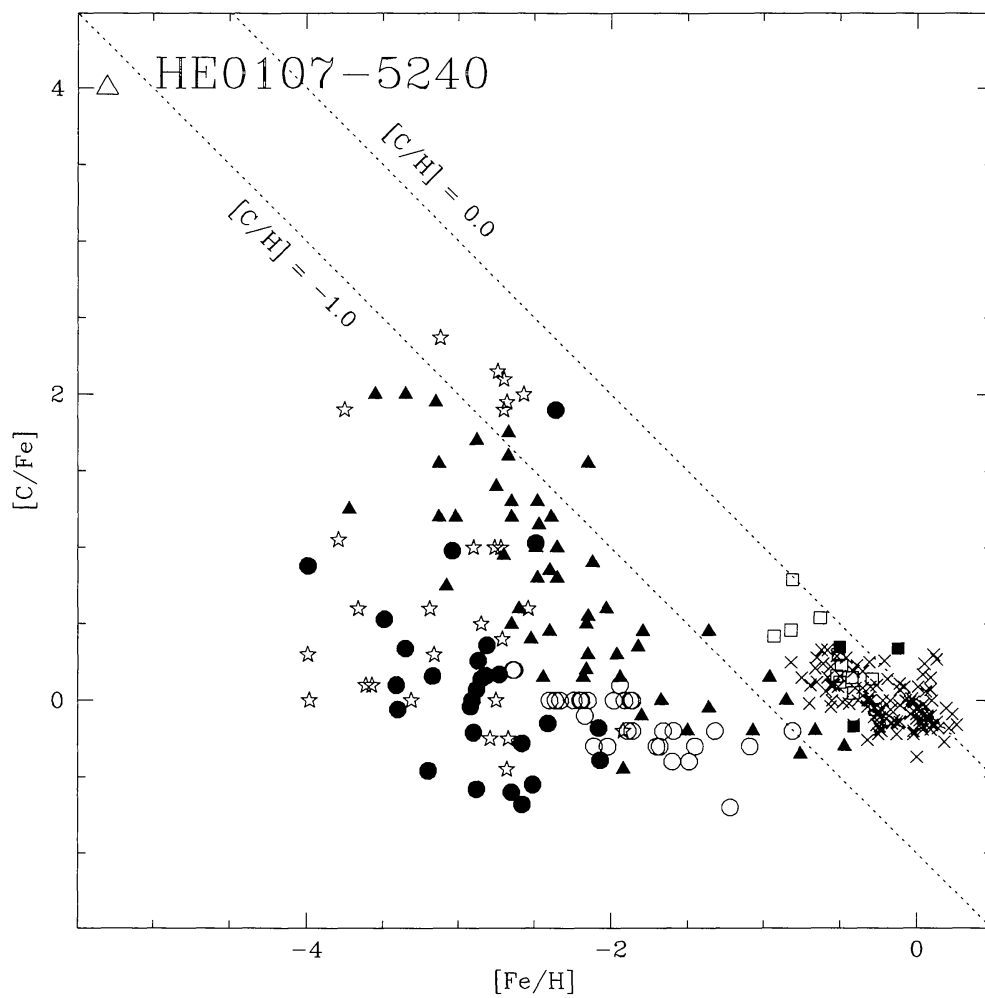


Figure 1. $[C/Fe]$ ratios for a range of stars from the literature.

radial velocity variations (Preston & Sneden 2001). It is possible that the AGB process is not responsible for the enrichment of these stars, but if that is so then the high s-process enhancement in LP 706-7 becomes difficult to explain.

However, it may be that some CH systems become unbound following mass-loss. Porto de Mello & Da Silva (1997) have identified the white-dwarf companion of the Pop. I Ba dwarf HR 6094 at a separation of 5360 AU. If such a system can be considered bound, which is doubtful given its escape speed of $\sim 1 \text{ km s}^{-1}$, then assuming masses of 1.0 and 0.6 M_{\odot} implies an orbital period $3.1 \times 10^5 \text{ yr}$. The radial velocity of this Ba star will not vary on the timescale over which a telescope allocation committee retains interest. Perhaps it is possible that some of the apparently-single, CH-subgiant-like stars have emerged from multiple systems that also became unbound.

5. Distinguishing s-rich and s-normal C-enhanced Stars

Aoki et al. (2002, their Figure 8) have examined differences between C-rich stars on the basis of their enhancements of s-process elements. These stars can be further distinguished on the basis of nitrogen enhancements and carbon isotopic composition (Ryan et al. 2003). In the samples observed so far, the stars which have normal s-process abundances are found only high up the first ascent giant branch, whereas s-rich stars are distributed over a much wider range of giant and subgiant stages of evolution. The s-normal stars also have higher nitrogen abundances. These features can be reconciled with two distinct origins for the stars, the s-rich objects being the ones which exhibit material transferred there by a companion, whereas the s-normal stars presumably began their lives with high ^{12}C fractions. These stars have converted some of their initial ^{12}C to ^{13}C and ^{14}N as they have evolved. In this scenario, the s-rich stars are s-rich and C-rich only in their outer layers, whereas the s-normal stars may be considered C-rich throughout. One consequence of this proposal is that the s-rich stars will gradually dilute their surfaces as they ascend the giant branch and hence will become less distinctive, whereas s-normal stars will maintain high excesses of the CNO group, albeit with a changing isotopic mix. S-normal stars will be found with a luminosity distribution that reflects the luminosity selection effects in the magnitude-limited objective-prism survey. On the other hand, s-rich stars will drop out of the survey as they become more convective, and hence their luminosity distribution will contain a lower proportion of evolved stars. This is in the same sense as the difference observed.

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