# The Frequency of C-Rich Extremely Metal Poor Stars[1]

Judith G. Cohen[2], Stephen Shectman[3] Ian Thompson[3], Andrew McWilliam[3], Norbert Christlieb[4], Jorge Melendez[2], Franz-Josef Zickgraf[4], Solange Ramírez[5] & Amber Swenson[2]

## ABSTRACT

We demonstrate that there are systematic scale errors in the [Fe/H] values determined by the Hamburg/ESO Survey (and by the HK Survey by inference) for certain extremely metal poor (EMP) highly C-enhanced giants. The consequences of these scale errors are that a) the fraction of carbon stars at extremely low metallicities has been substantially overestimated in several papers in the recent literature b) the number of EMP stars known is somewhat lower than has been quoted in the recent literature c) the yield for EMP stars by the HK and the HES Survey is somewhat lower than is stated in the recent literature. A preliminary estimate for the frequency of Carbon stars among the giants in the HES sample with $-4 <$ [Fe/H] $< -2.0$ dex is 7.4±2.9%, and for C-rich giants with [C/Fe] $\geq +1.0$ dex is 14.4±4%.

We rely on the results of an extensive set of detailed abundance analyses of stars expected to have [Fe/H] $\leq -3.0$ dex selected from the Hamburg/ESO Survey to establish these claims. These analyses of ∼50 HES candidate extremely metal poor stars have been carried out in as homogeneous a manner as possible. Here we present the key results of detailed abundance analyses of 14 C-stars selected in this way About 80% of such C-stars show highly enhanced Ba as well, with C enhanced by a factor of about 100, and [Ba/C] roughly Solar. These stars often show prominent lead lines, and presumably are the remnants of the secondary in a mass transfer binary system where the former primary was an AGB star, which transferred substantial mass at that evolutionary stage. The remaining 20% of the C-stars do not show an enhancemement of the s-process neutron capture elements around the Ba peak. They tend to be the most metal-poor stars studied. We suggest that they too result from mass transfer across a binary system. (published abstract will be shorter due to space limitations)

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[1]Based in part on observations obtained at the W.M. Keck Observatory, which is operated jointly by the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

[2]Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, Ca., 91125, jlc@astro.caltech.edu

[3]Carnegie Observatories, 813 Santa Barbara Street, Pasadena, Ca. 91101

[4]Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany

[5]Spitzer Science Center, Mail Stop 100-22, California Institute of Technology, Pasadena, Ca., 91125

## 1. The Fraction of Carbon Stars Among Extremely Metal Poor Stars

We are engaged in a large scale project to find additional EMP stars in the halo of our galaxy by mining the database of the HES. The normal procedures outlined by Christlieb (2003) to isolate EMP stars from the candidate lists produced by the HES were followed. The candidates were vetted via moderate resolution spectroscopy at large telescopes to eliminate the numerous higher abundance interlopers. Most of the follow up spectra for the stars discussed here were obtained with the Double Spectrograph on the Hale Telescope at Palomar Mountain. We intend to observe all candidates to the magnitude limit of the HES (B $\sim$ 17.5) in our fields; with $\sim$1600 moderate resolution spectra in hand from campaigns at Palomar and at the Las Campanas Observatory, observations are now complete in $\sim$990 deg$^2$, complete to B=16.5 in an additional $\sim$700 deg$^2$, and approaching completion in the remaining fields.

These follow up spectra are used to determine an accurate measure of the metallicity of the star via a combination of strength of absorption in H$\delta$ (determining $T_{eff}$) and in the Ca II line at 3933 Å (the KP index), which then determines [Fe/H]. The calibration between the strength of the indices and resulting metallicity [Fe/H](HES) adopted by the HES is described in Beers *et al.* (1999) and is essentially identical to that used by the HK Survey until recently; the latest updates to the algorithm as used by the HK Survey are described in Rossi *et al.* (2005).

We have found that there are systematic scale errors in the [Fe/H] values determined by this algorithm for certain EMP highly C-enhanced giants. As is shown in Cohen *et al.* (2005a), these scale errors act to make certain C-stars appear more metal poor by a factor of $\sim$10 than would be inferred from a detailed abundance analysis of their high dispersion spectra. These problems appear to arise due to molecular absorption of CH and CN in the specific continuum bandpasses used to measure the KP and the H$\delta$ line indices from which [Fe/H] is inferred. This makes both of these lines appear weaker, and hence the inferred Fe-abundance of such a C-star is underestimated. This effect is largest for the cooler C-stars ($T_{eff}$$\sim$5100 K) with high C-enhancement and high N/C ratios. Normal-C giants and the warmer C-stars are not affected; [Fe/H](HES) and [Fe/H](HIRES] are in good agreement for them.

We rely on the results of an extensive set of detailed abundance analyses of stars expected to have [Fe/H] $\leq -2.9$ dex selected from the Hamburg/ESO Survey to establish these claims. We have obtained and analyzed spectra with HIRES Vogt *et al.* (1994) at the Keck I Telescope of $\sim$60 HES candidate EMP stars. Cohen *et al.* (2005b) will present abundance analyses for 14 of the 16 known Carbon stars from this HES sample. Fifteen C-normal giants have been analyzed to date as well, while Cohen *et al.* (2004) studied a large sample of candidate EMP dwarfs from the HES.

The first consequence of these scale errors is that the fraction of carbon stars at extremely low metallicities has been substantially overestimated in several papers in the recent literature. Our operational definition of a C-star is one whose spectrum shows bands of $C_2$. If no $C_2$ bands are detected, but [C/Fe] $>$ 1 dex, we denote a star to be C-enhanced. The strength of the $C_2$ bands will be a function of $T_{eff}$, $\epsilon$(C), and to a lesser extent, log($g$) and [Fe/H]. Also we denote stars with

$T_{eff} > 6000$ K as "dwarfs", while all cooler stars are called "giants".

Even though the cooler C-stars comprise only a small fraction of the most metal poor stars, an underestimate of a factor of ∼1 dex in their [Fe/H](HES) will have significant effects. Fig. 1 shows [Fe/H](HES) versus V-K for a sample of 489 EMP candidates from the HES with moderate resolution spectra from the Double Spectrograph at the Hale Telescope. The known C-stars and the C-enhanced star with HIRES analyses from this sample are indicated. In the upper panel, the C-rich stars are plotted at their [Fe/H](HES) values, while in the lower panel they are plotted at their [Fe/H](HIRES) as determined from detailed abundance analyses. Although at their nominal Fe-metallicities the C-stars dominate the population of the giants below [Fe/H](HES) −3 dex, using the results from analysis of high resolution spectra in the lower panel the frequency of C-stars among the most metal poor EMP stars is reduced by a factor of 2.5. The C-star frequency for the Palomar sample of HES giants with [Fe/H](HES) $< -2.0$ dex is 7.4±2.9%. Adding in the fraction of C-enhanced stars among giants with [Fe/H](HES) $< -2.0$ dex we establish below of 6.5±2.7%, one obtains a total fraction of C-rich stars with [C/Fe] $> +1.0$ dex of 14±4% among our HES EMP sample with [Fe/H](HES) $< -2.0$ dex.

The metallicity distribution function is very sharply declining among halo stars at the lowest Fe-metallicities. Thus the systematic errors we have found in the calibration of the HES and by inference the HK metallicity scale of Beers *et al.* (1999), at least until quite recently (see Rossi *et al.* 2005) will also lead directly to systematic overestimates of the number of EMP stars and of the yield for EMP stars by these two major surveys. More details of this work can be found in Cohen *et al.* (2005a).

## 2. Extremely Metal Poor C-Enhanced Stars

We next establish the distribution of C abundances and C/Fe ratios for those stars that are not classified as C-stars. If [C/Fe] $\geq +1.0$ dex, we call such stars C-enhanced. Fig. 2 displays the GP (G band of CH) index as a function of V−K color for the Palomar sample. The entire set of known C-stars from our database is shown; for the giants they are concentrated at the top of the distribution, having the strongest GP indices at each color. To determine the C abundances we use the predicted CH band strengths computed by M. Briley described in Cohen, Briley & Stetson (2005). These were calculated using a full spectral synthesis for the GP index defined in Beers *et al.* (1999). $V - K$ is used to define $T_{eff}$, adopting a mean value of E(B−V) of 0.05 mag for the HES stars. Fig. 3 shows the resulting histogram of [C/Fe] for the giants from this sample with [Fe/H] $\leq -1.8$ dex.

The histogram suggests a peak near [C/Fe] ∼ 0.3 dex, somewhat higher than the normal value for unmixed very metal poor giants of [C/Fe] = 0.0 dex given by Cohen, Briley & Stetson (2005). There is a sharp drop towards higher C/Fe ratios, with the C-stars occupying the upper limit of the range near [C/Fe] ∼ +2.0 dex. The distribution slowly decreases for C/Fe ratios lower than

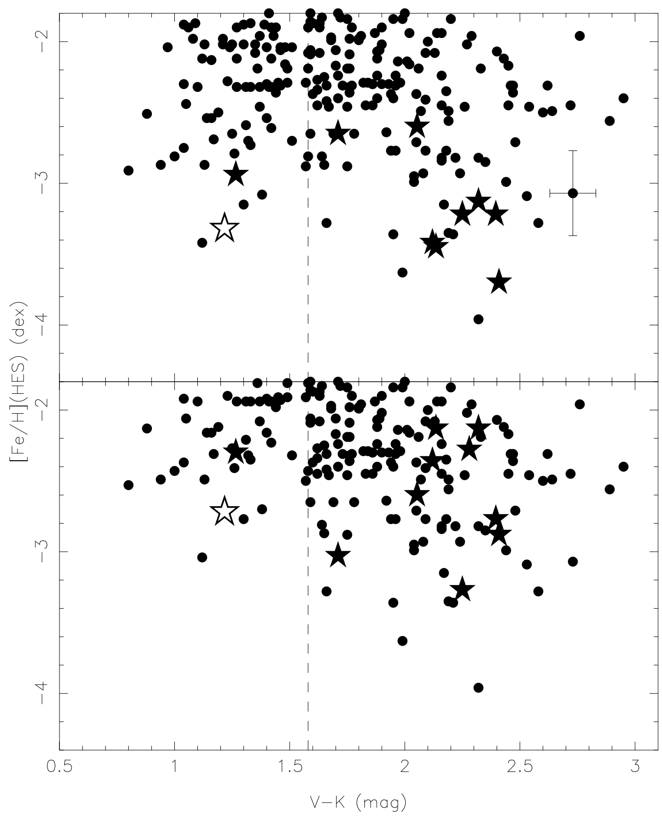


Fig. 1.— A plot of [Fe/H](HES) versus V-K for a sample of 489 EMP candidates from the HES with moderate resolution spectra from the Double Spectrograph at the Hale Telescope (filled circles, limited to stars with [Fe/H](HES) $< -1.8$ dex). The C-stars are from this sample are indicated by filled stars; the C-enhanced star is shown as an open star. In the upper panel the C-stars are plotted at their [Fe/H](HES) values, while in the lower panel, at their [Fe/H](HIRES) values. The C-normal dwarfs have also been shifted towards higher [Fe/H] by 0.38 dex in the lower panel. A typical error for a EMP giant with normal C is shown for a single star in the upper panel. The vertical dashed line separates the giants from the dwarfs.

the peak.

The fraction of giants that are C-enhanced but are not known C-stars is 6.5±2.7%.

## 3. Abundance Analysis of Carbon Stars From the HES

To establish the results presented above, we have carried out a detailed abundance analysis using high dispersion spectra from HIRES at Keck for a sample of 14 of the 16 carbon stars found in our database among candidate EMPstars selected from the HES. Using a $T_{eff}$ scale based on V-I, V-J and V-K colors, we find that the Fe-metallicities for the cooler C-stars ($T_{eff}$ ∼5100 K) have been underestimated by a factor of ∼10 by the standard HES survey tools. Since we have not used the high resolution spectra themselves to determine $T_{eff}$ or log($g$), the ionization equilibrium is a stringent test of our analysis and procedures, including the assumption of LTE. We obtain a mean for log$\epsilon$(Fe:Fe II) − log$\epsilon$(Fe:Fe I) of −0.08 dex, with a 1$\sigma$ rms scatter about the mean of 0.18 dex. C-enhancement in these very metal poor C-stars appears to reach a maximum just below the solar $\epsilon$(C), and shows evidence of decreasing with decreasing $T_{eff}$ (increasing luminosity), presumably due to mixing and dredge-up of C-depleted material.

Fig. 4 shows [Ba/C] as a function of Fe-metallicity for this sample of C and C-enhanced stars. Ten of the C-stars from the HES that we have analyzed show an enhancement of Ba (and of the other $s$-process neutron capture heavy elements) approximately equal to that of C. The other four show [Ba/C] $\leq -1.2$ dex, i.e. a strong C enhancement, with more normal heavy elements, as contrasted to enhancement of both C and the $s$-process elements in the majority of the C-stars. Including 10 additional C-stars compiled from the literature, ∼80% of the full sample of EMP/VMP C-stars show highly enhanced Ba, while ∼20% has [Ba/C] $\leq -1.2$ dex. It is clear from both the very high enhancements of lead and the Ba/Eu ratios seen among these C-stars that the $s$-process is responsible for the enhancement of the heavy neutron-capture elements, when present.

At first sight, this behavior suggests that two distinct processes are required to produce the Ba-enhanced C-stars and those that are not. Nucleosynthesis within an intermediate mass AGB star can reproduce the first set of characteristics, but these C-stars are in general of too low a mass and are not sufficiently luminous or evolved to be AGB stars. We suggest instead that the observed star is the former secondary in a binary system across which mass transfer has occured.

What about the ∼20% of the C-stars without heavy element enhancements ? We suggest that there is no need to resort to intrinsic production or any other additional mechanism, and that essentially *all* of these stars are the original secondary stars in mass transfer binary systems. We ascribe the differing enhancement of the $s$-process elements from C-star to C-star within our sample to some dependence in the nucleosynthetic yields involving, for example, the initial [Fe/H] and mass of the original primary star. At the lowest metallicities, Busso, Gallino & Wasserburg (1999) predict that little or no $s$-process enhancement will occur at the Ba peak as there will be so few Fe-seed nuclei that they will essentially all end up as lead. Fig. 4 provides some support for

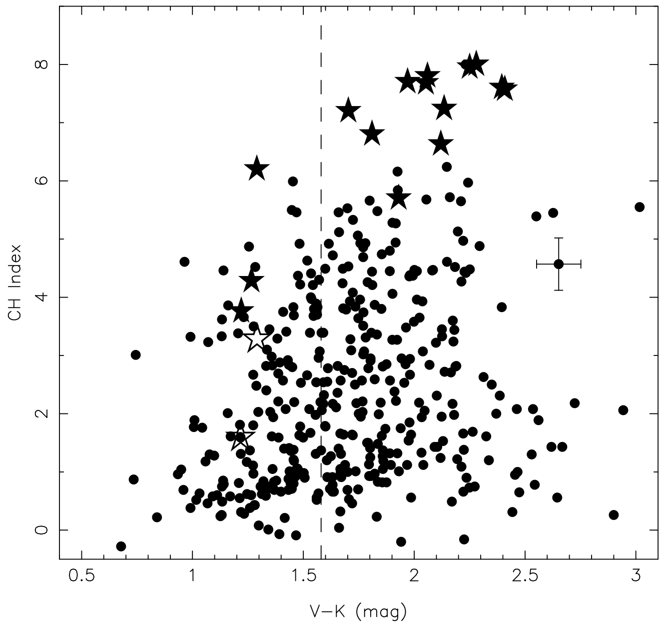


Fig. 2.— The CH index (GP) is shown as a function of V-K for the full P200 sample of EMP candidates from the HES. The known C-stars are shown as filled stars, the known C-enhanced stars as open stars. A typical error for a EMP giant with normal C is shown for a single star. The vertical dashed line separates the giants from the dwarfs.

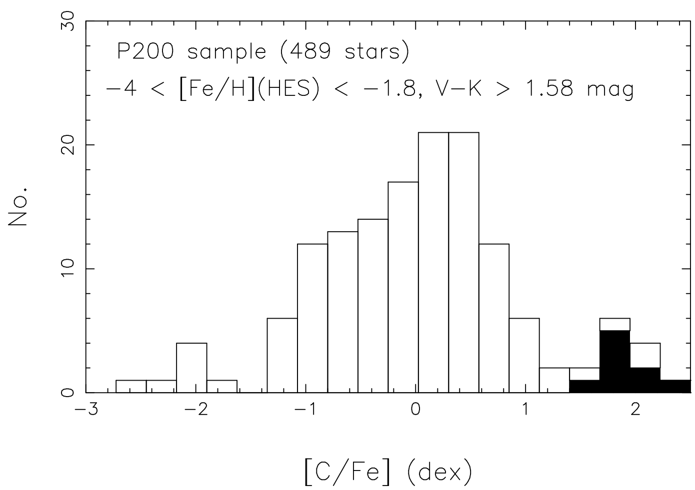


Fig. 3.— A histogram of [C/Fe] is shown for the giants from the P200 sample of candidate EMP stars with $-4 \leq$ [Fe/H](HES) $\leq -1.8$ dex. The known C-stars are denoted by solid fill. The predictions of M. Briley described in Cohen, Briley & Stetson (2005) for the strength of the G band of CH based on synthetic spectra were used.

this prediction.

In our hypothesis, essentially all of these C-stars were once binaries. Assuming most have survived to date without being disrupted, they should still be binaries with (invisible) white dwarf companions. The statistics of binary detection among very metal poor C-stars from the HES cannot be evaluated from our sample as most of the stars have only been observed at a single epoch. So we look instead at the sample of C-stars added from the literature, which are mostly from the HK Survey and are in general brighter than the HES C-stars in our sample. They have been known as interesting objects for timescales of several years to a decade, giving more opportunity for radial velocity monitoring. Four of these 11 C-stars are confirmed binaries with measured periods, consistent with the preliminary results of the $v_r$ monitoring program of Tsangarides, Ryan & Beers (2004) for $s$-process enhanced C-stars. Although the sample is small, considering the lack of suitable long-term radial velocity monitoring programs, the length of the typical period, the small velocity amplitudes, the faintness of the stars, and the relatively short time they have been known to be interesting, we find our detection rate for binaries among very metal poor and EMP C-strs to be consistent with all such stars being binaries; simulations by Lucatello *et al.* (2004) support this. There is as yet insufficient $v_r$ monitoring data for the much smaller sample of C-enhanced but not $s$-process enhanced stars. Cohen *et al.* (2005b) will present full details.

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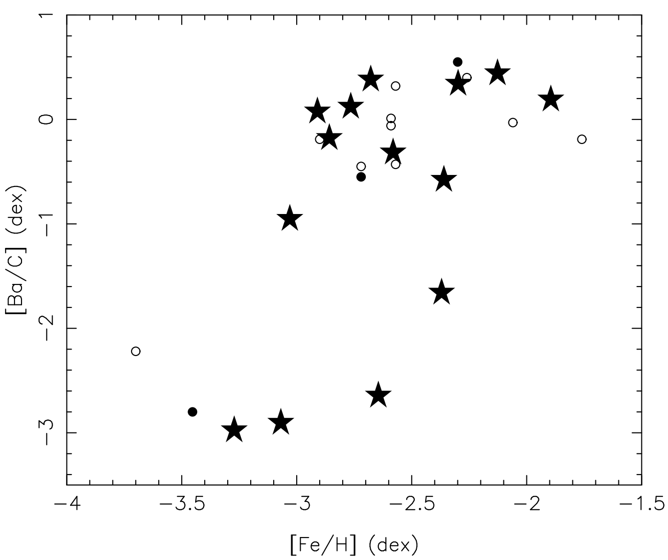


Fig. 4.— [Ba/C] is shown as a function of [Fe/H] for a sample of 24 C-stars (14 from the present sample, denoted by filled stars, 10 from the literature, indicated by open circles) and 2 C-enhanced dwarfs (filled circles).