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A Status Report on the 0Z Project

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Abstract

We present an update on the status of the 0Z Survey, an effort to datamine the Hamburg/ESO Survey to find and study in detail a large sample of extremely metal-poor Galactic halo field stars with [Fe/H] < -3.0 dex. After searching 1,565 moderate resolution spectra of candidates selected from the HES, we have acquired high resolution spectra of 103 of the most metal-poor of them. Detailed abundance analyses have been performed for all these stars. This has resulted in the discovery of 18 new stars below [Fe/H] -3.5 dex and 57 below -3.0 dex. Some results are presented regarding our search for outliers in chemical abundances of particular species among the sample of 103 stars. Ignoring C and N, about 15% of the sample are "abnormal" in some way. Our plans to complete this project and write the final set of papers are described.

1. Introduction

Extremely metal poor stars were presumably among the first stars formed in the Galaxy, and hence represent in effect a local high-redshift population. It is from this paradigm that the term "galactic archeology" arises. Such stars provide important clues to the chemical history of our Galaxy, the role and type of early SN, the mode of star formation in the proto-Milky Way, and the formation of the Galactic halo. The number of extremely metal poor (EMP) stars known as of 2005 is summarized by Beers & Christlieb(2005); it has grown slowly since that time, but the sample is still quite small. Our goal is to increase this sample substantially so that statistical studies of the Galactic EMP star population become feasible.

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2. Sample Selection Strategy

We are engaged in a long term program to datamine the Hamburg/ESO Survey for extremely metal-poor stars with [Fe/H] < -3 dex, i.e. less than 1/1000 the Solar Fe/H ratio[1]. The HES is an objective prism survey with low spectral dispersion taken with photographic plates of high-latitude Galactic halo fields. Given the low spectral resolution and, at the faint end of the sample, the modest SNR, the best that can be done is to produce lists of candidate EMP stars. Since the entire survey, although taken with photographic plates, was subsequently digitized, the selection of candidates was carried out using well defined and reproducible scripts and procedures, which can be modified based on experience, and the selection redone as necessary at later times.

The candidate lists thus generated are unreliable, with many contaminating higher metallicity stars. Thus the EMP candidates selected from the HES database must be verified by moderate resolution spectra taken at 5 m class telescopes. We observed 1,565 candidates with the 6.5 m Magellan Clay Telescope or the Double Spectrograph Oke & Gunn(1982) at the 5 m Hale Telescope at Palomar Mountain. Of these 26 were rejected as not Galactic halo field stars. Most of these interlopers are dMe stars.

By summer 2006, when observations at the P200 ended, followup spectroscopy for candidates in the fall north field (approximately 900 sq deg on the sky north of Dec $-20°$ covered by the HES) was 99% complete to the limit of the HES at $B = 17.5$ mag. The spring north field was complete to B = 16.5 mag, and missing only 5 stars to B = 16.6 mag.

After each such observing run, a metallicity [Fe/H](HES) was determined from the followup spectrum of each candidate observed. This was based on the strength of absorption at Hδ, a measure of stellar temperature, coupled with that of the 3933 Å line of Ca II, which provided the metallicity given T_{eff}. The algorithm of Beers et al. (1999) was used for this purpose.

Since this algorithm was improved with time, especially with the discovery by Cohen et al. (2005) of its problems in accurately predicting [Fe/H] from spectra of highly C-enhanced stars, all the moderate resolution spectra were re-processed at the end of this campaign in early 2007. At that time *no* [Fe/H](HES) value was assigned to highly C-rich stars. Furthermore the selection function from the HES evolved somewhat with time, and some stars which were on the original target list for followup spectroscopy were subsequently deleted, while others were added.

The accuracy of the values of [Fe/H](HES) as derived from the moderate resolution spectra was tested with multiple observations of a set of well studied low metallicity stars from the HK Survey Beers, Preston & Shectman(1985, 1992) as well as multiple observations of the candidates themselves.

These [Fe/H](HES) comprised a major part of the statistically complete sample used by Schorck et al. (2009) to determine the metallicity distribution function in the

[1] The standard nomenclature is adopted; the abundance of element X is given by $\epsilon(X) = N(X)/N(H)$ on a scale where $N(H) = 10^{12}$ H atoms. Then $[X/H] = \log_{10}[N(X)/N(H)] - \log_{10}[N(X)/N(H)]_{\odot}$, and similarly for [X/Fe].

Galactic halo, with emphasis on the EMP tail. This large sample, combined with careful consideration of selection effects, led to important new conclusions about the similarity of the MDF of the Milky Way halo MDF and that of its dSph satellites in the extremely metal-poor regime.

3. High Resolution Observations and Data Reduction

Since our goal is a detailed characterization of a statistically significant population of confirmed EMP field halo stars, we attempted to get high spectral resolution observations with either MIKE on the 6.5 m Magellan Telescope at Las Campanas or HIRES Vogt et al. (1994) at the 10 m Keck 1 Telescope for all stars which were assigned [Fe/H](HES) < -3 dex. Stars at slightly greater [Fe/H](HES), which were of course more numerous, were observed to fill in scheduled nights with MIKE/Magellan or HIRES/Keck when necessary. The earliest high dispersion observing runs (i.e. those in 2001-2002) included some EMP candidates suggested by N. Christlieb or T. Beers, as these runs occurred before the 0Z Survey could build up a substantial set of verified EMP candidates from its own followup spectra. The sample presented here includes 99 stars observed with HIRES and four with MIKE, for a total sample of 103 stars.

All of these spectra were analyzed by J. Cohen in a homogeneous manner with identical procedures, stellar parameter determinations, line lists, transition probabilities, etc with the help of post-doctoral fellows Jorge Melendez and Wenjin Huang. We used the LTE spectrum synthesis program MOOG (Sneden 1973) and the grid of plane-parallel (i.e. 1D) LTE model atmospheres from Kurucz (1993) to compute abundances from the measured equivalent widths. The effective temperatures were derived from broad-band optical and 2-MASS infrared photometry. Our program using the Andicam queue at CTIO was the primary source for V, I optical photometry. Results from SDSS were used when available, and as a last resort V(HES) was used for a very small number of stars. Our analysis uses the nominal T_{eff} from $V - I$, $V - J$, and $V - K_s$. Surface gravity is defined by assuming that the star lies along a very metal-poor Y2 isochrone. Because of uncertainties in the photometry, we felt free to slightly adjust T_{eff} if necessary to achieve a good result. Although the nominal assumption was that all stars were more luminous than the main sequence turnoff, occasionally we were forced to adjust $\log(g)$ to set a star below the turnoff. Fig. 1 shows the location of the sample in the T_{eff} – $\log(g)$ plane. Candidates which turned out to be EMP stars are indicated, as are those that have highly enhanced carbon abundance.

One test of the validity of the abundance analyses is to examine the ionization equilibrium of Fe, i.e. the deduced [Fe/H] from lines of Fe I versus those of Fe II, for each star. This is shown in Fig. 2, and looks quite reasonable. The mean difference between the Fe abundance derived from the neutral and the singly ionized species for 100 EMP candidates from out sample with with HIRES spectra and detailed abundance analyses by J. Cohen is 0.00 dex with $\sigma = 0.10$ dex

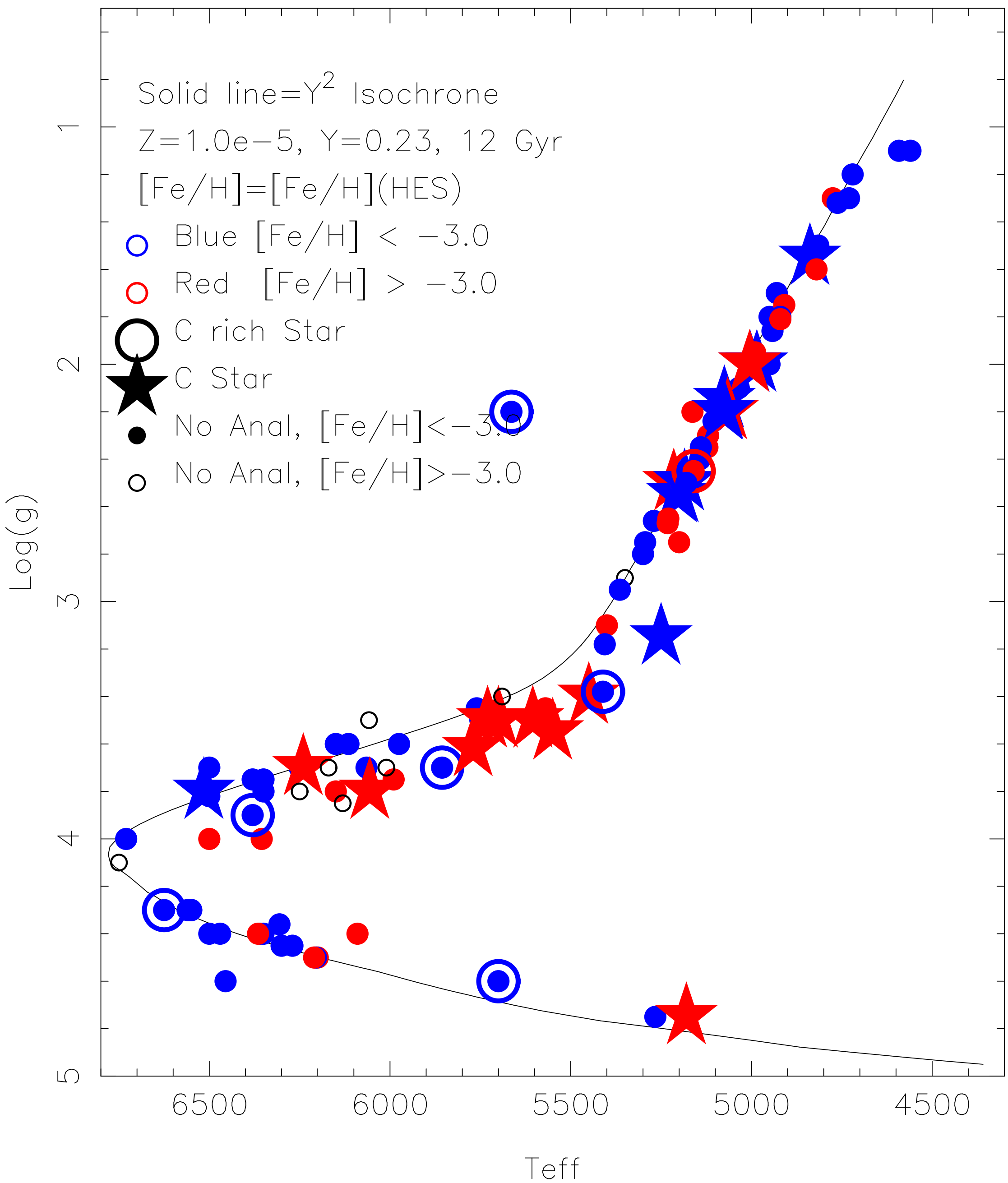

Figure 1.— The sample of stars with high dispersion observations is shown on the T_{eff} – $\log(g)$ plane together with a low metallicity Y^2 12 Gyr isochrone. Those stars with [Fe/H](HES) < -3.0 dex are indicated, as are C-rich stars.

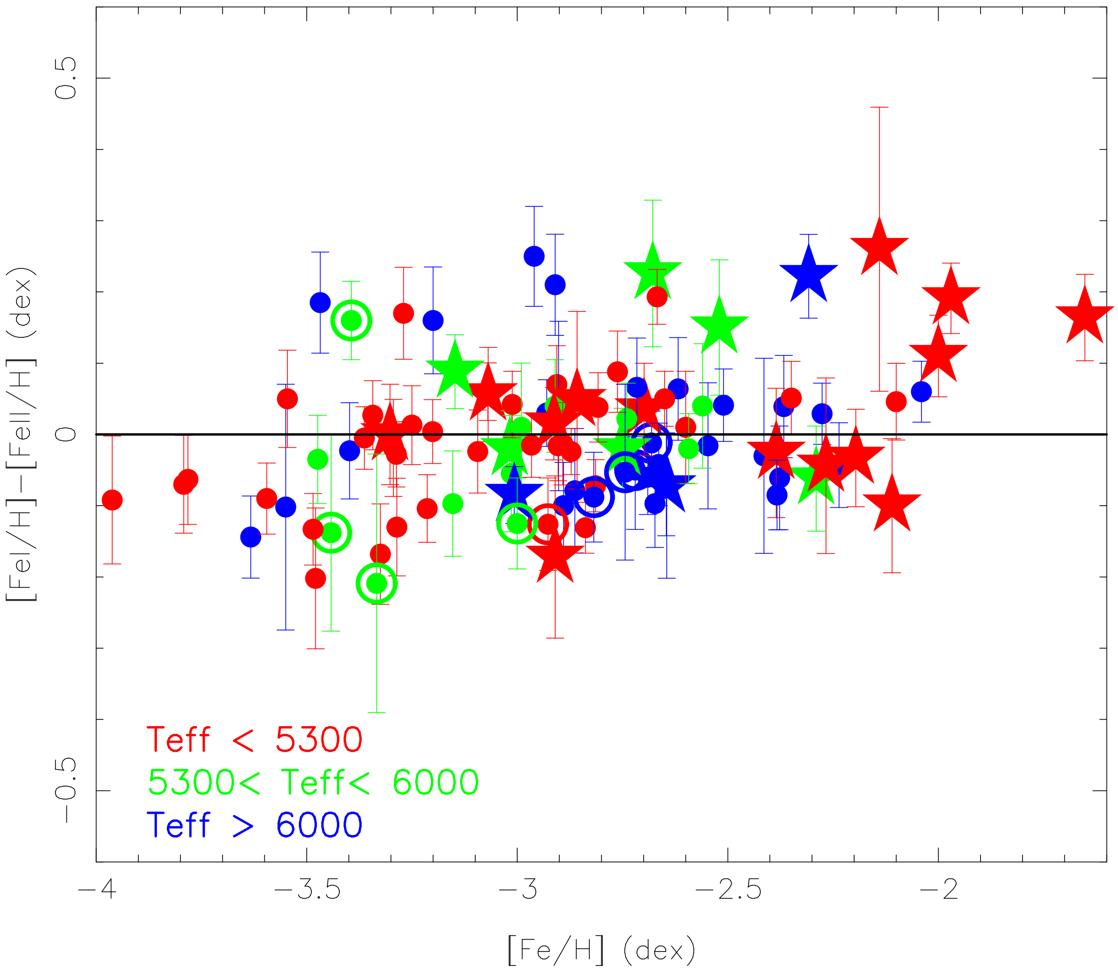

Figure 2.— The ionization equilibrium for Fe I vs Fe II is shown as a function of [Fe/H] (from Fe I) for the HES EMP candidates with detailed abundance analyses. Red points have $T_{eff} < 5300$ K, green $5300 < T_{eff} < 6000$ K, blue $T_{eff} > 6000$ K. Stars denote carbon stars,; circled points are highly C-rich, but do not show C_2 bands.

4. Current Status of the 0Z Project

Detailed abundance analyses by J. Cohen give [Fe/H] values systematically slightly higher than those which would be derived by most other large surveys in this field. The reasons for this small offset of ∼0.15 dex in [Fe/H] are understood, and are discussed in an appendix in Cohen et al. (2008). In the [Fe/H] scale of the VLT First Stars Survey (Cayrel et al. 2004), we have found 18 new stars with [Fe/H] below −3.5 dex and 57 new stars below −3.0 dex. These represent a substantial increase in the number of EMP stars known.

Ignoring the C-rich stars, a comparison of the derived [Fe/H](HIRES) with that from the moderate resolution spectra is shown in Fig. 3. Excluding one very discrepant star, the σ of the differences is 0.36 dex, most of which presumably should be ascribed to

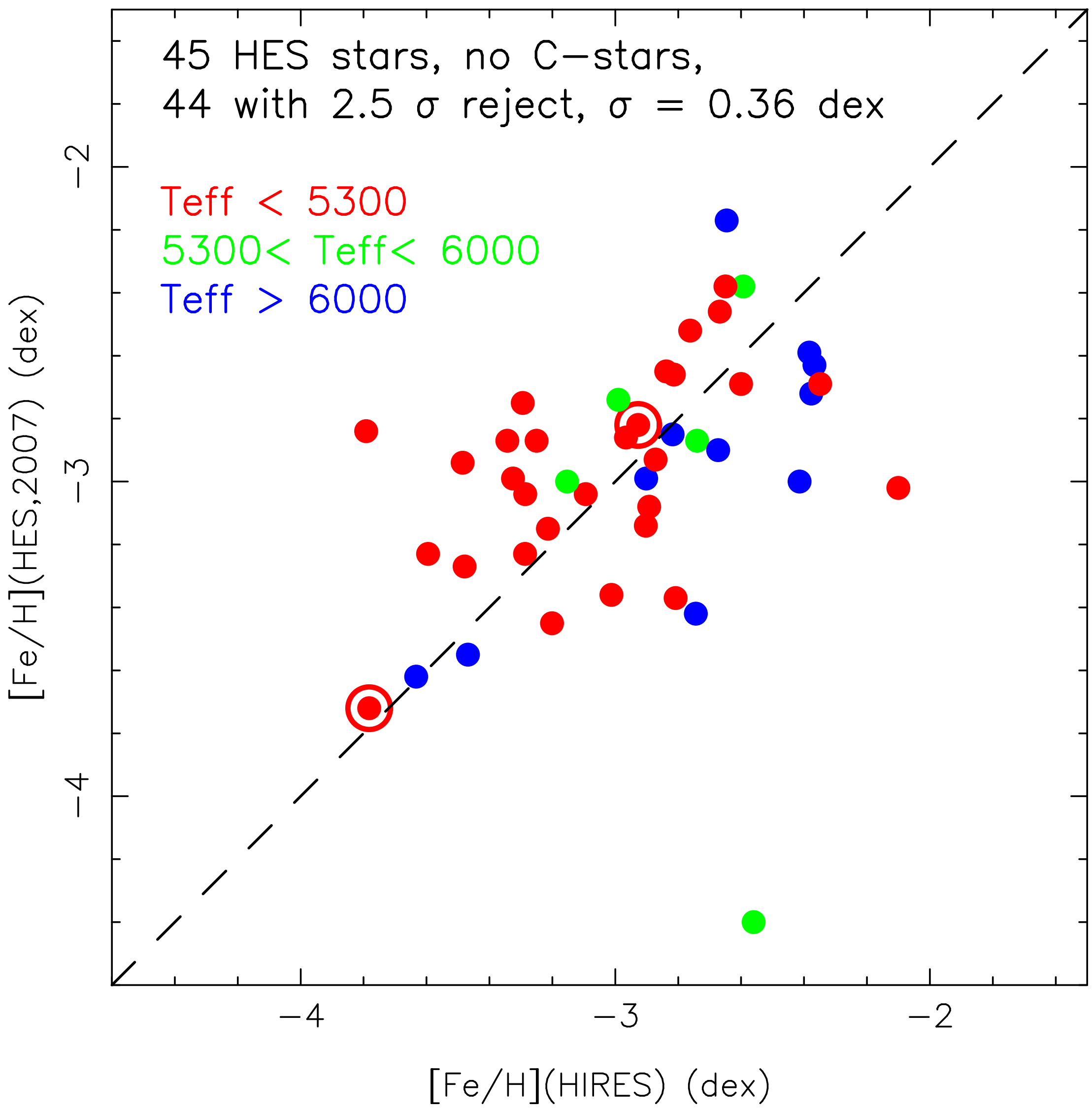

Figure 3.— A comparison of [Fe/H](HES) from the moderate resolution followup spectra to [Fe/H] derived from the high dispersion spectra with a detailed abundance analysis. Highly C-rich stars are ignored. Colors denote the three ranges of T_{eff} as in Fig. 2. Only a small systematic trend with T_{eff} is seen.

the uncertainty in [Fe/H](HES).

Once this sample of 103 homogeneous abundance analyses of supposed EMP stars was assembled, we constructed diagrams of relative abundance trends versus overall metallicity, i.e. of [X/Fe] versus [Fe/H]. As examples, we show the trends for [Mg/Fe] and for [Si/Fe] in Fig. 4 and 5. For each such plot, we have begun to check each of the outlier stars, looking for errors, examining the original spectra at the wavelengths of crucial lines when necessary, etc. So far between 4 and 8 outliers for each of 10 elements have been checked, with perhaps 10 more elements left to do. Those stars for which we have carried out such a check for a particular species and did not find any problem nor any reason not to believe the result are indicated by "V" in the plots, while those for which we could not be sure the result was valid are marked with "?". The latter usually happened for C-rich stars with strong molecular bands and with spectra taken early in the project prior to the HIRES detector upgrade in 2004. These early spectra do not extend far enough into the red to reach some key lines beyond the CH, CN, or the 5170 Å C_2 bands. Hence the abnormal relative abundance ratios initially derived may not be valid. Note that the two very high [Mg/Fe] values for two C-rich stars with [Fe/H] < -3.5 dex seen in the upper left corner of Fig. 4 have been carefully checked and appear valid. Large enhancements of Mg have been reported in a few cases among very metal-poor C-rich stars (e.g., see Aoki et al. 2002).

In the case of Fig. 5 the dependence of [Si/Fe] on T_{eff} noted earlier by Preston et al. (2006) (see their Fig. 10) is apparent in our abundance analyses as well. Presumably the problem lies in non-LTE corrections which vary significantly with T_{eff}. The most metal-poor star in this figure has a very low [Si/Fe]; it is HE 1424–0241, the very peculiar star whose discovery was announced in Cohen et al. (2007) and was discussed in detail in Cohen et al. (2008).

Among the sample of 103 stars, we found one new extreme r-process enhanced star with [Eu/Fe] +1.5 dex. It is somewhat hotter than the prototype of this class, CS22892–052, and is very slightly higher in [Fe/H].

5. Ongoing Work to Finish the 0Z Project

Although the 0Z Project has published a large number of papers on specific interesting stars found by the 0Z project (see, e.g. Lucatello et al 2003, Cohen et al 2003, Cohen et al 2004, Cohen et al 2006, Cohen et al 2007, Cohen et al 2008) our current goal is to finish the project by writing a set of papers which will present the entire sample of EMP candidates selected from the HES with moderate resolution spectra (1,565 stars). Another paper will give the detailed abundance analyses for the entire set of stars with HIRES spectra (103 stars), and describe the implications for early nucleosynthesis and supernovae in the young Milky Way that can be derived from this work. In particular, with such a large homogeneous data set we will be able to construct better comparisons and detect modest outliers from the mean trends more easily.

After we finish checking all the outliers, we need to define a better way of visualizing the interlinking of abnormalities in one specific species with the results for all other species detected in stars which are outliers as compared to stars which do not show any abnormalities. We are doing this by selecting the closest stars in T_{eff} to the peculiar star from our large sample as comparison objects and examining plots of [X/Fe] versus atomic number of the species X for the suspected outlier versus the comparison stars.

The process of checking the outliers and linking abnormalities across all the species

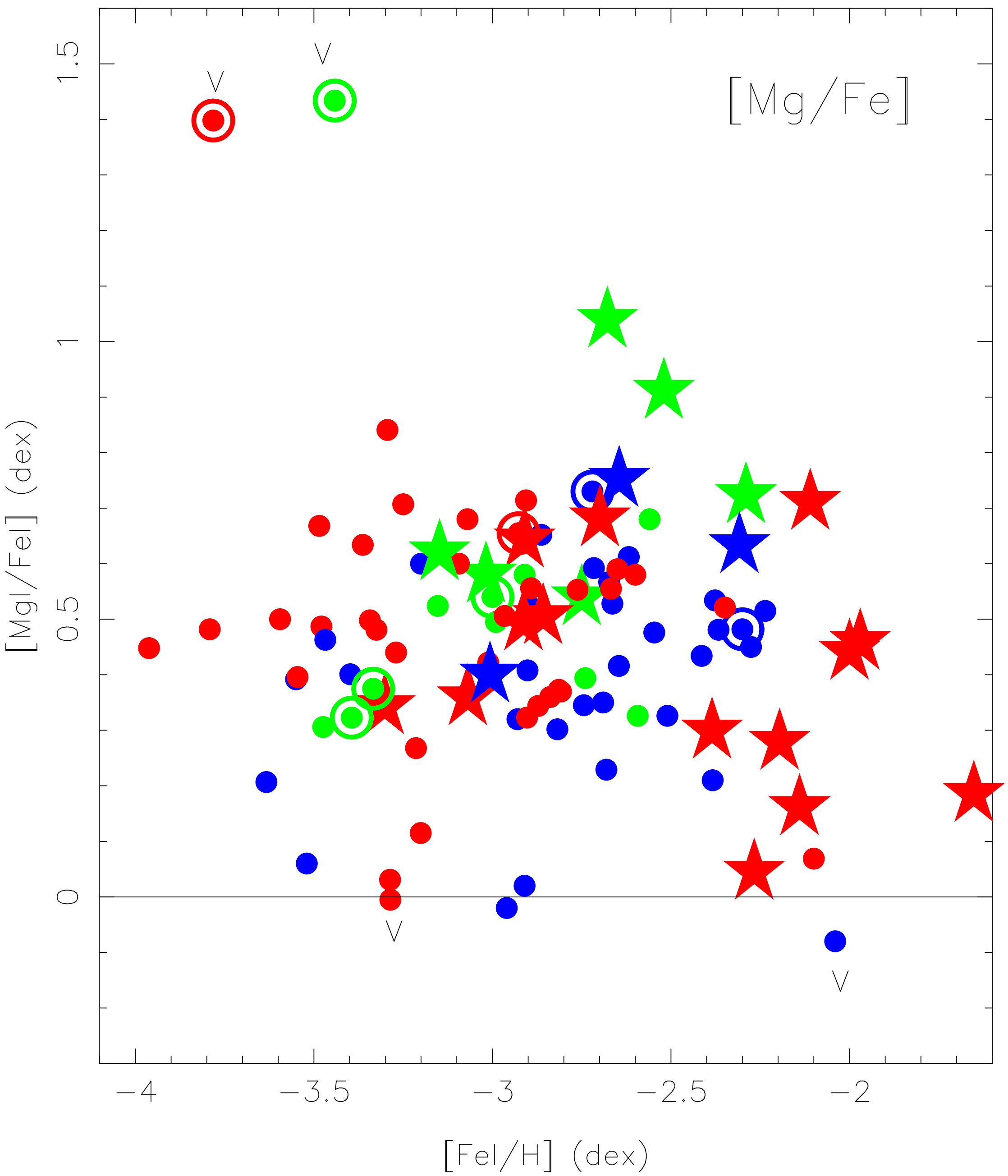

Figure 4.— [Mg/Fe] vs [Fe/H] for the HIRES sample. Colors denote the three ranges of T_{eff} as in Fig. 2. Stars denote carbon stars; circled points are highly C-rich, but do not show C_2 bands. "V" denotes abundance ratios that have been carefully checked and appear correct: those that may not be valid when carefully checked are marked with "?".

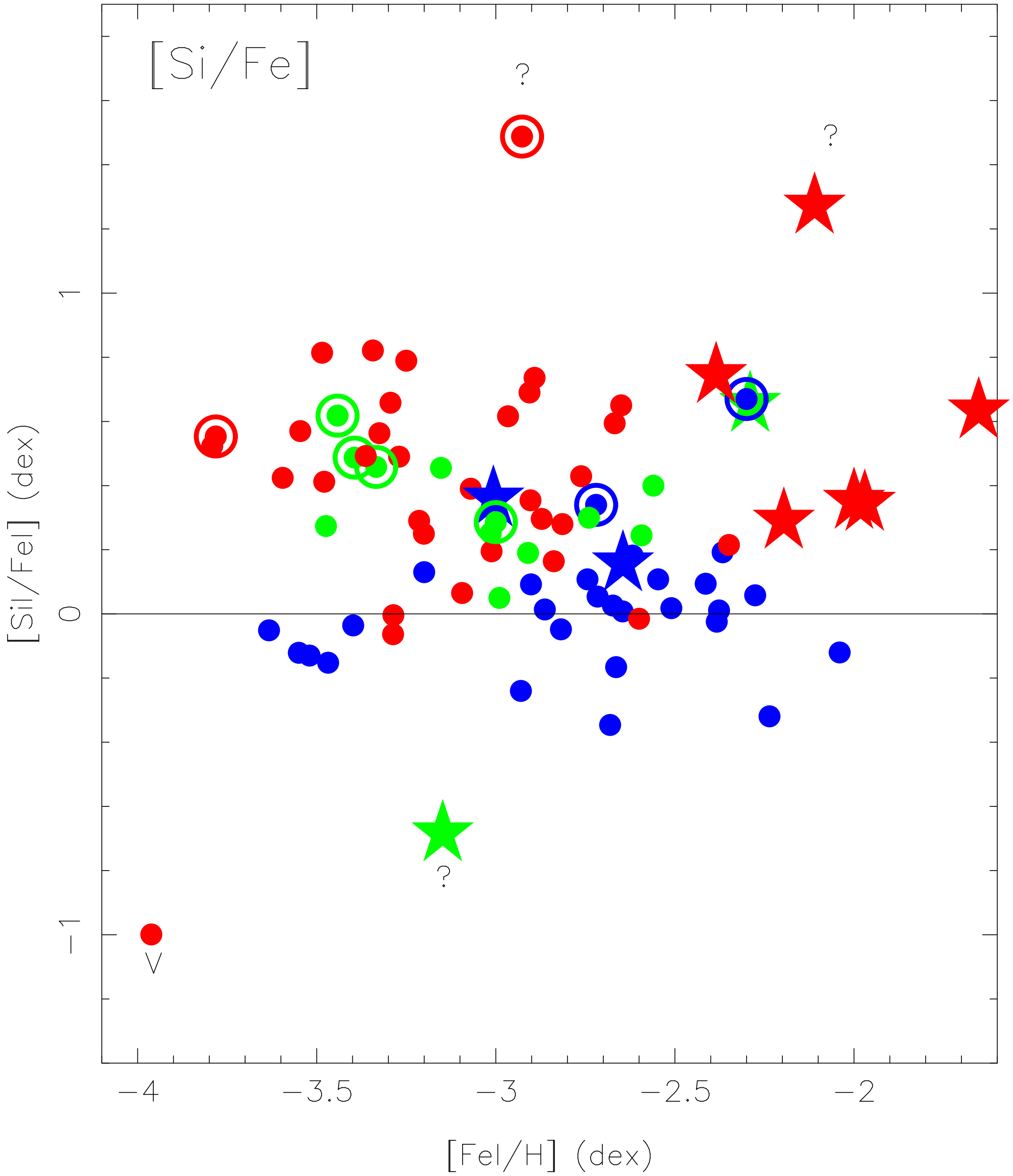

Figure 5.— The same as Fig. 4 for [Si/Fe]. The symbols are the same. In this case there is a trend of [Si/Fe] at a fixed [Fe/H] with T_{eff}, suggesting a problem in the analysis.

observed is currently underway. Because of our large homogeneous sample of EMP stars with homogeneous detailed abundance analyses we can find even modest outliers. Ignoring enhanced carbon and/or nitrogen, thus far approximately 15 of the 103 stars are peculiar in some way, but the vast majority are "normal" EMP stars which to within the uncertainties obey well defined trends of [X/Fe] vs [Fe/H] for all species observed.

6. Acknowledgements

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