Session III

Extremely Metal-Poor Stars

Monique Spite during her vivid review on extremely metal-poor stars.

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The Metallicity Distribution Function of the Halo of the Milky Way

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Abstract. We report on the distribution of metallicities, [Fe/H], for very metal-poor stars in the halo of the Galaxy. Although the primary information on the nature of the Metallicity Distribution Function (MDF) is obtained from the two major recent surveys for metal-poor stars, the HK survey of Beers and collaborators, and the Hamburg/ESO Survey of Christlieb and collaborators, we also discuss the MDF derived from the publicly available database of stellar spectra and photometry contained in the third data release of the Sloan Digital Sky Survey (SDSS DR-3). Even though the SDSS was not originally planned as a stellar survey, significant numbers of stars have been observed to date – DR-3 contains spectroscopy for over 70,000 stars, at least half of which are suitable for abundance determinations. There are as many very metal-poor ([Fe/H] < -2.0) stars in DR-3 as have been obtained from all previous survey efforts combined. We also discuss prospects for significant expansion of the list of metal-poor stars to be obtained from the recently funded extension of the SDSS, which includes the project SEGUE: Sloan Extension for Galactic Understanding and Evolution.

Keywords. Astronomical data bases: surveys, stars: abundances, stars: Population II, Galaxy: halo

1. Introduction

The distribution of stellar metallicities in the halo of the Galaxy has been intensively studied for many years, especially since it was recognized in the early 1980's that the halo contains field stars with [Fe/H] lower than that of the lowest metallicity globular clusters. The central difficulty of this enterprise is that low-metallicity stars, especially those with [Fe/H]$\,<-2.0$, are extremely rare in the solar neighborhood, comprising no more than $\sim$0.1% of the stars within a few kpc of the Sun. As a direct consequence, knowledge of the form of the Metallicity Distribution Function (MDF), in particular the shape of its low-metallicity tail, has long been limited by small-number statistics.

The difficulty of isolating a “fair” sample of halo stars based on in-situ studies has left astronomers with little choice but to identify likely halo stars based on their motions.

Spectroscopic follow-up of stars selected from proper-motion surveys has allowed the determination of at least a reasonably accurate picture of the global shape of the halo MDF. The studies of Ryan & Norris (1991) and Carney *et al.* (1996) were able to demonstrate that the MDF of halo stars peaks at a metallicity [Fe/H] $= -1.6$, including tails extending up to the solar metallicity on the high side, and to metallicities at least down to [Fe/H] $= -3.0$, or slightly below, on the low side. Both suggested MDFs are consistent with one another, and with the predictions of the so-called "Simple Model" (e.g. Hartwick 1976). The actual shape of the MDF at the lowest metallicities, and its precise cutoff, is limited by the small numbers of stars in these samples. Even taken together, these surveys only include some 250 very metal-poor stars with [Fe/H] $\leqslant -2.0$, and but a handful with [Fe/H] $\leqslant -3.0$.

Recent kinematically unbiased surveys for metal-poor stars have revealed the presence of at least two hyper metal-poor (HMP) stars, with [Fe/H] < -5.0 (Christlieb *et al.* 2002; Frebel *et al.* 2005). The presence of these two stars raise several additional questions concerning the nature of the MDF, including:

- What is the shape of the low-metallicity tail of the halo MDF, and in particular, is it continuous?
- Does there exist a sharp cutoff of the halo MDF, and if so, at what metallicity does it occur?
- Is the halo MDF constant throughout the halo, or does it vary with distance?

The answers to these, and other questions about the nature of the halo MDF, can only be obtained from much larger samples of very metal-poor stars, ideally chosen in-situ in the halo of the Galaxy, well outside the solar neighborhood. Fortunately, due to the collective efforts of many of the astronomers present at this conference, we have arrived at the point where the results of the large-scale objective prism surveys (the HK survey of Beers and colleagues; Beers *et al.* 1985, 1992, Beers 1999, and the HES of Christlieb and colleagues; Christlieb 2003) can now begin to shed light on at least some of these questions. Below we summarize the present picture of the low-metallicity tail of the halo MDF as obtained by these two efforts. We then consider the information provided by the large numbers of very metal-poor stars contained in the most-recent public data release of the Sloan Digital Sky Survey (York *et al.* 2000), and its planned extension, SDSS-II, which includes the SEGUE program.

2. The HK Survey and the Hamburg/ESO Survey

The HK survey (formerly known as the Preston-Shectman survey) was initiated over 25 years ago. During the course of the survey, a total of some 300 objective-prism plates covering 2800 deg^2 in the northern hemisphere and 4100 deg^2 in the southern hemisphere were obtained. The selection of candidate metal-poor stars was accomplished based on visual inspection with a binocular 10 X microscope. Since the visual inspection was performed without the benefit of the stellar colors (hence temperatures) it was expected that the HK-survey candidates would carry a rather severe temperature-related bias. The potential bias becomes less of a problem at the lowest metallicities, below [Fe/H] $= -2.0$, where the CaII K lines of even quite cool stars are difficult to detect at the resolution of the survey.

Medium-resolution (1-2 Å) spectroscopic and broadband photometric follow-up of candidate metal-poor stars from the HK survey has been underway for two decades. For the

Table 1. Observational Follow-Up of Surveys

Survey	Spectra	Unique	UBV	JHK
HK	14488	11212	4944	10438
HES	7465	6212	812	5078
SDSS-DR3	71396	~70000	...	...

majority of this period, the spectroscopic follow-up was conducted with single-slit spectroscopy using 1.5m-2.5m telescopes at a variety of observatories. Most recently, the use of the 6dF multiplexed spectrograph on the UK Schmidt telescope made it possible to obtain more than one hundred such spectra simultaneously, hence the pace of this effort was sped up considerably. Table 1 lists the total number of spectra of HK survey candidates (including large numbers of field horizontal-branch and other A-type stars in addition to the metal-poor candidates) obtained to date. This table also lists the numbers of HK survey stars with available spectroscopy that have had optical broadband photometry (primarily UBV) measured thus far. Near-IR JHK from the 2MASS Point Source Catalog (Cutri *et al.* 2003) is also available for over 90% of the HK-survey stars with available spectroscopy.

The HES objective-prism survey provides the opportunity to greatly increase the number of very metal-poor stars identified by the HK survey. It reaches about two magnitudes deeper than the HK survey ($B \sim 17.5$ vs. $B \sim 15.5$) and also covers regions of the southern sky not sampled by the HK survey; a total of about 8225 deg^2 of the sky above $|b| = 30^o$ is presently available from the HES. Another 1275 deg^2 covered by the HES is now being scanned and analyzed for candidates. The selection of metal-poor candidates from the HES database of digital objective-prism spectra is performed using quantitative criteria including automatic spectral classification (Christlieb, Wisotzki, & Grasshoff 2002). The strength of the CaII K line is determined using the KP line index (Beers *et al.* 1999), as measured directly from the objective-prism spectra. Due to the broad wavelength range covered by the HES spectra it is also possible to determine $B-V$ directly from the prism spectra, with an accuracy on the order of ~0.1 mag. Stars that have CaII K lines weaker than expected for their estimated $B-V$ colors and an approximate metallicity of $[\mathrm{Fe/H}] < -2.5$ are selected as low-metallicity candidates.

Medium-resolution spectroscopic follow-up of candidate metal-poor stars from the HES has been underway for the past five years, primarily with 2.5m-4m class telescopes. The use of larger telescopes and substantially more efficient spectrographs than were available for much of the HK survey follow-up results in a much faster assembly of this information. The HES has also benefitted from multiplex follow-up with the 6dF instrument. Table 1 summarizes the numbers of HES targets (including stars other than metal-poor candidates) with available medium-resolution spectroscopy obtained to date. Broadband optical photometry (primarily $BVRI$) is only now being obtained for the metal-poor HES candidates (Beers *et al.*, in preparation); about 80% of the stars with available spectroscopy have JHK from 2MASS. All of the SDSS stars discussed below have available $ugriz$ photometry.

3. Stellar Data from the SDSS

Many astronomers may not be aware that the publicly available medium-resolution (2.5 Å) spectroscopy and $ugriz$ photometry from the SDSS includes substantial numbers of stars in the Milky Way. At present, through the DR3 release, these total over 70,000 stars. Analysis pipelines have been developed (and are presently being refined), and value added catalogs that summarize best estimates of atmospheric parameters ($T_{\rm eff}$, log g, [Fe/H]), as well as radial velocities, distance estimates, and proper motions, are now being assembled (Beers *et al.* 2004). By the time the final data from the main SDSS are released (presently anticipated to be June 2006), the number of stars with similar data should be well over 100,000. Most stars contained in the SDSS database were not targeted specifically to be metal-poor halo objects, and indeed they represent a complex assembly of objects selected for calibration and reddening determinations, directed studies of various classes of stars (e.g. horizontal-branch stars, carbon stars, white dwarfs, late-type K and M dwarfs, etc), as well as objects originally targeted as quasars that turned out to be stars.

In spite of its rather inhomogeneous assembly, the SDSS stellar database does provide a useful means for sampling the tail of the halo MDF (though one of course must be open to the issues of selection bias).

4. Metallicity Determinations for HK, HES, and SDSS stars

The abundance calibration of Beers *et al.* (1999) is used to obtain estimates of [Fe/H] for the HK and HES stars. This method relies on the variation of the CaII KP index with $(B-V)_0$ color as a function of [Fe/H]. This approach works well, obtaining abundance errors on the order of $0.2-0.25$ dex over the color range $0.3 \leqslant (B-V)_0 \leqslant 1.2$ and for stars with abundances $-4.0 \leqslant$ [Fe/H] $\leqslant -0.5$. Near the red end of the color range, and near the high-metallicity end as well, saturation of the CaII K lines becomes more of an issue; at these extremes this method tends to underestimate the true metallicity of a given star. At the very lowest metallicities, below [Fe/H]$= -4.0$, the approach could *over*-estimate the true metallicity, as a result of contamination of the CaII K line by interstellar CaII, or by molecular carbon features in the spectra of carbon-enhanced metal-poor stars. In fact, both of these situations arose in the cases of the medium-resolution discovery spectra of the two known HMP stars HE 0107-5240 and HE 1327-2326.

Not all of the HK/HES objects have available $(B-V)_0$ colors at present. Thus, we have developed techniques that can be used to estimate this color, based on a calibration of the strength of the Balmer Hδ line. Previous tests indicate that the colors estimated in this manner should be good to on the order of about 0.03 mags over the range $0.3 \leqslant (B-V)_0 \leqslant 0.7$. For cooler stars the rapidly declining strength of the Hδ line with increasing $(B-V)_0$ renders the technique less useful. We are fortunate that many of the stars in the HK/HES surveys have 2MASS JHK available. This information is particularly useful for the redder stars that lack $B-V$ photometry, as a newly designed calibration based on KP and $(J-K)_0$ has been developed in order to provide estimates of [Fe/H] for such stars.

New methods have been developed for the estimation of metallicities (and other atmospheric parameters) for stars in the SDSS spectroscopic database (Allende Prieto *et al.* 2004, 2005), and are used in combination with the Beers *et al.* (1999) and Wilhelm, Beers, & Gray (1999) approaches in order to obtain estimates of [Fe/H] that are accurate to on the order of 0.20 to 0.25 dex over the temperature range 4,000 K $\leqslant T_{\rm eff} \leqslant$ 10000 K.

Carbon-Enhanced Metal-Poor (CEMP) stars, which are identified with large frequency in all three surveys, present special challenges because their optical colors can be confounded by the presence of molecular carbon features. A new calibration, based on the KP and GP indices and $(J-K)_0$, directly tied to stars with a range of (externally known) [Fe/H] and carbon abundances, has been developed by Rossi *et al.* (2005), and is used to estimate [Fe/H] and [C/Fe] for such stars.

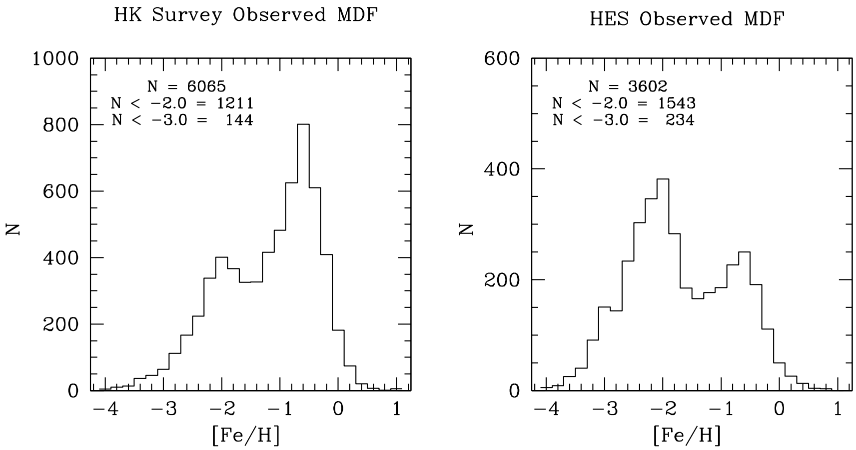

Figure 1. The as-observed Metallicity Distribution Functions for the HK survey (left panel) and the HES (right panel) candidate metal-poor stars. Bins are 0.2 dex in width. The numbers of stars with [Fe/H] < -2.0 and [Fe/H] < -3.0 in these surveys are listed individually. The selection efficiency of VMP stars in the HES is clearly higher than that of the HK survey.

5. The "As Observed" MDF of the Halo

Figure 1 (left panel) shows the distribution of [Fe/H] for some 6000 stars from the HK survey that have measured $(B-V)_0$ or inferred colors that fall in the range where our adopted calibrations can be applied. Note that the distinctly bi-modal character of this distribution is simply the result of the imperfect selection of candidate low-metallicity targets; the large number of stars with [Fe/H > -1.5 are the "mistakes". The 1200 stars with metallicities [Fe/H] $\leqslant -2.0$ are the sought-after objects.

Figure 1 (right panel) shows a similar plot for the HES stars. Although the total number of targets is only about half of the HK survey stars, the far higher efficiency of the HES in the identification of very metal-poor stars has greatly reduced the number of mistakes with [Fe/H] > -1.5. As a result, the total number of HES stars with [Fe/H] $\leqslant -2.0$ exceeds that of the HK survey by some 300 stars. There are almost twice as many [Fe/H] $\leqslant -3.0$ stars found in the HES as have been identified in the HK survey.

The combined samples of stars from the HK and HES includes some 2700 stars with [Fe/H] $\leqslant -2.0$ and almost 400 stars with [Fe/H] < -3.0. Note that we have not yet eliminated the HK-survey stars that were rediscovered by the HES. Hence, these numbers will be reduced somewhat in the final tally.

There are two issues that need to be resolved before we can use the results of these two surveys to place strong constraints on the shape of the low metallicity tail of the halo MDF. Clearly, owing to the manner in which the surveys were constructed (to find the lowest metallicity stars), a bias is introduced as metallicity rises above [Fe/H] $= -2.5$. Our plan to correct for this is to compare the shapes of the MDFs for stars in the range $-2.5 \leqslant$ [Fe/H] $\leqslant -2.0$ with those of the kinematically-based surveys discussed earlier, and derive a "bias correction factor" that can by applied to the numbers of stars in this interval to account for the fraction lost by the selection of candidates. A similar exercise was performed for the HK survey stars by Beers *et al.* (1998), who showed that the HK survey results available at that time appeared to become biased above [Fe/H] $\simeq -2.2$.

The second issue involves performing a careful check on the abundance estimates for the many CEMP stars that are found at low metallicity in both surveys. Experience has

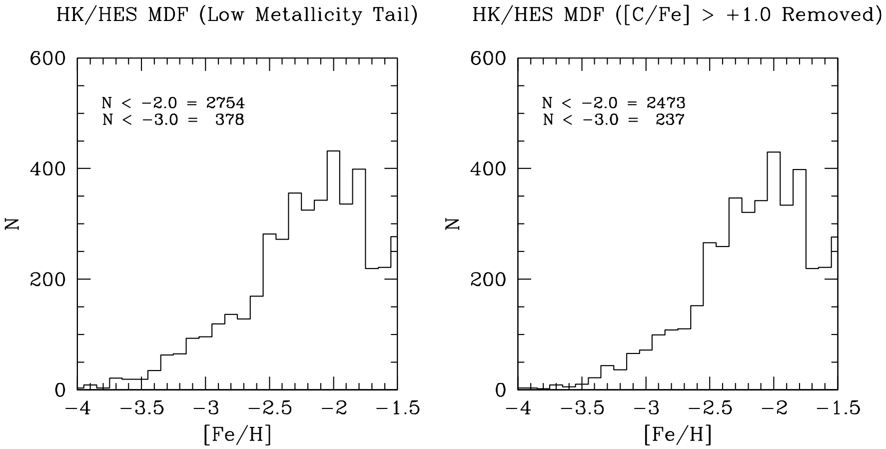

Figure 2. (left panel) The as-observed Metallicity Distribution Functions for the combined HK survey HES candidate metal-poor stars, for stars with [Fe/H] < -2.0. (right panel) The same distribution, but with the CEMP stars with [C/Fe] $> +1.0$ removed. Note that the bins are 0.1 dex in width.

shown that it is possible to underestimate the metallicity of the cooler, or more carbon-enhanced stars, even when making use of the new techniques of Rossi *et al.* (2005). We therefore have to evaluate such stars on a spectrum-by-spectrum basis, and either remove them or correct their abundances.

Figure 2 shows the low-metallicity tail of the combined HK and HES MDFs, which (for now) provides us with our best representation of the shape of this function. Because of worries concerning the derived [Fe/H] for the CEMP stars noted above, we show two versions of the combined MDF. The left panel is the complete set of stars. The right panel is the same distribution, but with the stars with estimated [C/Fe] $> +1.0$ removed. Two features are evident in these diagrams. (1) The low-metallicity cutoff appears at [Fe/H]$= -4.0$, although the small numbers of stars with [Fe/H] < -3.5 still make the actual location of the cutoff somewhat uncertain. The other feature is the possibility of a small "bump" in the MDF at around [Fe/H] $= -2.5$. In order to be certain about the presence of this bump, one would ideally like to obtain higher quality medium-resolution spectra (and photometry where needed) of the HK/HES stars with metallicities [Fe/H] < -2.0, using a single telescope/detector combination and consistent S/N targets. Now that we know which stars to point at, and with the use of high-efficiency modern spectrographs on 4m-class telescopes, this should indeed be feasible on a reasonably short time scale. Note as well that, due to the increase in the numbers of low-metallicity stars discovered over the course of the HK/HES surveys that have now been studied at high spectroscopic resolution, we have at our disposal a much larger set of objects with which one could obtain an improved calibration of the metallicity-estimation procedures employed in the original survey effort.

6. A Look Ahead – the Halo MDF from SDSS

By the time of publication of this volume, we will be almost one-third of the way through the next great expansion of the observational database of the lowest-metallicity stars in the Galaxy. The survey effort, known as SEGUE, will employ the same telescope

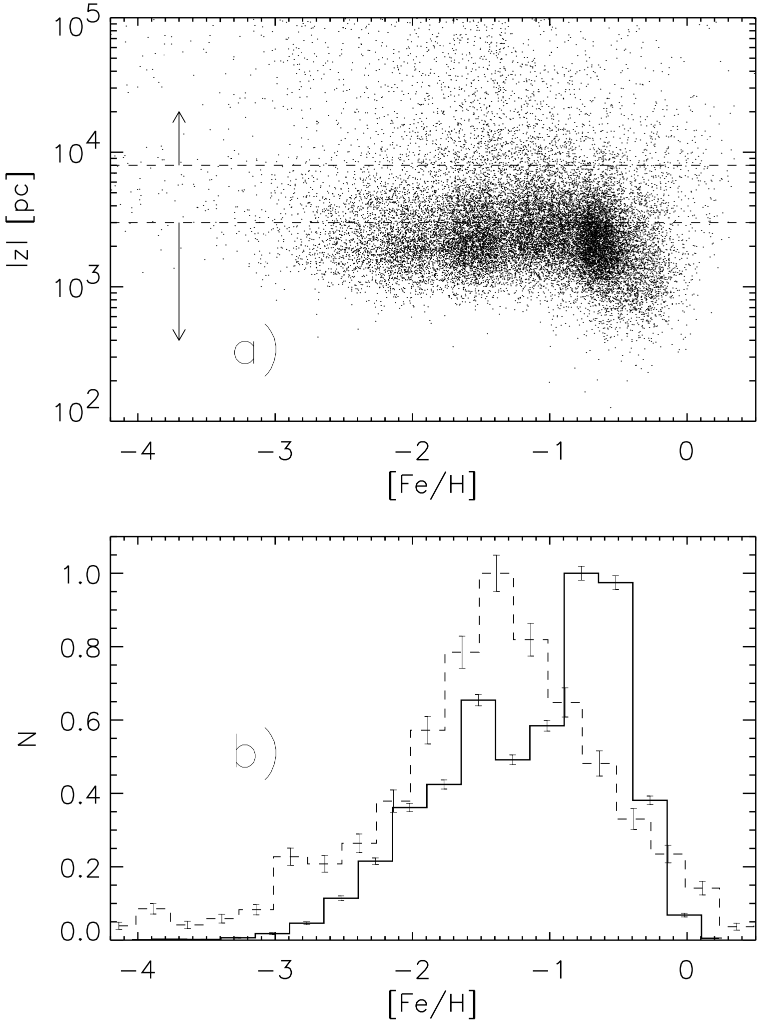

Figure 3. (a) MDF of SDSS-DR3 stars in the temperature range 5000 K $\leqslant$ $T_{\rm eff}$ $\leqslant$ 7000 K, as a function of distance from the galactic plane. The dashed lines indicate the divisions in distance applied. (b) MDFs of the stars from this sample within 3 kpc from the plane (solid line) and those farther than 8 kpc from the plan. Bins are 0.2 dex in width.

(the ARC 2.5m telescope on Apache Point, New Mexico), imager, spectrographs, and reduction pipeline as the original SDSS, to dramatically increase our knowledge of the stellar populations of the Milky Way. SEGUE, which begins in July 2005 and will end in July 2008, will obtain some 3500 additional square degrees of calibrated *ugriz* photometry at lower galactic latitude than the original SDSS, so as to better constrain the important transition from the disk population(s) to the halo. Most importantly, SEGUE will obtain medium-resolution spectroscopy for 250,000 stars in the magnitude range $13.5 \leqslant g \leqslant 20.5$, in 200 directions covering the sky available from Apache Point. SEGUE targets will be chosen to explore the Galaxy at distances from 0.5 to 100 kpc from the Sun.

One of the primary SEGUE categories is obtained from photometric pre-selection of likely very metal-poor (VMP) stars with $[\mathrm{Fe/H}] < -2.0$. Tests carried out to date indicate that it is reasonable to expect that SEGUE will yield a sample of at least 25,000 VMP stars, a factor of ten times the present number of such stars known from the summed

HK and HES efforts. Although the majority of these VMP stars will be too faint for easy high-resolution spectroscopic follow-up on 8m-10m class telescopes, there will be at least several thousand that *are* sufficiently bright. Plans are presently being made to undertake HERES-like "snapshot" high-resolution spectroscopy (see Christlieb *et al.* 2004, Barklem *et al.* 2005, and contributions from these authors in this volume) with the Hobby-Eberly telescope, followed by higher S/N studies of the most interesting objects that are revealed.

We can obtain a preview of the halo MDF that will be revealed by SEGUE from inspection of the distribution of metallicities for stars that have been observed (in a highly heterogeneous manner) during the course of the original SDSS. Allende Prieto *et al.* (2005) have produced an "as observed" MDF for the subset of SDSS stars in DR-3 with derived temperatures between 5000 K and 7000 K, where the abundance determination techniques developed for SEGUE are expected to work best. Figure 3(a) shows the distribution of height above the galactic plane as a function of estimated [Fe/H] for over 20,000 stars that fall in this temperature interval. Figure 3(b) shows the MDFs for two sub-samples of these stars, those with a distance from the galactic plane $|z| < 3$ kpc (14714 stars; solid histogram) and those with $|z| > 8$ kpc (2655 stars; dashed histogram). The nearby cut in z distance comprises a mix of halo and thick-disk stars, while the more distant sample should be essentially all halo stars.

It is remarkable how well the as-observed MDF of the SDSS DR-3 halo sample mimics our expectation of what a "fair" sample of the halo MDF should look like, though we re-emphasize that, owing to the peculiar selection of targets, this sample should not be construed as such. There may be a few stars in DR-3 with metallicities below [Fe/H] $= -4.0$, but these objects will have to be confirmed with high-resolution spectroscopy before a firm claim can be made as to their existence.

Note that, as part of the SEGUE target selection, there will be a very large ($N \sim 100,000$) number of G-type dwarfs covering the distance range from a few kpc out to 10-12 kpc from the Sun, and which are chosen in a "metallicity blind" fashion. This sample will provide the opportunity not only to construct an in-situ sample of stars from which a fair MDF of the halo can be obtained, but also will enable determination of the fraction of VMP stars in the solar neighborhood contributed by the Metal-Weak Thick-Disk population (see, e.g. Chiba & Beers 2000; Beers *et al.* 2002).

7. Final Thoughts

Clearly, the study of the MDF of the halo has entered a new era. The prodigious samples of halo stars that now exist from the HK survey, the HES, the SDSS, and those that will be identified in the soon to-be-executed SEGUE survey are finally producing sufficiently large numbers of objects to address the questions raised above, as well as to (no doubt) raise many new ones. Now is the time to develop plans for the high-resolution spectroscopic follow-up of the many thousands of SEGUE stars that will soon become available.

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Anna Frebel, presenting the new record for the most iron-poor star, chaired by John Norris.

Tim Beers, reviewing the current status of extremely metal-poor stars searches, chaired by Bruce Carney.