The First Stars, Supernovae, Nucleosynthesis, and Galactic Evolution

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Tremendous recent progress in the study of chemical abundances in metal-poor stars leaves us poised to address the following fundamental questions in the upcoming decade:

- **What were the properties of the first stars?** Identifying the chemical abundance signatures of the first stars in the composition of extant extremely metal-poor (EMP) stars will provide critical clues to the masses, IMF and UV fluxes of the first stars, the rate of black hole formation in the early Universe, and the signature of pair instability supernovae.
- **Can we measure the nucleosynthetic yields of metal-poor Type II supernovae (SNe) from the composition of EMP stars?** How much can the composition of EMP stars constrain SN explosion and nucleosynthesis theory?
- **What is the astrophysical site and neutron source of the r-process?** What is the nature of the recently uncovered separate source for light neutron-capture elements, and the apparent variation in Th and U.
- **Can the remnants of ancient structures in the Galactic thick disk, bulge and halo be identified by chemical means (chemical tagging), in addition to kinematic properties?** How do these structures inform us of the merger history of the Galaxy and the hierarchical growth of structure?
- **How did chemical evolution proceed in the early Universe?** Do low-luminosity dwarf galaxies preserve a fossil record of the protogalaxies that built up the Milky Way, and are such systems the source of the EMP stars in the Milky Way halo?

Introduction

As extragalactic observations push to ever higher redshifts, and local studies of the Milky Way reveal new clues to the early history of the Galaxy, interest has intensified in the properties of the first stars. These stars had an outsized influence on everything that happened in the universe afterwards: cosmic reionization (e.g., Bromm & Larson 2004, and references therein), the formation of the first black holes (e.g., Schneider et al. 2002), powerful feedback on early protogalaxies, and the chemical enrichment of subsequent generations of stars. While theoretical modeling has already provided important insights into the nature of Population III stars, one of the major goals of the next decade will be to obtain observational data that can directly constrain these models and provide real understanding of how the first stars reshaped the universe around them.

An extremely promising avenue for investigating the first stars is observing the chemical elements they produced in the most metal-poor stars in the nearby universe. Observations are already beginning to betray the unique signature of Population III supernova explosions, and future abundance measurements in larger samples of low-metallicity stars will produce key clues to the long-sought masses and nucleosynthetic yields of the first stars.

Recent Advances

Over the last 20 years, the search for and study of the most metal-poor stars in the Galactic halo has provided fascinating results, including:

(1) *An increasing frequency of stars with unusual chemical compositions towars lower metallicities* (to below [Fe/H]=−5) signals the breakdown of complete mixing of the ISM at early times. The huge enhancements of rapid neutron capture (r-process) elements in some of these stars indicates enrichment dominated by individual supernovae for the r-process elements.

(2) *The first direct age measurements for the metal-poor halo*, derived from abundances of the cosmo-chronometer elements Th and U in some extremely metal-poor (EMP; [Fe/H] $<$ -3) stars with large enhancements of r-process elements; however, only 3 EMP stars have detected U.

(3) *Evidence for an extra source of heavy elements near Sr that is unrelated to the classical r-process.* What this source is and what stars are responsible for it are unknown.

In this white paper, we investigate the impact that high-resolution spectroscopy with a giant ground-based telescope could have on further explorations of stars in the extremely metal-poor regime and the quest to understand the first stars.

Masses and Nucleosynthesis of the First Stars

The first stars are predicted to have formed in dark matter halos of $\sim 10^6$ $M_\odot$ at $z \sim 10-50$ (Tegmark et al. 1997). These Population III stars provided the FUV flux for reionizing the Universe, seeded the Universe with the first metals and collapsed into the first black holes.

McKee & Tan (2008) predicted typical masses for the first Population III (pop III.1) stars near $\sim$140 $M_\odot$, with a possible mass range of $\sim$60 to 320 $M_\odot$. According to Heger & Woosley (2002), zero metallicity stars with masses $140 \leq M \leq 260$ are expected to explode as Pair Instability SNe (PISN). Outside this mass range all stars end as black holes and produce no nucleosynthesis products, although mass ejection below the range occurs. However, the distinct chemical signature of PISN has not yet been seen in any known EMP stars; this is a major problem for the zero-metallicity SN nucleosynthesis predictions. Perhaps PISN were very rare, or it could be that PISN and known EMP stars were not made in the same regions (e.g., if PISN only occurred in the cores of massive halos).

Predictions from numerical simulations indicate that the oldest stars in the Milky Way now reside in the Galactic bulge (e.g., Brook et al. 2007). Therefore, it is critically important to survey the bulge for EMP stars that might contain the chemical signatures of PISN. To date, no such surveys have been undertaken.

Yoshida et al. (2007) showed that zero-metallicity stars born in an already ionized halo (pop III.2) should have masses of $\sim$40 $M_\odot$. Thus, these stars are not massive enough to show the chemical signature of PISN. However, Yoshida et al. note that the masses will not be significantly affected by contamination with small amounts of metals, and they speculate that these pop III.2 stars may be the source of the abundance patterns in the known EMP stars. It is interesting that stars in the Hercules dwarf galaxy (Koch et al. 2008, henceforth K08) possess [Mg/Ca] ratios consistent with the 35 $M_\odot$ Type II SN nucleosynthesis predictions ($Z=10^{-4}$) of Woosley & Weaver (1995, henceforth WW95).

Calculations by McKee & Tan (2008) indicate that rotation and entropy affect the final stellar mass, so a range of masses, or an IMF, is expected for pop III.1, and presumably applies to pop III.2 stars. Both pop III.1 and III.2 stars will show a top-heavy IMF compared to normal stars at higher metallicity.

Recently, EMP stars have been found in the ultra-faint dwarf galaxies (e.g., Kirby et al. 2008), and detailed abundance follow-up studies pursued (e.g., Frebel et al. 2009). With their incredibly low stellar masses ($M \leq 10^4$ $M_\odot$) and very low metallicitites, these galaxies were likely enriched by only a few SNe, or perhaps even single SN events. A study of EMP stars in many ultra-faint dwarf galaxies would therefore provide useful constraints on the SN IMF and nucleosynthesis yields. We strongly encourage efforts to find many more ultra-faint dwarf galaxies and measure their detailed chemical abundance patterns.

Fortunately, an explosion in the discovery of these systems is expected with LSST. However, a comprehensive chemical composition survey can only be carried out effectively with 25–30 m class telescopes equipped with high-resolution spectrographs, such as GMT (see *Dwarf Galaxies* section).

Towards the Primordial Composition

Two lines of chemical abundance evidence suggest that we are now approaching the fossil record of the first stars.

First, the omnipresent relation between [Co/Cr] and [Fe/H] in EMP stars shows no appreciable scatter, decreasing from [Co/Cr] = +1 at [Fe/H]=−4 to [Co/Cr] = 0 at [Fe/H]$\sim$ −2.5. This trend suggests that the most primitive material was characterized by high [Co/Cr] values, which is presumably a signature of Population III. However, the lack of scatter is difficult to explain in an inhomogeneous environment. Nomoto et al. (2005) invoked "hypernovae", where the energy of explosion is linked to Co/Cr yield ratio and the mixing of ejecta, to explain these observations.

Alternatively, it is possible that non-LTE effects could be responsible for a spurious Co/Cr trend in EMP stars. This possibility needs to be checked with non-LTE calculations, but the fundamental atomic data are not available: critical collisional cross sections and photoionization rates have not been measured or computed for these elements, so only approximate formulae are used. Given the potential relevance to hypernovae and Population III composition non-LTE abundance work on EMP stars is important.

The second line of observational evidence for primordial composition concerns recently discovered metal-poor stars with no detectable heavy elements (with extremely low abundance limits). Two stars observed in the Her dwarf galaxy (K08) have [Fe/H]$\sim$−2 and enhanced [Co/Cr], but [Sr/Fe] and [Ba/Fe] ratios deficient by at least 2 dex; this composition resembles normal stars at much lower metallicities ([Fe/H]=−3.5). This abundance pattern is similar to an unusual star in the Draco dwarf galaxy (Fulbright et al. 2004). It is possible that these stars possess the composition of primordial SNe, but at unusually high metallicity.

Spectra of larger samples of metal-poor stars in dwarf galaxies (and at bluer wavelengths to measure the abundances of heavier elements) will determine whether these unusual signatures are truly revealing the primordial abundance pattern produced by the first stars.

Supernova Nucleosynthesis Yields

A significant number of EMP stars with peculiar chemical compositions indicate an inhomogeneous Galaxy, presumably due to stochastic sampling of SN yields. HE 0107-5240, HE 1327-2326, CS 22892-052, CS 22949-037, CS 22169-035, BS 16934-002, CS 29498-043, HE 1423-0241 and CS 22952-015 are examples of EMP stars with confirmed peculiar abundances (e.g., Frebel et al. 2005; Christleib et al. 2002; Cayrel et al. 2004; Cohen et al. 2007; McWilliam et al. 1995), including large excesses and large deficiencies of various elements, which signifies incomplete sampling of the SN yields.

To disentangle the nucleosynthesis yields from the observed dispersion in EMP composition requires iteration between predicted element yields and a stochastic chemical evolution models. Well understood elements, such as C, O, and Mg, made in the hydrostatic phase provide important constraints. As a crude example, consider equal mixing of SN ejecta. Elements where a small fraction of SNe produce large enhancements persist after many mixing episodes: a 2 dex enhancement is detectable at 0.3 dex after 100 mixing events. On the other hand, element deficiencies are erased very quickly: the 1 dex Si deficiency in HE 1423-0241 would be undetected after just 1 to 3 mixing events. The observed element deficiencies in some EMP stars therefore argue that the composition of [Fe/H] ≤ -3 stars contains stars dominated by very few SN events.

Supernova nucleosynthesis theory, while making impressive progress (e.g., Heger & Woosley 2008), is still in a crude state: the physics of the explosion is unknown, the nucleosynthesis models are one dimensional, mixing, the mass cut, and explosion energy are input, and rotation, rotational mixing and winds are not included. Thus, the comparison of theoretical SN yields with the detailed chemical abundances of EMP stars can provide a unique way to constrain supernova nucleosynthesis, and ultimately the supernova explosion models. Informed by these observed abundance patterns, the supernova models will provide masses, IMF, and UV fluxes of the first stars.

The r-process has long thought to be *the* mechanism for synthesis of elements beyond the iron-peak in metal-poor environments. Except for the notion that it occurs in Type II SNe the details of the r-process mechanism and its astrophysical site remains unknown. Subsequently, there are no theoretical predictions for r-process yields. EMP studies show that for stable elements beyond Ba the r-process pattern appears to be a constant, as best demonstrated by Sneden et al. (1996). The range of $\sim$300-fold in the r/Fe ratio and the super r-process rich stars in EMP studies suggests that it occurs in a small fraction of SNe only. The anomalous Sr-rich EMP stars indicates a production mechanism for light neutron-capture elements, in addition to the classical r-process. Nothing is known about this newly identified source of nucleosynthesis. Some evidence suggests that the unstable r-process elements Th and U do not always follow the normal trend. These findings raise the question whether thare are 1, 2 or 3 r-processes, or a continuum.

The statistics of these heavy element variabilities, and their correlations with better understood elements will constrain the SN progenitor masses and mechanism. However, chemical abundances of 1–4 hundred EMP stars below [Fe/H]≤ -3 will be required to properly sample the range of SN masses; however, only a few tens are known, and only a handful below [Fe/H]$=-3.5$. It is remarkable that so little is known about the metal-poor synthesis of the elements above Z=30 (2/3 of all elements!).

The Importance of Dwarf Galaxies

One critical area in which major advances are expected during the coming decade is the chemical abundances in nearby dwarf galaxies. These systems offer our best look at how star formation and chemical evolution proceeded in environments different from the Milky Way, with lower metallicities and shallower potential wells. Dwarf galaxies also represent the closest existing analogs to (descendants of) the protogalaxies that formed at high redshift, merged together to form today's massive galaxies, and were responsible for cosmic reionization.

In the past ten years, we have built up a basic understanding of the chemical properties of the Milky Way's population of satellite galaxies (e.g., Shetrone et al. 1998, 2001, 2003; Venn et al. 2004; Geisler et al. 2005). Two of the puzzles that emerged from this work are that the abundance patterns of dwarf spheroidal (dSph) stars (most notably the [α/Fe] ratios) differ significantly from those seen in the stellar halo of the Milky Way (Venn et al. 2004) and that the dSphs seemed to lack the EMP stars (Helmi et al. 2006) that are known to be present in the Milky Way (MW) halo (e.g., Beers & Christlieb 2005). The first problem can be explained by appealing to the different evolutionary histories of the galaxies that merged with the MW already and those that have survived to the present day as bound systems (Robertson et al. 2005), but the second has been more stubborn. The most metal-poor stars in the Galaxy must have formed somewhere, and if not in low-metallicity dwarf galaxies, then where?

An important clue to the answer of this question was provided by Kirby et al. (2008), who demonstrated using medium-resolution spectra that the newly discovered ultra-faint dwarf galaxies (e.g., Willman et al. 2005; Zucker et al. 2006; Belokurov et al. 2007; Simon & Geha 2007) do indeed host EMP stars. In fact, the recent determination of the bias-corrected MW halo metallicity distribution function by Schörck et al. (2008) shows that the ultra-faint dwarfs *contain a higher fraction of EMP stars* than the halo. Strikingly, these galaxies also have [α/Fe] ratios that agree very well with those seen in metal-poor halo stars (Frebel et al. 2009), suggesting that the ultra-faint dwarfs may be the origin of the metal-poor component of the Milky Way halo.

These results suggest that observing stars in nearby dwarf galaxies may be a far more efficient way of finding EMP stars than traditional searches of the halo. Less than 2 % of halo stars have [Fe/H] < -3 (Schörck et al. 2008), but two out of the six brightest known member stars in the faintest dwarfs (selected independently of metallicity) turned out to have metallicities below -3. These stars also show hints of strange abundance patterns, containing remarkably small amounts of heavy elements such as barium and strontium (Frebel et al. 2009; K08).

Another long-awaited goal of stellar archaeological studies is the possibility of identifying the remnants of ancient structures in the MW's thick disk and halo through *chemical tagging*: searching for groups of stars with a unique chemical abundance pattern that must have been produced in a single progenitor (Freeman & Bland-Hawthorn 2002). The ongoing and upcoming RAVE and GAIA missions will provide the first data with which such fingerprinting could be done, but their results will be of limited utility without a proper comparison set of stars in dwarf galaxies. Currently, the only unique chemical signature detected in any dwarf galaxy are the unusual aluminum, sodium, manganese, copper, and s-process abundances seen in the Sagittarius (Sgr) dSph (e.g., McWilliam et al. 2003), so much larger samples of stars in each galaxy and observations of more heavy elements where atypical abundance patterns are more likely are needed to make chemical tagging feasible.

Unfortunately, stars in dwarf galaxies are only barely accessible to observations with current facilities at the high spectral resolution needed for detailed study of chemical abundances. For a galaxy at a distance of 100 kpc ($m - M = 20$ mag), even metal-poor stars at the tip of the RGB have V magnitudes around 17, requiring exposures of $\sim 1 - -3$ hours on an $8 - 10$ m telescope at $R \approx 30000$. Fainter stars rapidly become inaccessible (necessary integration times of a night or more). As a result, after a decade of work, published abundances are available for a total of just 49 stars in the 18 MW dSphs other than Sgr (Shetrone et al. 1998, 2001, 2003; Geisler et al. 2005; K08).[1] The vast majority of these (37 out of 49) have relatively high metallicities ([Fe/H] > -2), and none of them lie in the extremely metal-poor regime, so these stars are probably not representative of the earliest generations of star formation in dwarf galaxies. A much larger telescope, preferably with a multi-object echelle spectrograph, is urgently needed to make further progress on understanding the formation and evolution of dwarf galaxies and their relationship to the build-up of the Milky Way's stellar halo.

Observational Requirements

Progress in the areas outlined above requires detailed chemical abundance studies of EMP stars throughout the Galaxy and in nearby dwarf galaxies using efficient high resolution spectrographs on large telescopes. For the dwarf galaxies, and possibly the bulge, multi-object spectrographs would be especially useful.

While progress can be made with current instrumentation many situations require the light gathering power of $20 - 30$ m class telescopes: obtaining sufficiently large samples of EMP stars requires both wider sky coverage and deeper surveys, because distant EMP stars are faint; ultra-faint dwarf galaxies contain very few bright red giant stars (e.g., the brightest Her dwarf galaxy stars are V$\sim$19); most lines in EMP stars are at blue wavelengths, where the flux is limited, especially for the reddened EMP stars in the Galactic bulge.

To obtain the spectra of the EMP stars needed to answer the questions posed in this paper the planned high resolution optical spectrograph on GMT is ideally suited. Since TMT has decided against a first light high resolution spectrograph **GMT will be the only US facility capable of addressing these questions**.

Recommendations

In order to address the science questions described above, we suggest the following key research programs for the next decade:

- Surveys to identify hundreds of stars with [Fe/H]≤ -3.5 in the Galactic halo, bulge and nearby dwarf galaxies, followed by detailed high resolution chemical abundance studies. Efficient, high resolution spectrographs on Magellan, Keck, and GMT will be required.

- Deeper and wider-field searches for ultra-faint dwarf galaxies with Pan-STARRS, LSST, and other imaging surveys, followed by detailed chemical abundance analysis of their stars.

[1] This compilation excludes 51 stars that have been observed in Sgr, all of which have [Fe/H] > -1.6, as well as studies of stars in the Sgr stream and Sgr and Fornax globular clusters.

- Large scale chemical, kinematic and photometric studies of stars throughout the Galaxy (e.g., LSST, RAVE, GAIA, and APOGEE).
- Advances in supernova theory, and collision and photo rates for non-LTE calculations.

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