The First Stars and the Origin of the Elements

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Introduction

The cosmic Dark Ages ended with the formation of the first stars. These first stars, also known as Population III (Pop III), were the first baryonic structures to collapse, and they formed out of metal-free gas at $z \sim 40$ in $\sim 10^{5-6}\ M_{\odot}$ dark matter halos. These stars are predicted to have been unusually massive (characteristic masses ~10-100 $M_{\odot}$). The first stars created the first metals, enriched the interstellar medium (ISM) and intergalactic medium (IGM), emitted the first ionizing photons, seeded the first black holes, and set the fundamental mass scale for the first galaxies in the Universe.

Cosmological models predict that Pop III stars must have existed, but no direct evidence for such stars has ever been found. Decades of searching have identified Milky Way halo stars with total metallicity as low as $10^{-5} Z_{\odot}$ (Caffau et al. 2011) or stars with [Fe/H] < -7 (Keller et al. 2014).[1] Fundamental questions that remain unanswered include:

- What was the mass distribution of the first stars?
- By what mechanisms did they explode as supernovae?
- Which metals did they produce and eject, and in what quantities?
- What role did environment play in shaping the first stars and earliest metal enrichment?

Direct high-redshift observations with the James Webb Space Telescope and 21 cm cosmology may help answer some of these questions, but stellar archaeology is a key probe of detecting signatures associated with the first stars.

Low-mass stars ($M_{\star} < 0.8\ M_{\odot}$) survive for longer than the age of the Universe. Their atmospheres retain the chemical composition of the ISM at the time and place of their birth. Studying chemical abundances in the oldest, most metal-poor stars thus provides a unique window to probe the early Universe and infer the properties and details of the first stars and first supernovae.

Stars with metallicities [Fe/H] $\lesssim$ -4 are generally considered to be second-generation stars whose metals originate in a single Pop III progenitor. These stars are sometimes referred to as ultra metal-poor (UMP) stars. UMP stars are indistinguishable from metal-free stars in photometric surveys and medium-resolution optical/infrared spectroscopy. The occurrence frequencies of UMP stars probe the metal-poor regime of the metallicity distribution function (MDF). They retain chemical signatures that can be compared with supernova model predictions to reveal the nature, end states, and mass function of the first stars to eject metals.

We now pose some important questions related to the first stars and suggest paths to answer them in the next decade.

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[1] Metallicity can be expressed as Z, the total mass fraction of elements heavier than H and He, or [Fe/H], which denotes the logarithm of the ratio of the number densities of iron and hydrogen relative to the Sun. For example, [Fe/H] = -4 indicates that the number density of iron in a star is 1/10,000th that found in the Sun.

Are there metal-free Pop III stars that survive to the present day?

No metal-free stars are known at present. It remains unknown whether metal-free gas clouds could cool and fragment to form low-mass, long-lived stars that would still exist today in the Milky Way. Detecting even one metal-free star would demonstrate that low-mass star formation was possible in environments with no metals (Bromm & Larsen 2004; Stacy & Bromm 2014). A convincing detection of a surviving Pop III star would have [*Z*/H] < -6 or so, requiring high-resolution spectroscopy to provide a constraint. The current lack of metal-free stars may simply be due to the relatively small numbers of UMP stars (approximately 30) known, as shown in **Figure 1**. Hartwig et al. (2015) show that the sample sizes of metal-poor halo stars need to be increased by an order of magnitude (to ~400 UMP stars) to rule out the existence of metal-free stars at approximately 95% confidence.

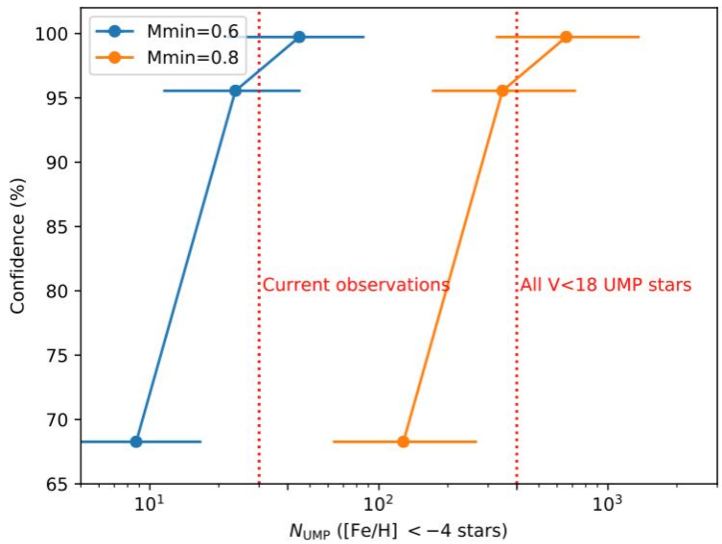

Figure 1: Number of UMP stars that need to be observed to reach the specified confidence levels that metal-free stars with masses 0.6 $M_{\odot}$ (blue line) and 0.8 $M_{\odot}$ (orange line) did not form if no metal-free stars are found. Approximately 400 UMP stars need to be confirmed to exclude the existence of metal-free stars at 95% confidence. *(Figure adapted from Hartwig et al. 2015)*

What was the mass distribution of the first stars?

The initial mass function (IMF) describes the distribution of stellar masses formed from a cloud of gas. The IMF of the first stars is expected to be extremely top heavy, because there were no metal atoms to enable primordial clouds of H and He to cool and fragment into low masses. However, the predicted characteristic masses of Pop III stars range widely from ~10 $M_{\odot}$ to ~100 $M_{\odot}$. This difference has dramatic implications for the metal enrichment of the ISM and IGM, the mass scale of the first self-enriching galaxies, the earliest redshifts of reionization, and the first stellar-mass black holes in the Universe (e.g., Bromm & Larson 2004, and references therein).

The chemical abundances found in UMP stars provide a path to reconstruct the IMF of the massive Pop III stars that ejected metals. The UMP stars known at present exhibit a wide variety of abundance ratios of one element to another, implying a great diversity of properties among the first supernovae. Stellar models and nuclear reaction networks can be used to predict elemental yields from stars of different masses, metallicities, rotation rates, explosion mechanisms, explosion energies, mass cuts, etc. (e.g., Heger & Woosley 2010; Nomoto et al. 2013; Tominaga et al. 2014). These predictions can be compared with the observed abundance patterns of individual UMP stars to characterize the diversity of properties and their relative frequency among the first supernovae (e.g., Placco et al. 2016; Ishigaki et al. 2018).

What is the low-metallicity tail of the metallicity distribution function?

The low-metallicity tail of the MDF is a key observational quantity (e.g., Karlsson 2006; Salvadori et al. 2007). For example, a cutoff in the MDF—if one exists—would mark a critical threshold below which low-mass stars cannot form. The MDF of the Milky Way halo declines sharply at [Fe/H] ≤ −4 (Schörck et al. 2009; although see also Yong et al. 2013), and the characteristics of this low-metallicity tail are poorly determined because the samples of UMP stars are so small.

Hundreds of candidate UMP stars with V < 18 are expected to be found among ongoing and future surveys, including SDSS, SkyMapper, Pristine, J-PLUS, LAMOST, 4MOST, and LSST. Medium-resolution spectroscopy can be used to establish the overall shape and normalization of the MDF at higher metallicities. High-resolution spectroscopy is essential in the UMP regime, however, because the metal lines are so weak. **Figure 2** demonstrates that features like the CH *G*-band are undetectable in moderate-resolution spectra in warm subgiants and main sequence stars, but high spectral resolution can detect these features. Observing ~400 UMP stars would definitively establish the shape of the metal-poor tail of the Milky Way MDF and provide a clear target for advanced models of the formation and evolution of the Milky Way stellar halo.

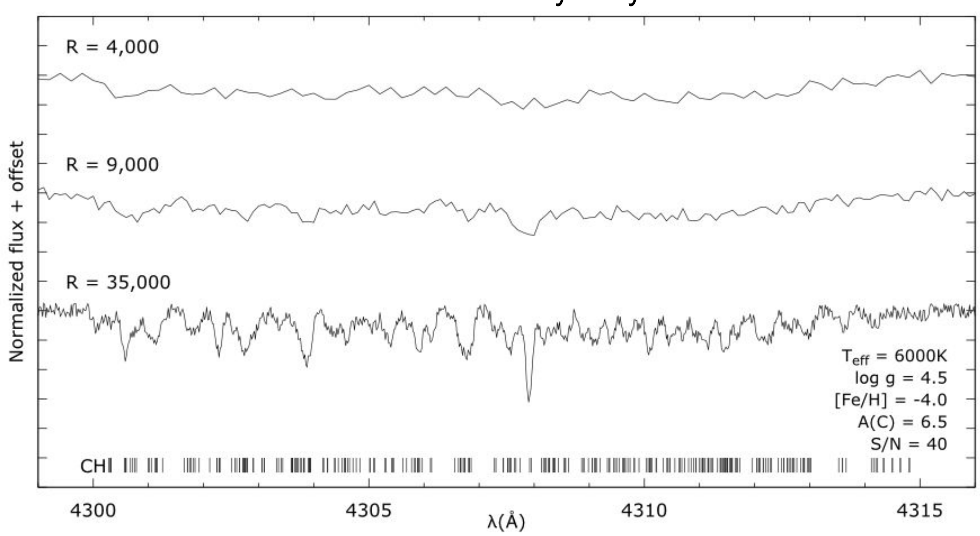

Figure 2: Model spectra with S/N ~ 50 around the CH *G*-band in a warm, metal-poor dwarf that is extremely carbon enhanced ([C/Fe] = +1.9). Metals like C are undetected in low-resolution (R ~ 4,000; top) and moderate-resolution spectra (R ~ 9,000; middle), but they are detectable in high-resolution spectra (R ~ 35,000; bottom).

What nucleosynthesis channels led to the first metals?

Comparisons between UMP stellar abundances and supernova yields reveal the nucleosynthetic origins of the first metals in the Universe. Metals detectable in UMP stars include Li, C, N, O, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr, and Ba. These elements represent products of all major nucleosynthesis channels that may be expected to operate in the earliest stellar generations. Detection of many elements per star is critical to reveal the nucleosynthesis channels that operated in the first stars.

How does environment shape the first stars and first metal enrichment?

Most UMP stars are expected to be members of the halo or bulge populations. Membership can be assigned based on proper motion and parallax measurements made using data from the *Gaia* satellite (cf. Frebel et al. 2018; Sestito et al. 2018). These memberships would be useful when examining how environment shapes the nature of the first stars and metal enrichment. The role of environment can be examined further by comparing with observations of surviving dwarf galaxies in the Local Group, where UMP or metal-free stars are found with higher relative frequency. Current models suggest that on average ~1% of stars in the faintest dwarf galaxies (stellar mass $\sim 10^{3\text{-}4}$ M_{sun}) could be metal-free (Magg et al. 2018).

How to recognize metal-free and second-generation stars

The first generation of stars would have formed from only hydrogen and helium, which were the only significant elemental products of Big Bang nucleosynthesis. These stars are uniquely identified by the lack of any absorption or emission lines from metals in their spectra. Detection of long-lived, low-mass metal-free stars—should they exist—is an obvious goal for the next generation of studies.

Subsequent generations of stars formed from pristine gas that mixed with the first-star metal ejecta. There is no definitive marker that signifies that a star is a second-generation star, but there are several pieces of circumstantial evidence that can be suggestive. A chemical signature, such as carbon enhancement (e.g., Beers et al. 1992; Norris et al. 2013; Placco et al. 2014), that preferentially appears in stars with lower metallicity is likely to be associated with the earliest generations of stars. Extreme enhancement or deficiency of a particular element or set of elements, such as unusual ratios among the α elements (O, Mg, Si, and Ca; e.g., Aoki et al. 2002; Cohen et al. 2007; Lai et al. 2009) can signal that a star may have formed in regions of the ISM where an individual supernova dominated the metal enrichment. In addition to having extremely low [Fe/H] ratios, UMP stars often exhibit one or both of these characteristics.

Unique opportunities for transformative advances in the next decade

Ambitious surveys of the scale described herein would almost certainly need to rely on the next generation of ground-based 30-meter extremely large telescopes (ELTs) to collect the observational material. UMP stars are extremely rare. The Pristine Survey

(Youakim et al. 2017) detected an average of 1 star with [Fe/H] < -3 and *V* < 18 per deg^2. UMP stars with [Fe/H] < -4 are expected to be ~1% as common as stars with [Fe/H] = -3 (Schörck et al. 2009), implying that the density of UMP stars is 1 star with *V* < 18 per 100 deg^2. Thus, an observing campaign to target 400 UMP stars requires searching the entire 40,000 deg^2 sky. This could not be accomplished with a single-hemisphere ELT alone. Rather, a coordinated survey among a two-hemisphere ELT system—like the Giant Magellan Telescope (GMT) in the south and the Thirty Meter Telescope (TMT) in the north—would be in a unique position to conduct such a survey for the first time.

Many of the strongest metal absorption lines are found in the blue region of the spectrum (λ < 4000 Å) in late-type stars. The number of detectable lines is small in UMP stars, and often only a few lines of a particular species are present. High S/N and high spectral resolution are necessary to detect and measure these lines. **Figure 3** demonstrates that the moderate- and high-resolution spectrographs planned for the GMT and TMT have superb blue wavelength coverage that enables the detection of these lines. In contrast, comparable spectrographs planned for the European ELT (E-ELT) will not be sensitive to these wavelengths.

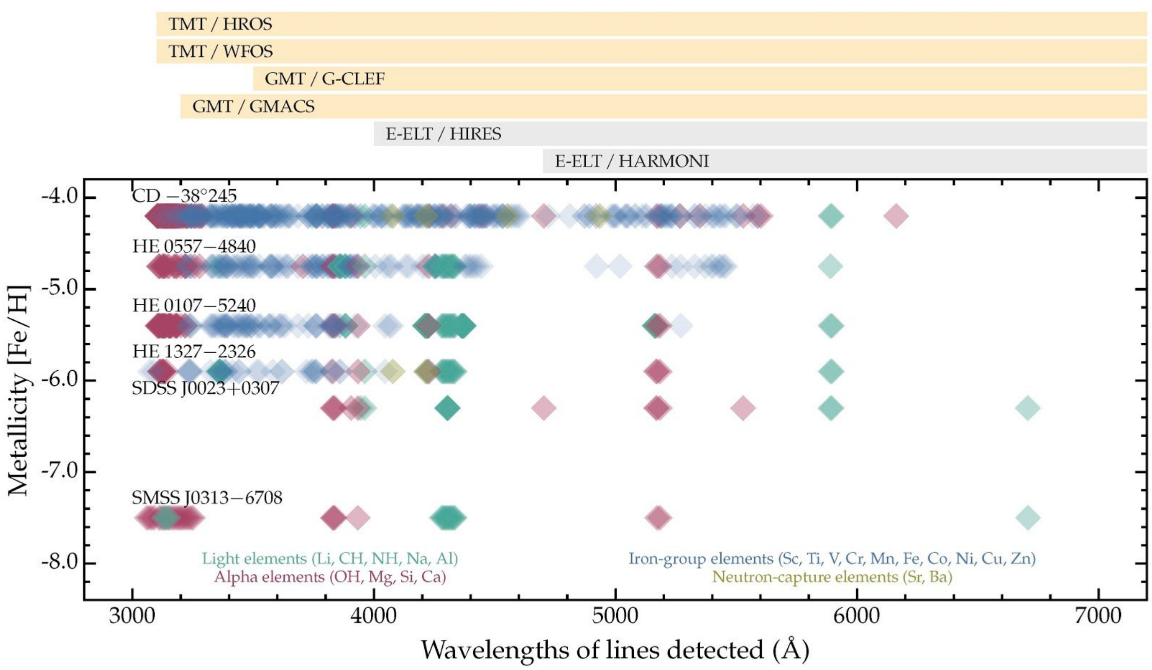

Figure 3: The wavelengths of absorption lines detected in the optical spectra of six UMP stars. Each point represents one line in one star, and the elements are identified by different colors. The vertical axis indicates the [Fe/H] ratio for each star. The wavelength coverage of moderate- and high-resolution spectrographs on the TMT, GMT, and E-ELT is indicated. The current designs of only the TMT and GMT instruments provide sufficient blue wavelength coverage to detect many important species, including iron, in the most metal-poor stars. *(Data from Cayrel et al. 2004; Christlieb et al. 2004; Aoki et al. 2006; Norris et al. 2007; Frebel et al. 2008, 2018; Keller et al. 2014; Roederer et al. 2014; 2018 unpublished; Bessell et al. 2015)*

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