The First Stars and the First Metals

A white paper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

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1. Key Science Questions— The nucleosynthetic signatures of the first stars and supernovae are imprinted on the atmospheres of the most metal-poor stars found today. What were the properties (e.g., masses, rotation rates, binary fractions) of these first Pop III stars, where were they formed, and what were their supernovae explosions like? These critical science questions, and others, can be addressed by studying the compositions of surviving second-generation stars that formed from the ISM polluted by metals produced by these Pop III stars. This goal is expressed in several of the Cosmic Origins science questions, including how the first stars influenced their environments, how the chemical elements were dispersed through the circumgalactic medium, and how galaxies and their constituent stars formed and evolved.

Six stars with Fe abundances less than $10^{-4.5}$ times the Solar abundance (i.e., [Fe/H] < -4.5) are known at present (Christlieb et al., 2002, Nature, 419, 904; Frebel et al., 2005, Nature, 434, 871; Norris et al., 2007, ApJ, 670, 774; Caffau et al., 2011, Nature, 477, 67; Keller et al., 2014, Nature, 506, 463; Hansen et al., 2014, ApJ, 787, 162). More are expected to be found among ongoing and future surveys (e.g., LAMOST, SkyMapper). One of the striking characteristics of five of these six stars is the high level of C, N, and O abundances relative to Fe (e.g., $+1 <$ [C/Fe] $< +4$). This suggests that a particular class of "faint" supernova with low explosion energies may have been relatively common in the early Universe (e.g., Iwamoto et al., 2005, Science, 309, 451; Meynet et al., 2006, A&A, 447, 623; Heger & Woosley, 2010, ApJ, 724, 341; Ishigaki et al., 2014, ApJL, 792, L32). Rapidly-rotating massive stars have been proposed as an alternative explanation (Maeder et al., 2015, A&A, 576, A56).

One critical—but, in principle, surmountable—challenge in studying these metal-poor stars is the lack of elements that can be detected. Only a few tens of absorption lines are commonly found in the optical spectra of these stars, so only $\approx$ 5–10 elements are regularly detected.

Many others (Be, B, Si, P, S, Sc, V, Cr, Mn, Co, Ni, and Zn) are expected to be present but are rarely detected, and the upper limits derived from their non-detections are often uninteresting.

The UV spectrum is an unexplored window that would allow all of these elements to be detected if present in the most metal-poor stars known. The challenge is that the known stars are much too faint for high-quality observations with HST, and the stars expected to be found in future surveys are likely to be as faint as these or fainter. A single UV spectrum would double or triple the number of elements detected in any of these stars, and observations of all such stars would revolutionize our understanding of the first stars, the first supernovae, and the first metals in the Universe.

2. Technical capabilities— The spectral region between 1700 Å and 3100 Å contains hundreds of potentially useful lines of elements from Be ($Z = 4$) to Zn ($Z = 30$). These lines are widely spaced from 1700 Å to 3100 Å, so a UV spectrograph would be most effective if it could record this entire wavelength region (or at least half of it) in a single observation. High spectral resolution ($R \equiv \lambda/\Delta\lambda$) is essential. $R \sim 60{,}000$ (5 km s^{-1}) is sufficient to resolve the lines, and $R \sim 30{,}000$ is the minimum acceptable resolution. Typical S/N goals would be $\sim$ 50–80 after co-adding multiple exposures.

Although any facility that meets these spectral and bandpass requirements will be of some use, a true step forward will require an overall telescope plus instrument throughput at least 10 times better (telescope aperture, optical transmission, detector quantum efficiency, etc.) than HST+STIS or HST+COS at these wavelengths. This would enable studies of about half of the most metal-poor stars known at present (red giants at distances up to $\sim$ 6 kpc, and subgiants at distances up to $\sim$ 2.5 kpc) and similar stars discovered in future surveys. Even greater overall throughput (a factor of $\sim$ 100 improvement over HST) would be needed to study the other known stars and many of those expected to be found by surveys in the next several decades. Multiplexing offers no scientific advantage since the field density of the most metal-poor stars is, and will likely remain, $\ll 1$ star deg^{-2} to $B \lesssim 18$.

3. Relevance of the four mission concepts— The UV/Optical/IR Surveyor mission concept has the potential to meet the science objectives and technical capabilities. Neither JWST, WFIRST, nor any of the other mission concepts is likely to offer the combination of sensitivity and spectral resolution at the UV wavelengths of interest.

4. New Technologies— Unknown to us at this time.

5. Large Mission Needed?— The high S/N ratios and spectral resolution needed to accomplish these science goals on faint targets require a large collecting area, so this almost certainly requires a flagship-sized mission.