The Potential of Ultraviolet Spectroscopy to Open New Frontiers to Study the First Stars

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Abstract

The elements found in second-generation stars probe the nature and end states of the elusive generation of metal-free first stars. High-resolution (R ≥ 30,000) ultraviolet (~1800 to 3100 Å) spectroscopy offers the potential to greatly expand the chemical inventory in second-generation stars. Access to next-generation ultraviolet spectrographs on facilities like CETUS, HabEX, or LUVOIR would open new frontiers that vastly improve our understanding of the first stars in the Galaxy.

Introduction

The first stars in the universe formed from the clouds of primordial hydrogen and helium created shortly after the Big Bang. These first stars, also known as Population III, are expected to have been massive and short lived (e.g., Bromm & Larson 2004). They produced the first metals through fusion reactions or during the supernova explosions that ended their lives. These first metals seeded the interstellar medium and enabled the first low-mass long-lived Population II stars to form.

No metal-free "first stars" have yet been found. The nucleosynthetic signatures of the first stars and supernovae are imprinted, however, in the elements observed in second-generation stars. These second-generation stars are found today among the metal-poor stars in the Milky Way bulge, halo, and dwarf galaxies (e.g., Tumlinson 2010; Frebel & Bromm 2012; El-Badry et al. 2018). The elemental abundance pattern of each second-generation star can be compared with supernova model predictions (e.g., Chieffi & Limongi 2004; Umeda & Nomoto 2005; Heger & Woosley 2010) to characterize the nature and end states of one of the first stars. Collectively, they reveal:

- the initial mass function of the first stars that produced metals (e.g., Hartwig et al. 2015; Ishigaki et al. 2018),
- detailed properties of the first star supernova explosions, including rotation rate, explosion energy, explosion mechanism, asymmetries, mass cut, and so on (e.g., Lai et al. 2008; Tominaga et al. 2014; Placco et al. 2016),
- the low-metallicity tail of the metallicity distribution function (e.g., Schörck et al. 2009; Yong et al. 2013),
- the chemical feedback and the distribution of the first metals (e.g., Smith et al. 2015), and
- the birthplaces of the first stars (e.g., Frebel et al. 2018; Sestito et al. 2018).

Furthermore, any field of study that is concerned with the mass or luminosity of the first stars (e.g., cosmic reionization, the first stellar-mass black hole seeds, etc.) will be impacted by advances in our understanding of these characteristics.

Current observational challenges

Progress to address these fundamental questions has been limited because of *small sample sizes* and the *small number of metals detected* in each second-generation star.

Many, though certainly not all, candidate second-generation stars have less than 1/10,000 of the solar iron abundance ([Fe/H] < −4). About 30 such stars are known today, and hundreds more are expected to be found among ongoing and future surveys (e.g., SDSS, LAMOST, SkyMapper, Pristine, DESI, WEAVE, PFS, 4MOST, LSST). High resolution (R ≥ 30,000) optical and near-IR spectra (λ > 3100 Å) reveal the presence of only a few tens of absorption lines, so only ~5-10 elements are regularly detected (e.g., Frebel et al. 2008; Caffau et al. 2012; Keller et al. 2014; see **Figure 1**).

The limited chemical inventories restrict the utility of these stars for understanding the nature of the first stars and first supernovae. Some of the elements that offer the greatest constraining power for model predictions (e.g., Si, P, Fe, Zn) are not detected in the optical region of the spectrum. Many other elements are expected to be present, but they remain undetected. The strongest transitions of these elements are in the UV, below the atmospheric cutoff, requiring space facilities for detection. *These UV transitions, and the abundances derived from them, are the key measurements to be made to advance the field.*

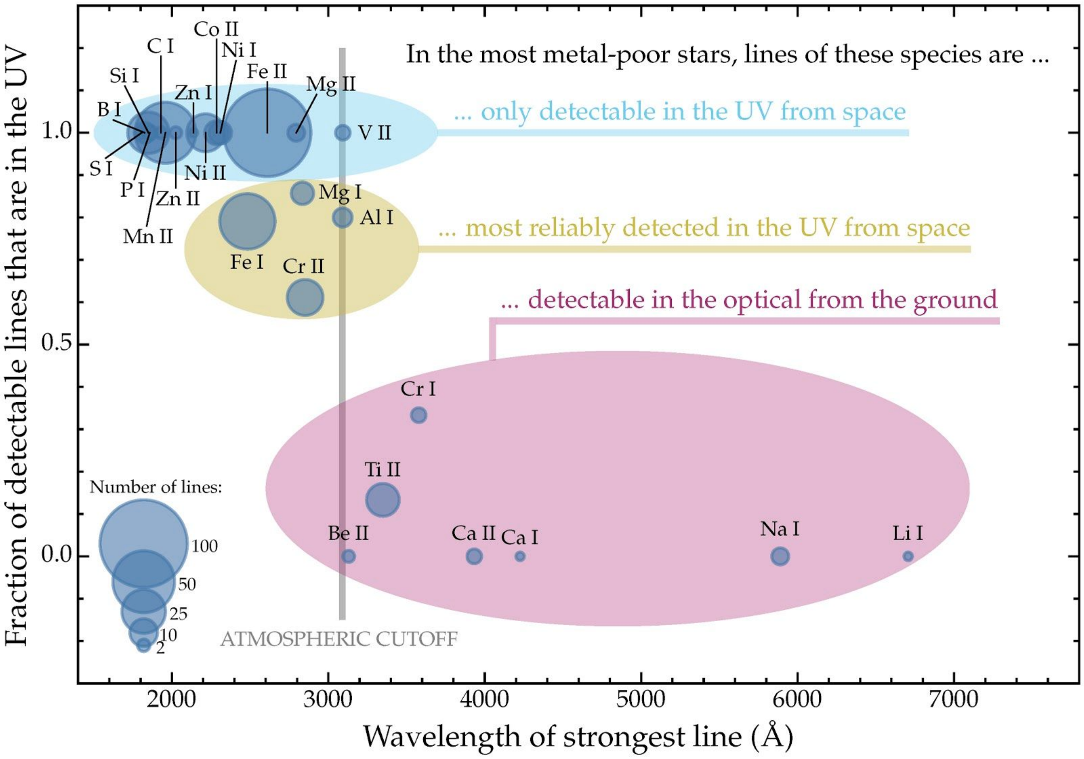

Figure 1: The improvement in metal detections in the most metal-poor stars enabled by UV spectra. Estimates are based on line strength calculations for lines with 1800 ≤ λ ≤ 10000 Å in a dwarf star with T_{eff} = 6000 K, log g = 4.2, and [Fe/H] = −5.0. Typically ~5-10 elements can be detected in optical spectra alone, but UV spectra can enable the detection of ~20 elements (ranging from lithium to zinc, 3 ≤ Z ≤ 30), probing supernova physics, Big Bang nucleosynthesis, stellar evolution, and spallation reactions.

Many of the most metal-poor (and/or iron-poor) stars are too faint for UV observations with the *Hubble Space Telescope* (*HST*), as shown in **Figure 2**. Only one star with V < 10 and [Fe/H] < −3.5 is known at present (BD +44º493, the most metal-poor star located in the band accessible to *HST*/STIS in **Figure 2**; Placco et al. 2014; Roederer et al. 2016). Ezzeddine & Frebel (2018) used lower resolution UV spectra from *HST*/COS to detect several Si **I**, Fe **II**, and Zn **I** lines in a fainter (V = 13.5) star with [Fe/H] < −5 (HE 1327-2326), but the narrow wavelength coverage of COS prohibited a comprehensive analysis of the UV spectrum. Other COS observations of the most iron-poor star known (SMSS J0313−6708, where the non-detection of Fe I lines in the optical spectrum constrains [Fe/H] < −7.5; Bessell et al. 2015) demonstrated the limits of *HST*. This star is too faint (V = 14.7) to obtain high-S/N, high-resolution UV spectra (Roederer 2017). The list of viable candidate second-generation stars for which high-resolution UV spectra could be obtained with *HST* has already been exhausted, and it is not anticipated to grow. *Measurements of the key UV line diagnostics cannot be made without access to the UV spectra of these stars.*

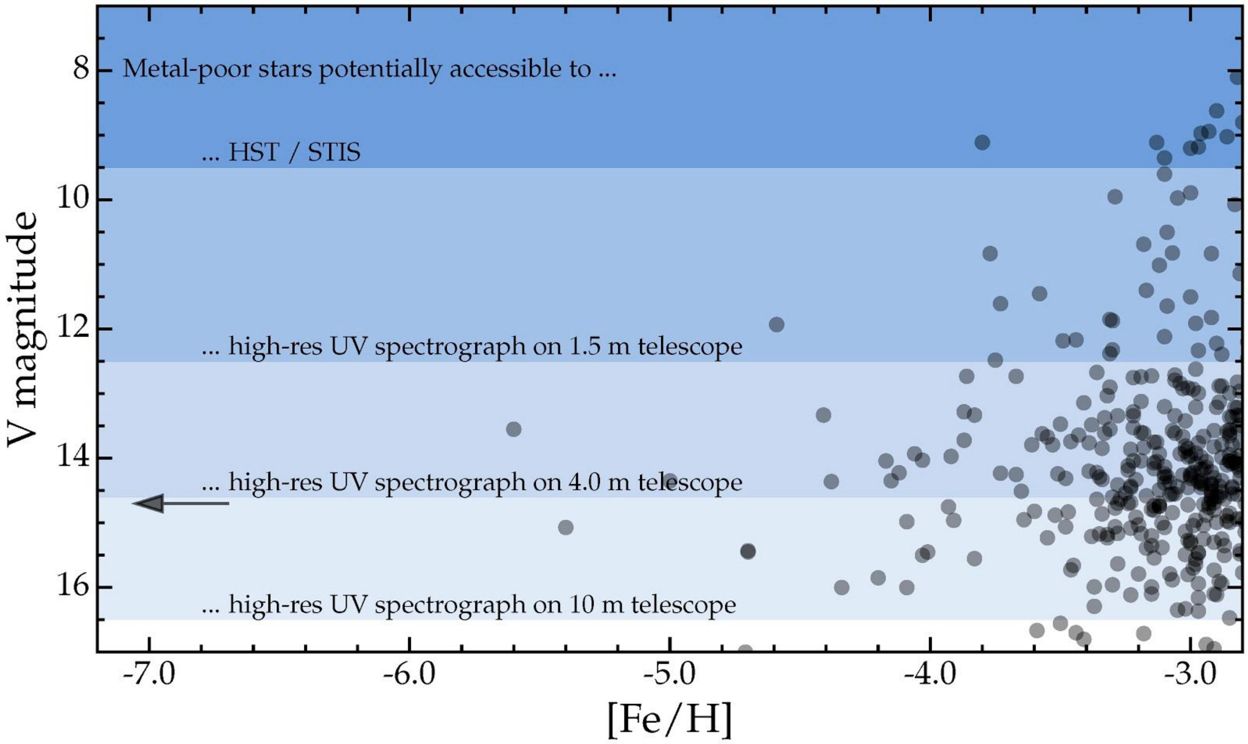

Figure 2: The brightest metal-poor stars. Shaded regions indicate the approximate magnitudes accessible for high-S/N, high-resolution (R = 30,000) UV spectroscopy using STIS on *HST* and next-generation UV echelle spectrographs on space telescopes with varying primary mirror diameters. *(Estimates based on early designs for the CETUS mission concept; Heap et al. 2018. Data mostly taken from the JINAbase abundance database; Abohalima & Frebel 2018.)*

New opportunities

Advances in our understanding of the nature and end states of the first stars will be limited without new observations, regardless of the extent to which supernova models and nucleosynthesis calculations progress. S/N ratios ~30-100 would enable the detection of all elements shown in **Figure 1**, if the elements are present.

Figure 3 illustrates an example of one such observation. Improvements in, e.g., coatings and detector technology over the last few decades enable telescopes with modest mirror sizes (~1.5 m in diameter) to successfully observe the UV spectrum of late-type stars that are ~3 magnitudes too faint for comparable observations with STIS on *HST*. More ambitious, flagship scale telescopes could push ~3-6 magnitudes fainter, enabling UV spectroscopy of virtually all stars accessible on practical timescales to optical echelle spectrographs mounted on present-day 6-10 m ground-based telescopes. This capability would revolutionize our understanding of the first stars, the first supernovae, and the production and distribution of the first metals in the Galaxy.

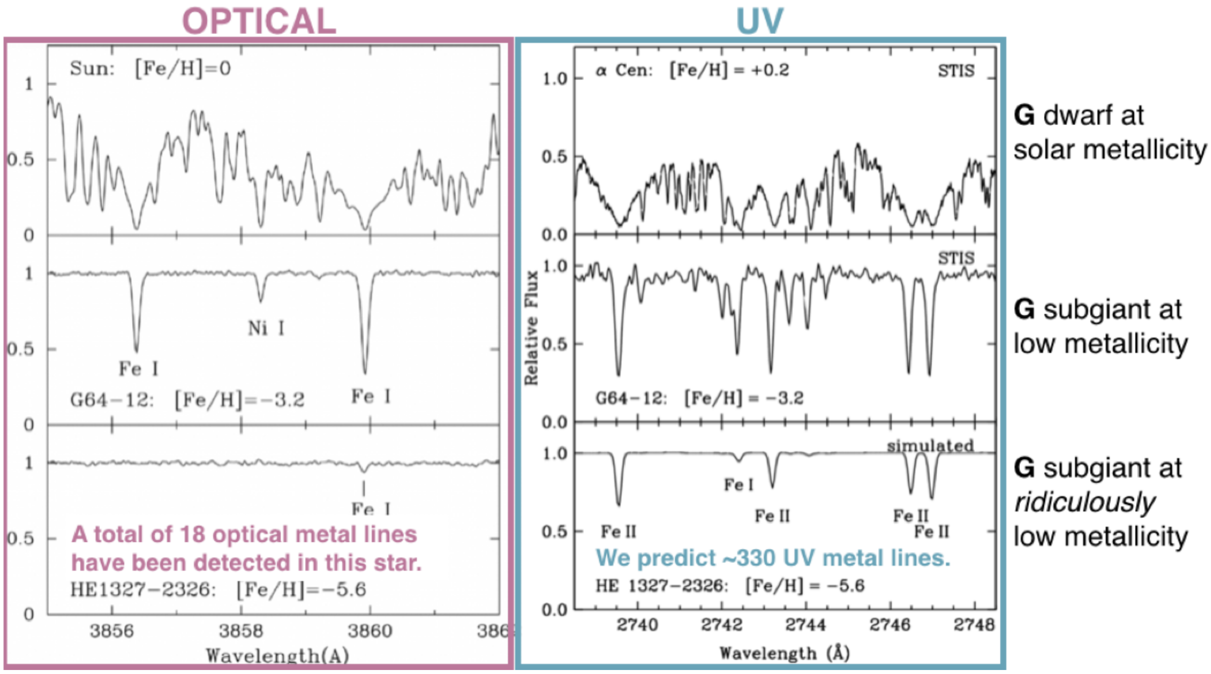

Figure 3: Comparison of optical spectra (left) of several G-type stars with UV spectra (right). The bottom right panel is a simulation of what could be obtained with a future high-resolution UV spectrograph. *(Left panel from Aoki et al. 2006.)*

Any telescope that offers high-resolution (spectral resolving power R ≥ 30,000 or so) and broad UV wavelength coverage (at least 1800 to 3100 Å in as few exposures as possible) will be poised to make unprecedented advances in this field. Proposed missions that would meet these goals include Cosmic Evolution Through UV Spectroscopy (CETUS), the Habitable Exoplanet Observatory (HabEx), or the Large UV/Optical/IR Surveyor (LUVOIR).

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