The Origin of the Elements Heavier than Iron

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1. Science Motivation

Understanding the origin of the elements is one of the major challenges of modern astrophysics. 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, how galaxies and their constituent stars formed and evolved, and how baryons destined to form planets grow to heavy atoms.

The metals in a star today are a snapshot of the metals in the interstellar medium (ISM) at the time and place where that star was born. Ancient halo stars offer the opportunity to make a reasonable connection between individual stellar nucleosynthesis events and the metal distributions found in the oldest stars. The elements heavier than iron, which have been detected in the ancient stars of the Galactic halo, in the ISM, dust grains, meteorites, and on Earth, are formed by neutron-capture reactions.

Relatively low neutron densities found in the He-rich inter-shell of AGB stars lead to heavy element nucleosynthesis by the slow neutron-capture process (s-process). Relatively high neutron densities lead to heavy element nucleosynthesis by the rapid neutron-capture process (r-process). Despite decades of analytical work and countless simulations, there are no definitive observations linking high-mass r-process material with an astrophysical site or sites of nucleosynthesis. Observations of Ba and Sr in SN 1987A have strengthened the case for production of some r-process material in core-collapse supernovae. In addition to the long favored core-collapse supernovae sites, there are now reasonable but unproven models of r-process nucleosynthesis in neutron star plus neutron star or black hole mergers and more exotic events such as quark novae.

One way to better constrain the physical conditions at the nucleosynthesis sites of the s-process and r-process is to study the complete atomic mass distribution produced. More than 25 elements heavier than the iron-group can be reliably detected in high-resolution, high-S/N optical spectra of late-type (FGK) stars obtained from ground-based facilities. Another 11 elements (including Ge, As, Se, Cd, Te, Lu, Os, Ir, Pt, Ag, and Pb) can be reliably detected in similar quality near-UV spectra. The near-UV spectral window offers the only opportunity to reliably detect these particular elements, which include some of those providing the most sensitive constraints on the nucleosynthesis models. These models, in turn, constrain the conditions at the astrophysical site(s).

The Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST) continues to be an effective tool for performing this kind of work. Several relevant examples of this science may be found in Sneden et al. (1998, Astrophys. J., 496, 235), Cowan et al. (2005, Astrophys. J., 627, 238), and Roederer & Lawler (2012, Astrophys. J., 750, 76). Yet, many interesting stars lie at distances too great for practical observations with HST+STIS, including stars with the highest levels of r-process enrichment, stars with severe deficiencies of r-process and s-process material, stars with unexplained deviations from the r-process and/or s-process abundance patterns, and the most iron-poor stars known (at least one of which contains substantial doses of elements heavier than the iron-group).

2. Requirements

The spectral region between 1900 Å and 3050 Å contains dozens of neutron-capture absorption lines that have been demonstrated to be good abundances indicators. Figure 1 illustrates this point for three Se I lines in the STIS spectrum of one metal-poor subgiant, HD 160617. Useful lines are widely spaced from 1900 Å to 3050 Å, so a future 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. $R \sim 100{,}000$ is ideal to oversample the line profile to resolve the many blended features in the near-UV, and $R \sim 30{,}000$ is the minimum acceptable resolution.

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 at these wavelengths. This would enable substantially larger samples of local stars (within ~ 400 pc) or individual stars with demonstrated nucleosynthetic value at significantly greater distances (up to ~ 6 kpc) to be observed in integration times comparable to successful observing campaigns with HST. Either of these approaches would offer an opportunity to address the scientific goals described in Section 1.

Modern surveys have already identified large numbers of disk and halo stars whose near-UV spectra would surely reveal valuable nucleosynthetic information. The field density of metal-poor stars is generally quite low, of order 1 star per 3 deg^2 down to $B \approx 16$ toward the Galactic poles, so multiplexing offers no advantage in most cases. High throughput and wide bandpass are preferable to object multiplexing, though such capability ($\sim$10 or more objects) could be useful for limited applications (e.g., Galactic globular or open clusters) with a modest field of view of $\sim 10 \times 10$ arcmin.

An instrument with these capabilities should allow for verification and cross-checks of neutron-capture element abundance patterns in a variety of astrophysical environments.

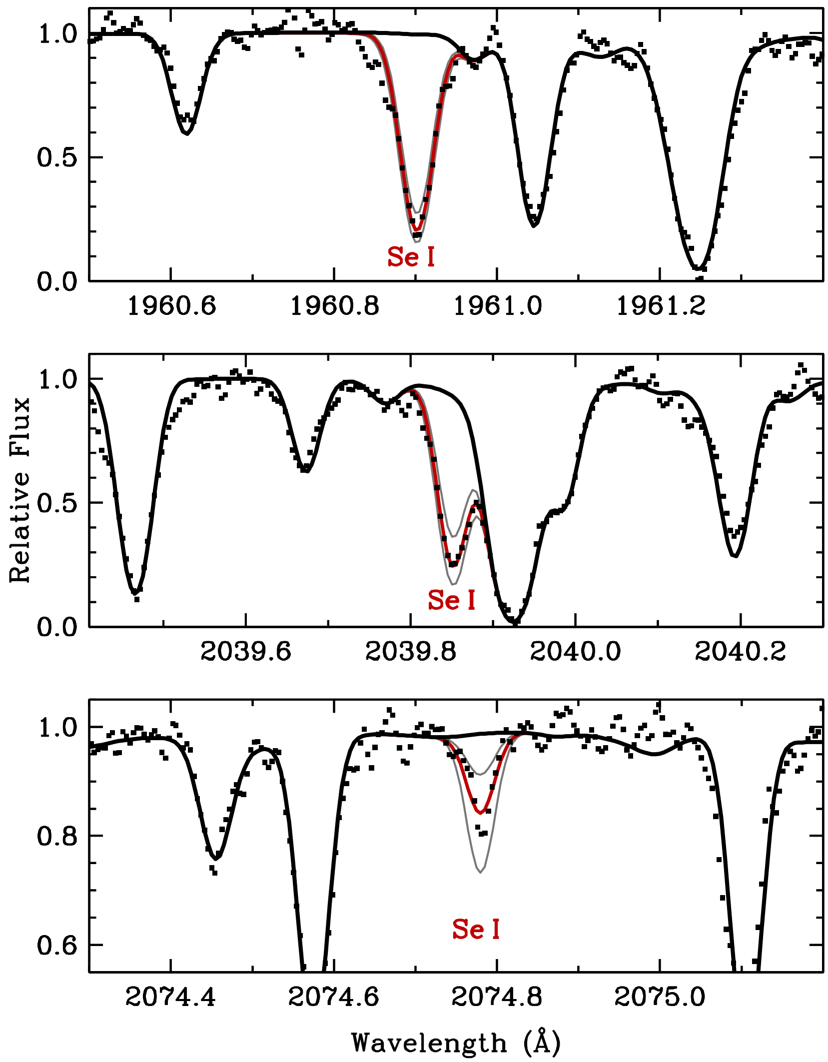

Fig. 1.— Three Se I lines in the STIS spectrum of the metal-poor subgiant HD 160617. This spectrum has $R \sim 110{,}000$ and S/N $\sim$ 30 to 50 pixel^{-1}. Overlaid synthetic spectra represent the best-fit abundance (red), factors of 2 variations (gray), and a synthesis with no Se present (black). This is Figure 6 of Roederer & Lawler (2012, Astrophys. J., 750, 76).

3. Summary

Understanding the origin of the elements heavier than iron remains one of the major challenges in modern astrophysics, and high-resolution near-UV spectroscopy offers an opportunity to detect elements that can constrain the unconfirmed astrophysical site(s) of r-process nucleosynthesis. The availability of high-resolution ($\lambda/\Delta\lambda > 30{,}000$) and high S/N ($\gtrsim 50$) near-UV ($1900 < \lambda < 3050\,$Å) spectra presently allows for a 40% increase in the number of elements heavier than the iron-group that can be detected in late-type stars. In stars useful for interpreting the nucleosynthetic record, these elements can only be reliably detected in the near-UV. We recommend that any future space UV mission should include an instrument capable of achieving these spectral qualities in single-object observing mode in reasonable integration times for late-type stars within ~ 6 kpc of the Solar neighborhood.

J.E. Lawler is available to participate in a science objective workshop.