# The Origin of the Elements Heavier than Iron

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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April 24, 2015

**1. Key Science Questions**— Understanding the origin of the elements is one of the major challenges of modern astrophysics. What are the physical mechanisms, conditions, and sites where heavy elements are produced? 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 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 characterize 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 15 elements (including Ge, As, Se, Cd, Te, Lu, Ta, W, Re, Os, Ir, Pt, Ag, Hg, 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).

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. Yet, many interesting stars lie at distances too great for practical observations with HST+STIS or COS, including stars with the highest levels of r-process enrichment, stars with severe deficiencies of r-process and s-process material, and stars with unexplained deviations from the r-process and/or s-process abundance patterns.

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), Roederer & Lawler (2012, Astrophys. J., 750, 76), and Roederer et al. (2014, Astrophys. J., 791, 32).

**2. Technical capabilities**— The spectral region between 1900 Å and 3100 Å contains dozens of neutron-capture absorption lines that have been demonstrated to be good abundances indicators. Useful lines are widely spaced from 1900 Å to 3100 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 $\mathrm{km\,s^{-1}}$) 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. Experience shows that S/N $\sim$ 50–100 after co-adding multiple exposures is sufficient to achieve the science objectives.

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 $\sim$ 400 pc) or individual stars with demonstrated nucleosynthetic value at significantly greater distances (up to $\sim$ 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 objectives.

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. If this feature is available, investigators would, of course, try to identify stars of interest that could be observed simultaneously. However, such considerations should be a secondary concern, at best, in the instrument design.

**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 described in this white paper. 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.