

The astrophysical r-process and the origin of the heaviest elements

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Abstract

The rapid neutron capture process, or r-process, is one of the fundamental ways that stars produce the heaviest elements. Photometric and spectroscopic surveys in the next decade will reveal many thousands of candidate r-process enhanced stars in the Milky Way field and Local Group dwarf galaxies. All will require follow-up high-resolution spectroscopy to assess their r-process abundance patterns and the global population demographics of stars that reflect the evolution of r-process nucleosynthesis sites across cosmic time. To make these measurements and leverage federal investments in related facilities, it is critical that the US astronomical community gains meaningful public access to high-resolution ($R > 30,000$), blue/optical ($3050 < \lambda < 7000 \text{ \AA}$) single- and multi-object spectroscopic instruments on the current generation of 6-10 m class ground-based telescopes and the next generation of 30 m ELTs. High-resolution ($R > 30,000$) UV ($1700 < \lambda < 3100 \text{ \AA}$) spectroscopy on the next generation of space telescopes like CETUS, HabEx, or LUVOIR will also be necessary to realize these opportunities.

Introduction

Understanding the origin of the elements on the periodic table is one of the major challenges of modern astrophysics. The elements heavier than the iron group are mostly produced by neutron-capture reactions, which can overcome the high Coulomb barriers of high-Z nuclei. Three neutron-capture processes have been identified as having contributed substantially to heavy-element production: a rapid process (r-process), a slow process (s-process)—both of which were first proposed by B²FH (Burbidge et al. 1957)—and an intermediate process (i-process; Cowan & Rose 1977).

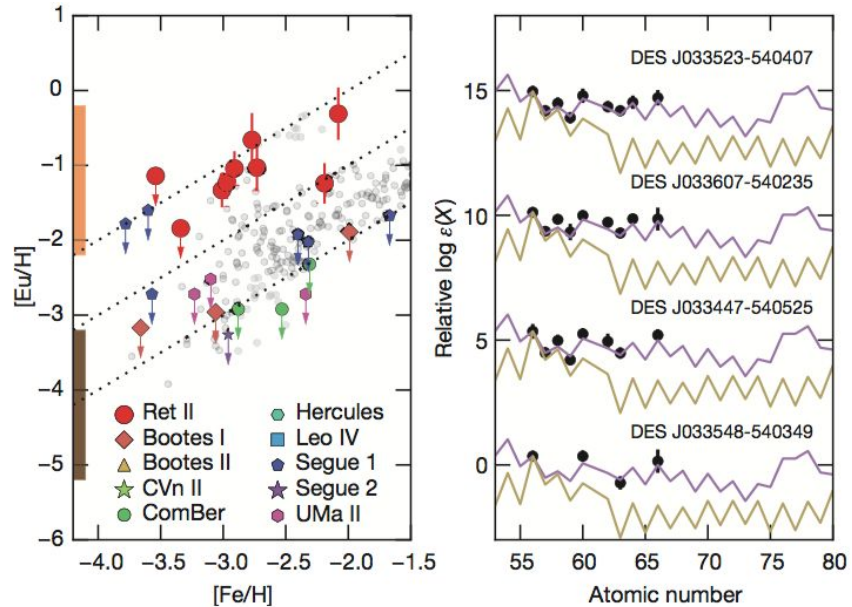
The r-process is the focus of this white paper. The r-process is the most extreme of these three processes, with neutron captures occurring ~ 15 - 35 nuclei to the neutron-rich side of the valley of beta stability on the chart of nuclides. It has proven to be more challenging to identify and assess the physical characteristics of r-process nucleosynthesis, the dominant sites of the r-process (including potentially core-collapse supernovae, jet-driven supernovae, collapsars, and mergers of neutron stars, among others), and the contributions of r-process sources to the Galactic budget of r-process elements.

Only within the last decade have observations, theory, and simulations begun to converge regarding the sites of r-process nucleosynthesis:

- Calculations affirm that normal core-collapse supernovae are unlikely to be viable sites for r-process nuclei heavier than $A \sim 110$ (e.g., Hüpdepohl et al. 2010; Arcones & Montes 2011; Wanajo 2013)
- Multimessenger observations of gravitational waves and the kilonova from the binary neutron star merger GW170817 demonstrate that mergers are a viable site of r-process nucleosynthesis (e.g., Cowperthwaite et al. 2017; Drout et al. 2017; Tanvir et al. 2017)

- Environmental constraints derived from observations of r-process enhanced stars in dwarf galaxies (e.g., Ji et al. 2016; Roederer et al. 2016; Hansen et al. 2017) and the Milky Way field (Roederer et al. 2018a) suggest that low-mass dwarf galaxies may be the birthplaces of r-process enhanced stars (see **Figure 1**), which point to rare, high-yield sites like neutron-star mergers.
- Measurements of the short-lived radioactive nuclide ^{244}Pu in sea-floor sediments favor a high-yield but infrequent r-process production site (Hotokezaka et al. 2015; Wallner et al. 2015).

Figure 1: (LEFT) The $[\text{Eu}/\text{H}]$ ratio, which is a proxy for the level of r-process enrichment, in metal-poor stars in low-mass dwarf galaxies (various symbol shapes and colors) and Milky Way field stars. Note that the stars in the Reticulum II (Ret II) dwarf are enhanced in Eu by several orders of magnitude relative to other dwarf galaxies. This level of enhancement matches the level of pollution estimated to have originated from a single neutron-star merger event in Ret II (orange bar), whereas the pollution level expected from a normal core-collapse supernova would be several orders of magnitude less (brown bar).



(RIGHT) The detailed abundance patterns (offset vertically for clarity) of heavy elements in individual stars in Ret II provide a close match to the scaled Solar r-process pattern (purple lines), but not the scaled Solar s-process pattern (yellow lines). (Figure adapted from Ji et al. 2016)

These advances have sparked renewed interest in the r-process throughout the community; Thielemann et al. (2017), Frebel (2018), and Cowan et al. (2019) have published recent reviews. Major outstanding questions about the r-process remain:

- How many r-process sites are required by observations?
 - For example, mergers of neutron stars have been confirmed as a viable site of r-process nucleosynthesis, but can they explain the presence of r-process elements in halo stars with extremely low metallicities?
- What are the yields of r-process elements from different r-process sites?
 - For example, which r-process elements can be produced by normal core-collapse supernovae, and in what amounts?
- To what extent does r-process enrichment vary across environment and cosmic time?

- For example, are the dominant sources of r-process elements the same at early times in low-mass dwarf galaxies and at later times in the Milky Way disk?
- What range of physical processes are responsible for producing the robust r-process yields between mass numbers $135 < A < 210$, yet variable yields for the lighter and heavier r-process nuclei?
 - For example, can the r-process production of long-lived radioactive isotopes ^{232}Th and ^{238}U be understood theoretically and calibrated observationally sufficiently well so that they can be used as chronometers that are competitive with other age-dating methods?
- How do variations in r-process composition observed in stars affect interpretations of multimessenger observations of r-process sites?
 - For example, how do observed variations in stellar abundances of heavy actinide elements like Th and U affect the heating rates and opacities for interpreting kilonovae?

We now highlight several key measurements to be made, and the requirements to make them, that would transform our understanding of the r-process in the next decade.

The detailed composition of ejecta from the r-process site—Metal-poor r-process enhanced stars in the Milky Way and Local Group dwarf galaxies present optical and UV spectra rich with transitions of more than 35 r-process elements (e.g., Sneden et al. 1998; Roederer et al. 2012; Siqueira Mello Jr. et al. 2013) (see **Figure 2**). Each of these stars likely reflects the yields of a single r-process event, like a kilonova. The detailed abundance patterns can be modeled to reveal the nature of each site and constrain the physics at the r-process site (e.g., Hayek et al. 2009; Ji & Frebel 2018). Not all r-process enhanced stars are the same; existing stellar samples suggest potentially important variations in the lightest and heaviest r-process elements, and larger samples are necessary to assess how frequently these variations occur.

Optical spectra are useful to identify and characterize some aspects of the r-process abundance patterns, but UV spectra enable a 40% increase in the number of elements that can be detected. UV spectra are required to detect elements at the three r-process peaks (Se, Te, Pt; e.g., Den Hartog et al. 2005; Roederer & Lawler 2012), which are among the most sensitive to the physics at the r-process site (e.g., Mumpower et al. 2016) and dominate the ejected mass in a kilonova.

The observational challenge is that there is only one source of high-resolution UV spectra (STIS on the *Hubble Space Telescope*), and there is limited public access to facilities capable of collecting high-resolution blue/optical spectra. Only three instruments at present can collect high-resolution optical spectra down to the atmospheric cutoff near 3050 Å (HIRES at Keck, UVES at the VLT, and soon, STELES at SOAR). Other high-resolution spectrographs with wavelength coverage to < 4000 Å are generally private (e.g., the Tull spectrograph at McDonald Observatory, ARCES at Apache Point Observatory, MIKE at Magellan, or the Echelle spectrograph at the du

Pont Telescope at Las Campanas Observatory). *It is therefore critical to expand access for the US community to high-resolution ($R \sim 30,000$ to $\sim 100,000$) spectrographs that cover the blue/optical (as close to the atmospheric cutoff near ~ 3050 Å as possible) and UV wavelength ranges (~ 1700 - 3100 Å) throughout the next decade.*

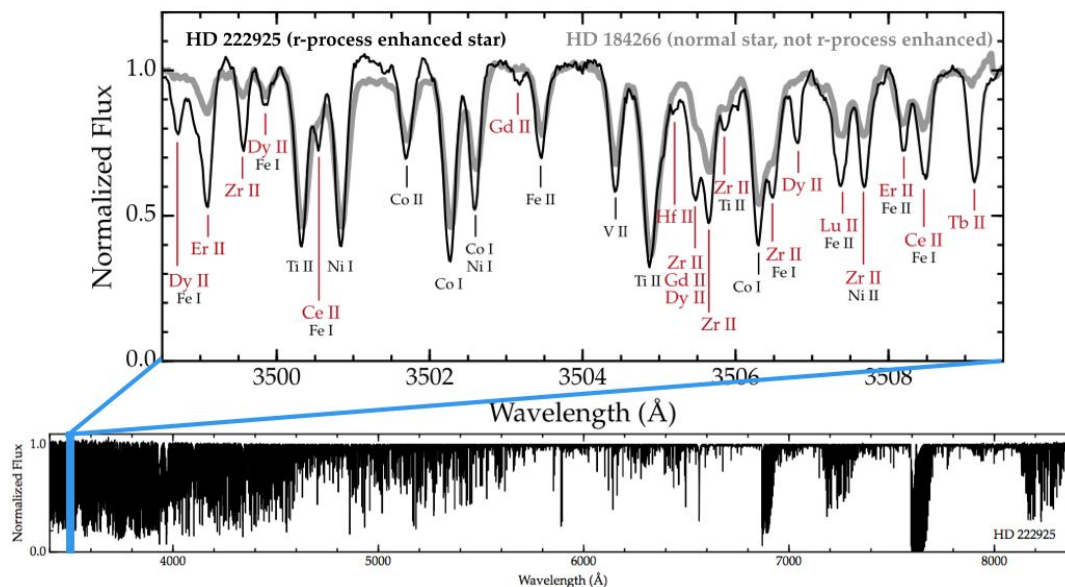


Figure 2: Zoom on a section of the blue/optical spectrum of a metal-poor r-process enhanced star. This $R \sim 65,000$ spectrum was taken using the MIKE spectrograph at Magellan. Note the rich absorption spectrum of r-process elements, which are labeled in red. (Figure adapted from Roederer et al. 2018b)

R-process sites across cosmic time—Roughly 25 highly r-process enhanced stars had been identified by modest-scale survey efforts prior to 2017. This small sample size limited studies of the demographics of the population of r-process enhanced stars—characteristics like the age dependence, occurrence frequencies, binary frequencies, environmental dependence, correlation with other chemical signatures, etc. Recent efforts by the R-Process Alliance demonstrate that focused, long-term efforts can identify large numbers of r-process enhanced stars (e.g., Hansen et al. 2018; Sakari et al. 2018). In the next decade, samples of field stars will expand rapidly, and many more low-mass dwarf galaxies are anticipated to be discovered (from surveys like LSST, DESI, LAMOST, SkyMapper, J-PLUS, SDSS-V), and all of these stars will require follow-up spectroscopy. *Public access to high-resolution ($R > 30,000$) optical spectrographs on 6-10 m and 30 m class telescopes will be necessary to confirm candidates and establish the population demographics of r-process enhanced stars.*

The detailed physical properties of r-process nucleosynthesis—One can think of the r-process abundances as being a product of the nuclear properties and the physical conditions (see Figure 3). If the nuclear properties and final abundances are known, the r-process conditions can be inferred. At present, the r-process nucleosynthesis models rely on extrapolation of nuclear properties (e.g., nuclear masses, neutron-capture cross sections, beta-delayed neutron emission probabilities) to regimes that are unconstrained experimentally. Next-generation accelerator facilities like the Facility for

Rare Isotope Beams (FRIB), scheduled for completion at Michigan State University in 2022, will be capable of generating 400 kW beams of short-lived heavy radioactive isotopes, including nearly 1,000 that are involved in the r-process. *It is critical to leverage this synergy between physics facilities like FRIB and astronomical telescopes by expanding public access to telescopes that can collect high-resolution blue and UV spectra.*

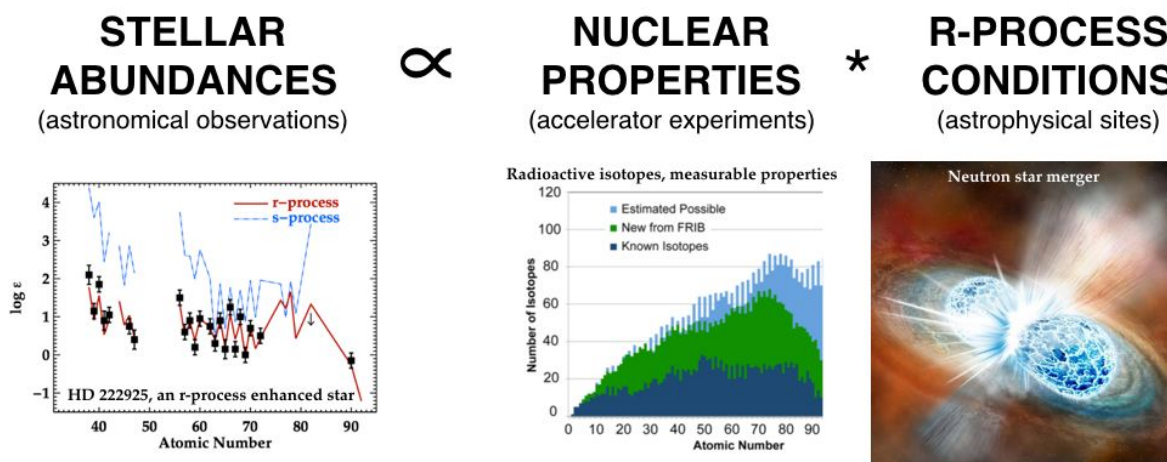


Figure 3: Stellar abundances can be thought of as a product of the nuclear properties and physical conditions of nucleosynthesis. If two are known, the third can be deduced. Spectra of r-process enhanced stars provide the detailed abundance patterns, rare-isotope accelerators provide the nuclear data, and thus the r-process conditions can be inferred through models well-constrained by observations and experiments.

Calibrating actinide production and r-process chronometers—The radioactive actinide isotopes ^{232}Th and ^{238}U are sometimes detected in high-resolution spectra of r-process enhanced stars. Ages derived from their decay are broadly consistent with the r-process events having occurred in the early Galaxy. However, the statistical uncertainties in the Th and U abundance measurements are rarely smaller than a few Gyr for a single star (e.g., Frebel et al. 2007; Placco et al. 2017), and systematic uncertainties in the theory of actinide production limit the utility of these chronometers (e.g., Holmbeck et al. 2018, 2019). Globular clusters offer a natural laboratory to calibrate the r-process actinide production, because they present hundreds of stars with nearly-identical ages and the absolute ages are known to ~ 1 Gyr by independent methods (e.g., Marín-Franch et al. 2009).

High-resolution ($R > 30,000$), blue ($\lambda < 4200 \text{ \AA}$) multi-object ($N > 100$) spectroscopy across a wide field (at least $\sim 10'$, ideally $\sim 30'$) is essential to take advantage of these opportunities. Presently, only two instruments offer such capability, FLAMES at the VLT and M2FS at Magellan, and neither instrument is publicly accessible to the US community. *Acquiring public access to these facilities and next-generation multi-object high-resolution spectroscopic facilities, like the Maunakea Spectroscopic Explorer or MANIFEST/G-CLEF on the Giant Magellan Telescope, will be essential to address questions relying on statistically-meaningful samples of r-process enhanced stars.*

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