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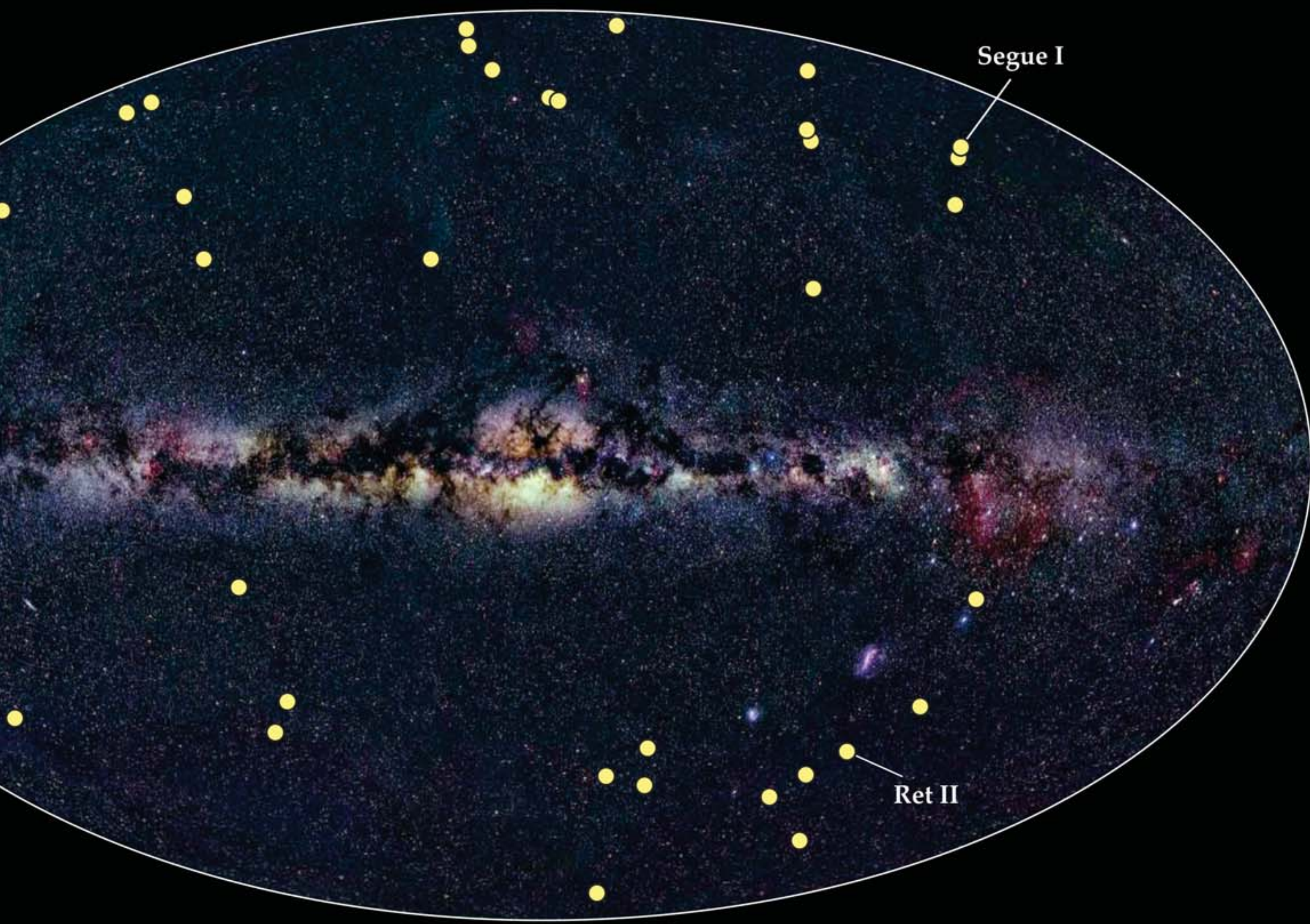
The formation of the HEAVIEST ELEMENTS

Anna Frebel and Timothy C. Beers

The rapid neutron-capture process needed to build up many of the isotopes heavier than iron seems to take place primarily in neutron-star mergers, not supernova explosions.

All of the hydrogen and most of the helium in the universe emerged 13.8 billion years ago from the Big Bang. The remainder of the chemical elements, except for a tiny amount of lithium, were forged in stellar interiors, supernova explosions, and neutron-star mergers. Elements up to and including iron are made in the hot cores of short-lived massive stars. There, nuclear fusion creates ever-heavier elements as it powers the star and causes it to shine. Elements heavier than iron—the majority of the periodic table—are primarily made in environments with free-neutron densities in excess of a million particles per cubic centimeter. The free neutrons, if captured onto a seed nucleus, result in a heavier, radioactive nucleus that subsequently decays into a stable heavy species. The so-called slow neutron-capture process, or s-process, mostly occurs during the late stages in the evolution of stars of 1–10 solar masses ($M_\odot$). But the s-process accounts for the formation of only about half of the isotopes beyond iron. Creating the other half requires a rapid capture sequence, the r-process, and a density of greater than 10^{20} neutrons/cm^3 that can bombard seed nuclei. The requisite neutron fluxes can be provided by supernova explosions (see the article by John Cowan and Friedrich-Karl Thielemann, Physics Today, October 2004, page 47) or by the mergers of binary neutron-star systems.



THIS MAP OF MILKY WAY SATELLITES (yellow dots) was generated by Helmut Jerjen in 2010. The satellite count is now up to about 60. Segue I and Reticulum II (Ret II), both mentioned in the article, are specifically identified. (Satellites map courtesy of Helmut Jerjen; background Milky Way image courtesy of the European Space Observatory.)

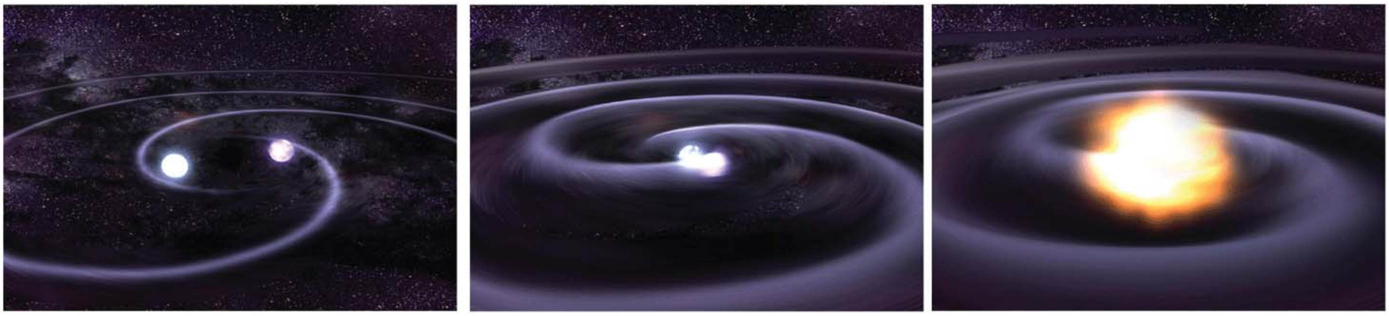


FIGURE 1. A COSMIC DANCE WITH A FIERY END. This artist's conception visualizes, from left to right, the ripples in spacetime created as two neutron stars orbit each other and eventually coalesce. During the merger, copious amounts of heavy elements are produced. (Courtesy of NASA.)

In 2016 the discovery of a tiny, faint galaxy, a satellite of the Milky Way called Reticulum II (Ret II), provided evidence that the supernova-explosion scenario that had long been favored could not be the main mechanism for the production of the heaviest elements. Instead, the chemical composition of the stars in Ret II strongly suggests that neutron-star mergers are the universe's way to make elements such as gold and platinum. The neutron-star formation scenario is supported by striking observations reported in October of last year: the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo interferometer measurements of gravitational waves from the merger of a pair of mutually orbiting neutron stars[1] and associated weeks-long outbursts of electromagnetic radiation pointing to a kilonova event (see references 2 and 3 and PHYSICS TODAY, December 2017, page 19).

Cosmic Rosetta stones

Neutron stars form in the death throes of stars with masses of 10–20 $M_\odot$. Such high-mass stars can form at any time. Theory suggests, though, that they are dominant in the early universe, a few hundred million years after the Big Bang, at which time they have a propensity to be born as binaries.[4]

Mergers of orbiting neutron stars, as we have noted, meet the criteria for the production of r-process nuclei. Figure 1 illustrates such a merger. But even the recent LIGO–Virgo detection of two neutron stars coalescing has added only one piece to the puzzle of understanding the origin of the heaviest elements. Nuclear physicists are still working to model the r-process, and astrophysicists need to estimate the frequency of neutron-star mergers to assess whether r-process heavy-element production solely or at least significantly takes place in the merger environment.

To test r-process models, nuclear physicists will need to obtain measurements or solid predictions of the fundamental properties of heavy, unstable nuclei that lie far from the valley of stability occupied by familiar long-lived isotopes—they'll need to know, for example, about masses, nuclear interaction cross sections, and decay rates. Procuring such data is a primary science driver for several international accelerator facilities. The US representative, the Facility for Rare Isotope Beams, is currently under construction at the campus of Michigan State University and is expected to be completed in 2022.

R-process nucleosynthesis models that use the data generated at accelerator facilities must clear another hurdle:

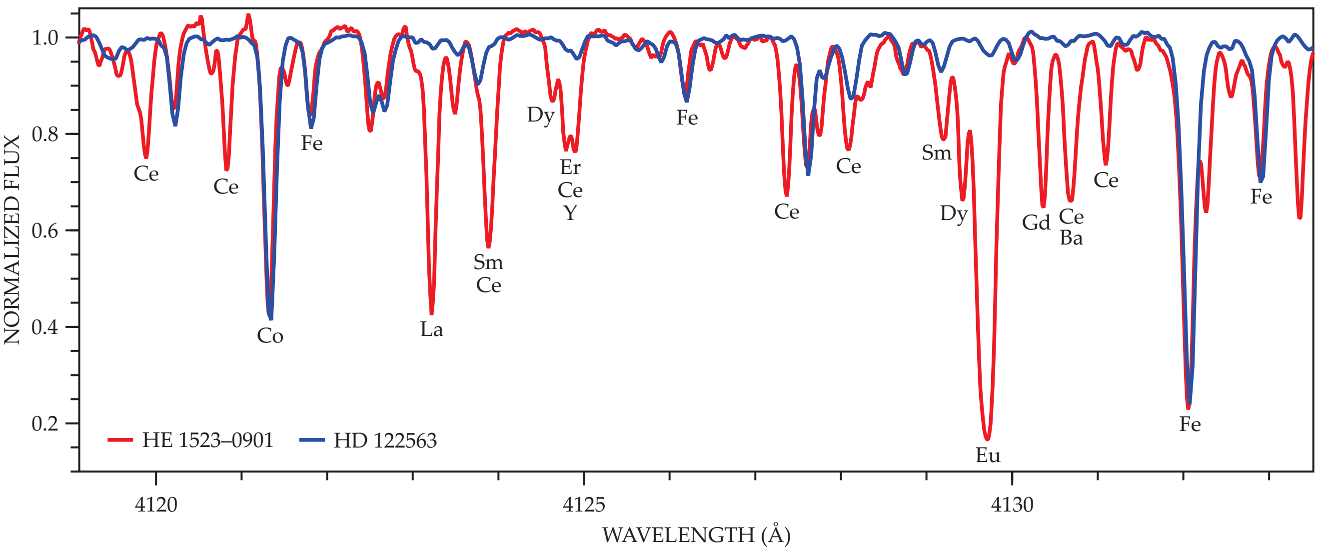


FIGURE 2. TWO OLD STARS. In these spectra, absorption lines are labeled by element symbols. The blue spectrum corresponds to the r-process deficient star HD 122563. The red spectrum, with its pronounced absorption lines for several rare-earth elements, was taken for HE 1523-0901, the most r-process enhanced of all the stars in the galactic halo. (Adapted from ref. 13.)

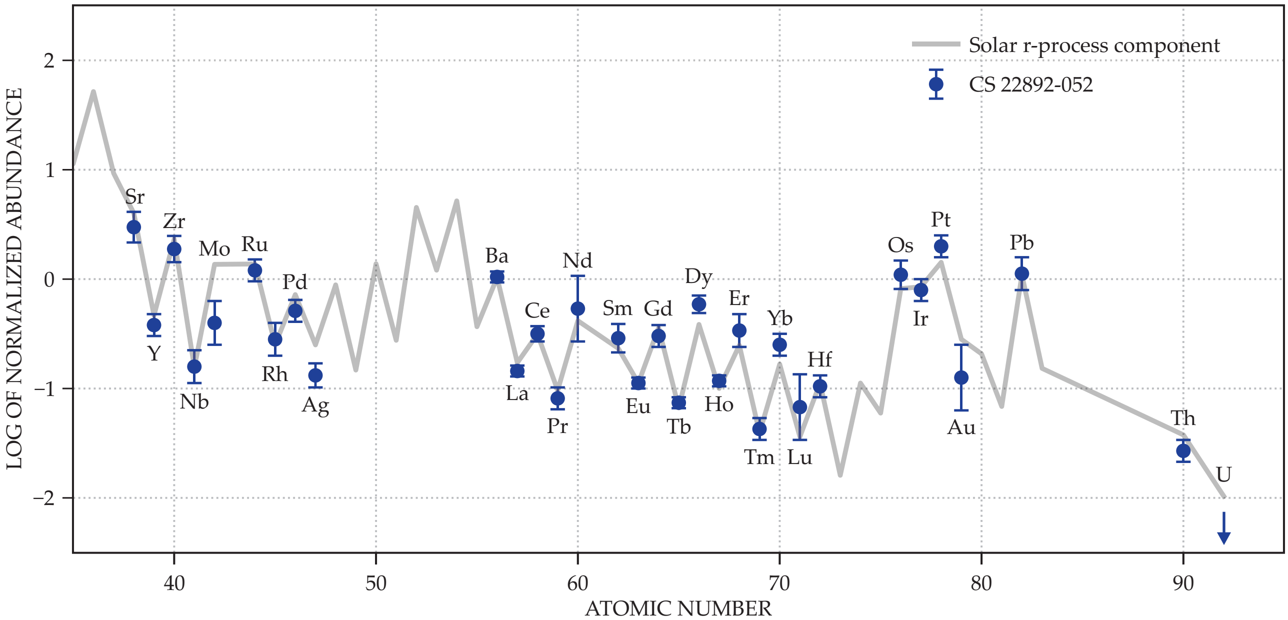


FIGURE 3. PATTERN MATCHING. The abundance pattern of r-process elements in the typical r-II star CS 22892-052 (blue data points) aligns with the r-process solar-system abundances, shown as a gray jagged line for comparison. (Courtesy of Erika Holmbeck, based on data from ref. 14.)

Their predictions must be consistent with constraints derived from astronomical observations of the abundances of heavy elements in the ultimate laboratory, the universe itself. In that regard, Nature has shown scientists a kindness by sprinkling the galaxy with chemically primitive stars that exhibit high levels of r-process elements.

When the r-process was first hypothesized six decades ago,[5,6] the abundances of r-process elements heavier than iron had to be inferred from solar-system material, specifically meteorites and the solar atmosphere. Unfortunately, the material from which the solar system formed included the products of some 8 billion years of chemical-element enrichment from previous generations of stars. That long-term accumulation makes it difficult to extrapolate details of the individual nucleosynthesis events that contributed at various times. But beginning in the 1980s, large-scale surveys began to identify the small population of iron-deficient stars that likely formed in the first billion years following the Big Bang. Those surveys expanded the number of recognized stars with iron abundances less than 1% of the Sun's; nowadays, many tens of thousands of such stars are known.[7,8]

During the past decade, high-resolution spectroscopic studies have revealed that something like 3–5% of those ancient stars have moderately or highly enhanced abundances directly associated with the r-process. They are rare needles in the haystack of the few hundred billion stars that make up our Milky Way, cosmic Rosetta stones that astrophysicists can use to decipher the site and origin of the r-process.

Accumulating clues

Traditional archaeologists examine fossil evidence on Earth to understand ancient civilizations. Practitioners of stellar archaeology search the Milky Way's halo, the low-stellar-density region enveloping the disk of the galaxy, to find the long-lived, low-mass stars that have recorded the chemical history of element production by the now extinct first generations of stars. (See the article by Anna Frebel and Volker Bromm, PHYSICS TODAY, April 2012, page 49.)

Two decades ago Christopher Sneden and colleagues identified CS 22892-052, the first highly r-process-enhanced star in the galactic halo.[9] The announcement came as a great surprise. Even though its measured abundances of iron and elements with similar atomic numbers were about 1000 times lower than those of the Sun, CS 22892-052 had detectable quantities of radioactive thorium. The observed spectral lines, together with theory, suggested that the star had an age in excess of 12 billion years. Admittedly, such determinations may be plagued by large systematic uncertainties, but at face value, the derived stellar age suggests that the r-process must have been operating when the universe was chemically quite primitive.

In CS 22892-052 and other so-called r-II stars, the abundance of r-process elements such as europium relative to that of iron is more than 10 times as great as the abundance ratio in the Sun. Such results are conventionally expressed with a bracket notation: $[Eu/Fe] > +1.0$. The quantity inside the brackets is the abundance ratio; the brackets tell you to compare it with the ratio in the Sun and take the base-10 logarithm. Figure 2 compares the absorption spectrum of an r-II star with that of a more typical old star and shows the strong absorption lines for several rare-earth elements. During the past 20 years, astrophysicists have discovered about 25 r-II stars and some 125 members of a class of moderately r-process-enhanced stars, r-I stars, for which $+0.3 < [Eu/Fe] < +1.0$).

Detailed studies of r-I and r-II stars with ground- and space-based telescopes have produced fundamental clues to the origin of the astrophysical r-process. Here we list some of them.

▶ As figure 3 shows, the overall abundance pattern of the r-process elements in r-II stars is essentially identical to that of the solar system. (The r-I stars also display the same pattern.) And that near identity is despite the fact that the r-I and r-II stars formed from gas that differs significantly from solar-system material. Those stars have $[Fe/H]$ values no larger than −1.5 and sometimes as low as −3.5. Called metallicity, $[Fe/H]$ indicates the overall abundance of elements beyond hydrogen and helium, up to and including iron. Also, r-I and r-II stars

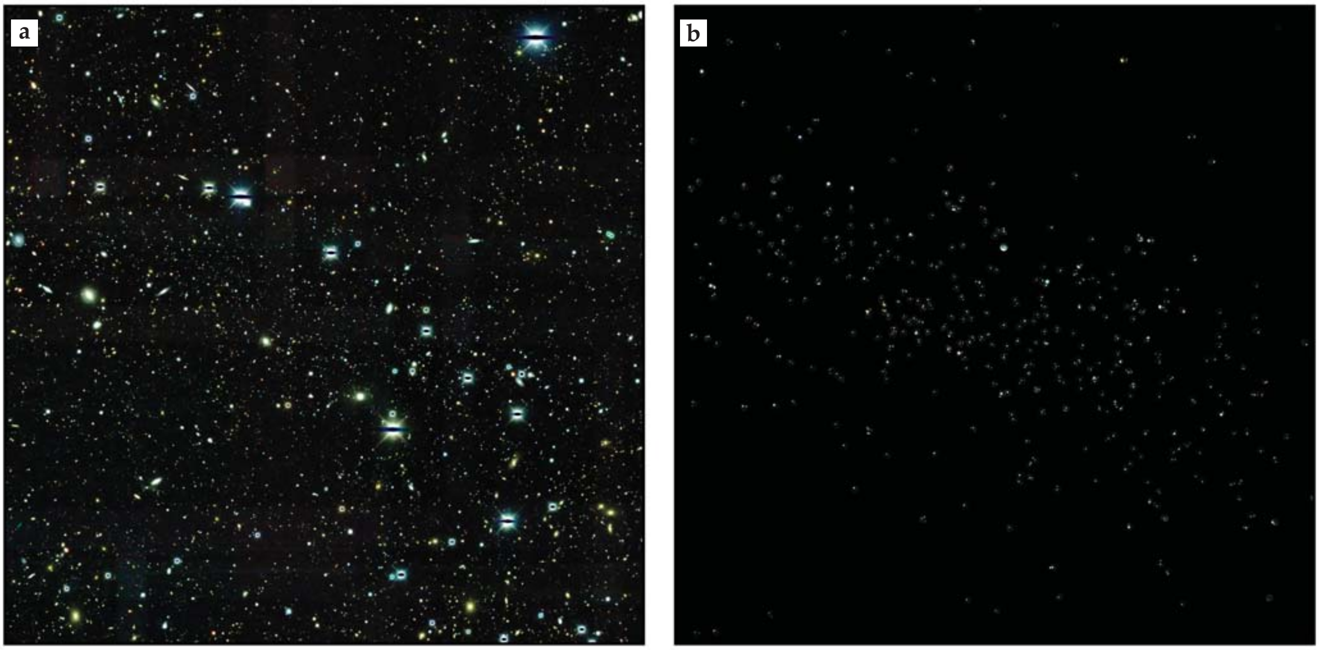


FIGURE 4. A HIDDEN, TINY GALAXY. Reticulum II (Ret II) is an ultrafaint dwarf galaxy on the outskirts of the Milky Way. **(a)** This image shows all the stars in the direction of Ret II. The horizontal bars on the brighter stars arise from saturation effects. **(b)** Sophisticated image search algorithms can identify the stars in panel a that are members of Ret II. A coherent structure is clearly visible. (Courtesy of the Dark Energy Survey/Fermilab.)

presumably formed early in cosmic history, whereas the solar system is a relatively youthful 4.5 billion years old. The similar abundance patterns in such disparate systems indicate a remarkably robust r-process behavior.

▶ Examples of r-I and r-II stars have been found in essentially all stages of stellar evolution, which precludes the possibility that their apparent r-process-element enhancement is the result of peculiar atmospheric chemistry in particular stages of their lives.

▶ Long-term monitoring of the radial velocities of r-I and r-II stars shows no telltale variations that would arise from the presence of a binary companion.[10] That observation argues against models in which r-process elements were formed by a companion star—for example, in a supernova—and then transferred to the presently observed r-I or r-II star. Apparently, the observed stars were born from gas that had already been enriched in r-process elements by a previous source.

▶ The [Fe/H] distributions for r-I and r-II stars are significantly different. For r-II stars, [Fe/H] is concentrated at values ranging from −3.5 to −2.5. For r-I stars, [Fe/H] extends as high as −1.5. The mismatched distributions may point to differences in the birth environments of the r-I and r-II stars. Even if r-I and r-II stars have the same birth environment, it is possible that r-process yields could be diluted differently in natal clouds with different masses. Subsequently formed stars would then display different abundance levels for r-process elements. Alternatively, stars with higher [Fe/H] may have formed from gas that was enriched in iron by an unusually large number of supernova explosions.

▶ About 30% of r-II stars have what is called an actinide boost. Measurements of thorium and in some cases uranium indicate that compared with the other r-II stars, the boosted stars have a three- to fourfold enhancement of those radioactive elements relative to stable elements such as europium. The astrophysical site responsible for the r-process must itself be able to replicate that chemical fingerprint, or else multiple nucleosynthesis pathways must exist that can give rise to the bifurcation of r-II stars.

Clearly, we astrophysicists still have plenty to learn. It does seem probable, though, that the production of the r-process elements took place in the early history of chemical evolution. Moreover, the ancient stars with r-process elements must have formed in environments that limited additional star formation, a process that could erase the distinctive r-process patterns. Such an environment has now been found. It's a tiny, satellite galaxy that we mentioned earlier and will revisit: Reticulum II.

The rise of the dwarfs

The oldest stars in the Milky Way date back to the earliest star-forming events. They likely originated in small galaxies that were later accreted by the Milky Way. As those small galaxies were absorbed, they spilled out their stars created the Milky Way's halo. As a consequence of that disruption, astrophysicists can no longer access the galaxies in which those old stars formed.

However, we can derive information about the destroyed galaxies through studies of the ancient stars in the satellite galaxies that still orbit the Milky Way. That approach uses surviving dwarf galaxies to explore the nature of similar galaxies in the early universe. The dwarfs are likely next on the table to be eaten by the Milky Way, but before they are consumed they provide safe havens for stars that have remained members of their parent galaxy since their birth. We can study the detailed chemical compositions of those stars to learn about the early chemical enrichment in dwarf galaxies. Even more important, we can study the environments in which those stars formed.

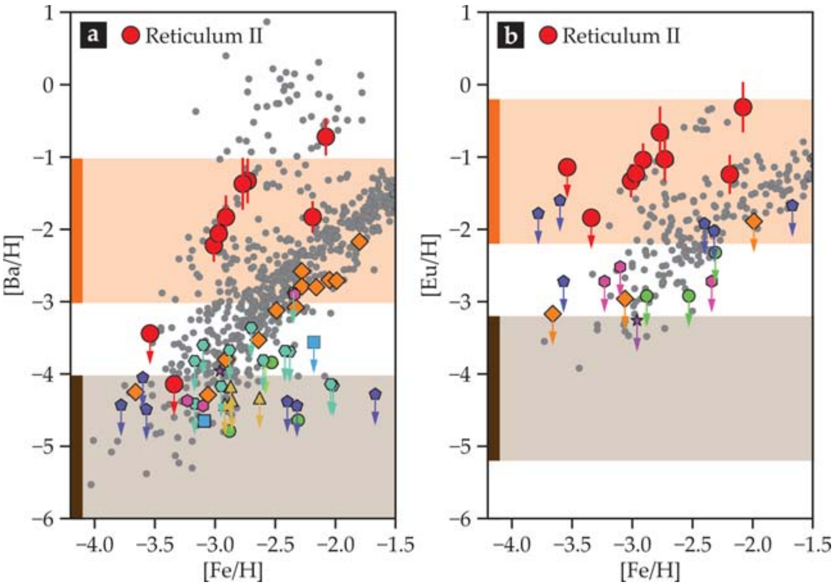


FIGURE 5. A CHALLENGE TO SUPERNOVAE. Shown here are **(a)** barium-to-hydrogen and **(b)** europium-to-hydrogen chemical-abundance ratios of stars as a function of their iron-to-hydrogen abundance ratio. (The bracket notation on the axes is explained in the main text.) Red filled circles indicate stars in the ultrafaint dwarf galaxy Reticulum II, the other colored symbols indicate stars in other UFDs, and gray filled circles indicate stars in the halo of the Milky Way. Arrows indicate data for which only upper limits are known, and error bars represent one standard deviation. The orange bars along the *y*-axes indicate a range of heavy-element abundances predicted by models that posit neutron-star mergers as the source of r-process elements; the brown bars give estimates assuming a supernova is the source. Until the discovery of Reticulum II, data tended to support the supernova picture. But even then, the supernova models had their problems, and Reticulum II is certainly inconsistent with a supernova source. (Courtesy of Alexander Ji; adapted from ref. 11.)

Prior to 2006 only a handful of dwarf satellite galaxies were known to orbit the Milky Way. Indeed, their apparently small numbers challenged formation models of large galaxies like ours. Theory and numerical simulation had predicted that many more smaller systems should be orbiting the Milky Way, like bees swirling around a giant hive. A couple of years later, once the Sloan Digital Sky Survey (SDSS) completed its imaging of the northern sky, much of the tension was alleviated. Moreover, analysis of the deep, large-scale imagery obtained by the SDSS revealed a new type of small, very faint dwarf—ultrafaint dwarf galaxies, or UFDs.

The SDSS eventually found about 15 UFDs; today the Milky Way's total satellite count is close to 60. Those little systems are remarkable. They are nearly devoid of gas and extremely old, and most contain only a few thousand stars—even fewer than typical star clusters. Yet many UFDs possess extended dark-matter halos, as determined from velocity dispersions derived from the motions of their stars. Those dark-matter envelopes define the UFDs as true galaxies, inasmuch as star clusters do not contain dark matter. Because UFDs are so sparsely populated, they cannot easily be seen as coherent objects in an astronomical image, which is why they were overlooked until recently. Spotting a UFD requires sophisticated algorithms to search an image and identify stars that, among other criteria, are located at the same distance from the Sun. Figure 4 shows an example of the sky in the direction of a UFD galaxy, compared with an image that includes just UFD member stars.

Data taken in 2015 by the Dark Energy Survey revealed a batch of UFDs in the southern sky. The new survey results confirmed that small satellite galaxies are ubiquitous, as originally predicted. Subsequent chemical-abundance studies of the stars in the newly discovered dwarf galaxies confirmed the satellites to be chemically primitive and very old. They exhibit the signatures of the earliest element-production events, and at least one of them, Segue 1, may be among the first galaxies to have ever formed. Somehow it managed to survive to the present.

Gold in the halo

Reticulum II is another of the noteworthy UFDs in the Milky Way halo. Located just 30 kiloparsecs (100 000 light-years) from Earth, Ret II is quite close for an orbiting satellite. Still, detailed high-resolution spectroscopy is necessary for an accurate estimate of the chemical composition of its individual stars and thus of its natal gas. To obtain the spectra, a spectrograph mounted at the telescope splits starlight into its rainbow colors. As a result, the starlight is distributed over many detector pixels; each individual pixel has only a small signal. Long exposure times compensate for the tiny signal, and for bright stars, one doesn't have to wait ridiculously long to obtain data with the desired quality. But faint stars such as those in even the closest UFDs push current telescope and detector technologies to their limits. Only the brightest stars in a dwarf galaxy are, in principle, observable, and each one of those may require an entire night's exposure time.

In 2015 Alexander Ji and one of us (Frebel) used the 6.5 m Clay Magellan telescope in Chile to obtain high-resolution spectra of the brightest stars in Ret II. We expected to find the same pattern of elemental abundances for the Ret II stars as had been seen in all other dwarf galaxies. To our surprise, we found instead that seven of the nine stars that could be observed showed an unusual, extreme enhancement in the heaviest elements of the periodic table—they were all r-II stars. Previously, the r-II signature had been seen only in rare Milky Way stars. We had found the first r-process galaxy.[11]

Apparently, when Ret II was still young, an r-process nucleosynthesis event enriched the gas that ultimately formed the stars we are observing today. The great enhancement of r-process heavy elements in the UFD's stars, coupled with a knowledge of the stars' formation environment, led us to conclude that a neutron-star merger was likely responsible for Ret II's r-process enrichment.

Figure 5 displays the abundances of the r-process elements europium and barium in Milky Way halo stars and dwarf galaxy stars, including those in Ret II. The plots also show estimates for the elemental yields in neutron-star mergers and supernovae. Before the discovery that Ret II was an r-process galaxy, the preponderance of data for ancient Milky Way stars had suggested that the likely site of r-process heavy-element production was core-collapse supernovae, which have a short enrichment time scale. Even so, for decades lingering doubts persisted among nuclear physicists. In hindsight, given the host of issues with supernova models, it has become clear that an understanding of the birth environment is crucial. A knowledge of, for example, the mass of a birth galaxy or the dynamical processes taking place therein could enable astrophysicists to estimate the degree to which an r-process yield is diluted. Theory could then be compared with the observational data and finally, perhaps, we'll be able to answer the questions of when, where, and how the r-process created the heaviest elements, including the jewelry-store elements gold and platinum.

At least for Ret II, one can clearly rule out a supernova origin for r-process-element production. The observed r-process enhancement would have required hundreds to thousands of supernovae, and a small UFD galaxy simply does not have sufficient binding mass to have survived such a large number of cataclysms. Of course, some supernovae must have exploded in Ret II, but a small number would not produce significant amounts of r-process elements.

On the other hand, as figure 5 demonstrates, the predicted r-process heavy-element yield of a single neutron-star merger does agree well with element abundances observed in Ret II. Furthermore, the merger picture passes a timing test that it could in principle have failed. It turns out that once the first generation of stars in a system like Ret II explodes and injects energy into the system, the galaxy needs about 100 million years to cool sufficiently for another round of star formations. That's just enough time for the members of a neutron binary to spiral in toward each other and merge.

The r-process-enhanced stars in Ret II and those in the galactic halo have basically identical elemental-abundance signatures. The only thing that separates them is that the dwarf galaxy stars have known birthplaces, whereas individual halo stars do not. From consideration of how the r-process-enhanced stars were formed in Ret II, it seems that the r-I and r-II halo stars were born in systems of a similar nature. In that sense, Ret II may be viewed as a missing link that connects the r-I and r-II stars strewn throughout the halo of the Milky Way.

Meanwhile, Terese Hansen and colleagues recently found another UFD galaxy—Tucana III, somewhat more massive than Ret II—that exhibits signs of r-process-element enrichment from a neutron-star merger.[12] They used high-resolution spectroscopy to observe the brightest of its stars, which they showed to be an r-I star. The astrophysical community is waiting for data from additional stars to firm up any conclusions about Tucana III, but in any case, more than a dozen r-I stars had been previously identified among dwarf galaxies that are not UFDs, including Draco, Ursa Minor, Sculptor, and Carina. Such observations imply that enrichments from neutron-star mergers, though rare, are not unique to the UFDs.

Putting it all together

The above-discussed clues to the astrophysical origin of the r-process have generated great excitement and spurred new efforts to identify r-I and r-II stars in the galactic halo. The goal is to find about 500 r-I stars and 100 r-II stars and use them to refine estimates of the frequency of such stars throughout the halo, quantify potential variations in the abundance patterns of r-process heavy elements, and better constrain the fractions of r-II stars that exhibit the actinide boost. Together with an international team and using various telescopes worldwide, the two of us are currently combing through thousands of candidates to find those rare gems. Our pilot survey has already identified at least 14 new r-II stars and many more new r-I stars.

As new UFD galaxies are discovered, their brightest stars will be observed with high-resolution spectroscopy to yield an understanding of their chemical makeup and thus their star-formation and chemical-enrichment histories. The identification of additional r-process-enhanced dwarf galaxies will enable astrophysicists and nuclear physicists to interpret, readily and in unprecedented detail, the nucleosynthetic products of the r-process in the simplest possible environment.

Ongoing research will also pave the way to learning more about the hierarchical buildup of the Milky Way halo itself. One clear advantage of the halo stars is that they are much brighter than stars in the dwarf galaxies; it is relatively easy to obtain high-quality spectroscopic abundance measurements for detailed studies of r-process elements. Moreover, the population of r-process-enhanced stars in the galactic halo can serve as a tracer of the early-accreted dwarf galaxies that built the outer-halo region of the galaxy. Admittedly, many uncertainties need to be addressed, but the promising new approach of studying galaxy formation via stellar chemical signatures is ultimately grounded in our understanding of the nuclear physics of element production. Armed with a more complete census of the r-process-enhanced stars both in the halo and in dwarf galaxies, astrophysicists should be able to reconstruct how the Milky Way was assembled and thus gain much needed clues about the nature of the r-process and in particular the astrophysical site where it takes place.

Theoretical and observational programs spanning the globe are providing increasingly strong constraints on the r-process, and new nuclear accelerator facilities under construction promise to furnish a wealth of new data. The multidisciplinary endeavor involves nuclear physics, gravitational physics, and astronomy. Properly synthesized, the contributions from those fields have the potential to yield a solution to one of the most challenging riddles posed by the cosmos and a full understanding of how the elements in the periodic table came to be.

REFERENCES

1. B. P. Abbott (LIGO Scientific Collaboration, Virgo collaboration), *Astrophys. J. Lett.* **848**, L13 (2017).
2. M. R. Drout et al., *Science* (2017), doi.10.1126/science.aaq0049.
3. B. J. Shappee et al., *Science* (2017), doi.10.1126/science.aaq0186.
4. S. E. de Mink, K. Belczynski, *Astrophys. J.* **814**, 58 (2015).
5. E. M. Burbidge et al., *Rev. Mod. Phys.* **29**, 547 (1957).
6. A. G. W. Cameron, *Astron. J.* **62**, 9 (1957).
7. T. C. Beers, N. Christlieb, *Annu. Rev. Astron. Astrophys.* **43**, 531 (2005).
8. A. Frebel, J. E. Norris, *Annu. Rev. Astron. Astrophys.* **53**, 631 (2015).
9. C. Sneden et al., *Astrophys. J. Lett.* **431**, L27 (1994).
10. T. T. Hansen et al., *Astron. Astrophys.* **583**, A49 (2015).
11. A. P. Ji et al., *Nature* **531**, 610 (2016).
12. T. T. Hansen et al., *Astrophys. J.* **838**, 44 (2017).
13. A. Frebel, in *Proceedings of the 10th Symposium on Nuclei in the Cosmos*, SISSA (2008), article 025.
14. V. M. Placco et al., *Astrophys. J.* **844**, 18 (2017).

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