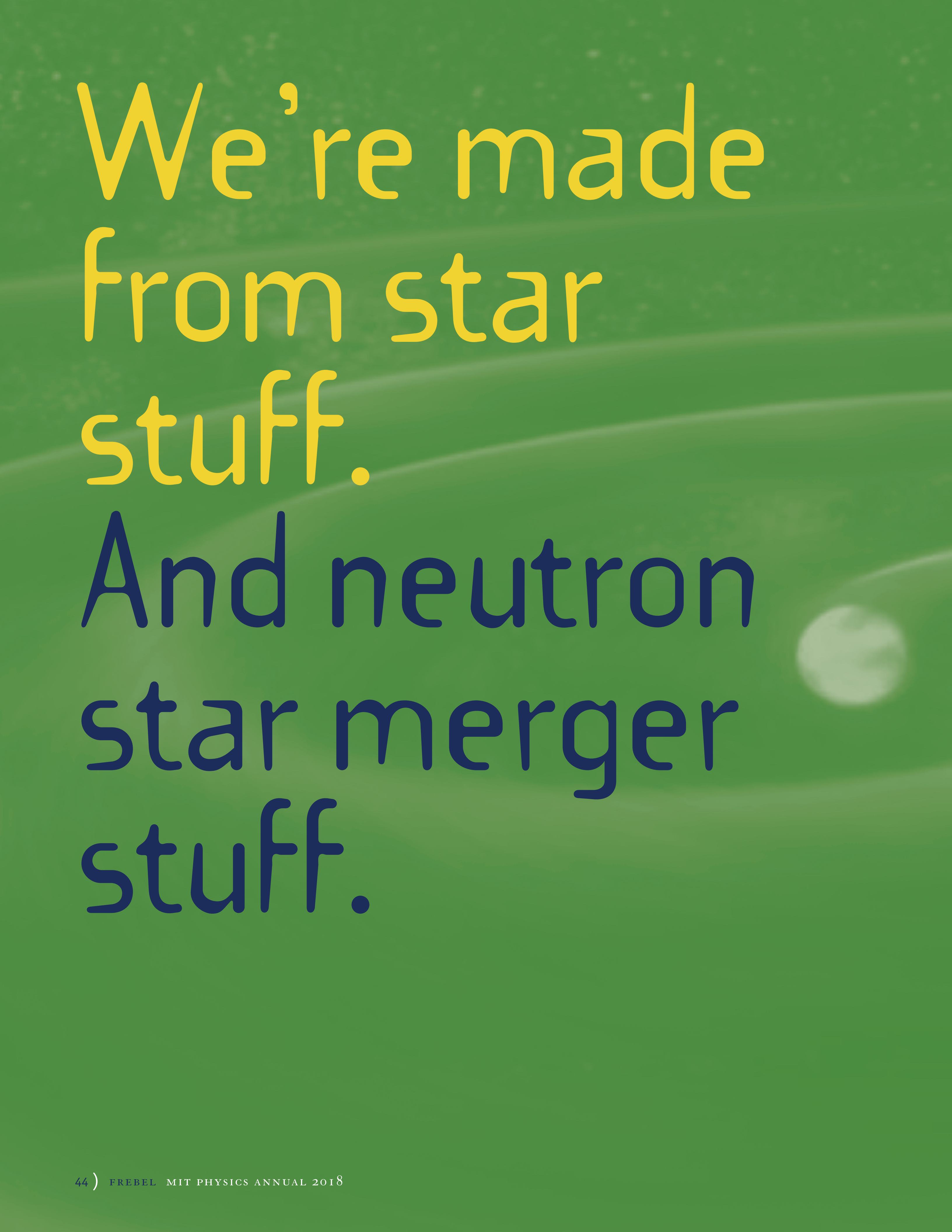


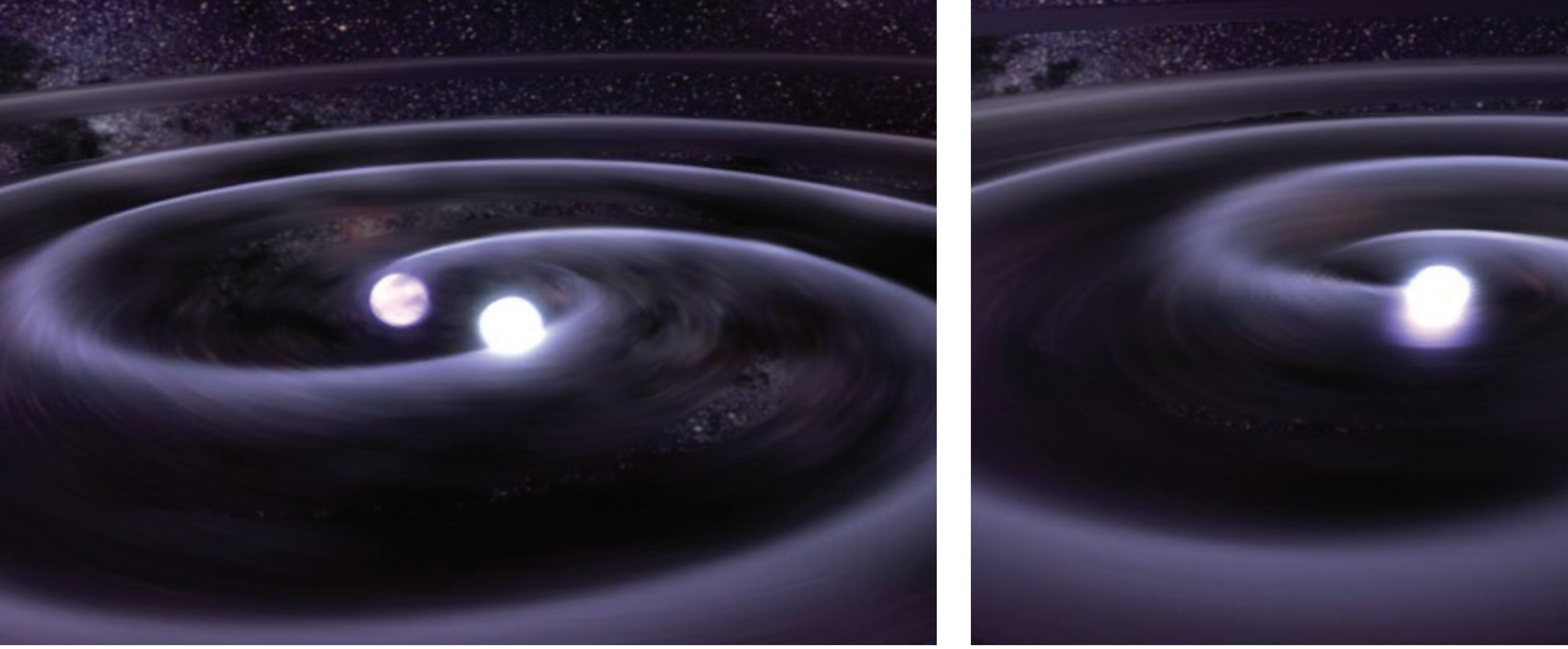
We’re made from star stuff.

And neutron star merger stuff.

by Anna Frebel

Most people are familiar with Carl Sagan's famous quote "We're made from star stuff." For decades, it conveyed to the general public the idea that the chemical elements are made in stars. It explained a connection between us and the cosmos that is usually hard to grasp. Recent discoveries in the fields of stellar archaeology and gravitational wave physics now suggest this connection to be even deeper; there is actually more to the story than previously thought.

Elements up to and including iron continue to be made in the hot cores of short-lived stars more massive than about eight solar masses. Through various nuclear fusion processes, protons are converted successively into heavier elements which produce the energy needed for a star to shine. But elements even heavier are made differently, and not necessarily exclusively in stars. Seed nuclei which find themselves in environments with a high density of free neutrons (greater than 10^6 neutrons per cm^3) grow by capturing those free neutrons. But very neutron-rich nuclei are



radioactive, so they decay into all the heavy elements found in the bottom portion of the periodic table. The so-called “slow” neutron-capture process (s-process) mostly occurs in the late stages of stellar evolution for stars in the mass range of one to about ten times the solar mass. Roughly half of the isotopes that make up all elements beyond iron are made this way. To produce the other half of the isotopes a much larger neutron density is required (greater than 10^{20} neutrons per cm^3). Then, the “rapid” neutron-capture process (r-process) can occur. In the r-process, seed nuclei are heavily bombarded with neutrons on timescales much faster than their radioactive decays. The resulting large unstable, neutron-rich nuclei then decay to form heavy stable isotopes. Recent astronomical observations have revealed new insights into the r-process—that it likely does not occur in ordinary stars but exotic stellar remnants, so-called neutron stars which are small about 10-km-sized objects made from neutrons packed at the density of atomic nuclei. This paints the deep connections between us and the cosmos in a new light.

How the heaviest elements are made: Solving a 60-year-old problem

In the six decades since nuclear physicists first inferred the existence of the r-process, it has been unclear where in the cosmos this type of element production occurs. Astrophysical sites that could possibly provide such strong neutron fluxes include supernovae explosions and the mergers of binary neutron stars. With recent discoveries, the latter possibility is now strongly favored. Despite their name, neutron stars are not powered by fusion energy like other stars. They are extremely compact remnants, formed in the death throes of stars in the range of 10-20 times the solar mass. Such high-mass stars can form at any time in the history of the universe, but were likely dominant a few hundred million years after the Big Bang. When two neutron stars happen to orbit each other and eventually coalesce, the explosive merger sends out tiny ripples in the fabric of space time—gravitational waves. *Figure 1* shows an illustration of such a merger. As of 2017, such events are now

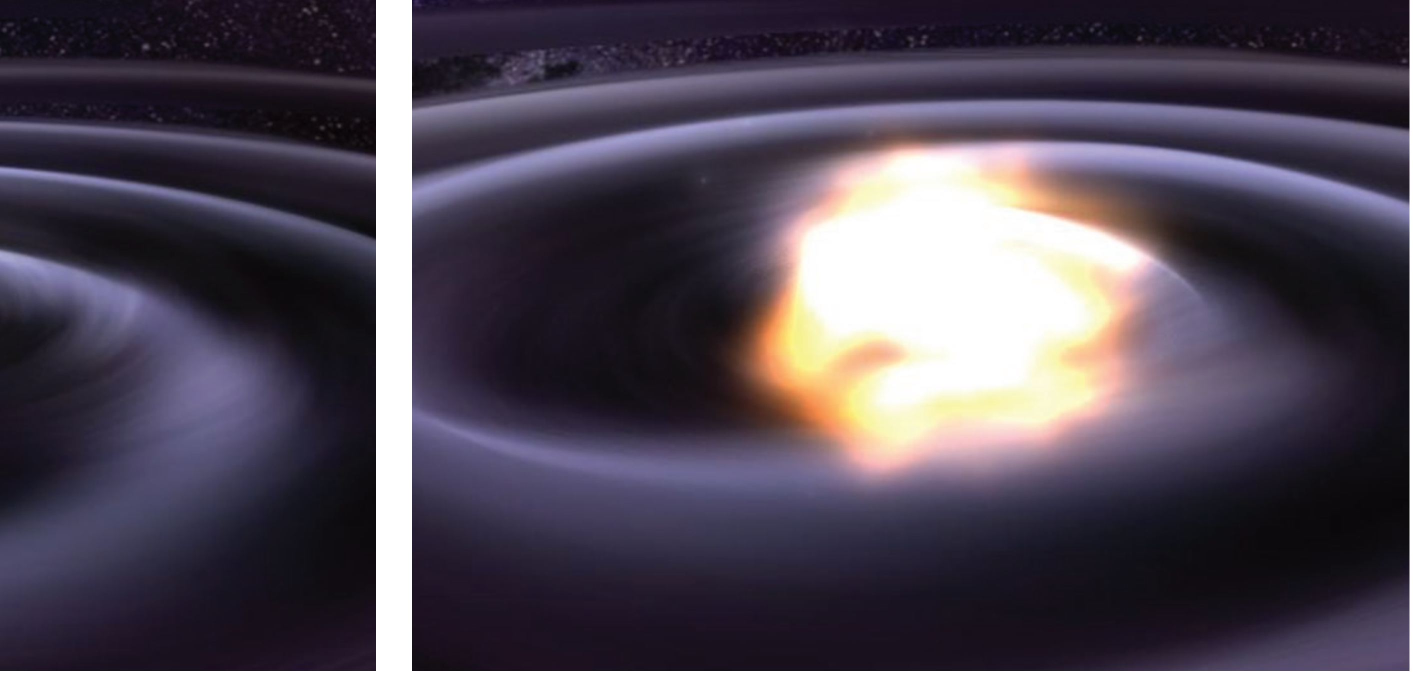


FIGURE 1

Artist's impression of a cosmic dance *with a fiery end: Two neutron stars that orbit each other eventually coalesce. During the merger, copious amounts of heavy elements are produced. [Credit: NASA / D. Berry]*

detectable by the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo interferometer observatory. Importantly, during such a merger, conditions are met for heavy element nucleosynthesis through the r-process to occur. After all, immediately following the first detection of a gravitational wave signature of a neutron star merger, a gigantic outburst of light and radiation—a so-called kilonova—was observable across the electromagnetic spectrum for several weeks. This "visible" event arose from the radioactive decay of the heavy neutron-rich isotopes produced by r-process nucleosynthesis during the merger.

Nearly two years prior to the LIGO detection, my then-student Alex Ji and I used our MIT-sponsored access to the 6.5 m Magellan telescope in Chile to observe the brightest stars in one of the faintest dwarf galaxies that orbits our Milky Way Galaxy, Reticulum II. *Figure 2* shows images of the portion of the sky in the direction of Reticulum II, one with all foreground stars still present and one with them carefully removed. As can be seen, what is left is a galaxy that is extremely faint and does not contain more than a few thousand stars.

Using high-resolution spectroscopy, we wanted to explore the chemical composition of this ancient, ~13-billion-year-old dwarf galaxy which appears to have been born in the early phases of the Universe. We expected to find a certain pattern of

FIGURE 2

Picture of the ultra-faint dwarf galaxy *Reticulum II. Left: All stars in the direction of Reticulum II. The horizontal bars on the brighter stars are saturation effects. A galaxy cannot easily be made out among all the stars. Right: Only those stars that were identified as members of Reticulum II; a coherent structure is now visible. [Credit: Dark Energy Survey/Fermilab]*

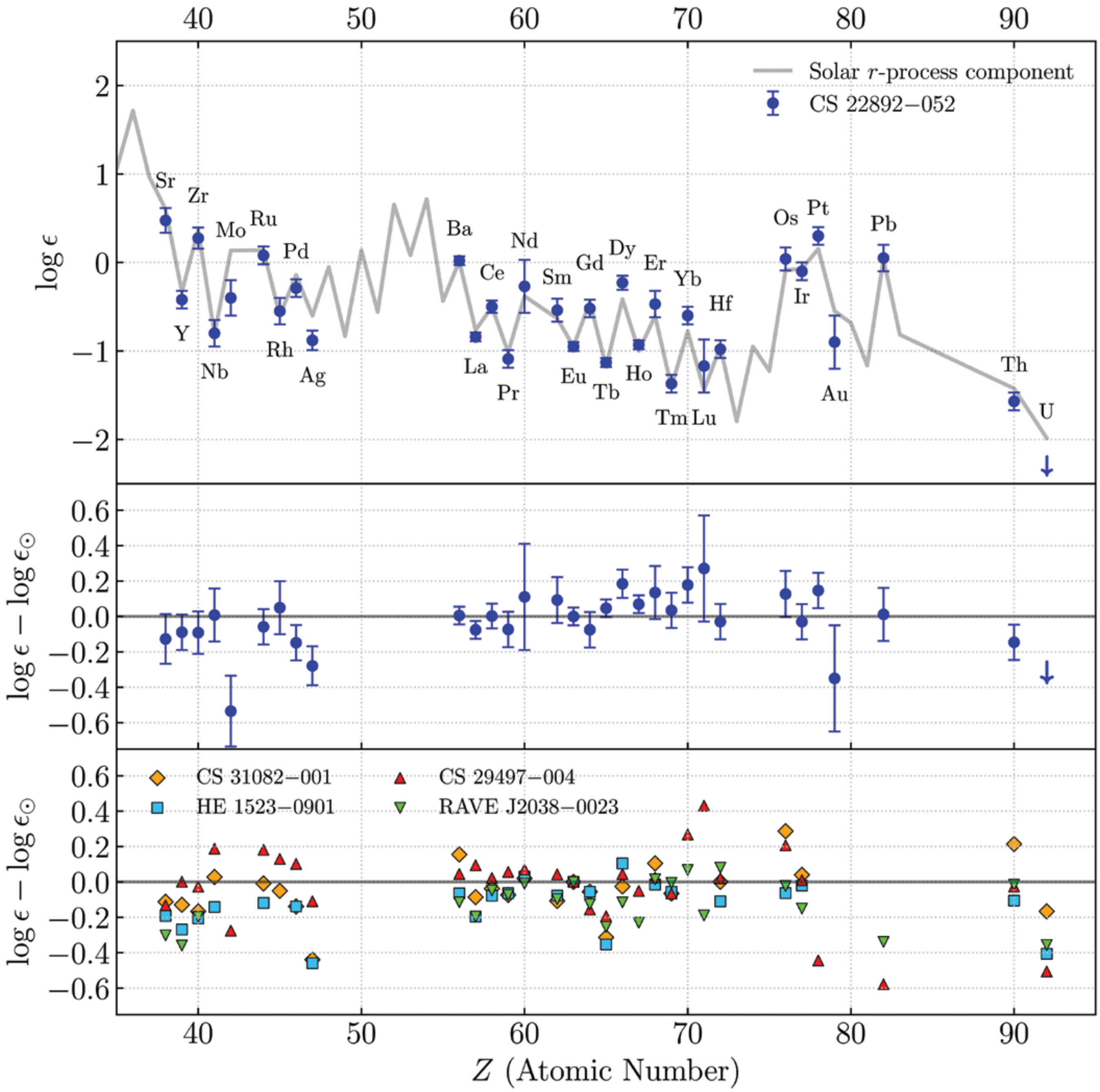


FIGURE 3

The r-process element abundance pattern *of the typical r-process enhanced halo star CS 22892-052, compared with the Solar System r-process pattern. This pattern is obtained by subtracting the well-understood s-process contribution from the total Solar abundances. The lower panel shows the residuals of these abundances relative to the Solar pattern. The derived patterns are quite robust from star-to-star. [Credit: Erika Holmbeck, based on data presented in Placco et al., 2017]*

elemental abundances for the Reticulum II stars, just the same as for stars in the other faint dwarf galaxies. Instead, from our detailed chemical abundance analysis, we found something rather different. Seven of the nine stars observed showed an unusual, strong enhancement in the heaviest elements known from the periodic table—*they were all r-process enhanced stars*. This characteristic universal r-process pattern had only been previously seen in rare Milky Way stars. The pattern of an r-process enhanced star compared to that of the Sun is shown in *Figure 3*. Thus, we had found the first "r-process galaxy."

This remarkable discovery of an entire r-process galaxy ultimately provided the critical evidence to rule out the long-favored supernova explosion scenario as

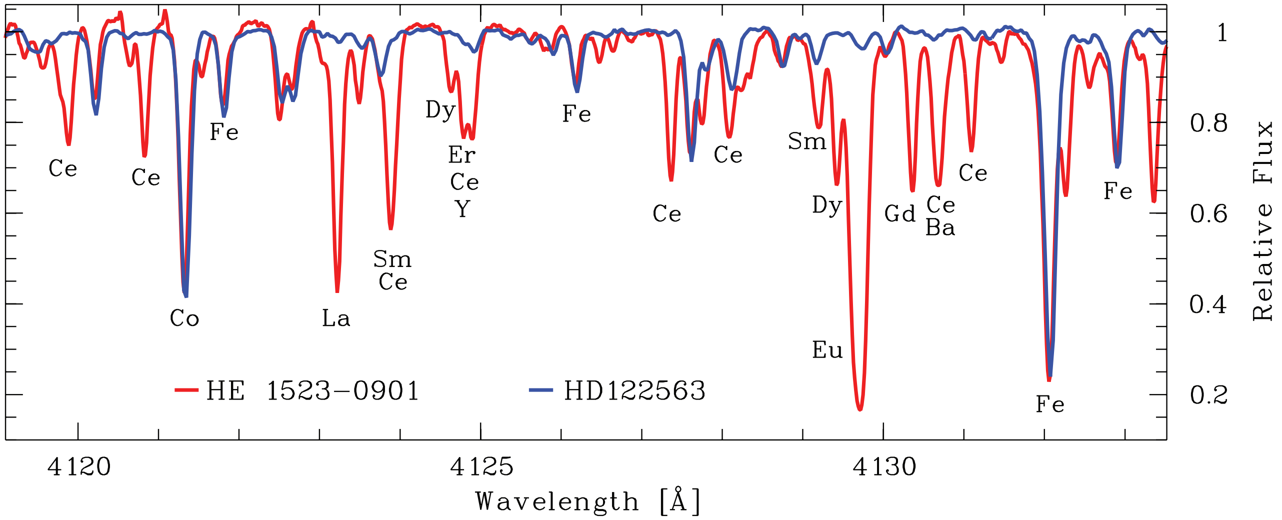


FIGURE 4

Comparison of the spectra *around a europium absorption line at ~ 4130 Ångstrom (= 413 nm) of two old stars. One (blue line) is the r-process element deficient star HD 122563, the other (red line) is the most r-process enhanced halo star HE 1523–0901. The existence of the spectral absorption lines from r-process elements is clear. [Credit: Frebel et al., 2008.)*

the main site responsible for the production of the heaviest elements. Details of this conclusion are explained below, where it is further laid out that the chemical composition of the stars in Reticulum II indeed strongly suggested that neutron star mergers are the Universe's way to create the heaviest elements, including the "jewelry store" elements gold and platinum.

Dwarf galaxy archaeology

Just as archaeologists examine the fossil evidence to understand ancient civilizations, practitioners of "stellar archaeology" search the Galaxy's halo to find long-lived, low-mass stars. "Halo" refers to the extended spherical low-stellar-density region that envelops the disk of the Milky Way where old stars, star clusters, and dwarf galaxies reside. The 13-billion-year-old stars have recorded in their atmospheres the chemical history of element production by the now long extinct first generations of stars. Over the past two decades, high-resolution spectroscopic studies of ancient halo stars with large telescopes have revealed the presence of a tiny subset (~ 3-5%) of stars with enhanced abundances directly associated with element production by the r-process. The spectrum of an r-process enhanced star in comparison with a "normal" old halo star is shown in *Figure 4*. The by now three dozen of known r-process enhanced stars are extremely rare among the hundreds of billions of stars in our Milky Way galaxy. But these gems are of great importance for deciphering the astrophysical site and origin of the r-process.

The rarity of these Milky Way stars explained our great surprise at suddenly finding multiple r-process enhanced stars in one single dwarf galaxy. But this fortuitous circumstance held the key to fundamentally advancing our understanding of the r-process. Because all of the observed stars come from the *same* dwarf galaxy, their place of origin is known. Hence, environmental information such as the mass of gas available for star formation is available.

The high level of enhancement for the heavy r-process elements in these stars, coupled with knowledge of the nature of the formation environment, led to the conclusion that a neutron star merger was likely responsible for Reticulum II's r-process enrichment. A comparison of estimates for the yields of a neutron star merger and a supernova with the stellar abundances of r-process elements in Reticulum II are presented in *Figure 5*. Prior to this discovery of Reticulum II, the preponderance of data for ancient Milky Way halo stars had strongly suggested that ordinary core-collapse supernovae were the likely site of heavy r-process element production. This scenario—which had not taken into account that the origin of these halo stars is essentially unknown—had encountered lingering doubts among nuclear physicists and supernovae nucleosynthesis experts for decades. The halo of our Galaxy was formed over billions of years by the accretion and disruption of smaller galaxies, many at the earliest times. The oldest stars found in the halo of the Milky Way today date back to the earliest star-forming events, and likely originated in some of these small galaxies. These were later absorbed into the Milky Way, spilling all their stars into the stellar halo. As a consequence, direct knowledge of the nature of the original host galaxies in which these stars formed was lost.

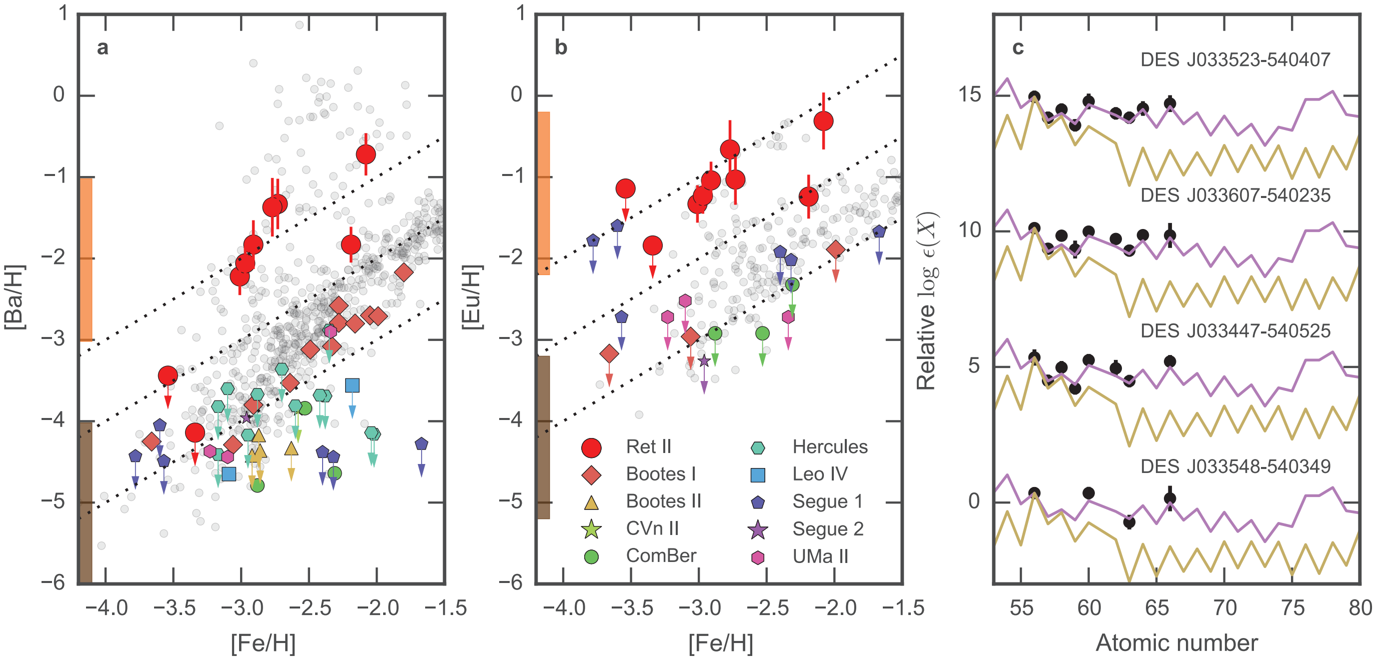


FIGURE 5

***Barium-to-hydrogen and europium-to-hydrogen** chemical abundance ratios of stars in Reticulum II, as a function of their iron-to-hydrogen metallicity. Stars in Reticulum II are shown as red filled circles. For comparison, halo stars are shown as gray open circles, and stars in ultra-faint dwarf galaxies in various colored symbols. Arrows denote upper limits. Error bars are one standard deviation. [Credit: A. Ji; adapted from Ji et al., 2016]*

With the wisdom of hindsight, it has quickly become clear that recognition of the birth environment of r-process enhanced stars provides the last missing piece of information in the quest of understanding the astrophysical site of the r-process. Hence, observing the signature of the r-process in a small, closed system prompted a drastic re-interpretation of its nucleosynthetic origin, as follows.

1. The supernova-origin model can clearly be ruled out, given that the observed total enhancement level achieved in Reticulum II would have required hundreds

to thousands of such explosions. A small dwarf galaxy does not have sufficient binding mass to have survived a large number of supernovae explosions, so one could not increase the total yield of r-process elements by simply adding more supernovae to the system.

2. However, the predicted heavy r-process element yield of a single neutron star merger agreed well with the observed level found in Reticulum II, as seen in *Figure 5*. Some supernovae must of course have exploded in Reticulum II—just without producing any significant amount of r-process elements. This is actually observed in the two of seven stars that did not show r-process enhancement.
3. About 100 million years are needed for such a small dwarf galaxy to cool sufficiently to form the next generation of stars, following the explosion of the very first stars that provided a major energy injection. This leaves just enough time for the members of a neutron star binary to in-spiral and eventually merge. Perhaps most conclusively, the level of r-process element enhancement in the Reticulum II stars matches that of the halo r-process enhanced stars, suggesting that they likely share a common origin. The amount of r-process elements in the gas could only have been diluted by a limited amount due to the relatively small gas content of the dwarf galaxy.
4. Another (somewhat more massive) dwarf galaxy has been recently found that also exhibits signs of r-process element enrichment from a neutron star merger: Tucana III. So far, only the very brightest star in this dwarf could be observed with high-resolution spectroscopy, and it was shown to be a moderately r-process enhanced star. Data for additional stars are needed to firm up any conclusions about this galaxy, but more than a dozen similar stars have been previously identified among the relatively more massive "canonical" dwarf spheroidal galaxies, such as Draco, Ursa Minor, Sculptor, and Carina—implying that enrichments from neutron star mergers may be rare, but they are not unique to the smallest, faintest dwarfs.

Excitement from these new critical clues to the astrophysical origin of the r-process have already spurred efforts to identify larger numbers of halo r-process enhanced stars, aiming for a total of about 500 r-process stars with a range of enhancement levels. These new data will enable refined estimates of their frequency throughout the Milky Way's halo, and quantify the extent of abundance variations in the patterns of the heavy r-process elements. Together with an international team, which includes students and a postdoc from my research group, and using a variety of telescopes worldwide, we are currently combing through thousands of candidates to find these rare gems. As of March 2018, about 80 r-process stars have already been identified from our pilot survey observations.

Once we have obtained a more complete census of the r-process enhanced stars in both the halo and in dwarf galaxies, we will be able to reconstruct how the Galaxy was assembled. While many remaining uncertainties still need to be addressed in the coming decade, this promising new avenue to study galaxy formation with stellar chemical signatures is ultimately grounded in our understanding of the nuclear physics of element production in the cosmos. Testing of the models for r-process production requires nuclear physicists to obtain measurements, or very good predictions, of the fundamental properties (*e.g.*, masses, nuclear interaction cross sections, and decay rates) of heavy, unstable nuclei that lie far from the valley of stability occupied by the familiar long-lived isotopes of the elements. The desire to carry out such studies is one of the primary science drivers for several international accelerator facilities, such as the Facility for Rare Isotope Beams (FRIB), now under construction on the campus of Michigan State University (expected completion in 2022). Other facilities that are gearing up for similar research are GSI-FAIR in Germany, CERN in Switzerland, RIKEN in Japan, GANIL in France, and RAON in South Korea.

In addition, as new, very faint dwarf galaxies are discovered, their brightest stars will then be observed with high-resolution spectroscopy to understand their chemical make-up, and thus their cosmic star formation and chemical enrichment history. The exciting prospect of identifying additional r-process enhanced dwarf galaxies will enable us to examine, in unprecedented detail, the nucleosynthetic products of the r-process in readily interpretable environments.

The convergence of a number of research fronts, including the LIGO/Virgo discoveries, the multiple new nuclear accelerator facilities under construction, and numerous theoretical and observational programs that span the globe, provides increasingly strong constraints on the nature of the r-process. The combined scientific advances currently being produced by nuclear physics, gravitational wave physics, and astronomy thus have the potential to resolve one of the most challenging outstanding questions of the cosmos. The long-awaited identification of the astrophysical site of the r-process, which is required for a full understanding of the origin of the elements in the periodic table, may well soon be obtained.

This article is an extensively revised version of a longer article by Professor Frebel, orginally published in Physics Today*, vol. 71, issue 1, pp. 30-37.*

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After studying physics in Freiburg, Germany, Frebel obtained her PhD in astronomy and astrophysics from The Australian National University's Mt Stromlo Observatory (2007). She was awarded the 2007 Charlene Heisler Prize for the best Australian astronomy PhD *thesis of 2006. She was a McDonald Postdoctoral Fellow at the University of Texas, Austin (2006–2008) and a Clay Fellow at the Harvard-Smithsonian Center for Astrophysics in Cambridge (2009–2011).*

Science News Magazine *selected Anna Frebel as one of their ten 2016 Outstanding Young Scientists, and she is a 2011, 2013, and 2015 Kavli Frontiers of Science Fellow (National Academy of Sciences). She won a 2013 CAREER Award from the U.S. National Science Foundation for her work on the oldest stars and the early Universe. Frebel also received the 2010 Annie Jump Cannon Award of the American Astronomical Society and the 2009 Ludwig-Biermann Young Astronomer Award from the German Astronomical Society.*

Anna Frebel also enjoys communicating science to the public through regular public lectures, magazine articles, and interviews as well as her popular science book, Searching for the Oldest Stars: Ancient Relics from the Early Universe.