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The Environment of the *r*-process: New Advances Enabled by the Study of the Orbits of *r*-process-enhanced Stars

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Major astronomical advances in understanding the nature of the *r*-process are a result of new environmental constraints that have become available recently. Key examples include the detection of many *r*-process-enhanced stars in the ultra-faint dwarf galaxy Reticulum II, analysis of the electromagnetic counterpart of a pair of merging neutron stars detected in gravitational waves, and the analysis of the orbital properties of a large sample of *r*-process-enhanced stars in the Milky Way field. I will primarily focus on how studies of *r*-process-enhanced field stars have advanced our understanding of the *r*-process. I will also highlight some new ways that *r*-process-enhanced stars enable chemical tagging of some of the potentially lowest-mass dwarf galaxies to have been accreted long ago by the Milky Way. This contribution presents a lightly edited transcript of the author's oral remarks.

KEYWORDS: dwarf galaxies, nucleosynthesis, stellar abundances

1. Introduction

The Milky Way halo is highly structured. There are dozens of low luminosity galaxies and stellar streams known around the Milky Way. New systems are being discovered each year, and many more will be discovered in the next decade. Much information is encoded in the detailed chemistry and dynamics of these systems: everything from the nature of dark matter to the origin and ancestry of the Milky Way. These new discoveries demonstrate yet again just how much synergy there is between the nuclear scale of atoms and Galactic scales. I see that as one of the major themes of this conference. In this contribution, I will try to connect the nuclear scale to the Galactic scale, using the *r*-process to help build that bridge. In particular, I will focus on the environment of the *r*-process.

Let's start with some background. The *r*-process is one of the fundamental ways that stars produce heavy elements. It uses a rapid burst of neutrons to overwhelm and grow the mass of existing nuclei. Reference [1] presents an animation of the *r*-process as it runs along the chart of the nuclides. The *r*-process shoots up from light elements to heavy ones in only a fraction of a second. Once the flow of neutrons shuts off, the neutron-rich radioactive nuclei β-decay back to stable ones. The *r*-process requires an explosive site with high neutron densities (e.g., [2]). The *r*-process is the dominant source of heavy elements in the oldest stars (e.g., [3]), and ancient *r*-process events in other stars produced about half of the heavy elements found in the Sun and on the Earth (e.g., [4]).

The *r*-process elements were not produced in the stars that we see today. Instead, they were produced before these stars formed. For decades, the prevailing wisdom was that the *r*-process probably operated in some fraction of normal massive-star supernovae. Over the last decade or so, however, evidence has been mounting from the supernova modeling community that neutron-rich conditions do not develop in most supernovae (e.g., [5]). On the other hand, theory also tells us that mergers of neutron stars can generate neutron-rich conditions and eject a substantial mass of freshly produced *r*-

process elements (e.g., [6]). We now know that these events happen, and in 2017 gravitational waves and electromagnetic radiation were finally detected from the same astrophysical event, GW170817 [7]. The electromagnetic part is called a kilonova, and it is consistent with being powered by the ejecta of a few hundredths of a solar mass of heavy, radioactive material produced by the *r*-process (e.g., [8, 9]). The most straightforward explanation is that the *r*-process occurred in this pair of merging neutron stars.

2. The First Environmental Test: Ultra-faint Dwarf Galaxies

Now, let's introduce the "environment" variable. What impact does the *r*-process have on its environment? One of our first constraints came from the observation as far back as the 1990s that a small fraction of metal-poor stars showed large enhancements of *r*-process elements (e.g., [3, 10]). These are stars in the Milky Way halo, and they are not affiliated with any known stellar structure, like a star cluster or a dwarf galaxy.

That situation fundamentally changed in 2016 with the discovery of a particular low-luminosity dwarf galaxy, called Reticulum II [11, 12]. This galaxy is a satellite of the Milky Way. Galaxies like this do not contain many stars, and that is why they are so challenging to find. These galaxies are commonly referred to as ultra-faint dwarf galaxies. Reticulum II is dark-matter-dominated and contains an old, metal-poor stellar population, one that possibly dates from before the epoch of reionization [13,14]. Measured by these standards, Reticulum II is a normal ultra-faint dwarf galaxy. But, however, Reticulum II is not a normal galaxy. In the Milky Way halo, about 5% of stars are highly-enhanced in *r*-process elements [15, 16]. In other ultra-faint dwarf galaxies, 0% of stars are highly-enhanced in *r*-process elements (e.g., [17, 18]). In Reticulum II, about 80% of stars are highly-enhanced in *r*-process elements [19–21]. This is what we call an *r*-process-enhanced galaxy.

Shortly after Reticulum II was discovered, another *r*-process-enhanced galaxy was found, Tucana III [22]. The level of *r*-process enhancement in Tucana III is lower than in Reticulum II, but the basic pattern holds [23]. Each of these galaxies experienced probably one *r*-process event, and all other known ultra-faint dwarf galaxies experienced none.

Reference [24], for example, uses the stellar abundances and the environmental constraints from Reticulum II to simulate how to produce and incorporate *r*-process material in stars. The most likely combination of rates and yields—about one event per few thousand supernovae that produces about 10^{-2} $M_\odot$ of *r*-process material—strongly favors the rates and yields of neutron-star mergers. It also appears to have been corroborated by the results from the kilonova associated with the GW170817, and it affirms the results from the supernova modeling community.

3. The Second Environmental Test: *r*-process-enhanced Stars in the Field

As of last year, we can also use physically-unrelated *r*-process-enhanced stars in the Milky Way field to make a second environmental test (ref. [25]; this section presents the primary results of this study). It is a form of chemical tagging. At the time, there were 83 highly *r*-process-enhanced stars known in the Milky Way field ([Eu/Fe] > +0.7). We did not know the birthplace of any of these stars, but that changed last year with the second data release from the *Gaia* satellite [26]. Thirty-five of these stars have reliable parallaxes—and therefore distances—in the *Gaia* catalog. We computed the kinematics of these stars, revealing their orbital shapes, energies, and angular momenta. What does that tell us about the environments where *r*-process-enhanced stars were born?

The highly *r*-process-enhanced stars do not have disk-like orbits. These stars might be passing though the disk—passing through the Solar Neighborhood—right now, but their kinematics are consistent with membership in the Galactic halo.

We have also checked whether any of these stars might have similar kinematics, which could indicate that they were born together in the same system. We applied three clustering methods to search for substructure in four dimensions of the kinematics. We identified 8 groups, ranging from 2 to 4 stars per group, and they exhibit the same characteristic spread in energy and angular momentum as found in the simulations conducted by ref. [27]. That result is suggestive, but it is not direct proof of an association.

Our clustering analysis was performed independent of the chemistry of these stars. Many of the groups seem to span a relatively small range in metallicity. Metallicity was not a property that was considered during the clustering analysis, yet it also appears clustered. Five of the 6 groups with 3 or more stars have less than a 20% probability of having such a small metallicity dispersion, and two of them have less than a 2% probability. There is still a lot of work to be done, especially efforts to improve on the small-number statistics. As a starting point for consideration, however, what can these groups tell us about the environment of the *r*-process?

A group of stars with a small, non-zero metallicity dispersion might have been born together in a dwarf galaxy. Figure 1 shows the luminosity-metallicity relation for dwarf galaxies. The different horizontal lines represent the average metallicity of stars in each of the groups we have identified. Most of the groups have low metallicities, and therefore they suggest these stars were born in low-mass systems, like the ultra-faint dwarf galaxies.

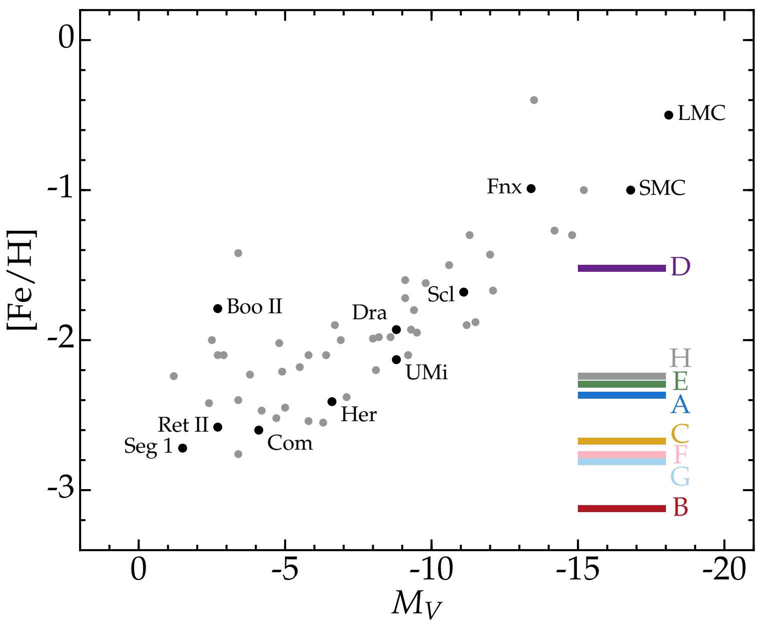

Fig. 1. The metallicity-luminosity relation for dwarf galaxies in the Local Group is shown. The average metallicities of the groups of *r*-process enhanced stars are indicated by the horizontal lines. (*Figure taken from Ref. [25]*)

So what have we learned from the environmental studies? Obviously there is a lot of *r*-process material present in stars in the disk, even in the Sun. But perhaps the only way to form an *r*-process-enhanced star is to form it in an environment with low iron, where the timescale for iron production is relatively slow. Like a dwarf galaxy. So the new insight from this work is that the level of *r*-process enhancement is perhaps linked to environment, not the astrophysical site that produces the *r*-process elements.

Let's carry this idea one step further. The orbital pericenters of these groups are within a few kpc of the Galactic center. An ultra-faint dwarf galaxy with low density, even when accounting for all its dark matter, will not survive the tidal forces it experiences at such small orbital pericenters. So those systems would have been disrupted a long time ago. Contrast that scenario with the ultra-faint dwarf galaxies, like Reticulum II, that have survived until today. Their orbital pericenters are at least 15 or 20 kpc from the Galactic center [28], which is probably why they survived. To find the ultra-faint dwarf galaxies that were disrupted long ago by the Milky Way, I propose that we should look for the *r*-process-enhanced stars in the field. We will not be able to find all of the disrupted dwarf galaxies this way, but it is a new method to reconstruct some fraction of the potentially lowest-mass systems to have been accreted early in the history of the Milky Way.

4. Outlook

To make the next advance, we are working to find many more *r*-process-enhanced stars. I am a member of a group called the *R*-Process Alliance, which is a collection of folks with an interest in solving the big questions related to the *r*-process. We are now in the early phases of the project, which are aimed at identifying large numbers of bright, highly *r*-process-enhanced stars. Figure 2 places this work in context. Various investigations have found about 30 such stars over the last 25 years. The *R*-Process Alliance aims to identify more than 100 *r*-process-enhanced stars over the next 5 years with a targeted survey. In the first two years of our survey, we have identified the three brightest highly *r*-process-enhanced stars known, and many others [16, 29–37].

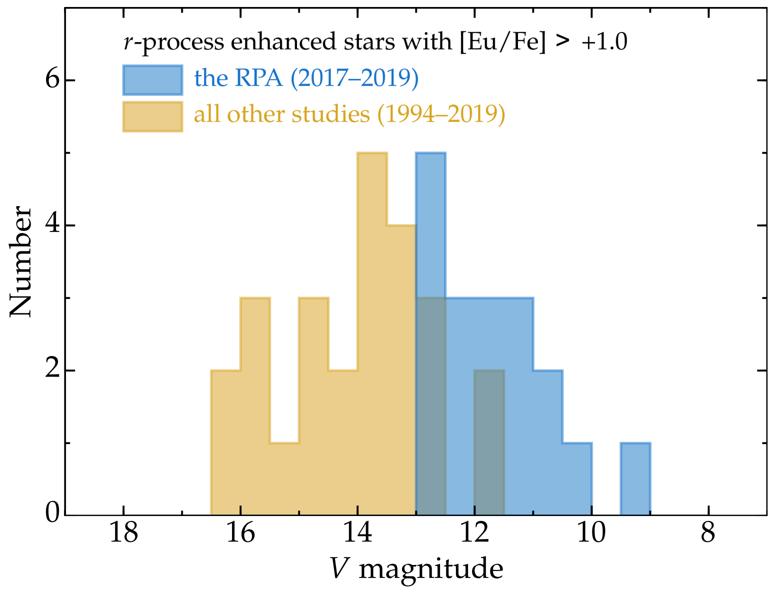

Fig. 2. Histograms of *r*-process-enhanced stars identified by the *R*-Process Alliance (blue) and all other studies (yellow) are shown.

As the sample sizes increase, through efforts by the *R*-Process Alliance and others, we will be able to determine the environmental dependence and precise occurrence frequencies of *r*-process-enhanced stars. Once we have those frequencies, we can map them to the occurrence frequencies of different characteristics of the future kilonovae associated with neutron star merger detections. This information enables you to associate specific pieces of physics with specific characteristics and specific sites. It also enables chemical tagging of some of the earliest and lowest-mass accretion events experienced by the Milky Way. The stars have long since phase-mixed around the Galaxy, but there is a nice synergy between the *r*-process chemical signature and kinematic signatures that will open new frontiers in nuclear astrophysics and Galactic astronomy.

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References

[1] Korobkin, O., Rosswog, S., Arcones, A., Winteler, C. Mon. Not. R. Astron. Soc. **426**, 1940 (2012).
[2] Kratz, K.-L., Farouqi, K., Pfeiffer, B., et al. Astrophys. J. **662**, 39 (2007).
[3] Sneden, C., Cowan, J.J., Gallino, R. Ann. Rev. Astron. Astrophys. **46**, 241 (2008).
[4] Cameron, A.W.G. Astrophys. Space Sci. **82**, 123 (1982).
[5] Arcones, A., Thielemann, F.-K. J. Phys. G: Nucl. Part. Phys. **40**, 013201 (2013).
[6] Rosswog, S., Korobkin, O., Arcones, A., Thielemann, F.-K., Piran, T. Mon. Not. R. Astron. Soc. **439**, 744 (2014).
[7] LIGO Scientific Collaboration and Virgo Collaboration, et al. Phys. Rev. Lett. **119**, 161101 (2017).
[8] Drout, M.R., Piro, A.L., Shappee, B.J., et al. Sci. **358**, 1570 (2017).
[9] Tanvir, N.R., Levan, A.J., González-Fernández, C., et al. Astrophys. J. Lett. **848**, L27 (2017).
[10] Sneden, C., Preston, G.W., McWilliam, A., Searle, L. Astrophys. J. Lett. **431**, L27 (1994).
[11] Bechtol, K., Drlica-Wagner, A., Balbinot, E., et al. Astrophys. J. **807**, 50 (2015).
[12] Koposov, S.E., Belokurov, V., Torrealba, G., Evans, N.W. Astrophys. J. **805**, 130 (2015).
[13] Koposov, S.E., Casey, A.R., Belokurov, V., et al. Astrophys. J. **811**, 62 (2015).
[14] Walker, M.G., Mateo, M., Olszewski, E.W., et al. Astrophys. J. **808**, 108 (2015).
[15] Barklem, P.S., Christlieb, N., Beers, T.C., et al. Astron. Astrophys. **439**, 129 (2005).
[16] Hansen, T.T., Holmbeck, E.M., Beers, T.C., et al. Astrophys. J. **858**, 92 (2018).
[17] Frebel, A., Simon, J.D., Kirby, E.N. Astrophys. J. **786**, 74 (2014).
[18] Ji, A.P., Simon, J.D., Frebel, A., Venn, K.A., Hansen, T.T. Astrophys. J. **870**, 83 (2019).
[19] Ji, A.P., Frebel, A., Chiti, A., Simon, J.D. Natur. **531**, 610 (2016).
[20] Ji, A.P., Frebel, A., Chiti, A., Simon, J.D. Astrophys. J. **830**, 93 (2016).
[21] Roederer, I.U., Mateo, M., Bailey, J.I. III, et al. Astron. J. **151**, 82 (2016).
[22] Hansen, T.T., Simon, J.D., Marshall, J.L., et al. Astrophys. J. **838**, 44 (2017).
[23] Marshall, J.L., Hansen, T., Simon, J., et al. Astrophys. J. submitted, arXiv:1812.01022 (2018).
[24] Beniamini, P., Hotokezaka, K., Piran, T. Astrophys. J. **832**, 149 (2016).
[25] Roederer, I.U., Hattori, K., Valluri, M. Astron. J. **156**, 179 (2018).
[26] Lindegren, L., Hernáandez, J., Bombrun, A., et al. Astron. Astrophys. **616**, A2 (2018).
[27] Gómez, F.A., Helmi, A., Brown, A.G.A., Li, Y.-S. Mon. Not. R. Astron. Soc. **408**, 935 (2010).
[28] Fritz, T.K., Battaglia, G., Pawlowski, M.S., et al. Astron. Astrophys. **619**, A103 (2018).
[29] Placco, V.M., Holmbeck, E.M., Frebel, A., et al. Astrophys. J. **844**, 18 (2017).
[30] Cain, M., Frebel, A., Gull, M., et al. Astrophys. J. **864**, 43 (2018).
[31] Gull, M., Frebel, A., Cain, M.G., et al. Astrophys. J. **862**, 174 (2018).
[32] Holmbeck, E.M., Beers, T.C., Roederer, I.U., et al. Astrophys. J. Lett. **859**, L24 (2018).
[33] Roederer, I.U., Sakari, C.M., Placco, V.M., et al. Astrophys. J. **865**, 129 (2018).
[34] Sakari, C.M., Placco, V.M., Hansen, T., et al. Astrophys. J. Lett. **854**, L20 (2018).
[35] Sakari, C.M., Placco, V.M., Farrell, E.M., et al. Astrophys. J. **868**, 110 (2018).
[36] Placco, V.M., Santucci, R.M., Beers, T.C., et al. Astrophys. J. **870**, 122 (2019).
[37] Sakari, C.M., Roederer, I.U., Placco, V.M., et al. Astrophys. J. **874**, 148 (2019).