Galactic Dynamics in the Era of Large Surveys
Proceedings IAU Symposium No. 353, 2019
M. Valluri & J. A. Sellwood, eds.

doi:10.1017/S1743921319008755

Kinematics of highly r-process-enhanced halo stars: Evidence for origins in now-destroyed ultra-faint dwarf galaxies

Kaley Brauer[1], Alexander P. Ji[2], Kohei Hattori[3], Sergio Escobar[4] and Anna Frebel[1]

[1]Dept. of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA, USA
email: kbrauer@mit.edu

[2]Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA, USA

[3]Dept. of Astronomy, University of Michigan, 1085 S. University, Ann Arbor, MI, USA

[4]Dept. of Physics, California Institute of Technology, 1200 E California Blvd, Pasadena, CA, USA

Abstract. The Milky Way's stellar halo preserves a fossil record of smaller dwarf galaxies that merged with the Milky Way throughout its formation history. Currently, though, we lack reliable ways to identify which halo stars originated in which dwarf galaxies or even which stars were definitively accreted. Selecting stars with specific chemical signatures may provide a way forward. We investigate this theoretically and observationally for stars with r-process nucleosynthesis signatures. Theoretically, we combine high-resolution cosmological simulations with an empirically-motivated treatment of r-process enhancement. We find that around half of highly r-process-enhanced metal-poor halo stars may have originated in early ultra-faint dwarf galaxies that merged into the Milky Way during its formation. Observationally, we use Gaia DR2 to compare the kinematics of highly r-process-enhanced halo stars with those of normal halo stars. R-process-enhanced stars have higher galactocentric velocities than normal halo stars, suggesting an accretion origin. If r-process-enhanced stars largely originated in accreted ultra-faint dwarf galaxies, halo stars we observe today could play a key role in understanding the smallest building blocks of the Milky Way via this novel approach of chemical tagging

Keywords. stars: kinematics, galaxies: formation

1. Introduction

The stars in the stellar halo form a fossil record of the smaller dwarf galaxies that merged with the Milky Way throughout its formation history. If we can link observations of these stars to information about their original progenitor galaxies, we can begin to recreate the assembly history of the Milky Way. The stellar halo can contain a significant number of *in situ* stars, though (Monachesi *et al.* 2019). We currently lack ways to definitively determine which stars are *ex situ* versus *in situ*. Furthermore, even among stars which are believed to be accreted, the properties of their progenitor galaxies are largely a mystery. We need reliable ways to identify which halo stars originated in which dwarf galaxies.

Chemical tagging may offer a solution. By selecting stars with specific chemical signatures, we may be able to identify stars with a high probability of originating in certain types of dwarf galaxies. In particular, early *r*-process (rapid neutron-capture process)

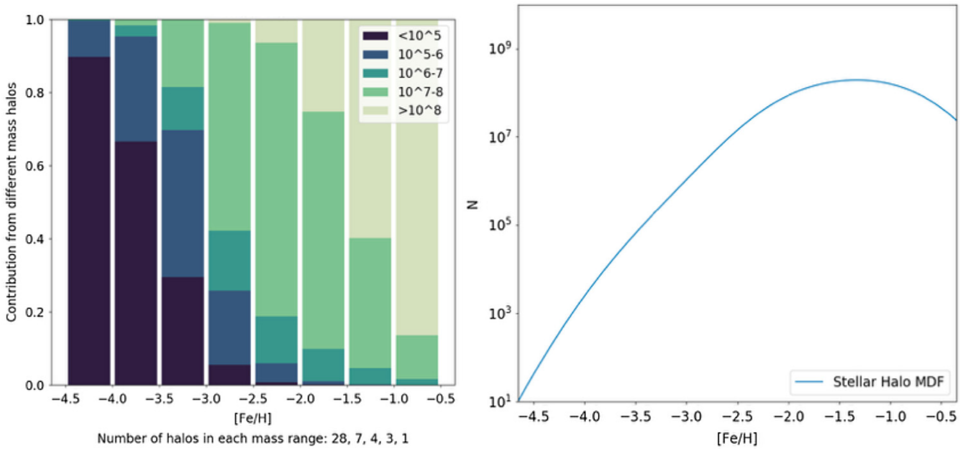

Figure 1. A galaxy's stellar halo is composed largely of stars that originally formed in accreted galaxies. This figure shows information about a simulated stellar halo. LEFT: Different mass accreted galaxies contribute different fractions of stars in different metallicity bins. Lower mass accreted galaxies (e.g., ultra-faint dwarf galaxies with stellar mass $\lessapprox 10^5$ $M_\odot$) only contribute a significant fraction of the stars below [Fe/H] $\lessapprox -2.5$. The higher metallicities are dominated by only a handful of large mergers. RIGHT: The metallicity distribution function for the simulated stellar halo peaks around -1.5. Stars become significantly rarer at lower metallicities. The metal-poor stars we are interested in are thus a small fraction of all of the stellar halo stars.

nucleosynthesis events in small dwarf galaxies would imprint a clean r-process signature on the subsequently formed stars in those galaxies. The r-process is responsible for producing around half of the abundances of the heaviest elements in the periodic table (Burbidge *et al.* 1957; Cameron 1957). In this paper, we present evidence that stars exhibiting strong r-process signatures (called "r-II stars") likely originated in ultra-faint dwarf galaxies.

Most of the results presented at Galactic Dynamics in the Era of Large Surveys were already published in Brauer *et al.* (2019). This paper summarizes the results of that paper and discusses ongoing observational work that expands upon those results.

2. Simulated Stellar Halos

We created 31 mock stellar halos, using the high-resolution dark-matter-only cosmological simulations of Milky-way-mass halos from the *Caterpillar Project* (Griffen *et al.* 2016). The simulated halos in the suite span an unbiased range of accretion histories. When creating the mock stellar halos, we only formed highly r-II stars in ultra-faint dwarf galaxies. We then compared these mock stellar halos at $z = 0$ to the Milky Way's stellar halo to investigate how many of the observed r-II stars we could account for via this one formation pathway.

Due to their low star formation efficiency, ultra-faint dwarf galaxies only significantly contribute stars at low metallicities (below [Fe/H] ~ -2.5; see figure 1). Because of this, we exclusively considered metal-poor stars below [Fe/H] $= -2.5$.

We found that forming r-II stars exclusively in ultra-faint dwarf galaxies could account for around half of the r-II stars observed in the Milky Way's stellar halo. To make this comparison, we determined both a simulated and observed r-II fraction. The r-II fraction is the fraction of metal-poor ([Fe/H] < -2.5) stars in the stellar halo that are highly r-process enhanced. Figure 2 shows the ranges of both the simulated and observed r-II fractions: $f_{r-II,sim} \sim 1 - 2\%$ and $f_{r-II,obs} \sim 2 - 4\%$. The simulated fraction differed between different simulations, resulting in the given range. The observed fraction also

https://doi.org/10.1017/S1743921319008755 Published online by Cambridge University Press

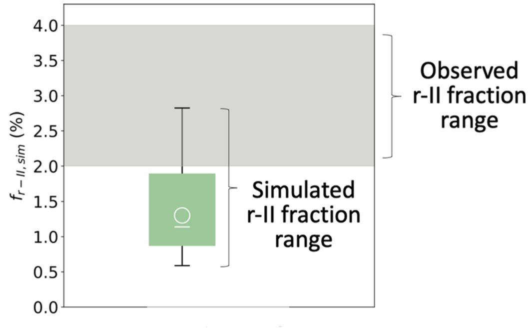

Figure 2. The r-II fraction is the fraction of metal-poor stars in the stellar halo that are highly *r*-process enhanced. The simulated r-II fraction was determined by simulating 31 mock stellar halos. In the mock stellar halos, r-II stars were simulated to only form in ultra-faint dwarf galaxies. The observed r-II fraction is based on metal-poor observations of the Milky Way's stellar halo. The fractions range both in different simulations and in different observational datasets, but overall we can account for around half of r-II stars via this one formation pathway. Figure 3 gives more information about the simulated r-II fraction range.

differed between different datasets (e.g., 3.3%, Jacobson *et al.* 2015; 2.2%, Roederer *et al.* 2014; 2.9%, Barklem *et al.* 2005). The R-Process Alliance is currently determining better statistics on *r*-process enhanced stars, so we will soon have better knowledge of the observed fraction.

Changing parameters in the mock stellar halo evolution model changed the final $f_{r-II,sim}$. The most important parameters were reionization redshift (z_{reion}), the maximum mass of an ultra-faint dwarf ($M_{UFD,max}$), the star formation mass (M_{SF}), and the filtering mass (M_{filt}). Figure 3 shows how the simulated r-II fraction changes with these parameters. These parameters are discussed in more detail in Brauer *et al.* (2019).

3. Caveats

There are potential issues with directly comparing our simulated stellar halos to the Milky Way stellar halo. We form our stellar halos exclusively out of accreted stars, but actual stellar halos are not exclusively and comprehensively composed of accreted material. This would be significant if we were interested in all of the halo stars, but it is a lesser problem in our analysis because we only consider stars with metallicities below [Fe/H] $= -2.5$. Metal-poor halo stars are believed to be largely accreted (Cooper *et al.* 2015; Bonaca *et al.* 2017; El-Badry *et al.* 2018).

We also do not model other r-II formation pathways; we only produce r-II stars in ultra-faint dwarf galaxies. In principle, we should be able to model all formation pathways (e.g., *in situ* formation, formation in larger dwarf galaxies) and fully account for all of the r-II stars in the Milky Way. In practice, though, modeling these other pathways is much more involved. This is something for future work.

Additionally, the empirical model used in this analysis is limited. We are able to match the bulk properties of the Milky Way stellar halo, but using a fixed Gaussian shape for the metallicity distribution function of each dwarf galaxy is not fully physical. We also assume that 10% of ultra-faint dwarf galaxies experience an *r*-process event based on a small number of observations of surviving ultra-faint dwarf galaxies.

4. Observational Evidence

Roederer *et al.* (2018) analyzed the kinematics of highly r-process-enhanced stars and found clusters in phase space, as we would expect if these stars came from a small

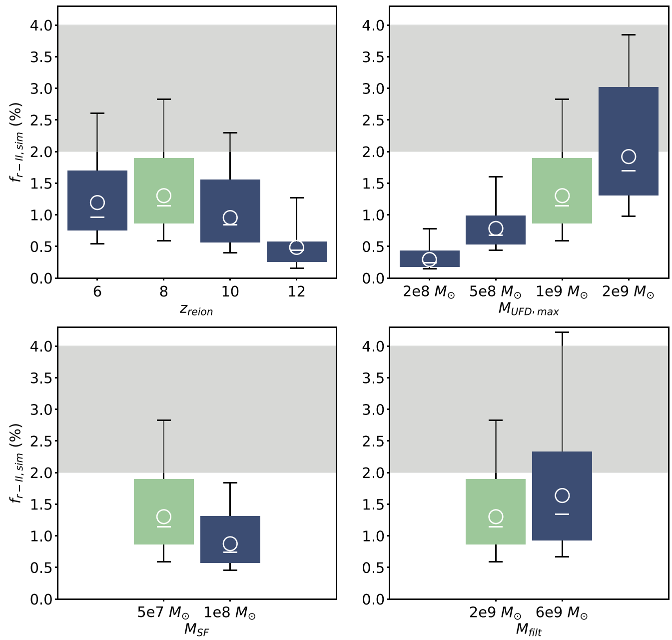

Figure 3. Figure 3 from Brauer *et al.* (2019) showing the simulated r-II star fraction, $f_{r-II,sim}$, as it varies with different mass thresholds and reionization redshifts. For each set of parameters, the mean $f_{r-II,sim}$ is shown as a white circle and the median is shown as a white line. The colored boxes correspond to 68% scatter between simulations, and the error bars shown the minimum and maximum $f_{r-II,sim}$. Our fiducial model is highlighted in light green, and single-parameter variations on the fiducial model are shown in blue. The currently observed fraction of r-II stars in the Milky Way stellar halo ($f_{r-II,obs} \sim 2-4\%$) is shown in grey.

number of accreted dwarf galaxies. Their analysis only included 31 stars, though, so we are expanding this analysis with a much larger dataset. We are combining the R-Process Alliance samples in combination with Gaia kinematics. These results are forthcoming, but already we see that highly r-process-enhanced stars may have higher galactocentric velocities. The kinematics of these stars thus suggest they may be preferentially accreted.

References

Barklem, P. S., Christlieb, N., Beers, T. C., *et al.* 2005, *A&A*, 439, 129
Bonaca, A., Conroy, C., Wetzel, A., *et al.* 2017, *ApJ*, 845, 101
Burbidge, E. M., Burbidge, G. R., *et al.* 1957, *Reviews of Modern Physics*, 29, 547
Brauer, K., Ji, A. P., Frebel, A., *et al.* 2019, *ApJ*, 871, 247
Cameron, A. G. W. 1957, *PASP*, 69, 201
Cooper, A. P., Parry, O. H., Lowing, B., *et al.* 2015, *MNRAS*, 454, 3185
El-Badry, K., Bland-Hawthorn, J., Wetzel, A., *et al.* 2018, *MNRAS*, 480, 652
Griffen, B. F., Ji, A. P., Dooley, G. A., *et al.* 2016, *ApJ*, 818, 10
Jacobson, H. R., Keller, S., Frebel, A., *et al.* 2015, *ApJ*, 807, 171
Monachesi, A., Gómez, F. A., Grand, R. J. J., *et al.* 2019, *MNRAS*, 485, 2589
Roederer, I. U., Preston, G. W., Thompson, I. B., *et al.* 2014, *AJ*, 147, 136
Roederer, I. U., Hattori, K., & Valluri, M. 2018, *AJ*, 156, 179