Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319007932

The contribution of Globular Clusters to the stellar halo using APOGEE and GAIA

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Abstract. Over the last decade, much of the key questions in Galactic Archaeology have been asnwered by studying the Milky Way's globular cluster (GC) system. Following on this, it has been shown that a substantial fraction of the Milky Way's stellar halo field arises from GC dissolution. In this work, we make use of the latest data release fromn the APOGEE survey to study GC dissolution ratios in different spatial regions of the Galaxy. Our results will allow us to constrain many astrophysical questions, such as: the origin of N-Rich stars, the mass contribution from GCs to the stellar halo of the Galaxy, the origin of the Galactic GC system and the mass assembly of the Milky Way.

Keywords. Globular Cluster, N-Rich stars, Galactic Stellar Halo, Galaxy.

1. Introduction

It is common knowledge that the Globular Cluster (GC) system of the Milky Way holds crucial insights into the formation and assembly history of the Galaxy. A milestone in this field was the work by Searle & Zinn (1978), who used the Galactic GC population to infer that GCs found in the Galactic halo formed over a longer period than those found in the inner Galaxy, leading to the conclusion that the former population originated from accreted satellite systems. This concept has since been refined with improved measurements of GC ages and chemical compositions, leading to the discovery of a bifurcation in the age-metallicity distribution of Galactic GCs (e.g., Marin-Franch *et al.* 2009), where the intermediate-age and metal-poor branch traces the GC population thought to result from satellite accretion (see also Forbes & Bridges 2010; Leaman 2013). Clearly, GCs play an important role as tracers of the formation and assembly history of the Galaxy, and in view of these results, it is interesting to assess the contribution of globular clusters to the stellar mass budget of the Galactic halo.

In this work, we focus on determining the contribution of *dissolved* GCs to the stellar mass budget of the Galactic halo. Dissolved GCs are traced via the identification in the halo field of so-called "second population" (P2) GC stars, whose chemical compositions stand out from those of average field stars with the same metallicity. In particular, we focus on so-called *N-rich stars*, which are P2 stars with high nitrogen abundances showing an anti-correlation with the abundance of carbon. N-rich stars were shown by Schiavon *et al.* (2017) to contribute ∼25% of the stellar mass budget of the inner halo ($R < 2$kpc). That unexpectedly high number is in sharp contrast with studies of the outer halo (∼3%, e.g., Koch *et al.* 2019), which may indicate the occurrence of different GC destruction mechanisms in the inner and outer halo, as suggested by Schiavon *et al.* (2017). Our goal is to address that question on the basis of a homogeneous data set. We aim to measure the frequency of halo N-Rich stars as a function of Galactocentric distance, in order to place constraints on the the origin of N-rich stars, the mechanisms of GC formation and destruction, and the assembly history of the Milky Way.

In order to assess the frequency of N-Rich stars in different regions of the halo we must first determine a stellar density model that accurately describes the halo as a function of Galactocentric radius. Such a model is needed because, unlike the outer halo where it is relatively easy to define a relatively clean halo sample at high Galactic latitude, the situation is far more complicated in the inner halo, where the bulge/bar, the thin disk, the thick disk, and the halo overlap spatially. A density model calculated on the basis of reliable outer halo samples can thus be used to disentangle the contribution of the halo to the stellar mix within 2kpc of the Galactic centre, against which the number of N-rich stars found in the inner halo can be contrasted for a measurement of N-rich star frequency.

2. Method

Our methodology consists on an adaptation of that used by Mackereth *et al.* (2017) and Bovy *et al.* (2015), employing a modified version of their publicly available code†, which peforms density law fits to the selection function-corrected number counts of stars in arbitrary bins of age and chemical composition. Briefly, we proceed as follows:

(1) We fit several spherically symmetric density models to the APOGEE outer halo star counts using a maximum likelihood fitting procedure, based on the assumption that star counts are well modelled by an inhomogeneous Poisson point process. The density models tested are variations of three broad model families: single power laws, broken power laws or Einasto profiles.

(2) We determine the top three best-fitting density models for our outer halo sample on the basis of a maximum likelihood approach combined with a Bayesian Information Criterion (BIC; Schwarz (1978)). A flatter density component is added in order to account for contamination, predominantly by thick disk stars in our sample. We find that his additional component has little influence on the final result, indicating that the contamination by non-halo sources is negligible. The density law is then used to initiate a Markov-Chain Monte-Carlo (MCMC) sampling of the posterior PDF, where we adopt the median and standard deviation of one-dimensional projections of the MCMC chain as our density model parameter values and uncertainties.

(3) Finally, to test whether the N-rich star frequency is the same in the inner and outer halo, we first use our best-fitting density models and the APOGEE selection function to predict how many *halo* stars are contained in the APOGEE sample within 2 kpc of the Galactic centre. The latter number can be used to predict the number of N-rich stars APOGEE would have observed in the case where the frequency of those stars was the same in the inner and outer halo, which can then be compared with the number of N-rich stars APOGEE actually observed in the inner halo.

3. Results

Density fitting is performed on our outer stellar halo field sample, which is comprised of ∼950 giant stars from the APOGEE DR16 sample with $[\mathrm{Fe/H}] < -0.9$, $logg < 3.5$, $T_{\mathrm{eff}} < 4750$ K, $|b| > 16°$. The match of one of the best fitting models to the distance modulus distribution of this sample is shown in Figure 1, left panel. On the right panel of Figure 1 we show the results of a Monte-Carlo Markov-Chain (MCMC) exploration of the posterior PDF for this model, yielding the best parameter values and its associated uncertainties.

† See https://github.com/jmackereth/apogee-maps and at https://github.com/jobovy/apogee-maps, respectively

https://doi.org/10.1017/S1743921319007932 Published online by Cambridge University Press

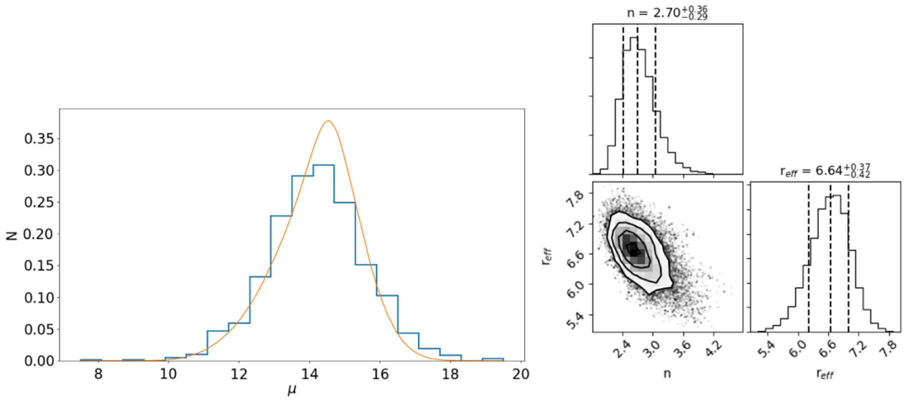

Figure 1. *Left*:Histogram of the distance moduli (μ) values of the outer halo sample used to perform the density modelling. Overplotted is the predicted values for the outer halo sample given by one of the best-fitting models (i.e. a spherical Einasto profile). *Right*:Parameter values and associated uncertainties output from the 10,000 Monte-Carlo Markov-Chain parameter exploration for our best-fitting model, a spherical power law.

N-rich stars are identified in this sample by adopting the same method as in Schiavon *et al.* (2017), as shown in Figure 2. An identical procedure is carried out for the samples in the outer and inner halo, for consistency. Therefore, our results can be summarized as follows:

1) After testing 15 different density models ranging in parameter complexity, we find that our data are best fit by a spherical power law, with exponent $\alpha = 3.23^{+0.05}_{-0.05}$, which is in good agreement with determinations from previous studies (e.g., Deason *et al.* 2011; Xue *et al.* 2015; Das *et al.* 2016; Iorio *et al.* 2018). However, our data **are** also well fit by a spherical power law with constant flattening and a spherical Einasto profile. This is not unexpected, as all the models tested have been said to describe the number density of the stellar halo well. Therefore, we choose to use the top three best-fitting models given by the BIC value.

2) We find 28 N-Rich stars in the outer halo for a sample of 949 stars, yielding a ∼2.9% contribution, which is in good agreement with the estimate by Koch *et al.* (2019). Our top two best fitting models are ruled out by the data, and we therefore use the spherical Einasto profile to estimate the frequency of N-Rich stars in the inner halo region. Using this model, we predict ∼170 inner halo field stars within the APOGEE inner Galaxy sample, which is in good agreement with the results obtained when using the best fitting models from previous work (e.g., Deason *et al.* 2011; Xue *et al.* 2015; Iorio *et al.* 2018). If the frequency of N-rich stars within 2 kpc of the Galactic centre were to be the same as estimated for the outer halo, APOGEE should have observed $\sim 5^{+1}_{-1}$ inner halo N-Rich stars. The actual number of stars observed by APOGEE within the same volume is 22. Using the number of predicted inner halo field stars obtained using the spherical Einasto density profile, our observed 22 N-Rich stars yield a ∼13% contribution. This is lower than the predicted number by Schiavon *et al.* (2017), but it is still significantly larger than for the outer halo. Our preliminary conclusion is that the dissolution rate of N-Rich stars is not constant throughout the Galaxy, being larger in the inner halo by over a factor of 4.

4. Conclusions

We set out to compare the ratio of globular cluster dissolution in the inner and outer regions of the Galaxy. The motivation behind this project was to obtain reliable observational results that would constrain current Galaxy mass assembly models, and to

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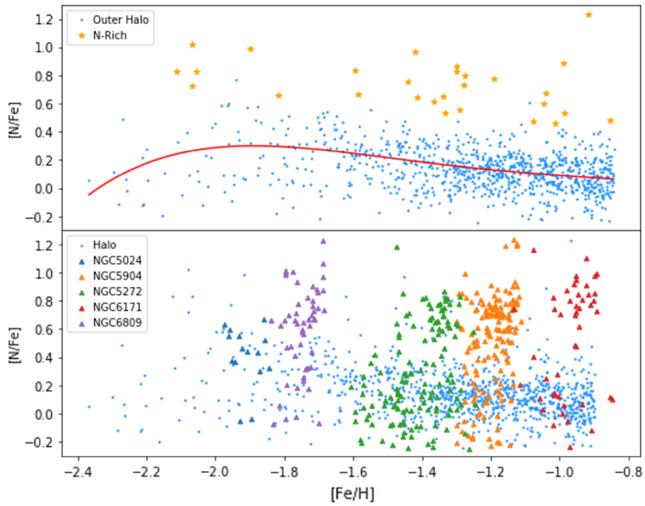

Figure 2. Distribution of the 949 outer halo stars in the [N/Fe] ve [Fe/H] plane. *Top*: Shown as blue points are the outer halo sample as described in Sec 2.2. Shown in orange stars are the final sample of N-Rich stars for the outer halo sample, and in green stars the initially targetted N-Rich stars that presented high [C/Fe] abundances,and therefore stars we do not associate to GC origin. Red line is the median trend obtained from fitting a 2^{nd} order degree polynomial.*Bottom*: The same outer halo sample is compared to APOGEE data for Galactic globular clusters.

obtain a better understanding of GC evolution as a whole. Our main conclusions can be summarised as follows:

1) Our outer halo data are best fit by a spherical power law density model. The data can also be well described by a spherical power law with constant flattening and a spherical Einasto profile. We conclude that this result is due to the low halo field star numbers obtained in APOGEE, but find that for the purpose of this project we are able to conduct our study. However, when predicting the number of inner halo field stars we obtain different number of inner halo field star estimates, depending on the density model used. Therefore, our predictions for the inner halo are uncertain, and we must resort to using a much better determined density model as in Deason *et al.* (2011); Xue *et al.* (2015) or Iorio *et al.* (2018). The model and the results obtained from employing this profile will be in the finalised paper (Horta *et al.* 2020 in prep).

2) The dissolution of GCs is not constant throughout the Galaxy. Our results show that the GCs in the inner halo get more largely destroyed when compared to the GCs residing in the outer halo. The dissolution rate is more than four times larger for the inner halo when compared to the outer halo.

This is an ongoing project and the final results, including an analysis of the predictions based on robust density model from the literature, will be soon be published as a refereed paper (Horta *et al.* 2020, in prep.). Preliminary calculations indicate that the results presented in this proceedings paper are confirmed.

References

Bovy, J., Rix, H.-W., Green, G. M., Schlafly, E. F., & Finkbeiner, D. P., 2015, 10.3847/0004-637X/818/2/130

Das, P., Williams, A., & Binney, J. 2016, *MNRAS*, 463, 3169

Deason, A. J., Belokurov, V., & Evans, N. W. 2011, *MNRAS*, 416, 2903

Forbes, D. A. & Bridges, T. 2010, *MNRAS*, 404, 1203

Horta D., Mackereth J. T., Schiavon P. R., *et al.* 2020, in prep.

https://doi.org/10.1017/S1743921319007932 Published online by Cambridge University Press

Iorio, G., Belokurov, V., & Erkal, D. 2018, *MNRAS*, 474, 2142
Koch, A., Grebel, E. K., & Martell, S. 2019, *A&A*, 625, A75
Leaman, R., VandenBerg D. A., & Trevor Mendel, J. 2013, *MNRAS*, 436, 122
Mackereth, J. T. *et al.* 2015, *MNRAS*, 471, 3057
Marin-Franch, A. *et al.* 2009, *ApJ*, 694, 1498
Schiavon, R. P. *et al.* 2017, *MNRAS*, 465, 501
Schwartz, G. 1978, *Annals of Statistics*, 461, 6
Searle, L. & Zinn, R. 1978, *ApJ*, 225, 357
Xue, X.-X., Rix, H.-W., Ma, Z., Morrison, H., Bovy, J., Sesar, B., & Janesh W. 2015, *ApJ*, 809, 144

https://doi.org/10.1017/S1743921319007932 Published online by Cambridge University Press