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The building blocks of the Milky Way halo using APOGEE and Gaia or Is the Galaxy a typical galaxy?

Ricardo P. Schiavon[1], J.Ted Mackereth[1,2], Joel Pfeffer[1], Rob A. Crain[1] & Jo Bovy[3]

[1]Astrophysics Research Institute, Liverpool John Moores University, Liverpool, L3 5RF, UK
R.P.Schiavon@lmu.ac.uk

[2]Dept. of Astrophysics and Astronomy, Birmingham University, Birmingham, UK

[3]Dept. of Astronomy and Astrophysics, University of Toronto, Toronto, Canada

Abstract. We summarise recent results from analysis of APOGEE/Gaia data for stellar populations in the Galactic halo, disk, and bulge, leading to constraints on the contribution of dwarf galaxies and globular clusters to the stellar content of the Milky Way halo. Intepretation of the extant data in light of cosmological numerical simulations suggests that the Milky Way has been subject to an unusually intense accretion history at $z \gtrsim 1.5$.

Keywords. Galaxy: halo; Galaxy: abundances; Galaxy: stellar content; Galaxy: globular clusters: general; Galaxy: formation; Galaxy: evolution

1. Introduction

The constitution of the Milky Way (MW) halo is one of the foundational unknowns of the field of Galactic Archaeology (GA, Eggen et al. 1962; Searle & Zinn 1978). Fundamentally one wants to know how much of the halo was formed *in situ*, how much was accreted, and the detailed properties of the *in situ* and accreted populations, namely masses, chemical compositions, stellar ages, IMF. Answering these questions will require determining the accretion history of the MW. As it turns out, accretion histories are a fundamental prediction of the Λ-CDM paradigm of structure formation, which opens up the fascinating perspective that GA can possibly pose tests to galaxy formation theory.

However, in order for observations of the MW to be deeply consequential in our pursuit of understanding structure formation, the defining properties of the MW must be representative of those of other galaxies. We are approaching a time where the question of whether the MW is a typical galaxy can be addressed, on account of a confluence of the following factors: the revolutionary growth of data on the MW stellar populations afforded by Gaia and massive spectroscopic surveys, large surveys of the global properties of galaxies in a range of redshifts, and the emergence of cosmological simulations that yield broadly realistic galaxy populations. The question is nonetheless not a simple one to formulate (e.g., typical in which respect?) and it surely will not be an easy one to answer. Nevertheless, it is crucial that we ask it, as it has far-reaching implications. From a broad perspective, the question ultimately has a bearing on the cosmic history leading up to our presence in the universe. In a more restricted context the power of MW data to constrain galaxy formation theory depends on whether it is representative of its similarly-massive peers, or an outlier.

In this paper we summarise three lines of evidence, from studies of the halo, disk, and bulge, suggesting that the Galaxy may not after all be a typical galaxy. The work by our group summarised in this paper was all based on analysis of data from SDSS-IV/APOGEE (Majewski et al. 2017), Gaia DR2 (Gaia Colaboration et al. 2018), and the EAGLE cosmological numerical simulations (Schaye et al. 2015; Crain et al. 2015).

2. The Galactic Halo

An exciting recent result in GA was the discovery by different groups that the local stellar halo is dominated by the remnants of the accretion of a single satellite galaxy (Haywood et al. 2018; Helmi et al. 2018; Belokurov et al. 2018; Myeong et al. 2018; Mackereth et al. 2019). The Gaia-Enceladus/Sausage (GE/S) system is thought to be a dwarf galaxy which merged with the MW $\sim$ 10 Gyr ago. It was identified as a relatively metal-poor, low-α stellar population dominated by highly eccentric and slightly retrograde orbits. It is also characterised by low [Ni/Fe], which is a typical abundance trait of nearby satellite galaxies (e.g., Shetrone et al. 2003). Based on the width of its metallicity distribution, Helmi et al. (2018) estimated the mass of GE/S to be $\sim\ 10^9 M_\odot$.

Further constraints on the mass of GE/S and the time of accretion were obtained from an examination of predictions by the EAGLE simulations. Mackereth et al. (2019) contrasted the chemical compositions and orbital properties of GE/S with those of their analogues in the L025N752-Recal (25^3 Mpc^3) EAGLE simulation, constraining $M^\star$ to be around $\sim\ 10^{8.5} - 10^9 M_\odot$ on the basis of the mean [Fe/H] and [Mg/Fe] of GE/S stars. Moreover, they showed that the highly eccentric nature of GE/S stars imply that the merger must have occurred no earlier than $z \sim 1.5$ (Mackereth et al. 2019, Fig. 9). That is because the maximum impact parameter for a successful accretion depends on the gravitational potential of the central halo. At higher z, when central galaxies were smaller and less massive, mergers with small enough impact parameters that result in highly eccentric orbits were too rare.

Interestingly, an analysis of the accretion histories of galaxies in the 25^3 Mpc^3 volume showed that only $\sim$ 10% of MW-like galaxies underwent an accretion event similar (in terms of mass and timing) to that of GE/S. By considering other ongoing and suspected accretion events, such as Sgr dSph, LMC, SMC, and the Kraken (Kruijssen et al. 2018), one would conclude that the accretion profile of the MW may be even more uncommon.

3. Disk α-bimodality and the accretion history of the MW

One of the most puzzling features of the MW disk is its so-called α-bimodality, which is defined as the occurrence, in the same location in the Galaxy, of two stellar populations with substantially different [α/Fe] and a sizeable overlap in [Fe/H] (see, e.g., Fig. 22 of Bensby et al. 2014). The phenomenon extends across most of the MW disk (Hayden et al. 2015, Fig. 4). In addition, the high-α component has a longer scale height and shorter scale length than its low-α counterpart (Bovy et al. 2012; Mackereth et al. 2018). These observations are very hard to explain on the basis of standard Galactic chemical evolution models (e.g., Andrews et al. 2017). In order to connect two stellar populations with same [Fe/H] and different [α/Fe] by a star formation and chemical enrichment path following the laws of chemical evolution, such models often need to resort to *ad hoc* assumptions on, e.g., gas inflows and star formation efficiency (but see Chiappini 2009; Schönrich & Binney 2009; Clarke et al. 2019).

Mackereth et al. (2018) analysed the EAGLE simulations in order to gain insights into the physical motivation behind the α-bimodality. They identified 133 MW-like galaxies in the Ref-L100N1504 (100^3 Mpc^3) EAGLE simulation on the basis of their masses and (kinematically defined) morphologies. After careful scrutiny of the distribution of stellar populations in the simulated MW-like galaxies on the [Fe/H] vs. [Mg/Fe] plane, only six galaxies were found to display some type of α-bimodality in their disk populations. Tracing back in time the evolution of the gas particles leading up to the formation of the low- and high-α stellar populations, it was found that they evolved in complete chemical detachment. In other words, they never exchanged gas and thus there is no need to devise a star formation and chemical enrichment path connecting populations with different [α/Fe]. Instead, low-/high-α populations were formed in regions of long/short gas consumption timescale, which in turn is regulated by gas pressure.

As mentioned above, only about 5% of all MW-like galaxies in the simulated volume display some kind of α-bimodality. Investigating what sets these few cases apart from the general MW-like galaxies in the simulation, Mackereth et al. (2018) found that they underwent a different accretion history. Simulated galaxies whose disk populations show α-bimodality accreted satellites more intensely at $z \gtrsim 1.5$ than their normal counterparts (Fig. 9 of Mackereth et al. 2018). Thus, in agreement with the stellar halo study described in Section 2, evidence from the chemistry of its disk populations suggests that the MW history has been characterised by atypical accretion activity.

4. Globular cluster remnants in the inner Galaxy

While analysing APOGEE DR12 elemental abundances for a sample of 5,200 bulge stars, Schiavon et al. (2017) discovered a large population of field stars within $\sim$ 2 kpc of the Galactic centre, characterised by very high N and Al abundances, which are anti-correlated with the abundance of C. The chemistry of these *N-rich stars* is typical of the so-called "second generation" stars first identified in globular clusters (GCs) many years ago (see Bastian & Lardo 2018; Renzini et al. 2015). The N-rich star metallicity distribution differs to a high degree of confidence from that of the existing Galactic GC system, so that N-rich stars cannot be explained by evaporation and tidal stripping from those GCs. Schiavon et al. (2017) hypothesised that N-rich stars result from destruction of an early population of GCs. The mass in destroyed GCs within 2 kpc of the Galactic centre is $\sim 1.5 - 2 \times 10^8$ M$_\odot$, corresponding to 20-50% of the halo stellar mass within that volume, depending on the destroyed GC and halo mass estimates. It also amounts to several times the mass of the existing GC system. It is possible that this population was deposited in the inner halo a long time ago, partly from accreting systems, and partly during *in situ* formation in a turbulent disc, followed by immediate tidal disruption (e.g., Kruijssen 2015) from interaction with massive molecular clouds.

The possible presence of a large stellar mass in destroyed GCs in the heart of the MW is another indication of a very high accretion rate in early times. A high accretion rate brings about high gas pressure, leading to high GC formation and destruction (Pfeffer et al. 2018), which would in turn cause the MW today to have a smaller/less massive GC system than average galaxies of the same halo mass.

But does the MW have a low total GC mass for its halo mass? In fact, the total mass in GCs (M_{GC}) is perhaps the best tracer of the halo mass of a galaxy (M_h), with a ratio $\eta = M_{GC}/M_h = 4 \times 10^{-5}$ that is constant over several decades in mass, with a scatter of only 0.2 dex (e.g., Hudson et al. 2014). Considering accepted ranges for $M_{h,MW}$ and $M_{GC,MW}$ (Watkins et al. 2019; Hudson et al. 2014; Kruijssen & Portegies Zwart 2009) we have $\eta_{MW} = 1 - 4 \times 10^{-5}$, or somewhere between average or too low by over 2σ.

The uncertainties in the relevant quantities are still too large for a call on whether the early formation/accretion/destruction of GCs was exceptionally large in the past. If η_{MW} is average, one would be led to conclude that in general galaxies destroyed GCs just as vigorously as the early MW, making GCs (or their parent populations) important contributors to the stellar mass budget at the central regions of all massive galaxies. If however η_{MW} is significantly low, the conclusion is again that the MW may have undergone an unusually intense accretion history in the distant past.

5. Concluding Remarks

We briefly reviewed recent work taking stock of the contributions to the stellar mass budget of the MW halo by dwarf galaxies and globular clusters, based on recent data from cutting edge surveys of Galactic stellar populations. Intepretation of these findings in light of state-of-the-art cosmological numerical simulations suggests that the accretion history of the MW may have been unusual, currently placing it in the 5% category. It will be interesting to see how this picture will evolve as a result of the upcoming ten-fold increase in halo sample size afforded by the next generation of spectroscopic surveys (e.g., WEAVE, Jin et al. 2019, in prep., Dalton et al. 2016; 4MOST, de Jong et al. 2019), complemented by improvements in both resolution and subgrid physics of numerical simulations. Maybe those developments will locate the MW ever farther from the typical $L^\star$ disk galaxy, or maybe they will shift it back to a position of normality. Either way, ten years from today we will have expanded our knowledge of the make up of the MW halo and the history of our Galaxy greatly. These are exciting times.

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