Early Disk-Galaxy Formation from JWST to the Milky Way
Proceedings IAU Symposium No. 377, 2024
F. Tabatabaei, B. Barbuy & Y.-S. Ting, eds.
doi:10.1017/S1743921323002910

Chemically characterising the Milky Way's stellar halo

Danny Horta[1,2], **Ricardo P. Schiavon**[1] **and APOGEE team**

[1]Astrophysics Research Institute, Liverpool John Moores University, Liverpool Brownlow Hill,L3 5RF, UK
email: dhortadarrington@flatironinstitute.org

[2]Center for Computational Astrophysics, Flatiron Institute, 162 5th Ave., New York, NY 10010, USA

Abstract. Galactic haloes in a Λ-CDM universe are predicted to host today a swarm of debris resulting from cannibalised dwarf galaxies. The chemo-dynamical information recorded in their stellar populations helps elucidate their nature, constraining the assembly history of the Galaxy. Using data from APOGEE and Gaia, we examine the chemical properties of various halo substructures, considering elements that sample various nucleosynthetic pathways. The systems studied are Heracles, Gaia-Enceladus/Sausage (GES), the Helmi stream, Sequoia, Thamnos, Aleph, LMS1, Arjuna, I'itoi, Nyx, Icarus, and Pontus. Abundance patterns of all substructures are cross-compared in a statistically robust fashion. Our results show that many halo substructures conjectured to be debris from individual accretions likely belong to either the omnipresent GES or to in situ populations, and that the Milky Way likely underwent three major mergers so far: Heracles, GES, Sagittarius dSph.

Keywords. Galaxy: halo—galaxies: abundances – galaxies: structure – galaxies: evolution – The Milky Way

1. Introduction

"How did the Milky Way form?" is likely the most fundamental question facing the field of Galactic archaeology. When posed in a cosmological context, the Λ-CDM model predicts that the Galaxy formed in great measure via the process of hierarchical mass assembly. In this scenario, nearby satellite galaxies are consumed by the Milky Way due to them being attracted to its deeper gravitational potential, and as a result merge with the Galaxy. In such cases, these merger events shape the formation and evolution of the Milky Way. Therefore, an understanding of the assembly history of the Milky Way in the context of Λ-CDM depends critically on the determination of the properties of the systems accreted during the Galaxy's history, including their masses and chemical compositions.

The core of the Sagittarius dSph system and its still forming tidal stream (Ibata et al. 1994) have long served as an archetype for dwarf galaxy mergers in the Milky Way. Moreover, in the past few years, several phase-space substructures have been identified in the field of the Galactic stellar halo that are believed to be the debris of satellite accretion events, including the Gaia-Enceladus/Sausage (GE/S, Helmi et al. 2018; Belokurov et al. 2018; Haywood et al. 2018; Mackereth et al. 2019), Heracles (Horta et al. 2022), Sequoia (Myeong et al. 2019), Thamnos 1 and 2 (Koppelman et al. 2020), Nyx (Necib et al. 2020), LMS-1 (Yuan et al. 2020), the substructures identified using the H3 survey: namely Aleph, Arjuna, and I'itoi (Naidu et al. 2020). While the identification of these substructures is helping constrain our understanding of the mass assembly history of the Milky Way, their association with any particular accretion event still needs to be clarified. Along those lines, predictions from numerical simulations suggest that a single accretion event can lead to multiple substructures in phase space (e.g., Jean-Baptiste et al. 2017; Koppelman et al. 2020). Therefore, in order to ascertain the reality and/or distinction of these accretion events, one must combine phase-space information with detailed chemical compositions for large samples

In this work we set out to combine the latest data releases from the APOGEE and Gaia surveys in order to dynamically determine and chemically characterise previously identified halo substructures in the Milky Way. We attempt, where possible, to define the halo substructures using kinematic information only, so that the distributions of stellar populations in various chemical planes can be studied in an unbiased fashion. This allows us to understand in more detail the reality and nature of these identified halo substructures, as chemical abundances encode more pristine fossilised records of the formation environment of stellar populations in the Galaxy.

2. Method

Our aim is to utilise the chemistry to further unravel the nature and properties of these halo substructures, and in turn place constraints on their star formation and chemical enrichment histories. We also aim to compare their chemical properties with those from in situ populations. By studying the halo substructures using different elemental species we aim to develop an understanding of their chemical evolution contributed by different nucleostynthetic pathways, contributed either by core-collapse supernovae (SNII), supernovae type Ia (SNIa), and/or Asymptotic Giant Stars (AGBs). Specifically, we seek to first characterise these substructures qualitatively in multiple chemical abundance planes, and after compare mean chemical compositions across various substructures in a quantitative fashion. We employ in our quantiative comparison a methodology that is immune to, or very minimally affected by, selection effects. For that reason, the metallicity distribution function does not enter our analysis. Our quantitative comparisons between various substructures is fully descrived in Section 5 of Horta et al. 2022.

3. Results

3.1. *Qualitative comparison*

Figure 1 shows the distribution of each substructure in the Mg-Fe plane (coloured markers) compared to the parent sample (2D density histogram). We find that all the substructures –except for Aleph and Nyx– occupy a locus in this plane which is typical of low mass satellite galaxies and accreted populations of the Milky Way (Tolstoy et al. 2009, Hayes et al 2018, Mackereth et al. 2019), characterised by low metallicity and lower [Mg/Fe] at fixed [Fe/H] than *in situ* disc populations. For further details on these results, see Section 4.1 from Horta et al. 2022.

3.2. *Quantitative comparison*

The resulting quantitative comparison between the halo substructures indicates that approximately half of the halo substructures are statistically equal with regards to their chemical abundances. For example, the χ^2 comparison between the GES and two of the Sequoia samples implies that these three substructures are statistically the same, as we find that the *M19* and *N20* Sequoia samples all have a high probability of being statistically similar to the GES substructure ($p_{\chi^2} > 0.4$). Conversely, for the *K19* Sequoia shows clear differences with the GES substructure, given its p_{χ^2}=0 and χ^2=47.9 values.

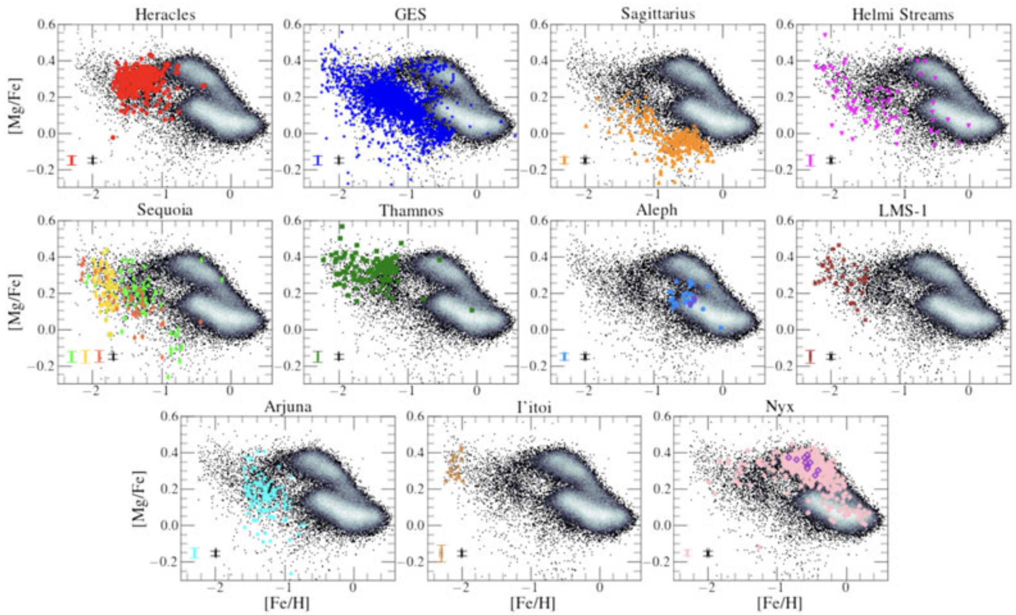

Figure 1. The resulting parent sample and identified structures in the Mg-Fe plane. The mean uncertainties in the abundance measurements for halo substructures (colour) and the parent sample (black) are shown in the bottom left corner. For the Aleph and Nyx substructures, we also highlight with purple edges stars from our APOGEE DR17 data that are also contained in the Aleph and Nyx samples from the Naidu et al. 2020 and Necib et al. 2020 samples, respectively.

Moreover, we also find striking similarities between GES and other halo substructures. For example, when comparing LMS-1 to GES we obtain a probability value of 0.46. Similarly, an ever closer match is found for the GES-Arjuna comparison, yielding a probability value of 0.92. Along similar lines, we find that when comparing Nyx to the high-α disc, we obtain a probability value of 0.78, which confirms our initial hypothesis that the Nyx is not an accreted substructure, but instead is a stellar population constituted of high-α disc stars. Moreover, we find that when comparing Heracles, Sgr dSph, and Thamnos with the GES that the probability of these substructures being statistically equal is $\sim$0. This result is not entirely surprising, as all these substructures are postulated to be debris from separate accretion events, and thus their chemical compositions are likely to differ. Interestingly, we find two surprising results: i) despite the Aleph substructure presenting qualitatively the same chemistry as the low-α disc, its χ^2 value yields a probability of 0.04, suggesting that these are not as similar as initially hypothesised. These differences are manifested most prominently in [Ti/Fe] and [Ce/Fe]; ii) although Heracles occupies a position in several chemical composition planes that appears to follow a single sequence with the inner high-α populations, the χ^2 yielded by that comparison indicates that these are statistically different (with a probability value of p_{χ^2}=0). For this comparison, we find that [O/Fe], [Mg/Fe], and [Si/Fe] (i.e., the lighter α elements) are the main culprits for this difference, and to a lesser degree [S/Fe]. For further details on these results, see Section 5 and 6 from Horta et al. 2022. Figure 2 presents a confusion matrix of the probability values obtained when comparing the chemical compositions of all the halo substructures with each other and with a high-/low-α discs.

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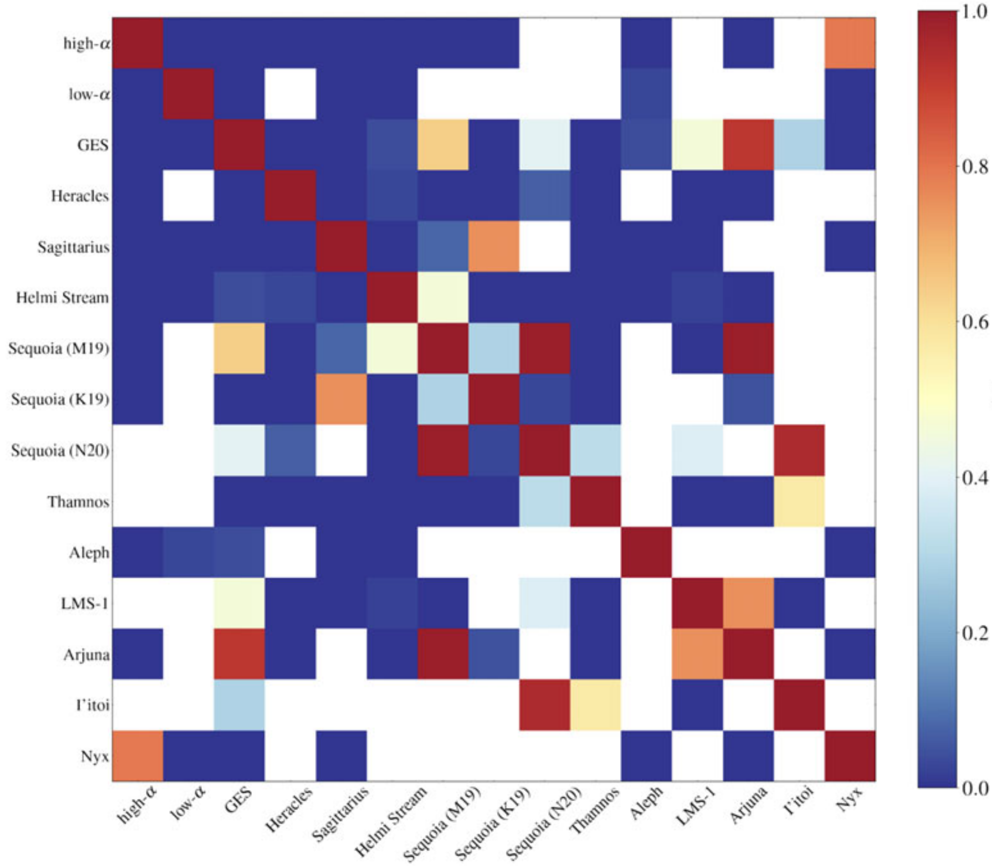

Figure 2. Confusion matrix of the probability values obtained when comparing the chemical compositions of all the halo substructures with each other and with a high-/low-α discs. Here, each substructure is compared with its counterpart using a [Fe/H] value that is well covered by the data, where red(blue) signifies a high(low) probability of two systems being statistically similar given their chemical compositions. Comparisons with blank values are due to the two substructures being compared not having any overlap in [Fe/H].

4. Conclusions

In this work we have utilised a cross-matched catalogue of the latest APOGEE (DR17) and *Gaia* (EDR3) data releases in order to study the chemo-dynamic properties of substructures previously identified in the stellar halo of the Milky Way. In short, our results show that many halo substructures conjectured to be debris from individual accretions likely belong to either the omnipresent GES or to in situ populations, and that the Milky Way likely underwent three major mergers so far: Heracles, GES, Sagittarius dSph. For further details on the conclusions of this work, please see Section 6 and 7 from Horta et al. 2022.

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