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P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

SPECTROSCOPIC SURVEYS UNVEALING THE GALACTIC STELLAR HALO.

E. Fernández-Alvar[1]

Abstract. Large area spectroscopic surveys have greatly improved our knowledge about the formation and evolution of the Galaxy. The analysis of hundreds of thousands of stellar spectra have allowed to better characterize the stellar chemical composition of each Galactic component and reconstruct the built-up of the Milky Way. I review the main results recently obtained about the study of the stellar halo from the analysis of spectroscopic data, in particular those performed as part of my research. The later feeds on the Sloan Digital Sky Survey (SDSS) low- and high-resolution spectroscopic programs dedicated to observation of stars in the Galaxy: the Sloan Extension for Galaxy Understanding and Exploration (SEGUE) and the Apache Point Observatory Galactic Evolution Experiment (APOGEE). The recent Gaia second data release (DR2) in combination with the spectroscopic databases have provided a new insight in this area. Next generation of spectroscopic surveys, as the Maunakea Spectroscopic Explorer (MSE) are promising projects to disentangle the formation and evolution of our Galaxy and in particular its accretion history through the better characterization of the stellar halo.

Keywords: spectroscopy, Galaxy, halo

1 Introduction

Galactic archaeology aims to decipher the formation history and evolution of our Galaxy. The main tool to achieve this goal is the analysis of the chemistry as well as the kinematical and dynamical properties of the stars now belonging to the Milky Way. Consequently, the accuracy in the chemical abundances determination and the distance and velocity measurements is crucial.

The spectroscopic and astrometric surveys of the last decades (e.g., SDSS – Blanton et al. (2017), the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) with the LAMOST Experiment for Galactic Understanding and Exploration (LEGUE) survey – Zhao et al. (2012), the GALactic Archaeology with HERMES (GALAH) survey – De Silva et al. (2015), Gaia – Gaia Collaboration et al. (2016), Gaia Collaboration et al. (2018b)) have considerably improved our knowledge of the current structure of the Milky Way. These observations have revealed the accreted origin of a large fraction of the stars, giving support to the current cosmological paradigm, the Λ-Cold Dark Matter model, which predicts that large structures in the Universe formed from the accretions of smaller subsystems. The study of the Galactic stellar halo is key in understanding the formation history of our Galaxy since it hosted old stars and accretion remnants.

Here I will explain how the improvement in quality of the spectroscopic surveys in the last decades, in combination with the unprecedent number and accuracy of the data provided by Gaia, has given a completely new perspective in this area. Finally, I will point out how the new generation of spectroscopic surveys, in particular the Maunakea Spectroscopic Explorer (MSE), will also revolutionize the halo research.

2 The Galactic stellar halo before Gaia.

The advent of large scale spectroscopic surveys which allowed the detection of numerous stellar overdensities crossing all over the Galactic halo, reliques of merger events ocurred in the past (e.g., Grillmair (2009), Bernard et al. (2016)) greatly helped to clarify our understanding of the origin of stars populating the Galactic halo, and the classical debate between the monolithic collapse (Eggen et al. (1962)) vs. the accretion of stellar systems

[1] Université Cote d'Azur, Observatoire de la Cote d'Azur, CNRS, 06300, Laboratoire Lagrange

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(Searle & Zinn (1978)) models. These results were in line with the cosmological predictions of the Λ-Cold Dark Matter model. However, evidences provided by several studies pointed to different spatial, kinematical and chemical properties between the inner and the outer parts of the Galactic halo (Carollo et al. (2007), Carollo et al. (2010), de Jong et al. (2010); An et al. (2013); Allende Prieto et al. (2014)).

In particular, Fernández-Alvar et al. (2015) showed gradients of α-elements-to-iron ratios decreasing with distance across the halo, steeper for the most metal-rich stars of the sample ([Fe/H] > -1.1) and negligiable for the most metal poor ([Fe/H] < -2.5). These trends, obtained from the low-resolution SDSS/SEGUE spectroscopic database (R $\sim$ 2000), were confirmed in the APOGEE high-resolution spectra (Fernández-Alvar et al. 2017) with the analysis of chemical species with a different nucleosynthetic origin. They pointed to that the inner parts of the halo would have undergone a different chemical enrichment. However, it was not clear if these differences would be linked to the existence of a population of stars formed in-situ during the first steps of Galaxy formation, currently dominating the inner parts of the halo, or it would be the result of more massive accreted satellites contributing to the inner regions.

On the other hand, a series of works (Nissen & Schuster (1997), Nissen & Schuster (2010), Nissen & Schuster (2011), Schuster et al. (2012)) had also revealed that a hundred field halo stars in the solar neighbourhood, not currently belonging to any stellar substructure, display two different trends of [α/Fe] with metallicity: one higher and less steep (the high-α population), and the other lower and faster decreasing with [Fe/H] (the low-α population). The increase of number of stars observed at high-resolution by the spectroscopic APOGEE survey allowed the work of Hayes et al. (2018b), in which they statistically proved that these two trends were the dominating ones in metal-poor stars ([Fe/H] < -0.9). Furthermore, Fernández-Alvar et al. (2018) compared both trends with chemical evolution models and inferred differences in the IMF and SFR of the two populations: a more intense and longer SFR and a slightly top-heavier IMF for the high-α population, and a lower and shorter SFR and a IMF with a lower upper mass limit for the low-α population.

Although an in-situ and accreted origin were proposed to explain the high-α and the low-α populations respectively, the lack of evidence in the analysis prevented to go further in the conclusions.

3 The Gaia Revolution.

Gaia hugely increased the number and accuracy of distance and velocity measurements in Galactic stars. The first data release provided in combination with the Tycho-Gaia solution allowed the distance determination for around 2 million stars. A cross-match of these data with the SEGUE database led to unveal that stars in the inner halo, moderately metal-rich [Fe/H] > -1.7, would be dominated by an accreted component moving in radial orbits, which would have come from possible one of the last major merger events ocurred in the Milky Way, at the epoch of the disc formation (Belokurov et al. 2018). The authors called it the Gaia Sausage.

But it was the second Gaia data release which gave a completely new insight in the stellar halo research. Gaia Collaboration et al. (2018a) revealed that kinematically hot stars (vtot > 200 km/s – classically classified as halo stars) in the inner halo region are distributed as two overdensities in the color-magnitud diagram. Haywood et al. (2018) investigated if these two sequences correspond to the two chemically distinct populations identified by Nissen & Schuster and others, thus confirming that the inner halo would be dominated by these two stellar populations. They observed that the high- and low-α populations split over the red and blue sequences respectively at metallicities larger than -1.1, but both lay on the blue sequences at lower metallicities. They confirmed this fact with the Nissen & Schuster sample of local stars, as well as the large and more extended sample of the APOGEE database. The high-α sequence, i.e. the red sequence in the HR diagram, shares the same α/Fe trend than the thick disk, and they suggested that they would probably be thick disk stars heated by the major merger of the satellite which provided the low-α population.

At the same time, Helmi et al. (2018) discovered within the Gaia database, a large fraction of halo stars showing coherence in the proper motion space and moving in retrograde orbits, indicating an accreted origin. By performing a crossmatch with the APOGEE DR14 database they confirmed that these accreted stars correspond to the low-α sequence. They inferred that this satellite would have a mass of $\sim 6 \cdot 10^8$ solar masses and would be accreted at an epoch in agreement with that inferred for the Gaia Sausage. Other groups performed analysis comparing observations and simulations and predicted also a merger with a significantly massive satellite to explain the chemical abundance distribution in halo stars (Kruijssen et al. (2019), Mackereth et al. (2019), Fernández-Alvar et al. (2019b)).

Following works tried to shed light on the origin of the red sequence discovered in the color-magnitud diagram of Gaia stars, with disk-like chemistry but halo-like kinematics. Fernández-Alvar et al. (2019a) analysed stars located very far away from the plane, at $|z| > 5$ kpc, and revealed three groups of stars with [Fe/H] > -0.75 which chemical and dynamical properties providing evidence of accretion events. Almost half of the sample shows a high, flat trend of [α/Fe] with [Fe/H], the same displayed by thick disc stars, which decreases at [Fe/H] $\sim$ -0.4 and moving with large velocities. They suggested that these stars would have formed in the thick disc and would have been heated by a significantly massive merger event in order to be able to put them in such large z with halo-like velocities. The fact that some of the stars appear to have thin-disk like abundances gave evidence that the Galaxy was already at the time were the bulk of SNIa were exploding and contributing to the interstellar medium when this major merger occurred. They also identified a group of stars showing a decreasing trend of low α/Fe ratios that resemble those displayed by Sagitarius stars. Finally, they also detected a group of stars with α/Fe in between, which they identified, from their chemistry and dynamical properties, as components of the Triangulum/Andromeda and A13 stellar overdensities, stars heated from the thin disc, as proposed by Bergemann et al. (2018), Hayes et al. (2018a)).

Di Matteo et al. (2018) found evidence that these high-α metal-rich stars now located far from the plane would be indeed disk stars heated when the Gaia Sausage was accreted, as the increase of velocity dispersion at [Fe/H] $\sim$ -1.1 indicates. They endorsed their interpretation with the detection of metal-poor stars ([Fe/H] $\sim$ -2) moving in rotational orbits. This would mean that at the time when metal-poor stars formed, there was already a disc configuration. Finally, Gallart et al. (2019) showed that the age distribution of both populations is consistent with this picture.

4 Conclusions and future work with MSE

The increase of the number and accuracy in measurements provided by the spectroscopic surveys during the last years, and in particular the hugely improvement in astrometric data provided by Gaia, has revolutionized our view about the Galaxy structure and their formation history. The following decades will see the upcoming of the next generation of spectroscopic surveys which will increase the number, quality and coverage of observations and, with them, exciting results in the clarification of the Galaxy formation.

One of these surveys will be the Maunakea Spectroscopic Explorer (MSE). This project consists on the transformation of the CFHT 3.6 m optical telescope (located at Maunakea, Hawaii) into a 10 m multiobject spectroscopic facility, observing $\sim$ 4000 objects simultaneously with a spectral resolution spanning 3000 to 40000. It will have the capacity to observe $\sim$ 1 million objects per month.

The MSE will provide observational support to dig into the still unreachable areas of the halo. In particular, the outer halo still lacks of reliable spectroscopic observations, due to the current instrumental limitations. With the MSE it will be possible to obtain accurate chemical abundances of millions of stars in the outer regions. This will allow to characterize the spatial distribution of chemical abundances, identify distinct stellar populations and clarify the late accretion history of our Galaxy.

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