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TRACING THE FORMATION OF THE MILKY WAY THROUGH ULTRA METAL-POOR STARS

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Abstract. We use Gaia DR2 astrometric and photometric data, published radial velocities and MESA models to infer distances, orbits, surface gravities, and effective temperatures for all ultra metal-poor stars ($[Fe/H] < -4.0$ dex) available in the literature. Assuming that these stars are old (> 11 Gyr) and that they are expected to belong to the Milky Way halo, we find that these 42 stars (18 dwarf stars and 24 giants or sub-giants) are currently within $\sim$ 20 kpc of the Sun and that they map a wide variety of orbits. A large fraction of those stars remains confined to the inner parts of the halo and was likely formed or accreted early on in the history of the Milky Way, while others have larger apocentres (> 30 kpc), hinting at later accretion from dwarf galaxies. Of particular interest, we find evidence that a significant fraction of all known UMP stars ($\sim$ 26%) are on prograde orbits confined within 3 kpc of the Milky Way plane ($J_z < 100$ km s^{-1} kpc). One intriguing interpretation is that these stars belonged to the massive building block(s) of the proto-Milky Way that formed the backbone of the Milky Way disc. Alternatively, they might have formed in the early disc and have been dynamically heated, or have been brought into the Milky Way by one or more accretion events whose orbit was dragged into the plane by dynamical friction before disruption. The combination of the exquisite Gaia DR2 data and surveys of the very metal-poor sky opens an exciting era in which we can trace the very early formation of the Milky Way

Keywords: Galaxy: formation, Galaxy: disc, Galaxy: halo, stars: distances, stars: UMP

Reminder

This proceedings has to be intended as a summary of the work from Sestito et al. (2019).

1 Introduction

Ultra metal-poor (UMP) stars, defined to have [Fe/H]* < -4 dex (Beers & Christlieb 2005), are extremely rare objects located mainly in the Milky Way (MW) halo. Because they are ultra metal-poor, also relative to their neighbourhood, it is assumed that they formed from relative pristine gas shortly after the Big Bang (e.g., Freeman & Bland-Hawthorn 2002). As such, they belong to the earliest generations of stars formed in the Universe (Karlsson et al. 2013). Because they are old, observable UMPs must be low-mass stars, however the minimum metallicity at which low-mass stars can form is still an open question (see Greif 2015, and references therein). The search for, and study of, stars with the lowest metallicities are therefore important topics to answer questions on the masses of the first generation of stars and the universality of the initial mass function (IMF), as well as on the early formation stages of galaxies and the first supernovae (e.g., Frebel & Norris 2015, and references therein). Careful studies over many decades have allowed us to build up a catalogue of 42 UMP stars throughout the Galaxy. Many of these stars were discovered in survey programs that were or are dedicated to finding metal-poor stars using some special pre-selection through prism techniques (e.g., the HK and HES surveys; Beers et al. 1985; Christlieb et al. 2002) or narrow-band photometry (such as for instance the SkyMapper and Pristine survey programmes; Wolf et al. 2018; Starkenburg et al. 2017). Others were discovered

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*[Fe/H] $= \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$, with N_X= the number density of element X

in blind but very large spectroscopic surveys such as SDSS/SEGUE/BOSS (York et al. 2000; Yanny et al. 2009; Eisenstein et al. 2011) or LAMOST (Cui et al. 2012).

In an effort to refine the comparison with models and unveil the phase-space properties of these rare stars, we combine the exquisite Gaia DR2 astrometry and photometry (Gaia Collaboration et al. 2018) with models of UMP stars (MESA isochrones and luminosity functions; Paxton et al. 2011; Dotter 2016; Choi et al. 2016, `waps.cfa.harvard.edu/MIST`) to infer the distance, stellar properties, and orbits of all 42 known UMP stars.

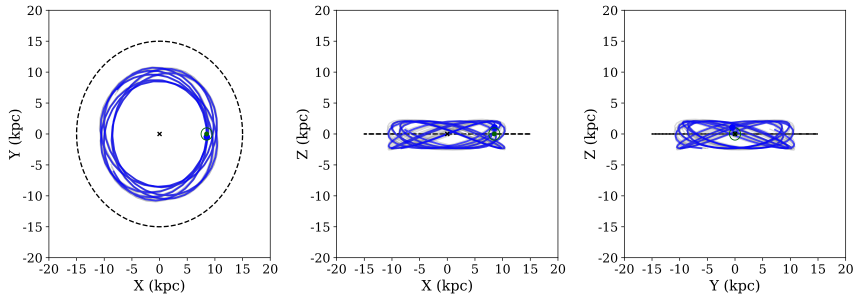

Fig. 1. Orbit of the most metal-poor star known, the Caffau star (SDSS J102915+172927). The blue line is the projected orbit of the star in the plane YX (left), ZX (center) and ZY (right). The Galactic plane within 15kpc (black line) and the Sun (green dot) are shown. Gray orbits represent randomisations around the values of position, distance, radial velocity and proper motions.

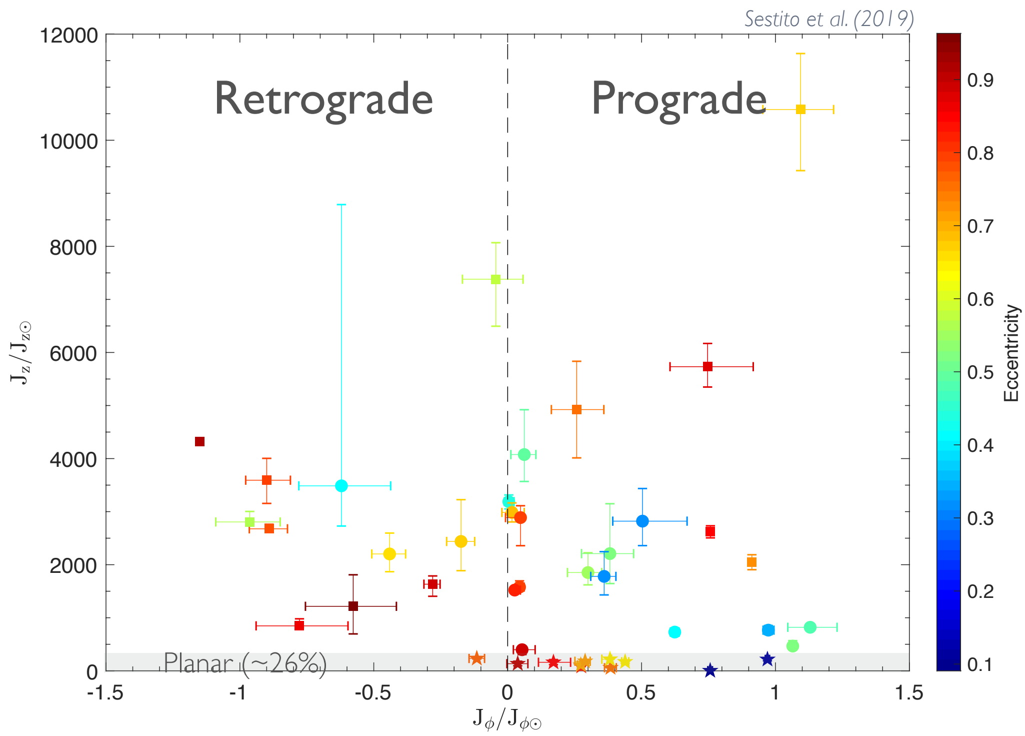

Fig. 2. Position of the sample stars in the rotational action J_ϕ ($= L_z$) and vertical action J_z space. The rotational and vertical action are scaled by the Sun values respectively $J_{\phi\odot} = 2009.92$km s^{-1}kpc, $J_{z\odot} = 0.35$km s^{-1}kpc. Stars confined close to the MW plane are marked with a star symbols, while "inner halo" and "outer halo" stars are represented by circles and squares, respectively. The markers are colour-coded by eccentricity.

2 Conclusions

Combining the Gaia DR2 photometric and astrometric information in a statistical framework, we determine the posterior probability distribution function for the distance, the stellar parameters (temperature and surface gravity), and the orbital parameters of 42 UMPs (see Figure 2 and Sestito et al. (2019)). Given that 11 of those stars remain confined close to the MW plane, we use both a pure halo prior and a combined disc+halo prior. Folding together distance posterior and orbital analysis we find that 18 stars are on the main sequence and the other 24 stars are in a more evolved phase (subgiant or giant).

Through the orbital analysis, we surprisingly find that 11 stars are orbiting in the plane of disc, with maximum height above the disc within 3 kpc. 2 of these 11 have a quasi-circular orbit as shown in Figure 1. We hypothesise that they could have once belonged to a massive building blocks of the proto-MW that formed the backbone of the MW disc, or that they were brought into the MW via a specific, massive hierarchical accretion event. Another 31 stars are from both the "inner halo" (arbitrarily defined as having $r_{\rm apo} < 30$kpc) and were accreted early on in the history of the MW, or the "outer halo" hinting that they were accreted onto the Galaxy from now-defunct dwarf galaxies.

This research has made use of use of the SIMBAD database, operated at CDS, Strasbourg, France (Wenger et al. 2000). This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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