SF2A 2017
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IMPACT OF GAIA ON UNDERSTANDING MILKY WAY EVOLUTION

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Abstract. Gaia space mission has published in September 2016 its first data release. In the years to come, exquisite astrometry, photometry and spectroscopy will be available for hundreds of millions of targets, opening a new era of discoveries in galactic archaeology. In this proceeding, I review some key aspects, such as kinematic and metallicity gradients in the Galaxy, that are linked to the internal and external mechanisms that influence Galaxy evolution and that have already started to be clarified with GDR1.

Keywords: Milky Way, stellar content, evolution

1 Introduction

In the context of a Λ-Cold Dark Matter Universe, disc galaxies are formed from the successive accretion of smaller galaxies (Springel et al. 2006). This paradigm, though very successful explaining the large structures in the Universe, has met a number of issues on smaller scales (of the order of the $\sim$Mpc), such as the missing satellite problem, the absence of classical bulges in the galaxies, and the age and size of galactic discs (Bullock & Boylan-Kolchin 2017). The thorough and detailed study of individual stars in our Galaxy, the Milky Way, can help us understand to a great extent the mechanisms that come into play in galaxy evolution. Indeed, internal processes such as stellar radial migration, galactic fountains, dynamical heating, chemical enrichment, as well as gas and star accretions and responses of the disc to those accretions are encoded in the stellar kinematics, chemistry and age (Freeman & Bland-Hawthorn 2002).

2 Galactic archaeology and Gaia performances

The fossils that are used in Galactic archaeology are *(i)* stellar distance and position on the sky (to identify stellar streams and characterise the morphology of the galactic structures), *(ii)* proper motions and radial velocities (to identify old accretions and moving groups through the obtention of the 3D kinematics of the stars, and assuming a Galactic potential, infer their orbit), and *(iii)* the stellar atmospheric parameters, including the metallicity and chemical abundances in order to perform chemical tagging of the stars (e.g. Tolstoy et al. 2009), and infer an age estimation (Soderblom 2010; Kordopatis et al. 2015b). The combination of all this information will in return allow to infer star formation histories at different regions and epochs of the Galaxy, and highlight indirect signatures of evolution (see next sections).

The difficulty of this endeavour is that data *(i)* to *(iii)* are of increasing difficulty to obtain, and that one needs to collect this data for at least several hundreds of thousand of stars. This is were the Gaia space mission comes into play (Gaia Collaboration et al. 2016b). By the end of its mission, Gaia will provide parallaxes up to $G \sim 20.7$, with 10% uncertainty at 10 kpc from the Sun (depending on the colour of the star), transversal velocities with uncertainties better than a few 100 $\mathrm{m\,s^{-1}}$ for $d < 2$ kpc, and a few $\mathrm{km\,s^{-1}}$ up to $d \sim 5$ kpc. $T_{\rm eff}$, $\log g$ and [M/H] will be derived from both the Blue and Red spectrophotometers (BP/RP) for most of the targets and the Radial Velocity Spectrometer (RVS) for $\sim 10^7$ stars brighter than $G_{\rm RVS} < 14.5$ mag (Bailer-Jones et al. 2013). Radial velocities will be obtained for $\sim 10^8$ stars with $G_{\rm RVS} < 16$ mag, with $\sigma_{V_{\rm rad}} \sim 2.5$ $\mathrm{km\,s^{-1}}$ (see proceeding of D. Katz, this volume). Finally, coarse stellar parameterisation (including [α/Fe] estimations) will be obtained spectroscopically for $\sim 10^7$ stars brighter than $G_{\rm RVS} < 14.5$ (though with $\sigma_{[\alpha/\rm Fe]}$ getting significantly degraded for stars fainter than $G_{\rm RVS} > 11$ mag), and individual element abundances for Fe, Ca, Mg, Ti and Si for the stars brighter than $G_{\rm RVS} \approx 11$ mag (Recio-Blanco et al. 2016).

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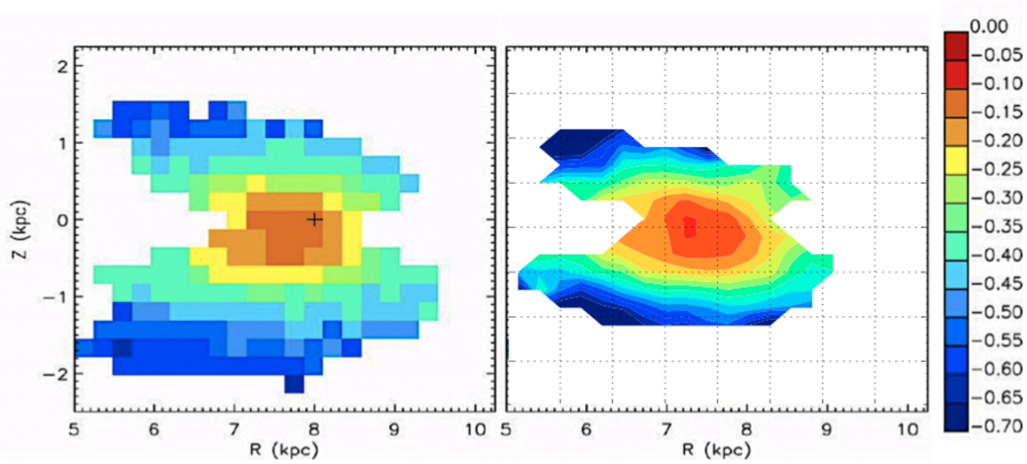

Fig. 1. Metallicity maps before Gaia (left, obtained with RAVE data, taken from Kordopatis et al. 2013b), and after Gaia (right, courtesy of I. Carrillo). The plot on the right is obtained for a smaller volume, since TGAS has a magnitude limit which is brighter than the RAVE one. Nevertheless, smoother structures in the extended Solar neighbourhood can be seen with the updated dataset.

3 Galactic Maps and gradients

A first glimpse of Gaia's potential has been given with its first data release (Gaia Collaboration et al. 2016a). In particular its sub-catalogue TGAS (Tycho-Gaia Astrometric Solution, Lindegren et al. 2016) published 2 million parallaxes and proper motions for stars brighter than the 11th magnitude, which can be combined with past or on-going ground-based spectroscopic surveys in order to get the radial velocities and chemical abundances of the stars. RAVE's fifth data release (Kunder et al. 2017), in particular, has the largest overlap with TGAS, with $\sim 2 \cdot 10^5$ stars in common. RAVE, when associated with distance estimates taking into account Gaia's parallaxes (provided by, for example, Astraatmadja & Bailer-Jones 2016 or McMillan et al. 2017), allow us to have much clearer (and smoother) view of the change of the stellar properties (velocities, metallicities) across the Galaxy. Figure 1 shows the updated metallicity map obtained with the Astraatmadja & Bailer-Jones (2016) distance set and the RAVE metallicities; even though the volume is smaller on the right hand-side figure, the vertical and radial gradients are now much smoother, due to sounder distances. Similar plots can be obtained for the different velocity fields too, see Carrillo et al. (2017). In the next subsection, I discuss some preliminary results regarding the metallicity distribution functions in the Galaxy and the spatial distribution of the super metal-rich stars.

4 Metallicity distribution functions and super-solar metallicity stars

The metallicity distribution function (MDF) of the stellar components of the Milky Way hold valuable information regarding the processes that have taken place in the evolution of our Galaxy. Up to recently, the study of the MDFs with precise stellar locations (via parallax measurements) for FGK stars could be done only up to a few 100 pc from the Sun, i.e. within the Hipparcos volume. To go beyond this limit, so-called spectroscopic distances projecting on isochrones the stellar atmospheric parameters were used (e.g.: Pont & Eyer 2004).

Figure 2 shows preliminary results taken from Kordopatis et al. (in prep). The box-plots represent the metallicity distributions as a function of height above the Galactic plane, at different galactic radii (different panels), using the RAVE-DR5 metallicities and the McMillan et al. (2017) distances. Excluding the $Z-$bins closest to the plane (which are suffering from selection biases and completeness issues that differ from one $R-$bin to the other, see Wojno et al. 2017), we measure the following vertical metallicity gradients, $\partial[\mathrm{M/H}]/\partial|Z|$, for the four 1 kpc-wide radial bins: $-0.27, -0.34, -0.33$ and $-0.19 dex$ kpc^{-1}, going from 6 kpc to 10 kpc, respectively. These values are compatible, within the errors (of the order of $0.07 dex$ kpc^{-1}), with the ones of Schlesinger et al. (2014) of $-0.243 \pm 0.05 dex$ kpc^{-1}, obtained using SEGUE G dwarfs. We note, however, that our measurements should be considered more reliable compared to previous studies, thanks to the improved distances that are being used here.

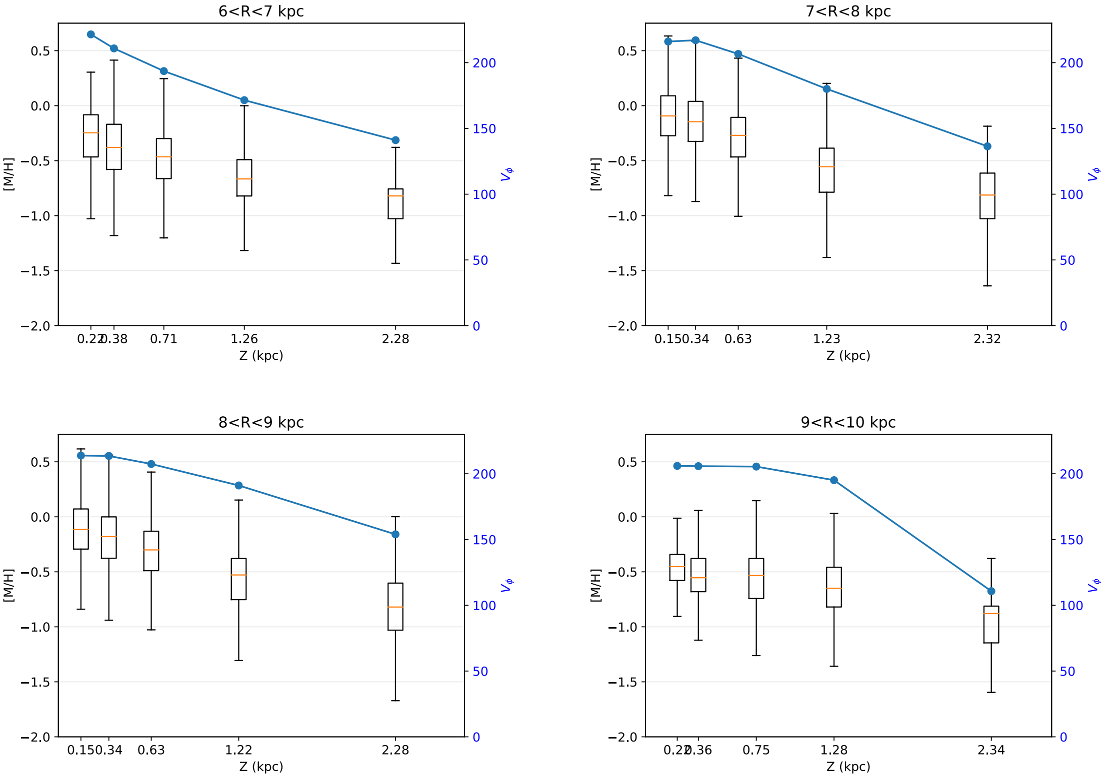

Fig. 2. Box plots representing the median metallicity (orange line) as a function of absolute distance from the Galactic plane, Z, for different radial ranges, R, from the Galactic centre. The actual boxes enclose the metallicity value of the first and third quartile, whereas the sizes of the bar span 99 per cent of the distribution. The median V_ϕ value, in $\mathrm{km\,s^{-1}}$, for each spatial bin is also represented in blue (and right-hand-side y-axis).

Regarding the skewness of the MDFs, no particular changes are noticed as a function of R; this is illustrated with the lack of change of the relative position of the median line within a box from one $R-$bin to another, at a fixed Z. This is not in agreement with the inversion of the MDF's skewness highlighted in Hayden et al. (2015) using APOGEE data. Nevertheless, we note that in Hayden et al. (2015) the skewness changes for the bins closest to the plane, regions where RAVE is potentially biased. A more thorough analysis, taking into account the completeness of our sample, needs therefore to be performed in order to confirm this statement.

Compared to results obtained without Gaia information (using the RAVE-DR4 parameters and distances, see Kordopatis et al. 2013a), we do not find any significant change on the mean of the MDFs. That said, the updated tails of the MDFs make more sense using the Gaia data: many super metal-rich stars ($[\mathrm{M/H}] > 0$, noted SMR hereafter) found previously to occupy large distances from the Galactic plane are found to be closer to the disc, whereas metal-poor stars are also shifted to higher Z. We note, however, that few SMR stars can still be detected, up to 1 kpc from the Galactic plane, confirming previous studies (see, for example, Kordopatis et al. 2015a). The majority of these SMR stars, even though they have updated eccentricities, are found to be in majority on circular orbits ($e < 0.2$), therefore having radially migrated from the inner parts of the disc through mechanisms involving co-rotation resonances with the spiral arms (e.g. Sellwood & Binney 2002).

Finally, it should be highlighted that we find a remarkably flat trend for the mean V_ϕ (obtained using UCAC5 proper motions, see Zacharias et al. 2017) as a function of Z for our outermost radial bin ($9 < R < 10$ kpc). Up to almost 750 pc from the plane, we find stars to have $< V_\phi >\approx 220\ \mathrm{km\,s^{-1}}$, i.e. associated to a stellar population dominated by the thin disc. This seems to confirm the thin disc flaring and the absence of the thick disc at the outer Galaxy, as already suggested by other studies (Bensby et al. 2011; Minchev et al. 2014; Bovy et al. 2016; Kordopatis et al. 2017), but now clearly indicated with the sole kinematics.

5 Signatures of accretion

Past accretion events can be identified directly in either the stellar positions (stellar streams), or energy-angular momentum space, or indirectly, by the dynamical effect that such accretions can have on the disc (Gómez et al. 2013).

Helmi et al. (2017) selected the metal-poor halo stars in the RAVE-TGAS sample in order to identify, in phase-space, over-densities associated with old accretions. Their work – which represents a first attempt of what will later be possible to achieve with better kinematics, distances and larger statistics– contains at least two important results. The first is that the selected halo stars that are identified as the less bound are in general in retrograde orbits, which is something that they evaluate not likely to happen in a smooth distribution, and the second is the identification of ten over-densities, an amount consistent with haloes formed purely by accretions. Future Gaia data-releases will allow to confirm this result, which at the moment is still hampered, to some extent, by low number statistics, and non-negligible uncertainty in stellar distance.

Carrillo et al. (2017) investigated the stellar motions in the galactic disc. The authors compared their results with the ones of Widrow et al. (2012) and Williams et al. (2013), where a wave-like pattern in the mean vertical velocity of stars near the Sun had been identified and been interpreted either as a vibration of the galactic plane due to the last major merger of the Milky Way, or as a dynamical signature of the potential of spiral arms on the stellar orbits, due to the inter-spiral arm position of the Sun (Faure et al. 2014; Monari et al. 2016). The new analysis, even though obtained in a smaller volume (limiting magnitude of TGAS $\sim 11\,\mathrm{mag}$ compared to $\sim 12\,\mathrm{mag}$ for RAVE), seem to suggest that the inner disc exhibits a breathing mode (provoked by either the accretion of a satellite or presence of the spiral arms), and that the outer disc exhibits a bending mode, solely explained by an accretion event (see their Figures 4 and 14). However, as the authors suggest, the error budget in the stellar kinematics, is still too large to make robust conclusions, and more accurate parallaxes and proper motions, together with (most importantly) a larger volume coverage by the future Gaia data-releases will allow to draw a definitive conclusion on the vibration modes of the disc.

6 Perspectives: Gaia and future ground-based spectroscopic surveys

Gaia DR2 is estimated to be released in April 2018. This data release will be a significant improvement over GDR1, since it will have better calibrations of the astrometry and the photometry, and will provide parallaxes and proper motion measurements up to $G \sim 20$ (i.e. up to 9 magnitudes fainter than TGAS), as well as radial velocities up to $G_{\mathrm{RVS}} \sim 12\,\mathrm{mag}$. The entire APOGEE, Gaia-ESO, LAMOST, GALAH and RAVE surveys, will be able to be crossmatched with GDR2, leading to a catalogue of $\sim 2 \cdot 10^6$ stars with metallicity and abundance measurements (and V_{rad} measurements for the faintest targets, for which the RVS will not get spectra). This fact, from itself constitutes an important milestone in galactic archaeology (as we have seen in the previous sections with just the crossmatch with RAVE), but the inhomogeneity of the chemical abundances, derived by different teams and different methods, might still be a limiting factor to achieve major breakthroughs in the field.

On the other hand, Gaia-DR3 (estimated to be released in mid-2020) will be the largest homogeneous spectroscopic catalogue ever available. Despite being derived from medium resolution spectra ($R \sim 11500$), the metallicities, radial velocities and abundances that will be published based on an homogeneous method, will be a huge leap towards investigating the relative abundances of the stellar populations, highlighting their chemo-dynamical differences and hence deciphering the evolution of our galaxy.

Finally, Gaia's potential will be even further increased thanks to WEAVE (Dalton et al. 2012), MOONS (Cirasuolo et al. 2011) and 4MOST (de Jong 2011), three spectroscopic surveys that will not start observing before the end of 2018, 2019 and 2022. WEAVE and 4MOST, in particular, will eventually provide high-resolution (up to $V \sim 15-16\,\mathrm{mag}$) and medium-resolution spectra (up to $V \sim 18-19\,\mathrm{mag}$) for tens of millions of stars and allow to map the Solar neighbourhood (up to $\sim$ 1 kpc), thought to contain stars coming from wide regions across the disc and halo, with unprecedented details thanks to the abundance measurements of several chemical elements of different nucleosynthetic families and kinematic accuracies of a few $100\ \mathrm{m\,s^{-1}}$. In addition, those surveys will allow to obtain spectra up to the magnitudes where Gaia will have proper motions and parallax measurements but no RVS spectra, leading to chemodynamical catalogues of stars with a precision that can be achieved nowadays only up to a couple of kpc away from the Sun.

G.K. would like to thank the PNCG for financial support.

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