Mem. S.A.It. Vol. 94, 24

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Mapping the Milky Way with large spectroscopic surveys in the Gaia era

The role of Cepheids, RRLyrae and seismic red giants

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Received: Day Month Year; Accepted: Day Month Year

Abstract. We discuss the ongoing efforts to create chrono-chemo-kinematical maps of our Galaxy, with the ultimate goal of unraveling its formation and evolution. Large spectroscopic surveys are now in progress, covering extensive volumes of the Milky Way. By combining data from spectroscopic surveys with Gaia parallaxes and complementary photometry it has been possible to compute precise distances for large stellar samples. Additionally, we can now compute isochrone ages for larger samples of main sequence turnoff and subgiant stars, albeit within a smaller volume of 1-3 kpc around us. Nevertheless, a pivotal aspect of this undertaking, even in the Gaia era, relies on subsets of data for which it is feasible to obtain highly precise distances and ages for distant stars. Pulsating variables assume a critical role in this context. Here, we give particular emphasis on the importance of RR Lyrae stars, Cepheids and seismic red giants. These stars constitute fundamental components of any extensive spectroscopic survey and have already furnished indispensable supplementary insights in the field of Galactic archaeology.

Key words. Stars: Variables: RR Lyrae stars, Cepheids, Seismic Red Giants – Milky Way: gradients, thick disk, stellar populations

1. Introduction

One of the important ways to expand the ESA-Gaia mission's legacy (see Brown 2021, and references therein) is to complement the Gaia astrometric and photometric data with additional photometry (Anders et al. 2019; Bailer-Jones et al. 2021; Anders et al. 2022; Andrae et al. 2023) and spectroscopy (Queiroz et al. 2020, 2023; Recio-Blanco et al. 2023; Guiglion et al. 2023). We have thus embarked, since the first Gaia data release, on a project to compute precise distances for Gaia and major spectroscopic surveys. For that purpose, we built the `StarHorse` code, a bayesian spectrophotometric code described in Queiroz et al. (2018).

Figure 1 (upper panels) shows the distance distribution of more than 300 million stars with Gaia magnitude brighter than 18.5 computed with `StarHorse` using Gaia EDR3 (Gaia Collaboration et al. 2021) and complementary photometric information (Anders

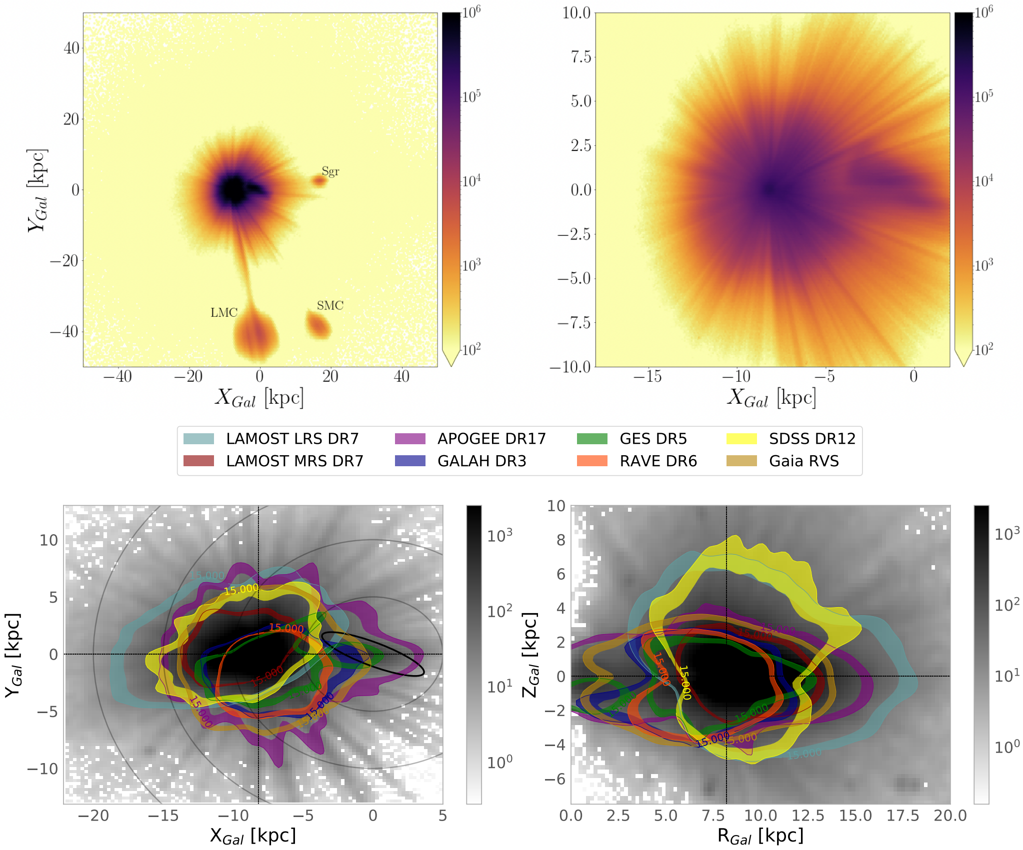

Fig. 1. Upper Panels: StarHorse density XY maps in galactocentric coordinates with Gaia EDR3 stars with G <18.5 and complementary photometry. Left: 100 kpc wide region centred on the Galactic centre. Right: zoom into a 20 kpc wide region centred on the Sun. Figure adapted from Anders et al. (2022). Lower Panels: StarHorse density XY and RZ maps with Gaia EDR3 stars with G <18.5 and complementary spectroscopy. Figure adapted from Queiroz et al. (2023)

et al. 2022[1]). Figure 1 (lower panels) shows similar diagrams as before, but now for around 12 million stars for which spectroscopic stellar parameters were also available (Queiroz et al. 2023[2]). In particular, the Queiroz et al. (2023) catalogue also includes isochrone ages for around 2.5 million main-sequence-turnoff and sub-giant stars. Two important things should be noted in Figure1: a) the bar is clearly seen in the density distribution of field stars (see also Anders et al. 2019), and b) the spectroscopic coverage of the Southern Hemisphere is rather poor, and will be complemented by the 4MIDABLE-LR survey of the disk and bulge (Chiappini et al. 2019). In addition, the figure shows that the APOGEE survey (Majewski et al. 2017), in the mid-infrared, is the only survey providing large number of targets close to the galactic mid-plane, reaching the Galactic bulge. Indeed, this survey, together with the ESA-Gaia mission, has been revolutionary for the field of Galactic Archaeology.

In the following we focus on some of the results coming from these large datasets and what is the contribution coming from

[1] http://data.aip.de/starhorse2021.htm
[2] http://data.aip.de/aqueiroz2023.htm

Cepheids, RRLyrae and seismic red giants. Indeed, variable stars are the back bones of Galactic archaeology. The reason is that for some of these stars it is possible to compute precise distances and ages. For instance, RRLyrae can show us a picture of our Galaxy more than 10 Gyrs ago. Furthermore, given their brightness, these objects have the capability to trace distant stellar populations, thus offering a crucial element in our understanding of the formation of the innermost regions of our Galaxy (Prudil et al. 2021). Seismic Red Giants, on the other hand, offer a large age-baseline (see Chaplin & Miglio 2013; Miglio et al. 2017, and references therein). For these objects precise distances and (model-dependent) ages can be obtained. Finally, Cepheids can be used to trace the young population in the thin disk of the MW, since for these stars precise distances can be obtained (see Lemasle et al. 2022; Riess et al. 2021, and references therein).

2. The chemical abundance-ratio map

Queiroz et al. (2020) combined high-resolution spectroscopic data from APOGEE-2 survey Data Release 16 (DR16) with broad-band photometric data from several sources as well as parallaxes from Gaia Data Release 2 (DR2) and derived distances for around almost 400 thousand APOGEE stars. For giants, the typical distance uncertainties achieved were of the order of 6%. With this dataset it was possible to obtain an extended chemical map of the Milky Way disk, achieving good coverage of regions close to the Galactic mid-plane and also covering a large galactocentric distance interval.

This dataset has unveiled a striking duality in the [α/Fe] vs. [Fe/H] in the innermost regions of the MW which was not clear from previous datasets. The chemical-dicothomy now extends into the MW bulge. Figure 2 shows the a similar figure of that of Queiroz et al. (2020) but now updated to APOGEE DR17 and Gaia EDR3 (using data from Queiroz et al. 2023). Among the several interesting results obtained with this data set, we here highlight the fact that the high-alpha stars do not extend towards the outermost parts of the disk. This has been seen in previous datasets as well (e.g. Anders et al. 2014; Nidever et al. 2014; Hayden et al. 2015). Also clearly seen from the figure is the fact that towards the outer regions (becoming more clear around 12 kpc from the Galactic center) the low-alpha stars dominate at all heights from the mid-plane (in the range considered in Figure 2).

3. Cepheids, the warp and the abundance gradients

If the low-alphas discussed above are tracers of the thin disk, and if they are observed at high mid-plane distances, some of the youngest stellar populations should also be seen far above the Galactic mid-plane. Indeed, young stellar populations such as Cepheids are also seen far above the Galactic mid-plane (see Lemasle et al. 2022, and references therein) and clearly trace the disk warp.

Cepheids are also important tracers of the present abundance gradient of the thin disk (see Genovali et al. 2014, and references therein). More recently the samples have been expanded covering a large azimuth range and including more metal-poor (see Trentin et al. 2023, and references therein) as well as more metal rich (inner disk) Cepheids (see Inno et al. 2019; Minniti et al. 2021; Matsunaga et al. 2023, and references therein). In particular, the recent results of Matsunaga et al. (2023) who report metallicities measured for Cepheids located between 3 and 5.6 kpc from the Galactic center, have shown the inner metallicities to be consistent with the extrapolation of a linear metallicity gradient traced by Cepheids beyond 6.5 kpc. In addition, the small scatter in the abundances again suggest the interstellar medium at young ages to be well mixed (at the level of 0.1 dex), although the sample size is still small and more data is needed to better constrain this point. This is a very important observational constraint for understanding the chemical evolution of the disk.

Finally, these more complete samples of Cepheids seem to agree with the main picture traced by young open clusters (e.g Casamiquela et al. 2019) indicating a present metallicity gradient of around −0.06 dex/kpc

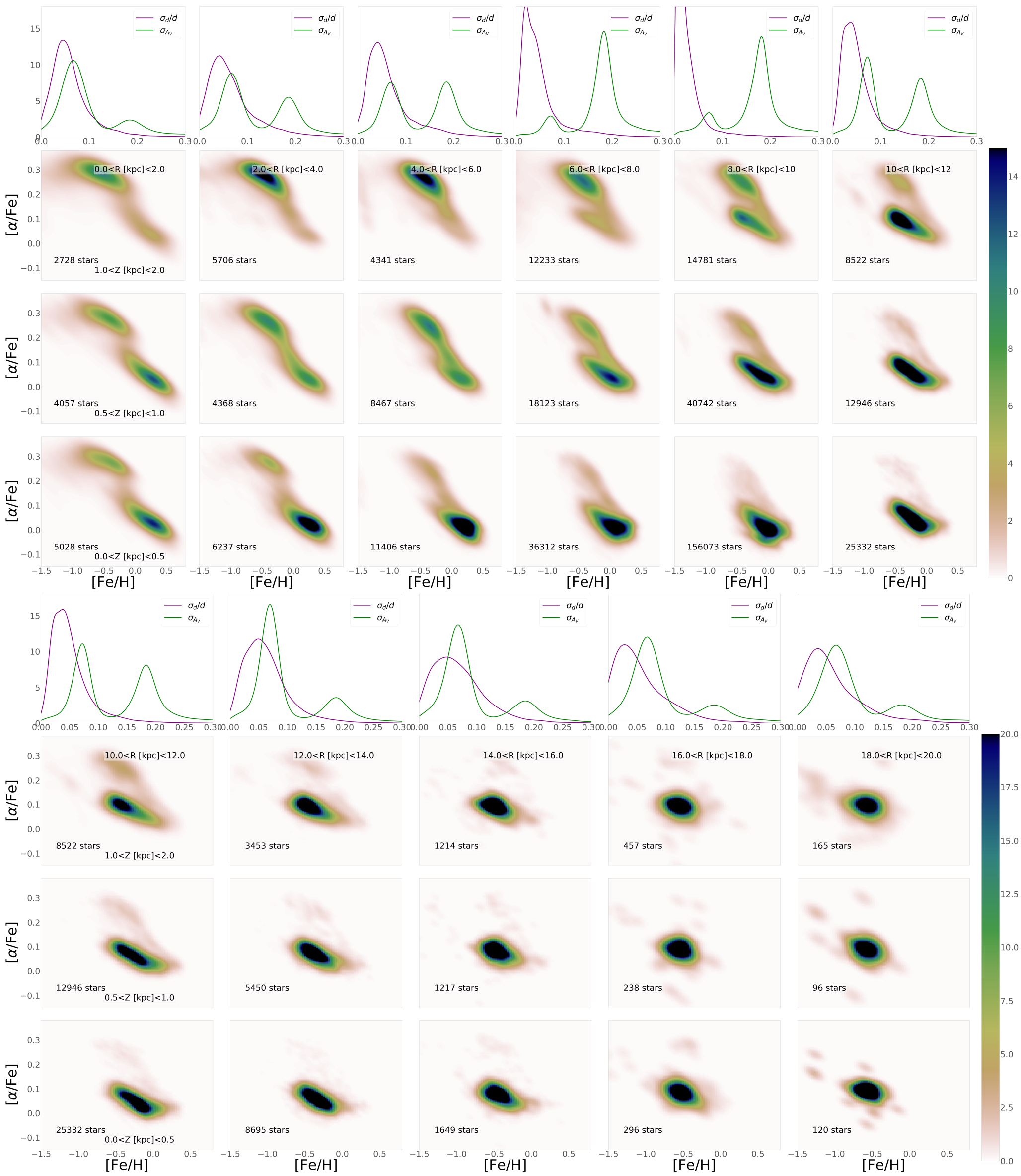

Fig. 2. [α/Fe] vs. [Fe/H] relation for different distances from the Galactic mid-plane and sampling the MW disk from the innermost regions to out to 20 kpc. This figure was made with the latest catalogue of Queiroz et al. (2023) - therefore it is an updated version of the same figure presented in Queiroz et al. (2020).

between 4-10 kpc from the galactic center. However, discrepancies appear towards the outer disk (see Trentin et al. 2023, for a recent compilation of gradients traced by Cepheids and open clusters). Cepheids seem to indicate a steeper gradient at larger distances, whereas open clusters indicate a flatter one. More statistic representative samples are needed to settle this question. Cepheids also indicate a larger scatter in the metallicity gradients at larger distances, suggesting that the current interstellar medium is less homogeneous in regions located further out from the galactic center.

4. Radial migration in the disk, open clusters and seismic giants

Seismic giants also enable the computation of precise distances, as well as ages. Because these are bright objects, they can be used to trace the properties of the disk at large distances from the Sun. As shown in Anders et al. (2017), the combination of the CoRoT sample and APOGEE spectra yielded measures of metallicity gradients traced by the youngest stars in the CoRoT sample (around 1 Gyr old) that agree well with the metallicity gradients traced by the Cepheids. However, the gradients traced by older stars show an increased scatter with age, illustrating the effects of radial migration (e.g Minchev et al. 2013, 2014). The same has been recently confirmed for a sample of K2 giants followed-up by APOGEE (Willett et al. 2023) as shown in Figure 3. Radial migration also explains why older open clusters can be more metal rich than younger ones at a given galactocentric distances, as it is the case, for instance, in the sample of OCCASO clusters (see Casamiquela et al. 2019, for a discussion).

5. The age of the chemical thick disk

Seismic giants have also been used to age-date the chemical thick disk, or genuine thick disk (traced by the high-alpha population seen in Figure 2). Around the solar vicinity (7-9 kpc from the Galactic center) it is possible to use the precise seismic constraints from Kepler, the gold standard for asteroseismic measurements. When combined with APOGEE spectra, ages precise to around 20% can be estimated (for some stars a precision of around 10% can be obtained, see Montalbán et al. 2021).

In Miglio et al. 2021 we find that the ages of the nearly 400 alpha-rich red-giant-branch (RGB) stars imply a chemical-thick disk that is around 11 Gyr old, and nearly coeval (with 95% of the population formed within 1.5 Gyr - see Figure 4)). This population also shows a jump in velocity dispersion compared to the low-alpha population, suggestive of different evolution path between the thick and the thin disk. The old age of the genuine chemical-thick disk is also in agreement with the recent analysis of Queiroz et al. (2023) who used isochrone ages and a new method based on machine learning to isolate thick disk stars from the larger sample of thin disk ones. Therefore, at the solar vicinity the chemical discontinuity hints to an age discontinuity (e.g Rendle et al. 2019; Das et al. 2020; Miglio et al. 2021)

6. The mixed populations in the Galactic Bulge

As discussed before, the combination of Gaia and APOGEE had a profound impact in our views of the innermost regions of the Milky Way. Using the even better Gaia EDR3, the exquisite distances obtained in Queiroz et al. (2021) unveiled the quadrupole feature that characterizes the bar in great detail, for the first time reaching the far side of the bar. This has been recently confirmed by Hey et al. (2023) who have used the period-amplitude-luminosity relation of evolved red giants to obtain distances to stars observed by the OGLE survey and radial velocities from Gaia DR3. In addition, the data confirmed a double sequence in the [α/Fe] vs. [Fe/H] in the innermost 3 kpc of our Galaxy (see Figure 2).

The high quality proper motion measurements of Gaia EDR3, together with the precise StarHorse distances and the APOGEE radial velocities were used to compute stellar orbits for a foreground cleaned sample of around 8000 stars confined in the innermost regions. This analysis has unveiled a mix of stellar populations on what we loosely call bulge, namely: an inner-thin disk, an inner thick disk, stars in bar-shape orbits and also hints of a pressure supported component, which we here call the old bulge (Queiroz et al. 2021). While this component in the APOGEE sample is buried in the overwhelming contribution of the more metal-rich disk and bar components, a much more clear view of the old bulge is provided by RRLyrae (e.g Prudil et al. 2019b,a; Savino et al. 2020; Kunder et al. 2020; Crestani et al.

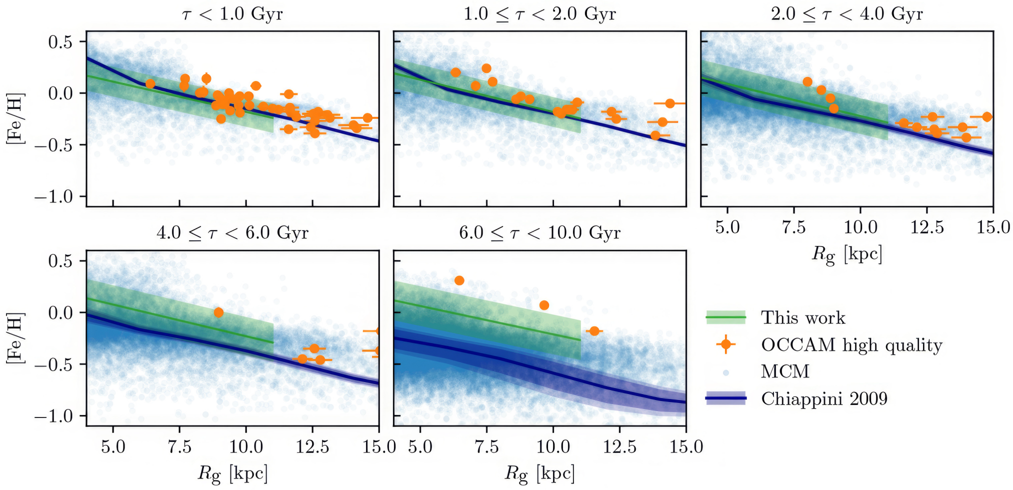

Fig. 3. Abundance gradients traced by seismic giants from K2 observed by APOGEE for which ages have been measured (green region), compared to simple chemical evolution models of a pure thin disk (blue line) and to chemodynamical models (blue data points) showing the effects of radial migration. Also shown are open clusters traced by the OCCAM survey (see Myers et al. 2022, and references therein). Figure taken from (Willett et al. 2023).

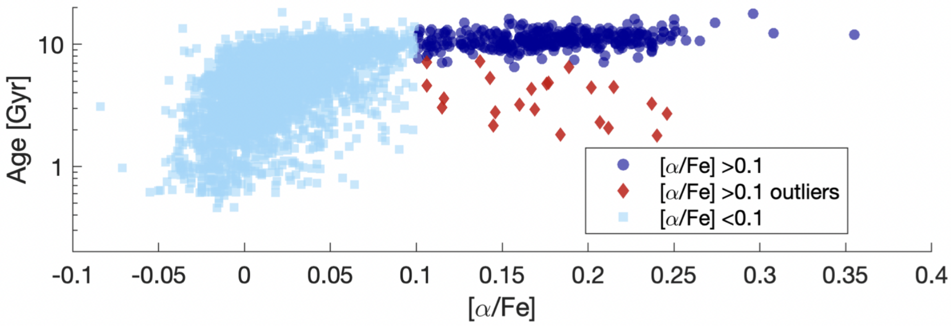

Fig. 4. The [α/Fe] vs. [Fe/H] for a sample of Kepler stars with APOGEE spectroscopy. For this sample precise ages have been obtained. These confirm the high-alpha (genuine thick disk) to be a very old stellar population, formed within no more than around 1.5 Gyr. Figure adapted from (Miglio et al. 2021).

2021, and references therein). Indeed RRLyrae reach the central regions of the Milky Way and therefore complement our mapping of the Galaxy at very old ages (e.g Clementini et al. 2023). RRLyrae stars are consistent with a so-called Classical bulge not contributing to the peanut shape (with only a few percent of halo interlopers). Other invaluable tracers of the old bulge are the bulge globular clusters, many of them most probably formed in situ (see Barbuy et al. 2018; Souza et al. 2023; Belokurov & Kravtsov 2023, for a discussion).

7. Conclusions

The new data now give very detailed information on the different stellar populations in our Galaxy. The large spectroscopic surveys are complemented by the smaller data sets for which precise distances and ages are available (here I have focused on Cepheids, RRLyrae and seismic red giants). It is crucial that developments and expansions of both types of samples proceed in lockstep if we are to make progress and extract robust conclusions about the formation and evolution of the Milky Way.

In conclusion, the main take home points are; a) the Milky Way has a very old chemical thick disk, which has a shorter scale length than the thin disk; b) the thin disk shows clear metallicity gradients all the way towards the inner regions (around 3 kpc from the Galactic center); c) radial migration leave its imprints in the abundance gradients and can be traced by stellar populations with a large age baseline (such as seismic red giants and open clusters). Finally, we note that in an era where even larger spectroscopic surveys will soon became reality (e.g. 4MOST, WEAVE, SDSS-V) and complement Gaia, it is crucial that the larger samples of variable stars now available are also targeted since these sources provide our anchors to robustly establish our distance ladder and age calibration. Without them we will build a sand castle that can easily fall apart.

Acknowledgements. I am grateful to my many collaborators, among which A. B. Queiroz, F. Anders, A. Khalatyan, S. Nepal and the `StarHorse` Team, my seismic giants friends A. Miglio, J. Montalban, V. Valentini, B. Mosser, D. Bossini, my bulge friends B. Barbuy, A. Perez-Villegas, S. Souza as well as the members of the 4MIDABLE-LR team and SDSS colleagues. Finally I would like to warmly thank the organizers of the RRLCEP2022 conference for a wonderful meeting which gave me the opportunity to meet the variable-stars community again (with a special thank you to the *Lost in Tenerife friends).*

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