# Realistic comparisons of Milky Way models and stellar surveys

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**Abstract:** The large Galactic coverage of spectroscopic stellar surveys provides a perfect test-bench for studying the chemo-kinematic properties of our Galaxy and allows us to check the validity of chemo-dynamical models of the Milky Way. In this project, we compare APOGEE data to the chemo-dynamical model of Minchev et al. (2013, 2014) using dedicated mock observations. We focus on [Fe/H] abundance and its radial and azimuthal distribution, which we find to show different behaviours in the inner and outer disc. We also discuss the time evolution of the model (using several snapshots), and how the azimuthal [Fe/H] variations depend on stellar age. This analysis is a first step towards understanding the measured azimuthal abundance variations in the Galactic disc.

## I. INTRODUCTION

Galactic Archaeology aims to disentangle the history of our Galaxy by studying stellar chemistry, kinematics, and ages (Freeman & Bland-Hawthorn 2002). As the Milky Way (MW) evolves, its stars synthesize increasingly more elements and return them to the interstellar medium (ISM). In the MW's thin disc, which has had a rather quiet evolution over the past couple of Gyr, the metallicity and composition of stars smoothly change as a function of their age and birth position (e.g. Chiappini et al. 1997; Matteucci 2021). Under certain assumptions, it is then possible to infer the chemo-dynamical history of the MW disc directly by analysing the positions, velocities, ages, and chemical compositions (Frankel et al. 2018; Minchev et al. 2018). However, the *Gaia* mission (Gaia Collaboration et al. 2016) has shown us that some of these assumptions may not be entirely fulfilled, and inferences of the Galaxy's chemical past could be more difficult (Antoja et al. 2018).

In our project, we will focus on observations and measures in the MW and MW-like Galaxy models. The MW is classified as *SB(rs)bc II* type (Binney & Merrifield 1998; Binney & Tremaine 2008), i.e. a barred spiral Galaxy, with loosely bound arms. It is composed of a central stellar bulge, and a bar that shows the end of the formative stage of our Galaxy, placed at 30 degrees with respect to the Sun and extending $4-5$ kpc. The bar formed due to the secular evolution of the Galaxy, in which gas and stars are slowly sent to the centre of the Galaxy, creating higher density and new stars inside. Most of the rest of the stars are located in a disc, divided into the thin disc (scale height $Z \leq 0,325$ kpc; younger stars) and the thick disc (scale height $Z \leq 1,5$ kpc; older stars).

Thanks to the data collected by large surveys like *Gaia* or APOGEE, we have unprecedented information about the stellar properties of millions of stars, such as their position, age, or chemical composition. During the life of stars in a Galaxy such as the MW, we know they can migrate over long distances and, as they are not born with the same chemical composition, we observe variations of metallicity in the azimuthal and radial directions. Taking into account one of the bases of Galactic Archaeology, that stars do not change their chemical composition (except for some light elements) during their lifetime, we can infer information about their past. Moreover, as MW composition evolves through time, stars should show different behaviour and properties as a function of their age.

To compare the developed theories with the observed behaviour of the MW, different simulations and models have been thriving for the last 20 years. We can approach from the dynamic or the chemical points of view. The dynamics take care of the movement and position of the stars, while the chemical approach handles the metallicity distributions and abundances. But, separately, they do not fit completely the reality. For many purposes, a chemo-dynamical approach is necessary to yield a simulation roughly similar to match the observed trends in the MW.

## II. DATA SELECTION

For this project, we collected and processed the following observational and simulated data:

- **APOGEE DR17 + Gaia EDR3 data:** APOGEE data (Abdurro'uf et al. 2022) include infrared spectra, stellar parameters and elemental abundances for more than 500 000 stars in the MW. We have worked with DR17, the latest and final data release from the Sloan Digital Sky Survey (SDSS-IV, Blanton et al. (2017)) fourth phase. In addition, we have included data from Gaia EDR3, (Gaia Collaboration et al. 2021). Some quality cuts have been applied, such as only accepting stars with 3800 K $\leq T_{eff} \leq$ 6000 K, little velocity scattering or within a vertical cut of $\pm 1$ kpc. It results in a total of 233 439 stars.

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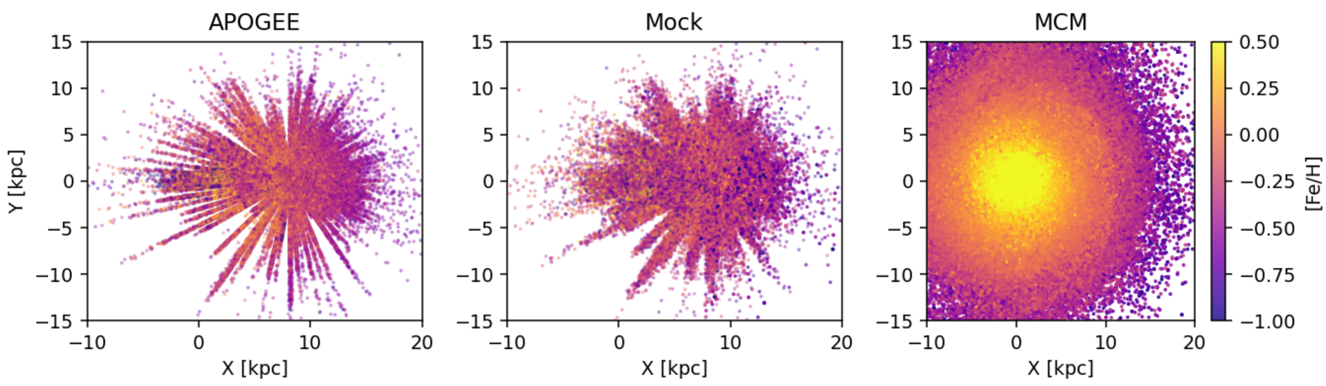


FIG. 1: Stellar distribution in the disc plane for the APOGEE DR17 + Gaia EDR3, Mock and MCM2013 model data.

- **MCM2013 model:** A dynamic galaxy model must follow some constraints to fit the MW, such as developing a bar and considering stars' migration during Galaxy's life. Many groups have attempted to model a detailed chemo-dynamical evolution of the MW in recent years. For example, Minchev et al. (2013, 2014) developed what we will call MCM model, in a cosmological context and only considering the thin disc. It consists of dividing the disc into 300-pc radial bins and choosing random born stars, fitting each star's chemistry for its radius and time to Galaxy's star formation history. It is made for $|Z| \leq 4$ kpc and $r \leq 16$ kpc. As for $r \leq 4$ kpc there is a lack of observational constraints and different Galactic regions superpose, we finally consider 4 kpc $\leq r \leq$ 16 kpc region in our comparisons, for a total of 953206 stars.

- **Mock:** An MCM mock observation of the APOGEE data has been selected from the MCM model using a simple procedure (Anders et al. 2016). For every star in observations, it tries to find a similar particle in the MCM Galaxy within a search distance of 300 pc. The particles are selected based on the probability of StarHorse (Queiroz et al. 2018) age PDF of each star. The mock thus has the same number of stars as the APOGEE disc red giant sample and matches the observed spatial distribution by construction.

As MCM and mock are derived from computational models, there are many possible star configurations in the simulated Galaxy due to its evolution. To not be biased by a particular point in simulation time, we have extracted the four final snapshots of the MCM model and created mock corresponding observations for each one.

Data collected by the three systems are shown in Fig. 1. In APOGEE and mock representations, stars follow a radial distribution from the Sun, located at $X = 8.2$ kpc from the Galactic centre and $\phi = 0$. Because of that, and the lack of data in other directions, we have the majority of their representations from $\phi = [-30, 60]$ deg.

## III. DATA ANALYSIS AND RESULTS

From Fig. 1 we see that [Fe/H] in the MCM model decreases as a function of radius. To compare this to APOGEE observations, we represent the chemical abundance trends ([Fe/H] and [Mg/Fe] proportions) as a function of the Galactocentric radius in Fig. 2.

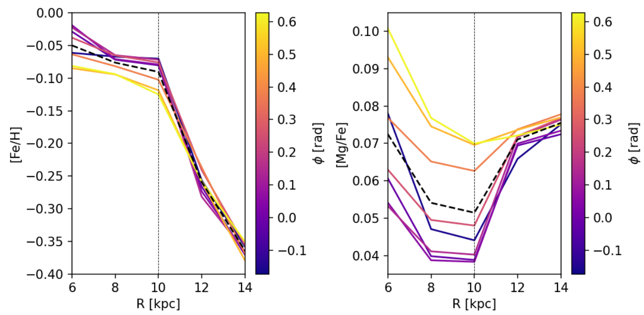


FIG. 2: Metallicity ([Fe/H] and [Mg/Fe]) for APOGEE data as a function of the Galactocentric radius. It is represented in 8 azimuthal bins between -0.1 and 0.6 rad. A dotted vertical line divides the metallicity behaviour in two radial regions, and a thicker one represents the mean metallicity.

As for the MCM model, a negative radial gradient of [Fe/H] exists for all azimuths. In addition, we observe a break in the gradient at 10 kpc, denoted by a dotted vertical line. This metallicity gradient change distinguishes two separated regions in the Galaxy, which might have different behaviour.

To study and compare the radial and azimuthal [Fe/H] distributions, we graphically compare the three datasets (observations vs. simulations). In Fig. 3 we show the two latest snapshots of the simulation (in total we have analysed 4 snapshots). In the left column, [Fe/H] as a function of azimuthal angle is represented for 8 radial bins from 4 to 14 kpc. External regions of the Galaxy show a lower metallicity than inner regions, with a difference of $\sim 0.2$ dex between them. This is consistent

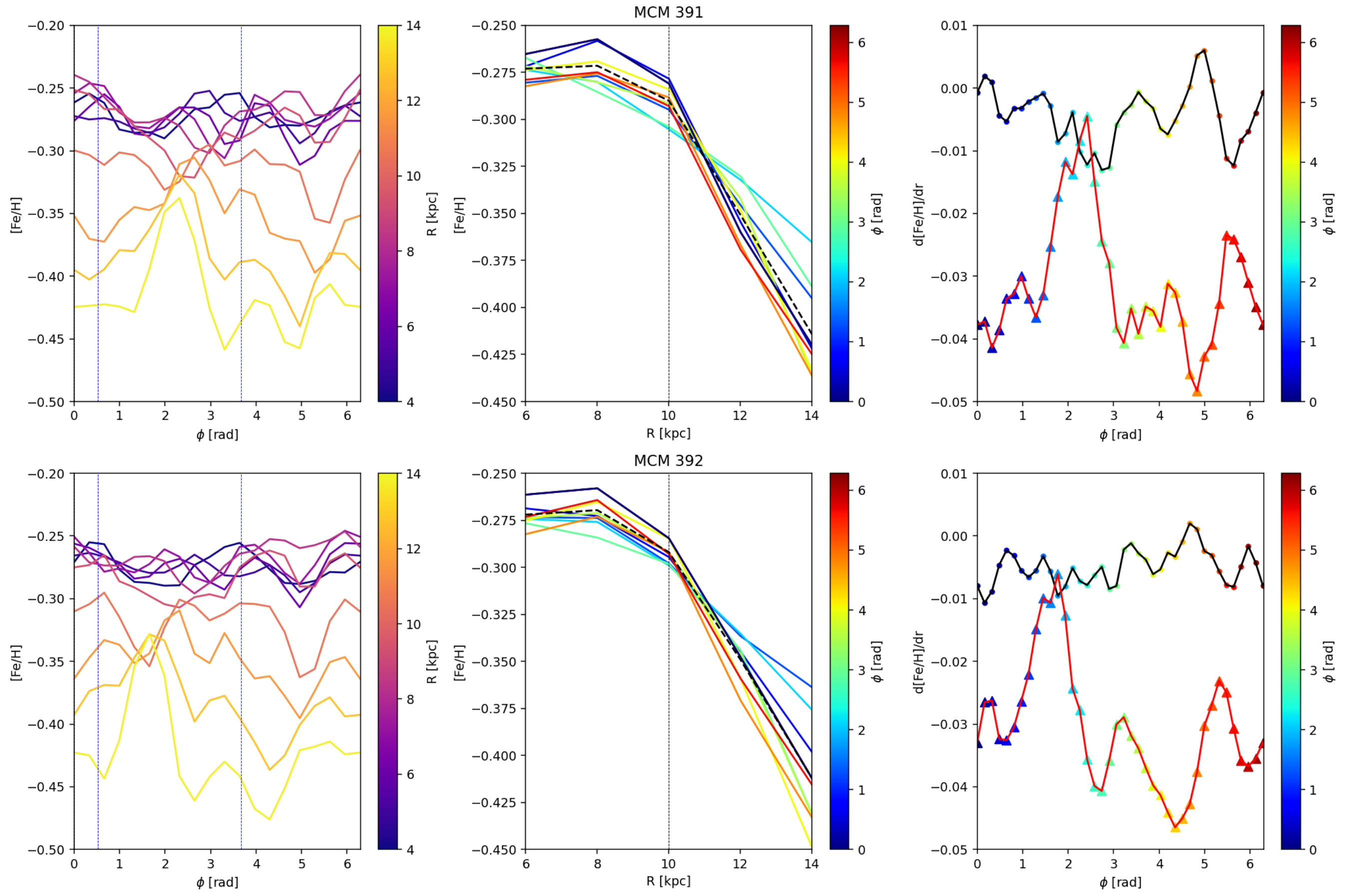


FIG. 3: Two snapshots from the evolution of the MCM simulation (MCM 391 in **top row** and MCM 392 in **bottom row**). **Left:** [Fe/H] azimuthal variation for 8 radial bins. The blue dotted vertical lines indicate the bar position. **Middle:** [Fe/H] radial variation for 8 azimuthal bins. The dotted vertical line indicates the slope division, and the thicker one represents the mean metallicity. **Right:** [Fe/H] gradient as a function of the azimuthal angle in the inner (black) and outer (red) discs.

with the models quoted above, which state a decreasing relation of [Fe/H] with radius for all-star ages (Minchev et al. 2013, 2014). We also observe that for $R = 4$ kpc, there are two maxima at $\phi = 0.5$ rad and $\phi = 3.7$ rad, that do not change with time (for different snapshots, keeping the solar position fixed with respect to the bar). This is evidence of the strong dynamical impact of the Galactic bar on the azimuthal chemical-abundance distribution: in the inner disc, stars on the bar tend to be slightly more metal-rich than stars not on the bar. For larger radii (yellow and orange lines), we see a significant peak of $\sim 0.1$ dex in metallicity that moves to lower angles with time, due to the rotation of the spiral arms of the Galaxy.

In the middle column, the metallicity versus radius relation is shown, by fitting the metallicity gradient in 4 radial bins, and for 8 azimuthal bins covering all angles. Compared to Fig. 2, a similar relation with observational data is visible, with a clear gradient change at 10 kpc. Nevertheless, the MCM model peaks at a lower metallicity, with a difference of 0.2 dex to APOGEE's peak. This is a consequence of the star distribution in the simulation, with the highest metallicity at small radii.

The right column shows the radial [Fe/H] gradient as a function of the azimuthal angle. Two regions are distinguished, with a black line for the inner disc and red for the outer. We observe that the inner disc presents a small metallicity variation. The outer disc exhibits the same peak as in the first column, potentially caused by slowly evolving spiral arm patterns. The shorter dynamical time scales in the inner disc, coupled with the complex mixture of stellar populations, tend to wash out azimuthal trends fast. In the outer disc, the low self-gravity of the disc enables chemo-dynamical inhomogeneities to persist for much longer. There are also regions where the two gradients cross each other because in the bar, arms or high-density regions there is a high star concentration and therefore metallicity variation. Moreover, we see that the azimuthal movement in the two regions is different (the red peak moves faster to the left than the black peaks), suggesting that the inner and the outer disc do not shift together with time, evidence of the differential rotation of the Galaxy.

It is necessary to compare APOGEE and mock data

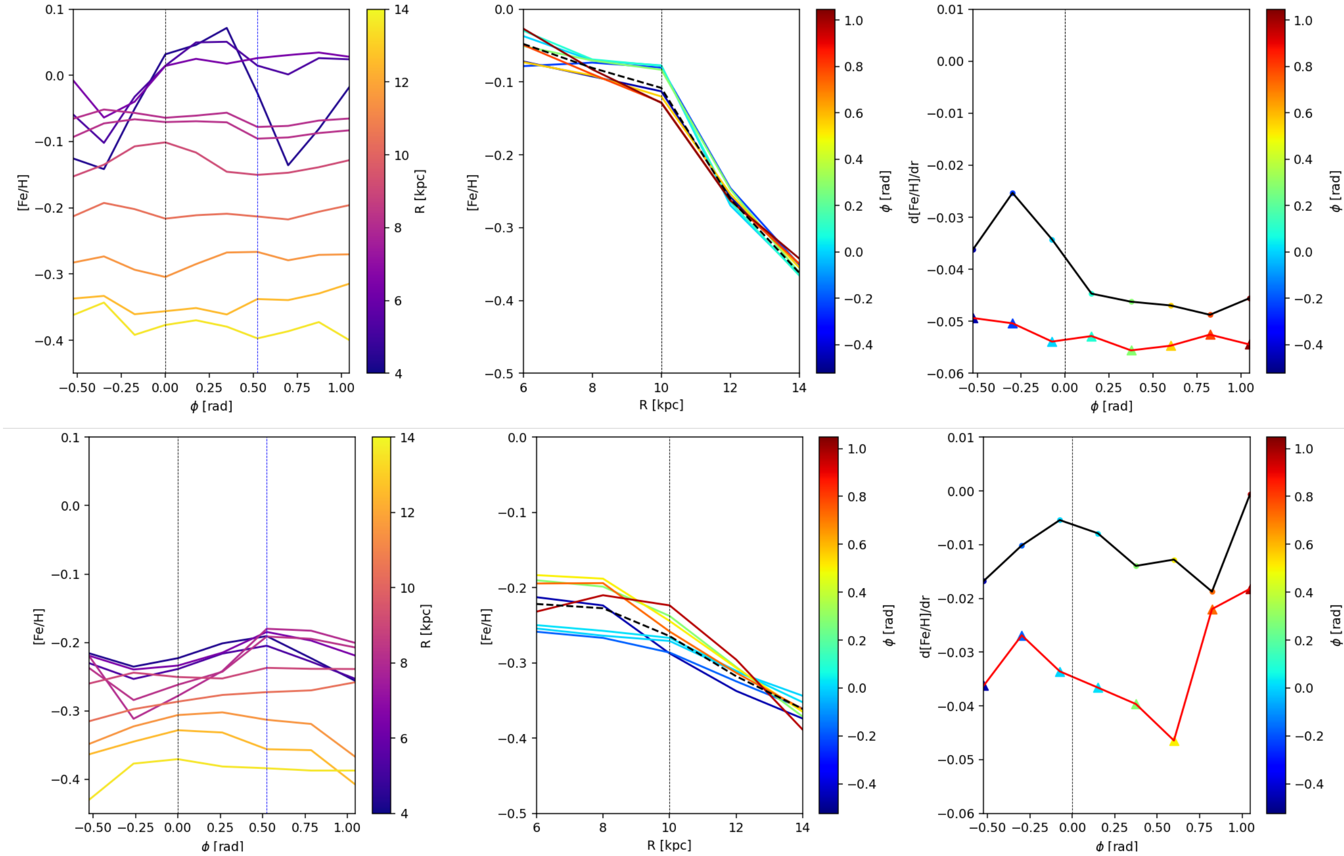

FIG. 4: Processed APOGEE data (**top panels**) versus mock (snapshot 389; **bottom panels**). **Left:** [Fe/H] azimuthal variation for 8 radial bins. The dotted blue vertical line indicates the bar position, while the black one denotes the Sun's. **Middle:** [Fe/H] radial variation for 8 azimuthal bins. The dotted vertical line indicates the slope division, and the thicker one represents mean metallicity. **Right:** [Fe/H] gradient as a function of azimuthal angle in the inner (black) and outer (red) discs.

to properly account for selection effects when comparing to the MCM model (Fig. 4). In the left column, mock data are more flattened, with mean metallicities between -0.2 and -0.4 dex, while APOGEE data reach higher values, until 0.05 dex. This is brought about because the mock takes its data from the MCM model, which has similar values of metallicity, indicating that the chemical-evolution prescription used in the MCM model should be updated. The position of the peaks at low radii, most likely produced by the Galactic bar, is seen both in the data and (although slightly weaker) in the mock. In the middle column, in the mock graphic, the radial variation of metallicity is more flattened too, due to the same reason, but gradient change at 10 kpc is clear in the two cases. In the right column, we observe that for APOGEE data the metallicity variation is steeper. For the inner regions of the mock, the gradient is small, as for the MCM model. Nevertheless, APOGEE data exhibit a smaller difference in gradient between the inner and outer regions ($\sim 0.1$ dex from APOGEE versus $\sim 0.3$ dex from mock). Peaks are also visible in the two regions, corresponding to gaps with a big change in metallicity.

To visualize the behaviour of the metallicity as a function of the age of the stars, the azimuthal [Fe/H] variations for two broad age groups are shown in Fig. 5. The top figure shows young stars (0-3 Gyr) while the bottom one is for intermediate-age (3-8 Gyr) stars. The position of the bar and the peaks in spiral arms are the same as in Fig. 3. We see a remarkable flattening of the previously observed metallicity trends with age owing to the simplicity of the MCM model. Furthermore, older star representations exhibit lower mean values in metallicity. It is evidence of an inverse relationship between [Fe/H] and age (Minchev et al. 2013, 2014), based on the metallicity of the ISM at the time stars are born. We also observe how peaks shift to the left as radii increase, because of the structure of Galaxy arms. However, these behaviours become less clear with age. As azimuthal velocity dispersion increases for older stars and stars migrate over time (effects also known as blurring and churning; Binney & Merrifield 1998), any chemo-kinematic relationship becomes less pronounced for larger ages.

## IV. CONCLUSIONS

After analysing and comparing MCM simulation, APOGEE data and mock, our conclusions are:

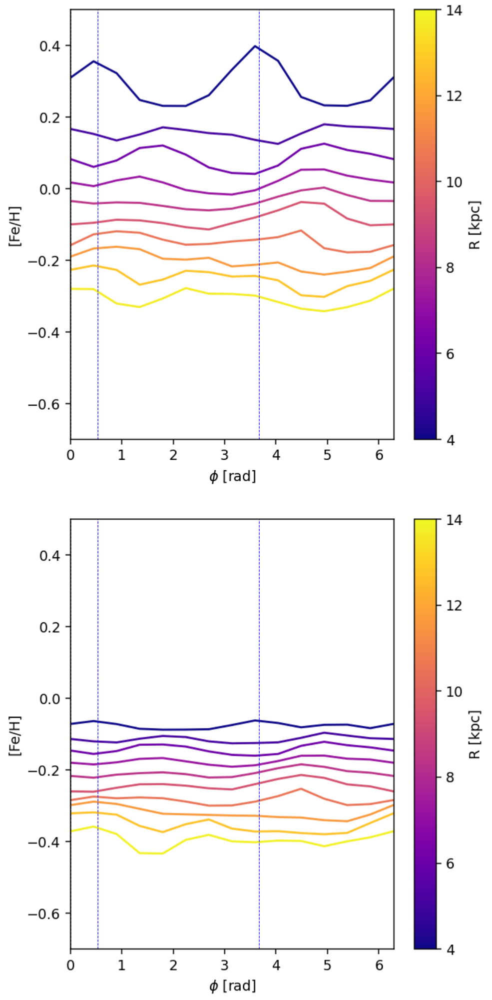


FIG. 5: Azimuthal variation of metallicity for young (0-3 Gyr, top) and intermediate-age (3-8 Gyr, bottom) stars of the MCM 389 snapshot.

- Similarities between comparisons are found. Chemo-dynamical models create the same structure as the observational data, with a distinguishable bar and spiral arms in the same positions. Moreover, there is evidence of the differential rotation of stars in the spiral arms.

- For all analysed datasets (observations and simulations), we detect a clear negative and azimuthally varying radial metallicity gradient. A break in the gradient is discernible at 10 kpc, dividing the disc into the inner and outer regions, corresponding to different dynamical behaviours and time scales.

- MCM model and mock reach lower metallicity values, and in a narrower range, than APOGEE data. This shows that future MW simulations should improve to match this observable better.

- Representations of MCM simulation for two age groups show a decrease in metallicity with age (related to ISM enrichment) and an increase in velocity dispersion with age. This, besides the flattening in [Fe/H] for older stars, is another sign of the need for improved MW simulations.

- Although we had more available data from observations than in previous investigations, it is necessary to further increase the azimuthal coverage of the Galactic disc with spectroscopic observations. A dedicated infra-red spectroscopic survey on a bigger telescope would allow us to cover a much larger part of the disc with better statistics.

This is a first step towards inferring the life of stars from the MW using only chemical information. Chemo-dynamical models fit relatively well with observations, although some differences may lead us to more research.

**Acknowledgments**

Without all the data collected by APOGEE and Gaia project, this work or related investigations would not be possible. Special thanks to my advisor, Friedrich Anders, who has guided me from the first moment. Finally, to my family and friends, who have always supported me.

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