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# Galactic Archaeology with CoRoT and APOGEE: Creating mock observations from a chemodynamical model

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In a companion paper, we have presented the combined asteroseismic-spectroscopic dataset obtained from CoRoT lightcurves and APOGEE infra-red spectra for 678 solar-like oscillating red giants in two fields of the Galactic disc (CoRoGEE). We have measured chemical abundance patterns, distances, and ages of these field stars which are spread over a large radial range of the Milky Way’s disc. Here we show how to simulate this dataset using a chemodynamical Galaxy model. We also demonstrate how the observation procedure influences the accuracy of our estimated ages.

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## 1 Introduction

Galactic models make predictions for the distribution of stars and gas in the multi-dimensional space consisting of time, kinematics and chemical composition. Therefore, one of the basic problems of Galactic Archaeology – the science of inferring the current state and the history of the Milky Way from present-day observations (e.g., Freeman & Bland-Hawthorn 2002; Págel 1997) – is dimensionality reduction. For a given dataset, we are looking for the most robust and telling statistical relations to constrain these models.

Asteroseismology of red giants delivers new promising constraints to Milky Way models since it provides masses and ages of distant field stars with unprecedented precision (e.g., Miglio et al. 2013). The present work and an accompanying series of papers (Chiappini et al. 2015; Anders et al., subm. to A&A) explore the power of asteroseismic constraints in Galactic Archaeology: we present one of the first attempts to combine stellar physics, asteroseismology, statistics, and spectroscopy – to learn about the chemo-dynamical history of our Galaxy. Specifically, we combine data from the infrared spectroscopic stellar survey APOGEE (Majewski et al. 2015) with asteroseismic data from the CoRoT mission (Baglin et al. 2006). In

**Table 1** Summary of the available CoRoGEE data.

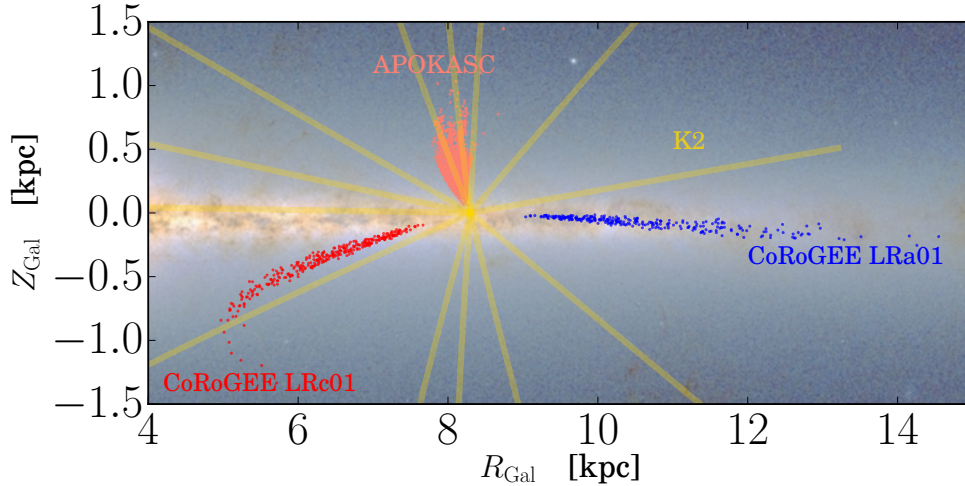
CoRoT-APOGEE stars	690
with “good” spectroscopic parameters	678
& “good” asteroseismic parameters	664
& $ \log g_{\text{ASPCAP}} - \log g_{\text{seismo}}  < 0.5$	617
Converged stellar parameters & distances	606
Field LRA01 (outer disc)	282
Field LRC01 (inner disc)	326

this paper, we describe how we simulated mock CoRoT-APOGEE (CoRoGEE) observations of the chemodynamical N-body Galaxy model of Minchev, Chiappini, & Martig (2013, 2014, MCM).

## 2 The dataset

We have assembled a comprehensive dataset (stellar parameters, elemental abundances, kinematics) of more than 600 solar-like oscillating red giant stars which have been observed by both CoRoT and APOGEE (CoRoGEE). Table 1 gives an overview of the dataset; Fig. 1 shows the distribution of our stars in Galactocentric cylindrical coordinates. The details of our analysis are provided in Anders et al. (A&A, subm.).

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**Fig. 1** Location of the APOGEE samples with seismic and spectroscopic observations in Galactocentric cylindrical coordinates. The K2 mission and its spectroscopic follow-up campaigns are presently adding several new sightlines to this picture (yellow rays).

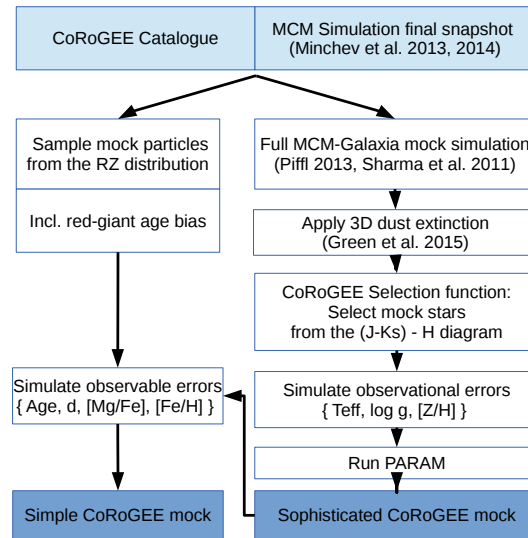
Using an updated version of the Bayesian stellar parameter estimation code PARAM (da Silva et al. 2006), we have determined the radii, masses, ages, and distances of the CoRoGEE stars by comparing the measured spectroscopic effective temperatures, metallicities, and asteroseismically determined  $\Delta\nu$  and  $\nu_{\max}$  with stellar evolutionary models. We achieve typical precisions of  $\sim 3\%$  in radius,  $\sim 9\%$  in mass, and  $\sim 25\%$  in age. By combining our stellar radii measurements with multi-wavelength photometry, we also derive very precise distances (precise to  $\sim 2\%$ ) and extinctions. The details are described in Rodrigues et al. (2014).

The first result obtained with the CoRoT-APOGEE dataset was the discovery of a population of disc stars which do not follow the relation between the  $[\alpha/\text{Fe}]$  abundance ratio and age predicted by canonical chemical evolution models of the Galactic disc. In Chiappini et al. (2015), we discuss several scenarios that can be invoked to explain the existence of these objects, and the fact that these stars are much more prevalent in the inner CoRoT field. No conclusive explanation has been presented so far, but possible solutions involve stellar mimicry (old stars disguised as younger ones because of close-binary evolution (Yong et al. 2016) or stellar mergers), abundance anomalies in star-forming bubbles, and a peculiar chemical evolution near the corotation radius of the Galactic bar.

### 3 CoRoGEE mock samples from a chemo-dynamical model

The direct interpretation of astronomical survey data is often hampered by non-trivial selection effects. As pointed out in, e.g., Binney & Sanders (2015), the comparison of survey catalogues with a Galactic model is much easier when a mock observation of the model is created.

In this Section we describe how to select a CoRoGEE-like sample from an N-body simulation, using the example

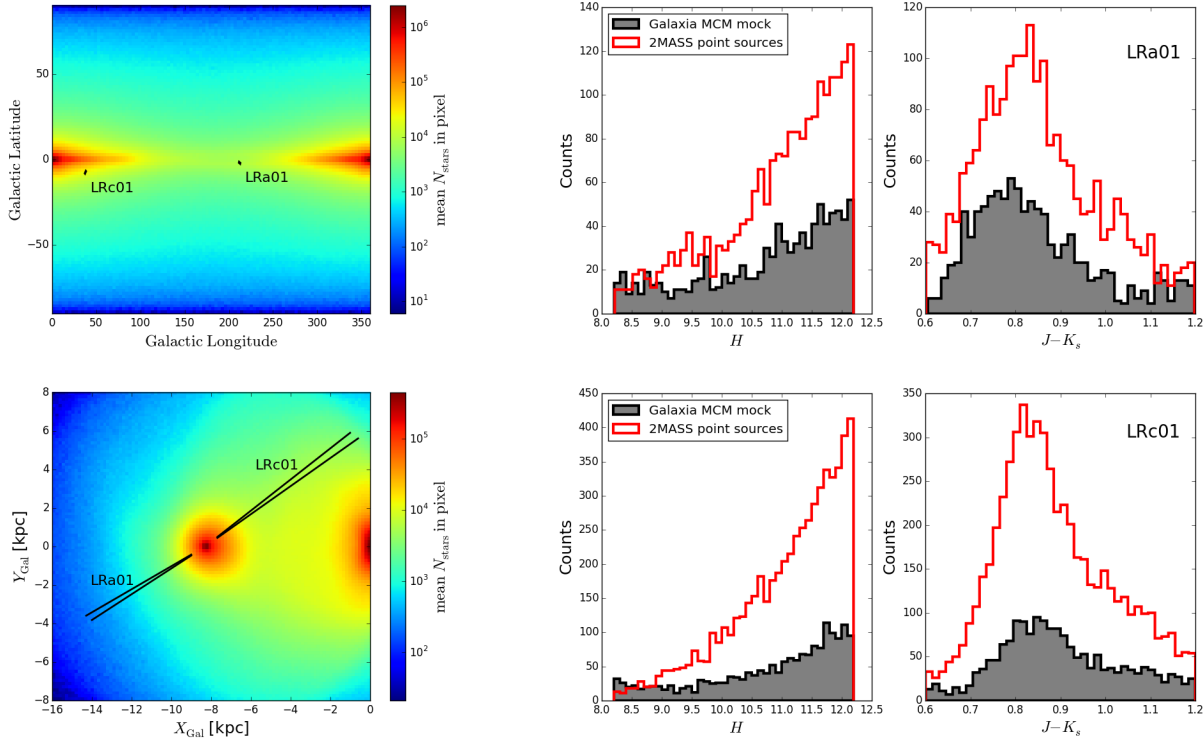


**Fig. 2** Scheme illustrating how our two versions of the CoRoGEE mock observations were obtained from the MCM model.

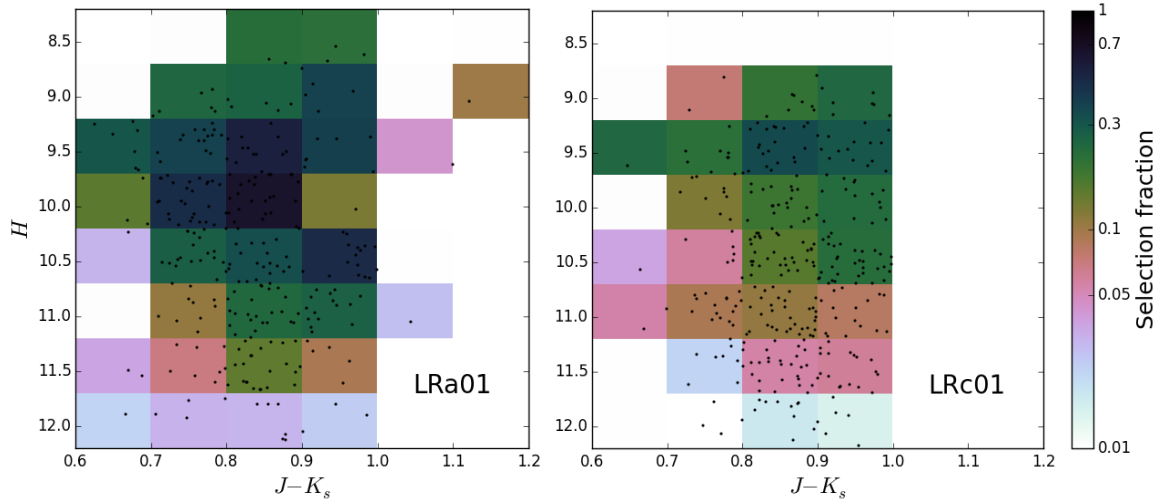
of the MCM model (Minchev et al. 2013, 2014). We have chosen two different paths to simulating the observations: a straightforward “simple” mock, and a more sophisticated one which uses a mock observation tool (Piffl 2013) based on the Galaxia stellar population synthesis code (Sharma et al. 2011). The procedures leading to the two versions of mock observations are sketched in Fig. 2.

#### 3.1 Sophisticated mock

The original Galaxia population synthesis code (Sharma et al. 2011) uses the analytic Besançon Milky Way model (Robin et al. 2003) and creates synthetic Galactic stellar



**Fig. 3** Star counts in the MCM Galaxy mock. *Left*: Density distribution of all simulated MCM stars (magnitude limit  $H_0 = 13.0$ ) in  $(l, b$ ; top left) and  $(X_{\text{Gal}}, Y_{\text{Gal}}$ ; bottom left). *Middle and right*:  $H$  magnitude and  $(J - K_s)$  star counts in the two CoRoT fields, comparing 2MASS (red histograms; Cutri et al. 2003) and the MCM mock Galaxy (grey histograms).



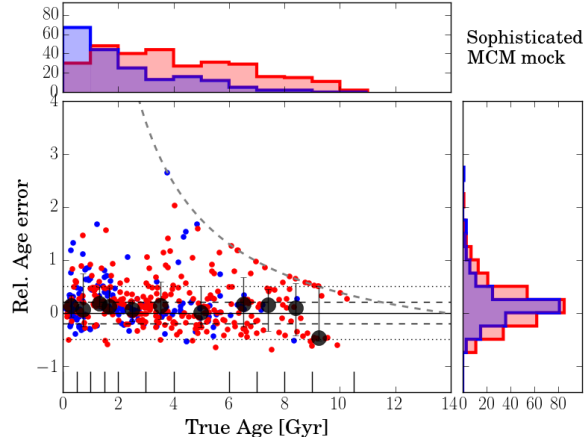
**Fig. 4**  $H$  vs.  $J - K_s$  colour-magnitude diagram (CMD) for the two CoRoGEE fields. The colour in each CMD box shows the selection fraction ( $N_{\text{CoRoGEE}}/N_{\text{2MASS}}$ ) in this box. We used the same boxes to simulate the CoRoGEE selection function for the ‘sophisticated MCM mock’.

populations in a given part of the sky. Additionally, it allows the user to include a stellar halo from an N-body simulation, i.e. a model in which the kinematic distribution functions are not analytic any more, but are taken from the mass particle distributions of the input simulation. Piffl (2013)<sup>1</sup> generalised this idea and first used the MCM model as an input for the Galaxia code in the context of a simulated RAVE survey. By spawning mock stars from the MCM mass particles (each star inherits its age and chemical properties from the parent particle) he showed that the model could recover realistic correlations between the kinematics and the chemical abundances of the stars, while it was not possible to obtain an absolute match with star counts and global kinematic parameters of the Milky Way. Here, we use the same code to simulate a CoRoGEE-like sample from the MCM galaxy.

We first simulated a complete synthetic photometric all-sky survey from the solar position<sup>2</sup> up to a limiting magnitude of  $H_0 = 13$  from the MCM galaxy using the modified Galaxia code (Piffl 2013). This translates the  $9.5 \cdot 10^5$  input N-body particles into  $7.8 \cdot 10^7$  mock stars (see density maps in Fig. 3). We then calculated observed magnitudes for the mock stars in the CoRoT fields using the new PanSTARRS-1 3D extinction map of Green et al. (2015)<sup>3</sup>. The resulting colour and magnitude distributions up to the magnitude limit of CoRoGEE ( $H = 12.2$ ) are also shown in Fig. 3. As expected, the absolute star counts are not well matched by the MCM-Galaxia model, but the relative distributions in the colour-magnitude diagram (CMD) are reproduced (see Piffl 2013 for a discussion). In the next step, we applied the effective CoRoGEE selection function (assuming that it only depends on  $H$  and  $J - K_s$ ) by randomly selecting the observed number of stars from small boxes in the CMD (see Fig. 4).<sup>4</sup> We further simulated Gaussian observational errors in the spectroscopic stellar parameters  $T_{\text{eff}}$ ,  $\log g$ ,  $[Z/H]$  and magnitudes, and then ran the Bayesian parameter estimation code PARAM (Rodrigues et al. 2014) to recover measured masses, radii, and ages.

### 3.2 Simple mock

A simpler way to simulate a CoRoGEE sample from the MCM simulation is to randomly select the most representative MCM particles from their distribution in configuration space. However, when we put the Sun at the correct distance to the Galactic center, the number of available particles is too small to yield enough mock stars in the two CoRoT fields. Therefore, we smoothed over the azimuthal angle in the Galactocentric cylindrical frame, and drew the mock stars directly from the observed distribution in the  $R_{\text{Gal}} - Z_{\text{Gal}}$  plane. Because red giant stars do not sample



**Fig. 5** Relative PARAM age errors  $\frac{\tau_{\text{PARAM}} - \tau_{\text{true}}}{\tau_{\text{true}}}$  for the sophisticated version of the MCM-CoRoGEE mock as a function of the true age of the parent N-body particle. The simulated stars in LRa01 and LRc01 are shown in blue and red, respectively. The black symbols correspond to the median age error in each age bin indicated on the x-axis. The various lines correspond to a one-to-one relation, 20% and 50% deviation, and the age boundary at 13.7 Gyr.

all ages evenly, we simulated this red-giant age bias by assuming that a red giant of age  $\tau$  is picked with a probability  $\propto (\tau + 1 \text{ Gyr})^{-0.7}$ .<sup>5</sup>

Finally, we added typical observational errors in age, distance, and metallicity. While the distance and metallicity uncertainties could be assumed to be small and Gaussian ( $\sim 2\%$  and 0.04 dex, respectively), the statistical age errors are not straightforward to simulate. We therefore opted for the following data-driven approach: we use the sophisticated mock to estimate the age errors. For each star, a random age error was added according to the relative error distribution shown in Fig. 5.

### 3.3 Simulated age distributions

Fig. 5 shows how well our method is able to recover stellar ages, using the sophisticated MCM mock described above. It is evident that our individual age estimates should be used with caution, in particular for measured ages  $> 4$  Gyr. However, we confirm that a small measured age does correspond to a true small age in almost all cases, thus strengthening the conclusions of Chiappini et al. (2015). More details about statistical and systematic uncertainties involved in our age determinations are presented in Anders et al. (2016).

In Fig. 6, we take a first look at the simulated “true” age distributions in the two CoRoT fields (grey histograms), the effect of adding age errors on this distribution (black histograms), and compare these with the measured age distributions of the real data (filled histograms).

<sup>5</sup> From population synthesis modelling with TRILEGAL, we find that this bias depends very weakly on the position in the Galaxy. It is also consistent with the age bias that Casagrande et al. (2016) determined for the *Kepler* field with different methods (their Fig. 12d).

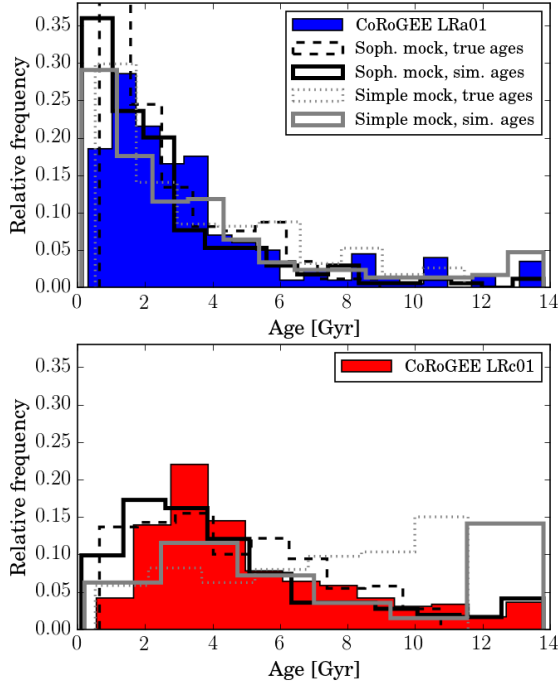
<sup>1</sup> [https://publishup.uni-potsdam.de/files/6790/piffl\\_diss.pdf](https://publishup.uni-potsdam.de/files/6790/piffl_diss.pdf)

<sup>2</sup> We assume  $R_{\text{Gal},\odot} = 8.3$  kpc, in line with recent estimates (see e.g., Bland-Hawthorn & Gerhard 2016)

<sup>3</sup> <http://argonaut.skymaps.info/>

<sup>4</sup> The justification for this approximation of the CoRoGEE selection is given in Anders et al. (2016, subm. to A&A).





**Fig. 6** Simulated and recovered age distributions for the two CoRoGEE fields LRA01 (top) and LRC01 (bottom).

While the simulated age distributions of the sophisticated mock match the data surprisingly well in LRC01, we see striking differences in the relative number of old stars in LRA01. Conversely, the simple mock performs better for LRA01, while it overpredicts the number of old stars in LRC01. We suggest that this may be related to a) a more complex selection function, or b) a stronger age bias towards the inner Milky Way.

## 4 Summary

In our companion paper (Anders et al. 2016), we demonstrate, in line with previous works, that combining seismology and spectroscopy brings us one step further in obtaining meaningful ages of field stars. We also show that our sample can be used to formulate new chemodynamical constraints on the evolution of the Milky Way disc over a large range in Galactocentric distance and ages.

The simulations presented in this paper have shown that some notes of caution are due: we demonstrated that the absolute age scale of our isochrone ages is prone to systematic shifts. We also remind the data user to be very careful when interpreting small subsets of the data, and to refrain from interpreting single data points.

In follow-up works we will explore the individual-element abundance space opened by APOGEE and provide a detailed comparison with a (semi-)cosmological chemodynamical N-body simulation, using mock observation tools. One of the key questions of Galactic Archaeology which our sample should help to answer is constraining

the migration efficiency in the Galactic disc as a function of time and position.

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