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Galactic archaeology: Understanding the metallicity gradients with chemo-dynamical models

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Abstract. Radial metallicity gradients measured today in the interstellar medium (ISM) and stellar components of disk galaxies are the result of chemo-dynamical evolution since the beginning of disk formation. This makes it difficult to infer the disk past without knowledge of the ISM metallicity gradient evolution with cosmic time. We show that abundance gradients are meaningful only if stellar age information is available. The observed gradient inversion with distance from the disk mid-plane seen in the Milky Way can be explained as the effect of inside-out disk formation and disk flaring of mono-age populations. A novel recent method is presented for constraining the evolution of the Galactic ISM metallicity with radius and time directly from the observations, while at the same time recovering the birth radii of any stellar sample with precise metallicity and age measurements.

Keywords. stars: abundances, ISM: abundances, Galaxy: abundances, Galaxy: evolution, Galaxy: disk, (Galaxy:) solar neighbourhood, Galaxy: kinematics and dynamics

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1. Inversion in radial abundance gradients with height above the disk mid-plane

An inversion of the radial metallicity gradient from negative close to the disk plane, to positive at higher distance above it, $|z|$, has been found in SEGUE, RAVE, APOGEE and LAMOST surveys. Similar inversion, but from positive to negative, exists for $[\alpha/\mathrm{Fe}]$. This phenomenon was also seen in the Milky Way chemo-dynamical model of Minchev, Chiappini & Martig 2013 (MCM13) and was interpreted by Minchev, Chiappini & Martig (2014) as the result of inside-out disk formation and disk flaring of mono-age stellar populations. While older, kinematically hot stars dominate in the inner disk at high $|z|$, due to disk flaring, younger stars populate the outer disk high $|z|$ regions; this also predicts a negative age gradient at high $|z|$ (Minchev et al. 2015), indeed found by Martig *et al.* (2016) using APOGEE data. This interplay among the density of stars with different ages as a function of r and $|z|$ can be seen in Fig. 1, where the vertical rectangles represent the stellar density.

2. Estimating stellar birth radii and the time evolution of the ISM metallicity gradient

One of the most important goals in Galactic Archaeology is finding the birth places of the stars we currently observe in the Milky Way. The recent work by Minchev *et al.* (2018) (see also Frankel *et al.* 2018) described a way to do that solely based on metallicity and age measurements (see Fig. 2). This also allowed to constrain the ISM metallicity evolution with Galactic radius for the first time, finding that at the onset of disk formation it was twice as steep as it is currently found (~ -0.15 vs ~ -0.07 dex/kpc). It should be

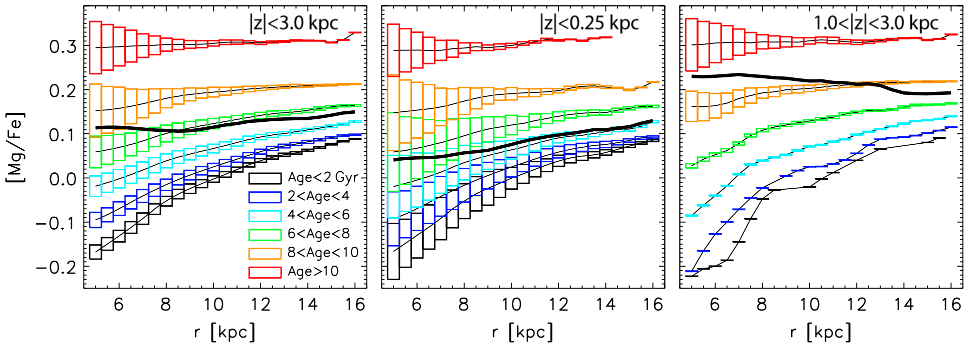

Figure 1. Inversion of the [Mg/Fe] gradient with distance from the disk mid-plane, $|z|$ in the MCM13 model. Thick black curves show the total sample for three different $|z|$ slices, as indicated. The height of rectangular symbols reflects the stellar density of each bin. The positive gradient seen at small $|z|$ (middle) is reversed at high distance above the disk mid-plane (right).

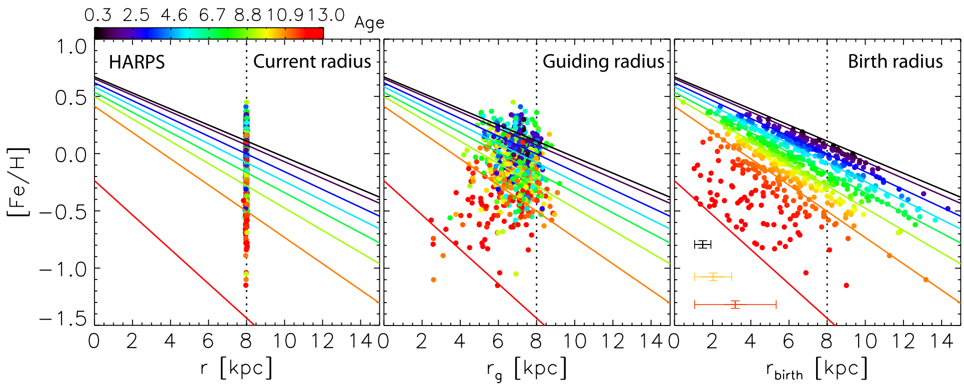

Figure 2. [Fe/H] of HARPS data (Adibekyan et al. 2011) coloured by age, versus current Galactic disc radius (left), guiding radius (middle), and estimated birth radius (right), as described in Minchev *et al.* (2018). The recovered ISM metallicity gradient evolution with time is shown by the coloured lines.

kept in mind that the age dependence of the abundance radial profile measured today (Anders *et al.* 2017) is significantly different from the ISM gradient at the time of stellar birth, more so for older populations, due to the effect of radial migration resulting from the angular momentum exchange in the disk.

Ages for turn-off stars from the Gaia (Gaia Collaboration *et al.* 2018) and asteroseismic missions, combined with ground-based spectroscopic surveys (e.g., SDSS-V, WEAVE, MOONS, and especially 4MOST) will much improve the determination of the Galactic chemical evolution and migration history needed to constrain the Milky Way formation.

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