The evolution of the Milky Way radial metallicity gradient with CoRoT, APOGEE, and *Gaia*

IAU XXX GA Vienna, FM7, 28.08.2018

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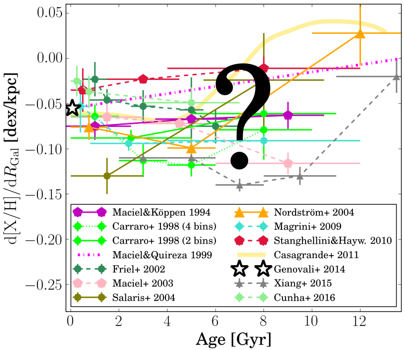
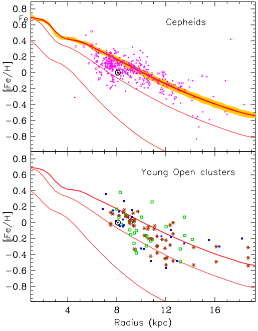
Radial gradients: age dependence $\neq$ evolution

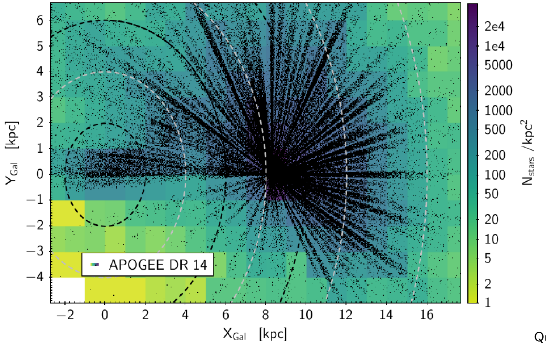




Kubryk et al. 2015

- Ages are extremely hard to measure (see Division Meeting G)
- If ages are precise (open clusters), then sample sizes are very small
- Small-sample results are mostly contradictory, biased, or inconclusive
- Gradient age dependence = Gradient evolution + radial mixing
- How much did radial migration smear out the gradient over time? How did the ISM gradient evolve over time? Is there a significant azimuthal term? What is the intrinsic [Fe/H] scatter at fixed $R_{\rm Gal}$?
- Consequences on the MW disc initial conditions + accretion/enrichment

Why red giants?



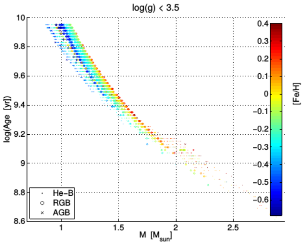
Queiroz,Anders+2018

- They are luminous (especially in the IR), ubiquitous, and trace ages between $\sim 0.5 - 13$ Gyr
- Ideal tracers for Galactic Archaeology: e.g. SDSS/APOGEE observed $300,000$ red giants in all Galactic components: precise abundances of ~ 15 elements, precise distances (5-15%)
- See Talk by Bovy @15:30
- **And for ages: asteroseismology!**

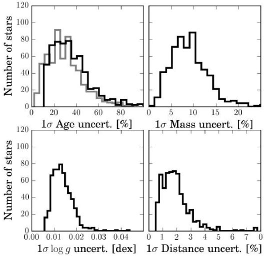
Ensemble/Stellar populations asteroseismology

- With CoRoT solar-like oscillation parameters $\Delta\nu, \nu_{\max}$ can be measured for large samples of stars de Ridder et al. 2009, Miglio et al. 2009, Chaplin&Miglio2013
- these scale with stellar mass and radius

  Tassoul1980,Ulrich1986,Brown+1991,Kjeldsen&Bedding1995...
- **Red giants** have a relatively tight age-mass relation
- $\frac{\Delta R}{R} \sim 5\%$, $\frac{\Delta M}{M} \sim 10\%$
- $\frac{\Delta\tau}{\tau} \sim 30\% \rightarrow$ ages useful in a statistical sense
- **further improvement by adding spectroscopic constraints** $T_{\rm eff}$, [Fe/H]

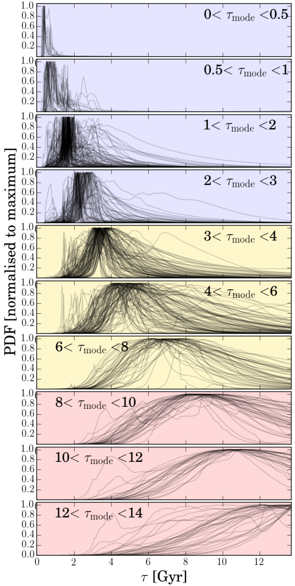


Miglio (2011)

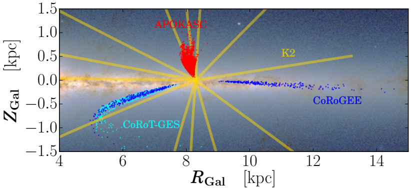


Anders et al. (2017a)

CoRoT + APOGEE: Precise distances, complex Age PDFs

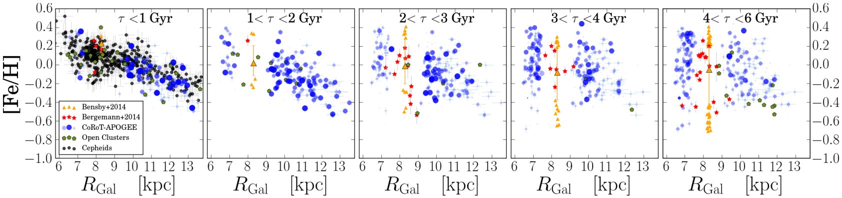


Anders et al. (2017a)



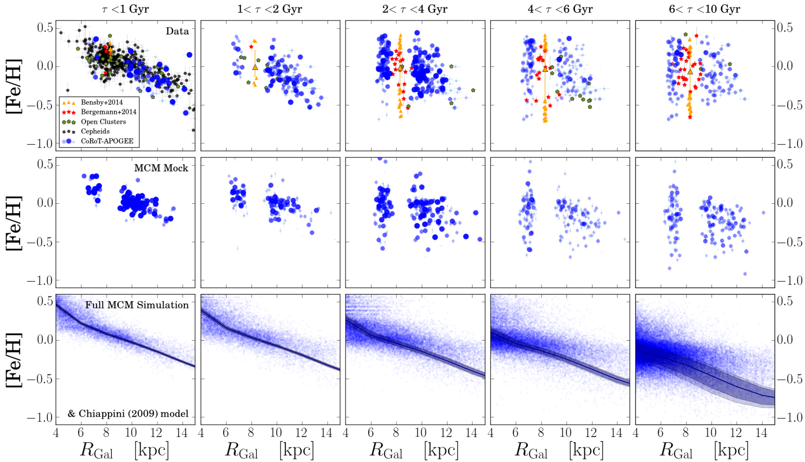
- Wide range of $R_{\rm Gal}$, geometric bias in $Z_{\rm Gal}$
- Age PDFs are typically non-trivial
- Careful statistical analysis is necessary to interpret the data; e.g. by using wide age bins
- Caution: systematic uncertainties (in stellar models) are still sizeable! Individual ages have to be treated with care... (e.g. Chaplin, Valentini @DivG)

CoRoGEE: age dependence of the radial abundance gradients

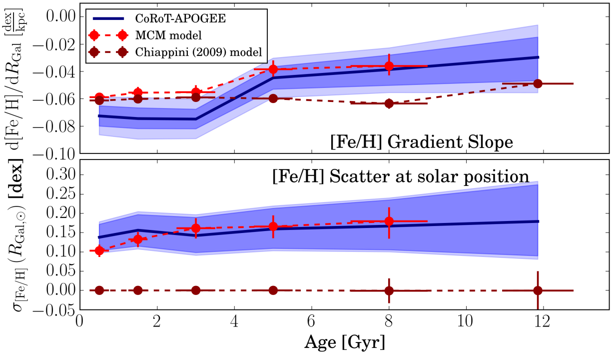


- We focus on $|Z_{\mathrm{Gal}}| < 300$ pc (418 stars)
- Each star is weighted by its age PDF in each panel
- Data are then compared to our custom CoRoGEE mock observations of the MCM galaxy to take into account selection biases and obs. uncertainties

Age dependence of the radial abundance gradients

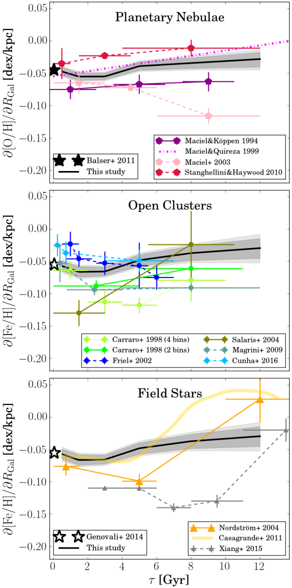


Quantifying the age dependence



- We determined the evolution of the gradient slope, mean metallicity in the inner and outer disc, and metallicity spread
- Models and data were fit in the exact same way; the MCM mock allows us to post-correct for geometric survey biases
- Chemo-dynamical model describes the data reasonably well: constant negative ISM gradient + efficient radial mixing

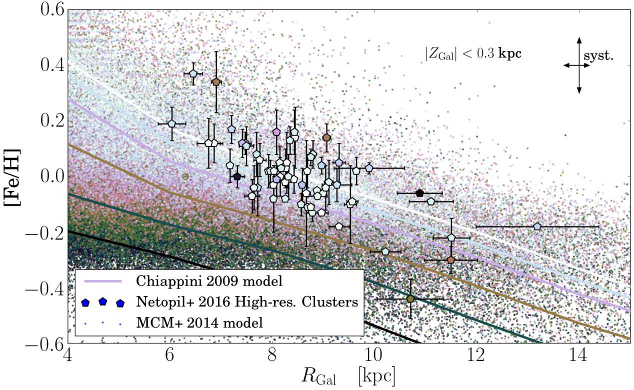
Comparison with other tracers



Anders et al. (2017b)

- CoRoGEE results in excellent agreement with Cepheids + HII regions, qual. agreement with GCS
- OCs suffer from low number statistics and unknown selection biases (OCs), PNe from uncertain age and distance estimates
- Utmost care has to be taken when interpreting small datasets...
- Gradient slope of 1–4 Gyr population slightly steeper than youngest population, but consistent with constantly negative as in MCM
- Radial mixing smears out the gradient of the older populations $\longrightarrow$ main driver of the gradient evolution for $\tau \gtrsim 2$ Gyr
- Our analysis relied on just 400 stars and we already supersede OC and PNe results in precision – seismology + spectroscopy works

How to bring OCs and field stars back into one story

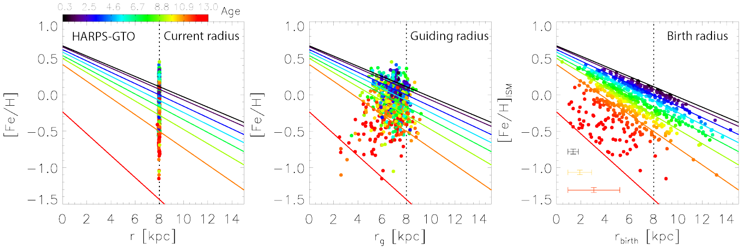


- Intermediate-age (2–4 Gyr) OCs in the solar neighbourhood can be more metal-rich and their radial metallicity gradient seems much steeper than that of the young population (e.g. Netopil+2015)
- The MCM model can potentially explain this: for every observed cluster, there is a similar point in the model! However, the mean trends are different...
- Proposal: Migrating clusters survive longer than non-migrating ones, thus skewing the observed OC distribution...

Summary

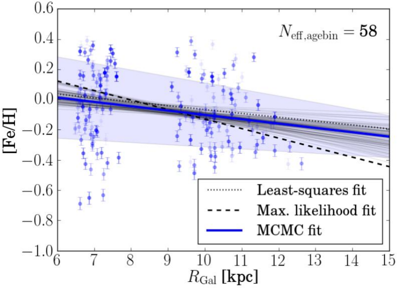
- Combining asteroseismology with spectroscopy of red giants brings us one step further in obtaining meaningful ages for distant populations (even beyond the *Gaia* volume)
- The CoRoT-APOGEE results provide the first application of the combined technique to Galactic Archaeology; other collaborations are following (GES-CoRoT, APOGEE-*Kepler*, RAVE-K2, etc.)
- Despite still sizeable age uncertainties (syst+stat), age-dating + spectroscopy of field stars is most efficient for solving Galactic Archaeology puzzles on Gyr timescales
- open clusters are very interesting for shorter time-scales: how do they migrate? what effects drive their survival time? what can we learn from discrepancies with field stars?
- More statistical seismic samples are needed: bright future with *Gaia*, K2, TESS, PLATO
- Controlling selection biases is crucial

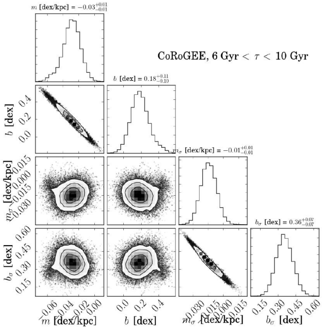
And *Gaia*? – Probing the time evolution of the ISM with field stars



- In Minchev+2018 we devised an empirical method to estimate the ISM gradient evolution and individual stellar Galactic birth radii (i.e. also the migration efficiency)
- We tested it on *Gaia* DR1/TGAS + HARPS data for turnoff stars and got very encouraging results
- The method only depends on accurate & precise age and chemistry measurements
- With *Gaia* DR2 + spectroscopic surveys this method (see also Frankel+2018) is even more powerful
- **See Ivan's Talk! (Wed 15:30)**

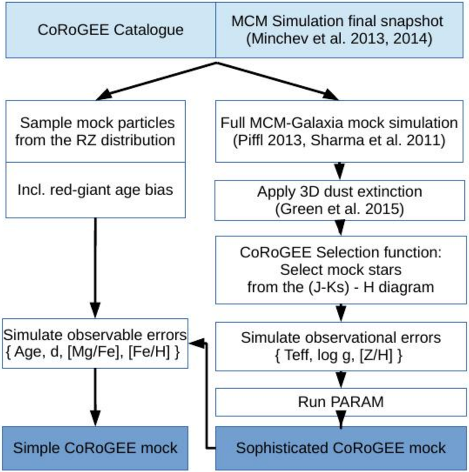
Quantifying the abundance gradient evolution



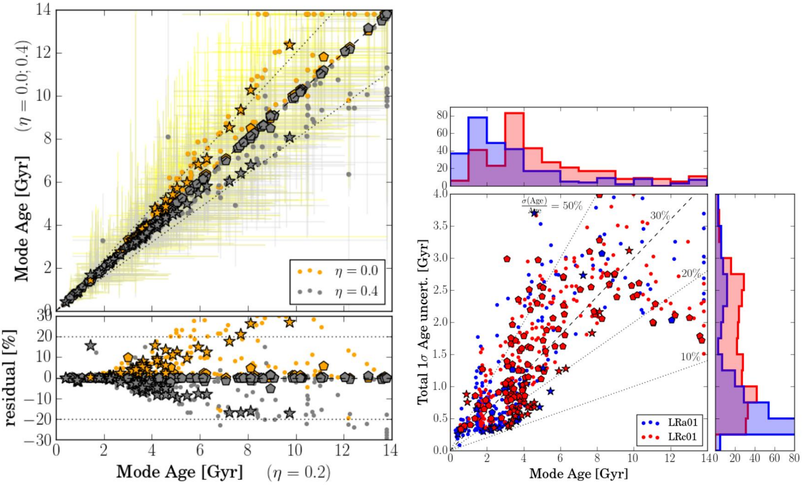


- because of low statistics and significant scatter in the [Fe/H]-R_{Gal} plots, sophisticated fitting necessary to avoid biased results
- 4-parameter fit model (linear gradient + R_{Gal}-dependent scatter) was found sufficient to describe the data between $6\ \mathrm{kpc} < R_{\mathrm{Gal}} < 13$ kpc

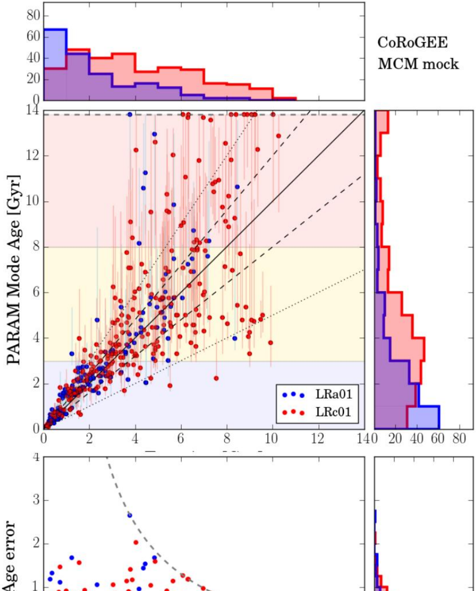
MCM mock procedure



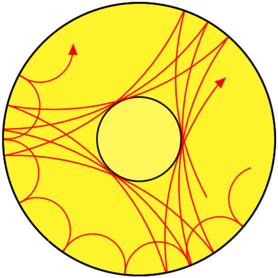
Age uncertainties: including systematics



Age uncertainties: testing the PARAM code with a mock sample



“Entry-level Asteroseismology” A. Miglio



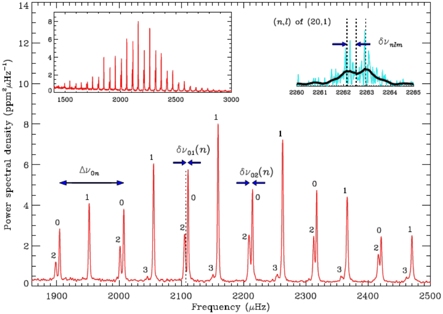
$$\left(\frac{R}{\mathrm{R}_\odot}\right) \simeq \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{max},\odot}}\right)\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-2}\left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{0.5}$$

$$\left(\frac{M}{\mathrm{M}_\odot}\right) \simeq \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{max},\odot}}\right)^{3}\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{1.5}$$

$$\left(\frac{\rho}{\rho_\odot}\right) \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{2}$$

$$\left(\frac{g}{\mathrm{g}_\odot}\right) \simeq \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{max},\odot}}\right)\left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{0.5}.$$

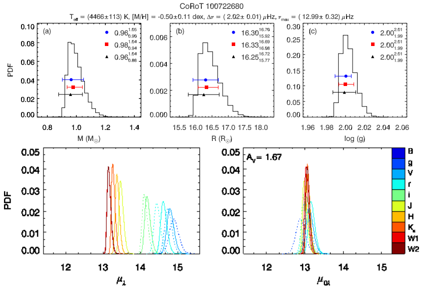
- “Solar-like” oscillations can be detected in stars through ultra-high precision photometry time series
- rich frequency spectra – modes are excited and damped by turbulence in the convective envelope



Miglio (2011)

PARAM: Combining asteroseismology and spectroscopy

- $\frac{\Delta R}{R} \sim 3\%$, $\frac{\Delta M}{M} < 10\%$
- Precise (2%) distances + extinctions
- Typical age uncertainties $\sim 25\%$
- Use of evolutionary stage information possible



PARAM code: da Silva et al. (2006), Miglio et al. (2012), Rodrigues et al. (2014) Figure courtesy of T.S. Rodrigues