APOGEE, Archaeology, and Asteroseismology

LIneA Webinar, 10.03.2016

Friedrich Anders (AIP)

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BPG, APOGEE, & CoRoT collaborations
Outline

Galactic Archaeology
APOGEE
Ages & Asteroseismology
Summary & Future

PhD thesis @ AIP/UP started 09/2013

C. Chiappini  M. Steinmetz
Data vs. modern Milky Way simulations

Radial velocity map from the RAVE survey.

Credit: The RAVE Collaboration; background image by A. Mellinger (2000).

Inside your coffee cup - An analogy
“Galactic Archaeology”

- Combination of Chemical evolution theory with Stellar Dynamics & Cosmology – how did the MW form?
- Use (semi-) empirical chemo-kinematical relations as well as forward modelling (Population synthesis, chemical evolution, pure dynamical + full chemodynamical models)
- Make use of spectral analysis, photometry & astrometry
- Main driver: Radial Migration – stars loose dynamical information about their birthplace (by interaction with the bar, the spiral arms, merging satellites, internal heating... )
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“Galactic Archaeology” – Stars as Time Capsules
Dissecting the Age-kinematics-abundance hypercube

- Galactic models make predictions for the distribution of stars in this multi-dim. space (or its subspaces)
- Basic problem of Galactic Archaeology: dimensionality reduction
- Look for the most robust and telling slices of this hypercube to constrain models for a given dataset
Example: Thick & Thin Disc

Thin & thick disc as two distinct formation epochs?

Gilmore & Reid (1983), MNRAS.


From Chiappini (2004), S&T.
### Spectroscopic stellar surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Period</th>
<th>Sky Area</th>
<th># of Spectra</th>
<th>app. mags</th>
<th>$\sigma(v_{\text{los}})$</th>
<th>$\sigma([\text{Fe/H}])$</th>
<th>char. dist.</th>
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</thead>
<tbody>
<tr>
<td>GCS</td>
<td>1981-2000</td>
<td>South</td>
<td>16,000</td>
<td>$V \sim 10$</td>
<td>0.5 km/s</td>
<td>individ.</td>
<td>0.003 kpc</td>
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<tr>
<td>RAVE</td>
<td>2003-2013</td>
<td>South</td>
<td>570,000</td>
<td>$I = 9 - 12$</td>
<td>3 km/s</td>
<td>0.2 dex</td>
<td>0.5 kpc</td>
</tr>
<tr>
<td>SEGUE</td>
<td>2004-2009</td>
<td>North</td>
<td>360,000</td>
<td>$g = 15 - 20$</td>
<td>8 km/s</td>
<td>0.2 dex</td>
<td>2 kpc</td>
</tr>
<tr>
<td>APOGEE</td>
<td>2011-2014</td>
<td>North</td>
<td>100,000</td>
<td>$H &lt; 13.8$</td>
<td>0.5 km/s</td>
<td>individ.</td>
<td>10 kpc</td>
</tr>
<tr>
<td>Gaia-ESO</td>
<td>2012-2015</td>
<td>South</td>
<td>150,000</td>
<td>$V &lt; 18$</td>
<td>0.5 km/s</td>
<td>individ.</td>
<td>4 kpc</td>
</tr>
<tr>
<td>LAMOST</td>
<td>2012-2018</td>
<td>North</td>
<td>3,000,000</td>
<td>$V &lt; 18$</td>
<td>10 km/s</td>
<td>0.2 dex</td>
<td>4 kpc</td>
</tr>
<tr>
<td>Gaia</td>
<td>2013-2018</td>
<td>all sky</td>
<td>50,000,000</td>
<td>$V &lt; 17$</td>
<td>10 km/s</td>
<td>0.25 dex</td>
<td>4 kpc</td>
</tr>
</tbody>
</table>
The SDSS-III/APOGEE survey

- three-year spectroscopic survey at the 2.5m telescope at Apache Point Observatory
- first multi-object fiber spectrograph in the NIR ever
- high-resolution ($R \sim 22.500$) high signal-to-noise ($S/N \sim 100 \text{ pixel}^{-1}$) spectra of red giant stars in the H band ($\lambda = 1.5 - 1.7 \mu m$)
- precise ($\sim 100 \text{ m/s}$) radial velocities & chemical abundances of up to 15 elements (0.1 dex precision)
The SDSS-III/APOGEE survey

The SDSS Telescope at APO.

APOGEE’s “first light” field. Credit: G. Zasowski.

APOGEE spectra

Basic interactive visualization tools at http://mirror.sdss3.org/basicIRSSpectra
Abundance patterns at different Gal. distances

Anders et al. (2014), with data from Bensby et al. (2011).
MDFs at different Gal. distances

Hayden et al. 2015
Ages provide crucial Galaxy model constraints: attack!
Age-dating stars: methods

- Stellar activity
- Gyrochronology
- Li depletion boundary
- U/Th decay
- Planetary nebulae
- Stellar kinematics

- **HRD/CMD methods**
  - Cluster CMDs
  - WD cooling sequence
  - Isochrone methods
  - Detailed modelling

SODERBLOM (2010), with data from TAKEDA ET AL. (2007)
Motivation

APOGEE Ages & Asteroseismology

Summary & Future

"Entry-level Asteroseismology"

- "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

\[
\frac{R}{R_\odot} \approx \left( \frac{v_{\text{max}}}{v_{\text{max,}\odot}} \right)^2 \left( \frac{\Delta\nu_{nl}}{\Delta\nu_{nl,\odot}} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff,}\odot}} \right)^{0.5}
\]

\[
\frac{M}{M_\odot} \approx \left( \frac{v_{\text{max}}}{v_{\text{max,}\odot}} \right)^3 \left( \frac{\Delta\nu_{nl}}{\Delta\nu_{nl,\odot}} \right)^{-4} \left( \frac{T_{\text{eff}}}{T_{\text{eff,}\odot}} \right)^{1.5}
\]

\[
\frac{\rho}{\rho_\odot} \approx \left( \frac{\Delta\nu_{nl}}{\Delta\nu_{nl,\odot}} \right)^2
\]

\[
\frac{g}{g_\odot} \approx \left( \frac{v_{\text{max}}}{v_{\text{max,}\odot}} \right) \left( \frac{T_{\text{eff}}}{T_{\text{eff,}\odot}} \right)^{0.5}
\]

Miglio (2011)
Ensemble/Stellar populations asteroseismology

- **Red giants** most useful through tight age-mass relation
- $\Delta \nu, \nu_{\text{max}}$ available for large samples
- $\frac{\Delta R}{R} \sim 5\%, \frac{\Delta M}{M} \sim 10\%$
- $\frac{\Delta \tau}{\tau} \sim 30\% \rightarrow$ ages useful in a statistical sense
- further improvement by adding spectroscopic constraints $T_{\text{eff}}, [\text{Fe/H}]$
Motivation

APOGEE Ages & Asteroseismology
Summary & Future

592. WE-Heraeus-Seminar – 1st to 5th June 2015
Reconstructing the Milky Way’s History: Spectroscopic Surveys, Asteroseismology and
Chemodynamical Models

Venue:
Physikzentrum Bad Honnef
Hauptstraße 5
53504 Bad Honnef (near Bonn, Germany)

The Physikzentrum (Physics Center) is run by the Deutsche Physikalische Gesellschaft e. V. (DPG) and is
jointly supported by the University of Bonn and the state of North Rhine – Westphalia.
Bad Honnef is located near Bonn (15 km) and Cologne (40 km). The stately mansion housing the
Physikzentrum is surrounded by a park at the foot of the Siebengebirge (“The Seven Hills”) on the right bank
of the Rhine River.

Important Dates:
- Registration closed: 15th March 2015
- List of participants published: 17th April 2015
- Registration Letters and final Abstracts due: 8th May 2015
- Conference dates: 1-5 June 2015

Accommodation and Meals:
- All participants will be hosted in the beautiful Bad Honnef mansion.
- Meals and accommodation will be covered by the organizers.
- Some support is available for travel expenses of invited speakers.
- We are allowed a maximum of 70 participants.

Time is now ripe to bring together again the representatives
from the extensive ground-based surveys, as well as
asteroseismology, Galaxy formation and stellar evolution experts
to set our roadmap for future endeavors in this field.
Currently available APOGEE seismic samples
The DR12 CoRoT-APOGEE Sample

CoRoGEE stars with “good” APOGEE results

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>CoRoGEE stars</td>
<td>690</td>
</tr>
<tr>
<td>with “good” APOGEE results</td>
<td>678</td>
</tr>
<tr>
<td>LRA01</td>
<td>333</td>
</tr>
<tr>
<td>LRc01</td>
<td>345</td>
</tr>
<tr>
<td>PARAM converged</td>
<td>623</td>
</tr>
<tr>
<td>Proper motions available</td>
<td>555</td>
</tr>
<tr>
<td>Good orbits ($\sigma(v_T) &lt; 20$ km/s)</td>
<td>147</td>
</tr>
</tbody>
</table>
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
Sanity checks: *HR* diagram

- Combination of asteroseismology and spectroscopy yields more precise HRD
- PARAM detects unphysical stellar parameter combinations
PARAM results: Complex Age PDFs

- Age PDFs are typically non-trivial...
What typical models predict for $[\alpha/\text{Fe}]-\text{vs.-age relation}$
(Apparently) young $[\alpha/{\text{Fe}}]$-enriched stars in CoRoGEE

▶ Many more in the inner disc field!
(Apparently) young $[\alpha/\text{Fe}]$-enriched stars

▶ Many more in the inner disc field!
Young $[\alpha/\text{Fe}]$-enriched stars – Possible explanations

1. Stars for which the scaling relations seem to break (e.g., stellar mergers; NGC 6819 results of Handberg et al., *in prep.*)

2. Close binaries (e.g., evolved blue stragglers) for which the mass-age relation breaks down

3. Massive satellite galaxy debris

4. Star-forming bubbles in the inner Galaxy (near the bar corotation)

- No conclusive evidence, possibly a mixture of these theories
Time evolution of the radial abundance gradients

- Ideally we want models to fit the full age-$R_{\text{Gal}}$-[Fe/H] relation
- but modelling the Age PDFs (and their systematics) is highly non-trivial
- therefore we look at the [Fe/H]-$R_{\text{Gal}}$ in wider bins of age
Time evolution of the radial abundance gradients

- Mean gradient largely constant over the past 5 Gyrs
- More information in the scatter (mixing and migration)
The $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ diagram at different Galactocentric Distances

- Trying to find signatures of migration with this diagram
- SMR stars seem to be dominantly young..
- What is the real shape of the $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$ diagram at super-solar metallicities?
Comparison with a chemodynamical model

This comparison begins to show where the model fails!
Summary

- Combining entry-level seismology with spectroscopy brings us one step further in obtaining meaningful ages.
- Be very careful when interpreting small subsets.
- Still sizeable systematic uncertainties.
- New chemodynamical constraints can be formulated over a large range in Galactocentric distance and ages.
Future: APOGEE-2

- APOGEE-2N started in autumn 2014
- First data will be released internally with DR13 (July)
- APOGEE-2S is being built up at Las Campanas (3.5 deg² FOV plates)
APOGEE-2 BPG/AIP/Brazil Science goals

- ongoing: detailed comparison with (semi-)cosmological N-body simulations using mock observation tools (Anders+)
- K2, Gaia, PLATO... (Valentini+)
- make full use of individual element abundances (Cunha+)
- Ultimate goal: constrain MW star formation + radial migration history (Chiappini+)
- Moderately metal-poor bulge in APOGEE (Barbuy+)
- High-res. abundance studies of B stars (Daflon+)
- Constrain stellar pop. models (Girardi+)
- Precisely calibrate spectro-phot. distances (Rodrigues+, Santiago+)
- ....
Gaia DR1 will contain parallaxes and proper motions with Hipparcos-like precision for 2.5 million Tycho stars (Michalik+2015)

The overlap with APOGEE is \( \sim 28,000 \) stars

These can be used to do chemo-kinematics outside the Hipparcos volume

and also to better test our spectro-photometric distances
Test your science ideas using this “pseudo-mock” sample!

**APOGEE-TGAS**

**APOGEE-TGAS mock**

TGAS = the Tycho-Gaia astrometric solution = Tycho-2 + Gaia :)

APOGEE 192 DR13 Overlap with Tycho-2: ~40,000
- unique Objects: ~36,000
- stars with reliable stellar parameters: 15,000
- stars with reliable parameters except log g (dwarfs): 0,000
- stars with BPG distances: 24,000 (all of them are in Tycho, but only 22,000 of those have measured proper motions)

This overlap of GR1/TGAS & APOGEE DR13, TGAS will probably provide proper motions and parallaxes that (so we expected) will be good enough to do chemodynamics outside the solar neighbourhood.

With the help of Coryn Balter-Jones, I made a what-to-expect realistic mock APOGEE-TGAS file that contains:

- APOGEE pre-proto DR13 results including data from APOGEE-2 (from ASPCAP & allStars+AGe 1.1,cs and its apogee2 counterpart -- TO BE UPDATRED!!)
- Proper motions from Tycho-2 --> our current best guess for the expected TGAS proper motions
- Custom distances from BPG (using all spectrophotometry for giants and everything but log g for dwarfs)
- Current best-guess parallax estimates based on these distances
- Rough expected TGAS uncertainties in parallax and proper motion
- APASS DR9 BV photometry

The file can be found on the AIP cloud (go for the latest version).

**File description**

Most columns should be self-explanatory, the most important ones in terms of kinematics are:

| RA, DEC, GLON, GLAT - positions from 2MASS |
| HELIO AVG - average heliocentric velocity (RV) |
| VSOGAT - RV scatter among different observations ('visits') |
| N/OBS - number of observations |
| RV/MED - median RV precision |
| Bmag, Vmag - Tycho magnitudes |
| pmRA, pmDEC - Tycho proper motions |
| d BPML, d BPME - median distance (Santiago et al. 2010) |
| d BPML, d BPME - 1 sigma lower and upper limits of the median |
| d BPML, d BPME - 2 sigma lower and upper limits of the median |

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F. Anders  
APOGEE, Archaeology, and Asteroseismology