The Apache Point Observatory Galactic Evolution Experiment

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The Apache Point Observatory Galactic Evolution Experiment (APOGEE)

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APOGEE at a Glance

• **Dual hemisphere** spectroscopic survey of MW stellar populations
• Bright time SDSS-III/IV survey, 2011.Q2 to 2020.Q2
• Two *300 fiber*, *R ≈ 22,500*, cryogenic spectrographs, large FOV
• *H*-band: 1510 – 1690 nm *(A_H/A_V ~ 1/6)*
• Typical *S/N = 100/pixel* @ H=12.2 for 3-hr integration
• RV uncertainty spec < 500 m/s in 3 hr  *Actual < 100 m/s in 1hr*
• Precision abundances for *≈ 20 chemical elements* (including C, N, O, Fe, other α, odd-Z, a few neutron-capture)
• *5 x 10^5*, predominantly **giant stars**, probing all Galactic populations, and those of their Local Group counterparts
2.5 m SDSS telescope at Apache Point Observatory

2.5 m du Pont telescope at Las Campanas Observatory

The APOGEE-N spectrograph
APOGEE at a Glance

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Why APOGEE makes a difference

High resolution

* Near Infrared

* 4-5x10^5 giant stars
Optical Sky
Near-Infrared Sky
APOGEE Field Plan

APOGEE Footprint

APOGEE DR12 coverage
APOGEE 2 Field plan - Zasowski et al. (2017)
Target Selection

- Main sample is selected from 2MASS (MIR from Spitzer and WISE for dereddening)

  \[(J-K)_0 \geq 0.5, \ 7 < H < 13.8 \Rightarrow \text{giants (RGB, AGB, RC) are 80\% of the sample}\]

- Open and globular clusters targeted for science and calibration purposes

- Ancillary science programs cover a variety of science targets (young Galactic clusters, M dwarfs, M31 GCs in integrated light)

- For details, see Zasowski et al. (2013,
APOGEE Scientific Footprint

- Galactic Archaeology
- Local Group galaxies
- Stars
- Stellar Clusters
- Interstellar Medium
- Sub-stellar Companions
- Spectral Analysis
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{ Disk
  Bulge
  Halo }
Galactic Archaeology

The Questions:

• What is the current “structure” of the Galaxy?
• What was the history leading up to it?
• What does that teach us about galaxy formation?
Galactic Archaeology

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Is the Galaxy a typical galaxy?
The Nearby Stellar Disk
Bensby et al. 2014

- Precision abundances for 714 F-G dwarfs
- R = 40,000-110,000
- Solar neighborhood

- A bimodal distribution in [\alpha/Fe] (at constant [Fe/H])
- High \alpha stars older, higher \(z_{\text{MAX}}\), shorter \(R_{\text{MEAN}}\) => Inner (thick) disk
- Low \alpha stars younger, lower \(z_{\text{MAX}}\), longer \(R_{\text{MEAN}}\) => reach Outer disk
A bimodal distribution in [$\alpha$/Fe] (at constant [Fe/H])

- High $\alpha$ stars: older, higher $z_{MAX}$, shorter $R_{MEAN}$ => Inner (thick) disk
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Precision abundances for 714 F-G dwarfs

R = 40,000-110,000

Solar neighborhood

Hard to Explain
“Reverse Engineering” Disk Formation

- Devise SFH and chemical enrichment history to produce observations
- Two-infall model (Chiappini et al. 2001), radial migrations (e.g., Schönrich & Binney 2009, Loebman et al. 2011)
- Match data for solar neighborhood with varying degree of success
The Disk According to APOGEE

Hayden et al. 2015

• Study $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$ for ~70,000 stars along RGB
• Data from DR12. Note bimodal $[\alpha/\text{Fe}]$.
• $3 < R_{\text{GC}} < 15$ kpc, $|z| < 2$ kpc
• See also Hasselquist et al. (2018)
• Understanding bimodality in light of state-of-the-art cosmological numerical simulations

• Some MW-like galaxies show bimodality in the simulations
The EAGLE project
Schaye+ 2015, Crain+2015

Cosmological simulations of the galaxy population.

Unknown feedback efficiencies calibrated to reproduce observables.

Largest run is a cubic volume of $L=100$ cMpc

~200 $L^*$ galaxies, each with 10,000 star particles.

Diverse formation histories & environments

Abundances of 9 metal species tracked, from:
- AGB stars
- Type Ia SNe
- Type II SNe
Origin of high-/low-\(\alpha\) according to EAGLE cosmological simulations


- High- and low-\(\alpha\) populations evolve in chemical isolation
- No need to concoct schemes to explain chemical evolution
Accretion History

- Only 6/133 MW-like galaxies in EAGLE show bimodal [$\alpha$/Fe] distributions.
- The phenomenon seems to be associated with intense accretion activity at $1<z<2$.
- The Milky Way may be a rare MW-like galaxy.

Mackereth, Crain, Schiavon et al. (2018)
C/N and Mass of RGB stars

- High-α/thick disk and low-α/thin disk stars have markedly different [C/N] ratios
- This is a by-product of a combination of stellar evolution (mixing), chemical evolution (weakly) and stellar mass
- The mass of an RGB star is directly related to its age!
RGB masses from asteroseismology

Scaling Relations + Spectroscopy = Mass and Age

\[ \Delta \nu^2 \sim \frac{M}{R^3} \]
\[ \nu_{\text{max}} \sim \frac{M}{R^2} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{-1/2} \]

=> Can Solve For M and R

16 Cyg A Metcalfe+ 2012

See Pinsonneault et al. (2018), Epstein et al. (2014)
Ages of field stars
Martig et al. (2016)

- Use APOKASC sample to fit relation between Mass and [C/N] for fixed stellar parameters
- Invert relation to estimate masses (thus ages) for 52,000 stars
- High-α stars ~8-11 Gyr old. Interesting pattern in thin disk.
- Spatial distribution interesting, not corrected for selection function
- See also Ness et al. (2016)
Low [a/Fe], youngest populations

Clear broken exponential

$1.0 < \text{age} < 3.0 \text{ Gyr}$

recover [Fe/H] gradient

$\log \Sigma(R) \times \text{constant}$

$R \ [\text{kpc}]$

Mackereth et al. (2017)
Profiles broaden with age

Timescale of radial migration / disk heating?
Evolution of disk scale-height, $h_Z$

Scale-height of both high- and low-$\alpha$ disks in solar annulus evolved steadily with time.

Fundamental constraint on models for the formation of the thick disk.
The Bulge
Schultheis et al. 2017, García-Pérez et al. 2018

- Mapping spatial structure and detailed chemical composition of bulge stellar populations
Dissolved Globular Clusters
Schiavon et al. 2017

- Stars discovered in the Inner Galaxy with GC abundance patterns (C,N,Mg,Al)
- GC destruction deposited 25% of halo stellar mass at $R_{GC} < 2$ kpc ($10^8 \, M_{Sun}$)
- Corresponds to 6-8 times the mass of the entire existing Galactic GC system
- See also Martell et al. (2017), Fernandez-Trincado et al. (2017)
GCs and DM halos

- Total mass in GC systems scales with the total mass of the system
- Only stellar population found to behave that way
- Suggestion that it formed early, before feedback processes became important

Hudson et al. 2014
• $\eta = M_{GC}/M_{TOT}$
• $\eta = (4 \pm 1) \times 10^{-5}$
• $\eta_{MW} = 9 \times 10^{-6} - 5 \times 10^{-5}$
Accreted vs “In situ” Halo
Nissen & Schuster (2010)

- Precision abundances for 94 F-G dwarfs
- R = 40,000-54,000
- Distance < 335 pc

- A bimodal distribution in [α/Fe]
- High α stars mostly on prograde orbits => Puffed up disk/bulge
- Low α stars mostly on retrograde orbits => Accreted
Abundance pattern of low $\alpha$ stars indeed similar to that of dwarf galaxies

See also Fernandez-Alvar et al. (2018)
Gaia-Enceladus
Helmi et al. (2018), Kopelman et al. (2018)

- Gaia DR2 reveals a large population of retrograde stars within 2.5 kpc of Sun
- Low-\(\alpha\) abundances (APOGEE)
- Single accretion event

- Distribution on the sky of potential G-E members
- Progenitor system mass estimated at \(6 \times 10^8\) \(M_{\odot}\)

See Also Belokurov et al. (2018), Deason et al. (2018)
The APOGEE view

- Discovery of an accreted population with very high eccentricity ($e$)
- Makes up for 2/3 of all APOGEE-Gaia sample
- Presence of a “knee” in Mg-Fe plane suggests massive system (MC-like)
- Low $e$ population shows no “knee” => mix of stellar populations

Mackereth et al. (2018b)
The EAGLE view
Mackereth et al. (2018b)

• The EAGLE simulations show that only systems accreted at $z < 1.5$ have such high eccentricity distributions.

• Due to cosmology, such systems tend to be more massive (up to $10^9 \, M_{\odot}$).

• Such accretion events happen for only 3/22 of MW-like galaxies. They are rare.
M Dwarfs

• Contain most of the stellar mass
• Least studied among cool stars
• Important in search for extra-solar Earths
• TESS and Plato will discover lots of those
• APOGEE has amassed spectra for an astounding 12,000 M dwarfs.
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Spectrum synthesis of Ross 128 — Souto et al. (2018)

Teff - 3200 K  log g = 5  near solar metallicity

Abundances of C, O, Mg, Al, K, Ca, Ti, and Fe
Example: spectral fits around CO lines

For details, see Holtzman et al. (2015), García Pérez et al. (2017), Majewski et al. (2017)
The Evolution of APOGEE Stellar Parameters

Download DR14 data from: https://www.sdss.org/dr14/irspec/
See Holtzman et al. (2018) and Jönsson et al. (2018)