Abundance Trends in the Milky Way Disk as Observed by the SEGUE Survey:

Constraints on thick disk formation and other galaxy-shaping processes

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Santa Cruz Galaxy Workshop, 2011 August 10
What processes shape the formation and evolution of galactic disks?

- High gas accretion at early times leads to turbulent clumpy disks (Elmegreen & Elmegreen 2005, 2006, Dekel et al. 2009)

- Minor mergers are common (Stewart et al. 2008, Martínez-Delgado et al. 2010)

- Stars can change their orbits through resonant radial migration processes (Sellwood & Binney 2002, Roskar et al. 2008, Schönrich & Binney 2009, Minchev et al. 2011)
These mechanisms have been proposed to explain the Milky Way thick disk

- Heating by molecular clouds and other density perturbations cannot explain the observed thickness (Jenkins 1992)
  - Stars formed in situ in turbulent gas clumps (Brook et al. 2005, Bournaud et al. 2009)
  - Minor mergers directly deposited stars in a thick disk (Abadi et al. 2003)
  - Minor mergers puffed up an existing thin disk (Kazantzidis et al. 2008, Bird et al. 2011)
  - Radial migration thickened an existing thin disk (Schönrich et al. 2009, Loebman et al. 2011)

- We can use observations of the thick disk to constrain the relative importance of these mechanisms in shaping the Milky Way disk
Thick disks are old and ubiquitous

- Thick disk stars are older than $\sim 8$ Gyr (Bensby et al. 2004) and serve as a “fossil record” of the early formation of the Galaxy.

- Thick disks in external galaxies have similar properties and are likely to be a generic feature of disk galaxies (Dalcanton & Bernstein 2002, Yoachim & Dalcanton 2005, 2006, 2008)

- **Kinematics and chemistry**
  - Lag in rotation by 20-50 km/s (Chiba & Beers 2000, Soubiran et al. 2003)
  - Metal-poor $[\text{Fe/H}] \sim -0.5$ (Gilmore et al. 1995)
  - $\alpha$-enhanced, consistent with rapid star formation history (Bensby et al. 2003, 2005)
Abundance trends in the thick disk provide hints about its formation

- The presence or lack of abundance gradients can constrain formation scenarios

- A thick disk that formed rapidly at early times will be chemically homogeneous, with no gradient (Brook et al. 2004, 2005)

- A thick disk that forms from an initially thin disk will have no gradient only if radial mixing processes are efficient
  - Disk heating through minor merger (Kazantzidis et al. 2008, 2009, Bird et al. 2011)
  - Resonances with transient spiral arms (Roskar et al. 2008, Schönrich & Binney 2009)
SEGUE Low Latitude Sample

- SEGUE: Sloan Extension for Galactic Understanding and Exploration (Yanny et al. 2009)
  - 360,000 medium resolution ($R \sim 2000$) spectra of Milky Way stars
  - Large, uniform sample

- ~7000 main sequence turnoff stars
  - $8 < |b| < 16^\circ$ (low Galactic latitude)
  - $5000 < \text{Teff} < 7000$ K
  - $6 < R < 16$ kpc, $0.15 < |Z| < 1.5$ kpc
  - $[\text{Fe/H}], [\alpha/\text{Fe}]$ from SEGUE Stellar Parameter Pipeline (Lee et al. 2008, 2011)

- Divide sample into bins in $R$ and $|Z|$, look at trends in $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$
The radial gradient in [Fe/H] becomes flat with increasing |Z|

- Flat gradient at |Z| > 1.0 kpc
- Consistent with chemically homogeneous thick disk, as predicted by in situ star formation during turbulent clumpy phase
- Could also indicate that radial mixing processes are strong

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Unlike [Fe/H], trends in [\(\alpha/\text{Fe}\)] are inconsistent with chemical homogeneity.

- Most \(\alpha\)-enhanced stars are confined to small radii \((R < 10 \text{ kpc})\)
- Our data are consistent with a short scale length for the high-\(\alpha\) population.
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\[ L_{\text{thin}} = 2.6 \text{ kpc} \]

\[ L_{\text{thick}} = 3.6 \text{ kpc} \]

\[ L_{\text{thin}} = 3.8 \text{ kpc} \]

\[ L_{\text{thick}} = 2.0 \text{ kpc} \]

The inner and outer disks show different vertical abundance trends and kinematic properties.
The inner and outer disk show different vertical trends in \([\alpha/Fe]\) vs. \([Fe/H]\)

- From observations of nearby stars, we expect the fraction of high-\(\alpha\) stars to increase as the thick disk becomes the dominant population at large \(|Z|\).

- At small \(R\), the fraction of high-\(\alpha\) stars increases at large \(|Z|\).

- At large \(R\), the fraction of high-\(\alpha\) stars is low at all \(|Z|\).
The inner and outer disk show different vertical trends in [α/Fe] vs. [Fe/H].

From observations of nearby stars, we expect the fraction of high-α stars to increase as the thick disk becomes the dominant population at large |Z|.

At small R, the fraction of high-α stars increases at large |Z|.

At large R, the fraction of high-α stars is low at all |Z|. 
The inner and outer disk show different vertical trends in $[\alpha/\text{Fe}]$ vs. $[\text{Fe/H}]$

- **Bensby et al.**
  - Thin (60)
  - Thick (38)

- **SEGUE**
  - $[\alpha/\text{Fe}] < 0.2$ (4511)
  - $[\alpha/\text{Fe}] > 0.2$ (1109)

→ From observations of nearby stars, we expect the fraction of high-$\alpha$ stars to increase as the thick disk becomes the dominant population at large $|Z|$.

→ At small $R$, the fraction of high-$\alpha$ stars increases at large $|Z|$.

→ At large $R$, the fraction of high-$\alpha$ stars is low at all $|Z|$.
The inner and outer disk show different vertical trends in $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$

- Weighted fractions of low- and high-\(\alpha\) stars
- From observations of nearby stars, we expect the fraction of high-\(\alpha\) stars to increase as the thick disk becomes the dominant population at large $|Z|$
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High-\(\alpha\) stars in the inner and outer disk have different kinematic properties

From observations of nearby stars, we expect a correlation between [\(\alpha/Fe\)] and kinematics.

At small \(R\), high-\(\alpha\) stars lag low-\(\alpha\) stars by \(\sim 20\) km/s, similar to observations of nearby stars.

At large \(R\), high- and low-\(\alpha\) stars have similar distributions in rotational velocity.
Summary

- Radial gradient in [Fe/H] is flat at |Z| > 1.0 kpc
  - Whatever mechanism takes stars to large |Z| leads to a flat gradient in [Fe/H]
  - Thick disk formed quickly in turbulent disk phase
  - Or radial migration (induced by spiral arms or minor mergers) is strong

- Short scale length for high-α stars
  - At small R, see same chemical and kinematic properties as thin and thick disk stars in solar neighborhood
  - At large R, high-α stars are fewer in number and do not lag behind low-α stars
  - Different populations in inner and outer disk? Different formation mechanisms at work?