Galactic Disks: chemodynamical properties and models

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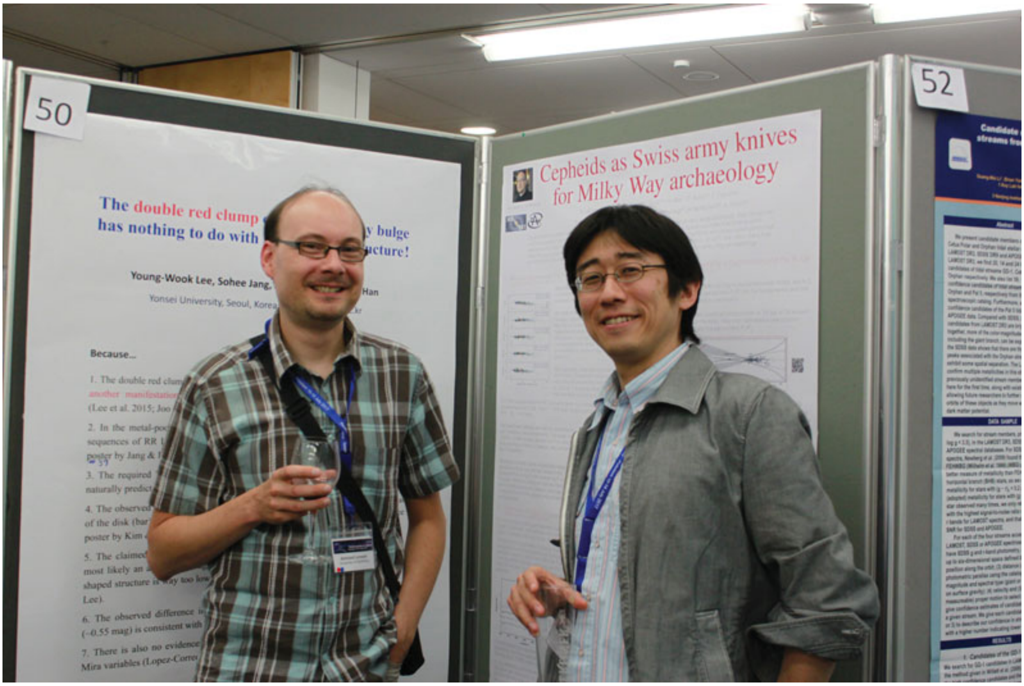

Bertrand Lemasle and Noriyuki Matsunaga

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APOGEE: the Sloan Digital Sky Survey Apache Point Observatory Galactic Evolution Experiment. Insights into the Galactic Disk: A Review

Jon A. Holtzman[1], **Sten Hasselquist**[1] **and the SDSS-IV/APOGEE-2 collaboration**

[1]Department of Astronomy, New Mexico State University
Box 30001/MSC 4500
Las Cruces NM 88003, USA
email: holtz@nmsu.edu, sten@nmsu.edu

Abstract. The SDSS Apache Point Observatory Galactic Evolution Experiment (APOGEE) has collected high resolution near-IR spectra for several hundred thousand stars throughout the Milky Way. We review some of the results related to chemistry of stars in the disk, where APOGEE has a particular advantage by virtue of being able to work in more obscured areas. The ability to measure carbon and nitrogen abundances in giants in the near-IR provides insight into stellar ages. We summarize results on the variation of mean metallicity, metallicity distribution functions, and the [α/Fe]–[Fe/H] relation across the Galactic disk, as well as results on the structural parameters in mono-abundance populations. Many of these results suggest that radial migration has played a significant role in the Galactic disk. It may be possible to disentangle radial mixing using multi-element abundance patterns.

Keywords. surveys, stars: abundances, Galaxy: abundances, Galaxy: stellar content

1. Introduction

The Sloan Digital Sky Survey (SDSS) Apache Point Observatory Galactic Evolution Experiment(APOGEE) survey has been running since 2011, using a custom fiber-feb IR spectrograph that provides $R \sim 22500$ spectra from 1.51-1.7μ for 300 targets simultaneously. Red giant branch (RGB) stars are the primary targets, and these can be seen to large distances.

The SDSS Data Release 14 (DR14, Abolfathi *et al.* (2017)) contains 3 years of APOGEE-1 data and 2 years of APOGEE-2 data, and includes spectra for $\sim$ 277,000 stars, of which $\sim$ 160,000 are giants with derived stellar parameters and chemical abundances (see Zasowski *et al.* (2017); Holtzman *et al.* (2017); Jönsson *et al.* (2017)). DR14 also includes several value-added catalogs (Abolfathi *et al.* (2017)), including a catalog of red clump (RC) stars, a catalog with distance estimates, and a catalog cross-matching APOGEE stars with those from TGAS.

Here we briefly review results on ages of APOGEE stars, maps of mean metallicity and mean age maps across the Galaxy, metallicity distribution function maps, [α/Fe]–[Fe/H] maps, structural parameters of chemical populations, and chemical tagging.

2. Ages of APOGEE stars

RGB stars have an advantage in that a stellar mass estimate directly translates to an age estimate; this has turned out to be especially advantageous given the development of

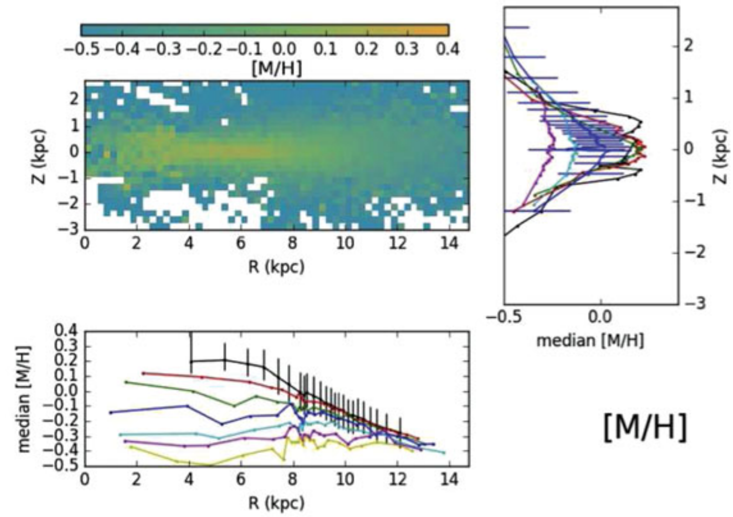

Figure 1. Map of mean [M/H] as a function of position in the disk from APOGEE DR14 for stars with log g > 1. Lower plot shows radial gradients at different heights above the plane; plot at right shows vertical gradients at different Galactocentric radii.

asteroseismology, and APOGEE has observed stars in the CoRoT field (the CoRoGEE sample, Anders *et al.* (2017a)), the Kepler field (the APOKASC sample, Pinsonneault *et al.* (2014)), and the K2 fields. Initial analysis of stars with asteroseismic ages yielded the unexpected result that stars with high [α/Fe] values are not exclusively old (Chiappini *et al.* (2015); Martig *et al.* (2015)).

Inferences about stellar ages can also be made from observed abundances of carbon and nitrogen, since these measure mixing at the base of the giant branch that is expected to be a function of stellar mass; higher [C/N] is expected in stars of lower mass/higher age. Observations of [C/N] can be translated to masses/ages through models (e.g., Masseron & Gilmore (2015)), or through empirical calibration using stars with asteroseismic masses (Martig *et al.* (2016), Ness *et al.* (2016)). It may be important to recognize that there could be primordial variations in [C/N] that need to be considered and also that there may be extra mixing along the RGB that leads to surface gravity and metallicity dependence of [C/N].

Feuillet *et al.* (2016) also discuss the ability to estimate ages from stellar parameters, especially in the situation where independent distances are available, which will soon be the case for many APOGEE stars when GAIA results are released.

3. Mean metallicity and mean age maps

Hayden *et al.* (2014) and Anders *et al.* (2014) discuss variations of mean metallicity with location in the Galaxy, generally finding higher metallicity towards the inner regions (negative metallicity gradient with Galactocentric radius) and towards the Galactic plane (negative metallicity gradient with distance from plane). Figure 1 shows a mean metallicity map with gradients.

In the plane, the radial gradient in the outer regions is ∼-0.09 dex/kpc, which is somewhat steeper than independent estimates, e.g. from HII regions. The radial gradient flattens in the inner Galaxy, more so in stars with lower [α/Fe], resulting in a more

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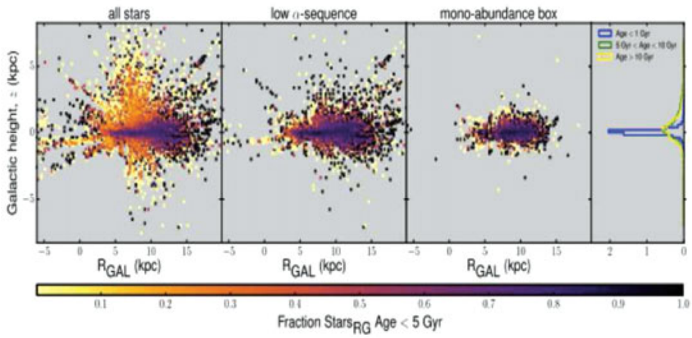

Figure 2. Maps of fraction of stars with age> 5 Gyr across the Galactic disk, from Ness *et al.* (2016). Different panels show maps for different subsamples: all stars (left), stars with low [α/Fe] (center), and stars with low [α/Fe] in a small bin of [Fe/H].

homogeneous inner population that perhaps results from increased orbital mixing caused by the Galactic bar.

Vertical metallicity gradients are flatter at larger radii. This leads to flat metallicity gradients above the plane, but these may not imply a homogeneous thick population, as discussed below.

Anders *et al.* (2017b) analyze gradients using stars from the CoRoGEE sample, for which independent ages from asteroseismology are available, and find that older stars have flatter gradients; this is consistent with the observation (Hayden *et al.* (2015)) that higher [α/Fe] stars have a flatter gradient. The flattening of the gradient for stars of older ages is not totally consistent with other measurements (e.g., clusters Cunha *et al.* (2016)); Anders *et al.* (2017b) provide several comparisons with independent measurements of Cepheids, planetary nebulae, and star clusters.

Ness *et al.* (2016) and Martig *et al.* (2016) present maps of mean ages (see Figure 2) as a function of location in the Galaxy, using ages from [C/N] that are empirically calibrated using observations in the Kepler fields. They find that the mean age increases towards the center of the Galaxy, and away from the Galactic midplane, but with a flaring of younger mean ages away from the plane at larger radii. Above the plane, a radial age gradient exists, so the geometric thick disk is not a homogeneous population (Martig *et al.* (2016)).

4. Metallicity distribution function maps

Hayden *et al.* (2015) present APOGEE results that show that the metallicity distribution function (MDF) varies across the Galaxy. In the Galactic midplane, the MDF has a negative skew with a tail towards lower metallicity, while in the outer disk the MDF has a positive skew with a tail towards higher metallicity. The MDF also varies with distance from the midplane, and the MDF at high z shows little radial variation apart from the outermost regions.

Hayden *et al.* (2015) suggest that the variation of the MDF in the midplane indicates the effects of radial migration, where the high-metallicity tail in the outer regions is likely to be comprised of stars that originated at smaller Galactocentric radii. They reach this conclusion by noting that it is challenging to get positive skew from chemical evolution models, and demonstrate that mixing from standard orbital "blurring" is not likely to be sufficient to reproduce the observed MDFs. This conclusion is supported by the simulations of Loebman *et al.* (2016), which show a variation of MDF skew that

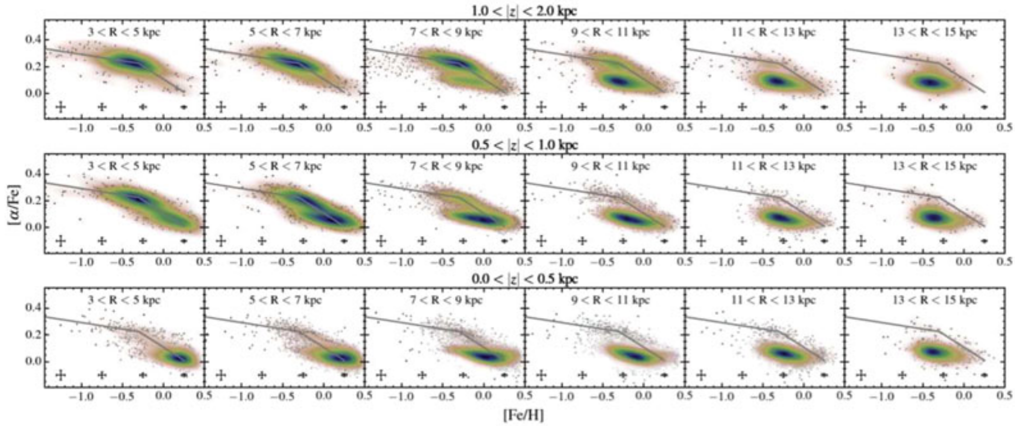

Figure 3. [α/Fe]vs [Fe/H]sequences at different locations in the Galactic disk, from Hayden *et al.* (2015).

closely matches that observed by APOGEE, and results from radial migration in the simulation. However, not all simulations agree on the effect of radial migration: MDFs presented in Minchev *et al.* (2014) do not agree as well with the APOGEE observations.

5. [α/Fe]–[Fe/H] maps

Nidever *et al.* (2014), Hayden *et al.* (2015), and Anders *et al.* (2014,2017b) discuss the variation of [α/Fe]–[Fe/H] sequences across the Galaxy using different APOGEE subsamples. As shown in Figure 3, APOGEE find the bimodal sequences in [α/Fe]–[Fe/H] that are observed in the solar neighborhood, but find that the relative number of stars on the two sequences varies strongly with location in the Galaxy. Higher [α/Fe] stars are found at a higher fraction at smaller Galactocentric radii and at larger distances from the midplane. In the innermost regions, most stars are found on the high [α/Fe] sequence, while in the outermost regions, most stars are found on the low [α/Fe] sequence.

The interpretation of the sequences and their changing location is still not totally clear, with different hypotheses including two separate epochs of star formation (e.g., Chiappini (2009)) and radial and vertical mixing of populations with different star formation histories. For the innermost regions, Freudenburg *et al.* (2016) suggest that the observed [α/Fe]–[Fe/H] distributions, along with the observed MDFs, is more consistent with a formation scenario that has a relatively slow vertical collapse over 2.5 Gyr than with a scenario that has a discrete event that vertically heats the disk.

Anders *et al.* (2017b) use the CoRoGee sample to study the [α/Fe]–[Fe/H] relation as a function of age as well as location. They find that there can be a mix of ages at any given location in the [α/Fe]–[Fe/H] plane, suggesting that the sequences are not completely evolutionary sequences. In the outer regions of the Galaxy, some of the most metal-rich stars appear to be older than more metal-poor stars, supporting the idea that these may have migrated from an inner region of the Galaxy.

A similar pattern is seen using ages inferred from [C/N], using a sample from a limited range in surface gravity (to try to avoid possible effects of mixing along the RGB), as shown in Figure 4. The larger number of stars in this sample suggests that the mean age-metallicity relation turns up to larger ages at higher metallicities in the outer regions of the Galaxy.

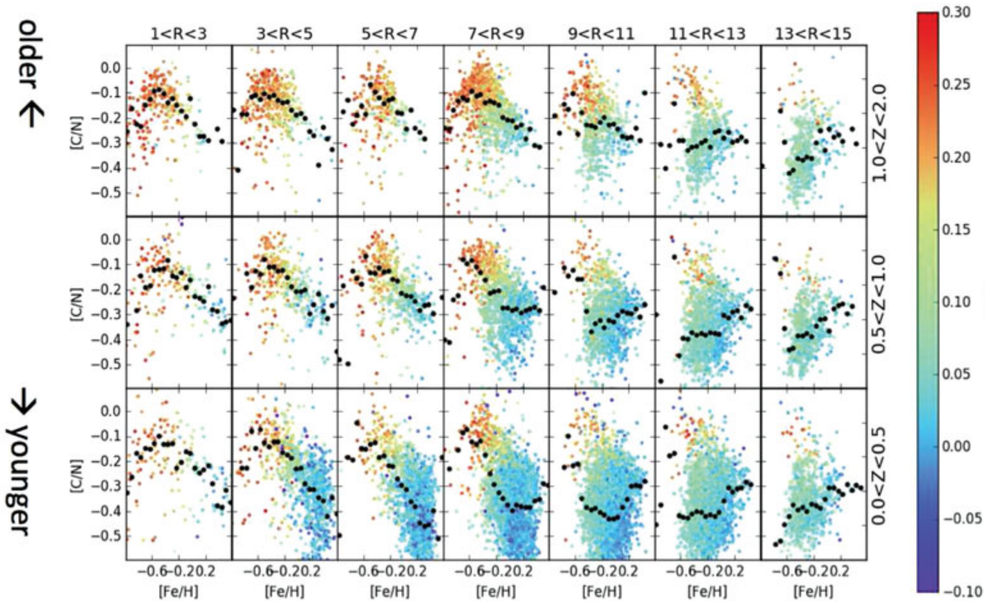

Figure 4. Locii of [C/N]vs [Fe/H]at different locations in the Galaxy. Black points show median values in different bins of [Fe/H].

6. Structural parameters of chemical populations

APOGEE data have also been used to study Galactic structure for samples of different chemical abundance and/or age. To do so requires a careful consideration of the APOGEE survey selection function and the effects of extinction, as outlined in Bovy *et al.* (2016b).

Bovy *et al.* (2016b) study the structural parameters of mono-abundance populations (MAPs), i.e. stars within a small range in [Fe/H] and [α/Fe]. For stars in the low [α/Fe] sequence, they find that the density distributions of MAPs are well-represented by a two-exponential radial distribution, with a rising exponential in the inner regions, transitioning to a falling exponential in the outer regions at a break radius, implying an annular concentration of stars for each MAP. The break radius shifts to smaller Galactocentric distance at higher metallicities. Stars in the high [α/Fe] sequence are well represented by a single declining exponential.

Mackereth *et al.* (2017) (also, these proceedings) extend this to MAPs as a function of age, and find that the break radius shifts to smaller Galactocentric distance for older populations. Furthermore, they find that the width of the annuli increase for stars with older ages, and suggest that this is another manifestation of radial migration, with older populations spreading more in Galactocentric radius. See the article by Mackereth in these proceedings for additional information and figures.

7. Other elements and chemical tagging

APOGEE provide abundances of many individual elements, and these may be useful for disentangling populations that may have comparable [Fe/H] and [α/Fe]. This is the basic idea behind "chemical tagging" (Bland-Hawthorn & Freeman (2002)). Here, we draw a distinction between "strong" chemical tagging, in which every star formation site is assumed to have a unique chemical abundance pattern, and "weak" chemical tagging (which has also been called chemical labeling), in which we consider whether there are

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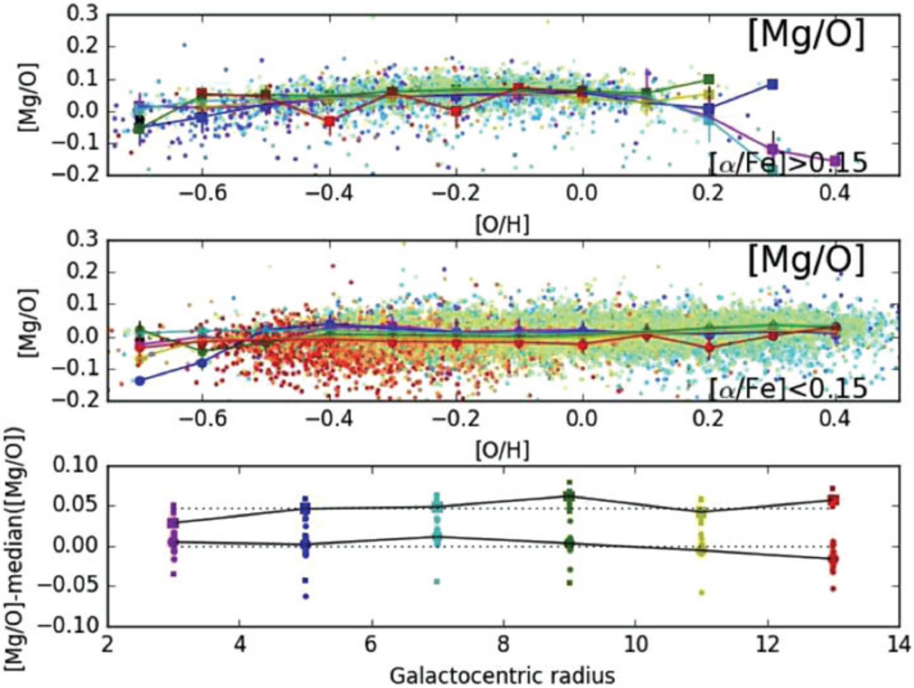

Figure 5. Measured APOGEE [Mg/O] ratios as a function of [O/H]. Top panel shows results for stars with high [α/Fe], while middle panel shows results for stars with low [α/Fe]. Different lines/colors show results for different bins of Galactocentric radii. The median values are plotted in the bottom panel as a function of Galactocentric radius.

systematic variations in abundance ratios across the disk. If such variations exist, then one might imagine using them, for example, to quantify the amount of radial migration by tagging stars in any given location to a birth radius.

Several different studies have addressed the issue of "strong" chemical tagging, both from the point of view of determining whether clusters appear to be chemically homogeneous (e.g., Bovy (2016a), Bertran de Lis *et al.* (2016) for [O/Fe]), as well as whether the APOGEE abundances can be used to disentangle stars from different birth sites (e.g., Hogg *et al.* (2016), Ness *et al.* (2017)). While the latter studies work in abundance space, Price-Jones & Bovy (2017) address the issue through a principal components analysis on the spectra themselves, and find that multiple principal components are required, which in principle means there could be many different chemical cells; however, one need to be careful about instrumental/telluric features in the spectra.

As an initial effort in "weak" tagging, Figure 5 presents some results for the [Mg/O] ratio as a function of metallicity and Galactocentric radius. The top panel shows the [Mg/O]–[Fe/H] relation for stars with high [α/Fe], while the middle shows the relations for stars with low [α/Fe]; different Galactocentric radii are shown in different colors/lines. High [α/Fe] stars clearly have higher [Mg/O] than low [α/Fe] stars. Furthermore, there are hints of very subtle trends in [Mg/O] as a function of Galactocentric radius for stars in a given [α/Fe] sequence (bottom panel). Whether these trends can be used, or are even real, given that there may be differences in the mean [α/Fe] within a sequence at different Galactocentric radius, is the subject of ongoing work.

Given that abundance differences appear to be subtle, tagging individual stars will likely require the simultaneous use of multiple chemical abundances. Figure 6 shows an

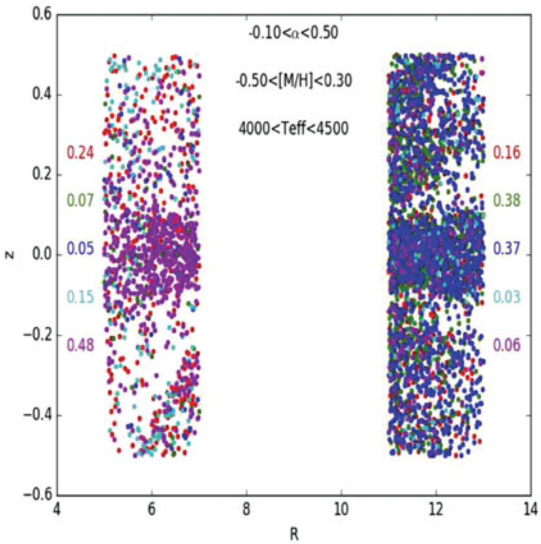

Figure 6. Results of a k-means analysis in multi-element abundance ratio space on a sample of stars drawn from two different radial annuli. The abundance clustering does a good job of distinguishing the annuli, as demonstrated by the dominance of different abundance clusters in the different radial zones (see online version for color).

initial attempt at combining 10 different abundance ratios, but excluding the overall abundance, in a k-means analysis to see whether stars at different Galactocentric radii fall in different regions of multi-abundance space. Here, stars from two different annuli in Galactocentric radii were input into a k-means analysis in which five different groups were identified. Figure 6 shows that these chemical groups separate most of the stars into their present Galactocentric radius, with the suggestion that the stars in "minority" groups at a given location might perhaps be associated with a different birth location. However, it is also possible that some of the abundance ratios are well-correlated with abundance, so that this may just be separating stars by metallicity. As suggested by other participants in the symposium, multi-dimensional analysis is a ripe area for future investigation.

8. Conclusion

The era of chemical cartography is here, with data from APOGEE and other surveys that allows the determination of the distributions of chemical abundances across the Milky Way. Analyses of mean metallicity maps, metallicity distribution functions, [α/Fe] pattern variations, [C/N] variations, age variations, and structural parameters for different subpopulations have been presented by a number of authors. Many of these studies suggest that radial migration plays an important role in the Milky Way.

Many open questions remain including:

- what is the origin of the dual chemical sequences?
- why is duality not seen in structural parameters of different populations?
- how much mixing comes from blurring as opposed to migration that does not preserve the angular momentum of each star?
- what fraction of stars are migrated as a function of location, and what is the distribution of the origin of the migrated fraction?

• what are the underlying abundance patterns at different locations, and what are the implications for variations in SFH, inflow, outflow, and IMF?

• how chemically homogeneous are stars born in a given location?

Chemical cartography and chemical tagging have the potential to address these questions.

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