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Abundances of stars in different Galactic subsystems

Thomas Bensby

Lund Observatory, Department of Astronomy and Theoretical Physics, Box 43, SE-221 00 Lund, Sweden, e-mail: `tbensby@astro.lu.se`

Abstract. This is a brief overview of the elemental abundance patterns that have been observed in the different Galactic stellar populations. Main focus is on studies that are based on high-resolution spectra of dwarf and subgiant stars, and in some cases red giant stars. Of particular interest is the thin-thick disk dichotomy, the variation of abundances and stellar ages with galactocentric radius, multiple stellar populations in the Galactic bulge region, and how some of these may be connected with other Galactic populations.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

The current understanding of our Milky Way galaxy is that it is a grand spiral galaxy containing a multi-population boxy/peanut-shaped bulge (López-Corredoira et al. 2005; Ness et al. 2013), a dual disk system (Gilmore & Reid 1983), and a dual stellar halo (Carollo et al. 2007). Furthermore, there are stellar overdensities and structures in velocity space (e.g., Antoja et al. 2012) as well as in three-dimensional space (e.g., Belokurov et al. 2006). This galactic complexity with different stellar subsystems and different origins hold the secrets and pieces to puzzle on galaxy formation and evolution that slowly is being laid.

It is in recent years that this complex picture of the main Galactic stellar populations (disk, bulge, and halo) has emerged. First, based on star counts towards the Galactic South Pole Gilmore & Reid (1983) found the that the galactic disk contains two disk populations, a thin disk and a thick disk. The thick disk has since then been observed to contain stars that on average are older, more metal-poor, and, at a given metallicity, more α-enhanced than the stars of the thin disk. These differences point to that they are distinct stellar populations with different origins. However, Bovy et al. (2012) claimed that there is no distinct thick disk in the Milky Way, and that the two disks form a continuous sequence of mono-abundance populations with increasing scale-heights. Contradictory, Lee et al. (2011) and Liu & van de Ven (2012) utilised the same data set as used by Bovy et al. (2012) and found two or perhaps even three distinct components of the Galactic disk. As the existence, or non-existence, of distinct thick disks in spiral disks galaxies is an important signature of the galaxy formation scenario (e.g., Minchev et al. 2012), it is crucial to firmly establish the properties of the Galactic disk. Next, the picture of the bulge has changed. A decade ago it was generally believed that the bulge was a classical bulge, originating in the early collapse of the pre-galactic cloud (Eggen et al. 1962), and hence containing only old and metal-rich stars (see, e.g., review by Wyse et al. 1997). Now, most observational evidence indicate that the bulge was formed from disk material, i.e. it is a pseudobulge (see review by Kormendy & Kennicutt 2004), and it has been found to contain a significant fraction of young and intermediate age stars. Lastly, the status of the stellar halo has also changed as well. It now appears as if there is at least two halos, one inner halo and one outer halo, with different chemical as well as kinematical properties (see Nissen & Schuster 1997, 2010; Carollo et al. 2007).

To trace the origins of these structures and stellar subsystems in the Milky Way it is utterly important to have clear pictures of their age, elemental abundance, and velocity distributions. However, kinematic properties may change with time due to gravitational interactions with other stars, gas clouds, and/or spiral arms. Also, a mechanism called radial migration Sellwood & Binney (2002) has in recent years gained a lot of interest, and if real, stars may "ride" on spiral waves and change from one circular orbit to another, and hence destroying the kinematical signatures of its formation. Instead, a stellar property that remain untouched through the history of the Galaxy is the atmospheric chemical composition of low-mass stars. In particular, relatively un-evolved F and G type stars on the main sequence, turn-off, or subgiant branch have lifetimes exceeding the age of the galaxy, during which their atmospheres remain intact and trace the chemical composition of the gas clouds they formed from. These types of stars have therefore been extensively used during the last decades to map the abundance structure of the disk and halo in the Solar neighbourhood (Edvardsson et al. 1993; Fuhrmann 1998; Reddy et al. 2003; Bensby et al. 2003). These types of stars have, however, a major drawback, and that is that they are intrinsically faint and cannot under normal circumstances be studied at large distances with high-resolution spectrographs. In order to study the abundance distribution at larger scales in the Galaxy one therefore turn to brighter stars, such as red giant stars.

I current era of large scale spectroscopic surveys, aiming at mapping the Galactic disk, halo, and even the bulge, several kpc from the Sun with hundreds of thousands of stars, it is of course impossible to constrain the star samples to un-evolved stars dwarf stars. Surveys such as GALAH (Zucker et al. 2012) and APOGEE (Allende Prieto et al. 2008) therefore mainly target red giants stars and aim to obtain relatively high S/N spectra. The Gaia-ESO survey (Gilmore et al. 2012), on the other hand, is mainly targeting the turn-off region, and will have to settle with the fact that the obtained spectra can have somewhat lower S/N. This will present a challenge to the analysis, that has to be carefully done and anchored, using stars with known properties, so called benchmark stars. It is also important to have good comparison samples, tracing different Galactic populations, analysed from high-resolution and high signal-to-noise spectra. In this paper I will give a brief overview of the abundance structure observed in the Galactic disk and bulge.

2. The solar neighbourhood disk

The part of the Galaxy that has been best mapped is the Solar neighbourhood. Following the seminal study by Edvardsson et al. (1993), Fuhrmann (1998) presented the first in a series of papers aimed at producing an unbiased volume-complete sample for all mid F-type to early K-type stars down to absolute magnitude $M_V = 6$, north of declination $-15°$, within a radius of 25 pc from the Sun. Thirteen years later this sample was 85 % complete and contained more than 300 solar type stars (Fuhrmann 2011). What Fuhrmann found was that that the sample divided roughly into two types of stars; one with stars that were old and that had high [Mg/Fe] abundance ratios, and one where the stars where young and that had low [Mg/Fe] abundance ratios. Most of the old stars were classified as thick disk stars while the young stars were classified as thin disk stars. In the [Mg/Fe]-[Fe/H] plane these two groups showed extremely well-defined and distinct abundance trends, with the thick disk stars laying on an elevated and flat [Mg/Fe] plateau ranging from [Fe/H] $\approx$ −0.9 up to [Fe/H] $\approx$ −0.25. The thin disk abundance trends were offset from the thick disk trends and showed a shallow decline in [Mg/Fe] from [Fe/H] $\approx$ −0.6 up to [Fe/H] $\approx$ +0.4. Only 15 of the more than 300 stars in the Fuhrmann studies were classified as thick disk stars, and it is clear that in order to really probe the abundance trends of the Galactic thick disk one has to extend to slightly larger distances.

The best strategy would of course be to observe thick disk stars where the thick disk is the dominating population. With current estimates of scale-heights and stellar density normalisations in the plane, one has to go distances of 1-2 kpc from the plane in order to obtain a sample that is dominated by thick disk stars. However, at these distances F and G dwarf stars have apparent magnitudes fainter than $V \approx 15$ and it is no longer feasible to obtain high-resolution and high signal-to-noise spectra for large samples. Instead, a convenient way to identify potential thick disk candidates for high-resolution spectroscopic observations is through kinematical selection criteria. These relies on the assumption that the velocity distributions of the different stellar populations have Gaussian distributions, that the average rotation velocities around the Galactic centre are different, and that they occupy certain fractions of the stellar density in the Galactic plane. Applying the kinematic criteria defined in Bensby et al. (2003) to the 16 000 stars in the Geneva-Copenhagen survey (GCS) by Nordström et al. (2004) around 500 stars have kinematic properties classifying them as candidate thick disk stars. Many of those stars have metallicities well above solar values (see, e.g., Bensby et al. 2013a).

Feltzing et al. (2003) and Bensby et al. (2003) showed that kinematically selected thick disk stars most likely reach higher [Fe/H] than observed by the Fuhrmann (1998) and that the signature of chemical enrichment from supernovae type Ia shows up as a downturn (the "knee") in the thick disk α-to-iron abundance trends. Other studies have also utilised kinematical criteria to define thick disk star samples and find similar results (e.g., Reddy et al. 2003, 2006; Soubiran et al. 2003; Bensby et al. 2004, 2005), and Bensby et al. (2007) showed that the thick disk reaches at least solar metallicities. A similar dichotomy has also been found by Adibekyan et al. (2012) that analysed the HARPS sample that initially was observed to detect exoplanets. The most recent study is Bensby et al. (2013a) who has selected a sample of 714 nearby F and G dwarf and subgiant in order to trace the extremes of the different Galactic stellar populations: the metal-poor limit of the thin disk, the metal-rich and metal-poor limits of the thick disk, the metal-rich limit of the halo, structures in velocity space such as the Hercules stream and the Arcturus moving group, and stars that have kinematical properties placing them in between the thin and thick disks. Among other things they show that kinematical selection criteria produce a lot of mixing between selected samples. A kinematically selected thick disk sample is polluted by high-velocity thin disk stars, and a kinematically selected thin disk sample is polluted by low-velocity thick disk stars. A better discriminator appears to be stellar ages, and a good dividing age between the thin and thick disk appears to be around 8 Gyr (see also Haywood et al. 2013). Unfortunately, as stellar ages at high precision are notoriously difficult to estimate, the large age uncertainties is likely to produce a mixing between age-selected thin and thick disk samples of the same magnitude as between kinematically selected samples. Bensby et al. (2013a) also show that the distinction between the thin and thick disk abundance trends becomes much clearer if stars that are coupled to higher uncertainties in the abundance ratios are rejected.

In summary, high-resolution and high signal-to-noise spectroscopic studies of solar-type dwarf stars in the Solar neighbourhood shows an abundance dichotomy in the Galactic disk, and that this dichotomy is associated with two different stellar populations that appear to be separated in time. The question is if this dichotomy persists if we move away from the immediate solar neighbourhood?

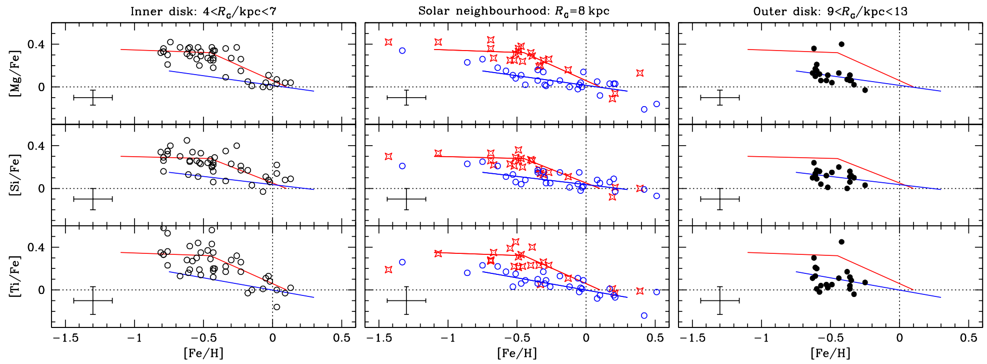

Fig. 1. Abundance trends for the α-elements Mg, Si, and Ti. The left panel shows the 44 inner disk red giants from Bensby et al. (2010), the centre panel shows the solar neighbourhood thin and thick disk stars (blue circles and red stars, respectively) by Alves-Brito et al. (2010). The right panel shows the 20 outer disk red giants from Bensby et al. (2011). The red and blue lines in the abundance plots are fiducial lines based on the solar neighbourhood abundance trends. Figure is taken from Bensby et al. (2011).

3. Inner and outer disk

Beyond the Solar neighbourhood the Galactic disk is sparsely studied. There are some studies in the inner disk of young bright O and B type stars (e.g., Daflon & Cunha 2004) and Cepheids (e.g., Luck et al. 2006), that both trace the chemical composition of the present day Galactic disk. The outer disk has been somewhat better studied using stars in open clusters (e.g., Yong et al. 2005; Carraro et al. 2007; Jacobson et al. 2011), O and B type stars (e.g., Daflon & Cunha 2004; Daflon et al. 2004), as well as Cepheids (e.g., Andrievsky et al. 2004; Yong et al. 2006), which all are tracers of relatively young populations. Field red giants, that can trace older populations, were observed by Carney et al. (2005), but their sample only contained three stars.

The situation was improved with the studies by Bensby et al. (2010) and Bensby et al. (2011) that presented detailed elemental abundances in 44 red giants in the inner disk and 20 red giants in the outer disk. The inner disk sample spans galactocentric radii 3 to 7 kpc, and the outer disk sample galactocentric radii 9 to 12 kpc. The stars of both the inner and outer disk samples are located up to 3 to 4 kpc from the plane and should trace both the thin and thick disk abundance trends if present at these locations in the Galaxy.

Figure 1 shows a comparison of the abundance trends as traced by the in situ red giant stars in the inner and outer disks from Bensby et al. (2010) and Bensby et al. (2011), to the local thin and thick disk abundance trends, as traced by red giant stars, from Alves-Brito et al. (2010). First, it is evident that the local red giant comparison sample shows the characteristic thin and thick disk abundance trends as seen by the local dwarf studies cited in the previous section. In the left panels of Fig. 1 we then see that the inner disk red giant sample occupy the region in abundance space where thin and thick disk stars are found in the solar neighbourhood, however with a deficiency of stars in the metal-poor "thin disk abundance region" below [Fe/H] ≈ -0.2. The outer disk red giant sample, on the other hand, shows a completely different abundance pattern. Essentially no one of the 20 outer disk stars, which are located up to 2 kpc from the plane (and one even 6 kpc from the plane), seem to have an abundance pattern resembling what is seen in the local thick disk. Instead they occupy a rather narrow metallicity regime around [Fe/H] ≈ -0.5, and none (or maybe one or two for Mg and Ti) show elevated α-to-iron abundance ratios. Bensby et al. (2011) interpreted the lack

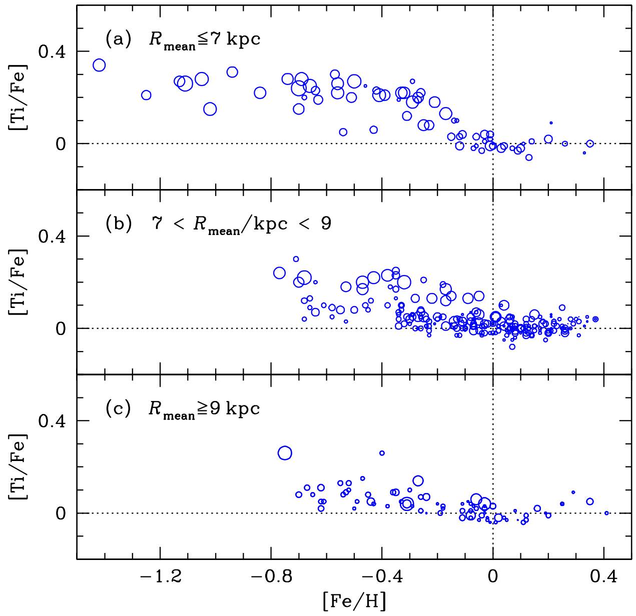

Fig. 2. [Ti/Fe]-[Fe/H] abundance trends for stars with different $R_{\rm mean}$. Only stars for which he difference between the upper and lower age estimates is less than 4 Gyr are included. The sizes of the circles have been scaled with the ages of the stars. Figure is taken from Bensby et al. (2013a).

of "thick disk stars" in the outer disk as being due to that the thick disk scale-length is shorter than that of the thin disk. Jurić et al. (2008) had previously estimated the thick disk scale-length to be 3.6 kpc and that of the thin disk to be 2.6 kpc. New estimates from Bensby et al. (2011) was 2.0 kpc for the thick disk, and 3.8 kpc for the thin disk, i.e., quite the opposite behaviour, meaning that the thick disk stellar density drops of much more quickly with galactocentric radius than the thin disk stellar density. The short scale-length for the thick disk has later been confirmed by Cheng et al. (2012) who based on the SDSS Segue G dwarf sample found scale-lengths of 3.4 kpc and 1.8 kpc for the thin and thick disks, respectively. A short thick disk scale-length is now also required in dynamical models of the Galaxy to match the observations (e.g., Binney & Sanders 2013) .

The lack of α-enhanced stars in the outer disk is also evident from the local sample of 700 F and G dwarf stars from Bensby et al. (2013a). Figure 2 shows the [Ti/Fe]-[Fe/H] trends for three subsamples, separated into three bins of the mean orbital galactocentric distance ($R_{\rm mean} \equiv (R_{\rm min} + R_{\rm max})/2$) and it is clear that old and α-enhanced stars with $R_{\rm mean} > 9$ kpc is lacking. We furthermore note that results from the first year of APOGEE data confirm the lack of α-enhanced stars in the outer disk (Anders et al. 2013).

In summary, the thin and thick disk dichotomy as observed in the solar neighbourhood is also present in the inner disk, although with a different relative contributions than observed at the solar radius. At the solar radius, in the Galactic plane the thick disk is around 10 %, but as a result of the short scale-length it increases when going to shorter galactocentric radii and decreases when going to larger radii. In a way, the thick disk appears to be truncated at, or slightly beyond, the solar radius.

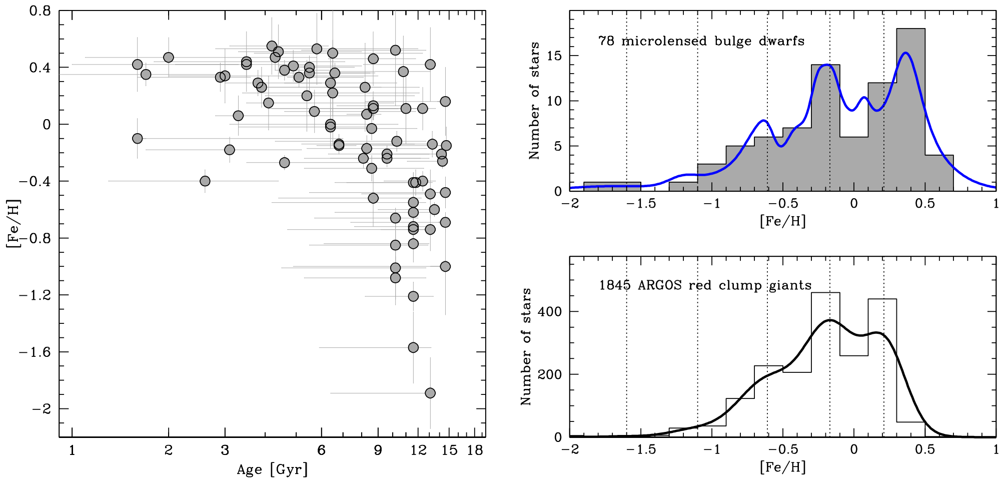

Fig. 3. Left-hand plot shows the age-metallicity diagram for the now in total 78 microlensed bulge dwarf and subgiant stars (58 microlensed dwarf stars from Bensby et al. (2013b), as well as 20 new stars from Bensby et al. (2014, in prep.)). Right-hand plot shows the metallicity distribution for the microlensed dwarf stars. Also shown is the MDF for 1845 red giant stars from the ARGOS survey fields at $(l, b) = (0, 5), (5, -5), (-5, -5)$ from Ness et al. (2013). The curved lines represent generalised histograms, and the dotted vertical lines mark the peaks claimed by Ness et al. (2013).

4. Bulge

Since the study by McWilliam & Rich (1994) who presented the first detailed elemental abundance study of red giants in Baade's window, the chemical evolution of the bulge has been extensively studied using red giants (e.g. Zoccali et al. 2006; Fulbright et al. 2007; Lecureur et al. 2007). These studies all showed that the α-to-iron abundance ratios were elevated even at super-solar metallicities, meaning that the bulge had experienced a very fast chemical enrichment, much faster than in any of the other stellar populations. As most of the large Solar neighbourhood studies had utilised dwarf stars comparisons had to be made between disk dwarfs and bulge giants. This changed with Meléndez et al. (2008) who did a differential analysis between bulge giants (including a re-analysis of the Fulbright et al. 2007 sample) and local thin and thick disk giants. They did not find the high α-element abundance levels at super-solar metallicities, but instead that the bulge abundance trends compared very well with what was observed in local thick disk red giants. Recent studies of red giant star samples in the bulge confirm these results (e.g., Babusiaux et al. 2010; Ryde et al. 2010; Hill et al. 2011; Gonzalez et al. 2011).

A new window to study the abundance structure of the Galactic bulge opened with the advent of microlensing surveys such as OGLE (Udalski et al. 1994) and MOA (Bond et al. 2001) that both have early warning systems that alert when new microlensing events occur, and when they will reach peak brightness. If the un-lensed magnitude of the background source is consistent with a dwarf star located at a distance of 8 kpc in the bulge, and if the peak magnification is sufficient, it is possible to obtain a high signal-to-noise high-resolution spectrum with 1-2 hours integration with the current generation of 8-10 m telescopes. The first detailed abundance analysis of a dwarf star in the bulge based on a high-resolution spectrum obtained during a microlensing event was presented by Johnson et al. (2006). Since then we have conducted an intense observing campaign, mainly through a target-of-opportunity program with UVES at VLT. Adding 20 new targets from the 2013 season to the 58 targets published in Bensby et al. (2013b) the sample currently consists of 78 dwarf and subgiants in the bulge (Bensby et al., 2014, in prep).

A comparison between the 58 bulge dwarfs in Bensby et al. (2013b) and the 700 nearby dwarf stars in Bensby et al. (2013a) confirms the similarities between the bulge and thick disk abundance trends. There are indications that position of the knee in the bulge α-to-iron abundance trends occur at a slightly higher metallicity (about 0.05 dex) than for the thick disk, indicating the possibility that the bulge experienced a slightly faster chemical enrichment history (Bensby et al. 2013b).

With the microlensed bulge dwarf it has also been possible to determine ages for individual stars in the bulge. The age-metallicity diagram in Fig. 3, containing all to date 78 microlensing events, shows that the bulge contain a significant fraction of young and intermediate age stars. This is contradiction with the old bulge claimed by studies of the colour magnitude diagram in different bulge fields (e.g., Zoccali et al. 2003; Clarkson et al. 2008). As was shown in Bensby et al. (2013b) a metal-poor and old isochrone is very hard to distinguish from a metal-rich and young isochrone. If the metallicities of individual stars are not know, which is the case in most photometric studies, the CMDs will show an apparent old turn-off.

In addition, results from the ARGOS survey claim multiple components in the bulge metallicity distribution (Ness et al. 2013). Now when statistics for the microlensed dwarfs are starting to build up, the components claimed by Ness et al. (2013) are evident also there (see Fig. 3). In combination with the results from the BRAVA survey, showing that the bulge has cylindrical rotation (Kunder et al. 2012), there is very little room left for a classical collapse population in the Galactic bulge. Instead it appears as if the bulge is the central region of the Milky Way where the other Galactic stellar populations meet and overlap.

5. Outlook

The ongoing large spectroscopic surveys (e.g., Gaia-ESO, GALAH, and APOGEE) in conjunction with astrometric data from the upcoming Gaia satellite will provide a gold mine for Galactic archaeology and our understanding for the origin and evolution of the Milky Way.

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