Structure and Evolution of the Milky Way

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Abstract This review discusses the structure and evolution of the Milky Way, in the context of opportunities provided by asteroseismology of red giants. The review is structured according to the main Galactic components: the thin disk, thick disk, stellar halo, and the Galactic bar/bulge. The review concludes with an overview of Galactic archaeology and chemical tagging, and a brief account of the upcoming HERMES survey with the AAT.

1 The Thin Disk: Formation and Evolution

Here are some of the issues related to the formation and evolution of the Galactic thin disk:

- Building the thin disk: its exponential radial structure, and the role of mergers.
- The star formation history: chemical evolution and continued gas accretion.
- Evolutionary processes in the disk: disk heating, radial mixing.
- The outer disk: chemical properties and chemical gradients.

Many of the basic observational constraints on the properties of the Galactic disk are still uncertain. At this time, we do not have reliable information about the star formation history of the disk. We do not know how the metallicity distribution and the stellar velocity dispersions in the disk have evolved with time. One might have expected that these observational questions were well understood by now, but this is not yet so. The basic observational problem is the difficulty of measuring ages for individual stars.

The younger stars of the Galactic disk show a clear abundance gradient of about 0.07 dex kpc$^{-1}$, outlined nicely by the cepheids (Luck et al., 2006). In the outer disk, for the older stars, the abundance gradient appears to be even stronger: the
abundance gradient (and the gradient in the ratio of alpha-elements to Fe) have flattened with time towards the solar values. A striking feature of the radial abundance gradient in the Galaxy is that it flattens for $R > 12$ kpc at an [Fe/H] value of about -0.5 (Carney et al., 2005). A similar flattening of the abundance gradient is seen in the outer regions of the disk of M31 (Worthey et al., 2005).

The relation between the stellar age and the mean metallicity and velocity dispersion are the fundamental observables that constrain the chemical and dynamical evolution of the Galactic thin disk. The age-metallicity relation (AMR) in the solar neighborhood is still uncertain. Different authors find different relations, ranging from a relatively steep decrease of metallicity with age from Rocha-Pinto et al. (2004) to almost no change of mean metallicity with age from Nordström et al. (2004). Much of the earlier work indicated that a large scatter in metallicity was seen at all ages, which was part of the motivation to invoke large-scale radial mixing of stars within the disk. This mixing, predicted by Sellwood & Binney (2002), is generated by resonances with the spiral pattern, and is able to move stars from one near-circular orbit to another. It would bring stars from the inner and outer disks, with their different mean abundances, into the solar neighborhood. Radial mixing is potentially an important feature of the evolution of the disk. At this stage, it is a theoretical concept, and it is not known how important it is in the Galactic disk. We are not aware of any strong observational evidence at this stage for the existence of radial mixing. More recent results on the AMR (e.g. Wylie de Boer et al., unpublished) indicate that there is a weak decrease of mean metallicity with age in the Galactic thin disk, but that the spread in metallicity at any age is no more than about 0.10 dex. If this is correct, then radial mixing may not be so important for chemically mixing the Galactic disk.

The age-velocity dispersion relation (AVR) is also not well determined observationally. The velocity dispersion of stars appears to increase with age, and this is believed to be due to the interaction of stars with perturbers such as giant molecular clouds and transient spiral structure. But there is a difference of opinion about the duration of this heating. One view is that the stellar velocity dispersion $\sigma$ increases steadily for all time, $\sim t^{0.2-0.5}$, based on Wielen (1977)'s work using chromospheric ages and kinematics for the McCormick dwarfs. Another view (e.g. Quillen & Garnett, 2000), based on the data for subgiants from Edvardsson et al. (1993) is that the heating takes place for the first $\sim 2$ Gyr, but then saturates when $\sigma \approx 20$ km s$^{-1}$ because the stars of higher velocity dispersion spend most of their orbital time away from the Galactic plane where the sources of heating lie. Data from Soubiran et al. (2008) support this view. Again, much of the difference in view goes back to the difficulty of measuring stellar ages. Accurate ages from asteroseismology would be very welcome. Accurate ages and distances for a significant sample of red giants would allow us to measure the AMR and AVR out to several kpc from the Sun. This would be a great step forward in understanding the chemical and dynamical evolution of the Galactic disk.
2 The Formation of the Thick Disk

Most spiral galaxies, including our own, have a second thicker disk component. For example, the thick disk and halo of the edge-on spiral galaxy NGC 891, which is much like the Milky Way in size and morphology, has a thick disk nicely seen in star counts from HST images (Mouhcine et al., 2010). Its thick disk has scale height \( \sim 1.4 \) kpc and scalelength \( \sim 4.8 \) kpc, much as in our Galaxy. The fraction of baryons in the thick disk is typically about 10 to 15 percent in large systems like the Milky Way, but rises to about 50% in the smaller disk systems (Yoachim & Dalcanton, 2008).

The Milky Way has a significant thick disk, discovered by Gilmore & Reid (1983). Its vertical velocity dispersion is about 40 km s\(^{-1}\); its scale height is still uncertain but is probably about 1000 pc. The surface brightness of the thick disk is about 10% of the thin disk’s, and near the Galactic plane it rotates almost as rapidly as the thin disk. Its stars are older than 10 Gyr and are significantly more metal poor than the stars of the thin disk; most of the thick disk stars have [Fe/H] values between about \(-0.5\) and \(-1.0\) and are enhanced in alpha-elements relative to Fe. This is usually interpreted as evidence that the thick disk formed rapidly, on a timescale \( \sim 1 \) Gyr. From its kinematics and chemical properties, the thick disk appears to be a discrete component, distinct from the thin disk. Current opinion is that the thick disk shows no vertical abundance gradient (e.g. Gilmore et al., 1995; Ivezić et al., 2008).

The old thick disk is a very significant component for studying Galaxy formation, because it presents a kinematically and chemically recognizable relic of the early Galaxy. Secular heating is unlikely to affect its dynamics significantly, because its stars spend most of their time away from the Galactic plane.

How do thick disks form? Several mechanisms have been proposed, including:

- thick disks are a normal part of early disk settling, and form through energetic early star forming events, e.g. in gas-rich mergers (Samland & Gerhard, 2003; Brook et al., 2004)
- thick disks are made up of accretion debris (Abadi et al., 2003). From the mass-metallicity relation for galaxies, the accreted galaxies that built up the thick disk of the Galaxy would need to be more massive than the SMC to get the right mean [Fe/H] abundance (\( \sim -0.7 \)). The possible discovery of a counter-rotating thick disk (Yoachim & Dalcanton, 2008) in an edge-on galaxy would favor this mechanism.
- thick disks come from the heating of the thin disk via disruption of its early massive clusters (Kroupa, 2002). The internal energy of large star clusters is enough to thicken the disk. Recent work on the significance of the high redshift clump structures may be relevant to the thick disk problem: the thick disk may originate from the merging of clumps and heating by clumps (e.g. Bournaud et al., 2009). These clumps are believed to form by gravitational instability from turbulent early disks: they appear to generate thick disks with scale heights that are
radially approximately uniform, rather than the flared thick disks predicted from minor mergers.

- thick disks come from early partly-formed thin disks, heated by accretion events such as the accretion event which is believed to have brought omega Centauri into the Galaxy \cite{BekkiFreeman2003}. In this picture, thin disk formation began early, at $z = 2$ to 3. The partly formed thin disk is partly disrupted during the active merger epoch which heats it into thick disk observed now. The rest of the gas then gradually settles to form the present thin disk, a process which continues to the present day.
- a recent suggestion is that stars on more energetic orbits migrate out from the inner galaxy to form a thick disk at larger radii where the potential gradient is weaker \cite{SchonrichBinney2009}.

How can we test between these possibilities for thick disk formation? Sales et al. \cite{Sales2009} looked at the expected orbital eccentricity distribution for thick disk stars in different formation scenarios. Their four scenarios are:

- a gas-rich merger: the thick disk stars are born in-situ
- the thick disk stars come in from outside via accretion
- the early thin disk is heated by accretion of a massive satellite
- the thick disk is formed as stars from the inner disk migrate out to larger radii.

Preliminary results from the observed orbital eccentricity distribution for thick disk stars may favor the gas-rich merger picture \cite{Wilson2011}. This is a potentially powerful approach for testing ideas about the origin of the thick disk. Because it depends on the orbital properties of the thick disk sample, firm control of selection effects is needed in the identification of which stars belong to the thick disk. Kinematical criteria for choosing the thick disk sample are clearly not ideal.

To summarize this section on the thick disk: Thick disks are very common in disk galaxies. In our Galaxy, the thick disk is old, and is kinematically and chemically distinct from the thin disk. It is important now to identify what the thick disk represents in the galaxy formation process. The orbital eccentricity distribution of the thick disk stars will provide some guidance. Chemical tagging will show if the thick disk formed as a small number of very large aggregates, or if it has a significant contribution from accreted galaxies. This is one of the goals for the upcoming AAT/HERMES survey: see section 5.

### 3 The Galactic Stellar Halo

The stars of the Galactic halo have [Fe/H] abundances mostly less than -1.0. Their kinematics are very different from the rotating thick and thin disks: the mean rotation of the stellar halo is close to zero, and it is supported against gravity primarily by its velocity dispersion. It is now widely believed that much of the stellar halo comes from the debris of small accreted satellites \cite{SearleZinn1978}. There remains a possibility that a component of the halo formed dissipationally during the
Galaxy formation process (Eggen et al., 1962; Samland & Gerhard, 2003). Halo-building accretion events continue to the present time: the disrupting Sgr dwarf is an example in our Galaxy, and the faint disrupting system around NGC 5907 is another example of such an event (Martínez-Delgado et al., 2010). The metallicity distribution function (MDF) of the major surviving satellites around the Milky way is not like the MDF in the stellar halo (e.g. Venn & Hill, 2008) but the satellite MDFs may have been more similar long ago. We note that the fainter satellites are more metal-poor and are consistent with the Milky Way halo in their [$\alpha$/Fe] behaviour.

Is there a halo component that formed dissipationally early in the Galactic formation process? Hartwick (1987) showed that the metal-poor RR Lyrae stars delineate a two-component halo, with a flattened inner component and a spherical outer component. Carollo et al. (2010) identified a two-component halo and the thick disk in a sample of 17,000 SDSS stars, mostly with $[\text{Fe/H}] < -0.5$. They described the kinematics well with these three components:

- **Thick disk**: $(\bar{V}, \sigma, [\text{Fe/H}]) = (182, 51, -0.7)$
- **Inner halo**: $(\bar{V}, \sigma, [\text{Fe/H}]) = (7, 95, -1.6)$
- **Outer halo**: $(\bar{V}, \sigma, [\text{Fe/H}]) = (-80, 180, -2.2)$

Here $[\text{Fe/H}]$ is the mean abundance for the component, $\bar{V}$ and $\sigma$ are its mean rotation velocity relative to a non-rotating frame, and velocity dispersion, in km s$^{-1}$. The outer halo appears to have retrograde mean rotation. As we look at subsamples at greater distances from the Galactic plane, we see that the thick disk dies away and the retrograde outer halo takes over from the inner halo. With the above kinematic parameters, the equilibrium of the inner halo is a bit hard to understand. It may not yet be in equilibrium. From comparison with simulations, Zolotov et al. (2009) argue that the inner halo has a partly dissipational origin, while the outer halo is made up from debris of faint metal-poor accreted satellites.

Recently Nissen & Schuster (2010) studied a sample of 78 halo stars with $[\text{Fe/H}] > -1.6$ and find that they show a variety of [$\alpha$/Fe] enhancement. Their sample shows high and low [$\alpha$/Fe] groups, and the low [$\alpha$/Fe] stars are mostly in high energy retrograde orbits. The high [$\alpha$/Fe] stars could be ancient halo stars born in situ and possible heated by satellite encounters. The low-alpha stars may be accreted from dwarf galaxies.

How much of the halo comes from accreted structures? An ACS study by Ibata et al. (2009) of the halo of NGC 891 (a nearby edge-on galaxy like the Milky Way) shows a spatially lumpy metallicity distribution, indicating that its halo is made up largely of accreted structures which have not yet mixed away. This is consistent with simulations of stellar halos by Font et al. (2008), Gilbert et al. (2009) and Cooper et al. (2010).

To summarize this section on the Galactic stellar halo: the stellar halo is probably made up mainly of the debris of small accreted galaxies, although there may be an inner component which formed dissipatively.
The boxy appearance of the Galactic bulge is typical of galactic bars seen edge-on. These bar/bulges are very common: about 2/3 of spiral galaxies show some kind of central bar structure in the infra-red. Where do these bar/bulges come from?

Bars can arise naturally from the instabilities of the disk. A rotating disk is often unstable to forming a flat bar structure at its center. This flat bar in turn is often unstable to vertical buckling which generates the boxy appearance. This kind of bar/bulge is not generated by mergers but follows simply from the dynamics of a flat rotating disk of stars. The maximum vertical extent of boxy or peanut-shaped bulges occurs near the radius of the vertical and horizontal Lindblad resonances, i.e.

\[ \Omega_b = \Omega - \frac{\kappa}{2} = \Omega - \frac{\nu_z}{2} \]

Here \( \Omega \) is the circular angular velocity, \( \Omega_b \) is the pattern speed of the bar, \( \kappa \) is the epicyclic frequency and \( \nu_z \) is the vertical frequency of oscillation. We note that the frequencies \( \kappa \) and particularly \( \nu_z \) depend on the amplitude of the oscillation. Stars in this zone oscillate on 3D orbits which support the peanut shape.

We can test whether the Galactic bulge formed through this kind of bar-buckling instability of the inner disk, by comparing the structure and kinematics of the bulge with those of N-body simulations that generate a boxy/bar bulge (e.g. Athanassoula, 2005). The simulations show an exponential structure and near-cylindrical rotation: do these simulations match the properties of the Galactic bar/bulge?

The stars of the Galactic bulge appear to be old and enhanced in \( \alpha \)-elements. This implies a rapid history of star formation. If the bar formed from the inner disk, then it would be interesting to know whether the bulge stars and the stars of the adjacent disk have similar chemical properties. This is not yet clear. There do appear to be similarities in the \( \alpha \)-element properties between the bulge and the thick disk in the solar neighborhood (e.g. Meléndez et al., 2008).

The bar-forming and bar-buckling process takes 2-3 Gyr to act after the disk settles. In the bar-buckling instability scenario, the bulge structure is probably younger than the bulge stars, which were originally part of the inner disk. The alpha-enrichment of the bulge and thick disk comes from the rapid chemical evolution which took place in the inner disk before the instability acted. In this scenario, the stars of the bulge and adjacent disk should have similar ages: accurate asteroseismology ages for giants of the bulge and inner disk would be a very useful test of the scenario.

We are doing a survey of about 28,000 clump giants in the Galactic bulge and the adjacent disk, to measure the chemical properties (Fe, Mg, Ca, Ti, Al, O) of stars in the bulge and adjacent disk: are they similar, as we would expect if the bar/bulge grew out of the disk? We use the AAOmega fiber spectrometer on the AAT, to acquire medium-resolution spectra of about 350 stars at a time, at a resolution \( R \sim 12,000 \).

The central regions of our Galaxy are not only the location of the bulge and inner disk, but also include the central regions of the Galactic stellar halo. Recent simu-
lations (e.g. Diemand et al. 2005, Moore et al. 2006, Brook et al. 2007) indicate that the metal-free (population III) stars formed until redshift $z \sim 4$, in chemically isolated subsystems far away from the largest progenitor. If its stars survive, they are spread throughout the Galactic halo. If they are not found, then it would be likely that their lifetimes are less than a Hubble time which in turn implies a truncated IMF. On the other hand, the oldest stars form in the early rare high density peaks that lie near the highest density peak of the final system. They are not necessarily the most metal-poor stars in the Galaxy. Now, these oldest stars are predicted to lie in the central bulge region of the Galaxy. Accurate asteroseismology ages for metal-poor stars in the inner Galaxy would provide a great way to tell if they are the oldest stars or just stars of the inner Galactic halo. This test would require a $\sim 10\%$ precision in age.

Our data so far indicate that the rotation of the Galactic bulge is close to cylindrical (see also Howard et al. 2009). Detailed analysis will be needed to see if there is any evidence for a small classical merger generated bulge component, in addition to the boxy/peanut bar/bulge which probably formed from the disk. We also see a more slowly rotating metal-poor component in the bulge region. The problem now is to identify the first stars from among the expected metal-poor stars of the inner halo.

5 Galactic Archaeology

The goals of Galactic Archaeology are to find signatures or fossils from the epoch of Galaxy assembly, to give us insight into the processes that took place as the Galaxy formed. A major goal is to identify observationally how important mergers and accretion events were in building up the Galactic disk, bulge and halo of the Milky Way. CDM simulations predict a high level of merger activity which conflicts with some observed properties of disk galaxies, particularly with the relatively common nature of large galaxies like ours with small bulges (e.g. Kormendy et al. 2010).

The aim is to reconstruct the star-forming aggregates and accreted galaxies that built up the disk, bulge, and halo of the Galaxy. Some of these dispersed aggregates can still be recognized kinematically as stellar moving groups. For others, the dynamical information was lost through heating and mixing processes, but their debris can still be recognized by their chemical signatures (chemical tagging). We would like to find groups of stars, now dispersed, that were associated at birth either

- because they were born together and therefore have almost identical chemical abundances over all elements (e.g. De Silva et al. 2009), or
- because they came from a common accreted galaxy and have abundance patterns that are clearly distinguished from those of the Galactic disk (e.g. Venn & Hill 2008).

The galactic disk shows kinematical substructure in the solar neighborhood: groups of stars moving together, usually called moving stellar groups. Some are
associated with dynamical resonances (e.g. the Hercules group): in such groups, we do not expect to see chemical homogeneity or age homogeneity (e.g. Bensby et al., 2007). Others are the debris of star-forming aggregates in the disk (e.g. the HR1614 group and Wolf 630 group). They are chemically homogeneous, and such groups could be useful for reconstructing the history of the galactic disk. Yet others may be debris of infalling objects, as seen in CDM simulations (e.g. Abadi et al., 2003).

The stars of the HR 1614 group appear to be the relic of a dispersed star-forming event. These stars have an age of about 2 Gyr and [Fe/H] = +0.2, and they are scattered all around us. This group has not lost its dynamical identity despite its age. De Silva et al. (2007) measured accurate differential abundances for many elements in HR 1614 stars, and found a very small spread in abundances. This is encouraging for recovering dispersed star forming events by chemical tagging.

Chemical studies of the old disk stars in the Galaxy can help to identify disk stars which came in from outside in disrupting satellites, and also those that are the debris of dispersed star-forming aggregates like the HR 1614 group (Freeman & Bland-Hawthorn, 2002). The chemical properties of surviving satellites (the dwarf spheroidal galaxies) vary from satellite to satellite, but are different in detail from the overall chemical properties of the disk stars.

We can think of a chemical space of abundances of elements: O, Na, Mg, Al, Ca, Mn, Fe, Cu, Sr, Ba, Eu for example. Not all of these elements vary independently. The dimensionality of this space chemical space is probably between about 7 and 9. Most disk stars inhabit a sub-region of this space. Stars that come from dispersed star clusters represent a very small volume in this space. Stars which came in from satellites may have a distribution in this space that is different enough to stand out from the rest of the disk stars. With this chemical tagging approach, we hope to detect or put observational limits on the satellite accretion history of the galactic disk.

Chemical studies of the old disk stars in the Galaxy can identify disk stars that are the debris of common dispersed star-forming aggregates. Chemical tagging will work if

- stars form in large aggregates, which is believed to be true
- aggregates are chemically homogenous
- aggregates have unique chemical signatures defined by several elements or element groups which do not vary in lockstep from one aggregate to another. We need sufficient spread in abundances from aggregate to aggregate so that chemical signatures can be distinguished with accuracy achievable (∼ 0.05 dex differentially)

de Silva’s work on open clusters was aimed at testing the last two conditions: they appear to be true. See De Silva et al. (2009) for more on chemical tagging.

We should stress here that chemical tagging is not just assigning stars chemically to a particular population, like the thin disk, thick disk or halo. Chemical tagging is intended to assign stars chemically to substructure which is no longer detectable kinematically. We are planning a large chemical tagging survey of about a million stars, using the new HERMES multi-object spectrometer on the AAT. The goal is to
reconstruct the dispersed star-forming aggregates that built up the disk, thick disk and halo within about 5 kpc of the sun.

HERMES is a new high resolution multi-object spectrometer on the AAT. Its spectral resolution is about 28,000, with a high resolution mode with $R = 50,000$. It is fed by 400 fibers over a 2-degree field, and has 4 non-contiguous wavelength bands covering a total of about 1000Å. The four wavelength bands were chosen to include measurable lines of elements needed for chemical tagging. HERMES is scheduled for first light in late 2012. The HERMES chemical tagging survey will include stars brighter than $V = 14$ and has a strong synergy with Gaia: for the dwarf stars in the HERMES sample, the accurate (1%) parallaxes and proper motions will be invaluable for more detailed studies.

The fractional contribution of the different Galactic components to the HERMES sample will be about 78% thin disk stars, 17% thick disk stars and about 5% halo stars. About 70% of the stars will be dwarfs within about 1000 pc and 30% giants within about 5 kpc. About 9% of the thick disk stars and about 14% of the thin disk stars pass within our 1 kpc dwarf horizon. Assume that all of their formation aggregates are now azimuthally mixed right around the Galaxy, so that all of their formation sites are represented within our horizon. Simulations (Bland-Hawthorn & Freeman, 2004) show that a complete random sample of about a million stars with $V < 14$ would allow detection of about 20 thick disk dwarfs from each of about 4500 star formation sites, and about 10 thin disk dwarfs from each of about 35,000 star formation sites. These estimates depend on the adopted mass spectrum of the formation sites. In combination with Gaia, HERMES will give the distribution of stars in the multi-dimensional {$position, velocity, chemical$} space, and isochrone ages for about 200,000 stars with $V < 14$. We would be interested to explore further what the HERMES survey can contribute to asteroseismology.

Some authors have argued that the thick disk may have formed from the debris of the huge and short-lived star formation clumps observed in disk galaxies at high redshift (e.g. Bournaud et al., 2009; Genzel et al., 2011). If this is correct, then only a small number of these huge building blocks would have been involved in the assembly of the thick disk, and their debris should be very easy to identify via chemical tagging techniques.

Chemical tagging in the inner regions of the Galactic disk will be of particular interest. We expect about 200,000 survey giants in the inner region of the Galaxy. The surviving old (> 1 Gyr) open clusters are all in the outer Galaxy, beyond a radius of 8 kpc. Young open clusters are seen in the inner Galaxy, but do not appear to survive the disruptive effects of the tidal field and giant molecular clouds in the inner regions. We expect to find the debris of many broken open and globular clusters in the inner disk. These will be good for chemical tagging recovery using the HERMES giants. The radial extent of the dispersal of individual broken clusters will provide an acute test of radial mixing theory within the disk. Another opportunity comes from the the Na/O anomaly, which is unique to globular clusters, and may help to identify the debris of disrupted globular clusters.
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