The Galaxy Disk in Cosmological Context
Proceedings IAU Symposium No. 254, 2008
J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.

doi:10.1017/S1743921308027579

Kinematical & Chemical Characteristics of the Thin and Thick Disks

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Abstract. I discuss how the chemical abundance distributions, kinematics and age distributions of stars in the thin and thick disks of the Galaxy can be used to decipher the merger history of the Milky Way, a typical large galaxy. The observational evidence points to a rather quiescent past merging history, unusual in the context of the 'consensus' cold-dark-matter cosmology favoured from observations of structure on scales larger than individual galaxies.

Keywords. Galaxy: disk, Galaxy: evolution, Galaxy: formation, Galaxy: stellar content, Galaxy: structure; cosmology: dark matter

1. Introduction: Formation of Thin and Thick Disks in ΛCDM

Dissipational collapse of a gas-rich system is an important ingredient in establishing the thin disks so prevalent today. In the context of hierarchical clustering scenarios, such as ΛCDM, gaseous mergers are required to produce disks (Zurek, Quinn & Salmon 1988; Robertson *et al.* 2006). Centrifugally supported, extended disks also are only produced if angular momentum is largely conserved during collapse within the dark halo (Fall & Efstathiou 1980; Mo, Mao & White 1998). However, angular-momentum transport and evolution, for example due to gravitational torques and tidal effects, are natural during the mergers inherent in ΛCDM, leading to low angular momentum, very concentrated disks (Navarro, Frenk & White 1995). The typical merger history (of dark haloes) is fixed by the dark matter power spectrum, so with ΛCDM additional baryonic processes are introduced to implement 'feedback', to both suppress early star formation and prevent dissipation, delaying disk formation until after the epoch of most active merging (cf. Simon White's talk). Later mergers into the disk will heat the thin disk, with minor mergers producing a thick stellar disk (some thin stellar disk component persists, e.g. Kazantzidis *et al.* 2007) and also driving gas into the central regions to build up a bulge (Mihos & Hernquist 1996).

During a merger, orbital energy is absorbed into the internal degrees of freedom of the merging systems, and orbital angular momentum is redistributed, some absorbed by the larger system, and some being lost to the system. The evolution of a satellite, and of its orbit, as it merges with, and is assimilated by, a larger system depends on the relative masses (the dynamical friction timescale on which the satellite sinks to the center scales like the mass ratio, being shorter for more massive satellites), on the relative density profiles of the satellite and host (denser satellites can survive tidal effects, leading to mass loss and disruption, closer to the center of the larger system), and on the initial orbital parameters (e.g. sense of rotation, inclination angle to the plane of the host, peri-Galacticon and orbital eccentricity). The effect of the satellite(s) on a pre-existing stellar disk is also a sensitive function of the satellite's properties and orbit. The mechanism by which a thin disk is heated by the merging process is a combination of local deposition of orbital energy from the satellite(s), local scattering (in which azimuthal streaming motions are transformed into random motions), and resonant excitation of modes in the disk, providing heating on a more global scale (e.g. Quinn & Goodman 1986; Tóth & Ostriker 1992; Sellwood, Nelson & Tremaine 1998).

Early simulations focussed on the impact of one minor merger (e.g. Quinn, Hernquist & Fullagar 1993; Velazquez & White 1999). These produced a plausible thick disk, similar in structure to that of the Milky Way (Gilmore & Reid 1982; see also Gilmore & Wyse 1985 for kinematics and an order-of-magnitude estimation of the mass of satellite needed), from a merger of a robust (dense) satellite with a mass ratio to the stellar *disk* (not to the total mass) of 10–20%, for a range of initial orbital parameters. Simulations of the merging of cosmologically motivated ensembles of satellites are more relevant, and also find significant heating of a pre-existing stellar disk, over an extended period of time (e.g. Hayashi & Chiba 2006; Kazantzidis *et al.* 2007, also this volume). The satellites in these later simulations have a orbital distribution similar to that of subhaloes identified in dissipationless ΛCDM cosmological simulations, with a mean ratio of initial apocenter to pericenter distance of around 6:1 (e.g. Ghigna *et al.* 2000; Diemand, Kühlen & Madau 2007). The distribution of pericenter distances is also important, since satellites with pericenters that are significantly beyond the disk (larger than say 10 disk scale lengths, see Fig. 2 of Hayashi & Chiba 2006) do not couple effectively to the disk. In addition to realistic orbits, the internal density profiles of the satellites are critical, since fluffy satellites are disrupted early and provide little heating (Huang & Carlberg 1997). High-resolution, N-body simulations of the formation of the dark halo of a 'Milky Way galaxy' with the CDM power spectrum have demonstrated that a significant population of substructure is indeed dense enough to persist and survive many pericenter passages. The shapes of the mass- and velocity-functions of subsystems are reasonably independent of redshift and at $z = 0$ are well-established as power laws (see convergence tests in Reed *et al.* 2005; S. White's talk at this conference). The amplitudes depend on resolution, with the number of satellite dark haloes still increasing with increased resolution (S. White, these proceedings); 'overmerging', particularly in the central regions of the larger host galaxy halo, can artificially reduce substructure. Indeed, the population of subhaloes within the analogue of the solar neighborhood is not yet well-established, even in pure dark-matter simulations (the addition of baryons will increase central densities). However, the present generation of (baryon-free) simulations imply that robust satellites penetrate the region of the disk (e.g. Diemand, Kühlen & Madau 2007). Simulations which model gas physics and star formation also find that thick (and thin) disks are produced. For example, the bulk of the younger stars (ages less than 8 Gyr) in the thick disk in the simulation of Abadi *et al.* (2003) are produced by heating of the pre-existing stellar disk (we return to the older stars in section 2 below).

The most massive satellite provides the greatest heating, with the scaling such that the increase in scaleheight (or, equivalently, in the square of the vertical velocity dispersion) is proportional to the square of the mass of the satellite (Hayashi & Chiba 2006). For an ensemble of satellites with the differential mass function seen in CDM simulations, namely a power-law with slope close to -2 (e.g. Diemand, Kühlen & Madau 2007), the cumulative heating is also dominated by the most massive systems (see also White 2000). The substructure distribution at earlier times contains more satellites of higher mass, since these are more affected by dynamical friction, which brings them into the central regions where they are more effectively stripped of mass from their outer parts (e.g. Zentner *et al.* 2005). These massive satellites, after this shriking of their orbits, can be more effective at heating the thin disk, prior to their demise. Thus at early times the satellite distribution is more concentrated than is the host dark matter halo, while at the present day it has evolved to be less concentrated. One must allow for this evolution of the mass function and orbital parameters, rather than simply adopting a surviving satellite retinue from the end-point of a simulation, which minimizes the predicted overall heating (as found by e.g. Font *et al.* 2001). Indeed following the full merging history is preferable. Such analyses imply that late (after redshifts of unity) heating of thin stellar disks seems to be inevitable in ΛCDM (e.g. Abadi *et al.* 2003; Stewart *et al.* 2008; Kazantzidis, this volume). The current models (Stewart *et al.* 2008) show that over the last 10Gyr, fully 95% of galaxy haloes of present total mass 10^{12} $M_{\odot}$ have accreted a system of mass equal to that of the present-disk ($5 \times 10^{10} M_{\odot}$ – their simulation resolution limit is 10^{10} $M_{\odot}$); the mass ratio of the substructure to that of the stellar disk at the epoch of accretion is the more important ratio for disk heating and such a large mass is highly likely to cause severe heating. More numerous, lower-mass mergers are also expected, continuing to late epochs.

Gas physics can also play a role in the formation of the thick disk, in terms of slow settling to the disk plane (Burkert, Truran & Hensler 1992) or a starburst in a rapidly changing potential such as a gas-rich merger (Robertson *et al.* 2006; Brook *et al.* 2007). The latter mechanism has some observational support at high redshift (see Elmegreen's and Genzler's contributions to this volume). One must of course also take account of adiabatic compression and heating of an existing thick disk by subsequent slow accretion of gas to buildup the thin disk (cf. Tóth & Ostriker 1992; Elmegreen & Elmegreen 2006). Here I will focus on the – apparently inevitable – late heating of thin stellar disks, as a probe of ΛCDM. The important issues are the predicted chemical abundance and age distributions of stars in the thin and thick disks, given a typical merger history, and how they compare with the observations.

2. Evidence for Minor Mergers in the Past

Satellites that are accreted are in general only partially assimilated, with 'shredded satellite' debris maintaining some coordinate-space coherence for a few orbits, kinematic coherence for longer, and with persistent stellar population signatures, in terms of their chemical abundances and stellar age distributions, allowing identification over a Hubble time. In general one can expect satellite debris to be deposited along the (evolving) orbit of its center-of-mass, leading to a prediction that former-satellite member stars will populate the thick disk – halo interface at a range of Galactocentric radii (see e.g. Fig. 19 of Huang & Carlberg 1997, Fig. 9 of Abadi *et al.* 2003, Fig. 3 of Meza *et al.* 2005), again with details depending on the satellite mass, internal density distribution and initial orbit. Indeed, it has been predicted that a large fraction of the old stars in the thick and thin disks consists not of stars formed *in situ* but rather stars accreted from satellites many Gyr after they were formed (Abadi *et al.* 2003), with debris from each satellite populating a different radial range, and the parent satellite having been brought to a circular orbit prior to mass loss. This late (redshifts $z < 1$) accretion of old stars, directly into the disks, on high angular momentum orbits, would allow reconciliation of the delayed formation of disks, required in ΛCDM as discussed above, with the presence of old 'disk' stars.

Only high mass, dense (robust) satellites can experience efficient circularization of their initial orbits through dynamical friction. Accretion of such objects into the plane of the disk should also cause heating of the thin disk that has formed by the epoch of their accretion, leading to a thick disk component with a stellar age distribution that reflects the thin disk star formation history up to that epoch. The derived star-formation history of the (local) thin disk is fairly smooth and continuous from the earliest times, corresponding to the lookback time of $\sim 10 - 12$ Gyr that equals the ages of the oldest

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stars in the thin disk (Binney, Dehnen & Bertelli 2000). Taking Abadi *et al.* as an example, with a significant accretion event at $z = 0.73$, i.e. a look-back time of ~ 7 Gyr, one expects stars in the thick disk as young as 7 Gyr, rather than a uniformly old population. This is indeed what they find in that simulation (their Fig. 8).

Note that the Monoceros Stream (Newberg *et al.* 2002) and Canis Major overdensity have been interpreted in terms of the in-plane accretion of a dwarf galaxy (Peñarrubia *et al.* 2005). The null detection of an associated over-density of RR Lyrae stars by Mateu *et al.* (poster this conference) would be unexpected in this scenario, but is consistent with dynamical instabilities – warp, flare, spiral arms – in the outer disk. †

2.1. *The Age Distribution of Stars in the Thick Disk*

All available observations are consistent with a dominant old age for the stars of the thick disk of the Milky Way, where 'old' means as old as the globular clusters of the same metallicity (e.g. 47 Tuc), or at least 10 Gyr, and probably 12 Gyr. The most reliable evidence comes from looking at the turnoff for *in situ* thick disk stars, several thin disk scale heights above the plane (to minimize contamination by outlier thin disk stars), as a function of metallicity. Samples analysed in this way show very few stars bluer than the 10-12 Gyr turn-off colour at a given metallicity, for both thick disk and stellar halo (Gilmore, Wyse & Jones 1995 and references therein).

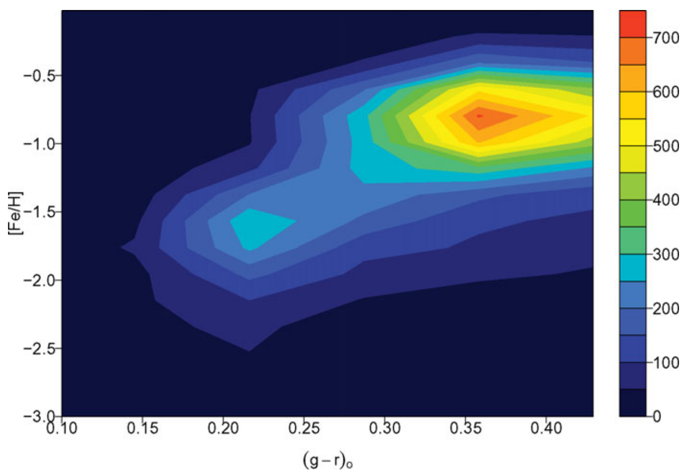

Figure 1. Contour plot of the locations of 8,600 faint F/G stars in the plane of de-reddened colour and metallicity. The rather abrupt turn-offs of each of the thick disk and halo are apparent, with few younger stars, which, if present, would occupy the upper left portion of the plane.

The data for 8,600 faint F/G dwarfs with metallicities from intermediate-resolution spectroscopy (obtained with the AAT/AAΩ multi-object spectrograph) are shown in Fig. 1 (Wyse, Gilmore & Norris, in preparation), where the dominant turn-off is seen. The turn-off colour of the thick disk (and the bluer turn-off colour of the more metal-poor stellar halo) from the full Sloan Digital Sky survey imaging data, covering a significant fraction of the sky, also implies this old age for both thick disk and stellar halo, more globally across the Galaxy (e.g. Ivezic *et al.* 2008). Local samples – making use of Strömgren photometry – are more susceptible to contamination by thin disk stars with extreme kinematics, such as due to three-body interactions, and require careful analysis to isolate a

† 'The Monoceros Stream' was first identified by Corlin (1920; his Table 2) as a local moving group. While clearly a different feature, this first Monoceros Stream may hold lessons for the interpretation of the current Stream.

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clean thick disk sub-sample. With this caveat, such samples are in general consistent with this dominant old age (e.g. Strömgren 1987; Nordström *et al.* 2004; Reddy *et al.* 2006; Schuster *et al.* 2006).

Such a high value for the age of the dominant stellar population of the thick disk has major implications for the minor merging history of the Milky Way. As noted above, stars of all ages are found in the local thin disk, with a derived star formation history that extends back to earliest times. Thus, if the thick disk originated through merger-induced heating of a pre-existing thin stellar disk, the last significant (defined as having a mass ratio to the disk of $\sim 20\%$, and surviving to interact with the disk) dissipationless merger can be dated by the age distribution of stars in thick disk: if the typical thick disk star is old, then the last such merger was long ago, with an age greater than 10 Gyr setting a limit of no significant merger activity and heating since a redshift of $\gtrsim 2$. This scenario also requires there to have been an extended thin stellar disk in place at $z \sim 2$ (even allowing for some radial mixing subsequently).

Mergers do not only heat thin disks, but can also drive gas and stars into the central regions to build-up the bulge. It may then be no coincidence that the old age of the dominant stellar population in the bulge of the Milky Way, again 10–12 Gyr (e.g. Zoccali *et al.* 2003; Feltzing & Gilmore 2001), provides a consistent limit on merger activity. As noted previously (Wyse 2001), it could be that the merger that created the thick disk induced gas inflow and an associated starburst to form the (bar/)bulge *in situ*.

2.2. *What fractions of the disks can be direct stellar accretion from satellites?*

2.2.1. *Kinematic Constraints*

Interloper stars, accreted during the merger with a satellite galaxy, should be identifiable, probably with different kinematics, chemical abundances, age and spatial distributions from stars formed *in situ*. It might be remembered that the Sagittarius dwarf spheroidal was discovered serendipitously during a spectroscopic survey of the Milky Way bulge (Ibata, Gilmore & Irwin 1994) by the distinct kinematics and colour distributions of its member stars. In the scenario whereby the thick disk results from heating of a pre-existing thin disk by minor mergers, the 'shredded-satellite' stars should be distinguishable from 'heated thin-disk stars'.

Such satellite debris was identified with 'thick disk' stars, observed several kiloparsecs above the thin disk plane, in two lines-of-sight at longitude $\sim 270°$, on orbits of significantly lower angular momentum than the standard thick disk star – with a lag in mean azimuthal streaming of $\sim$ 100 km/s behind the Sun, compared to the standard thick disk lag of $\sim$ 40 km/s (Gilmore, Wyse & Norris 2002). A similar population was found among the Galactic field stars along lines of sight to dwarf spheroidal galaxies, at widely separated lines-of-sight (Wyse *et al.* 2006). The radial velocity histogram from the subset of our AAT/AAΩ data at $\ell \sim 270°$, where the line-of-sight velocity has a significant contribution from the azimuthal streaming, is shown in Fig. 2 (Wyse, Gilmore & Norris, in preparation). There is clearly again a significant population with a rotational lag of $\sim$ 100 km/s. These stars have a broad range of metallicity (derived from the Ca II K line), down to -3 dex. A full analysis is underway.

While we interpreted our results in terms of discontinuous kinematics distinguishing 'shredded-satellite stars' from 'heated thin-disk stars' (true thick disk in this picture), others with similar quality spectroscopic data have modelled their velocities by smooth gradients as a function of height from the disk plane (e.g. Chiba & Beers (2000) with a similar sample size of around one thousand stars). The Sloan Digital Sky Survey photometric data for $\sim$60,000 F/G stars at the NGP ($b > 80°$) have been analysed together with proper motions by Ivezic *et al.* (2008), using photometric metallicity determinations

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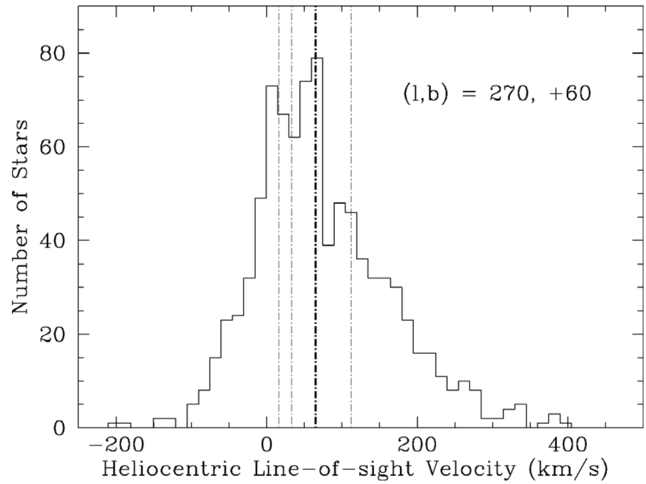

Figure 2. Line-of-sight velocity histogram for the ∼ 900 faint F/G stars at $\ell = 270°$ from our wide-area spectroscopic survey with AAΩ (some 12,000 stars in total). The predicted mean velocities for the standard (old) thin disk, thick disk and stellar halo are shown as fainter vertical dot-dashed lines (left to right), while the heavier vertical dot-dash line is the predicted mean for a component lagging behind the Sun by 100 km/s. This clearly matches the peak velocity.

to derive distances and hence tangential velocities (decomposable into velocity towards the Galactic center and azimuthal streaming velocity). They deduce a steep gradient in rotational lag with Z-height for the thick disk, similar in amplitude to that of Chiba & Beers (2000), namely ∼30 km s^{-1}/kpc. It will be interesting to try alternative models to describe the data, while noting that the heated thin-disk stars in the minor-merger simulations of Hayashi & Chiba (2006) shows a vertical gradient in rotational velocity of comparable amplitude.

2.2.2. *Age Constraints*

The surviving satellites in the Local Group all contain old stars, consistent with star formation in all small galaxies being initiated around the epoch of reionization (e.g. Hernandez, Gilmore & Valls-Gabaud 2000; Dolphin 2002). Most of the luminous satellites had an extended and fairly continuous star-formation history, albeit non-monotonic, and contain a dominant intermediate-age population, contrasting with the dominant old ages seen in the bulge, thick disk and stellar halo of the Milky Way. While satellites accreted early will therefore contain stars with the same age distribution of the non-thin-disk components of the Milky Way, satellites accreted later may be expected to contain significantly younger stars. Accretion of typical luminous satellites to form more than a few percent of the stellar halo is then limited to epochs prior to a look-back time of ∼10 Gyr, or again a redshift of ∼2 (Unavane, Wyse & Gilmore 1996). The similar old age of the thick disk stars produces similar constraints. Systems that contain uniformly old stellar populations, such as the Ursa Minor dSph, could of course be assimilated into the Galaxy at any epoch and would not be distinguishable by the stellar age distribution (or their stellar mass function; Wyse *et al.* 2002), but only a small fraction of the stars in dwarf galaxies now are as old as the stars in the Ursa Minor dSph, and the stellar mass of the Ursa Minor dSph, $\sim 10^6$ $M_\odot$, is a tiny fraction of even the stellar halo.

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2.2.3. *Overall Metallicity Constraints*

The metallicity distribution of the local thick disk is distinct from any of the other stellar components, but of course the tails overlap (see e.g. Wyse & Gilmore 1995). The mean metallicity of the local thick disk, expressed as an iron abundance, is around one-quarter of the Solar value. The luminosity-metallicity relation for galaxies in the Local Group (e.g. Mateo 1998) implies that only the most luminous satellites can self-enrich to this value, suggesting that the thick-disk stars formed in a system of relatively deep potential well. The Large Magellanic Cloud has enriched to this level, and the metallicity distribution of the inner disk of the LMC (Cole, Smecker-Hane & Gallagher 2000) is similar to that of the local thick disk. Further, the total stellar masses are comparable. However, the LMC had a much slower enrichment history than did the (progenitor of) the thick disk, and reached [Fe/H] ~ -0.6 dex only $\sim$5 Gyr ago (Hill *et al.* 2000). The rapid enrichment of the thick disk points to a high early star formation rate, and chemical evolution in a system significantly more massive than the LMC, suggestive that the overall Milky Way potential was already established at $z \sim 2$, and the bulk of the star formation was *in situ.*

2.2.4. *Elemental Abundance Constraints*

Stars of different masses synthesize and eject different elements, on different timescales, so that elemental abundances contain much more information than does overall metallicity. The latter is an integral over past star formation and chemical enrichment, while the former reflects the ratio of recent star formation rate (through enrichment by Type II supernovae, which evolve on timescales of $\sim 10^7$ yr after birth of the progenitor star, faster than the typical duration of star formation) to past star formation (e.g. through Type Ia supernovae, which evolve on timescales of several times 10^8 years, up to a Hubble time, after the birth of the progenitor stars). Massive stars, ending their lifes as core-collapse (Type II) supernovae, create and eject intermediate-mass elements, in particular those synthesized by the addition of successive helium nuclei, and known collectively as the 'alpha-elements'. The $r-$process elements are also created in the high neutron-flux environments of Type II supernovae. Stars that are formed early in a star-forming event, prior to significant Type Ia supernovae activity, (not necessarily early in absolute terms) will be enriched by only Type II supernovae. Provided there is good mixing of ejecta, and a massive enough star-formation event for the massive-star Initial Mass Function (IMF) to be fully sampled, the interstellar medium from which these early stars form will be enriched with a characteristic ratio of α-elements to iron. This characteristic ratio is set by the massive-star IMF, since the mass of iron that is produced is essentially independent of progenitor mass, while the mass of α-elements produced is a steeply increasing function of progenitor mass, independent of progenitor metallicity (see e.g. Fig. 1 in Gibson 1998; Kobayashi *et al.* 2006). Thus if the massive-star IMF were biased towards more massive stars (remembering the relevant range is $\sim$8 $M_\odot$ to $\sim$100 $M_\odot$), stars enriched by the resulting Type II supernovae only would show a higher value of [α/Fe]. As discussed in Wyse & Gilmore (1992), IMF slopes that have been proposed (for various reasons) predict values of this 'Type II plateau' that can differ by greater than 0.3 dex, certainly an observable effect. Such differences have not been observed, providing strong evidence against a variable IMF.

Type Ia supernovae are produced by accretion onto a massive white dwarf in a binary system and each produce a relatively large mass of iron, and a small mass in α-elements. The signature of the incorporation of the ejecta from Type Ia in the element ratios of long-lived low mass stars is a lower value of [α/Fe] than the Type II plateau. Irrespective of the details of the model, the minimum delay time after star formation, for a Type Ia

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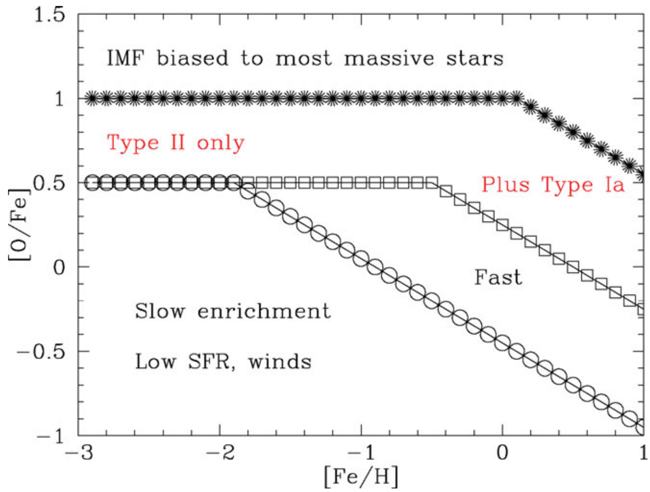

Figure 3. Schematic elemental ratio pattern for self-enriching star-forming regions. Stars formed at early times in the star-forming event are pre-enriched by only Type II supernovae and with good mixing of ejecta into the interstellar medium, this pre-enrichment has a fixed value of [O/Fe]. The asterisks represent an IMF biased towards the most massive stars, while the open squares and circles represent a normal IMF. The values of the 'Type II plateau' reflect the differences in massive-star IMF.

supernova, is given by the time taken for an $\sim$8 $M_\odot$ star (the most massive progenitor in this case) to become a white dwarf, accrete sufficient material to exceed the Chandrasekhar mass, and then explode. This is the origin of the several times 10^8 yr delay noted above; the shortest timescale for incorporation of significant iron into the ISM and the next generation of stars is usually estimated as $\sim 10^9$ yr. Lower-mass progenitors take longer to end up as white dwarfs, and different binary systems can range tremendously in their evolution and accretion times, leading to a long tail in delay times (see e.g. Matteucci & Greggio 1986; Smecker & Wyse 1991). The enrichment by Type Ia supernovae is set by a delay *time*, and the iron abundance corresponding to that time depends on the efficiency of chemical enrichment. The rate of chemical enrichment depends on the star formation rate, gas flows, and on the ability of the system to retain metals. In the absence of a mechanism to remove individual elements preferentially in a wind, none of these will modify the value of the Type II plateau, but will modify the iron abundance at which the downturn from this plateau appears.

The situation is illustrated schematically in Fig. 3 (modified from Wyse & Gilmore 1993). With a fixed IMF, the value of [α/Fe] is fixed, for stars that form early, and for a normal IMF that value is $\sim +0.3$. Thus one expects the metal-poor stars in any self-enriching system to show such values. Of course, if there are subsequent bursts of star formation, so that Type II supernovae dominate again, newly forming stars in that burst will also show these enhanced values of [α/Fe] (e.g. Gilmore & Wyse 1991 for models; Koch *et al.* 2008 for application to the Carina dSph).

It is clear that elemental abundance patterns reflect the IMF and star formation histories of the star-forming systems. In particular, systems like the dwarf spheroidal galaxies, with inefficient enrichment over extended periods, should show low values of [α/Fe] at low values of iron (Unavane, Wyse & Gilmore 1996), as observed (Venn *et al.* 2004). Each (surviving) satellite galaxy in the Local Group has its own star-formation and enrichment history, leading to the expectations of a unique pattern in elemental abundances for each system. The realisation of this expectation is demonstrated by Geisler *et al.* (2007; their

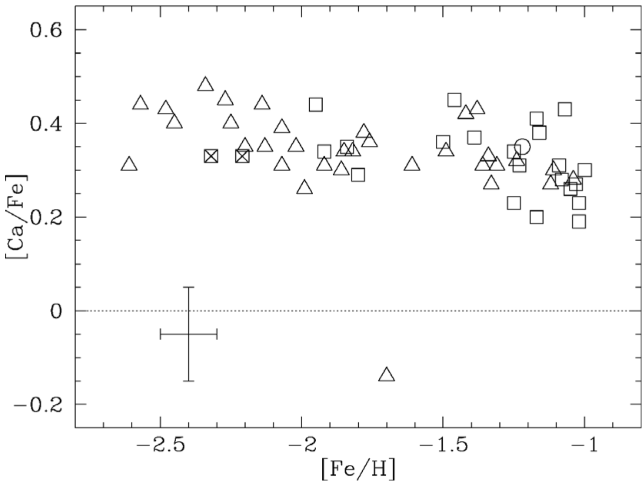

Figure 4. Elemental abundance ratios for the α-element Calcium, in metal-poor stars ([Fe/H] < -1 dex) selected from the RAVE catalogue on the basis of disk-like kinematics. The stars are assigned to populations using several criteria, based on the refined stellar parameters from high-resolution spectra. Circles are thin-disk stars, squares are thick-disk stars and triangles are halo stars. The crossed- square symbols at [Fe/H] < -2 dex represent two stars with uncertain thick disk–halo designation at present. The thick and thin disks clearly extend to low iron abundances, and those stars have enhanced [α/Fe], unlike the bulk of stars in satellite galaxies, which have values of [α/Fe] < 0.2 at these metallicities. We expect to double this sample this observing season.

Fig. 12), where the different loci in the [α/Fe]–[Fe/H] plane of Galactic stellar populations and of each dwarf satellite is rather dramatic. The vast majority of stars in dwarf galaxies now all lie below the Galactic populations in this plane, with $0.2 >$ [α/Fe] > -0.3. The distinct patterns of stars in different satellites means that one should be able to identify candidate 'interloper' stars from a given system, from their joint kinematics and elemental abundance distributions, provided their parent system formed stars for longer than $\sim 10^9$ yr, and the stars were accreted subsequently (see Nissen & Schuster, this volume, for an interesting discussion of 'low-alpha' stars with halo kinematics).

Thus late accretion of satellite galaxies into the plane of the disk may be expected to produce disk stars with low iron abundance and low [α/Fe]. The RAVE spectroscopic survey of apparently bright stars (Steinmetz *et al.* 2006, also this volume) provides an ideal sample in which to look for candidates: stars with low metallicity but disk-like kinematics. We (Ruchti *et al.*, in preparation) have initiated a programme to obtain follow-up high resolution spectroscopy of such candidates, using the AAT, Magellan and the ESO 2.2m telescope. These spectra provide improved stellar parameters and elemental abundances. Reflecting the magnitude-limited nature of the RAVE selection function, most of the candidates are giants, with distances in the range of 500 pc to a few kpc. Several criteria, with different dependences on the distance estimates and kinematics (radial velocities and proper motions), are used to assign each star to a given population. This assignment is probabilistic in nature and so cannot be definitive for any one star; large samples are needed and we have been awarded further observing time this semester to obtain a statistically significant sample. Elemental abundances are derived using the methodology of Fulbright (2000) and our results thus far for metal-poor stars are illustrated in Fig. 4. We find that the thick disk extends to at least [Fe/H] $= -2$ dex, and the thin disk below -1 dex. These metal-poor disk stars do not have the low ratios of [α/Fe] of the bulk of the population in dwarf galaxies. This limits the accretion of

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stars from satellite galaxies, into the disks, to have occurred only very early, and is not obviously consistent with late accretion, at epochs $z < 1$, as has been proposed (Abadi *et al.* 2003).

These data also serve to illustrate another unexpected and important point: the small scatter about the 'Type II plateau', even at the lowest abundances where only a handful of supernovae suffice to provide the enrichment (see also Cohen *et al.* 2004; Cayrel *et al.* 2004; Spite, this volume). The different star-forming regions that were the basis for the major stellar components of the Milky Way were apparently enriched by stars with a fixed (massive-star) IMF, and were well enough mixed, and massive enough, to average out the different yields from supernovae of different progenitor masses. The separation between different components, and lack of scatter, within any one component (e.g. Reddy, Lambert & Allende-Prieto 2006; Bensby *et al.* 2007a), around the downturn signalling the contributions of Type Ia supernovae, at least in samples probing a few kiloparsec of the solar circle, is hard to understand if many distinct small subsystems contribute.

2.3. *Substructure and Mergers into the Thin Disk*

As noted, it has been suggested that direct accretion of satellites on high angular momentum orbits could provide old stars in the thin disk, and perhaps explain the Monoceros Stream. However, the thin disk is clearly far from a smooth, equilibrium system which could provide a well-understood background population against which to define substructure. Similarly to the situation in external galaxies, spiral arms in the thin disk can cause significant disturbances in stellar kinematics and positions that persist long after the perturbation has passed (e.g. de Simone *et al.* 2004), and resonant scattering can lead to significant radial mixing (Sellwood 2008 and references therein; Roškar *et al.* 2008). Resonances with the bar in the Milky Way can also induce coherent motions (Dehnen & Binney 1998). These effects can all give rise to 'moving groups' within which there is a large range of stellar age and metallicity, consisting of stars that were not born together, but have been perturbed to move together. Observational evidence has been provided by detailed analysis of space motions (e.g. Famaey *et al.* 2005) and elemental abundances (Bensby *et al.* 2007b; Williams *et al.* this volume). Indeed, it appears that all disk substructure, including the Monoceros Stream (Momany *et al.* 2006), can be produced by dynamical effects in the disk.

3. Cosmological Context

The available stellar population evidence implies that the Milky Way galaxy had a quiet history, with no significant mergers with dark matter haloes since a redshift of ~ 2, where 'significant' means $\sim 20\%$ mass ratio to the disk, robust satellites, on non-circular orbits that take them into the region of the disk. This lack of merging is apparently unusual in ΛCDM, where subsystems are typically more concentrated than their hosts, and typically indeed on radially biased orbits. External disk galaxies also often have a thick disk component, and this component is again old (Mould 2005; Dalcanton, Seth & Yoachim 2007).

Gentle accretion must have dominated the mass build-up of the Milky Way, with fluffy, gas-rich systems being the primary means of matter infall. Late mergers are clearly contributing to the outer stellar halo, e.g. the Sagittarius dwarf spheroidal. Late accretion is perhaps building up the gaseous disk, in the form of high velocity clouds. With accretion dominated by gas-rich systems, most star formation will have occurred *in situ*, consistent with the high metallicity of the bulge, and of the thick and thin disks, the components that dominate the stellar mass of the Milky Way. The first detections of CO emission lines in massive disk galaxies at redshifts $z \sim 1.5$ also imply *in situ* star formation (Daddi *et al.* 2008), as inferred for the Milky Way (and thus satisfying the Copernican Principle).

However, we do still lack important knowledge of the large-scale stellar populations of the Galaxy, including the thick and thin disks far from the Sun. Our knowledge of how the different stellar components are connected is also far from satisfactory. There is a continuing need for large-scale spectroscopic studies, at both medium resolution, for broad kinematics and metallicities across the Galaxy, and high-resolution, for detailed elemental abundances and tracing streams. There is also a need for comprehensive surveys of M31 and M33, to place the results for the Milky Way in a better context. The proposed Gemini/Subaru MOS instrument WFMOS will play an important part in this endeavour.

Bengt Strömgren emphasised the role played by the stellar populations of the Milky Way Galaxy in guiding our models of galaxy formation. That this remains true is testament to his legacy.

Acknowledgements

I thank the organisers for financial support, the Aspen Center for Physics for a stimulating environment, Greg Ruchti for help with Fig. 1 and him and other collaborators for allowing me to show results in preparation.

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https://doi.org/10.1017/S1743921308027579 Published online by Cambridge University Press