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Lessons from surveys of the Galaxy

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Abstract. I present a brief survey of surveys, and their results and implications, intended to set the context for the ensuing discussion.

Key words. Galaxy – disk: Galaxy – solar neighbourhood: Galaxy – structure: Galaxy: abundances – Cosmology: observations

1. Introduction

These are exciting times to study local galaxies, due to the confluence of three approaches:

• Advances in technology have allowed large, high-resolution simulations of structure formation to model Galaxy formation in a cosmological context

• Large observational surveys of stars in Local Group galaxies are now possible, using wide-field imagers and multi-object spectroscopy, complemented by space-based imaging and spectroscopy, followed in the near future by the GAIA satellite and full phase space information

• High-redshift surveys are now quantifying the stellar populations and morphologies of galaxies at high look-back times

I will here focus on the second approach, while acknowledging the synergy with the others. I will not attempt a full historical review, but highlight advances with what I consider appropriate examples. I will also focus on *stellar* components, but one should not forget the importance of the interstellar medium.

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2. Early Surveys

2.1. Star Counts

Since the work of Kapteyn in the early 20th centuries, star counts, particularly at high Galactic latitude, have been utilised to define Galactic structure. However, their shortcomings, when taken alone, have also been long known. The apparent magnitude distribution of stars depends on many factors, not only their density distribution – their luminosity function depends on metallicity, their birth-rate and the underlying (invariant?) initial mass function (see e.g. Gilmore & Wyse 1987 for a review). Refining star counts to include colour allows more stringent testing of models, but again the result is critically dependent on the adopted luminosity function and colour-magnitude relation for different populations/components in the model (this may seem obvious, but the use of inappropriate choices was the source of much contentious debate in the 1980s).

Bearing their limitations in mind, star counts in selected lines-of-sight proved extremely useful for delineating the overall large-scale structure of the stellar components of the Galaxy. This is usually achieved not by direct

inversion of the star counts, but by comparisons of the observations with model predictions (van den Bergh 1980; Bahcall & Soneira 1980; Gilmore 1981). In particular, the stellar density laws (radial and vertical) of the thin disk were derived (Sandage & Katem 1977; Bahcall & Soneira 1981; Yoshii 1982); the density profile and shape of the stellar halo were estimated from a variety of tracers (e.g. Hartwick 1987; Wyse & Gilmore 1989; Reid & Majewski 1993; Kinman, Suntzeff & Kraft 1994); the thick disk was defined as a component with exponential scale height some 3–4 times that of the old thin disk (Gilmore & Reid 1983; Fenkart 1988; Larsen & Humphreys 2003).

The interpretation of early star counts was complicated by several factors. Degeneracies in reddening–age–metallicity were exacerbated by the fact that the counts were based on photographic photometry, in only a limited range of bandpasses. Poor star-galaxy separation at faint magnitudes ($V \gtrsim 20$) can cause problems, particularly for blue objects (see the discussion in Reid & Majewski 1993). The small number of lines-of-sight in any one survey and limited areal coverage further made it difficult to isolate the underlying cause(s) of discrepancies between different investigations.

Determination of metallicities greatly aids the interpretation. Those derived from photometry can of course be obtained for more stars with less investment of telescope time, compared with spectroscopic determinations. The broad-band (UBV) based metallicity distributions of faint F/G-dwarfs by Gilmore & Wyse (1985), combined with density laws derived from star counts, were critical in ascertaining that the thick disk was indeed a distinct component. Intermediate and narrow-band photometry such as Strömgren photometry remains an effective tool, most recently illustrated by the work of Nordström et al. (2004), providing the definitive analysis of the metallicity distribution of nearby F/G dwarfs.

2.2. Star Counts plus Kinematics

Photometric observations repeated after a sufficiently long baseline allow for the combination of star counts plus proper motions. The reduced proper motion diagram is a useful discriminant of different kinematic populations, in the absence of reliable distances. Chiu (1980) applied this technique to his database of proper-motions in Cardinal directions[1] for a faint ($V \lesssim 20.5$) magnitude-limited sample, based on deep photographic plates with a 25 year baseline. He concluded that 'Population I' far from the disk plane was of lower metallicity, and had higher velocity dispersions, than did Population I locally. A reanalysis of his data, without the requirement that there be only *two* components (the classical Populations I and II), showed the presence of the intermediate-kinematics thick disk (Wyse & Gilmore 1986).

Distances derived from photometric parallaxes plus proper motions, for stars selected purely as a magnitude-limited sample, i.e. not kinematically selected, in at least one of the Cardinal directions, can be used to probe one or more components of the space motion (e.g. Majewski 1992), as can radial velocities (Sandage & Fouts 1987b). Reliable distances based on photometry need good metallicity and gravity estimates, which are not always available. The Hipparcos/Tycho sample (with trigonometric parallaxes) allowed an analysis of very local space motions, such as the velocity dispersion tensor as a function of colour, on the scale of less than a hundred parcsecs, of course for mostly disk stars (e.g. Dehnen & Binney 1998).

The combination of star counts plus spectroscopy – to provide a metallicity estimate in addition to radial velocity – is more powerful than photometry alone, allowing joint analyses of metallicity and kinematics/dynamics. For example, this combination allows a robust dynamical analysis of local vertical motions to derive the vertical acceleration and associated mass density and surface density (K_z; Kuijken & Gilmore 1989). The conclusion from this analysis is that there is no 'extra' dissipative dark matter, confined to the disk, in additional

[1] The Galactic poles, the anti-center/center line and towards/away from Galactic rotation

to the dissipationless dark matter in the (dark) halo.

Radial velocities, plus distances and proper motions, allow full phase-space investigations. Early surveys used photometric parallaxes for distances, plus a minimum proper motion selection criterion to define the samples, in order to increase the 'yield' of non-thin disk stars in these necessarily local samples. This kinematic selection requires an understanding of, and correction for, the kinematic bias introduced. The analysis is complicated, but fruitful (Sandage & Fouts 1987a; Carney & Latham 1987; Carney, Laird, Latham & Aguilar 1996). Again the Hipparcos/Tycho sample provided the opportunity for the derivation of space motions for local stars, without proper-motion selection, once metallicities and radial velocities were obtained (Nordström et al. 2004).

The modern era of star counts derived from very wide-field CCD photometry such as available from the Sloan Digital Sky Survey (SDSS, e.g. Chen et al. 2001; Ivezić's and Newberg's talks in these proceedings) was preceded by pencil-beam CCD photometry in selected areas, providing multi-band, deep, data over several, to many, square degrees (e.g. Phleps et al. 2000; Siegel et al. 2002). These pointed to tantalizing inconsistencies in different fields.

3. Motivation for Surveys: Cosmology

3.1. Early Surveys

The idea that the stellar populations of the Milky Way Galaxy have critical importance for understanding larger issues in cosmology has been a major motivation for decades. Much fundamental early work on stellar populations and Galaxy formation by Sandage (e.g. Eggen, Lynden-Bell & Sandage 1962; Sandage 1970) was centered around the questions of 'how old are the oldest stars in the Galaxy, how long after the Big Bang did galaxies initiate their collapse, and what was the duration of that collapse?' These are crucial in constraining the age of the Universe – obviously as least as old as the oldest stars – and hence the values of cosmological parameters, particularly when these are estimated through comparison with measurements of the present value of the Hubble constant. The fact that the early, rapid collapse model developed in Eggen, Lynden-Bell & Sandage (1962) is still used as a paradigm for the formation of the Milky Way Galaxy is testament to its simplicity and power.

Significant impetus to use the Milky Way as a template for testing theories of galaxy evolution also came from inconclusive attempts to derive cosmological parameters from observations of galaxies, such as the Hubble diagram (apparent magnitude *vs* redshift), galaxy number counts etc. It was then realised that the evolution of galaxies must be understood first (summarised in Tinsley 1977), and the Milky Way was potentially an ideal testbed. The drive to understand the age distributions and metallicity distributions of the different stellar components of the Galaxy led to elegant analyses of the metallicity distribution of long-lived stars, manifest in the local G-dwarf metallicity distribution (Pagel & Patchett 1975, van den Bergh 1962; Schmidt 1963) and predictions for the chemical evolution of the Galaxy beyond the local disk. The simple, closed-box model of chemical evolution had been developed (e.g. Schmidt 1963; Searle & Sargent 1972) and the application to the local disk revealed a 'G-dwarf problem' in that the model significantly over-predicted the metal-poor tail of the metallicity distribution of long-lived stars. Analytic and numerical models of chemical evolution showed the several ways in which the G-dwarf 'problem' could be solved (e.g. Tinsley 1975; Pagel & Patchett 1975). These models included such currently topical aspects as inhomogeneities, and the interpretation of the pattern of elemental abundances, showing how they trace the past stellar Initial Mass Function and star formation history (Tinsley 1976; 1979). The data did not merit a full exploitation of these insights.

3.2. The Modern Era

Significant motivation for study of Galactic populations still comes from cosmology, but now not so much the estimation of the present values of cosmological parameters such as the

deceleration parameter q_0 or Hubble constant H_0, but the testing of predictions of galaxy formation in the context of particular cosmological models. The favoured model at present is ΛCDM ($\Omega_\Lambda \simeq 0.7$, $\Omega_{matter} \simeq 0.3$, $H_0 \simeq 70$ km/s/Mpc), based on the excellent agreement of its predictions with measurements of large-scale structure, such as the fluctuations in the cosmic microwave background (Spergel et al. 2006) and the galaxy power spectrum (Sanchez et al. 2006; Eisenstein et al. 2005). As is well-known, such a model predicts that large galaxies such as the Milky Way form and evolve through the merging and accretion of smaller systems, with the 'first objects' having a mass of perhaps $\sim 10^6$ $M_\odot$ (the characteristic mass, and the relation of these objects to present-day dwarf galaxies is the subject of much on-going work). As is also well-known, this model faces several challenges, particularly concerning its predictions on the scales of groups of galaxies and below.

The merging history of a typical massive-galaxy dark halo is fairly straightforward to calculate, since only gravity is involved. However, most simulations lack the resolution to follow how far inside a 'parent' halo a merging satellite penetrates, and this is crucial to determine the effect on the baryonic disk. During mergers the orbital energy goes into the internal degrees of freedom of the merging systems, thus 'heating' them. A corollary is that surviving dark substructure, as predicted in CDM simulations (Moore et al. 1999; Klypin et al. 1999), can also heat thin disks. Thin disks are thus fattened, and while gas can cool and re-settle to the disk plane, stellar disks remain 'hot'. During a 'minor' merger (mass ratio of less than $\sim 1:4$), the (relatively) low density, outer regions of the smaller system are removed by tides, to be absorbed into the larger system. Orbital angular momentum is also absorbed and redistributed, with in general outer parts gaining angular momentun and inner parts losing. In the process gas and stars are driven to the center, perhaps helped by a bar that is often predicted to form as a result of instabilities in the disk. The disk formed subsequently has a short scale-length: the corollary is that detailed angular momentum conservation is required in order to form extended disks as observed (Fall & Efstathiou 1980). Various schemes have been developed to suppress angular momentum transport and redistribution, usually invoking some 'feedback' process to maintain the baryons in a diffuse gaseous state for as long as possible (e.g. Weil, Eke & Efstathiou 1998; Maller & Dekel 2002; Robertson et al. 2006), until the epoch of active (major) merging is complete, perhaps even as recently as a redshift of unity.

Abadi et al. (2003) present a recent simulation of the formation of a present-day disk galaxy that demonstrates many of the important aspects, including the outstanding problem of how to include star formation and gas physics. Generic predictions for disk galaxies include the following:

- Extended disks settle and form late, after the last major mergers, typically (for a dark halo of mass $10^{12}M_\odot$) corresponding to a redshift of unity (e.g. Maller et al. 2006), or a lookback time of ~ 8 Gyr
- A large disk galaxy should have hundreds of surviving satellite dark haloes at the present day; these may well provide observable signatures through their gravitational interactions with the baryonic galaxy, such as heating of the thin disk, disruption of wide binaries, disturbance of extended tidal streams etc.
- The stellar halo is formed from disrupted satellite galaxies
- Minor mergers (a mass ratio of ~ 20% between the satellite and the disk) into a disk continue after the last 'major merger', and heat it, forming a thick disk out of a pre-existing thin disk, and create torques that drive gas into the central (bulge?) regions
- More significant mergers transform a disk galaxy into an S0 or even an elliptical
- Subsequent accretion of gas can reform a thin disk
- Stars can be accreted into the thin disk from suitably massive satellites (dynamical friction must be efficient) and if to masquerade as stars formed in the thin disk, must be on suitable high angular momentum, prograde orbits

3.3. The Fossil Record: Tests of Predictions

Stars of mass like the Sun, and lower, live for essentially the age of the Universe, and retain memory of many aspects of the conditions at early times. Studying old stars nearby thus allows us to study cosmology locally, a very complementary approach to direct study of high-redshift objects. There are copious numbers of stars in Local Group galaxies that have ages of greater than 10 Gyr, and thus formed at lookback times equivalent to redshifts of 1.5 and greater (see Figure 1).

The clues to galaxy evolution that one might wish to extract from the local fossil record include the star formation history, the form of the stellar Initial Mass Function and whether or not it varied between then and now, chemical evolution, and the relative importances of dissipative gas physics versus dissipationless processes. The overall dark halo potential well depth and shape can be inferred from stellar (and gas) kinematics. There are aspects of the stellar populations that are less sensitive to details of baryonic physics – such as the ages of stars in the thick disk – and these can be used to constrain the merging history – is this compatible with ΛCDM? Is the Milky Way a typical galaxy?

Most galaxies in the local Universe are observed to cluster in loose groups like the Local Group (which in itself is unusual in CDM models, Governato et al. 1997). While lacking a giant elliptical, the Local Group hosts a reasonably diverse selection, with large disk galaxies of a range of bulge-to-disk ratios (The Milky Way, M31, M33), gas-rich and gas-poor satellites ranging from the compact elliptical M32 through the numerous extremely low surface brightness dwarf spheroidals (dSph). Do trends in inferred merging history etc for the Local Group galaxies match predictions?

We can address these questions with current and planned capabilities, with which the motions, spatial distributions, ages and chemical elemental compositions can be measured (with varying accuracies!) for individual stars in galaxies throughout the Local Group, plus additional complementary tracers such as HII regions and planetary nebulae.

What have we learnt so far?

4. Milky Way Large Scale Structure

4.1. The Thin Disk

The large-scale structure of the thin stellar disk is reasonably well modelled by a double exponential with scalelength of $\sim$ 3 kpc and scaleheight of $\sim$ 300 pc (for stars older than a few Gyr). Extrapolating this smooth structure with a local normalization for stellar surface density of $\Sigma_* \sim 35 M_\odot$ pc^{-2} (Kuijken & Gilmore 1989; Flynn et al. 2006) gives a total mass of around $6 \times 10^{10} M_\odot$. The interstellar medium contributes $\sim 10 M_\odot$ pc^{-2} locally, and has a rather different radial profile from the stars, with atomic and molecular gas each having a distinct spatial distribution.

Stellar metallicity and age distributions are best-known at present for the local disk, within around one kpc of the solar circle. As noted above, Strömgren photometry has proven a robust technique of metallicity determination for large samples of F/G dwarfs, confirming the 'G-dwarf problem' in the local disk i.e. a narrow metallicity distribution, with few stars significantly more metal-poor than the peak, in contradiction to the large metal-poor tail predicted by the simplest chemical evolution models (e.g. Wyse & Gilmore 1995; Rocha-Pinto & Maciel 1996; Nordström et al. 2004). The peak metallicity of long-lived stars in the solar neighbourhood is somewhat below the solar value, ~ -0.15 dex, with good agreement between G-dwarfs and lower-mass K-dwarfs (Kotoneva et al. 2002). High-resolution spectroscopic studies of necessarily smaller samples provides a peak iron abundance of ~ -0.1 dex (Allende-Prieto et al. 2004).

The star formation history of the *local* stellar disk has been estimated through various techniques, and the general conclusion is for an early onset, an approximately constant overall rate, and with low-amplitude (factor of two) bursts on (few?) Gyr timescales (e.g. Hernandez, Valls-Gabaud & Gilmore 2000; Rocha-Pinto et al. 2000). There is cer-

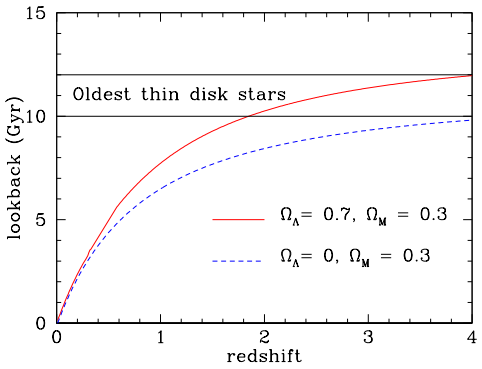

Fig. 1. Plot of lookback time versus redshift for two cosmological models, as labelled, each with present value of the Hubble constant of 70 km/s/Mpc. The horizontal lines indicate estimates of the ages of the oldest stars in the thin disk, from Binney et al. (2000).

tainly no lack of old stars in the local thin disk, a location that is some 3 scalelengths from the Galactic center. Assuming these stars formed in the thin disk, one concludes that an extended thin disk was in place at a redshift of around 2 (corresponding to the look-back time of 10–12 Gyr estimated for the onset of star formation in the local disk; Binney, Dehnen & Bertelli 2000). This is significantly earlier than a typical extended thin disk would form in CDM models.

Complementary data for external disk galaxies of similar scale-length to the Milky Way (half-light radii of between 5kpc and 7kpc) show little evolution in size or number back to a redshift of unity (the limit of the data, for the COSMOS survey sample of Sargent et al. 2006). Hence, extended disks do not seem to *start* forming at $z \sim 1$, but rather to be well-established by then. Models in which a significant part of the old thin stellar disk is formed by the later addition of old stars by satellite accretion directly into high-angular momentum orbits in the disk plane (e.g. Abadi et al. 2003) need to address this.

4.2. The Thick Disk

The large-scale structure of the thick stellar disk is (probably!) reasonably well modelled by a double exponential, with scalelength of $\sim$ 3 kpc and scaleheight of $\sim$ 1 kpc, giving an axial ratio that is a factor of three or so 'fatter' than the thin disk. Extrapolating this smooth structure with a local normalization of around 5% gives a total mass of around 15% of that of the thin stellar disk.

Again the metallicity and age distributions are best determined at present only fairly locally, within a few kpc of the Sun, both vertically and radially. The tails of the derived kinematic and metallicity distributions overlap with those of the thin disk, so there is the danger in very local samples of being overwhelmed by the much more numerous thin disk stars. Defining a thick disk sample *in situ*, for example above $\sim$ 1 kpc vertically from the disk plane, provides an effective filter. Such samples find a thick disk peak metallicity of ~ -0.6 dex, and that essentially all the stars have an age as old as the globular cluster of the same metallicity as the stars, or some 10-12 Gyr (e.g. Gilmore & Wyse 1985; Gilmore, Wyse & Jones 1995; see also Ratnatunga & Freeman 1989; Morrison, Flynn & Freeman 1990). Local proper-motion selected samples find similar results (e.g. Carney, Latham & Laird 1989), albeit with alternative interpretations (e.g. Norris & Ryan 1991).

The extension of the metallicity distribution of the thick disk to metallicities significantly below ~ -1 dex (e.g. Morrison, Flynn & Freeman 1990) remains topical, with its most robust detection in samples selected by having low metallicity, and thus with uncertain normalization to the main peak (e.g. Chiba & Beers 2000).

As discussed in Sofia Felzing's contribution, the stars in the local thick disk follow a distinct elemental abundance pattern, offset from stars in the thin disk (defined kinematically). This presumably reflects the different star formation histories of these two components, the thick disk having a (significantly) shorter duration of star formation. A well-defined separation of populations on the basis

of elemental abundance patterns holds much promise for identification of substructure and tracing the history of the Galaxy (cf. Freeman & Bland-Hawthorn 2002).

The thick disk has kinematics that are intermediate between those of the thin disk and stellar halo: a typical local thick disk star is on a fairly high angular momentum orbit, with a lag behind the mean azimuthal (rotational) velocity of the old thin disk of only $\sim 30-50$ km/s. The vertical velocity dispersion is around 45 km/s, hotter than can be achieved through heating the thin disk by local gravitational perturbations such as Giant Molecular Cloud complexes and/or transient spiral arms.

The dominant old age of stars in the thick disk, $\sim$ 11 Gyr, combined with the large age range of stars in the thin disk, argues against models in which the thick disk forms from the thin disk by a heating process that occurs over an extended period. If the heating is merger-induced (the minor-merger scenario for formation of the thick disk from a pre-existing thin disk), then the last significant merger into the thin disk was long ago, at a redshift $\sim$ 2, corresponding to a lookback time of $\sim$ 11 Gyr. This is unusually long ago in ΛCDM models, particularly when one remembers that for sufficient heating of the thin disk, the 'significant' merger need only have mass equal to 20% of the *disk* mass, not the total mass.

In any merger-model for the formation of the thick disk, there will be a contribution to 'the thick disk' from stars removed from the culprit satellite(s). Indeed, in some models tidal debris from shredded satellite galaxies is a very significant part of 'the thick disk' (e.g. Abadi et al. 2003). However, the high peak metallicity of the thick disk stars suggests that these stars formed within a fairly deep potential well, particularly given their old age; as an example, while the LMC has managed to self-enrich to a similar metallicity, [Fe/H]~ -0.6 dex, this is for stars only a few Gyr old. The putative satellites in which the majority of thick disk stars formed would have to be extremely different from those surviving satellites.

The evidence from observations of high-redshift systems is limited, but there has been a recent detection of what appears to be a kinematically hot (i.e. expected to be thick) stellar disk forming in a burst of star formation at a redshift of greater than 2 (Genzel et al. 2006). More nearby galaxies too appear to contain old thick disks (Mould 2005; Yoachim & Dalcanton 2005), not dissimilar to that of the Milky Way.

Identifying the analogue (if one exists) of the Milky Way thick disk in M31 is complex, due in part to the pervasive inhomogeneities in stellar surface densities (Ferguson et al. 2002) and disparate lines-of-sight with spectroscopic and deep photometric information. Is the 'spheroid' component with [Fe/H]~ -0.6 the thick disk in M31 (e.g. Wyse & Gilmore 1988)? Or is it more associated with the outer disk (Brown et al. 2006), and contains stars of a wide range of ages, thereby compatible with a more extended merger history than the Milky Way?

The lower-mass spiral galaxy M33 appears to have had a very quiescent life, with little evidence for significant mergers or interactions. While a trend between merging history and total mass is expected in ΛCDM, such that lower mass dark haloes have fewer recent mergers (e.g. Maller et al. 2006), it remains to be seen if the Milky Way, M31 and M33 can be produced easily.

4.3. The Central Bulge

The smooth structure of the central bulge is mildly triaxial, i.e. barred, with axial ratios of $\sim 1 : 0.35 : 0.3$ (Bissantz & Gerhard 2002). The profile is reasonably well-fit by an exponential, with scaleheight $\sim$ 300 pc, and thus the Milky Way bulge is not a classical '$r^{1/4}$-bulge' but rather perhaps a 'pseudo-bulge', often found in later-type spiral galaxies (e.g. Carollo, Stiavelli & Mack 1998). The total stellar mass of the bulge is $\sim 10^{10}$ M$_\odot$, and the central regions are very baryon-dominated (Bissantz, Debattista & Gerhard 2004).

The stellar populations have been studied mostly in 'windows' of low optical extinction. The peak spectroscopic metallicity from samples of K-giants is somewhat below the solar value (e.g. McWilliam & Rich 1994; Ibata &

Gilmore 1995; Fulbright, McWilliam & Rich 2006a), similar to the long-lived stars in the local thin disk. The dominant age is old, again 10-12 Gyr, with younger stars in lower latitude central regions (e.g. Ortolani et al. 1995; Feltzing & Gilmore 2000; Kuijken & Rich 2002; van Loon et al. 2003). The coincidence in age with the thick disk may point to one merger event to set the physical conditions for both components: the gas driven to the centre during the merger that heated the thin disk to form the thick disk, would form the bulge (e.g. Wyse 2001).

Determinations of elemental abundances are limited to small samples of K-giants (typically around 50 stars), and are consistent with enrichment by (normal IMF) Type II supernovae only, i.e. the stars formed in only a short duration of star formation (e.g. Fulbright, McWilliam & Rich 2006b; Zoccali et al. 2006). This short duration agrees with earlier inferences from more limited data (e.g. Matteucci & Brocato 1990; Rich 1999; Ferreras, Wyse & Silk 2003).

The low-mass end of the IMF in the bulge can be studied by direct star counts, with the result (Zoccali et al. 2000) that it is indistinguishable from that in (dynamically unevolved) metal-poor globulars. The low-mass IMF in the Ursa Minor dwarf Spheroidal galaxy (Wyse et al. 2002) is also indistinguishable from that in metal-poor globular clusters, and again the elemental abundances in dSph do not require any variations in massive-star IMF. The IMF seems remarkably invariant with metallicity, epoch of star formation, (present) stellar density etc.

Models of how the bulge in the Milky Way formed generally appeal either to its 'pseudo-bulge' density profile and triaxial shape to argue for an instability in the inner disk (in which case the formation of the bulge could have occurred significantly after the formation of the stars themselves), or to its rapid enrichment and high density to argue for an *in situ* starburst (e.g. Elmegreen 1999; see the review in Wyse 1999).

4.4. The Stellar Halo

The large-scale structure of the inner regions, within $\sim$ 15 kpc of the Galactic center is the best-constrained at present. The dominant population is old and metal-poor, with the stars on low angular momentum orbits. The overall density profile (traced by RR Lyrae stars) shows a smooth power-law fall-off with distance (measured in the disk plane) of $\rho_{RRL} \propto R^{-3.1}$ out to $\sim$ 50 kpc (Vivas & Zinn 2006). The stellar halo as traced by main sequence F/G stars and RR Lyrae stars is not spherical, but can be reasonably well fit by an oblate spheroid, with flattening at around the solar distance of $c/a \sim 0.5$ (Hartwick 1987; Wyse & Gilmore 1989) becoming rounder with distance, and approximately spherical at $R \gtrsim 20$ kpc (Vivas & Zinn 2006). The total stellar mass in this smooth distribution is $\sim 2 \times 10^9$ $M_\odot$ (e.g. Carney, Latham & Laird 1990). Hints of triaxiality are seen in deep imaging data, as discussed in the meeting by Heidi Newberg.

Both the age distributions (Unavane, Wyse & Gilmore 1996) and the elemental abundance patterns (Fulbright 2002; Stephens & Boesgaard 2002; Tolstoy et al. 2003; Venn et al. 2004) of the bulk of the field halo stars are very different from those in the present satellite galaxies of the Milky Way (with the abundance pattern consistent with the expectations from the extended star formation histories). Accretion of stars from systems like the satellite galaxies, into the field halo, is limited to less than 10% since a redshift of unity (Unavane et al. 1996). The rare halo stars with extremely high velocities, probing the outer halo, have lower values of [α/Fe], more similar to the stars in the dSph, but the overall abundance pattern remain different (Fulbright 2002).

The abundance ratios of lighter metals in the field halo stars show remarkably little scatter down to the lowest metallicities (e.g. Cayrel et al. 2004), defining a flat 'Type II plateau' in [α/Fe] and indicating that the stars formed in systems with only a short duration of star formation, allowing enrichment by only the short-lived progenitors of Type II supernovae.

The value of a predicted 'Type II plateau' in [α/Fe] depends on the massive-star IMF (see e.g. Wyse & Gilmore 1992), and the low amplitude of scatter indicates an invariant IMF.

The mean metallicity of the stellar halo is around -1.5 dex (e.g. Ryan & Norris 1991), significantly lower than the local (gas-rich) disk. With a fixed stellar initial mass function, and no gas flows, one expects a system of low gas fraction, such as the stellar halo, to be *more* chemically evolved than a system with higher gas fraction. Hartwick (1976) provided an elegant explanation to this conundrum: gas outflows from active star-forming regions in the proto-halo. The chemical evolution requirements are such that for a fixed stellar IMF, one that matches the local thin disk mean metallicity of just below the solar value, the outflows must occur at around 10 times the rate of star formation. An attractive corollary to this picture is that one can tie the gas outflow from low-mass halo star-forming regions to gas inflow to the central regions to form the bulge; the low angular momentum of halo material means that it will only come into centrifugal equilibrium after collapsing in radius by a significant factor. The mass ratio of bulge to halo is around a factor of ten, just as would be expected, and the specific angular momentum distributions of stellar halo and bulge match (Wyse & Gilmore 1992; see Figure 2 here).

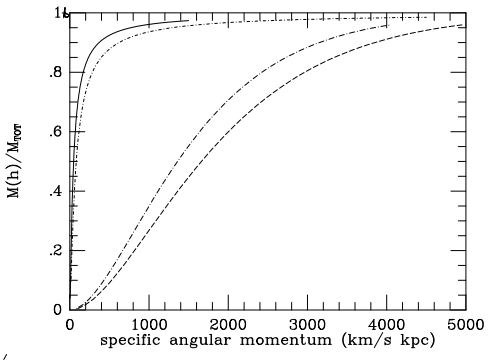

Fig. 2. Adapted from Wyse & Gilmore 1992, their Figure 1. Angular momentum distributions of the bulge (solid curve), the stellar halo (short-dashed/dotted curve), the thick disk (long-dashed/dotted curve) and the thin disk (long-dashed curve). The bulge and stellar halo have similar distributions, as do the thick and thin disks.

5. Small-Scale Structure

5.1. The Outer Stellar Halo

The outer halo, with dynamical timescales of > 1 Gyr, is the best location to search for structure. Indeed, several streams have been found, in both coordinate space and in kinematics. Most of these appear to be due to the Sagittarius Dwarf Spheroidal (Sgr dSph), a galaxy that was discovered serendipitously during a survey of the kinematics and metallicity distributions of stars in the Milky Way bulge (Ibata, Gilmore & Irwin 1994, 1995). Extended tidal streams from the Sgr dSph are now detected across the sky (Ibata et al. 2001; Majewski et al. 2003; Belokurov et al. 2006a). These are potentially extremely useful in constraining the shape and smoothness of the dark halo potential, although we are in the interesting situation of contradictory conclusions from different datasets (e.g. Helmi 2004; Johnston, Law & Majewski, 2005; Fellhauer et al. 2006).

The detection and characterization of structure in the stellar halo is a very fast-moving field! As described further in Heidi Newberg's talk in this volume, several (of order 10) candidate new dSph, globular clusters and streams (including at least one stream from a disrupting globular cluster – not all streams indicate accretion from an external source) have been announced this year, all exploiting the Sloan Digital Sky Survey imaging data (e.g. Belokurov et al. 2006a,b; Grillmair 2006). Determining the *masses* of the new putative satellite galaxies is crucial before one can say what impact these discoveries have on the 'satellite problem' of ΛCDM models – namely the over-prediction by the models of satellite-galaxy mass dark haloes. At present, the available radial velocity data internal to the dSph companions of the Milky Way are consistent with each dSph being embedded in a dark halo of *fixed mass*, of $\sim 4 \times 10^7$ $M_\odot$ (Wilkinson et al. 2006), out to the extent of the stars (saying nothing about the extent, or mass, at radii beyond available stellar kinematic data).

While it is reasonably easy, theoretically, to modify the baryon content of shallow potential well systems such as the satellite haloes and thus change their luminosity function, it is much harder to conceive of modifications to the predicted mass function of satellite haloes to match a narrow range in mass.

5.2. The Thick Disk

As noted above, a popular model for the formation of the thick disk is based on a minor merger into a pre-existing thin disk, with the orbital energy in large part going into heating the thin disk. The satellite galaxy (or galaxies) responsible for the heating does not survive unscathed, but will in general be tidally disrupted, the mass of any surviving remnant being set by how deeply it penetrates and the relative density compared that of to the larger (Milky Way) galaxy. The 'shredded satellite' stars will likely contribute to the stellar populations above the thin disk plane, and thus be included in samples of 'thick disk' stars. The spatial distribution of satellite debris will reflect the orbit of the satellite, and its (relative) density profile (e.g. Huang & Carlberg 1997, their Fig. 19; Abadi et al. 2003).

Such satellite debris has been identified, on the basis of distinct kinematics, namely lower angular momentum than the bulk of thick disk stars, in at least one sample of turnoff stars observed several kpc from the disk plane (Gilmore, Wyse & Norris 2002).

The details of the stellar populations in the thin disk – thick disk – halo transition region contains much information about the past merger history of the Milky Way. Large samples (many thousands) of stars are needed; we (Gilmore, Wyse & Norris) have undertaken a moderate survey with the new multi-object spectrograph on the Anglo-Australian Telescope, AAOmega, targeting $\sim 13,000$ F/G stars in the equatorial stripe of the imaging data of SDSS DR4. Results from the SDSS spectroscopic database are presented by Ivezić in this volume. The Galactic structure survey of the Sloan Digital Sky Survey Extension (SDSS-II/SEGUE) is also on-going.

5.3. The Thin Disk

The possibility that a significant fraction of old stars found now in the thin disk were formed in satellite galaxies that were subsequently accreted into the disk plane was suggested by the simulations of Abadi et al. (2003). A typical satellite orbit is far from circular in the disk plane (e.g. Benson 2005) so that this scenario requires that the satellites be massive enough for dynamical friction to damp the vertical orbital motion and circularize their orbit quickly enough, and it remains to be seen if, for example, the chemical composition of the satellite stars matches those observed in the old disk.

Ongoing large-scale spectroscopic surveys such as RAVE (targeting bright stars with the UK Schmidt Telescope of the Anglo-Australian Observatory and 6dF multi-object spectrograph; Steinmetz et al. 2006) and SDSS-II/SEGUE should provide ideal databases for an identification of kinematic substructure in the disk. The large Geneva/Copenhagen survey of the local disk (Nordström et al. 2004) is also a fertile hunting ground, with possible ancient substructure identified by Helmi et al. (2006). The high-resolution mode of the proposed multi-object spectrograph (WFMOS) for Gemini will provide unprecedented elemental abundance data, containing much more information than overall metallicity, and with signatures that persist longer than spatial or even most kinematic features.

The 'ring' around the Galaxy seen in star counts (e.g. Yanny et al. 2003; Ibata et al. 2003) could be either a remnant of satellite accretion into the plane of the disk (e.g. Bellazzini et al. 2006 and references therein) or more simply structure in the outer stellar disk, which most probably warps and flares (e.g. Momany et al. 2006 and references therein). Indeed the rich structure in HI gas in the outer disk may be seen in the Leiden/Argentine/Bonn HI survey (Kalberla et al. 2005). Even the old disk is unlikely to be well-fit by a smooth model, given the strong spiral structure seen in K-band images of external spirals (Rix & Zaritsky 1995).

Indeed, the fact that the underlying potential of the disk is neither smooth, axisymmetric nor time-independent cannot be ignored. As demonstrated by De Simone, Wu & Tremaine (2004)[2], transient perturbations, such as segments of spiral arms, not only heat the stellar disk, but can produce 'moving groups' that persist long after the gravitational perturbation has gone. These kinematic features are created from random collections of disk stars, and so will contain a range of ages and metallicities. Interestingly, such moving groups have been identified (Famaey et al. 2004).

6. Survey Requirements

I hope my brief survey of surveys has demonstrated that the field of 'Galactic Structure' is vibrant and exciting. While much has been learnt, much remains to be learnt. Future large surveys are needed to quantify both small-scale and large-scale structures. These surveys should be based on input catalogues with excellent and uniform multi-band photometry and also excellent astrometry, to give accurate and precise positions and proper motions. One can envisage a hierarchy of surveys, each providing input to the next level.

Immediately from imaging data one can analyse the spatial structure, in colour/magnitude space. Spectroscopic targets can also be defined, with a well-understood and uniform selection function across the sky.

Medium resolution spectroscopy (few Å resolution), providing radial velocities to a few km/s and metallicities to $\sim$ 0.2 dex, should be obtained for several hundreds of stars in each each line-of-sight, allowing the analysis to go beyond the means and dispersions of present surveys, and to look at the structure in the kinematic and metallicity distributions. Metallicity estimates are necessary for improved photometric parallaxes and space motions from proper motions. The sampling strategy – for example, sparse sampling, or overlapping fields? Stripes in longitude or one large contiguous area at high latitude, etc – plus the selection function – K-giants? F/G dwarfs? – should be tuned to the science goals. Observations in the IR may be required to probe the bulge, plus the lowest-latitude disk.

High resolution spectra should be obtained for the brighter stars, for elemental abundances and precise velocities. This allows mapping of substructures defined by kinematics and star formation history/chemical evolution. Again, large samples are required, and a multi-object spectrograph such as the proposed WFMOS Gemini instrument is ideal. This is discussed further in this volume by Joss Bland-Hawthorn.

These are indeed exciting times to study stars in Local Group galaxies.

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[2] Their analysis was based on a shearing sheet, only the $z = 0$ plane. A 3D analysis would be very interesting.

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