Galactic Structure

By **ROSEMARY F.G. WYSE**

Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA

Our Milky Way Galaxy is a typical large spiral galaxy, representative of the most common morphological type in the local Universe. We can determine the properties of individual stars in unusual detail, and use the characteristics of the stellar populations of the Galaxy as templates in understanding more distant galaxies. The star formation history and merging history of the Galaxy is written in its stellar populations; these reveal that the Galaxy has evolved rather quietly over the last ~ 10 Gyr. More detailed simulations of galaxy formation are needed, but this result apparently makes our Galaxy unusual if ΛCDM is indeed the correct cosmological paradigm for structure formation. While our Milky Way is only one galaxy, a theory in which its properties are very anomalous most probably needs to be revised. Happily, observational capabilities of next-generation facilities should, in the the forseeable future, allow the aquisition of detailed observations for all galaxies in the Local Group.

---

1. Introduction: The Fossil Record

The origins and evolution of galaxies, such as our own Milky Way, and of their associated dark matter haloes are among the major outstanding questions of astrophysics. Detailed study of the zero-redshift Universe provides complementary constraints on models of galaxy formation to those obtained from direct study of high-redshift objects. Stars of mass similar to that of the Sun live for essentially the present age of the Universe and nearby low-mass stars can be used to trace conditions in the high-redshift Universe when they formed, perhaps even the 'First Light' that ended the Cosmological Dark Ages. While these stars may well not have formed in the galaxy in which they now reside (especially if the CDM paradigm is valid), several important observable quantities are largely conserved over a star's lifetime – these include surface chemical elemental abundances (modulo effects associated with mass transfer in binaries) and orbital angular momentum (modulo the effects of torques and rapidly changing gravitational potentials). Excavating the fossil record of galaxy evolution from old stars nearby allows us to do Cosmology locally, and is possible to some extent throughout the Local Group, with the most detailed information available from the Milky Way Galaxy.

I here discuss our knowledge of the stellar populations of the Milky Way and the implications for models of galaxy formation. Complementary results for M31 are presented by Brown (this volume).

2. Large Scale Structure of the Stellar Components of the Galaxy

There are four main stellar components of the Milky Way Galaxy.

♡ The thin stellar disk: This is the most massive stellar component of the Milky Way, and contains stars of a wide range of ages and is the site of on-going star formation. A defining quality of the thin disk is that the stars are on orbits of high angular momentum, close to circular orbits. The age distribution of thin disk stars is not well determined even at the solar circle, but there are clearly old, ~ 10 Gyr, thin disk stars in the local vicinity.

♡ The thick stellar disk: This component, established some 20 years ago, has a scale-height around 3 times that of the thin disk. Again its properties are best established close to the solar Galactocentric distance; here the local thick disk consists of old stars, that are on average of lower metallicity than that of a typical old star in the thin disk, and are on orbits of lower angular momentum.

♡ The central bulge: This component is very centrally concentrated and mildly triaxial with rotational energy close to the expected value if it were an oblate, isotropic rotator. The dominant stellar population is old and metal-rich.

♡ The stellar halo: The bulk of the stars are old and metal-poor, on low angular-momentum orbits. A few percent of the stellar mass is in globular clusters

2.1. *Large Scale Structure of the Thin Disk*

Our knowledge of the stellar populations in the thin disk is in fact rather poor, with only very limited data on age distributions and metallicity distributions in either the inner disk or the outer disk. At the solar neighbourhood, the gross characteristics of the metallicity distribution of the thin disk have been known for a long time – the narrow distribution (peaking somewhat below the solar metallicity) giving rise to the 'G-dwarf Problem', or the deficit of metal-poor stars compared to the predictions of the Simple closed-box model of chemical evolution e.g. van den Bergh 1962; Pagel & Patchett 1975. The favoured solution to this 'problem' is to lift the 'closed-box' assumption, in particular to allow inflow of unenriched gas (cf. Larson 1972). Such inflow is rather natural in many models of disk formation and evolution (see Tosi's contribution to this volume).

The age distribution of stars in the thin disk is particularly important in setting the epoch of the onset of disk formation (assuming that the bulk of the old stars now in the thin disk were formed in the thin disk – see Steinmetz's contribution to this volume for an alternative view). In Cold-Dark-Matter-dominated cosmologies, the merging by which galaxies grow involves gravitational torques and dynamical friction, which result in significant angular momentum transport away from the central parts of dark matter haloes and their associated galaxies, and into the outer parts. This re-arrangement of angular momentum is particularly effective if the merging involves dense, non-dissipative (i.e. stellar and/or dark matter) substructure (cf. Zurek, Quinn & Salmon 1988; Zhang et al. 2002).

However, extended galactic disks as we observe them require detailed angular momentum *conservation* during the dissipative collapse and spin-up of proto-disk gas, within a dominant dark halo (cf. Fall & Efstathiou 1980). The angular momentum transport inherent in the merging process in a CDM-universe results in disks that are too concentrated and have radial scale-lengths that are too short (cf. Navarro, Frenk & White 1995; Navarro & Steinmetz 1997). A proposed solution to this problem delays the formation of stellar disks until after the epoch of most merging, with 'stellar feedback' as the proposed mechanism for the delay (cf. S. Cole et al. 2000). A delay in radiative cooling – the very first stage of stellar disk formation – until after a redshift of unity, or lookback times of $\sim$ 8 Gyr, is apparently required (Eke, Efstathiou & Wright 2000). This has the obvious side-effect that the extended disks that eventually form should contain few old stars. Further, the theoretical prediction is that disks form from the inside-out, with lower angular momentum gas settling to the (inner regions of the) disk plane earlier and only later settling of higher angular momentum material, destined to form the outer disk. The solar circle is some 2–3 exponential scale lengths from the Galactic center, and thus forms later than the inner disk. Detailed predictions are lacking (and should be made), but allowing for 1 Gyr for cooling and star formation, the expectation from this delay in disk formation would then be that there should be very few stars in the local thin disk that are older than $\sim$ 7 Gyr.

Distances and kinematics derived for nearby stars from parallaxes and proper motions from the Hipparcos satellite has allowed the determination of the colour-absolute magnitude diagram for thin disk stars. Analysis of the locus in the CMD of subgiant stars gives a lower limit to the age of the oldest stars of 8 Gyr, obtained with an adopted upper limit to the metallicity of [Fe/H] = +0.3 (Jimenez, Flynn & Kotoneva 1998; Sandage, Lubin & VandenBerg 2003); the age limit increases approximately 1 Gyr for every 0.1 dex decrease in the adopted metallicity (to set the age scale, the VandenBerg isochrones used give ages of $\gtrsim 13$ Gyr for metal-poor globular clusters). Analysis of the main sequence turn-off stars in the Hipparcos dataset provides a best-fit age for the oldest disk stars of $\gtrsim 11$ Gyr (Binney, Dehnen & Bertelli 2000), adopting a metallicity distribution that peaks below the solar value and using isochrones that provide an age of $\gtrsim 12$ Gyr for metal-poor globular clusters. It is clear that metallicity determinations for the Hipparcos sample are needed before a definitive value for the age of the oldest disk stars can be derived, but one should note that the available metallicity distributions, mostly for G/K dwarfs, all peak at [Fe/H] = −0.2 (e.g. Kotoneva et al. 2002), distinctly more metal-poor than the +0.3 dex that gave the lower limit in age of 8 Gyr for the oldest stars. An older age is then expected.

An alternative technique to derive ages uses the observed white dwarf (WD) luminosity function combined with theoretical models of white dwarf cooling. Hansen et al. (2002; see also Richer's contribution to this volume) analysed the disk WD luminosity function of Leggett et al. (1998) together with their own data for the WD sequence in the globular cluster M4. They derived a ~ 5 Gyr gap between the formation of M4 and the birth of the oldest disk stars, with ages of ~ 13 Gyr and ~ 8 Gyr respectively. However, completeness remains an issue for the disk WD luminosity function, and different determinations are available and provide older ages and less of a gap in age (e.g. Knox, Hawkins & Hambly 1999). Indeed, a recent re-analysis of the M4 data (De Marchi et al. 2003) has demonstrated that with a re-assessment of the errors, the derived WD luminosity function is in fact still rising at the last point and so only a lower limit in age, $\gtrsim 8$ Gyr, can be derived. Clearly more and better data are needed, and should be available, from the ACS on HST for M4, and from surveys such as SDSS for the faint, local disk WDs.

The star formation history of the local disk that is derived from the Hipparcos CMD (Hernandez, Valls-Gabaud & Gilmore 2000) has an amplitude that shows a slow overall decline, with quasi-periodic increases of a factor of a few on timescales of ~ 1 Gyr. This result is consistent with other age indicators such as chromospheric activity (Rocha-Pinto et al. 2000), and with chemical evolution models.

The available data are then all consistent with a significant population of stars in the local disk with ages ~ 8 Gyr, and perhaps as old as 11 Gyr. If these stars formed in the disk, then the formation of extended disks was *not* delayed until after a redshift of unity, as was proposed to 'solve' the disk angular momentum problem in CDM models.

The outer disk of M31 also contains old stars (Ferguson & Johnson 2001; Guhathakurta this volume) and similar conclusions hold. Further, deep, high-resolution IR observations have revealed apparently relaxed disk galaxies at $z \gtrsim 1$ (Dickinson 2000), which presumably formed at least a few dynamical times earlier. Indeed, a candidate old disk has been identified at $z \sim 2.5$ (Stockton et al. 2003).

2.2. *Large Scale Structure of the Thick Disk*

The thick disk was defined through star counts 20 years ago (Gilmore & Reid 1983) and is now well-established as a distinct component. Its origins remain the source of considerable debate. Locally, some $\sim 5\%$ of stars are in the thick disk; the vertical scale-height is ~ 1 kpc, and radial scale-length ~ 3 kpc. Assuming a smooth double-exponential spatial distribution with these parameter values, the stellar mass of the thick disk is 10–20%.

of that of the thin disk (the uncertainty allowing for the uncertainty in the structural parameters), or some $10^{10}M_{\odot}$.

Again the properties of the stellar populations in this component are rather poorly known far from the solar neighborhood. Locally, within a few kpc of the Sun, the typical thick disk star is of intermediate metallicity, [Fe/H] ~ -0.6 dex, and old, with an age comparable to that of 47 Tuc, the globular cluster of the same metallicity, $\sim$ 12 Gyr (see e.g. review of Wyse 2000). Detailed elemental abundances are now available for statistically significant sample sizes. These show that the pattern of elemental abundances differs between the thick and thin disks, with different values of the ratio [α/Fe] at fixed [Fe/H], implying distinct star formation and enrichment histories for the thick and thin disks (Fuhrmann 1998, 2000; Prochaska et al. 2000; Feltzing, Bensby & Lundström 2003; Nissen 2003; see Figure 1). Such a difference argues against the model (Burkert, Truran & Hensler 1992) whereby the thick disk represents the earliest stages of disk star formation during continuous, self-regulated dissipational settling of gas to the thin disk.

Thick stellar disks can be formed from pre-existing thin stellar disks by heating, and a (minor) merger of a reasonably dense and massive satellite galaxy into a pre-existing thin disk galaxy could be the heating mechanism (cf. Quinn, Hernquist & Fullagar 1993). In the merger, orbital energy is deposited in the internal degrees of freedom of both the thin disk and the satellite, and acts to disrupt the satellite and heat the disk. Depending on the orbit of the satallite, and on its density profile and mass (this last determines the dynamical friction timescale), tidal debris from the satellite will be distributed through the larger galaxy during the merger process. Thus the phase space structure of the debris from the satellite depends on many parameters, but in general one expects that the final 'thick disk' will be a mix of heated thin disk and satellite debris. The age and metallicity distributions of the thick disk can provide constraints on the mix.

Could the thick disk be dominated by the debris of tidally disrupted dwarf galaxies (cf. Abadi et al. 2003)? The removal of material from the satellite occurs under essentially the Roche relative density criterion, so that one expects that the lower density, outer parts of accreted dwarfs will be tidally removed in the outer parts of the larger galaxy, with the inner, denser regions of the dwarf only being removed if the dwarf penetrates further inside the larger galaxy. As noted above, the local (within a few kpc of the Sun) thick disk is old and quite metal-rich, with a mean iron abundance ~ -0.6 dex. Further, the bulk of these stars have enhanced, super-solar [α/Fe] abundances (Fuhrmann 1998, 2000; Prochaska et al. 2000; Feltzing et al. 2003; see Figure 1). Achieving such a high level of enrichment so long ago (the stellar age equals the age of 47 Tuc, at least 10 Gyr, as noted above), in a relatively short time – so that Type II supernovae dominate the enrichment, as evidenced by the enhanced levels of [α/Fe]) – implies a high star formation rate within a rather deep overall potential well. This does not favor dwarf galaxies.

Indeed, the inner disk of the LMC, our present most massive satellite galaxy, has a derived metallicity distribution (Cole, Smecker-Hane & Gallagher 2000) that is similar to that of the (local) thick disk, but, based on the color-magnitude diagram, these stars are of intermediate age. Thus the LMC apparently took until a few Gyr ago to self-enrich to an overall metallicity that equals that of the typical local thick disk star in the Galaxy. Further, the abundances of the α-elements to iron in such metal-rich LMC stars are below the solar ratio (Smith et al. 2002), unlike the local thick disk stars. This may be understood in terms of the different star-formation histories (cf. Gilmore & Wyse 1991). The LMC is not a good template for a putative dwarf to form the thick disk from its debris.

What about the Sagittarius dwarf, a galaxy that has clearly penetrated into the disk?

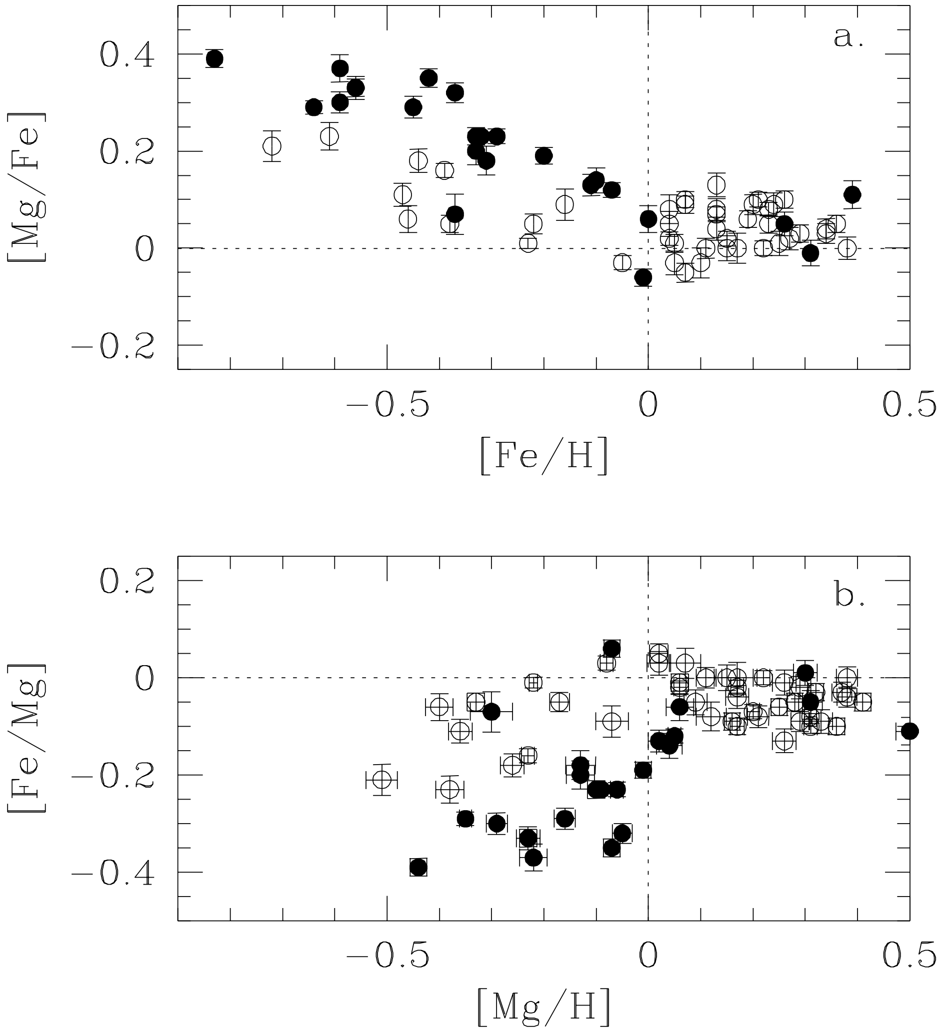

FIGURE 1. Taken from Feltzing et al. 2003, their Figure 2. Filled symbols represent stars whose kinematics are consistent with membership of the thick disk, while open symbols represent thin disk stars. The uncertainties in Mg abundance are indicated by the error bars; uncertainties in Fe are smaller than the symbol sizes. At a given value of [Fe/H], the thick and thin disk stars are separated, with thick disk stars having higher [Mg/Fe]. At the typical thick disk metallicity, [Fe/H]~ -0.5 dex, the value of [Mg/Fe] in thick disk stars is equal to that seen in the stellar halo, and consistent with enrichment by Type II supernovae. More metal-rich thick disk stars show some enrichment by iron-dominated ejecta from Type Ia supernovae.

From photometry the stars are on average quite enriched and of intermediate age (cf. the discovery paper of Ibata, Gilmore & Irwin 1994, where the member stars were clearly distinguished from the bulge field stars; see also Layden & Saradejini 2000 and Cole 2001). The overall metallicity distribution of the Sagittarius dwarf spheroidal galaxy is not well defined, but it contains a significant population of stars with metallicity as high as the solar value (Bonifacio et al. 2000; Smecker-Hane & McWilliam 2003). One of its globular clusters, Terzian 7, has a metallicity equal to that of 47 Tuc, but an age several Gyr younger (Buonannno et al. 1995), and thus by inference, several Gyr younger than the thick disk stars of the same metallicity. The derived age-metallicity relationship for the Sgr dSph, based on both the CMD (Saradejini & Layden 2000) and spectroscopy of selected red giants (Smecker-Hane & McWilliam 2003), is consistent with stars more metal-rich than [Fe/H] $= -0.7$ dex being less than 8 Gyr old. Further, these stars have essentially solar values of the ratio of $[\alpha/\mathrm{Fe}]$ (Bonifacio et al. 2000; Smecker-Hane & McWilliam 2003), and are thus different in several important properties from the local thick disk stars. The Ursa Minor dSph is the only satellite galaxy of the present retinue that contains only old stars, and thus has an age distribution similar to that of the local thick disk. However these are exclusively metal-poor, [Fe/H] ~ -2 dex, and again not a good match to thick disk stars.

Thus based on observations, there is no good analogue among the surviving dwarf galaxies for a possible progenitor of the thick disk. Theoretically, based on our (admittedly limited) understanding of supernova feedback, it seems very contrived to envisage a dwarf galaxy that had a deep enough potential well to self-enrich rapidly a long time ago, but that was sufficiently low density to be tidally disrupted to form the thick disk. One might argue that the satellites that were accreted earlier, initiated star formation earlier (e.g. Bullock, Kravtsov & Weinberg 2000) and were typically more dense and able to self-enrich faster. However, the analyses of deep color-magnitude diagrams for the extant satellites of the Milky Way are consistent with *all* containing stars as old as the stellar halo of the Milky Way (e.g. Da Costa 1999), implying that the onset of star formation was co-eval and there are no (surviving) satellites that initiated star formation earlier.

In summary, it appears implausible that the bulk of the thick disk is the debris of accreted dwarf galaxies.

Heating of a pre-existing thin disk by a minor merger remains a viable mechanism for creating the bulk of the thick disk (e.g. Velazquez & White 1999). In this case, the old age of the thick disk, combined with the fairly continuous star formation in the thin disk, has two important consequences – the first that there was an extended disk in place at a lookback time of greater than 10 Gyr, and the second that there has been no extraordinary heating – by mergers – of the thin disk since that time. Knowing the age distribution of stars in the thick disk – in both the observed thick disk and in predicted theoretical thick disks – is obviously crucial. Semi-analytic modelling of the heating of disks by merging of substructure in CDM cosmologies has shown that thin disks with reasonable scale-heights are produced at the present day (Benson et al. 2003). However the presence or otherwise of thick disks has yet to be demonstrated in such simulations. Further, predictions need to be made for the age distribution of member stars of the thick and the thin disk, to be confronted with the observations.

All this being said, some fraction of the metal-poor stars assigned to the 'thick disk', on the basis of having orbital kinematics that are intermediate between those of the stellar halo and those of the thin disk, may well be debris from a satellite (the one that caused the disk heating perhaps), and we return to this point below, in section 3.2.

2.3. *Large Scale Structure of the Central Bulge*

The metallicity distributions of low-mass stars in various low-reddening lines-of-sight towards the bulge (with projected Galactocentric distances of a few 100pc to a few kpc) have been determined spectroscopically (e.g. McWilliam & Rich 1994; Ibata & Gilmore 1995; Sadler, Terndrup & Rich 1996) and photometrically (e.g. Zoccali et al. 2003) with the robust result that the peak metallicity is [Fe/H] ~ -0.3 dex, with a broad range and a tail to low abundances (indeed the distribution is well-fit by the Simple closed-box model, unlike the solar neighborhood data). The available elemental abundances, limited to the brighter stars, show the enhanced [α/Fe] signatures of enrichment by predominantly Type II supernovae (McWilliam & Rich 1994; McWilliam & Rich 2003), indicating rapid star formation. Indeed the chemical abundances favor very rapid star formation and (self-)enrichment (Ferreras, Wyse & Silk 2003).

The age distributions derived from the analyses of deep HST and ISO color-magnitude diagrams – again over several degrees across the sky – are consistent with the dominant population being of old age $\gtrsim 10$ Gyr (Feltzing & Gilmore 2000 (HST); van Loon et al. 2003 (ISO); Zoccali et al. 2003 (HST)), confirming earlier conclusions from ground-based data (Ortolani et al. 1995). There is also a small intermediate-age component seen in the ISO data, and traced by OH/IR stars (Sevenster 1999), plus there is ongoing star formation in the plane. The interpretation of these younger stars in terms of the stellar populations in the bulge is complicated by the fact that the scale-height of the thin disk is comparable to that of the central bulge, so that membership in either component is ambiguous. Indeed the relation between the inner triaxial bulge/bar and the larger-scale bulge is as yet unclear (see Merrifield 2003 for a recent review). All that said, the dominant population in the bulge is clearly old and metal-rich.

In the hierarchical clustering scenario, bulges are built up during mergers, with several mechanism contributing. The dense central regions of massive satellites may survive and sink to the center; the dynamical friction timescale for a satellite of mass M_{sat} orbiting in a more massive galaxy of mass M_{gal} is $t_{dyn\,fric} \sim t_{cross} M_{gal}/M_{sat}$, where t_{cross} is the crossing time of the more massive galaxy. With $t_{cross} \sim 3 \times 10^8$ yr for a large galaxy, only the most massive satellites could contribute to the central bulge in a Hubble time. Gravitational torques during the merger process are also expected to drive disk gas to the central regions, and some fraction of stars in the disk will also be heated sufficiently to be 're-arranged' into a bulge (cf. Kauffmann 1996). The predicted age and metallicity distributions of the stars in the bulge are then dependent on the merger history; however a uniform old population is not expected.

An alternative scenario for bulge formation appeals to an instability in the disk, forming first a bar which then buckles out of the plane to form a bulge (e.g. Raha et al. 1991) or is destroyed by the orbit-scattering effects of the accumulation of mass at its center (e.g. Hasan & Norman 1990). Again one would expect a significant range of stellar ages in the bulge.

As noted above, the bulge is dominated by old, metal-rich stars. This favors neither of the two scenarios above, but rather points to formation of the bulge by an intense burst of star formation, *in situ*, a long time ago (cf. Elmegreen 1999; Ferreras, Wyse & Silk 2003). The inferred star formation rate is $\gtrsim 10 M_\odot$/yr. A possible source of the gas is ejecta from star-forming regions in the halo; the rotation of the bulge is consistent with collapse and spin-up of halo material (cf. Wyse & Gilmore 1992; Ibata & Gilmore 1995), and the chemical abundances are also consistent with the mass ratios (see Carney, Lathm & Laird 1990 and Wyse & Gilmore 1992).

2.4. *Large Scale Structure of the Stellar Halo*

The total stellar mass of the halo is $\sim 2 \times 10^9 M_\odot$ (cf. Carney, Laird & Latham 1990), modulo uncertainties in the stellar halo density profile in each of the outer halo, where substructure may dominate, and the central regions, where the bulge dominates. Some $\sim 30\%$ of the stars in the halo are on orbits that take them through the solar neighborhood, to be identified by their 'high-velocity' with respect to the Sun. These stars form a rather uniform population – old and metal-poor, with enhanced values of the elemental abundance ratio [α/Fe]. The dominant signature of enrichment by Type II supernovae indicates a short duration of star formation. This could naturally arise due to star formation and self-enrichment occuring in low-mass star-forming regions that cannot sustain extended star formation.

In contrast, the typical star in a dwarf satellite galaxy now is of intermediate-age, and has solar values of [α/Fe] (cf. Tolstoy et al. 2003). These differences in stellar populations between the field stellar halo and dwarf galaxies limit significant ($\gtrsim 10\%$ by mass) accretion into the stellar halo from satellite galaxies to have occurred at high redshift only, at lookback times greater than $\sim$ 8 Gyr (cf. Unavane, Wyse & Gilmore 1996). Typical CDM-models predict, in contrast, significant late accretion of sub-haloes, with around 40% of subhaloes that survive reionization falling into the host galaxy at redshifts less that $z = 0.5$, or a look-back time of less than 6 Gyr (Bullock, Kravtsov & Weinberg 2000). Again the later accretion is preferentially to the outer parts, and to be consistent with the observations of the Milky Way, these sub-haloes must contain very few young stars, and not over-populate the outer galaxy with visible stars.

2.5. *Large Scale Structure: Merging History*

The overall properties of the main stellar components of the Milky Way, as discussed above, can be understood if there was little merging or accretion of stars into the Milky Way for the last$\sim$ 10 Gyr (cf. Wyse 2001). How does this compare with 'merger trees' of N-body simulations? As an example, the publically available Virgo GIF ΛCDM simulations (Jenkins et al. 1998) have 26 final haloes with mass similar to that of the Milky Way – taken to be 2×10^{12} $M_\odot$. Of these, only 7% have not merged with another halo of at least 20% by mass since a redshift of 2, a look-back time of $\sim$ 11 Gyr in this cosmology (L. Hebb, priv. comm.). A merger with these parameter values could produce a thick disk as observed in the Milky Way. None of these 'Milky Way' analogues pass a more stringent mass ratio limit of no mergers more than 10% by mass (still capable of producing a thick disk, given appropriate orbit etc.) since a redshift of 2. Reducing the epoch of last significant merger to unity (a lookback time of 8 Gyr) and adopting a maximum merging mass ratio of 20%, makes the Milky Way more typical, with 35% of Milky Way analogues meeting these criteria. However reducing the highest mass ratio to 10%, while maintaining this lower look-back time limit, results in only 4% of Milky Way analogue haloes passing these criteria. The Milky Way appears to be rather unusual in the ΛCDM cosmology.

Note that predictions of smooth average 'universal' mass assembly histories (e.g. Wechsler et al. 2002) are not useful for this comparison, since these curves suppress the detailed information necessary to predict the effect of the mass accretion. More useful is the detailed merging history as a function of radius (cf. Helmi et al. 2003a), since ideally one would like to know what fraction of mergers can penetrate into the realm of the baryonic Galaxy.

3. The Small Scale Structure of the Stellar Components of the Galaxy

While there is no evidence for recent very significant mergers into the Milky Way, mergers are clearly happening, as best evidenced by the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1994, 1995; Ibata et al. 1997; see Majewski's contribution to this volume). While the present and past mass of the Sagittarius dSph are rather uncertain, its assimilation into the Milky Way is best classed as a 'minor merger', meaning mass ratio of less than 10%.

The small-scale structure in the Milky Way may reflect the minor-merger history – or may simply reflect inhomogeneities of different kinds.

3.1. *Small Scale Structure in the Thin Disk*

The small scale structure of the thin disk is rich and varied and includes stellar moving groups, the scatter in the age-metallicity relationship, spiral arms, the outer 'ring' structure and the central bar. All star formation appears to occur in clusters (e.g. Elmegreen 2002), which are then subject to both internally and externally driven dynamical processes that operate to disrupt them. Some clusters dissolve almost immediately star formation is initiated and some remain gravitationally bound for many Gyr. The creation of phase space structure is thus a natural part of the evolution of stellar disks.

The scatter in the age-metallicity relationship for stars at the solar neighborhood appears to be well-established (Edvardsson et al. 1993), as is the offset between the metallicity of the Sun, and of younger stars and the interstellar medium, in the solar neighbourhood, with the Sun being more chemically enriched. These may have their origins in some combination of radial gradients and mixing (e.g. Francois & Matteucci 1993; Sellwood & Binney 2002) and infall of metal-poor gas, from the general intergalactic medium, or perhaps from satellite galaxies (e.g. Geiss et al. 2002). It should be noted that further motivation for appeal to accretion events from satellite galaxies had been found in the scatter in element ratios at a given iron abundance in the Edvardsson et al. data. However, more recent data has instead suggested that a more correct interpretation is that the elemental abundances of stars belonging to the thick disk are distinct from those belonging to the thin disk (e.g. Nissen 2003; see also Gilmore, Wyse & Kuijken 1989 and Figure 1 above), with no scatter in elemental ratios within a given component.

The low-latitude 'ring' seen in star counts (Newberg et al. 2002; Ibata et al. 2003; Bellazzini et al. 2004) in the anticenter direction at Galactocentric distances of ~ 15 kpc may be structure in the outer disk, which has a well-established warp in the gas, and probably in stars (e.g. Carney & Seitzer 1993; Djorgovski & Sosin 1989). The recent detection of structure in HI, interpreted as a newly identified spiral arm, at just this distance (McClure-Griffiths et al. 2003) is intriguing. The ring may also be interpreted as resulting from the accretion of a satellite galaxy (e.g. Helmi et al. 2003b; Martin et al. 2004; Rocha-Pinto et al. 2003); a recent N-body hydrodynamic simulation within a ΛCDM cosmology has shown that it is possible for satellite galaxies to be accreted into a disk, provided they are massive enough for dynamical friction to circularize their orbit quickly enough (Abadi et al. 2003).

The available kinematics for 'ring' stars do not discriminate between the two possibilities of satellite or outer disk (Yanny et al. 2003; Crane et al. 2003). Given the complexity of the structure of outer disks, comprehensive color-magnitude data plus metallicity distributions plus kinematics will be needed to rule out the 'Occam's Razor' interpretation of the 'ring' as being a manifestation of structure in the outer disk.

The detailed structure of the thin disk will be revealed by large-scale spectroscopic surveys such as RAVE (Steinmetz 2003); the time is ripe to develop models that will distinguish between intrinsic structure due to the normal disk star formation process and other effects (cf. Freeman & Bland-Hawthorn 2002).

3.2. *Small Scale Structure in the Thick Disk*

As noted above, in the minor-merger scenario for formation of the thick disk, one expects the 'thick disk' to be a mixture of heated thin disk, plus satellite debris. An identification of satellite debris, made on the basis of distinct kinematics, was made by Gilmore, Wyse & Norris (2002). These authors obtained radial velocities for several thousand faint

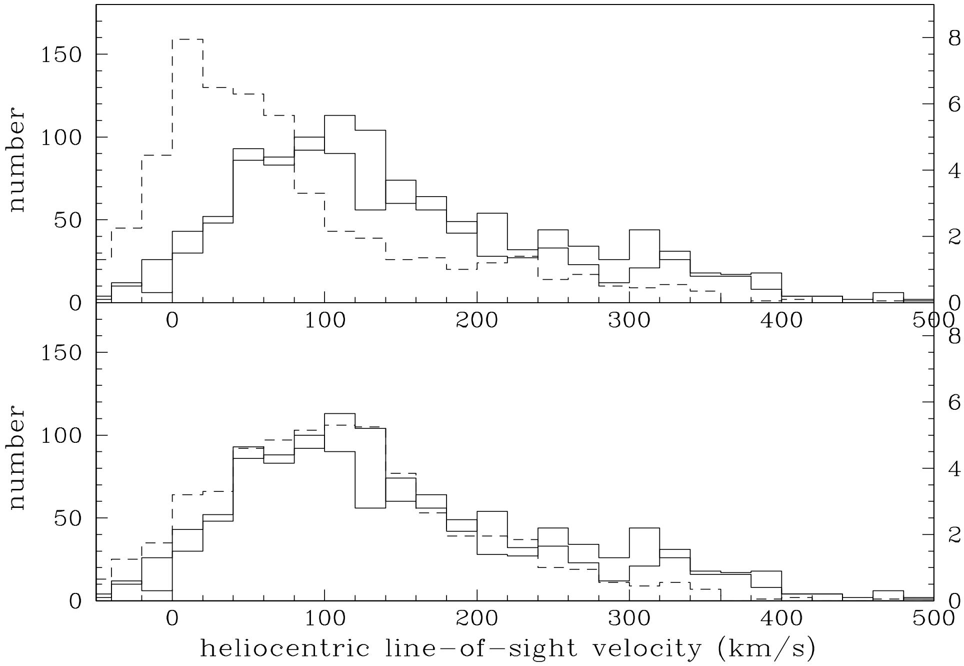

FIGURE 2. Modified from Gilmore, Wyse & Norris 2002. In each panel the solid histograms are observational data for faint $V \lesssim 19.5$ F/G stars in lines of sight where, at these distances, the line-of-sight velocity probes $\sim 0.7 - 0.8$ of the azimuthal streaming velocity. The dashed histogram is a model; in the upper panel the model is derived from standard local 'thick disk' kinematics which provide a good fit to the brighter stars, while the model in the lower panel has a significantly higher lag in $v_{rotation}$ behind the Sun. This provides a significantly better fit to the data.

($V \lesssim 19.5$) F/G dwarf stars, selected by photometry to be unevolved stars in the thick disk/halo interface at several kpc from the Sun, in key intermediate-latitude lines of sight that probe orbital rotational velocity (particularly $\ell = 270°$). They found that the mean lag behind the Sun's azimuthal streaming velocity was significantly larger for the fainter stars that for the brighter stars (see Figure 2). Either there are (discontinuous?) steep kinematic gradients within the thick disk (cf. Majewski 1993), or a separate population exists. In the latter case, a viable explanation would be stars from a shredded satellite. Indeed, these stars have low metallicities, typically −1.5 dex (Norris et al., in prep), a factor of ten below a typical thick disk star (e.g. Gilmore, Wyse & Jones 1995), but typical of the old population in dwarf galaxies.

However, the values of critical defining parameters for the 'canonical' thick disk, probed locally, remain variable from study to study. For example, the 'accepted' value for the rotational lag is around 40km/s (e.g. Carney, Laird & Latham 1989), but values as low as 20km/s (Chiba & Beers 2000) and as high as 80km/s (Fuhrmann 2000) have been reported. Some of this variation is undoubtably due to the difficulty of deconvolving a complex mix of populations. The thin disk will dominate any local sample, and comparison with distant *in situ* surveys will help (cf. the technique of Wyse & Gilmore 1995), as will using the discrimination inherent in the distinct elemental abundances of thick and thin disk stars (cf. Nissen 2003). Again, large statistically significant samples, so that tails of the distribution functions are well-defined, in key lines-of-sight, are needed.

3.3. *Small Scale Structure of the Bulge*

The bulge is clearly triaxial, but estimates of its three-dimensional structure are hindered by dust extinction, projection effects and the uncertainties in the structure of the disk along the line-of-sight (e.g. spiral arm pattern). The inner bulge, within ~ 1 kpc of the center, appears symmetric in deep infrared images taken with the ISO satellite (van Loon et al. 2003). The best fitting bar model (Bissantz & Gerhard 2002) to the COBE data has axial ratios 1:0.3–0.4:0.3 (i.e. barely triaxial) and a length of ~ 3.5 kpc. The effects of the bar potential may be the cause of the asymmetric stellar kinematics found by Parker, Humphreys & Beers (2003) in samples of stars on either side of the Galactic Center.

3.4. *Stellar Halo Small Scale Structure*

Structure in coordinate space mixes and dissolves on dynamical timescales. The outer regions of the halo, say at Galactocentric distances of greater than 15 kpc where dynamical timescales are $\gtrsim 1$ Gyr, are thus most likely to host observable substructure. Indeed, as discussed more fully in Majewski's contribution to this volume, several streams are found in the outer halo, in both coordinate space and kinematics. The vast majority of the confirmed structure is due to a single system, the Sagittarius dwarf spheroidal (e.g. Ibata et al. 2001; Dohm-Palmer et al. 2001; Majewski et al. 2003; Newberg et al. 2002; Newberg et al. 2003). This contrasts with the predictions of many disrupted satellites in CDM models (e.g. Bullock et al. 2000). The present mass of the Sagittarius dwarf is uncertain and model-dependent, but most estimates are within a factor of three of $10^9 \mathrm{M}_\odot$ (Ibata et al. 1997; Majewski et al. 2003). The mass lost by it to the halo is also model-dependent; presently identified streams are perhaps 15% of the remaining bound mass. The evolutionary history of the Sagittarius dwarf is as yet unclear and much work remains to be done.

Tidal streams can be, and are, also associated with dynamically evolving globular clusters. The excellent photometry from the Sloan Digital Sky survey has allowed the tracing of extended, thin arms from the outer halo globular cluster Palomar 5 over 10 degrees across the sky (Odenkirchen et al. 2003; see Figure 3).

Streams are rare in the inner halo (which contains most of the stellar mass!). Simulations suggest that signatures in phase space, particularly if integrals of the motion can be estimated, can survive for $\sim$ a Hubble time. A moving group has indeed be isolated (Helmi et al. 1999), but its mass is uncertain (see Chiba & Beers 2000), as is its origin – perhaps even it is associated with the Sagittarius dwarf (e.g. Majewski et al. 2003).

No structure is seen in coordinate space of the inner halo (within a few kpc of the Sun); the 2pt correlation function for main sequence stars brighter than $V = 19$ is flat (Gilmore, Reid & Hewett 1985; Lemon et al. 2003). This rules out significant recent accretion events that penetrate into the inner Galaxy, and ongoing disruption of inner globular clusters. Other tests for substructure show low-significance features consistent with known streams from the Sagittarius dwarf (Lemon et al. 2003), in agreement with results from blue horizontal branch stars (Sirko et al. 2003).

4. Concluding Remarks

The properties of the stellar populations of the Milky Way contain much information about the star formation history and mass assembly history of the Galaxy. The Milky Way has merged with, is merging with, and will merge with, companion galaxies, which contribute stars, gas and dark matter. Debris from the Sagittarius dwarf galaxy dominates recent accretion into the outer Galaxy, while the data are consistent with

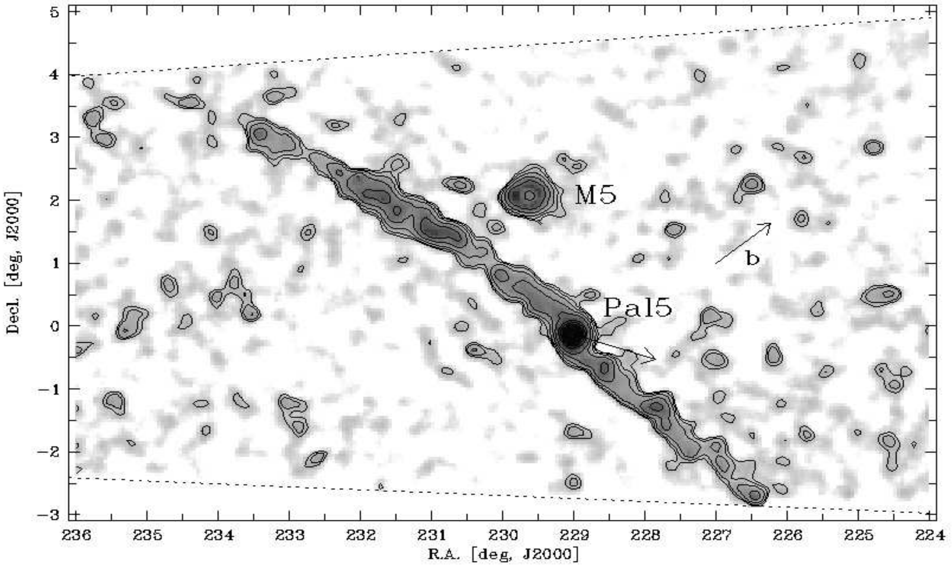

FIGURE 3. Taken from Odenkirchen et al. (2003), their Figure 3. The contours show the surface density of stars that are selected from their photometry to be members of Pal 5. There are clearly streams associated with this globular cluster. The arrow extending from the core of Pal 5 indicates the estimated direction of its orbit.

little stellar accretion into the inner Galaxy, including the disk. Predominantly gaseous accretion is relatively unconstrained, and is favoured by models of chemical evolution (cf. Tosi's contribution). Planned and ongoing large spectroscopic surveys will tightly constrain the existence and orgins of stellar phase-space substructure. The relatively quiescent merging history of the Milky Way that is implied by the mean properties of the stellar components is rather atypical in ΛCDM cosmologies. What about the rest of the Local Group?

REFERENCES

ABADI, M., NAVARRO, J., STEINMETZ, M & EKE, V. 2003 Simulations of galaxy formation in a Lambda CDM Universe II: The fine structure of simulated galactic disks. *Astrophys. J.* **597**, 21–34.

BELLAZZINI, M., IBATA, R., MONACO, L., MARTIN, L., IRWIN, M. & LEWIS, G. 2003 The moon behind the finger. Detection of the Canis Major galaxy in the background of galactic open clusters. *Mon. Not. Roy. Astr. Soc.* submitted (astro-ph/0311119).

BENSON, A., LACEY, C., FRENK, C., BAUGH, C. & COLE, S. 2003 Heating of galactic disks by infalling satellites. *Mon. Not. Roy. Astr. Soc.* submitted (astro-ph/0307298).

BINNEY, J., DEHNEN, W. & BERTELLI, G. 2000 The age of the solar neighbourhood. *Mon. Not. Roy. Astr. Soc.* **318**, 658–664.

BISSANTZ, & GERHARD, O. 2002 Spiral arms, bar shape and bulge microlensing in the Milky Way. *Mon. Not. Roy. Astr. Soc.* **330**, 591–608.

BONIFACIO, P. HILL, V., MOLARI, P., PASQUINI, L., DIMARCANTONIO, P. & SANTINI, P.

2000 First results of UVES at VLT: Abundances in the Sgr dSph. *Astron. Astrophys.* **359**, 663–668.

Buonanno, R. et al. 1995 Terzian 7: A young metal-rich globular cluster in the Milky Way. *Astron. J.* **109**, 663–671.

Burkert, A., Truran, J. & Hensler, G. 1992 The collapse of our Galaxy and the formation of the Galactic disk. *Astrophys. J.* **391**, 651–658.

Bullock, J., Kravtsov, A. & Weinberg, D. 2000 Reionization and the Abundance of Galactic Satellites. *Astrophys. J.* **539**, 517–521.

Carney, B., Latham, D. & Laird, J. 1989 A survey of proper-motion stars VIII: On the Galaxy's third population. *Astron. J.* **97**, 423–430

Carney, B., Latham, D. & Laird, J. 1990 A survey of proper-motion stars X: The early evolution of the Galaxy's halo. *Astron. J.* **99**, 527–589.

Carney, B. & Seitzer, P. 1993 Optical detection of the Galaxy's souhern stellar warp and outer disk. *Astron. J.* **105**, 2127—2137.

Chiba, M. & Beers, T.C. 2000 Kinematics of metal-poor stars in the Galaxy. III. Formation of the stellar halo and thick disk. *Astron. J.* **119**, 2843–2865.

Cole, A. 2001 The 2MASS CMD of the center of the Sagittarius dwarf galaxy. *Astrophys. J.* **559**, L17–L20.

Cole, A., Smecker-Hane, T. & Gallagher, J. 2000 The metallicity distribution function of red giant in the LMC. *Astron. J.* **120**, 1808–1827.

Cole, S., Lacey, C., Baugh, C. & Frenk, C.S. 2000 Hierarchical galaxy formation. *Mon. Not. Roy. Astr. Soc.* **319**, 168–204.

Da Costa, G. 1999 The dwarf spheroidal galaxies in the Galactic halo. In *Third Stromlo Symposium: The Galactic Halo* (ed. B. Gibson et al.), Astron. Soc. Pacific, San Francisco, 153–166.

Crane, J., Majewski, S., Rocha-Pinto, H., Frinchaboy, P., Strutskie, M. & Law, D. 2003 Exploring halo substructure with giant stars: Spectroscopy of stars in the Galactic anti-center stellar structure. *Astrophys. J.* **594**, L119–L122.

De Marchi, G., Paresce, F., Straniero, O. & Prada Moroni, P. 2003 On the age and mass function of the globular cluster M4: a different interpretation of recent deep HST observations. *Astron. Astrophys.* submitted (astro-ph/03106646)

Dickinson, M. 2000 Galaxy evolution at $0 < z < 2$ from the NICMOS HDF North. In *Building galaxies from the primordial Universe to the present*, XIXth Moriond meeting (ed. Hammer et al.) World Scientific Publishing p257

Djorgovski, G. & Sosin, C. 1989 The warp of the Galactic stellar disk detected in IRAS source counts. *Astrophys. J.* **341**, L13–L16.

Dohm-Palmer, R. et al. 2001 Mapping the Galactic halo V. Sagittarius dwarf spheroidal tidal debris 60^o from the main body. *Astrophys. J.* **555**, L37–L40.

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E. & Tomkin, J. 1993 The chemical evolution of the Galactic disk. I. Analysis and results. *Astron. Astrophys.* **275**, 101

Eke, V., Efstathiou, G. & Wright, L. 2000 The cosmological dependence of galactic specific angular momenta. *Mon. Not. Roy. Astr. Soc.* **315**, L18–L22.

Elmegreen, B. 1999 Galactic bulge formation as a maximum intensity starburst. *Astrophys. J.* **517**, 103–107.

Elmegreen, B. 2002 Star formation from galaxies to globules. *Astrophys. J.* **557**, 206–220.

Fall, S.M. & Efstathiou, G. 1980 Formation and rotation of disk galaies with haloes. *Mon. Not. Roy. Astr. Soc.* **193**, 189–206.

Feltzing, S. & Gilmore, G. 2000 Age and metallicity gradients in the Galactic bulge. A differential study using HST/WFPC2. *Astron. Astrophys.* **355**, 949–965

Feltzing, S., Bensby, T. & Lundström, I. 2003 Signatures of SNIa in the Galactic thick disk. *Astron. Astrophys.* **397**, L1–L4.

Ferguson, A.M.N. & Johnson, R. 2001 Constraints on galaxy formation from stars in the far outer disk of M31. *Astrophys. J.* **559**, L13–L16.

Ferreras, I., Wyse, R.F.G. & Silk, J. 2003 The formation history of the Galactic bulge. *Mon. Not. Roy. Astr. Soc.* **345**, 1381–1391.

Francois, P. & Matteucci, F. 1993 On the abundance spread in solar neighbourhood stars. *Astron. Astrophys.* **280**, 136–140.

Freeman, K. & Bland-Hawthorn, J. 2002 The new Galaxy: Signatures of its formation. *Ann. Rev. Astron. Astrophys.* **40**, 487–537.

Fuhrmann, K. 1998 Nearby stars of the Galactic disk and halo. *Astron. Astrophys.* **338**, 161-183.

Fuhrmann, K. 2000 Nearby stars of the Galactic disk and halo. II http://www.xray.mpe.mpg.de/~fuhrmann

Geiss, J., Gloeckler, G. & Charbonnel, C. 2002 Chemical evolution in our Galaxy during the last 5Gyr. *Astrophys. J.* **578**, 862–867.

Gilmore, G. & Reid, I.N. 1983 New light on faint stars III. Galactic structure towards the South Pole and the Galactic thick disk. *Mon. Not. Roy. Astr. Soc.* **202**, 1025–1047.

Gilmore, G., Reid, I.N. & Hewett, P. 1985 New light on faint stars. VII Luminosity and mass distributions in two high Galactic latitude fields. *Mon. Not. Roy. Astr. Soc.* **213**, 257–278

Gilmore, G. & Wyse, R.F.G. 1991 Chemical evolution with bursts of star formation – Element ratios in dwarf galaxies. *Astrophys. J.* **367**, L55–L58.

Gilmore, G., Wyse, R.F.G. & Jones, J.B. 1995 A determination of the thick disk chemical abundance distribution: Implications for galaxy evolution. *Astron. J.* **109**, 1095–1111.

Gilmore, G., Wyse, R.F.G. & Kuijken, K. 1989 Kinematics, chemistry and structure of the Galaxy. *Ann. Rev. Astron. Astrophys.* **27**, 555–627.

Gilmore, G., Wyse, R.F.G. & Norris, J. 2002 Deciphering the last major invasion of the Milky Way *Astrophys. J.* **574**, L39–L42.

Hansen, B. et al. 2002 The white dwarf cooling sequence of the globular cluster M4. *Astrophys. J.* **574**, L155-L158.

Hasan, H. & Norman, C. 1990 Chaotic orbits in barred galaxies with central mass concentrations. *Astrophys. J.* **361**, 69–77.

Helmi, A., White, S.D.M., de Zeeuw, P.T. & Zhao, H.-S. 1999 Debris streams in the solar neighbourhood as relicts from the formation of the Milky Way *Nature* **402**, 53–55

Helmi, A., White, S.D.M. & Springel, V. 2003a The phase-space structure of cold dark matter haloes: insights into the Galactic halo *Mon. Not. Roy. Astr. Soc.* **339**, 834–848.

Helmi, A., Navarro, J., Meza, A., Steinmetz, M. & Eke, V. 2003b On the nature of the ringlike structure in the outer Galactic disk. *Astrophys. J.* **592**, L25–L28.

Hernandez, X., Valls-Gabaud, D. & Gilmore, G. 2000 The recent star formation history of the HIPPARCOS solar neighbourhood. *Mon. Not. Roy. Astr. Soc.* **316**, 605-612.

Ibata, R. & Gilmore, G. 1995 The outer regions of the Galacic bulge: II. Analysis *Mon. Not. Roy. Astr. Soc.* **275**, 605–627.

Ibata, R., Gilmore, G. & Irwin, M. 1994 A dwarf satellite galaxy in Sagittarius. *Nature* **370**, 194.

Ibata, R., Lewis, G., Irwin, M., Totten, E & Quinn, T. 2001 Great circle tidal streams: Evidence for a nearly spherical massive dark halo around the Milky Way. *Astrophys. J.* **551**, 294–311.

Ibata, R., Gilmore, G. & Irwin, M. 1995 Sagittarius, the nearest dwarf galaxy. *Mon. Not. Roy. Astr. Soc.* **277**, 781–800.

Ibata, R., Irwin, M., Lewis, G., Ferguson, A. & Tanvir, N. 2003 One ring to emcompass them all: a giant stellar structure that surrounds the Galaxy. *Mon. Not. Roy. Astr. Soc.* **340**, L21–L27.

Ibata, R., Wyse, R.F.G., Gilmore, G., Irwin, M. & Suntzeff, N. 1997 The kinematics, orbit and survival of the Sagittarius dwarf spheroidal galaxy. *Astron. J.* **113**, 634-655.

Jenkins, A. et al. 1998 Evolution of structure in cold dark matter universes. *Astrophys. J.* **499**, 20.

Jimenez, R., Flynn, C. & Kovonta, E. 1998 HIPPARCOS and the age of the galactic disk. *Mon. Not. Roy. Astr. Soc.* **299**, 515-519.

Kauffmann, G. 1996 The age of elliptical galaxies and bulges in a merger model. *Mon. Not. Roy. Astr. Soc.* **281**, 487-492.

Knox, R., Hawkins, M. & Hambly, N. 1999 A survey for cool white dwarfs and the age of the Galactic disk. *Mon. Not. Roy. Astr. Soc.* **306**, 736–752.

KOTONEVA, E., FLYNN, C., MATTEUCCI, F. & CHIAPPINI, C. 2002 K dwarfs and the chemical evolution of the solar cylinder. *Mon. Not. Roy. Astr. Soc.* **336**, 879-891.

LARSON, R.B. 1972 Effect of Infalling Matter on the Heavy Element Content of a Galaxy. *Nature Phys. Sci.* **236**, 7–8.

LAYDEN, A. & SARAJEDINI, A. 2000 Photometry of the globular cluster M54 and the Sagittarius dwarf galaxy: The age-metallicity relation. *Astron. J.* **119**, 1760–1792.

LEGGETT, S., RUIZ, M. & BERGERON, P. 1998 The cool white dwarf luminosity function and the age of the Galactic disk. *Astrophys. J.* **497**, 294.

LEMON, D., WYSE, R.F.G., LISKE, J., DRIVER, S. & HORNE, K. 2003 The Millenium Galaxy Catalogue: Star counts and the structure of the Galactic halo. *Mon. Not. Roy. Astr. Soc.* in press (astro-ph/0308200).

MAJEWSKI, S.R. 1993 Galactic structure surveys and the evolution of the Milky Way. *Ann. Rev. Astron. Astrophys.* **31**, 575–638.

MAJEWSKI, S., STRUTSKIE, M., WEINBERG, M. & OSTHEIMER, J. 2003 A 2-MASS all-sky view of the Sagittarius dwarf galaxy I. Morphlogy of the Sagittarius core and tidal arms *Astrophys. J.* **599**, 1082–1115.

MARTIN, N., IBATA, R., BELLAZZINI, M., IRWIN, M., LEWIS, G. & DEHNEN, W. 2003 A dwarf galaxy remnant in Canis Major: the fossil of an in-plane accretion onto the Milky Way. *Mon. Not. Roy. Astr. Soc.* in press (astro-ph/0311010).

MCWILLIAM, A. & RICH, R.M. 1994 The first detailed abundance analysis of Galactic bulge K giants in Baade's window. *Astrophys. J. Supp.* **91**, 749–791.

MCWILLIAM, A. & RICH, R.M. 2003 Composition of the Galactic bulge. In *Origin and evolution of the elements*, Carnegie Observatories Astrophysics series, vol. 4, eds A. McWilliam & M. Rauch (Cambridge, Cambridge University Press) (astro-ph/0312628).

MCCLURE-GRIFFITHS, N., DICKEY, J., GAENSLER, B. & GREEN, A. 2003 A new arm for our Galaxy? *Astrophys. J. Letters* submitted (see http://www.atnf.csiro.au/news/press/spiralarm/)

MERRIFIELD, M. 2003 The Galactic bar. In *Milky Way surveys: the structure and evolution of our Galaxy,* (eds. D. Clemens, T. Brainerd & R. Shah), ASP Conf Proc. (ASP, San Francisco) (astro-ph/0308302).

NAVARRO, J. & STEINMETZ, M. 1997 The effects of a photoionizing ultraviolet background on the formation of disk galaxies. *Astrophys. J.* **478**, 13–28.

NAVARRO, J., FRENK, C.S. & WHITE, S.D.M. 1995 The assembly of galaxies in a hierarchically clustering universe. *Mon. Not. Roy. Astr. Soc.* **275**, 56-66.

NEWBERG, H. ET AL. 2003 Sagittarius tidal debris 90 kpc from the Galactic center. *Astrophys. J.* **596**, L191–L194.

NEWBERG, H. ET AL. 2002 The ghost of Sagittarius and lumps in the halo of the Milky Way. *Astrophys. J.* **569**, 245–274.

ODENKIRCHEN, M. ET AL. 2003 The extended tails of Palomar 5: A 10^o arc of globular cluster tidal debris. *Astron. J.* **126**, 2385–2407.

NISSEN, P. 2003 Thin and thick Galactic disks. In *Origin and evolution of the elements*, Carnegie Observatories Astrophysics series, vol. 4, eds A. McWilliam & M. Rauch (Cambridge, Cambridge University Press) (astro-ph/0310326).

ODENKIRCHEN, M. ET AL. 2003 The extended tails of Palomar 5: A 10^o arc of globular cluster tidal debris. *Astron. J.* **126**, 2385–2407.

ORTOLANI, S., RENZINI, A., GILMOZZI, R., MARCONI, G., BARBUY, B., BICA, E. & RICH, R.M. 1995 Near coeval formation of the Galactic bulge and halo. *Nature* **377**, 701–703.

PAGEL, B. & PATCHETT, B. 1975 Metal abundances in nearby stars and the chemical history of the solar neighbourhood. *Mon. Not. Roy. Astr. Soc.* **172**, 13-40.

PARKER, J., HUMPHREYS, R. & BEERS, T. 2003 The asymmetric thick disk: A star count and kinematic analysis. *Astron. J.* in press (astro-ph/0312017).

PROCHASKA, J.X., NAUMOV, S., CARNEY, B., MCWILLIAM, A. & WOLFE, A. 2000 The Galactic thick disk stellar abundances. *Astron. J.* **120**, 2513–2549.

QUINN, P., HERNQUIST, L. & FULLAGAR, D. 1993 Heating of galactic disks by mergers. *Astrophys. J.* **403**, 74–93.

RAHA, N., SELLWOOD, J., JAMES, R. & KAHN, F. 1991 A dynamical instability of bars in disk galaxies. *Nature* **352**, 411–412.

ROCHA-PINTO, H.J., SCALO, J., MACIEL, W.J. & FLYNN, C. 2000 Chemical enrichment and star formation in the Milky Way disk. II. Star formation history. *Astron. Astrophys.* **358**, 869–885.

ROCHA-PINTO, H.J., MAJEWSKI, S., SKRUTSKIE, M. & CRANE, J. 2003 Tracing the Galactic anticenter stellar stream with 2MASS M giants. *Astrophys. J.* **594**, L115–L118.

SADLER, E., RICH, R.M. & TERNDRUP, D. 1996 K giants in Baade's window II. The abundance distribution. *Astron. J.* **112**, 171–190.

SANDAGE, A., LUBIN, L. & VANDENBERG, D.A. 2003 The age of the oldest stars in the local Galactic disk from HIPPARCOS parallaxes of G and K subgiants. *Pub. Astr. Soc. Pac.* **115**, 1187–1206.

SELLWOOD, J. & BINNEY, J. 2002 Radial mixing in galactic discs. *Mon. Not. Roy. Astr. Soc.* **336**, 785–796.

SEVENSTER, M. 1999 Something about the structure of the Galaxy *Mon. Not. Roy. Astr. Soc.* **310**, 629–644.

SIRKO, E. ET AL. 2003 BHB stars in the SDSS I. Sample selection and structure in the Galactic halo *Astron. J.* submitted (astro-ph/0311324).

SMECKER-HANE, T. & MCWILLIAM, A. 2003 The complex chemical abundances and evolution of the Sagittarius dwarf spheroidal galaxy. *Astrophys. J.* accepted (astro-ph/0205411).

SMITH, V. ET AL. 2002 Chemical abundances in 12 red giants of the LMC from high-resolution IR spectroscopy. *Astron. J.* **124**, 3241-3254

STEINMETZ, M. 2003 RAVE, the RAdial Velicity Experiment. In *GAIA spectroscopy, science and technology* (ed. U. Munnari), ASP Conf Proc. vol. 298, p381–386. (ASP, San Francisco)

STOCKTON, A., CANALIZO, G & MAIHARA, T. 2003 A disk galaxy of old stars at $z \sim 2.5$ *Astrophys. J.* submitted (astro-ph/0312550).

TOLSTOY, E., VENN, K., SHETRONE, M., PRIMAS, F., HILL, V., KAUFER, A., SZEIFERT, T. 2003 VLT/UVES abundances in four nearby dwarf spheroidal galaxies II. Implications for understanding galaxy evolution. *Astron. J.* **125**, 707–726.

UNAVANE, M., WYSE, R.F.G. & GILMORE, G. 1996 The merging history of the Milky Way. *Mon. Not. Roy. Astr. Soc.* **278**, 727–736.

VAN DEN BERGH, S. 1962 The frequency of stars with different metal abundances. *Astron. J.* **67**, 486–490.

VAN LOON, J. ET AL. 2003 Infrared stellar populations in the central parts of the Milky Way galaxy. *Mon. Not. Roy. Astr. Soc.* **338**, 857–879.

VELAZQUEZ, V. & WHITE, S.D.M. 1999 Sinking satellites and the heating of galaxy discs. *Mon. Not. Roy. Astr. Soc.* **304**, 254–270.

WECHSLER, R., BULLOCK, J., PRIMACK, J., KRAVSOV, A. & DEKEL, A. 2002 Concentration of halos from their assembly history. *Astrophys. J.* **568**, 52–70.

WYSE, R.F.G. 2000 Formation Scenarios. In *The Galactic Halo: From Globular Clusters to Field Stars* (ed. A. Noels et al.), Liège, Institut d'Astrophysique et de Geophysique, 305–322.

WYSE, R.F.G. 2001 The merging history of the Milky Way disk. In *Galactic disks and disk galaxies* (ed. J. Funes & E. Corsini) ASP Conference series vol 230, (ASP, San Francisco) 71–80.

WYSE, R.F.G. & GILMORE, G. 1992 Formation and evolution of the Galactic bulge and spheroid - Where did the spheroid gas go?. *Astron. J.* **104**, 114–153.

WYSE, R.F.G. & GILMORE, G. 1995 Chemistry and kinematics in the solar neighbourhood. *Astron. J.* **110**, 2771.

YANNY, B. ET AL. 2003 A low-latitude halo stream around the Milky Way. *Astrophys. J.* **588**, 824–841.

ZHANG, B., WYSE, R.F.G., STIAVELLI, M. & SILK, J. 2002 The dynamical evolution of substructure. *Mon. Not. Roy. Astr. Soc.* **332**, 647–675.

ZOCCALI, M. ET AL. 2003 Age and metallicity distribution of the galactic bulge from extensive optical and near-IR stellar photometry. *Astron. Astrophys.* **399**, 931–956.

ZUREK, W., QUINN, P.J. & SALMON, J. 1988 Rotation of halos in open and closed universes – Differentiated merging and natural selection of galaxy types. *Astrophys. J.* **330**, 519–534.