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Galactic Stellar Populations

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Abstract.
The history of the formation and evolution of the Milky Way Galaxy is found in the spatial distribution, kinematics, age and chemical abundance distributions of long-lived stars. From this fossil record one can in principle extract the star formation histories of different components, their chemical evolution, the stellar Initial Mass Function, the merging history – what merged and when did it merge? – and compare with theoretical models. Observations are driving models, and we live in exciting times.

1. Context

The large scale structure of the Universe, as probed by the Cosmic Microwave background, provides strong evidence for a flat geometry, \( \Omega_{\text{tot}} = 1 \) (e.g. Spergel et al. 2003). The motions of galaxies constrain the matter contribution to be \( \Omega_{\text{matter}} \sim 0.3 \), while Big Bang Nucleosynthesis calculations provide an upper limit to the baryon content of the Universe of \( \Omega_{\text{baryon}} \lesssim 0.05 \) (e.g. Schramm 2000). These discrepant values are understood with the postulate of non-baryonic (dark) matter, and the realization that the usual decelerated expansion of matter-dominated universes does not describe the recent (redshifts \( \lesssim 0.5 \)) expansion of our Universe, which is instead accelerating its rate of expansion. This acceleration indicates the recent dominance of a component with negative pressure, most commonly and simply ascribed to a Cosmological Constant/Vacuum Energy/‘Lambda-term’, which has constant energy density as the Universe expands and at the present epoch provides \( \Omega_{\Lambda} \sim 0.7 \). The dark matter is most probably ‘cold’ i.e. was nonrelativistic when it decoupled from the other constituents of the Universe, resulting in the preservation of primordial fluctuations on all scales from sub-Galactic up.

Galaxy formation and evolution in such a ‘\( \Lambda \)CDM’ Universe starts with the collapse of perhaps \( \sim 10^6 \mathcal{M}_\odot \) overdense regions (the characteristic mass of ‘the first objects’ is the subject of much on-going work) and large galaxies like the Milky Way emerge as the end-point of a process of hierarchical clustering, merging and accretion. 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 form late, after a redshift of unity, or a lookback time of \( \sim 8 \) Gyr, in order to avoid losing too much angular momentum during active merging at earlier times.

• A large disk galaxy should have hundreds of surviving satellite dark haloes at the present day.

• The stellar halo is formed from disrupted satellites.

• Minor mergers (a mass ratio of \( \sim 10 - 20\% \) between the satellite and the disk) into a disk 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.

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. Semi-analytic techniques have been developed (e.g. Tóth & Ostriker 1992; Taylor & Babul 2004; Benson et al. 2004; Zentner et al. 2005) but these involve further uncertainties, the treatment of dynamical friction and tidal effects being crucial issues. Of course, inclusion of the baryons, as stars and gas, is more uncertain. Dealing solely with dissipationless physics, i.e. pure stellar baryonic components plus dark matter, N-body simulations have shown that a merger between a disk galaxy and a robust (fairly dense) satellite of even 10% of the mass of the disk, and thus even a smaller fraction of the whole galaxy, \(< 2\% \) in the models, is sufficient to result in significant thickening, as shown by Velaquez & White (1999) and by Walker, Mihos & Hernquist (1996). High-resolution cosmological simulations predict that a galaxy of the mass of the Milky Way now would typically have experienced of order 3 mergers with satellite systems of mass at least 10% of that of the total galaxy in the last 10 Gyr (A. Berlind, private communication). Many more mergers with smaller mass ratios, which from the simulations would be capable of thickening a thin disk, would be expected. As we discuss below, the thick disk of the Milky Way is apparently composed of uniformly old stars, ages \( \gtrsim 10 \) Gyr, implying that the thin disk of the Milky Way has not been heated by mergers over the last 10 Gyr. Consistency between these remains to be found, unless we are happy with a special place in the Universe.

ΛCDM models predict about a factor of ten more disrupted satellite galaxies than surviving (see Fig. 1 of Bullock, Kravtsov & Weinberg 2000), providing a total stellar mass to the field halo of \( \gtrsim 5 \times 10^8 M_\odot \), comparable to the estimated stellar mass of the entire halo (\( \sim 10^9 M_\odot \), Carney et al. 1990). Most disruption occurs ‘relatively early, \( z \gtrsim 0.5 \)’ (Bullock et al. 2000), or a lookback
time of \( \gtrsim 5.5 \) Gyr. One might still expect to see signatures of these hundred or so disrupted dwarfs, since simulations suggest that signatures in phase space, particularly if integrals of the motion can be estimated, can survive for \( \sim a \) Hubble time.

2. The Milky Way Galaxy: Ongoing Mergers

The Milky Way is clearly merging with at least one satellite galaxy at the present day, namely the Sagittarius dwarf spheroidal (Ibata, Gilmore & Irwin 1994). This tidal interaction has produced, and is producing, thin streams, or tidal arms, that can be traced across the sky (e.g. Majewski et al. 2003) – and that can in principle be used to constrain the shape and lumpiness of the Galactic dark halo. The mass ratio of this merger is far from clear – the present stellar mass is \( \sim 3 \times 10^7 \)\( M_\odot \) and present total mass is inferred from internal kinematics and models of the tidal debris to be \( \sim 5 \times 10^8 \)\( M_\odot \) (e.g. Law, Johnston & Majewski 2005 and references therein). The fact that the Sagittarius dwarf apparently self-enriched to approximately solar metallicity at least a Gyr ago (Bonifacio et al. 2000; McWilliam & Smecker-Hane 2005; Monaco et al. these proceedings) suggests a potential well deeper than that of the LMC, which has yet to reach this level of enrichment. Models of tidal disruption, over a 13 Gyr time period, in a fixed potential similar to that of the present Milky Way suggest a mass in tidal debris now that is some five times larger than that remaining bound, i.e. an initial mass around 6 times the present one (e.g. Helmi & White 2001) but this is not a very realistic model in the context of \( \Lambda \)CDM, and the results are sensitive to the assumed density profile of the satellite. It is also not clear when the Sgr dSph achieved its present orbit, and how that would be related to ‘merger epoch’ as defined in theoretical models. More work is clearly needed. In any case, interactions with the Sgr dSph may well be playing a role in driving/maintaining the complex structure of the outer disk (e.g. Ibata & Razoumov 1998).

Tidal arms, combining spatial and kinematic substruure, provide the cleanest evidence of interactions. However, the beautiful arms of the outer halo globular cluster Pal 5 (Odenkirchen et al. 2003), identified through the excellent photometry from the Sloan Digital Sky survey and extending over 10 degrees on the sky, serve to remind us that streams are not necessarily a sign of accretion and mergings.

The ambiguity between interactions and mergers may be illustrated by the LMC/SMC/Magellanic stream system. The relative roles of tidal effects and gaseous, ram-pressure stripping in this system remain unclear, with even the leading gaseous arm (Putman et al. 1998) perhaps being reproduced by gas physics (Mastropietro et al. 2005), albeit with associated shrinking of the peri-Galacticon of the LMC by \( \sim 10\% \) per \( \sim 2\) Gyr) orbit and significant tidal stripping of dark matter from the LMC halo.

3. The Stellar Populations and Evolution of the Thin Disk

As noted above, extended thin disks are constrained in \( \Lambda \)CDM to form after the bulk of merging is complete, \( z \lesssim 1 \) or lookback times of \( \lesssim 8 \) Gyr, in order to
avoid losing too much angular momentum (e.g. Navarro, Frenk & White 1995; Navarro & Steinmetz 1997; Eke, Efstathiou & Wright 2000).

Setting aside for the moment the thick disk and the constraints that the old ages of its constituent stars provide on the epoch of formation of its possible thin disk progenitor, one can estimate the epoch of the onset of star formation in the local thin disk by various means such as from isochrone-fitting of the Hipparcos colour-absolute magnitude diagram; isochrone fitting to Stromgren photometry of nearby stars; the distribution of atmospheric activity age indicators, and from the local white dwarf luminosity function. Each technique has its own limitations and uncertainties, but it appears that the local disk has no shortage of stars older than 8 Gyr (e.g. Nordstrom et al. 2004; Binney, Dehnen & Bertelli 2000).

The scale-length of old stars in the thin disk is 2–4 kpc (e.g. Siegel et al. 2002), so that the solar neighbourhood is some ~3 scalelengths from the center. Thus, provided the old stars locally were born locally, the formation of an extended disk in the Milky Way was not delayed until after a redshift of unity. This is a potential problem for ΛCDM models, particularly since M31 apparently also has an extended disk of old stars (Ferguson & Johnston 2001). Furthermore, direct observation of high redshift galaxies, out to a redshift z ~ 3, in the rest-frame optical (Trujillo et al. 2005), reveals little evolution in disk size, significantly less than predicted by semi-analytic CDM models (Mo, Mao & White 1999), but consistent with the simplest picture of gaseous infall and star formation within a fixed potential well, with the star formation rate higher in the central disk. Indeed, the interpretation from these high redshift observations is that ‘stellar disks form from early on, in large haloes’ (Trujillo et al. 2005).

An alternative interpretation of the old stars in the local disk is to posit that they formed somewhere else and were deposited in the local disk at some subsequent time. There has been much recent activity in disk dynamics and mixing (e.g. Fuchs 2001; Sellwood & Binney 2002; De Simone, Wu & Tremaine 2004), an aspect of which is how much net migration of stars outward across the disk is possible; at present the results are not clear. The possibility that a significant fraction of the old thin disk could have been accreted as debris from a few satellite galaxies was raised by Abadi et al. (2003). A typical satellite orbit is far from circular (e.g. Benson 2005) so that this scenario requires that the satellites be massive enough for dynamical friction to damp vertical motions and circularize their orbit quickly enough, and it remains to be seen if, for example, the chemical composition of the old disk stars is consistent.

Ongoing large-scale spectroscopic surveys such as RAVE (targeting bright stars with the UKSchmidt Telescope and 6dF multi-object spectrograph; Steinmetz 2003) and the Galactic structure survey of the Sloan Digital Sky Survey Extension (SDSS-II/SEGUE) should provide ideal databases for an identification of kinematic substructure in the disk. The high-resolution mode of the proposed multi-object spectrograph (KAOS/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. 2004; Martin et al. 2004; Rocha-Pinto et al. 2005), or more simply structure in the outer stellar disk, which most probably warps and flares (e.g. Momany et al. 2004). 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). Again, ongoing surveys will provide much-needed information.

However, the interpretation of large datasets of stellar kinematics and metallicity in the context of searches for substructure in the disk is complicated by the fact that the underlying potential of the disk is neither smooth, axisymmetric nor time-independent. As demonstrated by De Simone, Wu & Tremaine (2004), transient perturbations, such as segments of spiral arms, not only heat the stellar disk, but 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. An unwary astronomer might conclude that such a complex stellar population indicates disruption of a satellite galaxy.

Analysis of the K/M giants with accurate radial velocities and Hipparcos distances and proper motions has indeed identified several kinematic moving groups with members of a range of ages and/or metallicities (Famaey et al. 2004), which those authors have ascribed to dynamical perturbations within the disk. Helmi et al. (2005) analysed the rich dataset from Nordstrom et al. (2004), consisting of full 3-D space motions (from Hipparcos parallaxes, Tycho-2 proper motions, and new multi-epoch radial velocities) and effective temperatures and metallicities derived from $uvby\beta$ Strömgren photometry. They concluded that while some substructure was due to the bar potential and transient spiral arms, there remained substructures that they identified as having metallicity and age distributions more consistent with debris from accreted and disrupted satellites. It will be very interesting to cross-correlate these latter substructures with the spectroscopic metallicity and elemental abundance dataset of Soubiran & Girard (2005), to investigate their detailed abundance patterns.

4. The Stellar Populations and Evolution 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, not the tail of the stellar halo or of the thin disk. Its origins remain the source of considerable debate. Locally, some $\sim 5\%$ of stars are in the thick disk; the vertical scale-height is $\sim 1$ kpc, and radial scale-length $\sim 3$ 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 $10^{10} M_\odot$. Broadly similar structures have been seen in the resolved stellar populations of nearby spirals (e.g. Mould 2005; Yoachim & Dalcanton 2005).

Again the properties of the stellar populations in this Galactic 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, $[\text{Fe/H}] \sim -0.6$ 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 $[\alpha/Fe]$ at fixed $[Fe/H]$, implying distinct star formation and enrichment histories for the thick and thin disks (Fuhrmann 1998, 2004; Prochaska et al. 2000; Feltzing, Bensby & Lundström 2003; Nissen 2004; Bensby et al. 2005). The data show a ‘Type II supernova plateau’ for metal-poor thick disk stars, $[\alpha/Fe] \sim +0.4$ for $[Fe/H] < -0.5$, with a downturn for more metal-rich stars (see Figure 1, taken from Bensby, Feltzing & Lundström 2004), indicating contributions to iron from the longer-lived Type Ia supernovae. The fact that the Type II plateau has the same value as that seen in stars belonging to the stellar halo implies that these two populations were enriched by Type II supernovae from massive stars of the same Initial Mass Function (see e.g. Gilmore & Wyse 1998 for more discussion of this point). The turn-down implies that star formation in the progenitor of the thick disk persisted long enough for Type Ia supernovae to explode and for their iron to be incorporated in its chemical evolution; models imply this is a duration of 1–2 Gyr (e.g. Matteucci & Greggio 1986; Smecker-Hane & Wyse 1992).

![Figure 1.](image)

Figure 1. Taken from Bensby, Feltzing & Lundström 2004, their Figure 11. Filled symbols represent stars whose kinematics are consistent with membership of the thick disk, while open symbols represent thin disk stars. At a given value of $[Fe/H]$, the thick and thin disk stars are separated, with thick disk stars having higher $[O/Fe]$. At the typical thick disk metallicity, $[Fe/H] \sim -0.5$ dex, the value of $[O/Fe]$ 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.

The kinematics of the thick disk are intermediate between those of the thin disk and those of the stellar halo; in particular, the standard value for the mean
azimuthal streaming velocity of the thick disk is $V_{\text{rotation}} \sim 170$ km/s (Norris 1986; Morrison, Flynn & Freeman 1990; Chiba & Beers 2000). However, surveys of faint F/G stars tend to find a lower value, $V_{\text{rotation}} \sim 100$ km/s (e.g. Wyse & Gilmore 1986; Gilmore, Wyse & Norris 2002) and we return to the interpretation of this below.

The fairly high values for the velocity dispersions of the thick disk, $\sigma_W \sim 40$ km/s and $\sigma_{\text{total}} \sim 80$ km/s, argue against normal disk-heating mechanisms (the transient gravitational perturbations in the disk, bits of spiral arms, GMCs...) being involved in its formation – those processes generally saturate at the values of the velocity dispersions for the old thin disk, or $\sigma_W \sim 20$ km/s. Exceptional heating of the thin disk that occurs over cosmic time, such as would happen if the dark matter in the halo were massive black holes (Lacey & Ostriker 1985), is ruled out as the formation mechanism for the thick disk by the extended star formation in the thin disk, and the apparent lack of intermediate-age or young stars in the thick disk. Exceptional heating that occurs only very early in the evolution of the thin disk is a viable possibility, and this is what occurs in a minor merger at high redshift. The old age of the stars in the thick disk, $\sim 10 - 12$ Gyr (Gilmore, Wyse & Jones 1995; Nordstrom et al. 2004; Fuhrmann 2004), would constrain any merger violent enough to form a thick disk from the thin disk to have happened at this look-back time, or redshift $z \gtrsim 1.5$. Given that, as noted above, models have found that a merger with as little as 10% of the disk mass, or a few percent of the dark halo mass, is sufficient to form a thick disk (e.g. Velaquez & White 1999), and that cosmological calculations imply that such low mass-ratio mergers of dark haloes continue to later times, it is clearly important to (i) obtain reliable, precise and accurate ages for large samples of thick disk stars (large samples are needed to isolate contaminants, such as thin disk stars ejected into the thick disk by binary supernova explosions), and (ii) develop robust techniques for modelling baryonic galaxies in the cosmological simulations.

What signatures of a merger-origin for the thick disk might remain observable today? 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 satellite, 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)? 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 $\sim -0.6$ dex. Further, the bulk of these stars have enhanced, super-solar $[\alpha/\text{Fe}]$ abundances (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 $[\alpha/\text{Fe}]$ – 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 (see also Hill et al. 2000). 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, which is much older. 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 that could have been tidally disrupted to form the thick disk from its debris.

None of the retinue of dSph satellite galaxies has a stellar population well-matched to that of the thick disk, which requires old age, enhanced values of \([\alpha/\text{Fe}]\) for metallicities below \(\sim -0.5\) dex, and overall higher mean metallicity than a typical dSph (e.g. Tolstoy et al. 2003). One is left with the conclusion that if a disrupted dwarf forms the bulk of the thick disk, then that satellite was very different from those that survived (we will echo this conclusion below, in the discussion of the stellar halo).

However, it is very possible – and indeed, required in merger-models – that a significant minority of ‘thick disk’ stars are debris from accreted satellite(s). These stars would be expected to be more metal-poor than the bulk of the (true) thick disk stars, and to be on orbits more similar to that of a typical satellite, than the high-angular momentum orbit of a typical thick disk star. In ΛCDM cosmological models the typical satellite/subhalo initial orbital angular momentum is close to half that of a circular orbit of the same energy (e.g. Benson 2005; Zentner et al. 2005) so one would expect an azimuthal streaming velocity of around 100km/s for satellite debris in a system like the Milky Way with a flat rotation (circular velocity) curve, with amplitude \(\sim 220\) km/s. Of course in hierarchical clustering models the potential well of the Milky Way is not fixed, but theory predicts an early epoch of massive mergers that sets the potential well depth (e.g. Zentner & Bullock 2003).

A component with a mean azimuthal streaming velocity of around 100 km/s is indeed seen in the radial velocity datasets of faint \((V \gtrsim 18)\) F/G dwarfs of Gilmore, Wyse & Norris (2002) and Wyse et al. (2005), in widely separated lines-of-sight, and in datasets taken with a variety of multi-object spectrographs and telescopes. Reassuringly, hints are also seen in the K-giants of Morrison, Flynn & Freeman (1990, their Figure 7(d) and (g)) and in the local sample of Beers et al. (2000, as shown by Navarro, Helmi & Freeman 2004).

We interpret this as strong evidence in favour of the merger-heated disk origin for the thick disk.

5. The Stellar Populations and Evolution of the Stellar Halo

5.1. The Field 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 \([\alpha/\text{Fe}]\) (see e.g. Unavane, Wyse & Gilmore 1996). The dominant signature of enrichment by Type II supernovae indicates a short duration of star formation, so that the ejecta of the longer-lived Type Ia supernovae is not incorporated into stars. This could naturally arise due to star formation and self-enrichment occurring in low-mass star-forming regions that cannot sustain extended star formation. Indeed, the stellar density of the halo is sufficiently low that its stars must have formed in higher density systems and then been dispersed, given the observational and theoretical constraints on the location and environments of star formation – i.e. that star formation is limited to cold, dense gas clouds. Many theoretical and observational studies have suggested that star formation occurs in clusters and associations of a range of masses and binding energies, and a large fraction of the stellar structures formed are either never bound (after gas dispersal) or are disrupted on several crossing times by a combination of internal and external forces (e.g. review of Fall 2004). The field stellar halo could rather naturally be formed from the debris from such stellar ‘clusters’, with the on-going mass-loss from e.g. Pal 5 (Odenkirchen et al. 2003) the present-day manifestation of a continual and continuing process.

The mean metallicity of the stellar halo, around \(-1.5\) dex (e.g. Ryan & Norris 1991), is low compared with that of the solar neighborhood, which is around \(-0.2\) dex (Nordstrom et al. 2004). With a fixed stellar initial mass function, and no gas flows, one expects a system of higher gas fraction, such as the local disk, to be less chemically evolved than a system with lower gas fraction, such as the stellar halo. Hartwick (1976) provided an elegant explanation that related low mean metallicity to gas outflows during star formation; this is expected in scenarios of the formation of the stellar halo, such as just described, that postulate star-formation in low binding energy systems. The chemical evolution requirements are such that for a fixed stellar IMF, 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 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).

Indeed, the field stellar halo can be formed through the disruption of any flavour of system, as long as it formed stars only very early in cosmic time (to be compatible with the old age of the halo) and did not self-enrich significantly (to be consistent with the low mean overall metallicity plus the apparent lack of enrichment by Type Ia supernovae). Hierarchical clustering cosmologies such as \(\Lambda\)CDM postulate that the stellar halo formed through the disruption of small galaxies; the only example of a viable satellite galaxy for this, at the present day, is the Ursa Minor dwarf spheroidal (dSph), being the only one with a uniformly old, metal-poor population (e.g. Unavane et al. 1996). And even for this dSph, the pattern of elemental ratios may not match those in the stellar halo (e.g. Shetrone et al. 2003; Tolstoy et al. 2003). A typical star in a typical dSph,
which has had star formation over an extended period, longer than in the Ursa Minor dSph, lacks the enhanced level of [\(\alpha/Fe\)] seen in the field halo stars (Venn et al. 2004). Indeed, analysis of the age distributions of stars in dSph, and in the stellar halo, as a function of metallicity (Unavane et al. 1996) demonstrates that systems like the extant dSph could not form the bulk of the stellar halo unless they were accreted more than \(\gtrsim 8\) Gyr ago and further star formation was rapidly truncated after accretion. A similar conclusion, that extent dSph could not provide a significant fraction of stars in the stellar halo, follows from analysis of their elemental abundances (Venn et al. 2004). The response of \(\Lambda\)CDM advocates is to argue that the ‘satellites’ that formed the stellar halo were indeed accreted only very early, and that this early accretion necessarily makes those satellites different from the survivors, traced by the dSph, which were accreted later (e.g. Bullock & Johnston 2005). The required truncation of star formation for early accretions, but not for later accretion (e.g. LMC analogs), is simply assumed (e.g. Robertson et al. 2005).

A further constraint is the remarkably low level of cosmic (i.e. not observational uncertainty) scatter seen in the ratios of \(\alpha\)-elements to iron in halo stars (e.g. Cayrel et al. 2004), as low as \(\sim 0.05\) dex. This requires a fixed invariant massive-star IMF (e.g. Wyse & Gilmore 1992; Wyse 1998) and little ‘cross-
talk’ between star-forming regions (Gilmore & Wyse 1998; see also François et al. 2004).

Of course, as noted above, mergers and accretion from satellite galaxies do play some role in the evolution of the Milky Way. As kinematic and metallicity datasets increase in size and quality structure is being identified, such as a retrograde stream (Gilmore, Wyse & Norris 2002) that may be associated with the globular cluster \( \omega \) Cen, or at least the posited parent dwarf galaxy of which this globular cluster would be the surviving nucleus (Mizutani, Chiba & Sakamoto 2003). Streams are more rare in the inner halo \( (R_G \lesssim R_{solar} \text{ circle})\), which contains most of the stellar mass), perhaps reflecting shorter dynamical timescales. Moving groups in local high-velocity stars have indeed been isolated (e.g. Helmi et al. 1999; Meza et al. 2005), but mass estimates are uncertain when based on few stars (see Chiba & Beers 2000), as are their origins – perhaps even local streams are associated with the Sagittarius dwarf (e.g. Majewski et al. 2003), or the putative parent of \( \omega \) Cen (Meza et al. 2005).

More recent accretion into the stellar halo may be constrained by spatial structure, or lack thereof. The 2-point correlation function of relatively bright, \( B < 19 \), main sequence stars shows little structure, illustrated in Figure 3 (Lemon et al. 2004), as is the case for halo Blue Horizontal Branch stars (Brown et al. 2004). Recent accretion is not a dominant mechanism for formation of the bulk of the stellar halo. The outer halo does show structure in coordinate space, for example in analyses of faint imaging data from the Sloan Digital Sky Survey (Newberg et al. 2002), a significant part of which is due to the Sgr dSph, but not all. Kinematics and metallicity data will be crucial in the interpretation.

Analysis of the dynamics, evolution and survival of substructure in hierarchical models is beyond the resolution limits of most cosmological simulations, but can be addressed by galaxy-scale simulations and by semi-analytic means. Interactions between the subsystems can dominate (e.g. Zhang et al. 2002; Pernicrubia & Benson 2004; Knebe et al. 2005) requiring rather detailed information to make predictions.

Looking beyond the Milky Way, models for the field halo stellar population must address the apparent correlation between the mean metallicity of the halo stars and the host luminosity (Mouhcine et al. 2005; see also Brodie & Huchra 1991 for a version using globular clusters to trace the stellar halo, updated to include only the blue, metal-poor cluster subsystem in Strader, Brodie & Forbes 2004). Such correlations, including the overall luminosity–metallicity relationship (e.g. Dekel & Woo 2003) are not easily reproducible in hierarchical clustering models, where merger history plays a strong role (see e.g. Renda et al. 2005). Correlations of the properties of the stellar populations with overall potential well depth suggest that if mergers are indeed the dominant mechanism by which galaxies form and evolve, the mergers must be gas rich, and most stars form during the mergers, with the last significant merger dominating the star formation history.

### 5.2. Globular Clusters

The seminal paper of Searle & Zinn (1978) proposed that the globular clusters of the outer halo formed in ‘transient protogalactic fragments’ that were accreted
after the formation of the central regions. This conclusion was based on an analysis of the available metallicity and horizontal branch morphology data, which implied that (assuming that age is the ‘second parameter’) the outer clusters had a range of ages, while the inner clusters were uniformly old. This general age spread – Galactocentric distance trend has been confirmed by analyses based on deep colour-magnitude data, including the main sequence turn-off (e.g. Salaris & Weiss 2002). Furthermore, deep HST imaging has shown similarities between the outer globular clusters and those of satellite galaxies, in terms of both HB morphology as a function of metallicity and values of their core radii (Mackey & Gilmore 2004). Whether this indicates that the outer clusters were acquired by the Milky Way during the accretion of systems like the present-day satellites
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(Mackey & Gilmore 2004), or that star clusters that form and evolve in low density regions have large core radii, is unclear (see also Wilkinson et al. 2003). Elemental abundances of halo stars across the Galaxy will be of interest, to investigate whether the outer field halo has a similar pattern to the stars in dSph, and is part of the science case of the proposed multi-object high spectral-resolution next-generation Gemini instrument WFMOS.

The dynamical evolution of (globular) clusters is determined by a complex mix of internal and external effects. The beautiful tidal arms/tails from Pal 5 (Odenkirchen et al. 2003) confirm the expectation of mass loss. It will be very interesting to re-visit, with deep multi-band CCD photometry, the 20 globular clusters for which Leon, Meylan & Combes (2000) detected low surface density tidal tails from wavelet analysis of star counts from photographic plates. In particular, these authors found significant recent mass loss from ω Cen, which as we noted above has been proposed as a surviving core of an accreted dwarf galaxy (e.g. Bekki & Freeman 2003).

The formation and survival of (diffuse) clusters in relatively shallow potential gradients is of particular interest in the context of dwarf spheroidal galaxies and their retinue of globulars (setting aside the separate puzzle of why the orbits have not decayed through dynamical friction – Hernandez & Gilmore 1998; Lotz et al. 2001). Similarly to the situation with the field stellar halo in the Milky Way, the field population in dSph must have formed at significantly higher densities, presumably in star clusters that were subsequently dispersed. Again, similarly to the Milky Way halo, remnant structure may have been identified, in the form of cold streams, in the dSph (Kleyna, Wilkinson, Gilmore & Evans 2003; Kleyna, Wilkinson, Evans & Gilmore 2004).

5.3. The Dwarf Spheroidal Galaxies

The dSph satellite galaxies of the Milky Way have been the focus of much recent effort, both observational and theoretical, addressing the many ways in which these systems could interact with, and contribute to, the Milky Way, and could impact our understanding of galaxy formation and evolution and the nature of dark matter. The kinematic and photometric data that allowed the identification of the substructure in dSph mentioned in the last subsection is part of such a large survey, using several 8m-class ground-based telescopes. Chemical abundance data, including individual elements, are now available for most of the dSph (e.g. Venn et al. 2004; Koch et al. 2005). The radial velocities over the face of the galaxies, extending beyond the nominal ‘tidal radius’, provide constraints on the inferred dark matter distribution (e.g. Kleyna et al. 2002). These data, when combined with detailed star formation histories and radial profiles, will provide significant constraints on the physics of star formation and baryonic feedback, a major stumbling block in our understanding of how to model galaxies.

The modelling of the underlying dark halo needs to go beyond the obviously inappropriate one-component, mass-follows-light, King models that have been widely used in the past (e.g. review of Mateo 1998), and address issues such as the degeneracy between mass and velocity anisotropy that are inherent in previous analyses (see Binney & Mamon 1982 for an elegant discussion of this last point). Recent models that address these issues for isolated dSph include
Wilkinson et al. (2002) and Wang et al. (2005). However, the dSph are clearly not isolated, and the time-dependent dynamical effects of their environment must be taken into account in the modelling, particularly of the outer parts.

6. The Bulge

The age distribution of the dominant population of the bulge is reasonably well-constrained only for Galactocentric z-distances greater than about 400 pc, Galactic latitude $|b| \gtrsim 3^\circ$, since interior to this one faces the complexities of the local decomposition into bulge and local disk. Here, analyses of deep HST colour-magnitude diagrams, after correction of foreground disk stars, have shown that the dominant population is old, $\gtrsim 10$ Gyr (Feltzing & Gilmore 2000; Zoccali et al. 2003). The integrated population of the inner 10 degrees of the central regions has been studied through deep ISO mid-IR data, combined with near IR data from DENIS, and again the conclusion is that the dominant population is old (van Loon et al. 2003). There is also a less significant intermediate-age component seen in the ISO data, probably that traced by the OH/IR stars that have been surveyed interior to $|b| = 3^\circ$ (Sevenster 1999). A young population is also detected by van Loon et al. (2003), plus there is ongoing star formation in the plane near the Galactic Center, most notably traced by populous young clusters (Figer et al. 1999). 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. Continuous star formation at the present rate, over the last $\sim 10$ Gyr, could form the entire central stellar cusp, and evidence for this has been presented (Figer et al. 2004).

Indeed the relation between the inner triaxial bulge/bar, now fairly well-characterised (see Babusiaux’s contribution to this volume, and Babusiaux & Gilmore 2005) and the larger-scale bulge is as yet unclear (see Merrifield 2004 for a recent review). All that said, the dominant population in the bulge is probably old.

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 $[\text{Fe/H}] \sim -0.3$ 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 a handful of stars, show mostly the enhanced [$\alpha$/Fe] signatures of enrichment by predominantly Type II supernovae (McWilliam & Rich 1994; McWilliam & Rich 2004; Fulbright, Rich & McWilliam 2005), indicating rapid star formation. Indeed the chemical abundances favor very rapid star formation and (self-)enrichment (Ferreras, Wyse & Silk 2003).

Deep star counts in the bulge can be used to derive the faint stellar luminosity function and mass function (modulo mass-to-luminosity uncertainties; Zoccali et al. 2000). Comparison with low-metallicity globular clusters shows that the inferred stellar IMF is invariant over this range of metallicity. Further,
the faint luminosity function in the Ursa Minor dSph is also indistinguishable from that of globular clusters of the same metallicity (Wyse et al. 2002). The ‘Type II plateau’ in the elemental abundances of the bulge stars is equal to that in the stellar halo, implying a fixed massive star IMF. An invariant IMF is one of the few simplifying assumptions that we can make with confidence.

The formation of the central bulge then must produce a metal-rich, predominantly old stellar population, with central regions that contain a supermassive black hole, and a triaxial bar, with recent and ongoing star formation. In the hierarchical clustering scenario, bulges are built up during mergers, with several mechanisms 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). These secular processes would perhaps form ‘pseudo-bulges’, identified in observations through, for example, exponential, rather than $r^{1/4}$, light profiles (e.g. Carollo et al. 2001). Again, if this were to be a late-epoch process, with inward gas flows driven by bars etc., one would expect a significant range of stellar ages in the pseudo-bulge (see the comprehensive review of Kormendy & Kennicutt 2004).

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 $\gtrsim 10 M_\odot/yr$. As noted above, a possible source of the gas is ejecta from star-forming regions in the halo (see Figure 2 above and associated discussion).

Or is the bulge really a ‘pseudo-bulge’, formed through secular instabilities (see discussion in Wyse 1999)? What role is the bar playing in building the central regions? What is the connection to the supermassive black hole at the Galactic Center? Why does the Milky Way deviate significantly from the correlations of black hole mass with bulge properties (Tremaine et al. 2002)?

7. Concluding Remarks

The mean properties of the dominant stellar populations of the different components of the Milky Way are reasonably well-defined at a few locations only. Even at those locations, we have incomplete knowledge of the distribution functions. We do know that the properties of the different stellar populations overlap, and our ignorance causes possibly important physics to be lost.
We need to determine detailed age distributions, spatial distributions, kinematics, elemental abundance distributions etc. for large samples of galactic stars, both locally and globally. We need further to match the data with robust analyses. Unfortunately, time-dependent dynamics could be important in several aspects, and must be addressed – in the disk, through perturbations from transient spiral arms and the bar; in the halo and thick disk through tidal effects and disk ‘shocking’ on substructure; in the bulge through secular evolution and heating. We must also push galaxy formation theories into making more contact with reality, with testable predictions.

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**References**

Abadi, M., Navarro, J., Steinmetz, M & Eke, V. 2003, ApJ, 597, 21
Babusiaux, C. & Gilmore, G. 2005, MNRAS, 358, 1309
Beers, T. et al. 2000, AJ, 119, 2866
Bekki, K. & Freeman, K.C. 2003, MNRAS, 346, L11
Bellazzini, M., Ibata, R., Monaco, L., Martin, L., Irwin, M. & Lewis, G. 2004, MNRAS, 354, 1263
Bensby, T., Feltzing, S. & Lundström, I. 2004, A&A, 415, 155
Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005 A&A, 433, 185
Benson, A. 2005, MNRAS, 358, 551
Benson, A., Lacey, C., Frenk, C. Baugh, C. & Cole, S. 2004, MNRAS, 351, 1215
Binney, J. & Mamon, G. 1982, MNRAS, 200, 361
Binney, J., Dehnen, W. & Bertelli, G. 2000, MNRAS, 318, 658
Bonifacio, P., Hill, V., Molari, P., Pasquini, L., DiMarcantonio, P. & Santini, P. 2000, A&A, 359, 663
Brodie, J.P. & Huchra, J.P. 1991, ApJ, 379, 157
Brown, W.R. et al. 2004, AJ, 127, 1555
Bullock, J. & Johnston, K. 2005, ApJ submitted, [astro-ph/0506467](http://arxiv.org/abs/astro-ph/0506467)
Bullock, J., Kravtsov, A. & Weinberg, D. 2000, ApJ, 539, 517
Carollo, C.M., Stiavelli, M., de Zeeuw, P.T., Seigar, M. & Dejonghe, H. 2001, ApJ, 546, 216
Carney, B., Latham, D. & Laird, J. 1990, AJ, 99, 572
Cayrel, R. et al. 2004, A&A, 416, 1117
Chiba, M. & Beers, T.C. 2000, AJ, 119, 2843
Cole, A., Smecker-Hane, T. & Gallagher, J. 2000, AJ, 120, 1808
Dekel, A. & Woo, J. 2003, MNRAS, 344, 1131
De Simone, R., Wu, X. & Tremaine, S. 2004, MNRAS, 350, 627
Eke, V., Efstathiou, G. & Wright, L. 2000, MNRAS, 315, L18
Elmegreen, B. 1999, ApJ, 517, 103
Fall, S.M. 2004, in ‘The Formation and Evolution of Massive, Young Star Clusters’, ASP Conference series vol 322, eds H.J.G.L.M. Lamers, L.J. Smith & A. Nota (ASP, San Francisco) p399
Famaey, B. et al. 2005, A&A, 430, 165
Feltzing, S. & Gilmore, G. 2000, A&A, 355, 949
Feltzing, S., Bensby, T. & Lundström, I. 2003, A&A, 397, L1
Ferguson, A.M.N. & Johnson, R. 2001, ApJ, 559, L13
Ferreras, I., Wyse, R.F.G. & Silk, J. 2003, MNRAS, 345, 1381
Figer, D.F. et al. 1999, ApJ, 525, 750
Figer, D.F., Rich, R.M., Kim, S.S., Morris, M. & Serabyn, E. 2004, ApJ, 601, 319
François, P. et al. 2004, A&A, 421, 613
Fuchs, B. 2001, MNRAS, 325, 1637
Fuhrmann, K. 1998, A&A, 338, 161
Fuhrmann, K. 2004, AN, 325, 3
Fulbright, J., Rich, R.M. & McWilliam, 2005, Nucl. Phys., A758, 197
Gilmore, G. & Reid, I.N. 1983, MNRAS, 202, 1025
Gilmore, G. & Wyse, R.F.G. 1991, ApJL, 367, L55
Gilmore, G. & Wyse, R.F.G. 1998, AJ, 116, 748
Gilmore, G., Wyse, R.F.G. & Jones, J.B. 1995, AJ, 109, 1095
Gilmore, G., Wyse, R.F.G. & Norris, J.E. 2002, ApJL, 574, L39
Hartwick, F.D.A. 1976, ApJ, 209, 418
Hasan, H. & Norman, C. 1990, ApJ, 361, 69
Helmi, A. & White, S.D.M. 2001, MNRAS, 323, 529
Helmi, A., White, S.D.M., de Zeeuw, P.T. & Zhao, H.-S. 1999, Nature, 402, 53
Helmi, A. et al. 2005, MNRAS, submitted, astro-ph/0505401
Hernandez, X. & Gilmore, G. 1998, MNRAS, 297, 517
Hill, V., François, P., Spite, M., Primas, F. & Spite, F. 2000, A&A, 364, L19
Ibata, R. & Gilmore, G. 1995, MNRAS, 275, 605
Ibata, R. & Razoumov, A. 1998, A&A, 336, 130
Ibata, R., Gilmore, G. & Irwin, M. 1994, Nature, 370, 194
Ibata, R., Irwin, M., Lewis, G., Ferguson, A. & Tanvir, N. 2003, MNRAS, 340, L21
Kalberla, P.M.W. et al. 2005, A&A in press, astro-ph/0504140
Kaufermann, G. 1996, MNRAS, 281, 487
Kleyna, J., Wilkinson, M., Evans, N.W. & Gilmore, G. 2004, MNRAS, 354, L66
Kleyna, J., Wilkinson, M., Evans, N.W., Gilmore, G. & Frayn, C. 2002, MNRAS, 330, 792
Kleyna, J., Wilkinson, M., Gilmore, G. & Evans, N.W. 2003, ApJ, 588, L21
Knebe, A., Gill, S., Kawata, D. & Gibson, B. 2005, MNRAS, 357, L35
Koch, A. et al. 2005, AJ, submitted
Kormendy, J. & Kennicutt, R. 2004, ARAA, 42, 603
Lacey, C.G. & Ostriker, J.P. 1985, ApJ, 299, 633
Law, D., Johnston, K.V. & Majewski, S. 2005, ApJ, 619, 807
Lemon, D., Wyse, R.F.G., Liske, J., Driver, S. & Horne, K. 2004, MNRAS, 347, 1043
Leon, S., Meylan, G., Combes, F. 2000, A&A, 359, 907
Lotz, J. et al. 2001, ApJ, 552, 572
Mackey, A.D. & Gilmore, G. 2004, MNRAS, 355, 504
McWilliam, A. & Rich, R.M. 1994, ApJS, 91, 749
McWilliam, A. & Rich, R.M. 2004, in ‘Origin and evolution of the elements’, Carnegie Observatories Astrophysics series, eds A. McWilliam & M. Rauch (Pasadena, Carnegie Observatories) p38
McWilliam, A. & Smecker-Hane, T. 2005, in ‘Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis’ eds. F. Bash & T. Barnes (ASP: San Francisco), astro-ph/0409083
Majewski, S., Strumsky, M., Weinberg, M. & Ostheimer, J. 2003, ApJ, 599, 1082
Martin, N.F., et al. 2004, MNRAS, 348, 12
Mastropietro, C. et al. 2005, MNRAS submitted, astro-ph/0412312
Matteucci, F & Greggio, L. 1986, A&A, 154, 279
Mateo, M. 1998, ARAA, 36, 435
Merrifield, M.R. 2004, in ‘Milky Way surveys: the structure and evolution of our Galaxy’, (eds. D. Clemens, T. Brainerd & R. Shah), ASP Conf Proc. vol. 317 (ASP, San Francisco) p289
Meza, A., Navarro, J., Abadi, M. & Steinmetz, M. 2005, MNRAS, 359, 93
Mizutani, A., Chiba, M. & Sakamoto, T. 2003, ApJ, 589, L89
Wilkinson, M., Kleyna, J., Evans, N.W. & Gilmore, G. 2002, MNRAS, 330, 778
Wilkinson, M., Hurley, J., Mackey, A., Gilmore, G. & Tout, C 2003, MNRAS, 343, 1025
Wyse, R.F.G. 1998, in ‘The Stellar Initial Mass Function’, ASP Conference series vol 142, eds G. Gilmore & D. Howell (ASP, San Francisco) p89
Wyse, R.F.G. 1999, in ‘The Formation of Galactic Bulges’, Cambridge Contemporary Astrophysics series, eds M. Carolla, H.C. ferguson & R.F.G. Wyse (Cambridge, CUP) p195
Wyse, R.F.G. 2000, in ‘The Galactic Halo: From Globular Clusters to Field Stars’, ed. A. Noels et al., (Liège, Institut d’Astrophysique et de Geophysique), p305
Wyse, R.F.G. & Gilmore, G. 1986, AJ, 91, 855
Wyse, R.F.G. & Gilmore, G. 1992, AJ, 104, 144
Wyse, R.F.G., Gilmore, G., Houdashelt, M., Feltzing, S., Hebb, L., Gallagher, J. & Smecker-Hane, T. 2002, New Astr, 7, 395
Wyse, R.F.G., Gilmore, G., Norris, J.E., Wilkinson, M., Kleyna, J., Koch, A., Evans, W. & Grebel, E. 2005, ApJL, submitted
Yanny, B. et al. 2003, ApJ, 588, 824
Yoachim, P. & Dalcanton, J. 2005, ApJ, 624, 701
Zentner, A. & Bullock, J. 2003, ApJ, 598, 49
Zentner, A., Berlind, A., Bullock, J., Kravtsov, A. & Wechsler, R. 2005, ApJ, 624, 505
Zhang, B., Wyse, R.F.G., Stiavelli, M. & Silk, J. 2002, MNRAS, 332, 647
Zoccali, M. et al. 2000, ApJ, 530, 418
Zoccali, M. et al. 2003, A&A, 399, 931