*The Ages of Stars*
*Proceedings IAU Symposium No. 258, 2009*
*E.E. Mamajuk, D.R. Soderblom, & R.F.G. Wyse, eds.*

DOI: 00.0000/X000000000000000X

# The star-formation history of the Milky Way Galaxy

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**Abstract.** The star-formation histories of the main stellar components of the Milky Way constrain critical aspects of galaxy formation and evolution. I discuss recent determinations of such histories, together with their interpretation in terms of theories of disk galaxy evolution.

**Keywords.** Galaxy: disk, (Galaxy:) evolution, (Galaxy:) stellar content

## 1. Context: Disk galaxy formation and evolution

The Milky Way appears to be a typical disk Galaxy, albeit the one for which we can obtain the most detailed information, for the largest samples of tracer objects (I will mostly discuss samples of stars). The star-formation histories of the main stellar components of the Milky Way constrain critical aspects of disk galaxy formation and evolution. These include aspects of the merger history, such as what merged with the Milky Way and when did it merge, and also the epoch at which extended disks started to form. These in turn depend upon the nature of dark matter, possible 'feedback' mechanisms once stars start to form, and the amplitudes, onset and duration, and signs, of gas flows.

Much observational evidence, in particular from large-scale structure such as the spectrum of fluctuations in the cosmic microwave background, and the statistics of massive galaxy clusters, has led to a 'concordance' cosmological model, wherein the recent (since a redshift of $\sim 1$) rate of overall expansion of the Universe is driven by Dark Energy, and the matter content of the Universe is predominantly non-baryonic Cold Dark Matter (e.g. Spergel et al. 2007). The primordial power spectrum of Cold Dark Matter (CDM) has most power on small scales, resulting in a hierarchical sequence of structure formation, whereby small scales form first, then subsequently merge to form larger systems. This concordance model will be referred to below as $\Lambda$CDM.

While baryons are a minor constituent of such a $\Lambda$CDM Universe, contributing less than 3% of the energy density at the present day, they are of course how we trace most of the mass in the Universe. The baryonic physics of gaseous dissipational cooling and subsequent star formation is much more difficult to model than is the (Newtonian) gravity that is the only force of significance for dissipationless CDM. The most detailed simulations of the formation and evolution of an analog of the present-day Milky Way have therefore been purely N-body, with gravity the only force and all matter being CDM. The state-of-the art in October 2008 is illustrated by the Via Lactae II simulation (Diemand et al. 2008). This simulation follows the formation of the dark halo of a model Milky Way Galaxy, with initial conditions selected from a larger simulation to ensure that there will be no major merger after a redshift of 1.7 (a look-back time of somewhat less than 10 Gyr – as we discuss below, this restriction on the merger history is to prevent destruction of the thin disk within the lifetime of old stars presently observed in the local disk).

A striking feature of this very high-resolution simulation is the persistent substructure, even near the analog of the solar circle: 97% of subhaloes that are initially identified at redshift unity still leave a bound remnant at the present epoch. Depending on the details of their mass and density distributions, these subhaloes are expected to lead to heating and fattening of the thin stellar disk (e.g. Hayashi & Chiba 2006).

The overall trends of stellar ages in such hierarchical clustering models are illustrated by the predictions of Abadi et al. (2003), who simulated the formation of a disk galaxy using a hybrid N-body and Smoothed Particle Hydrodynamics code, with simple gas-cooling and star-formation criteria.† The galaxy that forms is more bulge-dominated than is the Milky Way, reflecting the typical, active merger history in the ΛCDM cosmogony (and hence the need to pre-select initial conditions to form a Milky Way analog, as done by Diemand et al.). The model galaxy can be decomposed into spheroid (bulge/halo), thick disk and thin disk, with these components being distinct in terms of both surface-brightness profiles and kinematics. The spheroid is old, and was created by major mergers that disperse the pre-existing disk, plus tidal debris from more minor mergers (in this simulation, about half by each mechanism). The thin disk seen today is mostly stars that formed *in situ* after the cessation of merger activity, from gas that was accreted smoothly into the disk plane, as it cooled in the dark halo. The inner thin-disk formed faster, reflecting the shorter accretion times of lower-angular-momentum gas, destined to dissipate into circular orbits in the central regions (Mo, Mao & White 1998). There is therefore a gradient in mean stellar age at the present epoch, declining from a mass-weighted age of 6 Gyr close to the center to 3 Gyr in the outer parts. The active merging, typical for the ΛCDM cosmogony, means that the overall galactic potential is not steady enough for formation of an extended thin disk until more recently than a look-back time of $\sim 8$ Gyr (redshifts less than unity). A disk can form early, then be destroyed, but the early disks are compact, due to the low angular-momentum content of their progenitor gas, reflected in the 'inside-out' formation of disks (e.g. Scannapieco et al. 2009).

In the Abadi et al. realization, the thick disk is predominantly old, and the bulk of it consists not of stars formed in the potential well of the final galaxy, but instead of stars formed in satellite galaxies that were later accreted, with half due to a satellite that merged $\sim 6$ Gyr ago, while the stars are older than $\sim 10$ Gyr old. The old stars (older than $\sim 8$ Gyr) in the thin disk are also predominantly accreted. This of course requires that the satellite hosts be on high-angular-momentum orbits, with periGalacticons within the disk, before their stars are assimilated into the disk. Given that the typical initial orbit of a satellite dark-halo is far from circular, this in turn requires that the satellite halo be rather massive, so that dynamical friction can operate to circularize and shrink the orbit.

### 1.1. *Tracing the merger history*

In a merger, orbital energy is absorbed into the internal degrees of freedom of the merging systems, heating them. A major merger, one with approximately equal mass ratio, essentially destroys pre-existing disks, transforming them into a pressure-supported spheroid or stellar halo (with $\sim 1:3$ being the limiting mass ratio; Cretton et al. 2001). The effects of the accretion of satellites (galaxies plus pure dark matter) depends on the time of accretion, their initial orbits, masses and density profiles, since these dictate how easily they are tidally disrupted, and to which component their stellar debris will contribute. Minor mergers (mass ratios of less than $\sim 1:5$) of a fairly robust satellite should puff up an existing thin stellar disk into a thick disk (e.g. Quinn & Goodman 1986; Kazantzidis

† Watch the movie at `http://www.aip.de/People/MSteinmetz/Movies.html`

et al. 2008), plus deposit tidal debris from the satellite along its orbit. Some fraction of the stellar mass of the thin disk is also often assumed, in semi-analytic models, to be directly added to the bulge after a minor merger (Kauffmann 1996; de Lucia & Blaizot 2007). Gravitational torques during mergers cause transport of angular momentum, resulting in gas being taken into the central regions, where, after an induced star-burst, it can contribute to the bulge (Mihos & Hernquist 1996). Gas flows driven by mergers can possibly also build-up the bulge by triggering disk instabilities, in a fusion of dynamical and secular mechanisms (Bower et al. 2006). Dense, inner regions of massive satellites (the higher mass meaning dynamical friction timescales are shorter) could also contribute stars to the bulge (Ostriker & Tremaine 1975).

The stellar age distributions of thin disk, thick disk, stellar halo and bulge populations therefore depend on the merger history, and observational determination of these distributions can constrain the mergers.

## 2. The star-formation history of the thin disk

Unfortunately, the star-formation history (SFH) of the thin disk is poorly known far from the solar neighborhood. This lack of data needs to be rectified; hopefully the next generation of imaging surveys, such as Pan-STARRS, will provide data for both the inner disk and the outer disk. Theoretical expectation in a wide range of models is that star formation should proceed on faster timescales in the denser regions, due to the shorter dynamical times there, so that inner (denser) regions of disks are expected to have an older mean age, even if the time of the onset of star formation is fixed. Chemical evolution models (see Pipino & Matteucci's contribution to this volume) also favor slower star-formation in the outer parts, to match metallicity gradients. In hierarchical-clustering models, as noted above, the onset of star formation in the thin disk is later for the outer parts, due to the later accretion of the higher-angular momentum gas to form the outer disk.

### 2.1. *The onset of star formation in the local disk*

The star-formation history of the local disk has been derived using a variety of techniques, the details of which are discussed (with limitations and advantages) elsewhere in this volume. Ages of the oldest stars have been estimated from isochrone-fitting, with the result that the oldest stars are less than 2 Gyr younger than the metal-poor globular clusters, i.e. ages of $\sim$ 11 Gyr (e.g. analyses of the Hipparcos dataset by Binney et al. 2000; analyses of local stars with Strömgren photometry by Nordström et al. 2004; Nordström, this volume; Holmberg, Nordström & Andersen 2008). White-dwarf cooling ages are model-dependent, as discussed at length in the contributions by Salaris and by Kalirai in this volume, and oldest ages of $\sim$ 12 Gyr are compatible with the luminosity function data (e.g. Fig 8 of Salaris, this volume, but note that the models of Hansen et al. 2002, utilised in Kalirai's paper in this volume, favour a younger oldest age). These old ages are consistent with an early onset of star formation in the local disk (assuming that the stars found locally were born locally), the lookback time of the onset corresponding to redshift $z \gtrsim 2$.

The exponential scale-length of low-mass stars (of spectral type like the Sun and later) in the disk is $\sim 2-3$ kpc (e.g. Jurić et al. 2008 who used M-dwarfs as tracers). Thus if the old stars in the solar neighborhood were formed close to their present location in the disk, star formation was initiated at $\sim 3-4$ scalelengths at $z > 2$. This would then imply that the formation of extended disks was *not* delayed until after a redshift of unity – the typical epoch of the last major merger for a $10^{12}\,M_{\odot}$ halo, in $\Lambda$CDM – as has been proposed in CDM-models with feedback (e.g. Weil et al. 1998; Thacker & Couchman 2001; Governato et al. 2007).

Alternatively, the old stars in the local thin disk could have formed elsewhere and more recently arrived in the solar neighborhood – two such scenarios have been proposed, with these old stars forming in either (a) satellite galaxies that are assimilated later, on circular orbits (Abadi et al. 2003), or (b) the inner disk and migrating outwards due to the influence of transient spiral arms† (Roškar et al. 2008a,b). In the first scenario, the satellites that could provide stars on near-circular orbits at the solar neighborhood would most probably have to be massive, so that dynamical friction (operating on a timescale proportional to the inverse of the satellite mass) can be effective in damping the satellite's orbit prior to its member stars being accreted. These satellites are the most capable of self-enrichment, and may be expected to contribute not just old stars, but also younger stars. If the pattern of elemental abundances produced were anything like those found in the surviving satellites (bearing in mind that these 'old disk' satellites are proposed to be accreted relatively recently, after a redshift of unity) then these should give a distinct signature, in particular low values of [$\alpha$/Fe] at low [Fe/H]. At least two groups – Ruchti, Fulbright, Wyse et al. (2009, in prep.), using the RAVE survey (e.g. Steinmetz et al. 2006) to select their sample, and Reddy & Lambert (2008) – are obtaining and analyzing elemental abundance data for metal-poor (thick) disk stars, and have found nothing distinctive.

In the second scenario, one again expects a signature in the elemental abundance pattern of local stars, since efficient radial mixing of stars from distant regions with different star-formation histories gives increased scatter (e.g. François & Matteucci 1993; Schoenrich & Binney 2009). Migration has been proposed to explain in particular metal-poor disk stars locally in the disk (Haywood 2008) with a large fraction of these stars to have come inwards to the solar neighborhood, from the outer disk. These metal-poor disk stars are again of all ages (except younger that $\sim 2$ Gyr, plausibly the travel time of the migration), including the oldest ages, so this migration would imply an early onset for the outer disk beyond the solar circle, even more difficult to explain in $\Lambda$CDM than early star formation at the solar circle. Haywood (2008) proposes that migrated stars do indeed complicate the interpretation of trends in the elemental abundance patterns, but as we discuss below (section 3.2, cf. Reddy, Lambert & Allende Prieto 2006), the scatter is small and the uncertainties in the kinematic basis for the assignment of stars to the different components of the Galaxy provides an alternative explanation for outliers.

### 2.2. *Variation over time*

Again, various techniques have been used to estimate the temporal variation of the star-formation rate in the local disk. Several find evidence for 'bursts' in star-formation activity, of amplitude $2-3$, superposed on an underlying slow variation. Examples include the isochrone-based analysis of the Color Magnitude Diagram (CMD) of the Hipparcos dataset by Hernandez, Gilmore & Valls-Gabaud (2000), providing a temporal resolution of 50 Myr, albeit with a sample selection that limited the analysis to only the last $\sim 3$ Gyr (and adopting a fixed metallicity, which is a reasonable simplification for this narrow age range). These authors found a quasi-periodic variation with period of $\sim 0.5$ Gyr, which they suggested could be due to the passage of spiral arms.

Cignoni et al. (2006) developed their own approach to the analysis of the Hipparcos CMD and derived the star-formation history back to $\sim 12$ Gyr (adopting an age-metallicity relation). They found good agreement with the earlier results of Hernandez et

† I thank Roelf de Jong for his question after my talk.

al. for the younger stars, after rebinning them into 1 Gyr bins to match time resolutions. As is well-known, older disk stars have higher-amplitude random motions, with resultant wider epicyclic excursions about their orbital guiding-center. The derived star-formation rates at older ages then trace a larger portion of the disk, and stars formed locally a long time ago may have been lost from the sample. Cignoni et al. investigated the possible kinematic dependence of their derived SFH by excluding stars more than $n\sigma$ ($n = 1, 2$) away from the canonical local thin-disk 3D-space motion distribution, and found that the resulting distributions, focussing on ages less than $\sim 6$ Gyr, were indistinguishable, and thus unaffected by dynamical diffusion.

The major result is a broad peak at ages $\sim 2 - 6$ Gyr, with the star formation rate at $\sim 3$ Gyr being a factor of 2-3 higher than either of the present-day rate or the rate at ages greater than 6 Gyr. This increase is perhaps attributable to triggering of star-formation activity by an accretion event. This overall SFH is consistent with the analysis of low-mass M-stars (using H$\alpha$ activity as an age indicator) by Fuchs, Jahreiß & Flynn (2009; see their Fig. 5 for comparisons with others); the chromospheric-activity based analysis of G-stars by Rocha-Pinto et al. (2000) shows more high-frequency variations and less of a consistent increase in star-formation activity back to $\sim 5$ Gyr.

Fuchs et al. (2009) argue that the Milky Way follows the 'Schmidt-Kennicutt' star-formation law found for external disk galaxies, which would imply that an increase in gas supply (inflow? accretion?) accompanied the increased level of star-formation rate $\sim 5$ Gyr ago. In any case it is reassuring to find that the Milky Way is typical.

The possibility of significant re-distribution of stars via 'radial migration', in addition to the radial epicyclic excursions considered already in the above papers, needs to be considered, as it raises the issue of to which region(s) of the disk does the derived SFH apply? Roškar et al. (2008a) appeal to radial migration in particular to build-up the outer disk, defined by a break in the gas surface density (and correspondingly, following the Schmidt-Kennicutt law, in the stellar surface density). The outer HI disk of the Milky Way does indeed show such a break, at Galactocentric distance of $12 - 13$ kpc, well beyond the solar circle (see Fig. 5 of Levine, Blitz & Heiles 2008), and similar in location to the 'edge' of the stellar disk at $12-14$ kpc (Reylé et al. 2008). In the model of Roškar et al. (2008a), stars currently beyond the break are those that are most likely to have migrated several kpc outwards ($\Delta R \sim 4$ kpc, see their Fig. 2), a significantly larger distance than their typical epicyclic excursions of $\sim 2$ kpc. The root-mean-square change in radius across the scale, and lifetime, of all the disk stars in this model is $\sim 2.4$ kpc, more comparable to the $\sim \pm 1.5$ kpc epicyclic excursions (estimated from observed kinematics) of the $\sim 3 - 5$ Gyr-old stars that dominate locally. Looking more closely at the model 'solar circle', Roškar et al. (2008b) find that as much as half of the stars could have been born outside $7-9$ kpc, with a bias to metal-rich stars from interior regions. As discussed above, the mixing of stars from regions of different star-formation histories should lead to scatter in the elemental abundances, and the evidence is that only a small fraction of stars do not follow well-defined trends, within observational uncertainty (Bensby et al. 2005; Feltzing & Bensby, this volume; Haywood 2008; Reddy, Lambert & Allende Prieto 2006; Reddy & Lambert 2008). The implication is that radial excursions are limited to mixing predominantly regions of very similar star-formation histories and chemical enrichments – either because there is little radial variation in star-formation history over much of the disk, or there is little radial migration. It will be very interesting to analyse the significantly larger samples of fainter stars with elemental abundances that will be feasible with planned instruments such as HERMES on the Anglo-Australian telescope, and WFMOS (a Gemini instrument) on the Subaru telescope.

## 3. The star-formation history of the thick disk

### 3.1. *Formation and early evolution*

The Galactic thick disk was defined 25 years ago through star counts at the South Galactic Pole in which two vertical exponential components were manifest (Gilmore & Reid 1983), with the general concensus now that is separate and distinct from the Galactic thin disk. Analysis (Jurić et al. 2008) of the deep, uniform wide-field imaging data from the Sloan Digital Sky Survey (SDSS) confirmed the necessity for two disk components, and the best-fit 'global' thick-disk parameters are an exponential scale-length of 3.6 kpc and exponential scale-height of 900pc, with 12% of the local stellar mass-density in the thick disk. These combine to give a total mass equal to 10–20% of the stellar mass of the thin disk, or $\sim 10^{10}\,M_{\odot}$. Stars in the thick disk have distinct kinematics, elemental abundances (and ratios) and age distributions, when compared to the thin disk or stellar halo. Similar structures have been identified in the resolved stellar populations of external disk galaxies (e.g. Mould 2005; Yoachim & Dalcanton 2006).

There are several mechanisms by which a thick stellar disk could result (see, e.g., Gilmore, Wyse & Kuijken 1998; Majewski 1993). Thick disks seems inevitable in ΛCDM due to the heating inherent during the expected late merging and assimilation of satellites into pre-existing thin stellar disks. Simulations with a cosmological distribution of subhalos, in terms of both their mass function and their orbital characteristics, confirm this, and also show that the most massive satellite dominates the heating (e.g. Hayashi & Chiba 2006; Kazantzidis et al. 2008; see Hopkins et al. 2008 for a dissenting view, based however on an analysis using the same satellite orbital distribution as Hayashi & Chiba). In agreement with earlier simulations that focussed on the accretion of one satellite in isolation, a satellite that is dense enough to survive to influence the disk, and of total dissipationless mass ratio 10-20% of that of the stellar disk, will produce a thick stellar disk.

The heating is achieved *via* a mix of local deposition of energy plus excitation of resonances (Sellwood, Nelson & Tremaine 1998), and a thin-disk component can persist (Kazantzidis et al. 2008). Of course, subsequent accretion of gas, and perhaps stars, can (re)-form a thin disk. Dissipation naturally leads to a thin disk after accretion of gas, while accretion of stars into a thin-disk component requires circular orbits for the parent system of those stars.

The stars in the thick disk in this scenario (creation by heating from a pre-existing thin disk) would have an age distribution that reflected that of the thin disk that was heated into the thick disk. With the continuous, fairly smooth, derived star-formation history of the (local) thin disk, starting at the earliest epochs, (lookback times $\sim 10-12$ Gyr), recent accretion, merging and associated heating would then produce a thick disk that at the present time would have stars of age equal to the look-back time of the accretion, unless the accreted satellite were easily destroyed e.g. was of low (relative) density. Turning this around, if the thick disk originated through merger-induced heating of the thin stellar disk, the last significant (defined as $> 20\%$ mass ratio to the disk, robust, dense satellite of stars and dark matter) merger can be dated by the young limit of the age distribution of stars in the thick disk: an age distribution of stars in the thick disk that goes down to, say, 5 Gyr would allow a merger and heating at a redshift of $z_{last} \sim 0.5$, when the lookback time equals 5 Gyr, but if all thick disk stars are old, then the last significant merger was long ago. The age of the oldest thick disk stars, in this scenario, also further constrains the epoch at which an extended, thin stellar disk was in place, available to be heated.

### 3.2. *Ages of the oldest stars*

Analyses of the turn-off age of the thick disk stellar population, within a few kpc of the solar neighborhood, agree that the bulk of the thick disk stars are *old*. The (well-defined) turn-off color, for the spectroscopically derived typical metallicity of a star in the thick disk of $\sim -0.6$ dex, is equal to that of Galactic globular clusters of similar metallicity, e.g. 47 Tuc, corresponding to an age of $10-12$ Gyr (e.g. Gilmore & Wyse 1985; Carney, Latham & Laird 1989; Gilmore, Wyse & Jones 1995; Ivezic et al. 2008, their appendix). This is equal to the estimated age of the oldest *thin* disk stars locally, as discussed above.

Ages for *individual,* slightly evolved thick-disk stars can be estimated from Strömgren photometry. These analyses show that the mean age is certainly older than that of the local thin disk, but there are disagreements in the fraction of 'thick disk' stars that are younger than the globular cluster ages, plausibly largely due to the difficulties in the assignment of an individual nearby star to a specific component, either the thin or thick disk. This probabilistic assignment is based on kinematics, and the standard assumption is that the space motions of each of the local thin disk and thick disk are adequately modelled by three one-dimensional Gaussians (e.g. see Feltzing & Bensby's contribution to this volume; Bensby et al. 2007a, 2004a,b; Reddy, Lambert & Allende Prieto 2006). This is clearly an over-simplification for the thin disk, given that moving groups have been robustly identified in the local disk (e.g. Dehnen 1998; Dehnen & Binney 1998; Famaey et al. 2005; Bensby et al. 2007b), with properties consistent with being dynamically induced by a combination of the Galactic bar and transient spiral arms (e.g. Dehnen 2000; de Simone, Wu & Tremaine 2004). As noted above, radial migration within the thin disk may occur and may also be a complicating issue for the kinematics-based population assignments, and this has yet to be analysed in detail. The likely production of high-velocity outliers in the thin disk kinematics by such mechanisms as three-body interactions can also complicate the population assignments.

Indeed, Reddy et al. (2006; their Fig. 24) suggest that a significant fraction of 'younger' thick disk stars are in fact contaminants from the thin disk. Evidence for an age-metallicity trend within the thick disk does remain in their sample, although once these thin disk contaminants are removed, the thick disk shows no evidence for the incorporation of iron from Type Ia supernovae, in the elemental abundance pattern (their Fig. 20). An age spread of several Gyr could be consistent with this constant 'Type II plateau' in the [$\alpha$/Fe] ratios, plus a typical timescale for Type Ia chemical enrichment of $\sim 1$ Gyr, if the thick disk consisted of stars from several independent star-formation regions, each of which had a short ( $\lesssim 1$ Gyr) duration, but different onset times. However, with age uncertainties of $\pm 2$ Gyr, the data are also consistent with a narrow age range, with mean $\sim 12$ Gyr (on their age-scale), and a simpler interpretation of the elemental abundance pattern as reflecting a global short duration of star formation, $\sim 1$ Gyr.

### 3.3. *Implications for merger history*

The old age of thick disk stars, $\gtrsim 10$ Gyr, limits the last significant minor merger to have occured at a redshift $\gtrsim 2$. While the last *major* merger in $\Lambda$CDM typically is at this epoch, it is minor mergers that are constrained by heating of the thin disk into a thick disk, and these are expected to continue to lower redshifts (e.g. Stewart et al. 2008). The inferred quiescent merger history of the Milky Way is atypical in $\Lambda$CDM. As we will now discuss, consistent limits on the minor-merger history are obtained from the derived star-formation history of the central bulge.

## 4. The star-formation history of the central bulge

During mergers, the expectation is that existing disk stars, and gas to fuel star formation, will be added to the bulge (e.g. Kauffmann 1996), perhaps through an intermediate stage of build-up of a massive inner disk that subsequently becomes unstable (e.g. Bower et al. 2006). The dense, inner regions of satellites can also survive to be added to the bulge, if dynamical friction is efficient enough (and the satellite massive and dense enough). Gravitational torques due to the (mildly) triaxial inner bulge/bar will also drive modest gas inflows at the present day (e.g. Englmaier & Gerhard 1998), in the plane of the disk.

As discussed in detail in Fulbright's contribution to this volume, while there are younger stars in the central regions, these are confined to the disk plane, and the central bulge is dominated by old ($10 - 12$ Gyr), metal-rich stars, with enhanced alpha-element ratios. These properties point to bulge formation in an intense short-lived burst of star formation, *in situ* (a deep potential-well being required to reach the observed high metallicities), a long time ago (e.g. Elmegreen 1999; Ferreras, Wyse & Silk 2003; and the contribution by Pipino & Matteucci in this volume). The inferred star-formation rate is reasonable, of order 10 $M_\odot$/yr for a total mass of $\sim 10^{10}\, M_\odot$ and an age range of $\sim 1$ Gyr.

Thus unless the inner disk is composed of uniformly old stars, there can have been no recent disk instability to form the bar/bulge. There is little room for significant build-up of the central bulge by recent mergers, with the old age again limiting significant merger activity to redshifts $\gtrsim 2$. This matches the constraints from the thick disk, and leads to the suggestion (Wyse 2001) that perhaps both bulge and thick disk were formed by the same last significant minor merger.

An alternative suggestion, consistent with the low value of the angular momentum content of the bulge, and the similarity of the specific angular momentum distributions of the bulge and stellar halo (see Fig. 1), is that the bulge formed from gas ejected from the early star-formation regions in the halo (Carney, Latham & Laird 1990; Wyse & Gilmore 1992). Gas must have been lost from the stellar halo since all indications are that the stellar Initial Mass Function (IMF) was normal, at both high and low masses (e.g. Wyse 1998), but the mean metallicity is far below the yield for that IMF (see Hartwick 1976 for the basic model).

## 5. The star-formation history of the halo

The bulk of the stellar halo by mass, interior to Galactocentric distances of $\sim 20$ kpc, is rather uniform in its properties: the stars – and globular clusters – are old and metal-poor, and show enhanced elemental abundances ([$\alpha$/Fe] in particular) that are indicative of short duration(s) of star formation, in low-mass star-forming regions, with 'normal' Type II-progenitor stellar IMF. These properties are unlike those of most stars in satellite galaxies now. Particular attention recently has been paid to the differences in elemental abundance patterns (cf. Venn et al. 2004; Geisler et al. 2007). The differences can be understood in terms of the different star-formation histories of the field halo and the surviving satellite galaxies – the former having a narrow stellar age-range and rapid chemical enrichment, and the latter having a wide stellar age-range and slow, inefficient enrichment, allowing incorporation of iron from Type Ia supernovae (and hence low [$\alpha$/Fe]) even at low levels of overall enrichment (e.g. Gilmore & Wyse 1991; Unavane, Wyse & Gilmore 1996; Lanfranchi & Matteucci 2003).

Comparison of the age distributions alone leads to the conclusion (Unavane et al. 1996)

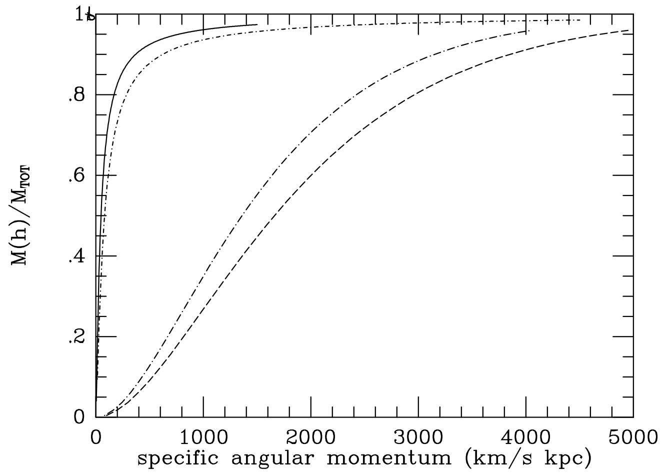


**Figure 1.** Adapted from Wyse & Gilmore 1992, their Figure 1. Specific angular momentum distributions of the bulge (solid curve), the stellar halo (short-dashed/dotted curve), the thick disk (long-dashed/dotted curve) and the thin disk (long-dashed curve). The bulge and stellar halo have similar distributions, with most of the mass at low angular momentum (curves passing through upper left of the figure). The distributions of thick and thin disks are also similar to each other, with significant mass fraction at high angular momentum.

that accretion into the field halo from stellar satellites with a typical extended SFH has not been important for the last $\sim 8$ Gyr, this time coming from the estimated lower limit to the ages of stars in the field halo. Their analysis of the distribution of the field halo stars in the color-metallicity plane allows perhaps $\sim 10\%$ by mass to have been accreted later, predominantly in the metal-rich tail of the halo. Of course satellites like the Ursa Minor dSph, composed of only old, metal-poor stars, could be accreted and assimilated into the field halo at any time and would not be distinguishable on the basis of age or metallicity. However, such satellites are rare at the present time. Early disruption of a few massive satellites could form the stellar halo, of total stellar mass $\sim 10^9\,M_\odot$ (e.g. Robertson et al. 2005), but we need to understand what causes the necessary cessation in star formation, when, for example, the LMC has not been so affected.

A significant fraction of stars in the outer halo could have been accreted from the Sgr dSph (Ibata, Gilmore & Irwin 1994), which is on an orbit with periGalacticon of $\sim 25$ kpc and apoGalacticon $\sim 50$ kpc (e.g. Ibata et al. 1997). Tidal arms from this system are seen across the Galaxy (e.g. Majewski et al. 2003; Fellhauer et al. 2006).

## 6. Concluding remarks

The old mean stellar ages and short durations of star formation of the thick disk and bulge argue for little late accretion and merging into the Milky Way. Accretion after a redshift of $\sim 2$ should have been predominantly smooth, of gas-dominated, low-density systems. The relatively high mean metallicity, plus inferred rapid star formation (from the ages and elemental abundance patterns), of both components argues for star formation within deep potential wells. This favours *in situ* star formation of each of the bulge and thick disk, and rapid mass assembly of the overall Milky Way.

The presence of very old stars, ages $\gtrsim 10$ Gyr, in the local thin and thick disks argues for the existence of an extended disk at redshift $\sim 2$.

The old mean stellar age and inferred short duration of star formation of the bulk of the stellar halo implies that the field halo cannot have formed from systems like the existing satellites, which typically have had much more extended star-formation histories. The low mean metallicity, plus curtailed star formation, argues for star formation within shallow potential wells, so that early mass loss is facilitated. Instead of such low-mass systems, the ΛCDM-based models favour a few massive satellites, accreted early, as the source of the field halo (Robertson et al. 2005; Sales et al. 2007); rapid gas loss is assumed to occur by ram pressure stripping, but this assumption needs to be modelled.

The quiescent merging history, and rapid mass assembly, of the Milky Way, is unusual in ΛCDM. However, surveys of galaxies at redshift $z \sim 2$, find rapid star formation and chemical enrichment, and extended disks, similar to the inferences for the Milky Way at that look-back time (e.g. Maiolino et al. 2008; Daddi et al. 2008; Genzel et al. 2008).

However, our understanding of the global star-formation history of the Milky Way remains incomplete. For this we need to determine the detailed age distributions, spatial distributions, space motions, and elemental abundances for large samples of Galactic stars, both locally and more globally. Several large imaging surveys are planned in the near future, and these need to be matched by large spectroscopic surveys, at both high and low spectral resolution. These will be challenging, but worth the investment.

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**Discussion**

de Jong: Recently it has, for instance, been argued by Roškar et al. (2008) that radial migration of stars is much larger than previously estimated, meaning that stars in the solar neighbourhood do not reflect the local star formation history, but instead a combination of central Galaxy star formation and migration history. If this is the case, how can we disentangle these effects?

Wyse: The thin disk at the solar neighborhood shows little scatter in elemental abundance ratios, and this is hard to reconcile with stellar migration over many kpc, mixing regions of different star-formation history. If migration is limited to $\lesssim 1$ kpc then I do not believe it will affect the derived local SFH significantly since normal stellar orbits sample that range.

Melbourne: What percentage of stars in the thin disk are old? Are they coeval with the thick disk? Would they be thick disk stars?

Wyse: The analyses of the derived local star-formation histories do not have a very good handle on the oldest stars (since they are faint) but estimates (e.g. Cignoni et al. 2006) suggest $\sim$10% in the 10-12 Gyr range. These have thin-disk kinematics so they are probably not thick-disk members (modulo uncertainties in population assignment). It is difficult to distinguish ages 10-12 Gyr, so although the oldest thin disk stars may be $\sim 1$ Gyr younger than the thick disk, it is best to say both are 'old'.

King: You've said little or nothing about the bar. Is it merely the manifestation of a dynamical instability, or should we be able to learn something from it about the formation history of the Milky Way?

Wyse: We still don't know much about the evolutionary state of the bar. It is clear that the Milky Way bulge shows some characteristics of 'pseudo-bulges', for example an exponential surface-density profile, but the uniform old age argues against a recent disk-bar instability to form the bulge, given the evidence for recent star formation in the inner disk. But we do need to get more data on the stellar populations in the inner disk.