The Merging History of the Milky Way Disk

Rosemary F.G. Wyse

*The Johns Hopkins University, Dept. of Physics & Astronomy, Baltimore, MD 21218, USA*

**Abstract.** The stellar populations of the stellar halo and of the thick disk of the Milky Way reveal much about the merging history that our Galaxy, a typical large disk galaxy, has experienced. Our current understanding, described here, implies a rather quiet evolution for the disk, back to redshifts of order 2.

1. Introduction

Following the Copernican principle, the Milky Way is a typical galaxy, albeit one for which we can obtain atypically detailed observational data. Thus galaxies like the Milky Way should form naturally in viable models of galaxy formation and evolution. I here discuss what 'like the Milky Way' means, in terms of the derived merging history of the Milky Way disk. These constraints relate to the mass assembly and accretion history, and complement those constraints from the star formation history of the various stellar components of the Milky Way Galaxy (cf. Gilmore, this volume). Interactions and mergers clearly happen, for example the Milky Way is currently having a close encounter with the Sagittarius dwarf spheroidal galaxy (Ibata, Irwin & Gilmore 1994; 1995).

All models of galaxy formation involve star formation in self-gravitating regions that are smaller than the initial ‘proto-galaxy’, whether they reflect the small-scale power in the primordial power spectrum of density fluctuations (e.g. in Cold-Dark-Matter-dominated cosmologies, Blumenthal et al. 1984) or rather are Jean-mass fragments (e.g. Fall & Rees 1985). Subsequent disruption of these systems, by internal effects such as stellar feedback and/or by external effects such as tides, forms the field stellar populations of galaxies we observe today. Thus merging and assimilation of small-scale structure is present at some level in all models of galaxy formation, and the crucial questions are what merged, and when did they do so?

Accretion, the acquisition and assimilation of (smaller) objects that had an independent existence for many dynamical times, can occur in a variety of scenarios. For example dynamical friction can cause the orbits of massive satellite galaxies to decay (on a timescale of \( \sim (M_{\text{galaxy}}/M_{\text{satellite}}) t_{\text{crossing}} \)). Alternatively, the accretion could reflect the hierarchical growth of structure set by the initial primordial power spectrum and the cosmological parameters. Indeed, one should remember that even ‘monolithic collapse’ models predict long time (continual even) infall, again depending on the cosmological parameters.
Rosemary F. G. Wyse

(Gunn & Gott 1972). But again, the models may be distinguished by what is accreted, and when.

The Galactic disk is particularly relevant since disks are cold, and susceptible to heating by merging/accretion – thus their fragility constrains the past merging history. If a satellite of mass $M_{\text{satellite}}$, on an initial orbit characterised by velocity $v_s$, can impart all of its orbital energy into a stellar disk, mass $M_{\text{disk}}$ and internal velocity dispersion $\sigma_{\text{disk}}$, then the disk is heated by (e.g. Ostriker 1990)

$$\Delta \sigma_{\text{disk}}^2 \sim \frac{M_{\text{satellite}}}{M_{\text{disk}}} v_s^2.$$ 

The actual heating efficiency depends on many parameters, but unless the merging systems are essentially completely gaseous, and so can radiate away a large part of the energy, the concept of imprinting a signature of merging is valid. The merging history of the disk is written in its vertical structure.

In principle one can rule out cosmological models, assuming the ‘cosmic variance’ is small and the Milky Way is typical, but even so, predictions from the models for the merging rates of galaxies, as opposed to dark haloes, remain uncertain. Toth & Ostriker (1992) evaluated the constraints from the disk structure back to the formation of the Sun, some 5Gyr ago. Here we demonstrate how improved data can extend this back essentially to the onset of disk formation.

2. Low Density (parts of) Satellites: the Stellar Halo

The relative density and mass of a satellite galaxy are the important parameters that determine its effect on the Galactic disk. Low density, ‘fluffy’, satellites will be tidally disrupted at large Galactocentric radius, and, assuming a typical orbit (cf. Moore et al. 1999a), their stars will contribute to the stellar halo and their gas to the disk, modulo angular momentum. Further, the outer, low-density, regions of satellites will contribute to the halo, while their higher density core regions could be accreted into the disk. Thus evidence for accretion into the halo is arguably necessary, but of course not sufficient, for accretion into the disk.

What evidence is there for accretion into the stellar halo? As described further by Gilmore (this volume), the age distributions both the field stars and the globular clusters of the halo show a dominant old population, with at most 10%, biased to the more metal-rich tracers, being candidates for ‘intermediate-age’. Thus if the accretion of satellite galaxies is the dominant process of halo formation (e.g. Helmi & White 1999; Bullock, Kravtsov & Weinberg 2000), the satellites must be accreted when they contain only old, metal-poor stars (although note that even 5% of the stellar halo is several tens of the present dwarf spheroidal companion galaxies). As discussed further by Gilmore, the star formation histories of the existing/surviving low surface brightness dwarf companions to the Milky Way are varied, but rarely is there the case of a very short-lived, early burst of star formation. Thus assuming that a dwarf galaxy left to itself would form stars over an extended period, as did the typical surviving dwarf, then any accretion is restricted to have occurred only very early (Unavane et al. 1996). Plausibly the putative satellites were quite gas-rich at those early epochs, and would indeed contribute to growth of the gaseous disk.
Phase space signatures of accretion would persist longest in the outer halo, where all timescales are longer (e.g. Johnston, Hernquist & Bolte 1996). It should be noted that the bulk of the mass of the stellar halo is located interior to the solar circle; for typical models of the density profile of the stellar halo (e.g. Carney, Latham & Laird 1990; Morrison 1993), the halo exterior to 8 kpc is $\sim 2 \times 10^8 L_\odot$ and is around 20% of stellar halo interior to 8 kpc. The mass exterior to the periGalacticon of the Sagittarius dwarf spheroidal galaxy, $r \sim 16$ kpc (Ibata et al. 1997), corresponds to $\lesssim 10^8 L_\odot$, somewhat less than ten times the present luminosity of the dSph itself (providing a real constraint on models for the disruption of the Sgr dSph, which can contravene this limit).

Early results from the imaging part of the Sloan Digital Sky Survey have shown the immense wealth of information in a uniform, wide-area survey. Structures in the outer halo have been identified from non-uniform A-star counts, with as much as $6 \times 10^6 M_\odot$ in a structure out at $r \sim 45$ kpc (Yanny et al. 2000), and in counts of RR Lyrae stars (Ivezic et al. 2000). These may be streams from the Sgr dSph (Ibata, Irwin, Lewis & Stolte 2000), but one should note that ‘globular clusters’ could have contributed a significant stellar mass to the halo (cf. Fall & Rees 1977; Gnedin & Ostriker 1997). Indeed, this is an on-going process, with ‘tidal tails’ detected around at least twenty of the present-day globular clusters (Leon, Meylan & Combes 2000). Thus one expects many tidal streams of old, metal-poor stars in the halo, which have nothing to do with ‘accretion’ or cosmological structure formation.

Accreted stars (and disrupted globulars) may also be observable through kinematics, as moving groups. And indeed a metal-poor, old (typical of the stellar halo) ‘debris stream’ has been identified in the solar neighborhood (Helm & et al. 1999) that may contain, by mass, several percent of the stellar halo outside of the solar circle, or $\lesssim 10^7 M_\odot$ (based on $\sim 10$ stars). The broad metallicity distribution (cf. Chiba & Beers 2000) argues against an origin in a ‘proto-globular cluster’, and supports a dwarf galaxy. More data are clearly warranted.

The surviving remnants/cores/systems of tidal disruption will act on, and contribute to, the disk if they are massive enough.

3. Massive, Dense Satellites: the Thick Disk

3.1. Simulations

There have been many simulations of the effect on a pre-existing thin stellar disk of a ‘minor merger’. As displayed clearly in Figure 11 of Quinn & Goodman (1986), their ‘standard model’, a massive and dense satellite on a prograde circular orbit inclined moderately (45°) to the plane of the disk, couples efficiently into the vertical motions of the disk, and the $z$–motions of the satellite are rapidly damped, followed by subsequent spiralling in of the satellite, in the plane of the disk. The satellite loses material as it spirals in and its effective tidal radius decreases, and it heats the disk as it gives up orbital energy. The heating is a combination of local effects, plus resonant excitation of large-scale bending waves (Sellwood, Nelson & Tremaine 1998). The heating amplitude depends on many parameters of the initial orbit of the satellite, such as the inclination, the pericenter, amplitude and sense of angular momentum, on its internal structure – density profile and mass – and on the coupling between the
various components of the interacting systems (e.g. Walker, Mihos & Hernquist 1996; Huang & Carlberg 1997; Velazquez & White 1999). A robust satellite of around 20% of the present mass of the stellar disk could create a thick disk with a scale-height of around 1kpc.

However, as we will see below, the extant simulations are not appropriate to model the formation of the Galactic thick disk. Rather, we need simulations that better match the early stages of disk evolution. At a minimum, gas – which of course can cool after being heated – must be included, both in the satellite and in the disk.

3.2. The Real World

![Figure 1](image)

The metallicity distributions of representatives of the stellar populations of the Milky Way Galaxy. Where possible, a measure of the true iron abundance is plotted. The panels are (top to bottom) the local stellar halo (Carney et al. 1994, their kinematically-selected sample); the outer bulge K-giants (Ibata & Gilmore 1995), truncated at solar metallicity due to calibration limitations; the volume-complete local thin disk F/G stars (derived from the combination of the Gliese catalogue and in situ survey); the volume-complete local thick disk F/G stars (derived similarly); and lastly the ‘solar cylinder’, i.e. F/G stars integrated vertically from the disk plane to infinity. This figure is based on Fig. 16 of Wyse & Gilmore (1995).

The Galactic thick disk was first detected through star counts at high latitude (Gilmore & Reid 1983), although surface photometry of external S0 galaxies
had earlier revealed ‘thick disks’ in them (Burstein 1979; Tsikoudi 1979). Many subsequent star count analyses have shown that a thick disk component is required in addition to the standard thin disk and stellar halo (e.g. Buser, Rong & Karaali 1999; Phleps et al. 2000). The structural parameters for the thick disk are rather uncertain using star count data alone, and it is extremely important to determine the global structure and mass of the thick disk. Available constraints from star counts suggest a scaleheight about a factor of four greater than that of the thin disk, a local normalisation of around 2% (these two are anti-correlated in the analyses) and a scale-length equal to that of the thin disk. The mass of the thick disk is then around 10% of the mass of the thin disk, although some determinations as high as 20% are also consistent.

The astrophysical parameters of the thick disk reveal its evolutionary status. At the time of its discovery, it was postulated that the thick disk was formed by local compression of the stellar halo by the potential of the thin disk (Gilmore & Reid 1983). This was soon disproven (Gilmore & Wyse 1985) by the determination of distinct metallicity distributions of thick disk and stellar halo (see Fig. 1 here). The thick disk is also distinct from the thin disk in terms of kinematics, seen most clearly using the vertical velocity, \( W \). Fig. 2 here plots the rank number of a star in iron abundance versus the sum of the absolute value of the vertical velocity of the stars up to and including that rank, for the sample of local F stars of Edvardsson et al. 1993 (iron abundances are obtained from echelle spectra, and the kinematics are from the combination of radial velocities and proper motions). For a Gaussian velocity distribution, the slope of this plot is the value of the velocity dispersion. The distinct metallicity distribution of Fig. 1 leads to the expectation that the thick disk should be dominant at iron abundances less than about \(-0.4\) dex. And indeed, the rank corresponding to this metallicity is just where one detects a break in the kinematics, specifically an increased velocity dispersion. Essentially all kinematic studies of the thick disk find that its vertical velocity dispersion is \( \sim 40\) km/s (e.g. review of Majewski 1993), which fits with a scale-height of around 1 kpc, in the vertical potential derived from other samples (e.g. Kuijken & Gilmore 1989).

The vertical velocity dispersion of the thick disk, \( \sim 40\) km/s, is too high to result from the ‘normal’ thin-disk heating processes of scattering by disk density perturbations such as giant molecular clouds or transient spiral structure, as these saturate at lower values of the velocity dispersion (e.g. Spitzer & Schwarzschild 1951; Lacey 1991; Quillen & Garnett 2000). An alternative to a ‘heating’ mechanism is a cooling mechanism, with the possibility that the thick disk formed during the dissipative settling of gas into the proto-disk (Wyse & Gilmore 1988; Burkert, Truran & Hensler 1992). The distinct nature of the thick disk in these models results from the sensitivity of star formation rate and cooling to a parameter, for example metallicity (Wyse & Gilmore 1988). Such a cooling scenario would, however, predict a fairly uniform population of thick disks, which is not observed (e.g. Morrison 1999).

The analogous plot to Fig. 2 that employs rank in age within this sample rather than in iron abundance shows similar behaviour (Freeman 1991), in that there is a clear change in kinematics at some rank, and that rank corresponds to an age of \( \sim 12\) Gyr (the ages are derived from Stromgren photometry, and are based on comparisons with the VandenBerg (1985) isochrones, but Ng &
Figure 2. The rank number of a star in iron abundance versus the sum of the absolute value of the vertical velocity of the stars up to and including that rank, for the sample of Edvardsson et al. (1993) (taken from Wyse & Gilmore 1995). For a Gaussian velocity distribution, the slope of this plot is the value of the velocity dispersion. There is a clear change of slope at the metallicity at which the thick disk dominates over the thin disk, indicating distinct kinematics.

Bertelli (1998) find little changes with use of later isochrones, or with Hipparcos distances). This limit for the youngest stars in the thick disk is also seen in Fig. 3, where again one finds few stars in the thick disk that are younger than the globular cluster 47 Tuc (given the calibration uncertainties in absolute ages, the relative age compared to a globular cluster is the most robust means of stating the age limits on the thick disk).

This old age for the thick disk, at least probed within several kpc of the solar circle, is in agreement with the analyses of several other samples and groups (e.g. Wyse & Gilmore 1985; 1988; Carney, Latham & Laird 1989; Fuhrmann 1998). The spread in ages older than this limit is poorly constrained by colours, but the age distribution of the Edvardsson et al. sample continues to extremely old ages. The pattern of elemental abundances in the thick disk can also constrain the duration of star formation, but there is at present no consensus (compare Prochaska et al. 2000 and Gratton et al. 2000).

The lack of young stars in the thick disk is a very significant constraint on its formation, as we discuss below. A robust age distribution is a definite desideratum.

Thus the Galactic thick disk is plausibly the result of heating of a pre-existing thin disk during the process of a minor merger. The ‘smoking-gun’ evidence in support of this would be identification of the stars now part of the Galaxy, that were initially in the satellite responsible for the heating. We (Gilmore, Wyse, Norris & Freeman) have an on-going survey of thick disk/halo
stars using the ‘2 Degree Field’ spectrograph on the Anglo-Australian Telescope to analyse the overlapping halo/thick disk populations and constrain the phase space structure of the stripped satellite.

4. Implications

The properties of the thick disk discussed above, and in particular the conclusion that the favoured formation mechanism for the generation of the thick disk is through a minor merger, have major implications for the formation and evolution of disk galaxies.

First, the fact that the youngest stars in the thick disk are essentially as old as the globular cluster 47 Tuc (some 12.5 Gyr with the most recent isochrones and distance calibrations; Carretta et al. 2000) limits the last significant merger event to have occurred a long time ago. The limit arises due to the fact that star formation in the thin disk has been fairly continuous since its onset, albeit...
with the amplitude of star formation varying radially; for example, derived star
formation histories in the local thin disk show an overall decline of a factor of
a few from the earliest times, with superposed ‘bursts’ of amplitude of a few
(e.g. Rocha-Pinto et al. 2000; Gilmore, this volume). A merger at any given
time would heat the thin disk stars formed up to that time, and thus a later
merger would create a thick disk which contains younger stars. Hence the Milky
Way cannot have undergone a significant – some 20% by mass from the extant
simulations and analyses – merger for a very long time. Adopting 11 Gyr as a
fiducial look-back time for this epoch (cf. the oldest stars in the Hipparcos sample
of the thin disk, Binney, Dehnen & Bertelli 2000), then with the ‘standard’
cosmological parameter values of $\Omega_{\Lambda} = 1 - \Omega_{\text{matter}} = 0.7$, $H_0 = 65 \text{ km/s/Mpc}$, there has been no significant merger since a redshift of $z_{\text{thick disk}} \sim 2$.

Of course, there are many uncertainties in this argument, but it is an impor-
tant enough conclusion that significant effort needs to be expended to address
those areas of uncertainty. Accepting the merger origin of the thick disk, these
uncertainties include the existence and value of the critical mass (and density)
of a minor merger to provide sufficient heating, the age distribution of the thick
disk (both locally and globally) and indeed the properties of the thick disks of
external galaxies.

A second major conclusion within this scenario is that a fairly massive
stellar thin disk was already in place at the epoch of this last significant merger,
to provide the thick disk as observed now, perhaps as much as 20% of the
present thin stellar disk, or of order $10^{10} M_\odot$. This early thin disk extended at
least out to the solar Galactocentric radius. There were certainly extended disks
at redshifts significantly above unity (cf. Somerville, this volume). While there
is an obvious need for a robust determination of the global structure of the thick
(and thin!) disk, this conclusion is consistent with the analysis of Brinchmann
& Ellis (2000) of field galaxies at redshifts out to unity (see also Ellis, this
volume), which concluded that the bulk of star formation had already occurred
by a redshift of 1. This of course rules out scenarios that propose delayed infall
of proto-disk gas, until after merging is complete, or redshifts of unity, as the
solution to the angular momentum problem in hierarchical-clustering pictures
for disk galaxy formation (e.g. Weil, Eke & Efstathiou 1998).

As a corollary to this, one can envisage a bulge-disk connection that provides
an explanation for the near equality in age between the central bulge (Ortolani et
al. 1995; Feltzing & Gilmore 2000) and the thick disk, by positing that the bulge
formed from rapid star formation in gas driven inwards by the torquing inherent
in the merging process, perhaps accompanied by bar formation (e.g. Noguchi
1988; Hernquist & Mihos 1995) and globular cluster formation. This would also
produce a correlation between bulges and thick disks, which may indeed by the
case (e.g. Morrison 1999).

Further, the apparent unimportance of merging in the history of the bulk
of the baryonic mass of the Milky Way, combined with the angular momentum
problem for disks in general (e.g. Navarro & Steinmetz 1997; Steinmetz this
volume), the over-prediction of surviving satellite galaxies (Moore et al. 1999a;
Klypin et al. 1999), and the steep inner halo density profiles (Moore et al. 1999b,
but see Navarro, this volume) perhaps point to a problem with the underlying
Cold-Dark-Matter power spectrum. Suppression of the small scale power can
provide a solution to many of these problems (e.g. Sommer-Larsen & Dolgov 1999; Moore et al. 1999a).

Acknowledgements: I am indebted to the conference organisers for their financial support, enabling me to participate in this highly enjoyable and stimulating conference.

References

Binney, J., Dehnen, W. & Bertelli, G. 2000, MNRAS, 318, 658
Blumenthal, G., Faber, S., Primack, J. & Rees, M.J. 1984, Nature, 311, 517
Brinchmann, J. & Ellis, R.S. 2000, ApJ, 536, L77
Bullock, J., Kravtsov, A.V. & Weinberg, D. 2000, ApJ, submitted [astro-ph/0007295]
Burkert, A., Truran, J. & Hensler, G. 1992, ApJ, 391, 651
Burstein, D. 1979, ApJ, 234, 829
Buser, R., Rong, J. & Karaali, S. 1999, A&A, 348, 98
Carney, B., Latham, D. & Laird, J. 1989, AJ, 97, 423
Carney, B., Latham, D. & Laird, J. 1990, AJ, 99, 572
Carney, B., Latham, D., Laird, J. & Aguilar, L. 1994, AJ, 107, 2240
Carretta, E., Gratton, R., Clementini, G. & Fusi Pecci, F. 2000, ApJ, 533, 215
Chiba, M. & Beers, T.C. 2000, AJ, 119, 2843
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E. & Tomkin, J. 1993, A&A 275, 101
Fall, S.M. & Rees, M.J. 1985, ApJ, 298, 18
Freeman, K. 1991, in ‘Dynamics of Disk Galaxies’ ed. B. Sundelius (Goteborg, Goteborg University), 15
Feltzing, S. & Gilmore, G. 2000, A&A, 355, 949
Fuhrmann, K. 1998, A&A, 338, 161
Gilmore, G. & Reid, I.N. 1983, MNRAS, 202, 1025
Gilmore, G. & Wyse, R.F.G. 1985, AJ, 90, 2015
Gilmore, G., Wyse, R.F.G. & Jones, J.B. 1995, AJ, 109, 1095
Gratton, R.G., Carretta, E., Matteucci, F. & Sneden, C. 2000, A&A, 358, 671
Gunn, J.E. & Gott, J.R. 1972, ApJ, 176, 1
Helmi, A. & White, S.D.M. 1999, MNRAS, 307, 495
Helmi, A., White, S.D.M., de Zeeuw, P. & Zhao, H.-S. 1999, Nature, 402, 53
Hernquist, L. & Mihos, J.C. 1995, ApJ, 448, 41
Hesser, J. et al., 1987, PASP, 99, 739
Huang, S. & Carlberg, R., 1997, ApJ, 480, 503
Ibata, R. & Gilmore, G. 1995, MNRAS, 275, 605
Ibata, R., Gilmore, G. & Irwin, M. 1994, Nature, 370, 194
Ibata, R., Gilmore, G. & Irwin, M. 1995, MNRAS, 277, 781
Ibata, R., Lewis, G., Irwin, M. & Stolte, A. 2000, ApJL, submitted [astro-ph/0004255]
Ibata, R., Wyse, R.F.G., Gilmore, G., Irwin, M.J. & Suntzeff, N.B. 1997, AJ, 113, 634
Iveciz, Z. et al. 2000, AJ, 120, 963
Johnston, K.V., Hernquist, L. & Bolte, M. 1996, ApJ, 465, 278
Kuijken, K. & Gilmore, G. 1989, MNRAS, 239, 605
Lacey, C.G. 1991, in ‘Dynamics of Disc Galaxies’, ed B. Sundelius (Goteborg, Goteborg University), 257
Majewski, S.R. 1993, ARAA, 31, 575
Mateo, M. 1998, ARAA, 36, 435
Moore, B. Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. & Tozzi, P. 1999a, ApJ, 524, L19
Moore, B., Quinn, T., Governato, F., Stadel, J. & Lake, G. 1999b, MNRAS, 310, 1147
Morrison, H. 1999, in ‘The Galactic Halo’, ASP Conf. Ser. Vol. 165, eds B. Gibson, T. Axelrod & M. Putman (San Francisco: ASP), 174
Morrison, H. 1993, AJ, 106, 578
Navarro, J.F. & Steinmetz, M. 1997, ApJ, 478, 13
Ng, Y.K. & Bertelli, G. 1998, A&A, 329, 943
Noguchi, M. 1988, A&A, 203, 259
Ortolani, S. et al. 1995, Nature, 377, 701
Ostriker, J.P. 1990, in ‘Evolution of the Universe of Galaxies’, ASP Conf. Ser. Vol. 10, ed. R.G. Kron (San Francisco: ASP), 25
Phleps, S., Meisenheimer, K., Fuchs, B. & Wolf, C. 2000, A&A, 356, 108
Prochaska, J., Naumov, S., Carney, B., McWilliam, A. & Wolfe, A. 2000, AJ, accepted (astro-ph/0008075)
Quillen, A. & Garnett, D. 2000, ApJ, submitted (astro-ph/0004210)
Quinn, P. & Goodman, J. 1986, ApJ, 309, 472
Rocha-Pinto, H.J., Scalo, J., Maciel, W. & Flynn, C. 2000, ApJ, 531, L115
Sellwood, J., Nelson, R. & Tremaine, S. 1998, ApJ, 506, 590
Sommer-Larsen, J. & Dolgov, A. 1999, ApJ, submitted (astro-ph/9912166)
Spitzer, L. & Schwartzschild, M. 1951, ApJ, 114, 385
Toth, G. & Ostriker, J.P. 1992, ApJ, 389, 5
Tsikoudi, V. 1979, ApJ, 234, 842
VandenBerg, D. 1985, ApJS, 58, 711
VandenBerg, D. & Bell, R. 1985, ApJS, 58, 561
Velazquez, V. & White, S.D.M. 1999, MNRAS, 304, 254
Walker, I., Mihos, J.C. & Hernquist, L. 1996, ApJ, 460, 121
Weil, M., Eke, V. & Efstathiou, G. 1998, MNRAS, 300, 773
Wyse, R.F.G. & Gilmore, G. 1985, AJ, 90, 2015
Wyse, R.F.G. & Gilmore, G. 1988, AJ, 95, 1404
Wyse, R.F.G. & Gilmore, G. 1995, AJ, 110, 2771
Yanny, B. et al. 2000, ApJ, 540, 825