The Thick Disk-Halo Interface

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**Abstract.** The star formation history of a galaxy, explicitly here our Milky Way Galaxy, where the most detailed information is attainable, is the convolution of two functions. One function describes the rate of formation of the stars which are today in the Galaxy. The second describes the assembly of those stars into the present Galactic potential well. There is direct evidence that this assembly continues today, with both stars and gas being assembled into, or at least rearranged in, the Galactic potential. But is this recent accretion significant? Was the last significant accretion the formation of the thick disk, some 10Gyr ago.? Recent spectroscopic studies support this unexpected result, while dynamical studies find increasing numbers of specific examples of smaller scale more recent accretion. We present early results for one specific such survey, the Anglo Australian Old Stellar populations Survey, to illustrate current studies.

1. Old Stellar Populations: the Context

While present stellar populations are a undoubtedly a manifestation of the fossil record of Galactic evolution, quantification and interpretation of that fossil record remains a subject of lively debate and rapid progress. Among the key issues are the places and times of formation of the oldest stellar populations: the halo, thick disk and bulge - and their overlaps and evolutionary relationships, if any. Analysis of these stellar populations will in principle quantify the history of merging and accretion in a typical galaxy, of great importance in determining galactic evolution, and constraining cosmological theories of galaxy formation.

The metallicity and kinematic distribution functions of complete samples of long-lived stars have long been recognised as providing unique constraints on the early stages of chemical evolution of the Galaxy. The main sequence lifetime of F/G dwarf stars is greater than the age of the Galaxy and hence the chemical-abundance distribution function of such stars provides an integrated record of the chemical-enrichment history without the need for model-dependent corrections for dead stars (van den Bergh 1962; Tinsley 1980). Pioneering studies focussed on the only reasonably-complete sample available, which is that for stars in the immediate solar neighborhood; in effect stars within about 30pc of the Sun.
These samples have been sufficiently small that reliable study of those stellar populations whose kinematics are such that member stars spend only a small fraction of an orbit in the solar neighborhood has necessarily been difficult. This is potentially a serious restriction, as such stars might in principle be a major contributor to the stellar population in a valid, representative volume of the Galaxy. In addition, intrinsically-rare stellar populations are missed entirely.

Thus, it is important, in deriving a reliable determination of Galactic structure and evolution, that one consider the joint distributions functions over chemical abundance and kinematics.

The observational situation has been improved recently in two ways: by collection and analysis of spectroscopic data for all-sky samples of stars extending to somewhat greater, but still essentially local, distances (Norris, Bessel & Pickles 1985; Carney et al 1990; Beers et al 1999; Carney, this volume; Chiba & Beers 2000), and by deeper pencil-beam surveys, to isolate in situ samples of old disk (Kuijken & Gilmore 1989a), thick disk (Gilmore, Wyse, & Jones 1995) and halo stars. The combination of the large but local samples with the small but distant samples has allowed the deconvolution, to first order, of the abundance distribution functions, and the mean velocity dispersions, of the dominant Galactic populations. While our understanding of Galactic structure and evolution has advanced considerably of late, extension of these analyses has become limited by the intrinsic breadth and overlap of the population distribution functions and by the small size of the available in situ samples.

The theoretical situation has also become more specific. Though the many dynamical, structural and chemical evolution questions one poses concerning galactic evolution may seem well-defined and relatively distinct, it is now clear that the answers are intimately interrelated. For instance, galaxies probably accrete their neighbours, so that the place of origin of a star may be far from its present location; dynamical instabilities in disks result in the mixing through phase space of stellar populations, further blurring the relation between a star’s present location and its birthplace. Bar instabilities are also likely to cause significant gas transport, and may drive star bursts and possibly nuclear nonthermal phenomena. Major mergers may thicken disks. Bulges may be accreted, or created during mergers.

Modern models of Galaxy formation make fairly specific predictions concerning each of these possibilities. A detailed review is provided by Silk & Wyse (1993) where further discussion may be found. For example, fashionable Cold Dark Matter models, which contain aspects of both the monolithic (‘ELS’) and the multi-fragment (‘Searle-Zinn’) pictures often discussed in chemical evolution models, ‘predict’ growth of the Galaxy about a central core, which should contain the oldest stars. Later accretion of material forms the outer halo and the disks, while continuing accretion will continue to affect the kinematic structure of both the outer halo and the thin disk. Considerable phase-space substructure should be detectable, when one looks sufficiently far from the Plane and the Galactic centre that dynamical timescales are long (Ibata, Gilmore, & Irwin 1995; Arnold & Gilmore 1992), and has recently been seen with plausible significance (Helmi et al 1999).

Dissipational models for thick-disk formation predict observable abundance gradients (cf. Burkert, Hensler and Truran 1992), and similar scale lengths for
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Specific column-integral abundance distributions can be calculated (numerically) for some of these models and compared to observations. Satellite merger models for thick disk formation require the stars from the satellite to be detectable, as a tail in the thick disk distribution functions below [Fe/H] = −1 (Silk & Wyse, 1993) ‘Continuum’ models of thick disk formation from the thin disk require that an accurately defined joint distribution function over chemical abundance and kinematics for the oldest stars be smooth and continuous (Norris & Ryan, 1991). Alternative models, such as the discrete merger model, can then be distinguished by their prediction that the distributions overlap in abundance, and perhaps velocity dispersion, but not in angular momentum (Gilmore, Wyse & Kuijken 1989). Most detailed models make specific predictions concerning the abundance distribution function in a cylinder, through the Galactic disk - the ‘G-dwarf problem’ – which remains widely studied, and a valuable diagnostic of early accretion and gas flows in the disk (Pagel & Patchett 1975).

That is, quantitative study of the essential physics of galaxy evolution, requires that one must study the distributions over chemistry, kinematics and spatial structure of the oldest stars (eg Sandage & Fouts 1987). Determination of the wings of the distribution functions, and their separation or deconvolution, is however feasible, given adequate samples. One such project, which we introduce here, is the Anglo-Australian Old Stellar Populations Survey, with joint UK (the present authors) and Australian (J Norris, K Freeman) involvement.

2. Old Populations: what should one observe?

The ideal tracer of Galactic Structure is one which is selected without any biases, does not suffer from stellar age-dependent selection effects, is representative of the underlying populations, and is easily observable. Historically, the need for easy observation restricted studies to the immediate solar neighborhood. The primary limitation of the nearby star sample is its small size. This inevitably means that stars which are either intrinsically rare – such as halo population subdwarfs – and stars which are common but whose spatial distribution is such that their local volume density is small – such as thick disk stars – are poorly represented. Most recent and current efforts to extend present local volume-limited samples to include minority populations have, for practical observational reasons, utilized kinematically-selected samples defined in the solar neighborhood, following the pioneering work of Eggen, Lynden-Bell and Sandage (1962). Subsequent correction for the kinematic biases inherent in these samples requires careful modelling (Norris and Ryan 1991). An in situ sample, truly representative of the dominant stellar population far from the Sun, circumvents these large, model-dependent corrections.

Several surveys of tracer stars which can be observed in situ are available. Intrinsically luminous tracers are a priori favored in terms of telescope time, but the likely candidates have other characteristics that diminish their suitability: RR Lyrae stars have intrinsic age and metallicity biases in that only stars of a given range in metallicity and age exist in this evolutionary stage; the accessible globular clusters are few in number; bluer horizontal branch stars are also rare, and their color distribution depends on chemical abundance and on the
unidentified ‘second parameter(s)’. K-giants are the most representative evolved tracers of the spheroid, and have been used extensively. However, one must first identify giant stars from among the substantially larger number of foreground K dwarfs with similar apparent magnitudes and colors, and even with that selection, reliable determination of the distance of a halo K giant has proven to be extremely difficult.

A desirable solution to these limitations, which has become feasible with current multi-object spectroscopic systems and large-scale photometric surveys, is to identify and study F/G dwarfs to significant distances from the Sun. This is the solution which we have adopted. Chemical abundances for these stars provide the integrated record of the star formation and enrichment history during the early stages of Galaxy formation, analogous to the local G-dwarf distribution. Radial velocities allow discrimination between stellar populations, when combined with abundances and spatial distributions.

Thus, the AAOSPS project is optimised to provide the next stage of quantitative analysis of the structure, contents and evolution of the early Milky Way, building from current observational and theoretical expertise developed in precursor phases of this study.

The scientific aim of the AAOSPS project is to determine the distribution functions over metallicity, kinematics, and spatial distributions of the oldest stellar populations, with particular emphasis on the overlapping wings of each distribution function. To achieve this, the primary technical requirement is that each of the three variables - metallicity, radial velocity, distance - be determined to a precision which is less than the intrinsic ‘cosmic’ dispersion in that parameter.

3. The Anglo Australian Old Stellar populations Survey: AAOSPS

Is the thick disk a merger remnant? How does it overlap the halo? What are the systems that merge, how frequently does this happen over a Hubble time, and with what consequence? Could we identify stars from the intruder, and from our own early disk?

To address these questions, we are using the two-degree-field multi-object spectrograph (2dF) on the Anglo-Australian Telescope, which provides 400 spectra simultaneously, to measure the radial velocities and chemical abundances for F/G main sequence stars at distances from the Sun of 3–7kpc down several key lines-of-sight.

3.1. AAOSPS: the specific goals

Mergers and strong interactions between galaxies happen, as evidenced today by the Sagittarius dwarf spheroidal galaxy (Ibata, Gilmore & Irwin 1994, 1995; Ibata et al. 1997). The occurrence of a ‘minor merger’ between the Milky Way and a small satellite galaxy provides an attractive explanation for the thick disk (see Gilmore & Wyse 1985; Gilmore, Wyse & Kuijken 1989; Freeman 1993; Majewski 1993; Walker, Mihos & Hernquist 1996; Huang & Carlb erg 1997; Velazquez & White 1999).

What are the systems that merge, how frequently does this happen over a Hubble time, and with what consequence?
Depending on the mass, density profile and orbit of the merging satellite, ‘shredded-satellite’ stars will leave a kinematic signature, distinct from the canonical thick disk that will result from the heated thin disk. Satellites on prograde (rather than retrograde) orbits couple better to the disk and provide more heating, and thus are favoured to form the thick disk (e.g. Velazquez & White 1999). Thus one might expect a signature to be visible in the mean orbital rotational velocity of stars, and for a typical satellite orbit, lagging the Sun by more than does the canonical thick disk. The relative number of stars in the ‘shredded satellite’ versus the heated-thin disk (now the thick disk) depends on the details of the shredding and heating processes, and is a diagnostic of them, and may well vary strongly with location.

We are measuring radial velocities and abundances for F/G main sequence stars at distances from the Sun of 3–7kpc. The sample is selected on the basis of colour and apparent magnitude (V=19-20; 0.5 ¡ B-V ¡ 0.9). The 2dF spectra have 1 Angstrom/pixel and cover 3700–4600 Angstroms. The external velocity accuracy of the data is around 10–15 km/s, from repeat observations of program stars and from a globular cluster standard. We (mostly work by Norris) have extended the abundance determination techniques developed by Beers et al. (1999). As well as abundances based on Ca II K, values are being determined from the G-band of CH. For stars with sufficient S/N we can derive metallicities from an autocorrelation Fourier method, which uses all the weak lines in the available spectral range. Standard star data show that abundances with precision better than 0.3dex are already obtainable.

Our primary targets are fields towards and against Galactic rotation, to provide optimal halo/thick disk discrimination through orbital angular momentum. We measure the time-integrated structure of the halo and thick disk, evolved over many orbital times at these Galactocentric distances. This is the only statistical survey targeting fields that probe the angular momentum, far from the thin disk and without strong metallicity bias.

Our earlier multi-object (AUTOFIB) survey demonstrated that there is a negligible fraction of stars in the canonical thick disk that are younger than the globular clusters of the same metallicity (Wyse & Gilmore 1995) strengthening the earlier inferences from kinematically-biased local surveys; Gilmore & Wyse 1985, Carney et al 1989. This result limits the time of the last significant merger event to be very early in the history of the Galaxy (Gilmore, Wyse & Jones 1995), challenging standard CDM cosmologies (cf Wyse 2001).

First Results: We have detected a substantial population of low metallicity stars with disk-like kinematics, intermediate between those of the canonical thick disk and the canonical (non-rotating) stellar halo. Figure 1 shows the radial velocity histogram for around 900 stars with high signal-to-noise spectra, in a line-of-sight for which, at these distances, radial V-velocity is approximately 0.8 times the rotational lag behind the Sun’s orbit. Our efficient selection against thin disk contamination – radial velocity near zero – is apparent. The smooth Gaussian represents a smooth halo in this line-of-sight, appropriately normalised to fit the high-velocity data. The canonical thick disk has a rotational lag of some 40km/s. Thus the large number of stars with radial velocity around 100km/s is not expected, and probably traces a new kinematic component of the Milky Way Galaxy.
Figure 1. Scatter plot of iron abundance vs B-V colour for thick disk F/G stars, selected in situ in the South Galactic Pole at 1-2kpc above the Galactic Plane (stars), together with the 14 Gyr turnoff colours (crosses) from VandenBerg & Bell (1985; Y=0.2) and 15 Gyr turnoff colours (asterisks) from VandenBerg (1985; Y=0.25). The open circle represents the turnoff colour (de-reddened) and metallicity of 47 Tuc (Hesser et al. 1987). The vast majority of thick disk stars lie to the red of these turnoff points, indicating that few, if any, stars in this population are younger than this globular cluster. This figure is from Wyse (2001).

The 100km/s stars are best interpreted as being the actual debris of the satellite. The debris ‘stream’ is detected in widely-separated lines-of-sight, but requires a larger statistically-significant sample for confirmation and to allow quantification of the properties of the former satellite galaxy. This quantification would be a strong constraint on hierarchical models of galaxy formation.

_Metallicity and Phase Space Structure?_ The combination of kinematics and metallicity provides the best constraints on stellar populations. We are quantifying the distributions of the Galaxy’s populations in metallicity-velocity space, to higher precision than simple Gaussian fits: it is these distributions which encode galaxy formation.

Our first results (figure 2) show substantial numbers of stars with very low metallicities, and very high angular momentum: that is, we have discovered the much sought metal-weak thick disk, perhaps the remnants of the Milky Way’s last big merger.
Figure 2. Radial velocity histogram for around 900 stars in a line-of-sight chosen to probe orbital rotation. The smooth curve represents the stellar halo, and while it clearly is a reasonable description of the shape of the distribution of the highest velocity stars, it fails to describe the majority of the stars. The canonical thick disk provides the stars with radial velocity of less than 100km/s; the broad shoulder between 100km/s and 200km/s is not expected.

Our velocity accuracy is adequate to identify any high-frequency phase-space structure which may exist. The clumpiness in the metallicity vs velocity diagram shown, and the spikiness in the number vs Galactic rotation velocity data, are kinematically resolved: our goal now is to obtain sufficient numbers of adequate quality spectra to quantify the statistical significance of these features, and the scale length on the sky with which they are associated.

The key result is apparent from figure 2. At every scale we see mildly significant structure, and deviations from Gaussians: are the groupings of stars in phase space, and the deviations from kinematic smoothness, physical? Statistical tests show that substructure is significant, but only marginally, and only when the data are restricted by angular scale length on the sky. This is just what some spaghetti models predict (eg. Helmi & White 1999; Helmi et al 1999; Harding et al 2001). We are continuing to investigate its reality.

4. Conclusions:

Modern large area surveys, complemented by deeper multi-object facilities, are obtaining and analysing the combination of metallicity and kinematic data for large samples of Galactic stars in the thick disk – halo interface. Our preliminary results for one such study, AAOSPS, show intriguing, but low statistical
Figure 3. 2dF metallicities vs heliocentric radial velocity, for our stars with sufficient S/N, in one line of sight. Radial V velocity at these distances in this line-of-sight is approximately Galactic rotational velocity, with 180km/s approximately zero net orbital rotation. The many stars with low metallicity and disk-like (small-V) velocities are the identification of a low metallicity tail of the thick disk. There is no metal-rich halo. Lumpiness in the figure is apparent: if real it will indicate phase-space structure, allowing quantification of the past merger history.

significance, deviations from canonical distributions. These may signal the remnant of the satellite whose merger with the young Milky Way formed the thick disk, the last high-impact merger that our Galaxy experienced. Further, the amplitude of small-scale lumpiness constrains the more recent merger history, with recent detections from HIPPARCOS local data again being complemented by more distant studies. We are on the way to deciphering the fossil record of the physical processes in the formation and evolution of a typical large disk galaxy, the Milky Way.

References
Arnold, R & Gilmore, G 1992 MNRAS 257 225
Beers, T et al 1999, AJ 117, 981
Burkert, Hensler and Truran 1992 ApJ 391, 651
Carney, B et al 1989, AJ 97, 423
Chiba,M., & Beers, T., 2000 AJ 119, 2843
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Eggen, O., Lynden-Bell, D. and Sandage, A. 1962 ApJ 136 748
Ferrini, F. et al 1994 ApJ 427 745
Freeman, K., 1993, ASP Conf series 49, eds Majewski, p12.
Gilmore, G & Wyse, R. 1985, AJ 90, 2015
Gilmore,G., Wyse, R., & Kuijken,K. 1989, ARAA, 27, 555
Gilmore,G., Wyse, R., & Jones,B., 1995, AJ 109, 1095
Harding et al, 2001, AJ in press, astro-ph/0012307
Helmi, A., & White, S. 1999, MNRAS 307, 495
Helmi,A., White,S., de Zeeuw, T. & Zhao, H. 1999, Nature, 402, 55
Huang, S. & Carlberg, R. 1997, ApJ 480, 503
Ibata,R., Gilmore, G., & Irwin,M. 1994, Nature, 370, 191
Ibata,R., Gilmore, G & Irwin,M. 1995, MNRAS 277, 781
Ibata,R., Wyse,R., Gilmore,G., Irwin,M. & Suntzeff,N. 1997, AJ 113, 634
Kuijken,K. & Gilmore, G. 1989 MNRAS 239 571
Majewski, S., 1993, ARAA, 31, 575
Norris, J., 1996, ASP Conf Series 92, eds Morrison and Saradajeni, p14
Norris, J., Bessel, M. & Pickles, A. 1985 ApJS 58 463
Norris, J. & Ryan,S. 1991, ApJ 340 739
Pagel, B. & Patchett,B. 1975, MNRAS 172, 13
Silk,J. & Wyse,R. 1993, Physics Reports 231 293
Tinsley, B. 1980 Fund Cosmic Phys 5 287
van den Bergh, S. 1962 AJ 67 486
VandenBerg, D. 1985, ApJS, 58, 711
VandenBerg, D. & Bell, R. 1985, ApJS, 58, 561
Velazquez,A., & White, S. 1999, MNRAS 304, 254
Walker, C., Mihos,C. & Hernquist, L. 1996, ApJ 460, 121
Wyse, R. 2001, astro-ph/0012270, to appear in Galactic Disks and Disk Galaxies.
Wyse, R., & Gilmore, G. 1995 AJ 110, 2771