GALACTIC STRUCTURE AND STELLAR POPULATIONS

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Running Head : Galactic Structure

ABSTRACT. The Milky Way Galaxy offers a unique opportunity for testing theories of galaxy formation and evolution. I discuss how large surveys, both photometric and spectroscopic, of Galactic stars are the keystones of investigations into such fundamental problems as the merging history – and future – of the Galaxy.

1. INTRODUCTION

The study of the spatial distribution, kinematics and chemical abundances of stars in the Milky Way Galaxy constrains models of disk galaxy formation and evolution. One can address specific questions such as

(i) When was the Galaxy assembled? Is this an ongoing process? What was the merging history of the Milky Way?

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[1] Permanent address

(ii) When did star formation occur in what is now 'The Milky Way Galaxy'? Where did the star formation occur then? What was the stellar Initial Mass Function?

(iii) How much dissipation of energy was there before and during the formation of the different stellar components of the Galaxy?

(iv) What are the relationships among the different stellar components of the Galaxy?

(v) Was angular momentum conserved during formation of the disk(s) of the Galaxy?

(vi) What is the shape of the dark halo?

(vii) Is there dissipative (disk) dark matter?

These questions are part of larger questions such as

(a) What was the star-formation rate at high redshift? – in this context remember that the oldest stars in the Galaxy formed at a lookback time of 10–15 Gyr, or redshifts significantly greater than unity.

(b) Does light trace mass?

(c) What determines the Hubble Sequence of galaxies?

(d) What was the power spectrum of primordial density fluctuations?

(e) What are the values of the cosmological parameters H_0 and Ω_0? For example, the length-scale of the Galactic disk compared with those of external galaxies constrains H_0, on the presumption that the Milky Way is a typical spiral (van der Kruit 1986).

In this talk I will focus on two (related) questions for which large surveys of stars in the Galaxy are crucial, namely 'what is the shape of the stellar halo?' and 'what is the merging history of the Milky Way Galaxy?' The shape of the stellar halo constrains the shape of the dark halo, especially when the spatial data are combined with stellar kinematic data, in addition to containing information about the important physical processes during the formation of the stellar halo – was there large-scale dissipation of energy during a collapse phase? Are there subcomponents to the halo that may indicate accretion and merging? The thick disk of the Galaxy may have been formed by a merger event with a satellite of perhaps the mass of the Large Magellanic Cloud; the stars of such accreted satellites may still be identifiable in 'moving groups'. When will the next merger event occur? Large multi-color databases such as those soon to be available from the Sloan Digital Sky Survey and the APS facility in Minnesota will provide necessary input to these problems.

2. GALAXY FORMATION

I shall briefly summarise current ideas of galaxy formation and evolution to place Galactic work in context (see *e.g.* Silk and Wyse 1993 for a more complete review). The nature of Dark Matter determines the way in which structure forms in the Universe. The popular theory of Cold Dark Matter (CDM; *e.g.* Blumenthal *et al.* 1984) predicts that the first objects to collapse under self-gravity are a small fraction of the mass of a typical galaxy, so that galaxies form by clustering and merging of these smaller objects. All density fluctuations are initially just gas and dark stuff, and the rate at which stars form is very model-dependent, but feedback from stars plays a major role in the energy balance. The rate of merging and growth of mass of a protogalaxy can be estimated by studying the dark matter, which is assumed to be dissipationless and hence to have simpler physics than the baryonic component, but most probably underestimates the longevity of individual baryonic structures which would be observed as distinct galaxies (*e.g.* Lacey and Cole 1993; Kauffmann and White 1993; Navarro, Frenk and White 1994). Lacey and Cole (1993) have a particularly vivid schematic representation of the merging process (their Figure 6) as a tree, where time increases from top to bottom, and the width of the branches indicates the mass of a particular halo associated with galactic substructure. The final product, the galaxy, is represented by the single trunk at the ground, and the relative thicknesses of branches meeting reflect the mass ratios in a merger. The merging history of a galaxy is then described by the shape of the tree. The extremes of morphological type may perhaps be the result of merging histories that are described by the two types of trees that I at least was taught to draw as a child – either one main trunk from top to bottom, with many small branches joining the trunk at all heights, as a fir tree, or a main trunk that splits into two repeatedly, more like an English oak tree. The latter, dominated by 'major mergers' or equal mass mergers, may lead to an elliptical galaxy. The former, where the merging history is dominated by 'minor mergers', or very unequal mass mergers with a well-defined central core at all times, may lead to a disk galaxy. This picture of disk galaxy formation – building up by accretion of substructure onto a central core – provides a synthesis of elements of the much-discussed and previously apparently mutually exclusive 'monolithic collapse' paradigm of Eggen, Lynden-Bell and Sandage (1962) and the 'chaotic' halo formation envisaged by Searle and Zinn (1978). One of the reasons for the popularity of CDM is its analytic tractibility; Gunn (1987) presents an elegant exposition of the formation of the Milky Way.

Constraining the merging history of the Milky Way is of obvious importance, as is determination of the star formation history. Aspects of these problems are briefly discussed here.

3. IS THE STELLAR HALO ROUND, FLAT, BOTH, OR MORE COMPLEX?

Dissipationless N-body simulations of hierarchical clustering tend to form flattened, triaxial halos, with mean axial ratios of $< b/a >\sim 0.64$ and $< c/a >\sim 0.45$ at 50kpc for a standard CDM power spectrum (Dubinski and Carlberg 1991). Iso-potential surfaces are in general rounder than iso-density surfaces – for reasonable axisymmetric potentials at a few core radii the ellipticity of the potential contours is only about one-third that of the density contours (Binney and Tremaine 1987) – and, depending on kinematics, one may expect a system of test particles to have an axial ratio that is closer to that of the potential rather than that of the gravitating density (for example Binney and May 1986). Thus one might expect luminous galaxies to be rounder than their dark haloes. Further, the effect of the baryonic component, once it dissipates and settles to the center of the potential well, on the dark halo will be to decrease its flattening and make it more oblate (Katz and Gunn 1991; Dubinski 1994). However, one would not expect any component to be spherical.

Counts of stars in different lines-of-sight can be used fairly directly to obtain an estimate of the shape of the stellar halo, although a dependency on models enters through the need to isolate *halo* stars; this is generally attempted by concentrating on blue stars, $B-V \lesssim 0.6$. Analyses of Schmidt plates to $V \sim 20$, or distances of unevolved halo stars from the Sun of $\sim 5-6$kpc, favor a flattened stellar halo, $c/a \sim 0.6$ (Wyse and Gilmore 1989; Larsen and Humphreys 1994). Deeper star counts, to V$\sim$ 21, have favored rounder isophotes, $c/a \sim 0.8$ (Bahcall and Soneira 1980; Reid and Majewski 1993). Accurate star-galaxy-qso separation is obviously crucial especially for the analysis of faint blue stars. However, it may be that there are indeed two components to the stellar halo, with the more distant stars being in a rounder component. Kinman, Wirtanen and Janes (1966) found a general increase in the flattening of the field RR Lyrae population with increasing Galactocentric distance. Hartwick (1987) found that the metal-poor, [Fe/H] $\lesssim -1$ dex, halo globular clusters and the metal-poor RR Lyrae stars both had a spatial distribution that was better fit by two components; his inner component, which dominates in the solar neighborhood, is flattened with an axial ratio of ~ 0.6, while the outer component, dominant at $R \gtrsim 15$kpc is spherical. Kinman, Suntzeff and Kraft (1994) also found evidence for two components, one significantly flattened which dominates locally and one more spherical, in their sample of halo blue horizontal branch stars. However, these analyses of horizontal branch stars are hampered by the small number of stars available; studies of unevolved tracers are not in principle.

The kinematics of the stellar halo provide only a weak constraint on the shape at present, but it is difficult to fit both the local and the distant data simultaneously (Arnold 1990; van der Marel 1991). Answering the question of whether or not the flattened component to the halo horizontal branch stars is rotationally supported requires more data.

The existence of two components may be evidence that the stellar halo formed by a hybrid chaotic/monolithic collapse process as described in section 2 above (*cf.* van den Bergh 1993; Zinn 1993; Norris 1994), or that the stellar halo is locally flattened in response to the disk potential (*cf.* Binney and May 1986), or perhaps reflects the different orbital parameters and internal structure of disrupted satellite galaxies that were accreted by the Galaxy to form the stellar halo (Freeman 1987). Satellite galaxies are slowed in their orbit by dynamical friction against the background halo (assuming their orbit penetrates the mass distribution of the Galaxy), depositing orbital energy and angular momentum. The satellite galaxy will be tidally shredded as it sinks towards the Galactic center, essentially losing material with density less than the average density of the background Galaxy interior to the satellite's current position. Thus the internal structure of the satellite plus its initial orbit determine how much of the satellite's vertical motion is damped prior to significant disruption of the satellite. This is discussed further below.

Thus improved distant samples are required for halo kinematics and also for chemical abundances to constrain the interpretation of the star count analyses, by better isolation of 'halo' stars. Probably only spectroscopy will allow quantification of quasar contamination of representative blue star samples (as will be carried out by the Sloan Digital Sky Survey), but multi-color photometry combined with measuring machines such as the APS will suffice for the bulk of the stars.

4. THE THICK DISK AND THE MERGING HISTORY OF THE MILKY WAY

4.1 The Thick Disk

As discussed briefly above, mergers between galaxies and/or galactic substructure are inherent in hierarchical-clustering scenarios for the growth of structure in the Universe. Since the pioneering work of Toomre (*e.g.* 1977) much effort has gone into study of the effects of both stellar and gaseous mergers upon galaxy morphology. The thick disk of the Milky Way Galaxy at least morphologically could be a minor-merger remnant; provided all the orbital energy of an accreted satellite, mass M_{sat}, is available to increase the random energies of the stars in a thin disk of mass M_{disk}, then after a merger the thin disk will be heated by an amount (Ostriker 1990)

$$\Delta v^2_{random} = v^2_{orbit} M_{sat}/M_{disk}.$$

Of course the internal degrees of freedom of the satellite could also be excited and any gas present could, after being heated, cool by radiation, so this is a definite upper limit to the heating of the disk. This estimate is suggestive, however, that the thick disk, which has a vertical velocity dispersion of $\sim 45\,\mathrm{km\,s^{-1}}$, could be formed from a thin disk with vertical dispersion of $\sim 20\,\mathrm{km\,s^{-1}}$ by accretion of a satellite of about 10% of the mass of the disk. Note although there is indeed an age–velocity dispersion relationship for stars in the thin disk, the value of the vertical velocity dispersion is observed to saturate at $\sim 20\,\mathrm{km\,s^{-1}}$ for stars older than a few Gyr (*e.g.* Freeman 1991), which may be understood if the heating mechanism responsible is confined to the thin disk itself, such as scattering by encounters with giant molecular clouds (*e.g.* reviewed by Lacey 1991).

Mergers between disks and satellites have been studied by Quinn, Hernquist and collaborators. The most detailed N-body simulation they have published to date (Quinn, Hernquist and Fullager 1993) follows the evolution of a satellite galaxy, initially in a prograde, circular orbit about a disk of mass ten times that of the satellite, with the orbit inclined 30° to the plane of the disk, and at a Galactocentric radial distance of six disk scalelengths. Further parameters that need to be specified define the internal density profile and kinematics of the satellite, and of the disk. The generic evolution is that the satellite's vertical motion is damped rather quickly, with a slower radial decay to the central regions (displayed very clearly in their Figure 11). The orbital energy is indeed deposited both in the disk particles and in the internal degrees of freedom of the satellite; the final galaxy has a thick disk which consists of both heated thin-disk stars and shredded-satellite stars. The mix of these obviously depends on the (many) model parameters, both orbital and internal to the galaxies. Both the radial and vertical structures of the disk are altered. The radial heating and re-arrangement of material by angular momentum transport results in an asymmetric drift (lag behind local circular velocity) that is only $\sim 10\,\mathrm{km\,s^{-1}}$ higher than the initial disk. The vertical heating increases the disk scale-height by about a factor of two.

How does this compare to the observed thick disk in the Milky Way? The scale-height is in reasonable agreement with star count analyses. Determination of thick disk kinematics is complicated by the fact that there is strong overlap with the other stellar populations of the Galaxy, and in particular the thin disk. The most recent determinations have used robust decompositions of the observational data and find that the thick disk asymmetric drift is constant with height above the plane, at least over 500pc – 2kpc, and has a value of $V_{lag} \sim 50 - 60\,\mathrm{km\,s^{-1}}$ (Soubiran 1993; Ojha *et al.* 1994), which is not in wonderful agreement with this particular simulation. Of course the 'standard' merger of Quinn *et al.* is only illustrative.

The chemical abundance distribution of the thick disk is an obvious discriminant of models of thick disk formation. For example, in the dissipationless stellar accretion scenario, the thick disk should be a mix of the pre-existing thin disk, and the accreted satellite. An alternative picture that can produce sufficient heating to explain the thick disk appeals to rare close encounters of thin-disk stars with massive black holes in the halo, and predicts that the thick disk should contain the same range of chemical abundances as the present thin disk (Lacey and Ostriker 1985). The available estimates of age for the bulk of the thick disk imply that its stars formed early in the evolution of the Galaxy, perhaps at the same time as the metal-rich globular clusters (Gilmore, Wyse and Kuijken 1989; Edvardsson *et al.* 1993), which argues against an on-going process of disk thickening.[♡] This also implies that in the merger scenario the chemical abundance distribution of the thick disk should reflect that of the thin disk and satellite perhaps

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[♡] In fairness to Lacey and Ostriker they were concerned more with explaining the population of high-velocity A stars (*e.g.* Lance 1988) as being the product of rare close encounters of disk stars with massive halo black holes; however one might also note that massive black holes have fallen out of favor as candidates for halo dark matter, due to recent calculations concluding that for masses of $\gtrsim 10^3 M_\odot$ they are too efficient at heating and would disrupt halo globular clusters (Moore 1993) and the disks of low-mass galaxies (Rix and Lake 1993).

14 Gyr ago. While this is rather model-dependent, studies of the older stars in the present satellites of the Milky Way might lead one to expect a metal-poor component to the thick disk, with metallicities $\lesssim -1$ dex, in addition to the contribution from direct heating of the thin disk, with [Fe/H] $\gtrsim -1$ dex. A metal-poor component of the thick disk may also be expected if the thick disk/thin disk formed with no pre-enrichment (the ejecta from stellar evolution in the stellar halo is, due to its low angular-momentum per unit mass, destined to flow to the central regions of the Galaxy).

The thick disk is observed to have a well-defined peak chemical abundance of ~ -0.6 dex (Gilmore and Wyse 1985; Carney, Latham and Laird 1989; Gilmore, Wyse and Jones 1994) and a fairly broad spread, $\sigma_{[Fe/H]} \sim 0.3$ dex. Metal-poor stars with thick-disk kinematics have been reported by Norris, Bessell and Pickles (1987) and by Morrison, Freeman and Flynn (1991) on the basis of DDO photometry; however as these stars were discovered as part of a survey of metal-poor stars, their normalisation relative to the main thick disk is very uncertain, and may be consistent with determinations of the metallicity distribution from unbiased surveys with spectroscopic metallicities. Further, the calibration of the DDO photometric metallicity estimator has recently been called into question for just the metallicity, [Fe/H] ~ -1.2 dex, of the 'metal-poor thick disk' (Twarog and Anthony-Twarog 1994). However, the situation is not settled since another survey for metal-poor stars has found similar results to Morrison *et al.* but with improved metallicity determinations (Beers and Sommer-Larsen 1994). Clearly an unbiased, large dataset is required.

4.2 How Much Merging is On-going?

Do we have a complete census of the satellite galaxies of the Milky Way? All-sky surveys, with good photometry in several bands, and robust star-galaxy separation, offer the best way to identify overdense regions in color-magnitude space, and to find clumps of rare stars, for example carbon stars, which may indicate a physical entity. The hierarchical clustering and merging picture of galaxy formation predicts that there should be many shredded satellite galaxies for every parent galaxy. Lynden-Bell (1982) noted that the major axes of the stellar isophotes of many of the dwarf spheroidal companion galaxies to the Milky Way align with their orbits, as predicted for galaxies that are being tidally distorted. This effect has been nicely illustrated by McGlynn (1990) in his Figure 2c. Since particles which become unbound have low positive energies, they thus only slowly drift away from their distressed parent galaxy. As discussed in a slightly different context by Tremaine (1993), a tidally disrupted object will spread out into a tidal stream of length determined by the spread in orbital frequency over the size of the object. After time t, the size of the remnant, s, relative to the radius of the satellite at which tidal stripping began, $R_{satellite}$, is $s/R_{satellite} \sim \Omega\, t$, where Ω is the angular frequency of a circular orbit at the galactocentric radius where the satellite was disrupted. For disruption at 50kpc, after 1Gyr the satellite is spread out to only four times its original size.

Satellite galaxies at high Galactic latitude may often be found by simply plotting stellar surface density contours projected on the sky. For example, the dwarf galaxy discovered in the Sextans constellation, latitude $b = 42.3$, by Irwin *et al.* (1990) is clearly seen in their Figure 1(b), which plots all stellar objects down to the plate limit ($B_J \sim 22.5$); note the paucity of objects classified as stars – the contours plotted start at 1.5 images/arcmin^2 and increase in steps of 0.5 images/arcmin^2. The dwarf has an angular extent of a degree or so.

Dwarf galaxies could be hiding at lower latitudes, where there is sufficient foreground disk that the over-density of the satellite is too small a perturbation to be detected by a simple sum of all stellar images. An example of this is the Sagittarius dwarf, recently discovered (Ibata, Gilmore and Irwin 1994), as part of a survey of the kinematics of the bulge (Gilmore and Ibata, in prep). The dwarf initially manifest itself as a moving group, with very distinct kinematics from the bulge, and rather localised in angular position. The color-magnitude diagram of the field where the moving group is seen kinematically contains a fairly obvious core-helium-burning red 'clump' (indicative of an intermediage-age population) and giant branch, which are not detected in those fields where the stars have normal bulge kinematics. Isolating stellar images which have the color and apparent magnitude of the clump, and plotting isodensity contours of the difference between the 'moving group' field and an offset field, revealed the spatially-extended dwarf galaxy (Ibata, Gilmore and Irwin 1994). The distance to the dwarf may be estimated from the clump/HB magnitude, resulting in a position ~ 12 kpc from the Galactic center on the other side of the Galaxy, ~ 5 kpc below the disk plane. The dwarf is inferred to be rather massive, similar to the Fornax dwarf galaxy, from application of the observed luminosity-metallicity relation of the extant satellite galaxies (Caldwell *et al.* 1992), and from the red clump/giant population. At least three globular clusters have kinematics and distances that are suggestive of their being physically associated with the dwarf galaxy.

How many of these are there out there? Digital databases provide the ideal searching ground to apply optimised filters to detect moving groups/satellites.

ACKNOWLEDGEMENTS

The Center for Particle Astrophysics is supported by the NSF. I thank the Seaver Foundation for support, and Roberta Humphreys for organising the special session at the AAS at which this talk was presented.

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