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GALACTIC STRUCTURE AND STELLAR SURVEYS

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Large Scale Galactic Structure

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Abstract. Modern models of Galaxy formation make fairly specific predictions which are amenable to detailed tests with galactic kinematic and chemical abundance data. For example, popular Cold Dark Matter 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. This picture, which contains aspects of both the monolithic ('ELS') and the multi-fragment ('Searle-Zinn') pictures often discussed in chemical evolution models, makes some specific predictions which can be tested. The essential feature of these predictions is that they are believable only for the largest scale effects. Large scale properties of the Galaxy must be measured to test them. It is these studies which need large angular scale data. One specific example of current interest is the 'prediction' that mergers of small satellites are an essential feature of galactic evolution. This leads one to look for kinematic and spatial structures, and 'moving groups', as a primary test of such models.

1. Galaxy Formation: an overview

One really studies stellar kinematics and galactic structure to learn about the assumptions underlying models of galaxy formation. To appreciate the plausibility and validity of those assumptions it is helpful to recall current models of galaxy formation. These models then identify those aspects of stellar kinematic analyses where the simplifying assumptions which are necessary to provide tractable problems are least likely to be soundly based, and thus where greatest caution need be taken. Conversely, testing the assumptions in Galactic kinematics tests current models of galaxy formation and evolution. An excellent recent review of models of galaxy formation and evolution is provided by Silk & Wyse (1993), where details and references may be found.

The most detailed models of galaxy formation at present involve cold dark matter (CDM) as the dominant contribution to the gravitational potential. It is worth emphasising that CDM models are popular as much because they allow one actually to test calculable predictions as because they are plausible. A basic feature of CDM is spottiness. Many small 'condensations' of this CDM form early in the expansion of the Universe. Many of these, but perhaps not all, acquire a baryonic gas component as ordinary mass cools and falls into the local potential well. Large galaxies then form by the merger of a significant number of these sub-units.

Two basic paths then are available for the formation of what we see today as a large galaxy: a large number of small units may accrete onto a dominant 'core', or many comparable units may merge, with no single unit being identifiable as "the" proto-galaxy. In both these cases the merger process may be effectively complete at very early times, or it may be continuing at a significant rate at the present.

A picture of 'galaxy formation' at high redshifts then becomes the merger of CDM halos. In such a merger the (probably) hot diffuse gas in each mini-halo is assumed in the simplest case to be shock heated up to the virial temperature of the newly-formed composite halo. It will then assume a smooth $\rho \propto r^{-2}$ density profile, and eventually cool onto the density centre, which will be occupied by the largest pre-existing mass of cool condensed gas, if such existed. More complex situations, particularly involving secondary infall, can of course be envisaged, but are not fundamental to the discussion here. If a substantial amount of cool condensed gas were available in each mini-halo before merger then that gas mass may survive for some time as a definable condensation, and may form new stars and chemical elements in effective isolation from its surroundings. Eventually dynamical friction and/or cloud-cloud collisions will destroy such condensations, and the contents will disperse. Any gas will become part of the centrally condensed, well-mixed system, any stars will move along dispersion orbits in the larger potential well, as will the dark matter. The timescale on which such sub-units will be destroyed, and their contents mixed into the larger background, is comparable to a dynamical time, so significant substructure is not expected to be a long-lived phenomenon (Gilmore & Wyse 1993; Tremaine 1993).

This blend-and-stir process will have been common at high redshifts, when a rain of dwarf 'proto-galaxies' was normal weather for a budding giant. It continues today, at a rate which may still be significant for some galaxies. The term 'significant' here is worth some thought: in the central regions of galaxies, masses are large, timescales are short and dynamical friction effective. Thus significant changes to a galaxy require mergers of components of comparable mass. It has been suggested that such mergers would destroy the thin disk of a galaxy like the Milky Way, as argued recently by Ostriker. If this argument were correct then normal late-type spirals must have completed the bulk of their merger events at very early times.

In the outer parts of galaxies mass densities are low, the fraction of the total luminous galaxy which is seen is very small, and timescales are comparable to a Hubble time. Thus one expects relatively little fossil kinematic structure to be visible in the central regions of normal galaxies, but it is probable that a large fraction of the outer parts of a large galaxy is a recent (on kinematic timescales) acquisition from afar. Fundamentally, the central regions of a galaxy need not be related in any obvious way to the outer parts of that same galaxy.

The dark matter which makes up the dominant contribution to the gravitational potential will have its spatial distribution modified by the rearrangement of the baryonic gas during this merger process. The gas dissipates its energy radiatively, and sinks towards the centre of the potential well. The resulting increase in central concentration of a significant part of the mass will alter the orbital distribution of the dark matter particles. Detailed simulations of this effect (e.g. Dubinski 1994) predict triaxial distributions with $b/a \geq 0.7; c/a \approx 0.5$.

A triaxial mass distribution in the halo predicts observable effects on stellar kinematics, and in turn can be tested from kinematic analyses. The most direct of such tests include ellipticity in the Galactic disk and non-stationarity of the kinematics of the solar neighbourhood (Kuijken & Tremaine 1993), both of which are probably seen, and which therefore support the case for a triaxial dark halo.

As with all sophisticated models, one should ask before proceeding if any robust evidence exists to support the fundamental assumptions and conclusions. In this case the evidence in favour of CDM models is marginal rather than conclusive (Ostriker 1993). However, not only do careful dynamical studies confirm the dominance of galactic potentials by an extended dark halo (Gilmore, Wyse, & Kuijken 1989; Fich & Tremaine 1991) but direct evidence for continuing mergers is provided by the impending merger between the Galaxy and the Magellanic Clouds.

2. Is the Galactic Bulge the Galactic Seed?

A specific choice presented by CDM galaxy formation models is that the Galactic Bulge is either (part of) the central core about which the Galaxy grew, or it is a later arrival. Discussion of the chemical evolutionary implications of these choices has been provided by, among others, Wyse & Gilmore (1992, 1993). A direct discrimination is best based on comparisons of the specific angular momentum distributions. For the bulge such data are hard to obtain, as the angular extent on the sky is some tens of degrees. Too much for one spectrograph slit. With wide field systems on a star-by-star basis, it can be done, however.

New rotational velocity data for the bulge have been derived recently by Ibata & Gilmore (1993). Their data, based on radial velocities for $\sim$ 1000 stars, are consistent with differential rotation, with an amplitude rising to $V =$ 100 kms^{-1} at a Galactocentric distance of 3 kpc. Using Hernquist's(1990) analytic density profile, with radial half-light radius $r_{eff} = 300$ pc, yields the angular momentum distribution for the bulge as shown in Wyse & Gilmore (1992). The angular momentum distributions of the central bulge and of the stellar halo are clearly very similar, showing that it is indeed possible for the present central bulge to be formed from the same gas as formed the oldest stellar populations in the Galaxy without requiring significant angular momentum loss.

The angular momentum distribution of the thick disk may be derived as above, once a density profile and rotation curve have been adopted. However, the global properties of the thick disk are yet poorly defined. The approximation of an infinitely thin disk (Freeman 1975) in differential rotation with constant rotation velocity, V, gives

$$M(h) = \frac{\pi \Sigma_o}{\alpha^2} \gamma(2, h\alpha/V),$$

with γ being an incomplete gamma function, and Σ_o is the central mass surface density. Adopting an exponential scale-length equal to that of the thin disk, $\alpha^{-1} = 4.5$ kpc (van der Kruit 1990), and a constant rotational velocity of amplitude $V = 180$ kms^{-1} (Ratnatunga & Freeman 1989), gives the angular momentum distribution plotted in Wyse & Gilmore (1992), where they have taken the edge of the disk at 4.5 scalelengths.

That is, available chemical abundance models (Wyse & Gilmore) and dynamical constraints are both consistent with the Galactic bulge being part of that fragment of the early Universe about which the remainder of the present-day Milky Way Galaxy accreted.

The remaining important information required to test this, is determination of the stellar velocity dispersion tensor in the bulge. The specific angular momentum distribution allows the bulge and the halo to be related, presumably with the bulge being the highly dissipated core of the halo. For this to be true one would expect a velocity ellipsoid in the bulge which is no more anisotropic than is that of the field subdwarf population (assuming no significant dynamical evolution of the bulge after its formation).

Ibata & Gilmore (1994, in preparation) have obtained spectra for ≈ 1500 stars in six Galactic bulge fields. By comparing the resulting velocity distributions to a Galaxy model, they find a good fit with an oblate bulge model with constant angular rotation, whose velocity ellipsoid is isotropic and constant at $\sigma = 65$ kms^{-1} over the range of their observations. The oblate bulge model constructed by Kent (1992), derived self-consistently from a Galactic mass model, also fits the data acceptably well; this model has isotropic velocity dispersion in the relevant bulge regions. However, the data do allow the bulge to have a significantly anisotropic velocity ellipsoid ($\sigma_r/\sigma_\theta \approx 2$), but then its angular velocity must vary with radius in a contrived way.

Ibata & Gilmore also derive approximate metallicities for K giants in their sample by calibrating the equivalent width of the Mg‘b’ feature. The metallicity distributions do not vary significantly over the region investigated; the peak of these distributions is found to be ≈ -0.25 in all fields, identical to the value derived by McWilliam & Rich (1994) for K giants in Baade’s Window. This homogeneity in abundances over the ≈ 3 kpc that the above fields cover, is consistent with models that require the bulge to form rapidly.

3. Kinematic Evidence for Mergers

The galaxy formation concepts outlined above suggest that a considerable amount of structure in the phase space distribution function for those stars (and DM particles) which inhabit the outer reaches of the galaxy is to be expected. This structure will be the remnant dispersion orbits occupied by the debris of former galactic satellites and near-neighbours which have now lost their former isolated identity. The existence of this structure provides a challenge in two ways: to devise dynamical analysis methods and/or sample selection methods which will still provide a ‘fair sample’ of the outer galaxy for dynamical studies; and to identify the fractional amount of phase space substructure, if any, and so test the (CDM) galaxy merger models.

The modelling limitations are minimized by ensuring that any kinematic sample which is to be analysed contains of order one star from any clump in phase space. That is, sparse sampling surveys over large areas of the sky are preferable to detailed pencil-beam surveys. Since extant data tend to have few stars down any one line of sight, it seems that current analyses which are designed to determine gross structural properties of the galaxy – such as the extent of the dark halo – benefit from patchy data. This is perhaps the only situation in astronomy where poor weather during observing allocations is beneficial, in that it prevents the accumulation of too much data on a single dispersion orbit

One would however like to prove that such orbits exist, and do contain much of the stellar mass of the outer halo. Since stars on a single orbit will be distributed over much of the sky, as seen by us in spatial projection, after only a few orbits, it is only very recent mergers which could be detected by spatial clumping, or in a spatial correlation function. Such remnants are likely to be rare, and may be restricted only to the Magellanic Stream. The most direct evidence is to determine the phase space distribution function, and to search for structure in that. Considerable efforts are being expended to do this for a variety of outer halo tracers. The most useful tracer objects studied to date are the metal poor globular clusters and distant horizontal branch HB stars.

A very considerable effort has been expended to derive proper motions for galactic globular clusters (and the Magellanic Clouds), and to complement the resulting space motions with age data. The present situation remains confused irreducibly by small number statistics: there simply are not very many clusters in the Galaxy. Nonetheless, recent efforts do suggest that perhaps 20 of the metal poor globular clusters have horizontal branch morphology such that they appear younger than the bulk of the population (Zinn 1993). A simple explanation of this result is that a fraction of order one-quarter of the very outer halo was accreted a few dynamical times after the bulk of the Galaxy became an identifiable gravitationally bound unit. Distant horizontal branch stars have also been studied by several groups, with the current status of such work being well reviewed by Kinman (1993). A specific example of a survey of this type is that discussed by Arnold & Gilmore (1992; and 1994 in preparation).

An interesting feature of the Arnold & Gilmore results is the direct apparent evidence in their data for structure in phase space. They have studied two lines of sight. In one a group of blue horizontal branch stars at galactocentric distance 30 kpc is seen, with all four stars in their sample near this distance having indistinguishable velocities. This is discussed in Arnold & Gilmore (1992).

In the second field studied by Arnold & Gilmore all eight stars in their sample with galactocentric distances between 15 kpc and 25 kpc have galactic orbits with the same sign of angular momentum, and again the local dispersion in the velocity distribution for those few stars is small. Each of these two results independently is of only marginal statistical significance. The interesting feature however is that the significance of these results has increased as the data set has increased, and that similar, again marginal when considered in isolation, results are seen in several other surveys. The existence of such phase space structure in stars of the thick disk and halo, in addition to the younger stellar populations, has been persuasively argued by Eggen for many years (Eggen 1987). Such moving groups are of course a specific high contrast example of the structure being considered here.

Direct evidence for an ongoing merger event has been discovered recently in a study by Ibata, Gilmore & Irwin (1994, submitted). While investigating the kinematic structure of the Galactic bulge, they discovered a large phase-space structure consisting of > 100 K giant, M giant and carbon stars in three low Galactic latitude fields. The group has a velocity dispersion of < 10 kms^{-1}, and a mean heliocentric radial velocity of 140 kms^{-1}, that varies by less than 5 kms^{-1} over the 8° wide region of sky that the three kinematic fields cover. The colour–magnitude (CM) diagram of this region of sky was obtained from APM scans of UKST plates; over the expected Galactic CM signature an unexpected excess was revealed, in the form of a tight CM relation similar to that of the SMC. A giant branch, red horizontal clump and horizontal branch are clearly visible. Stars belonging to the low velocity dispersion group lie on the upper giant branch of the unexpected CM relation. From the magnitude of the horizontal branch, Ibata, Gilmore & Irwin find that the object is situated 15 ± 2 kpc from the Galactic centre; this value agrees well with that obtained by direct comparison to the CMD of the SMC. An isodensity map shows the object to be elongated (with axial ratio ≈ 3), spanning > 10° on the sky in a direction perpendicular to the Galactic plane.

Ibata, Gilmore & Irwin argue that the most plausible interpretation for this group of stars is that they drawn from a hitherto unknown dwarf galaxy. They estimate its mass by comparing the number of giant branch and red horizontal clump stars in this object to that in the dwarf spheroidal Fornax; similar numbers are found, implying a similar mass. Its metallicity is estimated from the equivalent width of the Mg'b' feature in kinematically selected K giant members and by calibrating the colour of the giant branch at $M_I = -3$; both estimates give $[\mathrm{Fe/H}] \approx -1$. Thus if this object were to follow the trend of metallicity vs absolute magnitude seen in dwarf galaxies, an object of mass intermediate between Fornax and the SMC would be implied.

The tidal radius of the dwarf galaxy is then approximately an order of magnitude smaller than its apparent size on the sky, so most of its members will disperse into the Galactic halo over the next $\approx 10^8$ years. This finding clearly supports galaxy formation scenarios of with significant merging events happening right up to the present epoch.

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Discussion

McCarthy: Are the C stars cool or hot carbons? What are their apparent magnitudes in the red or near-infrared? (N.B. No cool carbon stars were found by Blanco or myself in the direction of Baade's window).

Gilmore: The apparent R magnitudes are in the range $14 \leq R \leq 15$, but that is in part a selection effect, as that is where we looked. Our spectra were optimized to derive radial velocities for K giants, so do not help much for the C stars. They were discovered at the end of the last observing session, so we have been unable to follow them up, or obtain infrared data as yet. All the limited data we have are consistent with them being cool AGB C stars.

Collins: Do you know whether the $I - K = 4$–5 objects you report in the Cowie survey, are stars or galaxies?

Gilmore: All the objects with $K \leq 19$, and a lot of the fainter ones, have spectra. Interestingly, the very reddest objects are galaxies. Some more details are in a paper by Hu et al. (in press), in ApJ Supplements.

Ratag: Has anybody looked at the difference (if it exists) in abundances between the stars in the "asymmetric structure" and those in the central part of the bulge?

Gilmore: We have abundances for most of the $\sim$ 2000 stars in our bulge survey. The mean abundance is about half solar and there is no sign of a correlation with abundance and kinematics. More directly, there is no abundance gradient in the bulge from $\sim$ 1–3 kpc from the centre. In the very centre there are very late M giants which may well be metal rich. Their status remains unclear but they are very concentrated to the Galactic centre. The abundance of the stars in our cold dynamical structure remains poorly determined. The colour of the giant branch suggests high metallicity, perhaps ~ half solar, while the spectra suggest a value which is a bit lower but is poorly calibrated.

Moody: The plausibility that you are seeing an infalling object is enhanced if you can show that this type of assimilation happens regularly. What evidence is there that this may be a regular occurence?

Gilmore: There are two ways to evaluate the frequency of merger events with dwarf galaxies; theoretical calculations of the effect of such an event on the dynamics of the Galactic disk and observational searches for structure in velocity space in field halo stars. The second approach has been attempted by many authors, notably by Eggen in his "moving groups" and more recently by (among others) Arnold & Gilmore (MNRAS 1991) and by Bothun et al. (1992, 1993) for field BHB stars. Most authors find structure at a level of about $2\,\sigma$, so interpretation remains marginal. The theoretical work uses both N-body models (e.g. Hernquist & Quinn 1992, ApJ) and analytic calculations (Toth & Ostriker 1992, ApJ, 389, 5). There are many sensitive parameters. The important point is that a massive satellite would thicken the disk more than is observed, although of course, the thick disk may be just such an event. Since that formed, perhaps 100 Gyr ago, at most a small number, maybe 4–5 mergers of this type can have happened.