Galactic Structure and Evolution: a decade of surveys

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Abstract.

Surveys of the local and distant Universe are the means to test and improve our models of galaxy formation. Substantial successes in the models are evident, while there is also considerable recent progress in identifying what remains to be learned. The key weaknesses of present models are related to merging histories, and small-scale structures, which are both significantly at variance with observations. Observers are polite, and often emphasise their agreements with models. Data is objective, and shows us the way to focus future surveys, to allow improved understanding and knowledge.

1. Introduction

The mass assembly history of galaxies remains one of the critical issues in observational cosmology: did galaxies reach their present stellar mass only recently (say, at \( z \sim 1 \))? Or were most (massive) galaxies already in place by \( z \sim 1 \)? Is late/current accretion significant or merely a perturbation? These questions may best be addressed by a combination of detailed surveys of the Local Group, where quantitative resolved information may be obtained, together with spectroscopic surveys of galaxies as a function of redshift. Substantial progress on both fronts is being made through the wealth of surveys underway and recently reported.

Surveys are indeed the currently favoured means to progress in astrophysics: a search through the journals or astro-ph for ‘survey’ immediately overloads any reading list. Equally noticeable is the current fashion to add a speculation about current mergers to any paper studying any object in the Local Group, irrespective of its direct relevance to the specific data at hand. More fundamental is to consider if the rate and amplitude of the (clearly still happening) current accretion into the Milky Way is signal or noise, and is or is not consistent with model expectations.

That is, we should not aspire to show that current formation models correctly predict the Local Group, and its current merger activity: we know, from direct observation, that current models require many better constraints to allow their improvement, to correspond to real galaxies. Our goal is to consider the observations objectively, to quantify those constraints.

Spectroscopic surveys of faint galaxies, especially those selected in the \( K \)-band, currently offer an excellent opportunity to address these questions for the distant universe (Broadhurst et al. 1992; Cimatti et al 2003: see especially...
The results of these surveys, together with current simulations of galaxy formation, provide the context in which Local Group studies can be interpreted, by highlighting those aspects of current models where most progress is required.

One specific result of current deep surveys, which has been long established in the Galaxy, is the apparently long time since the galaxies were assembled. This result, long known locally, and the subject of many continuing local investigations (eg Sandage, Lubin and VandenBerg 2003; see also Nördstrom et al 2004) identifies one of the most promising ways in which our understanding of galaxy formation can be improved and extended. In essence, galaxies seem to have formed earlier than current models expect, and have remained (relatively) undisturbed for a longer time than predicted. Extending and explaining this contradiction promises to improve significantly our understanding not only of galaxy evolution, but also of the coupled question, the distribution of Dark Matter on small scales, and its corresponding temperature.

In one of the most impressive of recent studies, Cimatti et al (2002) present the redshift distribution of a complete sample of 480 galaxies with $K_s < 20$ distributed over two independent fields covering a total area of 52 arcmin$^2$. A “blind” comparison was made with the predictions of a set of the most recent ΛCDM hierarchical merging (HMM) and a set of pure luminosity evolution (PLE) models. The hierarchical merging models overpredict and underpredict the number of galaxies at low-z and high-z respectively, whereas the PLE models match the median redshift and the low-z distribution, while still being able to follow the high-z tail of $N(z)$. These results are summarised in Figure 1.

These observational surveys illustrate the areas where current paradigmatic models can be most improved. In particular, ΛCDM hierarchical merging models as they are currently implemented overpredict the total number of galaxies with $K_s < 20$ in the K20 survey area by factors of 30-45%, and are inconsistent with the observed galaxy redshift distribution by substantial factors, especially at high redshifts. A Kolmogorov-Smirnov test showed that all the hierarchical merging models disagree with the observations at >99% level.

Nonetheless, the hierarchical merging ΛCDM scenario has spectacular success in reproducing large scale structure and CMB results, and is certainly the paradigm of choice in which we should analyse survey and galactic structure data today. Our ambition is to improve the ability of this framework to become consistent with the real physics of small-scale structure and galaxy formation, by identifying areas in which the input physics can be improved. The observed discrepancies derived from the high-redshift studies are related to what is essentially a purely heuristic set of algorithms adopted to describe the star formation processes and their feedback, both within individual galaxies and in their environment. The high-redshift results suggest that the galaxy formation recipes should allow galaxy formation in a CDM dominated universe to occur in a manner described by the old-fashioned pre-CDM monolithic collapse scenario. This requires the recipes to allow enhanced merging and star formation in massive haloes at high redshift (say, $z \sim 3$), while at the same time suppressing star formation in low-mass haloes.
Figure 1.  **LHS: Top panels:** the observed differential $N(z)$ for $K_s < 20$ (histogram) compared with the PLE model predictions. **LHS Bottom panels:** the observed fractional cumulative redshift distribution (continuous line) compared with the same models. The left and right panels show the models without and with the inclusion of the photometric selection effects respectively. Sc and Sp indicate Scalo and Salpeter IMFs respectively. **RHS: Top panels:** the observed differential redshift distribution for $K_s < 20$ (histogram) compared with the HMM predictions. **RHS: Bottom panels:** the observed fractional cumulative redshift distribution (continuous line) compared with the same models of top panels. The right panels show the model with the inclusion of the photometric selection effects. These figures and captions are from Cimatti et al. 2002.
We now ask if this improved recipe would be consistent with the Milky Way, an L∗ galaxy whose properties should not be too rare in any plausible formation scenario.

2. Mergers, phase-space structures, fashion accessories

Search for and interpretation of phase-space structure in the Galaxy has always been important, but has recently become a major industry. Significant structure is unexpected in a context where galaxy photometrists provide convincing evidence for symmetric and smooth surface brightness profiles (eg Kormendy & Djorgovski 1989), where density profiles for special tracers (RR Lyraes being popular) show smooth profiles over very many scale lengths, and where local stellar kinematics looks closely Gaussian (cf Gilmore, Wyse & Kuijken 1989): clearly whatever process makes galaxies makes smooth-looking relaxed-looking galaxies. Nonetheless, testing the paradigm is important. The current fashion is perhaps to start from the other extreme (cf Freeman & Bland-hawthorn 2002) where some aspire to “associate components of the Galaxy to elements of the protocloud”, an interesting alternative to the statistical distribution function analyses on which the science of stellar dynamics has been built.

Earlier searches for structure in the stellar distribution used techniques such as correlation functions (eg Gilmore, G.; Reid, N.; Hewett, P. 1985) or presumed local evolutionary processes were the default explanation of identified field halo clustering (eg Arnold & Gilmore 1992). The many studies of Eggen on moving groups were perhaps not given due recognition, since most were of thin disk stars, disk structure is inevitably lumpy in phase space, and tells little of global or long-term galaxy evolution. His study of the Arcturus Moving Group was however long understood as significant for thick-disk studies (cf Fuhrmann 2004, sect 2.4) and appears as such in encyclopedias, though is still being rediscovered. [Eggen however (private communication) was deeply sceptical of the distinction between thin and thick disk moving groups.] Gould (2003) has recently reminded us that an apparently smooth distribution is either really smooth - in which case its history is lost into statistical distribution functions – or the central limit theorem applies – in which case its history is lost into statistical distribution functions.

The field changed rapidly after discovery of the Sgr dwarf galaxy (Ibata, Gilmore & Irwin 1994, 1995), an object genuinely discovered in phase-space in real-time at the AAT where Ibata and Gilmore were plotting colour-magnitude-velocity diagrams during their study of the Galactic Bulge (Ibata & Gilmore 1995a, 1995b). While this discovery certainly activated the field (though the forthcoming 2MASS and SDSS surveys would have made the same discovery through traditional photometric, rather than phase-space, techniques) the reason it was possible seems not to have been fully appreciated by those attempting to emulate the discovery: Sgr was found because its stellar population is very different from that of the Galactic bulge or the Galactic halo. It is an intermediate age and intermediate metallicity population, and is unique in that respect.

One (should have) immediately deduced that Sgr was a rare event, not a paradigm for the average (see Unavane, Wyse & Gilmore 1996). The outcome of a truly impressive and truly vast amount of work since its discovery mapping
the distribution of Sgr-related debris trails around the Galaxy has reinforced this early conclusion: while much of Sgr is strewn around the Galaxy, nothing else like it has left any trace of its demise in the last Hubble time. Except, of course, the Thick Disk (Gilmore & Reid 1983), whenever that got into place.

Figure 2. Element ratio data (LHS) and kinematic correlations (RHS) in metal poor stars in the Galactic halo. These figures are from Gratton etal 2003.

3. The chemical elements as archaeological tracers

The recent surveys which have delivered the most quantitative information on Galactic history are those which provide high-precision elemental abundances for many stars. There are many such recent surveys since the arrival of 8m telescopes with excellent echelle spectrographs, with many more due to be published soon. These range from studies of the most extreme metal-poor stars, through the ‘halo’, ‘thick disk’ and ‘thin disk’ metallicity ranges, with only the Bulge and inner disk still awaiting useful statistics. The bulge and inner disk studies are especially needed, since the common (modellers’) presumption that ‘the average star forms in a disk, and then merges into a spheroid’ merits a check.

The results from these studies are outstanding science, and provide information which must be considered fully in any discussion of Galaxy formation and evolution.

The common feature to all studies is the extremely well-defined pattern of element ratios, spanning huge dynamic ranges. One example is shown in Figure 2, taken from a superb study by Gratton etal 2003. This figure shows the common result: different stellar population show smooth systematic element ratio patterns across very wide dynamic ranges.

The systematic chemical abundance patterns evident here, and the different systematics between different stellar populations, provide undisputable evidence that the formation of the field stars which are today in the Galactic halo happened in a single environment, or a range of environments, in which the rate of star formation, the rate of mass loss and the rate of chemical enrichment had an
extremely small range. No one has yet suggested how this is possible if indeed the halo is built up over time from a large number of systems with uncorrelated histories.

Other recent studies extend this conclusion to the stars of the thick disk and the old thin disk.

![Figure 3](image)

**Figure 3.** The dissolving globular cluster Pal5 is creating phase space structure in the Galactic halo which is unrelated to merger histories. Some hundreds of similar phase-space structures are expected to exist, all equally unrelated to mergers.

4. **Merger rates**

Mergers happen. The Hubble-Toomre sequence is built that way.

The Sagittarius dwarf is direct evidence. In M32 the debris from the stripped elliptical M32 has recently been observed directly, decades after its prediction. The Magellanic Stream exists. It is possible that a further debris remnant has been discovered at low latitudes, although at the time of writing the ‘normal’ complex structure of an outer warped disk is a more likely explanation of the observations. Similarly, speculations that structures, such as clusters, could be trapped into the Galactic disk from a ‘merger parent’ need to treated with some caution. The depth of a potential scales as the square of its velocity dispersion, Thus the Galactic halo potential (dispersion ∼100km/s) is an order of magnitude deeper than that of the disk (dispersion ∼30km/s). Trapping something into the outer disk is not an obvious dynamical process without very special geometries, and adroit use of dynamical friction.
Is Sgr all there is?

Phase space structures are not an indication of mergers. The most dramatic local phase-space structures are spiral arms, Gould’s belt, and star-formation regions. Even in the halo, very considerable phase-space structure must exist even if there has never been a single merger in the Hubble time.

Globular clusters evolve, and evaporate eventually. It is often speculated that many hundreds of dissolved globular clusters exist in the halo. A globular cluster, Pal5, has recently been observed in the final stages of dissolution (Odenkirchen et al 2003) and is shown in Figure 3.

The same limits on accretion histories which can be deduced from the difference of the stellar populations of Sgr, and are quantified for field stars by Unavane, Wyse and Gilmore (1996), can be applied to other tracers. The severe difficulty of hiding stars with different enrichment histories in the element ratio data is noted above. One may do the same thing for globular clusters. Bellazzini and collaborators are extending the census of former members of Sgr utilising that fact that Sgr stellar populations are different from field stars. One may do the same slightly more generally.

Figure 4. The size distributions of the various population types of Galactic globular clusters (LHS) and the old clusters in Galactic satellites (RHS). These data are from Mackey & Gilmore 2003a, 2003b, 2003c.

Figure 4 shows the size distribution (core radii, from of the different groups of Galactic globular clusters, and those old clusters in Galactic satellites. Most clusters in Galactic satellites are young, thereby trivially excluding any (non-Sgr) mergers in the last $\sim$6-8Gyr with anything resembling anything which exists in the Local group now, or its precursors. Even older mergers are interesting in this context: the only Galactic globulars which are consistent, on size grounds, with having arrived in a merger are the few younger ones, including those associated already with Sgr.

Once again, we conclude that mergers with sufficient mass to perturb the history of the Galaxy in an observable way must be rare in recent times.
Figure 5. Kinematics of the thick disk in situ. The mean rotation velocity about the Galaxy, $V \sim 100\text{km/s}$ of field stars is significantly less than expected from local studies, indicating perhaps that the (merger?) origins of the thick disk are amenable to direct study. This figure is from Gilmore, Wyse & Norris 2002.

5. **Field star kinematic surveys: much still to learn**

Kinematic surveys of field stars in the Galaxy remain as rare as is evidence for multiple mergers in the Milky Way. Each of the few attempted has made significant discoveries (eg SDSS) which should be an encouragement. One for which the first results have recently been reported indicates the discovery potential. Gilmore, Wyse and Norris (2002) report first results from a survey using 2dF
Figure 6. The Hubble-Toomre sequence: mergers matter, at least in life-changing situations. But how often and when in daily existence is less clear. This figure is a jpg file

on the AAT, their first results are summarised in Figure 5, and show significant disagreement with expectation.

The mean star a few kpc from the Plane has angular momentum intermediate between that of the halo and the thin disk. This argues strongly for an independent origin, and is consistent with - but does not require - a merger origin.

6. Conclusion

Mergers happen. The Hubble-Toomre sequence is built that way (Figure 6).

This is an age of surveys. We are learning to process and distribute vast data volumes. We are learning to extract astrophysics. While fashions still reign in interpretation, the story in the data is there to be read: it tells the story of Galaxy formation.

References

Arnold, R., Gilmore, G 1992 MNRAS 257 225
Cimatti etal 2002 A+A 391 L1 2002
Cimatti etal ESO Messenger, March 2003, No. 111, p. 29.
Freeman, K., Bland-Hawthorn, J., 2002 ARAA 40 487
Fuhrmann, K. 2004 Astr Nachr 325 1
Gilmore,G., Reid, I.N 1983 MNRAS 202 1025
Gilmore, G.; Reid, N.; Hewett, P. 1985 MNRAS 213 257
Gilmore, G., Wyse, R., & Norris, J. 2002 ApJ 574 L39
Gilmore, G., Wyse, R., & Kuijken, K. 1989 ARAA 27 555
Gould, A. 2003 ApJ 529 L63
Gratton etal 2003 2003A&A 406 131
Ibata, R., Gilmore G 1995a MNRAS 275 591
Ibata, R., Gilmore G 1995b MNRAS 275 601
Ibata, R., Gilmore, G., Irwin, M. 1994 Nature 370 194
Ibata, R., Gilmore, G., & Irwin, M. 1995 MNRAS 277 781
Kormendy, J., & Djorgovski, G., 1989 ARAA 27 235
Mackey, D., & Gilmore, G. 2003a MNRAS 338 85
Mackey, D., & Gilmore, G. 2003b MNRAS 338 120
Mackey, D., & Gilmore, G. 2003c MNRAS 340 175
Nordstrom, B etal 2004 ' the Geneva-Copenhagen survey of the Solar neighbourhood, A+A 2004 in press
Odenkirchen. M., et al. 2003 Astron. J. 126 2385
Sandage, A., Lubin, L., VandenBerg, D., PASP 115 1187 2003
Unavane, M., Wyse, R., & Gilmore, G. 1996 MNRAS 278 727
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