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Galactic History: Formation & Evolution

J. Bland-Hawthorn[1] & K.C. Freeman[2]

[1] Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia
[2] Mount Stromlo and Siding Spring Observatory, Private Bag, Woden, ACT 2611, Australia
e-mail: jbh@aao.gov.au

Abstract. We explore the motivation behind large stellar surveys in Galactic astronomy, in particular, surveys that measure the photometric, phase space and abundance properties of thousands or millions of stars. These observations are essential to unravelling the sequence of events involved in galaxy formation and evolution, although disentangling key signatures from the complexity continues to be very challenging. The new data will require major advances in our understanding of stellar atmospheres, stellar chemistry, the dynamics of the Galaxy and the Local Group.

Key words. Stars: abundances – Stars: kinematics – Stars: Population III – Galaxy: abundances – Galaxy: kinematics – Cosmology: observations

1. Galactic Surveys – Why Bother?

In this Joint Discussion, we explore the motivation behind large surveys in Galactic astronomy. We focus our attention on surveys that measure the photometric, phase space or abundance properties of individual stars. In recent years, we have seen the release of optical and infrared all-sky photometric catalogues for $\sim 10^8$ stars (SDSS: Gunn et al 2001; 2MASS: Cutri et al 2003), and new astrometric catalogues from the Hipparcos satellite and the US Naval Observatory (UCAC2: Zacharias et al 2004). The first major kinematic stellar survey of roughly 15,000 stars was recently completed by Nordstrom et al (2004), with two new much larger surveys now under way (RAVE: Steinmetz et al 2006; SEGUE: Rockosi 2005). There is on-going discussion of extending these million-star surveys to 8m class telescopes early in the next decade (WFMOS: Colless 2005). At that time, the European Space Agency is set to launch the Gaia astrometric satellite with a view to establishing phase space information for a billion stars (Perryman et al 2001; Wilkinson et al 2005). But why go to all this trouble?

Increasingly, we are required to defend big survey machines with rigorous and compelling science cases, and these must be argued carefully within the context of ”Big Questions” that are posted on the web sites of major funding agencies. In fact, it is probable that only one of these questions bears directly on galactic stellar surveys – the formation and evolution of galaxies. But here, a good case can be made, as we discuss below.

It is no exaggeration to say that the study of galaxy formation and evolution will dominate observational cosmology and galactic studies for decades to come. This is because it is difficult to define a unique model for galaxy formation, assuming one even exists. A theoreti-

Send offprint requests to: J. Bland-Hawthorn

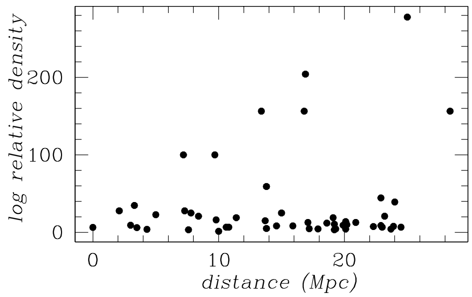

Fig. 1. The dependence of group density with distance from a sample of 50 galaxy groups taken from Tully (1987). Most groups are much like the Local Group in their average density.

cal astrophysicist may be content to establish the existence of galactic ”building blocks” at high redshift, and to demonstrate that numerical simulations can explain the properties of these objects, and the basic properties of galaxies at all epochs to the present age. But an applied physicist may argue that this is far from a complete picture where all of the salient microphysics is demonstrated self-consistently.

We have long known that galaxies form over cosmic time through the gradual build-up of dark matter and baryons within a vast hierarchy. This process, which can be studied in the near and far field, is likely to depend in part on the mean density field in the vicinity of the coalescing galaxy (e.g. Maulbetsch et al 2006). There are recent claims that large photometric surveys of galaxies argue against strong environmental factors (Blanton et al 2006), but this influence will be much clearer once the individual components are properly resolved.

In the near field, the Local Group is a relatively low-density region of the Universe; to study galaxies over a wide dynamic range in density contrast will require that we push our stellar surveys out to Virgo, something that is only conceivable with 30-40m class telescopes and the James Webb Space Telescope (JWST). This is made abundantly clear in Fig. 1 where we show the mean density of the 50 nearest galaxy groups.

The environmental dependence is not something that can be established easily in the far field much beyond the well known distinction of evolved galaxies in virialized clusters and generally younger stellar ages in the filaments between clusters (cf. Cucciati et al 2006). But a fact well known to galactic astronomers is that essentially all galaxies show evidence of an underlying old stellar component, something that is difficult to resolve out in the far field.

There are numerous ways in which large-scale stellar surveys can provide fundamental insight on the process of galaxy formation. But first we review what has been learnt in recent years.

2. What recent surveys have revealed

2.1. Resolved stellar populations

Even in an era of Extremely Large Telescopes (ELTs), we will only be able to resolve individual stars and stellar populations out to Virgo (Local Volume), but this may be enough to ultimately unravel the processes involved in galaxy formation, particularly when supported by observations of the high-redshift universe. Some of the most revealing insights have come from the Local Group with its two dominant rajahs and numerous courtiers. The Galaxy and M31 have comparable mass, and show evidence of substructure in most stellar components (e.g. Juric et al 2005). Both have extended disks and stellar haloes, although the former has a small bulge, while M31 has a prominent bulge.

Some of the most remarkable observations have come from the Hubble Space Telescope (HST) which targetted the spheroid, outer disk and the major tidal stream in M31 (Brown et al 2006). All fields of view were found to have an extended star formation history, with most stars being in the age range of 4 to 10 Gyr. The inner spheroid is intermediate age (6 – 9 Gyr) and metal rich and slightly older than the Stream, and may well comprise mostly stream material. This is in stark contrast to the mostly old Galactic spheroid. The outer disk in M31 is younger (4 – 8 Gyr) but still older than the thin disk population in the Solar neighbourhood.

Resolved stellar population studies are now achieving much fainter effective surface brightness levels than are possible with observations of diffuse stellar light. The disks in M31 and M33 have been detected at $\mu_V = 30$ mag arcsec^{-2} and are seen to extend to more then 10 scale lengths. The metal-poor stellar halo in M31 is now thought to extend to at least 160 kpc (Guhathakurta et al 2005), i.e. a halo subtending 20° across the sky! The halo of M33 has now been detected and found to be comparable in metallicity to M31 and the Galaxy (McConnachie et al 2006), which is interesting in light of the fact that it has no detectable bulge. At the present time, stellar haloes have not been detected in either of the Magellanic Clouds (e.g. Gallart et al 2004).

2.2. Thick disks & outer disks

It is well established that the thick disk is 10−12 Gyr old and therefore provides us with an ancient snapshot of what took place in the early universe (q.v. Reddy et al 2006). A recent development is that thick disks may be relatively common in disk galaxies (Yoachim & Dalcanton 2005).

The character of the Galactic thick disk is now known to be distinct from the thin disk in essentially all measurable parameters. The dynamically hot population is characteristically older and more metal poor than the thin disk, with an unexpectedly strong rotational lag. There may be evidence that the thick disk has a longer scale length (Robin et al 1996) and a distinct abundance gradient (Brewer & Carney 2006).

Beyond the Local Group, the closest galactic disk is NGC 300 at a distance of 1.95±0.05 Mpc. This galaxy is a virtual twin of M33 but showing a different behaviour in the outer parts. The red stellar disk is exponential over 10 scale lengths with no evidence for a truncation of any kind (Bland-Hawthorn et al 2005). In contrast, M33 shows dramatic truncation close to the Holmberg radius with no evidence of tidal streams (see below), quite unlike its dominant neighbour.

Pohlen & Trujillo (2006) have obtained SDSS photometry on 90 galaxies to find that 60% truncate in the outer parts, 10% remain exponential to the limits of the data, and 30% appear to show flattening in the outermost parts. While these data do not reach the same effective surface brightness as the resolved stellar surveys, it is clear that outer disks are telling us something important about the build-up of disk material over billions of years. The picture is not as tidy as we used to imagine (e.g. Fall & Efstathiou 1980).

2.3. Abundance patterns and gradients

Stellar abundances are discussed by S. Feltzing; the discussion here is limited to a few key points. The Hipparcos survey has allowed a very clean kinematic separation of the thick disk from the thin disk (Bensby et al 2005; Reddy et al 2006). This has revealed a very clear distinction between the chemistry of the thick and thin disk, particularly in the α elements.

By now, we are used to the idea of nebular abundance gradients in spiral galaxies determined from HII regions. In contrast, stellar populations can be aged and these appear to show an overall abundance gradient that is flattening with time. For example, open clusters appear to show that the Galactic abundance gradient was -0.1 dex/kpc 8 Gyr ago, softening to -0.04 dex/kpc at the present day (Daflon & Cunha 2004; Salaris et al 2004). This may be consistent with new evidence of young metal-poor cepheid variables in the outer disk (12−17 kpc) with enhanced [α/Fe] and [Eu/Fe] (Yong et al 2006), suggestive of recent accretion. An interesting new development is spatial abundance *maps* for a single population (e.g. Luck et al 2006).

Elemental abundances have long been argued as a key constraint on the accretion history of satellites onto the Galaxy (Unavane, Wyse & Gilmore 1995). A new development is the concept of chemically tagging stars to a parent population from the element abundance patterns (Freeman & Bland-Hawthorn 2002; Bland-Hawthorn & Freeman 2004). The basis for tagging is that stellar clusters are highly uniform in certain chemical elements (e.g. De Silva et al 2006). has now been demonstrated for the moving group HR 1614 originally identified by Eggen. What is remarkable here is that HR 1614 covers most of the sky which has led others to question the integrity of Eggen's group. In an era of Gaia, chemical tagging will be enormously powerful in that it will provide an independent confirmation of the integrity of a stellar group, or allow us to disentangle cells in phase space.

Simulations show that dwarf galaxies spiral into larger ones, where they are torn apart to produce the star streams observed in the big galaxies. But the patterns of heavy elements from UVES observations at the VLT (DART: Tolstoy et al 2003) indicate that no major component of the Galaxy could have been assembled largely by accretion of dwarfs of the kind observed today. M31 and the Galaxy could have formed by merging of dwarfs in the early universe; the curious thing is that the dwarfs that were left behind to be observed as dwarfs today have to be substantially different (Robertson et al 2005).

2.4. Substructure & streams

This topic is discussed by A. Helmi so we limit our discussion here. One of the major developments since the mid 1990s is the discovery of the infalling Sgr dwarf (Ibata et al 1994) from radial velocity observations at the AAT, using stellar identifications towards the Galactic bulge identified in UK Schmidt plates. This was the first detection of a disrupting galaxy within the orbit radius of the Magellanic Stream which led to a resurgence of interest in Galactic studies. Since then, other streams have been identified by the SDSS and 2MASS surveys although these may be associated with either the Sgr stream (Newberg et al 2003) or the outer disk (Ibata et al 2003).

We have become used to hearing about substructure out of the plane, but the Hipparcos survey reveals kinematic substructure even within the thin disk (Dehnen 1998; Fux 1997). The ages of individual clumps are quite distinct (Famaey et al 2005) such that they are likely to be dynamical in origin rather than due to patchy star formation.

The overlap of the Hipparcos survey with the Geneva-Copenhagen survey allowed Navarro et al (2004) to identify a possible moving group associated with Arcturus. They suggest an infalling group $\sim$ 8 Gyr ago. This shows the potential for astrometric surveys used in combination with wide-field kinematic surveys.

Interestingly, the SDSS has identified complex substructure in the thick disk (Juric et al 2005). Tomographic slices through the galaxy were obtained using photometric distances. Gilmore et al (2002) observed 2000 F/G stars with the 2dF at the AAT that were chosen to extend to high Galactic latitude. They found that the rotation of the thick disk is half the expected value of 180 km/s. A possible interpretation is that the thick disk arose from a satellite merger 10–12 Gyr ago.

Looking further afield, wide-field observations from the INT reveal complex system of streams in the outer disk of M31 (Ibata et al 2005), something that is not seen in M33 (Ferguson et al 2006). That these are discrete subcomponents has now been confirmed kinematically using LRIS on the Keck telescope (Chapman et al 2006).

3. Future surveys

3.1. The case for extending beyond the Local Group

The observations to date provide evidence of a complex tapestry that is only now coming into focus. We will need to study this tapestry in far more detail before we can begin to unravel its origins, and the processes by which it came into being. In the next decade, it will be possible to study the star formation histories in hundreds of nearby galaxies, both in dense and loose groups, and for distinct galactic subcomponents. With these observations, we can choose to compare individual galaxies, or compare the volume-averaged star formation histories between groups in order to answer these questions.

One thing is clear: we must extend these large-scale surveys beyond the Local Group, particularly in an era of ELTs and JWST (see

§1). These telescopes promise diffraction limited performance in infrared bands, which is good news for crowded fields. But we will also need optical bands for metallicity sensitivity in warm stars. We will need to reach down to the main-sequence turn-off to derive accurate ages. Remarkably, high Strehl ratios may not be required in crowded fields (Olsen et al 2003). But just how well can one achieve accurate photometry when using adaptive optics in long exposures? It is hard to guess at what the future has in store without an answer to this troubling question.

3.2. The origin of the thick and thin disk

Freeman & Bland-Hawthorn (2002) argue that establishing a theory of galaxy formation is largely about understanding the processes involved in forming disks in the early universe. The ancient thick disk is a particularly attractive target because it takes us back to an early epoch when large disks were forming for the first time.

The origin of the thick disk remains controversial. Various scenarios have been suggested: (i) snap-frozen relic of the old thin disk heated by an ancient merger event; (ii) material from one or more major merger events; (iii) dissipational collapse; (iii) the byproduct of unbound star clusters in the early universe (Kroupa 2002). Interestingly, Elmegreen & Elmegreen (2006) measure the scale heights of large star forming complexes in the Hubble Ultra Deep Field (HUDF) and find these are broadly consistent with the thick disk, in support of Kroupa's model.

We often think distribution functions of dominant stellar components as being smooth for the most part. But is that really true in practice? In light of Juric et al (2005), important clues on disk formation may be revealed in the substructure. Simulations by Abadi et al (2003) suggest that substructure could survive throughout the disk, presumably because much of this material spends much of its time out of the plane. Strong scattering near resonances may wash out some of the substructure, but equally one can imagine fossil structures that are trapped in resonances.

In §2.2, we discussed new results on the disks of spirals. Does the extent and the specific angular momentum of the outer stellar disk reflect certain properties of the collapsing protocloud? If the answer is no, then is the outer stellar disk still forming? If the answer is yes, what is the origin and role of the HI that extends beyond the stellar disk in most instances? Where stellar disks are seen to extend far into the HI, the inferred Q values are much too high to form stars, so how is this possible?

In our view, a major shortcoming of contemporary Galactic studies are accurate stellar ages, especially on timescales of billions of years. One can envisage experiments to rectify this problem for $\sim 10^5$ stars, an issue we discuss elsewhere (Freeman & Bland-Hawthorn 2002). The present resurgence of interest in open clusters is partly due to the prospect of a decent age for the stellar ensemble. As a result, the chemistry of stellar clusters may allow us to determine how large-scale enrichment took place in the Galaxy over cosmic time. Early results seem to indicate that the chemical gradient today is flatter than it was 10 Gyr ago (§2.3). An alternative scenario to gradual disk accretion is that Galaxy-wide enrichment events from the nucleus has gradually built up the chemical elements in the outer disk, much like a volcano building up its ramparts from successive events over many dynamical times.

3.3. The origin of the bulge and halo: ancient stars

An area of intense future interest is expected to be the spheroidal components of M31 and the Galaxy. Just how did these form and what is their relation to the rest of the galaxy? The highest resolution simulations tell us that we can expect to find far more evidence of substructure throughout the inner 10 kpc or so (Gao & White 2006). These surveys are likely to turn up an ancient stellar populations over the entire metallicity spread, from ultra metal poor to extremely metal rich stars.

A rare population of ancient ultra-metal-poor stars in the Galactic halo provides critical information on the chemical yields of the first generation of massive stars (Beers & Christlieb

2005; Tumlinson 2006). Larger concentrations of ancient stars may be hiding in the centres of galaxies where the mass density is high and conditions likely first favoured star formation. Future instruments will search for these ancient stars, but once again, dealing with crowding and dust obscuration will require a high spectroscopic resolution, near-diffraction limited spectrograph working at infrared wavelengths.

A new generation of multi-object survey instruments will be critical to unravelling some of the biggest questions in modern cosmology today. In addition to the fully-funded Gaia mission in 2012, the Japanese are expected launch the JASMINE explorer in 2015 to obtain infrared astrometry on 10 million bulge stars (Gouda et al 2005). Seidelmann & Monet (2005) summarise a number of related missions in the next decade. There is a great deal to be learnt on the nature of galaxies from explorations of this kind.

4. The importance of a dynamical framework for the Galaxy

It is tempting to think that the billion-star Gaia survey will be the final word on Galactic studies. However, the effective spectroscopic magnitude limit of Gaia is only $V<17$, equivalent to a G dwarf at a distance of 6 kpc in the absence of dust. We can go much deeper than this with large-ground based telescopes. Such observations will be essential if we are to extract chemical information over a large volume of the Galaxy. Future ground-based optical and infrared surveys will likely map the Galactic bulge and provide a self-consistent model for the bulge and bar. Deep pencil beam surveys towards dust-free inner windows will establish the strength and orientation of the spiral arms, and allow us to correct the rotation curve (and Oort's constants) for streaming motions.

A self-consistent dynamic model of the Galaxy is essential in understanding the smooth underlying potential. Once we have established the basic parameters reliably, we can revisit the distribution of dark matter within the Solar Circle and beyond, an essential piece of information if we are to reproduce the main features of the Galaxy from ΛCDM simulations. The kinematics of the outer halo stars will ultimately constrain the shape and figure rotation of the dark matter halo.

Binney (2004) has highlighted the need to get ready for the impending data revolution. Now that Gaia is fully funded, the case is even more compelling. Binney makes clear that we need a consistent multi-component model that can be modified to give a better fit as data become available. To complicate things further, we suspect that these models may need to take on board the fact that the Galaxy is not in dynamical equilibrium, and therefore to think in the wider context of the Local Group. This may become possible with improved 3D space motions of individual galaxies (Brunthaler et al 2006). Finally, Binney's vision considers only the phase space information when in fact the chemical space is likely to be equally unwieldy (Bland-Hawthorn & Freeman 2004).

5. Testing CDM in the non-linear regime

Wide-field surveys have been highly successful in testing ΛCDM in the linear regime to the extent that future surveys have been proposed to explore the nature of dark energy (Seo & Eisenstein 2003). We can now extend this powerful methodology to resolved studies of galaxy formation and evolution over cosmic time.

Computer simulations of how the Big Bang unfolded over 13.7 Gyr to yield present-day galaxies can involve up to 10 billion particles. These computations yield structures that look a good deal like real galaxies and clusters of galaxies, adding to the evidence that our picture for the evolution of the universe is on the right track. But close examination of nearby galaxies shows discrepancies with what the simulations might lead one to expect. For example, CDM models predict higher concentrations of dark matter than is believed to exist in the high surface-brightness cores of galaxies. Some of the best evidence to date has come from attempts to construct self-consistent models of the Galactic bulge (for a progress report, see Binney [2004]). A key conclusion is that baryons dominate everywhere within the Solar Circle, in sharp conflict with almost all CDM simulations.

A more sensitive test of the CDM model however requires that we greatly increase the kinematic samples in galaxy cores beyond the Galaxy (Gilmore et al 2006). Thus, future wide-field and pencil-beam Galactic surveys will be necessary in order to continue to challenge CDM calculations in the non-linear regime.

6. A complete theory of galaxy formation?

Inevitably, when we find ourselves swimming in a sea of complex data, one begins to worry about fundamental limits of knowledge. But in many applied fields, important clues to fundamental physics often emerge from complex data, particularly when complex physical processes are at work (cf. beam-line experiments in particle physics). In fields where we are far from understanding key physical processes, as in the study of galaxy formation and evolution, this effort must be worth it.

Astronomers now recognize this: every large survey has unveiled new lines of enquiry or revealed something important about our environment. We talk in terms of data mining, virtual observatories, and so forth. Furthermore, the numerical simulators push down to ever decreasing scales, and work to include new algorithms that capture an important process.

At what stage do we declare that galaxy formation is basically understood? Such a declaration becomes possible when one is able to reproduce the salient features of galaxies today, in a host of different environments, with a theory that is firmly rooted (presumably) in ΛCDM. This same axiomatic theory should be able to reproduce observations of galaxies at different epochs out to high redshift, until we reach an epoch where objects no longer look like modern day galaxies. The HUDF indicates that this appears to happen at about $z \approx 2$.

A moderately complete theory of galaxy formation must also tell us whether the Galaxy is typical or unusual in any way. It is often stated that if the Galaxy is pathological, it is hardly worthy of the attention we give it. But in fact, recent observations by R.B. Tully and collaborators suggest that ”Local Group” collections of galaxies are common throughout the local universe (see Fig. 1). Therefore, it would be a surprise to discover decades from now that our large-scale surveys were seriously misleading us in our quest to understand galaxy formation and evolution.

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