Deciphering Galaxy Formation with Resolved Stellar Populations

Rosemary F.G. Wyse

Physics & Astronomy Department, Johns Hopkins University
wyse@pha.jhu.edu
Phone: (410)516-5392

Co-authors: Tim Beers (Michigan State); James Bullock (UC Irvine); Katia Cunha (NOAO); Arjun Dey (NOAO); Jon Fulbright (JHU); Kathryn Johnston (Columbia); Heidi Newberg (RPI); Knut Olsen (NOAO); Connie Rockosi (UCO Lick); Verne Smith (NOAO)

Abstract

Resolved stellar populations contain a wealth of information constraining both mass assembly of galaxies and the star formation history. We propose the aquisition and analysis of large datasets of chemical elemental abundances and radial velocities of stars in galaxies of the Local Group, with the aim of deciphering the physics of galaxy formation. Low-mass stars live for essentially a Hubble time at the present epoch, and thus trace the evolution of stellar populations back to their formation. Analysis of the fossil record in old stars nearby is complementary to observations of high-redshift systems, and has the capability of breaking degeneracies inherent in analysis limited to integrated spectra or integrated photometry of unresolved systems. For this to be achieved, large imaging surveys should be complemented by large spectroscopic surveys at both medium and high resolution.

1. Introduction

The origins and evolution of galaxies, such as our own Milky Way, and of their associated dark matter haloes are among the major outstanding questions of astrophysics. Particularly in the context of hierarchical clustering scenarios for structure formation, the mass-assembly history of a galaxy and the star-formation history of a galaxy may be rather different. The mass-assembly history will be dominated by the merger history, largely determined by the nature of the dark matter that dominates the overall potential well of galaxies. The star-formation history will be determined largely by the supply of self-gravitating cold gas, itself controlled by the physics of gas-cooling, the gas content of merging entities, and the 'feedback' of energy and momentum from stars into gas.

While hierarchical clustering, Cold Dark Matter-dominated models – in particular those including the effects of dark energy, i.e. the 'concordance' ΛCDM – have found considerable success in describing the large-scale structure of the Universe, several potential problems with this scenario have arisen on scales of galaxies and their satellites. These problems include there being too many predicted satellite haloes compared to observed satellite galaxies in the Local Group, (Moore et al. 1999; Klypin et al. 1999), a problem that persists even with more satellites being discovered in the Sloan Digital Sky Survey images (e.g. Willman et al. 2005; Belokurov et al. 2006a,b, 2007; Grillmair 2006; Koposov et al. 2008; Tollerud et al. 2008). Current observational constraints on the mass function of satellites and the inferred density profile of the dark matter halo are a poor match to predictions (e.g. Gilmore et al. 2007; Strigari et al. 2008). Further, the models predict too much late merging, and associated angular momentum transport and heating, for extended disk galaxies to form (e.g. Navarro & Steinmetz 1997) and for disk galaxies to host exclusively old thick disks (Wyse 2001; Stewart et al. 2008).

The proposed solutions to these problems maintain the nature of dark matter and instead invoke a variety of astrophysical processes to alter the predicted properties of galaxies. For example, "feedback" processes (i.e., gas heating, cooling, shocks, etc., associated with star formation, star death and AGN) are invoked to modulate the star formation histories of galaxies (e.g. Robertson et al. 2006, Governato et al. 2007). Such solutions, while solving some of the discrepancies, generally create other contradictions with observations. The physics by which these proposed feedback mechanisms suppress star formation will leave behind observational signatures in the elemental-abundance ratios and kinematics of the stellar populations that form under their influence. In local galaxies we can isolate the rare and sparsely distributed oldest stars and use their individual properties to test predictions for the evolution of the nascent Local Group.

The most extreme feedback has been proposed for the lowest-mass systems, suppressing star formation after an initial burst (e.g. Bullock et al. 2001) in order to reconcile the observed satellite galaxy populations of the Milky Way and M31 with predictions (Koposov et al. 2008 and references therein). It is not clear whether the impact or physics of "feedback" in the models is compatible with the observed stellar populations.

These are exciting times to study local galaxies, due to the confluence of capabilities in three approaches to galaxy formation and evolution: (i) surveys of high-redshift systems are now quantifying the stellar populations and morphologies of galaxies at high look-back times. (ii) Ever larger, high-resolution simulations of structure formation (presently limited to ΛCDM cosmologies) are allowing predictions of the formation of galaxies like the Milky Way, in a cosmological setting. (iii) Large – panoramic – observational surveys of stars in Local Group galaxies are now feasible, using wide-field imagers and multi-object spectrographs.

Detailed study of the zero-redshift Universe provides complementary constraints to those from direct study of the integrated light from high-redshift objects. Observations of the high-redshift universe provides constraints on the macroscopic (or globally averaged) properties of galaxies, and in some cases the ability to directly observe "feedback" processes at work, but it is really in the local fossil record that we can hope to determine the role of these phenomena in the formation of our Milky Way and Local group neighbours. It is only locally that one can ever map the real three-dimensional distribution of dark matter, and break age-metallicity degeneracies in stellar populations, or constrain the past massive-star Initial Mass Function through elemental abundances, and the low-mass IMF by star counts. One can extract not only the history of the baryons, but infer much about the dark matter that dominates gravity on the scale of galaxies. Current theories predict statistically what the 'typical' galaxy of a given mass should have experienced over time, and the properties of its stellar populations now. Any theory in which the galaxies of the Local Group are very unusual should be revised.

2. Observational Determination of Galaxy Evolution

How might one trace galaxy evolution using the fossil record in stars nearby? To quote Binney & May (1986) 'Galaxies, like elephants, have long memories.' Since the seminal paper of Eggen, Lynden-Bell & Sandage (1962) the importance of the joint distributions of kinematics and chemical abundances have been recognised. A second lasting influence of that work was the emphasis on the importance of identifying (approximately) conserved quantities. A third was the subsequent realization of the importance of being able to understand, and correct for, sample selection effects. A corollary is the limitation of small samples. Much physics lies in the detailed *shape* of the distributions, not just the low moments (mean, dispersion) which is all small sample sizes constrain. The ideal dataset would thus consist of chemical abundances and motions for large samples of stars, selected without bias in either metallicity or kinematics, in galaxies of as wide a range of Hubble Type as possible. The Local Group provides two large disk galaxies, the Milky Way and M31, one small disk galaxy (M33; its very small bulge being a particular challenge for ΛCDM) and numerous gas-rich and gas-poor satellites.

What are the observable quantities that are conserved, even through hierarchical clustering? In a merger, the orbital energy is absorbed into the internal degrees of freedom of the merging systems. Stars that are removed by tides from satellite systems remain on orbits close to that of the center-of-mass of the satellite galaxy at the time of removal. Orbital angular momentum is often an approximate integral of motion (conserved over long times) and thus accreted, 'former-satellite' stars may well have a signature in their azimuthal streaming velocity, and allow the orbit of the parent satellite galaxy to be traced. The chemical composition and time of formation of a star are other conserved quantities that persist through dynamical processes in galaxy evolution. The star-formation history and gas flows into/out of a system (plus the massive-star IMF) determine the pattern of chemical-elemental abundances and stellar-age distribution in that system (see e.g. the review of Wyse 2008). In general this leads to patterns in dwarf galaxies that are distinct from those of the stars formed in larger galaxies, since the star-formation histories are different. 'Assimilated' satellites may be traced by distinct patterns of elemental abundances and kinematics, and indeed, the potential well depth in which stars formed may be constrained by these patterns. Different models of disk formation and evolution also predict different distributions and radial gradients.

Thus the merging history of a galaxy, together with its star formation history, and mass re-arrangement (such as gas flows or stellar radial migration) is written in its structure, stellar ages, kinematic and chemical-elemental abundance distribution functions, with angular momentum particularly important. The critical observational inputs to constrain the theory of how a typical disk galaxy forms and evolves may be obtained by wide-field spectroscopic studies, at both high- and medium-resolution, of large samples of stars in dynamically old components in Local Group galaxies.

The merging history in turn is determined largely by the nature of dark matter (and statistics, but we have no reason not to assume that the Local Group members are typical). Complementary constraints on dark matter come from dynamical analyses of the stellar motions. Having a large enough sample to include statistically significant numbers of stars with extreme orbits, such as high-velocity, or with very distant apoGalacticon, is critical in this regard. For example, determination of the local escape velocity requires the determination of the velocity distribution function close to the cut-off velocity (see Smith et al. 2007 for an analysis of the high-velocity stars in the RAVE dataset), and motions of faint, distant stars are required to provide probes of the potential in the outer Galaxy (see Xue et al. 2008 for an analysis of distant BHB stars from the SDSS). Line-of-sight velocities for member stars in dwarf spheroidal galaxies can be analysed to determine the underlying mass profile, provided sample sizes are large enough and cover the entire radial extent of the system (e.g. Gilmore et al. 2007). With sufficiently large samples (thousands of stars, meaning that one must use intrinsically faint stars in low luminosity systems) analysis of the full line-of-sight velocity distribution can be used to break the degeneracy between velocity dispersion anisotropy and mass (e.g. Gerhard 1993).

3. Current Understanding of Local Group Galaxies

3.1 The Milky Way

The deep, wide-area imaging from the Sloan Digital Sky Survey has revitalized the field of Galactic structure. Dramatic results such as the 'Field of Streams' (Belokurov et al. 2006a) has shown that the high-latitude stellar distribution is far from uniform, with structures ranging from newly discovered dwarf galaxies and star clusters (as mentioned above) to the very large-scale tidal streams from the Sagittarius dwarf spheroidal, and the enigmatic lower-latitude 'Monoceros stream'. The Milky Way Galaxy is clearly a very complex system.

Indeed, recent attempts to model the star counts from the SDSS have led to the speculation that the entire stellar halo could be composed of disrupted satellites (Bell et al. 2008), albeit that the vast majority of observed substructure in coordinate space, predominantly in the outer Galaxy where mixing timescales are long, appears to be due to the Sgr dSph (is this compatible with predictions of ΛCDM?). However, analysis of the spectra of the wide-area, very sparsely sampled 'reddening calibration' F-stars observed to support the SDSS redshift survey rather finds distinct kinematic and metallicity distributions for only two components, the 'inner' and 'outer' halo (Carollo et al. 2007). Kinematics and chemical abundances are clearly critical to understand photometry, and a sample of stars with selection criteria specifically aimed to determine the unbiased properties of Galactic stellar populations (as opposed to calibrate a galaxy redshift survey) is needed.

Similarly, the SDSS star count data confirmed the distinct thin disk/thick disk spatial structure of earlier surveys (Juric et al. 2008), but the distributions of transverse kinematics (from proper motions and photometric parallax-based distance estimates) and photometrically derived metallicities have been interpreted in terms of just one disk, not two distinct structures (Ivezic et al. 2008). Spectroscopic metallicities would allow a more robust analysis – particularly since the photometric metallicities as derived have no stars, even in the thin disk, more metal-rich than -0.5 dex (Ivezic et al, their Fig. 7). The moderate spectroscopic survey of Gilmore, Wyse & Norris (2002), using the multi-object spectrograph on the AAT, suggests that even the thick disk has structure, perhaps due to an accreted dwarf. The global structure of the thick disk remains ill-determined.

The Monoceros Stream (Newberg et al. 2002; Ibata et al. 2003) is a feature in the outer disk of the Milky Way, and may represent accretion of material on high angular momentum orbits, perhaps an assimilated satellite (e.g. Penarrubia et al. 2005). It may, more prosaically, simply be a manifestation of normal non-axisymmetric structure in the outer region of the disk (e.g. Momany et al. 2006). Again, we are lacking the required large-scale spectroscopic surveys to place this structure in the correct context. Not only is the outer disk ill-understood, the transition between the inner disk and the bar/bulge is essentially unknown. This is particularly frustrating attempts to test models whereby the bulge forms from a disk instability.

Studies of the central bulge itself have focused on a few optical windows, and show a fairly uniform population, old and metal-rich (e.g. Fulbright, McWilliam & Rich 2007), with overall kinematics showing little signature of the triaxial bar. The transition between bulge and halo is very poorly mapped.

Elemental abundances, derived from high-resolution spectra, have great potential for isolating substructures, but present samples are limited to at most 100 stars, all of them within a few kiloparsec of the Sun. Differences between the details of the analysis from author to author unfortunately limit the usefulness of merging datasets. However, the existing data are consistent with a fixed massive-star IMF (see e.g. Gilmore & Wyse 1998) for all stellar components, and a short duration of star formation for the bulk of the stellar halo, the central bulge and the thick disk. Larger datasets of fainter stars would allow us to trace the star-formation history, and identify interlopers, over much of the Galaxy and beyond (with the next generation of telescopes).

3.2 M31 & M33

Deep imaging surveys of M31 were undertaken in the last decade by Ibata, Ferguson et al. using the Isaac Newton Telescope's Wide Field Camera (Ibata et al. 2001, Ferguson et al. 2002). By mapping the surface density of red giant branch (RGB) stars down to ~ 3 magnitudes below the tip of the RGB ($I \sim 23.5$) over a ~ 50 square degree area, the inner halo of M31 - where most previous studies had concentrated - was revealed to be polluted by copious low surface-brightness stellar debris. The most spectacular such feature is a coherent stellar stream that has now been mapped to more than 100 kpc in projection (Ibata et al. 2007) and is a tell-tale signature of the ongoing accretion of an intermediate-mass galaxy. That such accretion events are the norm in CDM models is reassuring, but to date there is little evidence to suggest any other significant accretion events have taken place over the last several gigayears. Indeed, a large fraction of the inner halo substructure has now been shown to be consistent with material torn from the stream progenitor during one or more pericentric passages, while the remainder matches predictions of disturbed portions of the M31 disk (e.g. Richardson et al. 2008).

A new wide-field photometric survey (PAndAs) with MegaCam on the Canada France Hawaii Telescope is mapping individual RGB stars in a 350 square degree region around M31 and M33 (the virial radius of M31) and reaches effective surface-brightness levels as faint as $\Sigma_V \sim 32 - 33$ magnitudes per square arcsec; star-count studies are the only way to probe the structure and content of these outlying parts.

Spectroscopic surveys of individual RGB stars, to derive kinematics and metallicities, have been initiated with Keck/DEIMOS but it has been a challenge to obtain significant samples of high-quality spectra and results from studies conducted so far have not always been consistent. While DEIMOS (and to a lesser extent, GMOS) will continue to probe the M31 environs in the coming years, the small FOV of the instrument (0.02 square degree) poses a significant challenge, rendering samples highly susceptible to contamination from localised substructures.

Small-number statistics really limit our current understanding of M33, where even the imaging surveys are just getting properly underway. To date, no high surface brightness coherent substructure has been observed in the outskirts of M33. McConnachie et al. (2006) have published Keck/DEIMOS spectroscopy for two fields in the outer regions of M33, lying at 9 kpc along the southern major axis. Three distinct kinematic components were detected, one of which is consistent with a pressure-supported halo with a velocity dispersion of 50km/s and [Fe/H]~ -1.5 dex. However this latter component was identified on the basis of only ~ 10 stars and clearly needs to be confirmed.

4. The Observational Requirements

Large spectroscopic surveys, enabling us to derive line-of-sight velocities and chemical abundances for statistically significant samples of stars across the galaxies of interest, are clearly required. Definitive surveys of resolved stars in Local Group galaxies require wide fields at high multiplex, for statistical power over a representative volume of the galaxies, and high throughput on 8-m class telescopes, in order to reach distances dominated by the old stellar populations. Surveys at both medium and high spectral resolution are required, ideally capable of delivering spectra over the entire optical wavelength range, from the Ca K line in the blue to the Ca triplet in the red (this last requirement coming from the need to measure stellar parameters and a range of chemical elements in a variety of spectral types).

Medimu resolution, $\mathcal{R} \sim 2000$, suffices to provide an overall metallicity to ~ 0.2 dex, a rough [α/Fe], and kinematics to ~ 10 km/s (demonstrated by e.g. SDSS and stellar surveys with 2dF and AAOmega, for a broad range of stellar spectral types). This allows a broad classification into thin disk, thick disk or halo, and the identification of candidate substructures. Assuming an 8m telescope, this is ideal to map M31 and M33, in RGB stars, with statistically significant samples in all fields, and also main sequence stars throughout the Milky Way.

High resolution, $\mathcal{R} \sim 30000$, provides kinematics to $\lesssim 1$ km/s and detailed elemental abundances to ~ 0.1 dex, again for a broad range of spectral types. The ability to measure abundances for elements made in different nucleosynthetic sites with different lifetimes provides resolution needed to map the chemical evolutionary history of galaxies. High resolution also provides the velocity accuracy required to map substructure, and the combination would give chemo-dynamical histories of the surviving Local Group galaxies and their progenitors.

Detailed simulations and analyses with multi-dimensional group-finding algorithms (Sharma & Johnston, in preparation; in support of a gemini/WFMOS conceptual design study, soon to be posted to astro-ph) have shown that samples sizes of $\sim 10^6$ stars, in a contiguous large area on the sky (of order 1000 square degrees for each of the high-resolution and medium-resolution surveys of the Milky Way, and hundreds of square degrees for M31/M33), is the optimal survey design, with the preferred geometry being a latitudinal strip for studies of the halo and thin/thick disks.

Current and near-future spectroscopic surveys will obviously make contributions, but none, with the exception of the primarily astrometric ESA mission GAIA, will be on the scale required to provide the required definitive dataset. RAVE (Steinmetz et al. 2006) is limited to apparently bright stars, $I < 12$, and is at an intermediate spectral resolution of $\mathcal{R} \sim 7500$), so that detailed elemental abundances are not possible (though this will be the definitive survey of the metallicity and kinematic distributions of the local disk). The SDSS/SEGUE surveys also lack a high-resolution mode, and are designed to identify, but not provide detailed mapping of, substructure, and have adopted a sparse-sampling strategy with fields separated across the sky, unlike the larger, deeper, contiguous survey we envisage. In addition, these ongoing surveys are not designed to study M31/M33.

The large-scale surveys envisaged here require a substantial allocation of time – $\sim$ 3000 hours over 3-4 years – on 8m-class telescopes, equipped with highly multiplexed, wide-field multi-object spectrographs, at both medium and high spectral resolution. No existing facility can provide this. The huge scale of this undertaking would be matched by unprecedented legacy value of the database, and the scientific impact of the intended analyses.

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