The Milky Way and Local Volume as Rosetta Stones in Galaxy Formation

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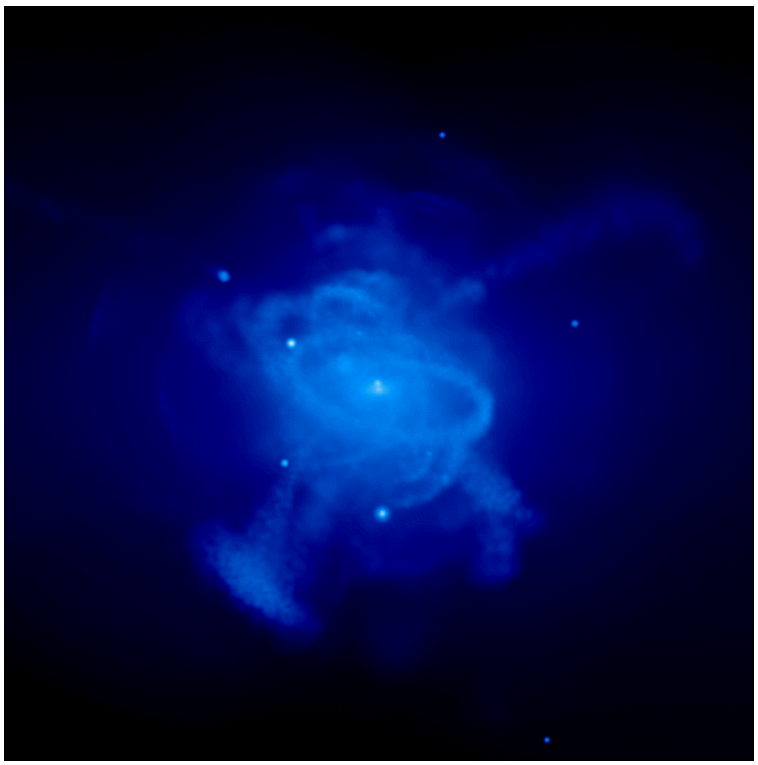

Simulated stellar halo formed from accreted satellite galaxies (Bullock & Johnston 2005). Box is 400 kpc on a side. The majority of structures are very low surface brightness – dectectable only via resolved star studies.

1. Introduction

The last decade has seen a renaissance in the study of our own and other galaxies in the Local Volume (LV). The multi-dimensional, contiguous maps of the Milky Way (MW) provided by star-by-star surveys (e.g. HIPPARCOS, 2MASS and SDSS) have rendered smooth fitting functions developed to describe the properties of galaxies and popularized by integrated light studies obsolete in this context. Vast numbers of resolved stars and the addition of new dimensions have uncovered: structures in the disk due to dynamical resonances (Dehnen 2000); lumps in the halo from hierarchical structure formation (e.g. Newberg et al. 2002; Majewski et al. 2003; Belokurov et al. 2006); the shapes of tails in abundance and velocity distributions (Helmi et al. 2006; Kollmeier et al. 2008); and a new population of satellite galaxies (Willman et al. 2005; Belokurov et al. 2007). At the same time, simulations of structure formation in the cosmological context have for the first time resolved dark matter structure within Galactic-scale halos (Moore et al. 1999; Klypin et al. 1999). These observational and theoretical advances have combined to launch a new discipline of "near-field cosmology". Next generation photometric (LSST, PanSTARRS), spectroscopic (SEGUE2, LAMOST, WFMOS, APOGEE, HERMES) and astrometric (GAIA, SIM, LSST and PanSTARRS) surveys are poised to move beyond these glimpses of low-significance structures and produce the first maps of the full shape of the stellar distribution in space, velocity and abundances throughout the MW and beyond.

These combined chemical-dynamical-spatial maps of the MW and other local galaxies will provide insight into their assembly histories and star formation trajectories unrivaled by any studies that rely on integrated light from the far field. This White Paper examines the unique contributions that these future LV studies can make to the field of galaxy formation and evolution. The intention is not to describe specific pieces of this puzzle or highlight contributions by a particular type of survey (as done very effectively in White Papers by Wyse et al, Rockosi et al, Shaya et al, Kirby et al and Covey et al). Rather, we outline: how we can in principle use detailed knowledge of one galaxy to learn about the nature of galaxy formation throughout the Universe (§2); and how the ensemble of future surveys together provide a comprehensive strategy for this endeavor (§3).

2. Why study 1 (or 10) in a 100 billion galaxies?

A key concern when studying galaxy formation using the nearby Universe is that the MW is just one galaxy with an individual history — even with a very detailed picture of its assembly we may be left understanding little about the majority of galaxies. Fortunately, the Dark Energy + Cold Dark Matter hierarchical paradigm provides the necessary theoretical framework that allow the interpretation of local data within a larger context: the stars that make galaxies are expected to form within dark matter halos that are themselves growing through gravitational collapse and mergers. Assuming that every galaxy in the Universe is shaped by the same underlying physics, the MW can then be thought of as a laboratory

for testing these theoretical inputs. In this sense, the observational work of the last decade has confirmed the general nature of the experiment that is being run in this laboratory(i.e. star formation against the backdrop hierarchical structure formation). The next generation surveys will determine the conditions under which the experiment is running (e.g. the specific hierarchy from lumps in phase- and abundance-space) and measure the results (i.e. stellar populations). Hence, the lasting legacy of the next decade studies may not be what they can tell us about the MW, but what they can tell us about the physics of galaxy formation — about the hierarchical aglomorration of dark matter halos, the baryonic physical processes that form the stars within them and, ultimately, the formation of disks.

2.1. Reconstructing the hierachy

One of the most stunning acheivements of LV surveys in the last decade has been the mapping of not one or two, but dozens of new dwarf galaxies and streams in the stellar halo of our Galaxy (e.g. Newberg et al. 2002; Majewski et al. 2003; Willman et al. 2005; Belokurov et al. 2006) – discoveries that serve as dramatic confirmations of the first-order predictions of hierarchical structure formation (e.g. Bullock et al. 2001; Bullock & Johnston 2005). Similar studies of resolved giant stars have revealed a new population of satellites and stellar substructures around the Andromeda galaxy (e.g. Ibata et al. 2007; McConnachie et al. 2008).

In trivial terms, surveys in the next decade promise to discover more streams and satellites. It is important to assess how this will help us in our quest to understand galaxy formation. Any increase in the *numbers* of stars catalogued or *accuracy* of distance estimates means that lower significance features will be revealed, corresponding to objects accreted longer ago or of lower luminosity. On the other hand increasing the *depth* of a survey (to the virial radius of the Galaxy and beyond) will reveal features corresponding to later events and those on more radial orbits. Adding *new dimensions* to get full phase-space coordinates (e.g. GAIA) will allow groupings of stars in their integrals of motion to be formed, pushing back sensitivity to even earlier accretion epochs as the dispersal of these associations is governed by (typically slower) scattering rather than (typically faster) phase-mixing processes (Helmi & de Zeeuw 2000).

The promise of significant samples (tens to hundreds of thousands within volumes of 10-20kpc) of stars with high-resolution spectroscopic measurements (e.g. WFMOS, APOGEE – see Wyse et al and Rockosi et al White Papers) heralds the coming-of-age of another approach to finding primordial stellar associations: "chemically tagging" stars according to their abundances (Bland-Hawthorn & Freeman 2003). The great hope of this approach is that, since the abundance patterns of stars reflect their birthclouds, there is in principle no barrier to how far back in time we can probe. Clearly, the volume accessible to these studies is far smaller than photometric work, but this technique brings new power to dissecting regions (e.g. the Galactic disk) where phase-space has been well-mixed and scattered (see §2.3).

2.2. Testing the baryonic physics

While we have a clear picture of how we think dark matter halos form and evolve, the behavior of the baryonic matter within them is much less well understood, with unanswered questions about the conditions for star formation, the importance of energetic feedback from and chemical enrichment by supernovae, and the process of mixing and pollution of gas following star formation events. In this case, the great advantage of living in a hierarchical Universe is that the Milky Way's evolution did not proceed in isolation and in that sense it is not just one galaxy: it contains the signatures of the *thousands* of galaxies that made it. The stars in those galaxies formed over a range of timescales, within different mass dark matter halos, undergoing few or many encounters at different places in the Universe. Hence they can tell us about galaxy formation under diverse conditions - they represent many different "experiments" running within the Milky Way laboratory.

Table 1 provides a sketch of this idea – the different rows represent different experiments in galaxy formation, while the columns label how the controls on each experiment are set. For example, field dwarf irregular galaxies are thought to live in moderate-sized dark matter halos ($10^9 - 10^{10} M_\odot$), still contain gas and are actively forming stars. Because of their high gas content and existence far from the main LV galaxies, they are thought to have a relatively quiet history with infrequent dynamical interactions (Grebel et al. 2003). In contrast, while the progenitors of the brightest stellar streams are thought to be of comparable size to field dIrr (Font et al. 2008), they contain no gas, are not currently forming stars and must have been completely destroyed by dynamical interactions.

It is tempting to dismiss the dwarf galaxies (the last six rows of Table 1) as holding little interest to the question of how the majority of stars in the Universe formed. However, precisely because of their size, we must be able to model the physics in this regime if we are to have any hope of understanding star formation in disks and bulges – they can be modeled as one- or few-zone systems rather than the multitude of overlapping and interacting zones in a larger galaxy. Moreover, they are the only type of galaxy which are both close enough to study star-by-star and for which we have a statistical sample. We can subdivide the dwarfs according to the importance of external influences (e.g. tidal interactions or ram-pressure stripping) and explore the general consequences of these influences for their stellar populations. Finally, dwarfs represent the lower limit of galaxy formation - they provide an essential boundary condition on dark halo mass that must be satisfied.

The stellar halo also provides its own unique contribution to this picture. We expect a significant fraction of this component to be made from stars accreted during merger events rather than being formed *in situ* within the dominant parent halo. It is here that we might find the cleanest sample of stars from the mythical "building blocks" of galaxy formation, free from contamination from subsequent star formation and perhaps containing signatures from the very earliest star formation in the Universe. (See White Paper by Kirby et al for more specific illustrations of these ideas.)

component	progenitor potential well	duration of star formation	dynamical history
bulge	intermediate	short	moderate interactions
disk	deep	long/ongoing	moderate interactions
smooth halo	intermediate	short	destroyed
stellar streams	intermediate	long/truncated	destroyed
ultra-faint satellites	very shallow	long/truncated	strong interactions
classical satellites	shallow	long/truncated	strong interactions
field dwarf irregulars	intermediate	long/ongoing	few interactions
field dwarf spheroidals	shallow	long/truncated	strong interactions
field transition objects	shallow	long/truncated	moderate interactions

Table 1: Possible influences on formation of stellar populations within different LV components.

In addition to identifying the diverse conditions under which LV objects formed, next generation surveys will constrain how star formation proceeded as a consequence of these different conditions. For example, the proposed large samples of stars with high resolution spectroscopic measurements will be sensitive to elements produced by supernovae type II (via α- and r-process), type Ia ([Fe/H]) and AGB stars (via s-process) and hence provide tracers of enrichment that takes place on different timescales and with different energy scales. This suggests that the abundance patterns in populations will be able to tell us both about the duration of star formation as well as how mixing progressed in response to different energetic inputs and in a variety of potential wells, from the Milky Way to the smallest dwarfs. (See White Papers by Wyse et al, Rockosi et al and Covey et al for more detailed discussion and some specific examples.)

2.3. Making galactic disks

The ultimate aim in the study of galaxy formation is to understand the bulk of the stars, which in the Milky Way lie in the Galactic disk. One crucial question is how disks can survive as long as they do in our hierarchical Universe. Galaxies should bear the imprint of merger events in the form of tidal distortion and heating, yet the majority of Milky-Way size spirals are dominated by thin, cold disks of stars. Any formulation of galaxy formation must account for this tension between theory and observations — indeed there are a number of competing suggestions aimed at explaining how thin disks may survive and/or emerge from the expected bombardment (Abadi et al. 2003; Robertson et al. 2006; Hopkins et al. 2009).

It is important to emphasize that the competing theories are *designed* to reproduce the broad-brush statistics obtained from large galaxy surveys (e.g. the fraction of galaxies that

are disks). In contrast, the rich kinematic, spatial, and chemical data set possible for the Milky Way provides an entirely disjoint (and more stringent) testing ground for models aimed at explaining disk formation in a cosmological context. Specifically, if the Milky Way disk did experience a significant number of merger events in the past ~ 10 Gyr there should be evidence of it in the outer, low-surface brightness disk region (Kazantzidis et al. 2008). Indeed, plausible merger-induced structures have already been uncovered around both the Milky Way (the Monoceros Ring – Newberg et al. 2002) and Andromeda (Ferguson et al. 2002).

A second question is how stars form within galactic disks. As outlined above, future spectroscopic samples will provide new constraints on star formation, feedback and mixing in the disk in the form of measurements of stars in many-dimensional abundance-space. Moreover, since stars form in the disk in clusters, even this *in situ* mode of star formation can be viewed as a process of destruction and accretion of small clumps, much like the stellar halo. Unlike the halo, the mixing timescales are shorter than the ages of the stars, and scattering more frequent, so the signatures of long-dead clusters are unlikely to be detectable in phase-space. We can instead use "chemical tagging" to empircally reconstruct these primordial star clusters, and in turn, directly read the star formation history of the disk.

3. Prospects for the next decade

The previous section outlined how LV studies can in principle be used to study galaxy formation under diverse circumstances. An idealized implementation of these ideas would involve: (i) separating stellar populations formed in distinct objects (using phase- and/or abundance-space); (ii) identifying signatures of the original potential well (from internal dynamics) and interaction history (from morphology, orbit and/or location); (iii) outlining the star formation history (from detailed abundance distributions); and (iv) using the results as constraints on the baryonic physics that makes galaxies.

The numerous surveys proposed for the next decade provide the necessary network of approaches to fulfill these aims. Specifically:

Deep, wide-field, multi-epoch photometric surveys: LSST and PanSTARRS will map the LV to unrivaled depth (beyond the virial radius of the MW) and accuracy using RR Lyrae stars, and even with vast numbers of main sequence turnoff stars out to 100kpc. These maps promise new discoveries as they are more sensitive to objects accreted from lower down the mass function and longer ago than those found in surveys today. In addition, the multi-epoch nature of LSST will yield proper motions accurate to ~ 10 km/s at distances as large as ~ 30 kpc, with bulk proper motions for the Milky Way satellites and streams — and hence their orbits — even further away. All these results will contribute to reconstructing properties of Galactic progenitors and their place in Galactic history. In addition, methods similar to those discussed in Jurić et al. (2008) will allow the metallicity distribution throughout

the disk to be mapped with 200 million F/G main sequence stars. This map will provide a crucial framework for studies that may measure additional dimensions, but have smaller sample sizes or volume.

Pointed astrometric mission: While it can study only of order ten thousand Galactic stars, SIM is the only survey that can provide accurate constraints on the potential of our Galaxy on the very largest scales, as well as measure the central density profiles of Galactic satellites (thus "taking the temperature" of dark matter via phase space constraints). These are essential inputs in any model that attempts to understand the process of star formation as a function of dark matter halo mass. (See White Paper by Shaya et al.)

Astrometric survey: GAIA's unique contribution will be a full phase- and metallicity-space map of the inner 10kpc of our Galaxy, offering the opportunity to probe the accretion hierarchy further back in time in integrals-of-motion space, as well as map the structure of and substructure within the Galactic disk.

High-resolution spectroscopy: WFMOS, APOGEE and HERMES will provide an explosion in the number of stars catalogued with measurements of elements from the full spectrum of nucleosynthetic sources. While they probe a smaller volume with fewer stars than the photometric/astrometric surveys, they provide an entirely new perspective on galaxy formation. These measurements themselves offer the tantalizing possibility of reconstructing primordial stellar groupings via chemical tagging. Abundance distributions also provide direct constraints on the processes of star formation, feedback and mixing. (see White Papers by Wyse et al and Rockosi et al)

Large aperture telescopes: 25 to 30m class telescopes (e.g. TMT, GSMT) would increase the volume over which both M31-type giant star maps, and spectroscopic follow-up of candidates might be feasible – thus a larger sample of galaxies that could be used as constraints on our galaxy formation models. (See White Paper by Kirby et al).

Together, these proposed surveys cover the first three steps in our idealized program quite comprehensively. What is missing from this list is not an observational survey, but rather the models with which such surveys can be compared. The significant new insights on galaxy formation from the next generation of LV studies provide the solid and detailed foundation on which such models might be built.

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