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The Future of Stellar Populations Studies in the Milky Way and the Local Group

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Abstract. The last decade has seen enormous progress in understanding the structure of the Milky Way and neighboring galaxies via the production of large-scale digital surveys of the sky like 2MASS and SDSS, as well as specialized, counterpart imaging surveys of other Local Group systems. Apart from providing snaphots of galaxy structure, these "cartographic" surveys lend insights into the formation and evolution of galaxies when supplemented with additional data (e.g., spectroscopy, astrometry) and when referenced to theoretical models and simulations of galaxy evolution. These increasingly sophisticated simulations are making ever more specific predictions about the detailed chemistry and dynamics of stellar populations in galaxies. To fully exploit, test and constrain these theoretical ventures demands similar commitments of observational effort as has been plied into the previous imaging surveys to fill out other dimensions of parameter space with statistically significant intensity. Fortunately the future of large-scale stellar population studies is bright with a number of grand projects on the horizon that collectively will contribute a breathtaking volume of information on individual stars in Local Group galaxies. These projects include: (1) additional imaging surveys, such as Pan-STARRS, SkyMapper and LSST, which, apart from providing deep, multicolor imaging, yield time series data useful for revealing variable stars (including critical standard candles, like RR Lyrae variables) and creating large-scale, deep proper motion catalogs; (2) higher accuracy, space-based astrometric missions, such as Gaia and SIM-Lite, which stand to provide critical, high precision dynamical data on stars in the Milky Way and its satellites; and (3) large-scale spectroscopic surveys provided by RAVE, APOGEE, HERMES, LAMOST, and the Gaia spectrometer, which will yield not only enormous numbers of stellar radial velocities, but extremely comprehensive views of the chemistry of stellar populations. Meanwhile, previously dust-obscured regions of the Milky Way will continue to be systematically exposed via large infrared surveys underway or on the way, such as the various GLIMPSE surveys from Spitzer's IRAC instrument, UKIDSS, APOGEE, JASMINE and WISE.

Keywords. Galaxy: abundances, Galaxy: halo, Galaxy: kinematics and dynamics, Galaxy: evolution, Galaxy: structure, Local Group, dark matter, astronomical databases, surveys

1. Introduction: Stellar Populations Studies in the "Industrial Age"

The topic I have been asked to review — the future of stellar population studies in the Milky Way (MW) and Local Group (LG) — is a vast one, within which I can do no more than a whirlwind tour of various topics. To make the task more manageable, my goal will be primarily to highlight some facets of the area of *resolved* stellar populations that are now, and that will soon be, addressable as stellar populations work enters the "industrial age" — an age where vast databases and automated analysis of these vast databases can be brought to bear on both newly revealed as well as age-old problems in the field. To this end, a major portion of this contribution will be to summarize those large-scale surveys about which I am aware; I apologize in advance for any surveys I have failed to include or whose parameters I have misrepresented.

2. Galaxy Evolution in a Cold Dark Matter Universe

Before starting this whirlwind tour of the “industrial age” of resolved LG stellar populations work, it is important to be mindful of the great advances being made in sister subdisciplines, such as cosmology, large scale structure formation, dark matter and the analysis of these matters through large numerical simulations. For example, it is now well established through such simulations (and with growing corroboration by observations) that the growth of structure in a Cold Dark Matter (CDM) universe is hierarchical, with small structures merging along filaments to form larger structures, like MW-sized galaxies and LG-sized galaxy associations.

But while hierarchical merging until late times (even presently) is now well established as a key element of CDM structure formation models, it is useful to recall that both late infall and hierarchical formation was anticipated as a central aspect of MW formation studies through the stellar populations work of Searle & Zinn (1978), who showed that the outer halo globular clusters exhibit a significant age spread (inferred through interpretation of horizontal branch morphologies). This foundational, early result demonstrated the power of stellar population studies for unlocking the secrets of galaxy formation. But with ΛCDM a now firmly entrenched and generally successful theory, it is sensible to approach future stellar population work with this context in mind, and, in part, look to stellar population studies for testing and/or refining this widely-accepted thesis. This is only possible because the advanced state of ΛCDM simulations allows them to make a rich variety of predictions about the structure, dynamics and chemistry of CDM structures. But checks on the theory with resolved stellar population studies are all the more important because, while ΛCDM has enjoyed great success in matching observations of structures on the largest scales, several problems still remain in matching the theory to observations on galaxy scales. Among these problems on small scales are (1) the “missing satellites problem”, where the models predict a mass spectrum of galaxy subhalos that are strongly in disagreement with that observed around the MW (e.g., Klypin *et al.* 1999); (2) the “central cusps problem”, where ΛCDM predicts the mass density of galaxies to have steeply rising central cusps (e.g., Navarro *et al.* 1997) for which there is little observational evidence in the MW (see, e.g., Merrifield 2005) and which is belied by the flat central density profiles of dwarf galaxies; and (3) problems with the predicted angular momentum distributions in galaxies, wherein the models have difficulty making large, extended disks like that of the MW (e.g., Abadi *et al.* 2003). Thus, a current focus for advancing ΛCDM theory is attempting to resolve problems on galaxy scales, and clearly there are potent avenues by which stellar populations work in the LG, MW and their satellite systems can contribute not only to progress in understanding hierarchical galaxy formation and evolution, obviously, but also to fine-tuning ΛCDM theory.

3. Astrometry: Testing Hierarchical Formation and Late Infall

As one example of how stellar population studies can contribute to fine-tuning ΛCDM theory, take the notion of infall along filaments, one of the elements of hierachical galaxy formation vividly seen in the simulations as well as in the observed distribution of galaxies on large scales. Is this something we can find evidence for in the LG?

Infall of DM subhalos along filaments should leave rather specific dynamical fingerprints in terms of preferred shapes, orientations and coincidences of orbits of LG systems and MW satellites, accreted globular clusters and (halo) stars (e.g., Knebe *et al.* 2004). It has long been known that most of the “classical” MW satellites show a relatively strong planar alignment (e.g., Kunkel & Demers 1976, Kunkel 1979, Lynden-Bell 1976, 1982, Majewski 1994, Fusi Pecci *et al.* 1995, Metz *et al.* 2007, 2009a) almost perpendicular to the Galactic plane. This preferential spatial distribution holds up statistically even with the inclusion of the new "ultrafaint" satellites revealed by the Sloan Digital Sky Survey (SDSS), and when the orientation of the SDSS "footprint-bias" (i.e., towards the North Galactic Cap) is accounted for (Metz *et al.* 2009a). Such spatial alignments could be a signature of a dynamical association of the satellites, but must be checked with full 3-dimensional velocity measurements for the satellites. Through painstaking work, the proper motions, μ, of MW satellites are slowly being accumulated, though in most cases with still only marginally significant μ/ϵ_{μ}, at least for ground-based data (see summary in Metz *et al.* 2008). More recently, proper motions measured using Hubble Space Telescope imaging of the Magellanic Clouds ("MCs" hereafter; Kallivayalil *et al.* 2006a,b, Piatek *et al.* 2008), other dSph satellites (Piatek *et al.* 2003, 2005, 2006, 2007) and globular clusters (e.g., Bedin *et al.* 2006, Kalirai *et al.* 2007) have shown significantly reduced proper motion uncertainties, despite very small time baselines — with improvements to be expected if more epochs can be accumulated with the newly-installed WFC3.

Analysis of the proper motions of these MW satellites has more or less supported the notion of dynamical kinship of at least some satellites, at least in that a number of these systems seem to share similar orbital poles, showing common directions of angular momentum (Majewski *et al.* 1996, Palma *et al.* 2002, Metz *et al.* 2008). The meaning of such alignments and whether they are at odds with, or consistent with, expectations of typical satellite configurations around MW-like galaxies in CDM models has been much debated of late. Among the postulated theories, such dynamical correlations could reflect siblinghood among satellites: (1) through the break-up of once large satellites — e.g., a greater Magellanic or Fornax system (Kunkel 1979, Lynden-Bell 1982, Majewski 1994, Metz *et al.* 2008); (2) through the formation of satellites as tidal dwarfs (e.g., Kroupa *et al.* 2005); (3) through the infall of satellites onto the MW in groups (Li & Helmi 2008, D'Onghia & Lake 2008, Metz *et al.* 2009b); or (4) through the preferential infall of satellites along CDM filaments (Kang *et al.* 2005, Zentner *et al.* 2005).

According to the simulations, the surviving galaxies of today reflect the most recent infall onto the MW — of subhalos now in the MW, those in current satellites were the most distant subhalos at earlier times. Earlier material to fall in came from initially closer matter and is now spread out among the star and star cluster debris of the halo. Thus, comparing the orbits of the satellites to the orbits of halo stars is a comparison of how infall proceeded at these different epochs, and this translates to spatial variations in the dynamics. According to high-resolution numerical simulations (e.g., Diemand *et al.* 2005) the outermost Galactic halo stars and globular clusters should be on radially biased orbits while the inner regions should contain more isotropic orbits. The predicted kinematics for the late-infalling satellite dwarf galaxies is different, with small anisotropies even in the outer parts. In addition, the net angular momentum of these components is expected to be small and simply reflect that of the dominant dark matter component at this epoch.

To test such predictions requires measures of halo star and satellite orbital anisotropy; these should be done *in situ* to avoid orbital biases attendant with solar neighborhood samples. (To this end, it is interesting to note the much more complex inner/outer halo structure suggested by recent analysis of the SDSS SEGUE stellar sample with proper motions by Carollo *et al.* 2007, including the suggestion that the outer halo dominates the *low* eccentricity component of their relatively nearby stellar sample.) This, in turn, requires the measurement of not only the bulk proper motions of the MW satellites, but the much more demanding star-by-star measures of *distant*, individual halo stars.

At this dawn of the "industrial age" of stellar populations studies we can look forward to astrometric studies and surveys on a vast and more precise scale — to the realm of

Table 1. Current and Future Astrometric Surveys and Pointed Instruments

Catalog†	**Accuracy**	**Flux. Limit**	**Stars**
USNO B1.0	200 mas	$V \sim 21$	1 billion
Tycho-2	60 mas	$V \sim 12$	2.5 million
UCAC2	20-70 mas	$R \sim 16$	40 million
Pan-STARRS	30 mas	$r \sim 23$	2 billion
LSST	3 mas	$r \sim 24$	10 billion
Hipparcos	1 mas	$V \sim 12$	117,955
HST+WFPC2/STIS/ACS/WFC3	1 mas	$V \sim 24$	pointed instrument
J-MAPS	1 mas	$V \sim 15$	40 million
WIYN ODI	0.6 mas	$I \sim 22$	pointed instrument
HST/FGS	0.2 mas	$V \sim 17$	pointed instrument
JASMINE	0.010 mas	$z \sim 14$	100 million
VLBA	0.010 mas	~200 mJy‡	pointed instrument
Gaia	0.020 mas	$V \sim 15$	1 billion
SIM-Lite (wide angle mode)	0.004 mas	$V \sim 20$	pointed instrument (~10,000 sources lifetime)

†Ground-based facilities in italics. ‡Depth depends on frequency observed.

billions of stars and microarcsecond precisions — that will help us move forward on such issues. Table 1 gives a sampling of astrometric capabilities (quoted as "mission end" positional accuracies for the surveys and "achieved/achievable" accuracies for the pointed instruments *at the magnitude limited given*) either already underway or expected in the next decade (with table values taken from the project websites or published papers). The projects include large ground-based surveys that probe deeply but at lower relative precision (USNO B1.0, UCAC2 and the future Pan-STARRS and LSST astrometry) as well as more focused ground-based facilities that can obtain higher precision — for example VLBA observations of radio sources (such as masers) and the soon-to-be-commissioned One Degree Imager on the WIYN telescope, with its Orthogonal Transfer Arrays capable of on-chip local corrections for atmosphere-induced, differential image wander. But upcoming space-based astrometric missions — including J-MAPS (which will provide a new epoch of positions that can be matched to those from Hipparcos and Tycho), JASMINE (a mission to do infrared astrometry of the Galactic bulge), Gaia and SIM-Lite — will revolutionize the field of Galactic kinematics with astrometry reaching to microarcsecond precision (SIM-Lite in narrow angle mode). These capabilities will enable us to achieve the scientific goals outlined above, considering that to derive transverse velocities of 10 km s^{-1} accuracy for MW satellites at ~100 kpc requires ~20 μas yr^{-1} proper motions. This is within range of SIM-Lite for individual stars and for Gaia after the averaging of the proper motions for many V~17.5 giant stars in each satellite. However, only SIM-Lite will be able to measure the proper motions of satellites like Leo I, Leo II or CanVen I, which are beyond 200 kpc and have their brightest members at V~19.5. Moreover, only SIM-Lite will be able to measure precise proper motions for many of the newfound ultra-faint dSphs, which, even though at closer distances, have a paucity of bright giant stars. Obviously, for single stars, where one cannot take advantage of averaging, the problem is more acute, but Gaia will give an unparalleled view of the dynamics of inner halo stars, with SIM-Lite providing *in situ* measures of stars in the outer halo.

SIM-Lite, along with VLBA astrometry on the few LG galaxies with detectable masers (like IC10 and M33), will allow the orbits of galaxies within the LG and beyond to be derived. This will make it possible to constrain the matter distribution over Mpc scales and test cosmological expectations such as infall along filaments (Shaya *et al.* 2009). There have been some tantalizing suggestions of late LG infall by the discovery of some "hypervelocity dwarf galaxies" near M31, namely And XII and And XIV. Given most reasonable estimates for the M31 mass, these systems have radial velocities suggesting that the dwarfs are not presently bound to M31 or even the LG (Majewski *et al.* 2007, Chapman *et al.* 2007); M31 would need to be at least two times more massive than previously thought to keep these satellites bound to it. Meanwhile, analysis of the HST-based proper motions of the MCs (see above) by Besla *et al.* (2007) strongly suggests that these galaxies are making their first pass around the MW, which implies that they are among the latest hierarchical accumulations of matter by the MW.

4. Deep, Pointed Surveys of Nearby Galaxies, Part I

Of course, the MCs are dIrr type systems, and it is interesting that their hyperbolic orbits are consistent with the overall distributions of dwarf satellites of different types within the LG: It is well known that there is a general density-morphology relationship within the LG, with dSph and dE galaxies mostly clustered around M31 and the MW, while most dIrr galaxies — the MCs among the notable and nettlesome exceptions — are typically found in isolated regions of the LG. But the new MC orbital data suggest (1) that the MCs violate the density-morphology relationship by being near the MW *now* due to a coincidence of fortuitous timing in the dynamical evolution of the MCs and the LG, and (2) that the MCs may be on the first stages of transformation from a dIrr morphology to another class of dwarf system.

Such evolution of the morphologies of LG dwarf galaxies should be reflected in the star formation histories (SFHs) of these systems. Through systematic high resolution imaging — especially with the Hubble Space Telescope — combined with stellar population synthesis, the SFHs of these LG dwarf galaxies are being painstakingly assembled (e.g., see summary in Dolphin *et al.* 2005). This work shows clear differences in the SFHs among nearby dwarf galaxies, with a clear morphology-density-SFH relation that strongly demonstrates how environment is a major driver in the evolution of small galaxies. This may occur through the tidal shocking of more frequent gravitational encounters with the large LG spirals that accelerates star formation by fostering bursts and leading to an earlier exhaustion of gas, or it may relate to this gas being stripped out by ram pressure interaction with hot coronal gas around the large systems.

The morphology-density-SFH relation also suggests the possibility, long discussed, that dSph galaxies and dIrrs may be evolutionarily related. Such a connection is made via N-body simulations (e.g., Mayer *et al.* 2001a,b, Klimentowski *et al.* 2009) that show *tidal stirring* to be an active agent transforming late type morphologies — e.g., high surface brightness dwarf disks — into dSph or dE-like systems when placed inside a MW-sized halo. This process involves the formation and subsequent buckling of bars in the evolving dwarf, which transforms it from a rotation to pressure-supported system. In this regard it is interesting that the Large MC (and possibly the Small MC) contains a bar. If, as these models suggest, dIrrs are simply systems that haven't yet been dynamically stirred, then the LG dIrrs should be on very large LG orbits, or they may be the most recent infalling systems into the LG and onto the large LG spirals (as e.g., the MCs); thus dIrrs may represent the most "pristine" of luminous subhalos. But much work remains to verify this picture, especially given the arguments made by, e.g., Grebel *et al.* (2003)

that the central surface brightness-luminosity and luminosity-metallicity distributions of dwarf galaxies do not favor an evolutionary connection between dIrrs and dSphs, but rather a closer evolutionary connection between dSphs and "transitional" type dwarfs (like the Antlia, Phoenix and LGS3 systems) — a connection that, nevertheless, still belies environment (i.e., tidal forces) driving the differential evolution of dwarf galaxies. (On the other hand, Brown *et al.* 2007 show that the dIrr Leo A is similar to dSphs in having a large velocity dispersion and M/L, i.e. $> 20 \pm 6$ in solar units.)

Clearly, more stellar populations work — in particular, ever deeper HST CMDs on the LG dIrrs — could help resolve these questions of dwarf evolution. The ACS Nearby Galaxy Survey Treasury (ANGST) project is a great help in this regard, taking this detailed CMD work out to 4 Mpc (Dalcanton *et al.* 2009). With the advent of ever larger telescopes, as well as more efficient instruments on existing 10-m class telescopes, we also have the promise in the coming decade of detailed chemistry of individual stars in these systems, as is now being done on the closer, LG dSphs (see §7). Of course, more accurate information on the orbits of these systems, and understanding better the overall dynamics of the LG, would be extremely helpful in probing the evolutionary history of dwarf galaxies, beyond the tantalizing example offered by the MCs (§3).

5. Wide Field Photometric Surveys in the Coming Decade

Of course, another prediction of CDM models is that infalling subhalos onto MW-like systems, which continue to the present, will face dynamical shredding and create a web of luminous (and dark) streams around these systems (e.g., Bullock & Johnston 2005). This vision of a MW halo networked by streams has been hinted at for several decades by small, pointed pencil-beam surveys — with the conclusion that the *entire* halo is made from accreted systems (see, e.g., Majewski 1993, 2004, Majewski *et al.* 1996). But this vision of the MW really has been born out by deep, wide-field photometric surveys like the Two Micron All-Sky Survey (2MASS) and the Sloan Digital Sky Survey (SDSS) which have enabled the construction of large portraits of the halo where many of these streams can be seen plainly (e.g., Newberg *et al.* 2002, Majewski *et al.* 2003, Belokurov *et al.* 2006, Grillmair 2006). Continued active mining of these data bases continues to unveil not only new tidal debris streams (e.g., Rocha-Pinto *et al.* 2004, Sharma *et al.* 2009 for 2MASS, and Belokurov *et al.* 2007b, Grillmair 2009, Newberg *et al.* 2009 for SDSS, to name just some examples), but of course a plethora of new dSph galaxies of extremely low luminosity (e.g., Willman *et al.* 2005, Zucker *et al.* 2006, Belokurov *et al.* 2007a, Irwin *et al.* 2007, Grillmair 2009). These ultrafaint dSphs tend to have very high M/L ratios (Muñoz *et al.* 2006b, Simon & Geha 2007) that point to a common dSph mass scale (Strigari *et al.* 2008), which may arise from some critical scale in the formation of galaxies or a characteristic scale for the clustering of DM. But a few ultrafaints show evidence for tidal disruption and dynamical instability (e.g., Coleman *et al.* 2007, Carlin *et al.* 2009) and may represent exceptions to the common mass scale (Adén *et al.* 2009).

The astounding pace of discovery and revolution in our understanding of the structure of our MW that has occurred as a result of these large-scale photometric surveys can be expected to continue in the next decade with impending photometric surveys that will cover a large fraction of the sky more deeply (Table 2). Not only will these surveys allow deep searches for streams and satellites through color-magnitude filtering for specific stellar tracers of these structures, but their inclusion of a time series dimension will enable the search for pulsational variables, which are high quality standard candles that have already proven to be quite powerful in the search for halo substructure — e.g., with

Table 2. Wide Field Photometric Surveys Past and Future

Survey	Hemisphere	Filters	Magnitude Limit	Area	Dates
2MASS	north & south	J, H, K_s	15.8, 15.1, 14.3	41,253 deg^2	1997-2001
SDSS I/II/III	north	u, g, r, i, z	22.0, 22.2, 22.2, 21.3, 20.5	10,400 deg^2	2000-2009
Dark Energy Survey	south	g, r, i, z	24	5,000 deg^2	2011-2016
SkyMapper	south	u, v, g, r, i, z	22.9, 22.7, 22.9, 22.6, 22.0, 21.5	20,000 deg^2	2009-2014
Pan-STARRS	north	g, r, i, z, y	24	30,000 deg^2	2012-2022
LSST	south	u, g, r, i, z, y	24	20,000 deg^2	2015-2025

RR Lyrae stars from SDSS (e.g., Ivezić *et al.* 2004, Watkins *et al.* 2009) or the QUEST project (e.g., Duffau *et al.* 2006, Vivas & Zinn 2006).

The discovery and exploration of increasing numbers of tidal streams not only tells us about the assemblage of the *luminous* MW, but also the structure and size of the MW's dark halo because the shapes and orbits of tidal streams are extremely sensitive probes of the overall mass distribution of the host galaxy. The greatest sensitivity comes with full 6-D phase space information on stream stars (again, requiring SIM-Lite-accurate proper motions for distant streams — e.g., $<10\ \mu$ as yr^{-1} at $V \sim 18$ for $\sim$100 kpc giant stars — but with enormously greater numbers of stars from Gaia exploration of closer streams). However, great progress is already being made with the positions and radial velocities of Sagittarius (Sgr) stream stars. While up to now no study of the Sgr stream has been capable of simultanously fitting the positions *and* the radial velocities of the debris (see discussion of this problem in Law *et al.* 2005), it has been shown recently (Law *et al.* 2009) that adoption of a triaxial MW dark halo solves this problem. As more phase space data are collected on the Sgr and other streams sampling other Galactic radii, a more accurate description of the MW's mass distribution will evolve; this then can be compared to expectations for mass distributions of MW-like galaxies in CDM models.

6. Deep, Pointed Surveys of Nearby Galaxies, Part II

With large-scale photometric surveys like those in Table 2, we can really fine tune the predictions of CDM models, including an understanding of the mass distributions, orbits and timescales of infalling subhalos. For example, one prediction of CDM simulations (e.g., Johnston *et al.* 2008) is that a typical MW-like galaxy should presently contain on average about one large, high surface brightness ($\Sigma < 30$ mag arcsec^{-2}) stream. Of course, in the MW such a stream exists — the Sgr stream (Ibata *et al.* 1995, Newberg *et al.* 2002, Majewski *et al.* 2003, Belokurov *et al.* 2006); but is the MW typical?

Fortunately, new insights into two more spiral halos are coming from large-scale mapping of the M31 and M33 spirals — particularly from the Pan-Andromeda Archaeological Survey (PAndAS) survey by Ibata and collaborators (e.g., Ibata *et al.* 2007) and the Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo (SPLASH) Survey by Guhathakurta and collaborators (e.g., Kalirai *et al.* 2006). This work has revealed the Giant Southern Stream (Ibata *et al.* 2001), a halo substructure connecting with other filagree noted around the M31 disk (e.g., Ibata *et al.* 2004, Fardal *et al.* 2006, 2008 Gilbert *et al.* 2007), which makes it a "Sgr stream-equivalent" in our spiral twin sister. Other M31 halo substructure has also been revealed (e.g., Chapman *et al.* 2008) as well as an entire host of newly found M31 dSph satellites (e.g., Martin *et al.* 2006, 2009, Majewski *et al.* 2007, Zucker *et al.* 2007, Irwin *et al.* 2008, McConnachie *et al.* 2008). SPLASH and PAndAS include deep spectroscopic analyses of the giant stars discernible in M31 and allow information on the chemistry of these systems to be gathered. With HST, these probes of M31 can reach the main sequence turnoff and garner information on the ages of these stellar populations as well (e.g., Brown *et al.* 2006, 2009).

In the coming decade we can expect the number of well-probed halos to expand — our statistical sample increased by moving to more distant systems. Already, significant tidal streams have been identified through deep surface brightness imaging of the disk galaxies NGC 5907 (Zheng *et al.* 1999, Martinez-Delgado *et al.* 2008b), NGC 4013 (Martinez-Delgado *et al.* 2009), M94 (Trujillo *et al.* 2009), and other systems (Martinez-Delgado *et al.* 2008a). Study of *resolved* stellar halos in more distant galaxies will also become more commonplace, with proven work already from the ground (Vansevicius *et al.* 2004) as well as with HST (Ibata *et al.* 2009).

But one need not go to great distances to find additional stellar halos — recent work has shown that the Large MC has an extended halo (Muñoz *et al.* 2006a) with an exponential density profile of 4.9° scalelength (Majewski *et al.* 2009). This new Large MC halo seems to show all of the complexity of other halos around larger galaxies, with a mix of stars of different metallicities. It includes an apparently rather metal-rich component that is similar in metallicity to the Small MC, and that may be related to a tidal interaction between these two systems. In any case, these results suggest that even halos around smaller systems like the Large MC can have substructure. Other work (e.g., Harris 2007, Noel & Gallart 2007, Nidever *et al.* 2010) shows that even the Small MC has an extended outer population of stars to at least a 6° radius that may be a halo, as is expected in hierarchical models. Interestingly, this extended structure seems to contain stars that are relatively young and metal rich ([Fe/H] = −1.0, 2 Gyr; Nidever *et al.*, in preparation).

7. Current and Future Spectroscopic Surveys of the Galaxy

Different merger histories for galaxies will yield different chemical patterns in their substucture. As shown by Johnston *et al.* (2008), [Fe/H] is a tracer of accreted masses (because larger mass satellites typically have higher metallicity), while [α/Fe] more or less traces the accretion times of satellites (because more recent mergers — satellites and tails — tend to have lower [α/Fe]). Thus, there are strong motivations to study the chemistry of galactic substructure, including (1) constraining parent halo accretion histories, (2) learning about the SFHs and chemical enrichment histories of stream progenitors, (3) establishing the connection between present, bound host satellites and stars in the host halo, (4) reconstructing the chemical distribution of the original satellite galaxies, (5) chemically fingerprinting stars to their parent source, and (6) checking the chemical make-up of halos against CDM model predictions.

While a lot of work has been carried out to measure detailed chemical abundance patterns in LG dwarf galaxies and interpret them in the context of chemical evolution models (see, e.g., the summaries by Gibson 2007 and Lanfranchi *et al.* 2008), detailed chemical analysis of tidal streams is still in its early stages, with most of the focus to date on the MW's Sgr stream, which is relatively close and contains bright stars accessible to echelle resolution study. The Sgr system shows strong population gradients along its tidal arms (Bellazzini *et al.* 2006, Chou *et al.* 2007, Monaco *et al.* 2007), and illustrates a time dependence in the chemistry of stars contributed to the MW halo as well as the danger of assuming that the chemistry of stars left in a disrupting dwarf are representative of what that system contributed to the halo. Indeed, the population gradients in the Sgr stream are so strong that certain dynamical inferences can be made: Either Sgr lost mass over a small radial range in the satellite over which there was originally an enormous metallicity gradient, or Sgr recently suffered a more catastrophic loss of stars over a radial range with a more typical metallicity gradient (Chou *et al.* 2007). Detailed chemical analysis of the Sgr stream also allows us to reassemble a portrait of the Sgr progenitor; Chou *et al.* (2009) find that this progenitor had α and s-process element abundance patterns greatly resembling those of the Large MC, which seems to be a reasonable prototype for the Sgr progenitor. Thus, by way of stellar population similarities we obtain even more evidence pointing to the evolutionary connection between dIrr and dSph galaxies discussed in §4.

Table 3. Current and Future Spectroscopic Surveys of the Galaxy

Survey	R	Stars	Wavelength	Dates
LAMOST-LR	2000	5,000,000	370-900 nm	2009-2015
SEGUE	2000	240,000	480-920 nm	2004-2009
RAVE	7500	1,000,000	840-875 nm	2003-2011
LAMOST-MR	10,000	100,000		2009-2015
AAOmega	10,000	50,000	370-950 nm	2006-
Gaia	11,500	100,000,000	847-874 nm	2015-2020
APOGEE	30,000	100,000	1520-1690 nm	2011-2014
HERMES	30,000	1,200,000	370-950 nm	2011-2012
WINERED	100,000	1,000,000	900-1300 nm	TBD

Significant advances in the understanding of the chemical evolution of our galaxy and its network of disrupted dSphs can be expected in the next decade, where huge databases of medium to high resolution spectroscopy of Galactic stars will be generated with a variety of instruments (Table 3). Obviously, the accumulation of high quality radial velocities for many millions of stars will also shape a very detailed understanding of the dynamics of Galactic stellar populations. Not only will the Galactic halo and its substructure be thoroughly probed by these upcoming surveys, but so too will the populations of the inner Galaxy — including those typically hidden by dust obscuration — by infrared spectroscopic surveys like APOGEE (see Schiavon *et al.*, this proceedings).

8. Probing the Inner Galaxy with Infrared Surveys

Of course, ΛCDM surveys show galaxies forming *entirely* from hierarchical merging in an “inside-out” manner, so detailed studies of the inner MW are essential to unlocking the dust-concealed story of its early formation. Because of this dust obscuration, explorations at infrared wavelengths hold the most promise for this work. Fortunately, the coming decade brings a host of new infrared capabilities to add to the near-infrared (NIR) imaging brought by 2MASS and other more focused surveys. The UKIDSS project (Lucas *et al.* 2008) will increase the depth of these NIR imaging probes at low Galactic latitudes, and also provide second epoch positional data that can be combined with 2MASS for proper motions (e.g., Deacon *et al.* 2009). A more focused effort of z-band astrometry of the Galactic disk and bulge is the goal of the Japan Astrometry Satellite Mission for Infrared Exploration (JASMINE; Gouda *et al.* 2005).

The Spitzer Space Telescope, which has significantly opened up longer wavelength photometric and spectroscopic study of the inner MW, will continue to provide longer wavelength imaging capability even as it enters its more wavelength-limited, Warm

Mission. In particular, the Infrared Array Camera (IRAC) will continue to map the Galactic midplane at 3.6 and 4.5μm through the GLIMPSE-360 mission, extending the earlier GLIMPSE I and II projects (Churchwell *et al.* 2009), which have been instrumental in uncovering the structure of the central Galaxy (e.g., Benjamin *et al.* 2005). Even more coverage (wavelength and area) will be given by the Wide-Field Infrared Survey Explorer (WISE), to be launched in the autumn of 2009. And APOGEE will provide high resolution NIR spectroscopy of stars otherwise inaccessible behind tens of magnitudes of optical extinction.

Despite the diminished effects of infrared studies to the presence of dust, it cannot be completely ignored. Continued efforts must be made to understand the Galactic extinction law, especially given that it is not universal either by ISM density or by position in the Galaxy (e.g., Fitzpatrick & Massa 2009, Zasowski *et al.* 2009, Gao *et al.* 2009). Fortunately, the combination of NIR and MIR photometry (e.g., 2MASS/UKIDSS + GLIMPSE/WISE) gives direct information on the reddening foreground to each star, which will make it possible in the future to develop maps not only of the 3-D distribution of stars in the Galactic disk, but also of the dust (Zasowski *et al.*, in preparation).

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