SEGUE-2 and APOGEE: Revealing the History of the Milky Way

White Paper for the Astro2010 GAN Science Frontier Panel

Submitted by the SDSS-III Collaboration

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1. Introduction

Observations over the past decade have demonstrated that the Milky Way is spatially and kinematically complex, and includes numerous lumps and streams in the stellar halo (which itself can be resolved into two distinct components, an inner and outer halo), substructures in the stellar disk systems, and dwarf satellites with an enormous range of luminosities. Cold dark matter (CDM) cosmological models predict complex assembly histories for galaxies like the Milky Way, with many or most spheroid stars formed in smaller systems that have since been disrupted, and with the stellar disk frequently perturbed by minor mergers and dynamical interactions with halo substructures. While some of these predictions are supported by the observations, the physics of disk galaxy formation in CDM remains poorly understood. Large stellar spectroscopic surveys can map the spatial and kinematical structure of the Galaxy, and probe its star formation history by measuring the chemical enrichment patterns in today's stellar populations. Abundances in the most chemically primitive spheroid stars allow "archaeological" investigations of the earliest epochs of cosmic star formation, whose nucleosynthetic products enriched these stars. In short, massive spectroscopic surveys of the Milky Way do more than simply map our Galactic home – they open a new frontier in the study of galaxy formation, dark matter, stellar nucleosynthesis, and star formation in the early Universe.

Many recent advances in Galactic structure have come from the Sloan Digital Sky Survey (SDSS; York et al. 2000), especially the SEGUE (Sloan Extension for Galactic Understanding and Exploration) survey of SDSS-II. Using the existing SDSS spectrographs, SEGUE-2 will obtain medium-resolution (R = 2000) spectra of an additional 140,000 stars in selected high-latitude fields to a magnitude limit $r \approx 19.5$, more than doubling the sample of distant halo stars observed in the SEGUE. These two surveys will provide maps of the kinematics and metallicities of stellar populations over a large volume of the Galaxy, from the inner halo to large Galactocentric distances where late-time accretion events are expected to dominate the outer-halo population.

The Apache Point Observatory Galactic Evolution Experiment (APOGEE) will use a new, 300-fiber H-band spectrograph ($\lambda = 1.5 - 1.7\mu$m) to carry out a high-resolution ($R \approx 24,000$) spectroscopic survey of 10^5 red giant stars to a magnitude limit $H \approx 12.5$, penetrating interstellar dust obscuration to provide the first large scale, uniform, high precision spectroscopic study of *all* Galactic stellar populations (bulge, disk, bar, halo). APOGEE spectra will allow radial velocity measurements with < 0.5 km/s precision and abundance determinations (with ~ 0.1 dex precision) of 15 chemical elements for each program star, which can be used to reconstruct the history of star formation that produced these elements, and reveal subtle kinematic disturbances or pinpoint kinematic substructures. Together, SEGUE-2 and APOGEE will provide a picture of the Milky Way that is unprecedented in scope, richness, and detail. The combined data set will play a central role in "near-field cosmology" tests of galaxy formation physics and the small scale distribution of dark matter.

SEGUE-2 and APOGEE are part of SDSS-III, a six-year program (2008-2014) that will use existing and new instruments on the 2.5-m Sloan Foundation Telescope to carry out four spectroscopic surveys on three scientific themes: dark energy and cosmological parameters; the structure, dynamics, and chemical evolution of the Milky Way; and the architecture of planetary systems.[1] All data from SDSS-I (2000-2005) and SDSS-II (2005-2008), fully calibrated and accessible through efficient data bases, have been made public in a series of roughly annual data releases, and SDSS-III will continue that tradition. SDSS data have supported fundamental work across an extraordinary range of astronomical disciplines, including the large-scale structure of the universe, the evolution and clustering of quasars, gravitational lensing, the properties of galaxies, the members of the Local Group, the structure and stellar populations of the Milky Way, stellar astrophysics, sub-stellar objects, and small bodies in the solar system. A summary of some of the major scientific contributions of the SDSS to date appears in the Appendix.

By the time of the Astro2010 report, we hope that SDSS-III fundraising will be complete. We are providing SDSS-III White Papers to the Astro2010 committee and panels mainly as information about what we expect to be a major activity for the first half of the next decade, and about datasets that will shape the environment for other activities. We also wish to emphasize the value of supporting projects of this scale, which may involve public/private partnerships and international collaborations like the SDSS, and thus the importance of maintaining funds and mechanisms to support the most meritorious proposals that may come forward in the next decade.

2. Description of SEGUE-2 and APOGEE

SEGUE-2 is a continuation of SEGUE, similar in overall strategy but with targeting designed to focus more on the outer-halo population. The 240,000 targets in SEGUE emphasized stars in the relatively nearby regions of the Galaxy, with the majority of the fibers placed on stars expected to be within 10 kpc, including a substantial number of thick-disk and inner-halo stars (Yanny et al. 2009). SEGUE-2 will survey the Galaxy's stellar halo *in situ* at distances from 10 kpc to beyond 60 kpc. The goal is to use the combination of SEGUE and SEGUE-2 to map the kinematics and stellar populations over a large volume of the Galaxy, from the inner halo to the outer halo. Ultimately, this information will be used to constrain existing models for the formation of the stellar halo(s), and to inform the next generation of high-resolution simulations of galaxy formation.

The outer halo has already been shown to be of particular interest, as analysis of SDSS/SEGUE spectroscopy revealed that "the halo" of the Galaxy can be resolved into at least two distinct components with markedly different distributions of (1) metallicity (the outer-halo metallicity distribution function, MDF, peaking at [Fe/H] $= -2.2$, a factor of 3 lower than that of the inner halo), (2) kinematics (the outer-halo exhibiting a net retrograde rotation on the order of -70 to -80 km/s, compared to a zero or slightly prograde net rotation of the inner halo), and (3) density (the outer halo exhibiting rounder spatial density contours, compared to a moderately flattened inner halo). See Carollo et al. (2007) for additional details. The desire to better constrain the nature of the inner- and outer-halo populations, and to examine the critical transition region from the populations, which occurs between 15 and 20 kpc from the Galactic center, strongly influences the targeting philosophy of SEGUE-2.

[1] Because the different SDSS-III surveys are relevant to different Astro2010 survey panels, we are providing three separate White Papers, though the general material on the SDSS is repeated. A detailed description of SDSS-III is available at `http://www.sdss3.org/collaboration/description.pdf`.

The roughly 140,000 stars targeted by SEGUE-2 are selected from SDSS imaging, isolated by a variety of color cuts (and in some cases, mild proper motion cuts) to populate the primary selection categories. The categories include blue horizontal-branch stars, K- and M-type giants, and an unbiased (with respect to metallicity and kinematics) sample of F-turnoff stars. SEGUE-2 also includes categories for very metal-poor stars, extreme and ultra-cool subdwarfs, and other rare but interesting subsamples, such as hyper-velocity star candidates. In selecting distant and rare objects, SEGUE-2 benefits from the experience of SEGUE in developing optimized and efficient selection techniques, setting magnitude limits to balance survey depth, sky coverage, and data quality, and in having a stable stellar parameters pipeline (the SDSS/SEGUE Stellar Parameters Pipeline, SSPP; see Lee et al. 2008a,b and Allende Prieto et al. 2008), with well-understood errors as a function of color and signal to noise.

SEGUE-2 employs the existing SDSS spectrographs (which provide wavelength coverage 3800 - 9200 Å, at R = 2000), with integration times set to achieve an average S/N per pixel of 20/1. With these data, the SSPP achieves typical external errors of $5 - 10\,\mathrm{km/s}$, 140 K, 0.29 dex, 0.24 dex for radial velocity, T_{eff}, log$g$, and [Fe/H], respectively. The combined SEGUE+SEGUE-2 data set is expected to approach 400,000 stars, with more than 100,000 of these targets sampling the outer-halo population (doubling the SEGUE sample of such distant stars). When combined with stellar observations obtained as part of the SDSS-I/SDSS-II Legacy programs, the final sample should be on the order of 500,000 stars.

The anticipated science outcomes of the combined SEGUE/SEGUE-2 samples include:

- Greatly enlarged samples to enable the detection and analysis of individual stellar streams in the inner and outer halo (e.g., Harrigan et al. 2009; Klement et al. 2009; Willet et al. 2009), as well as the "global" level of kinematic substructure present throughout the Galaxy (e.g., Schlaufman et al., in preparation). The velocity and metallicity accuracies achieved by SEGUE/SEGUE-2 are sufficient for first-pass identification, which can be followed up (for nearby streams) with APOGEE and (for more distant streams) with other surveys.

- Expanded samples of distant blue horizontal-branch stars and M-giants, which enable refined estimates of the mass (and mass profile) of the Galaxy (e.g., Xue et al. 2008), as well as *in-situ* studies of the change of the halo MDF with distance.

- Assembly of a sample of over 20,000 stars with [Fe/H] < -2.0, enabling a definitive study of the shape of the low-metallicity tail of the inner- and outer-halo MDFs (e.g., Beers et al. 2009). The lowest metallicity stars identified are, and will continue to be, studied with high-resolution spectroscopy using existing 8-10m telescopes, and in the future, with Extremely Large Telescopes. Such studies are invaluable for revealing the elemental abundance patterns that were produced by the first generations of stars.

- Determination of the velocity ellipsoids and relative normalizations of the thick-disk, metal-weak thick-disk, inner- and outer-halo populations. This goal, already underway with existing data from SDSS/SEGUE (Carollo et al., in preparation), provides the required constraints for new generation, cosmologically tuned models of galaxy formation and evolution (e.g., Tumlinson 2006).

- The identification and kinematic study of many thousands of extreme sdM stars in the local volume, enabling explorations of the low-mass stars of the halo populations (e.g., Lepine et al. 2009).

APOGEE will produce the first systematic survey of the *3-D distribution functions* of the abundances of 15 chemical elements that are key for the understanding of the star formation and chemical evolution of the Galaxy. This will be achieved by use of a new 300-fiber cryogenic high-resolution spectrograph that will provide access to regions of high extinction in the Galactic inner disk and bulge. Accurate abundances (0.1 dex) will be obtained for elements such as oxygen, carbon, and nitrogen, which are the most abundant metals and preferred chemical evolution tracers, as well as other metals with particular sensitivity to the star formation history and the initial mass function, such as iron-peak, odd-Z, and α-elements. APOGEE will also obtain accurate (0.5 km/s) kinematical data useful for constraining dynamical models for the disk, the bulge, the bar and the halo, and for discriminating substructures in these components, if/where they exist. The enormous APOGEE data set will make possible the determination of metallicity and abundance pattern distribution functions for many dozens of Galactic zones (R, θ, Z) at the level of detail currently available only for the solar neighborhood.

Some of the prime science goals of APOGEE include:

- To constrain models of hierarchical formation of the Galaxy by searching for residues of merging processes in the form of velocity substructure and/or through chemical fingerprinting, thus establishing the relative contributions of *in situ* star formation and accretion of previously formed stellar populations. APOGEE will increase, by orders of magnitude, the samples of bulge stars with accurately determined abundance patterns and kinematics, which will place definitive constraints on its accretion and star formation history.

- To identify low-latitude halo sub-structure like the Monoceros stream, and to determine velocity dispersions of the currently known tidal streams, in order to constrain the mass of the disrupted parent satellites and to place limits on dynamical heating of streams by lumps in the dark matter halo.

- To constrain the mass profile of the Galaxy, by combining radial velocities with spectroscopic parallaxes to map the large scale dynamics of the bulge, bar, and disk, thereby probing the global distribution of light and dark matter via the first comprehensive determination of the rotation curve to the outermost reaches of the disk.

- To infer properties of Population III stars (thought to reside or to have resided in the Galactic bulge) by detecting them directly if they survive to the present day, or by measuring their nucleosynthetic products in the most metal-poor stars surviving to the present day.

- To carry out a legacy survey of low-latitude star clusters, which will provide strong constraints on the history of star formation and chemical enrichment of the inner Galaxy, via the combination of detailed abundance patterns with CMD-based ages.

- To constrain the high-mass end of the initial mass function in early stellar populations at different Galactic zones from abundance ratios sensitive to yields from stars of different masses.

- To characterize the dynamics and chemistry of the Galactic bar from the first major survey of its stars. Effects of the bar on the dynamics of the disk and nearby halo will also be studied.

3. Conclusions

SEGUE/SEGUE-2 (along with RAVE) are the first of numerous observational campaigns over the coming decade that will revolutionize our understanding of the history of the formation and evolution of large galaxies such as the Milky Way. Future surveys include Galactic studies to be conducted by LAMOST in China, HERMES at AAO, WFMOS at Gemini/Subaru, ESAs GAIA satellite, Pan-STARRS in Hawaii, SkyMapper in Australia, and the LSST. The ground-breaking work of the SDSS survey efforts will inform and greatly improve the scientific return from all of these future missions.

The uniqueness of APOGEE emanates from the fact that it is a *high-resolution, near-infrared* survey of a *huge (*10^5*)* sample of Galactic stars. High-resolution spectroscopy will make possible the determination of very accurate elemental abundances via the application of classical abundance analysis methods to a large stellar sample in an automated fashion. Moreover, the significantly reduced extinction in the H-band compared to optical wavelengths ($A_H = A_V/6$) will allow APOGEE to reach uncharted territory, well beyond distances accessible to any of the other major surveys coming to fruition in the next decade. Finally, in keeping with SDSS tradition, the immense homogeneous database produced by APOGEE is poised to spark numerous follow-up observational pursuits aimed at further exploring the many avenues that it will open for investigation.

In round numbers, SDSS-III is a $40 million project, and the funding is largely in hand thanks to generous support from the Alfred P. Sloan Foundation, the National Science Foundation, the Department of Energy, and the Participating Institutions (including international institutions and participation groups supported, in some cases, by their own national funding agencies). The SDSS has demonstrated the great value of homogeneous surveys that provide large, well-defined, well-calibrated data sets to the astronomical community. In many cases, such surveys are made possible by novel instrumentation, and they often require multi-institutional teams to carry them out. The case for supporting ambitious surveys in the next decade is best made by considering the contributions of the SDSS to the astronomical breakthroughs of the *current* decade, as summarized in the Appendix below.

Appendix: The SDSS Legacy

The SDSS (York et al. 2000) is one of the most ambitious and influential surveys in the history of astronomy. SDSS-II itself comprised three surveys: the Sloan Legacy Survey completed the goals of SDSS-I, with imaging of 8,400 square degrees and spectra of 930,000 galaxies and 120,000 quasars; the Sloan Extension for Galactic Understanding and Exploration (SEGUE) obtained 3500 square degrees of additional imaging and spectra of 240,000 stars; and the Sloan Supernova Survey carried out repeat imaging (~ 80 epochs) of a 300-square degree area, discovering nearly 500 spectroscopically confirmed Type Ia supernovae for measuring the cosmic expansion history at redshifts $0.1 < z < 0.4$. Based on an analysis of highly cited papers, Madrid & Machetto (2006, 2009) rated the SDSS as the highest impact astronomical observatory in 2003, 2004, and 2006 (the latest year analyzed so far). The final data release from SDSS-II was made public in October, 2008, so most analyses of the final data sets are yet to come.

The list of extraordinary scientific contributions of the SDSS includes, in approximately chronological order:

- *The discovery of the most distant quasars,* tracing the growth of the first supermassive black holes and probing the epoch of reionization.
- *The discovery of large populations of L and T dwarfs,* providing, together with 2MASS, the main data samples for systematic study of sub-stellar objects.
- *Mapping extended mass distributions around galaxies with weak gravitational lensing,* demonstrating that dark matter halos extend to several hundred kpc and join smoothly onto the larger scale dark matter distribution.
- *Systematic characterization of the galaxy population,* transforming the study of galaxy properties and the correlations among them into a precise statistical science, yielding powerful insights into the physical processes that govern galaxy formation.
- *The demonstration of ubiquitous substructure in the outer Milky Way,* present in both kinematics and chemical compositions, probable signatures of hierarchical buildup of the stellar halo from smaller components.
- *Demonstration of the common origin of dynamical asteroid families,* with distinctive colors indicating similar composition and space weathering.
- *Precision measurement of the luminosity distribution of quasars,* mapping the rise and fall of quasars and the growth of the supermassive black holes that power them.
- *Precision measurements of large scale galaxy clustering,* leading to powerful constraints on the matter and energy contents of the Universe and on the nature and origin of the primordial fluctuations that seeded the growth of cosmic structure.
- *Precision measurement of early structure with the Lyman-α forest,* yielding precise constraints on the clustering of the underlying dark matter distribution $1.5 - 3$ Gyr after the big bang.

- *Detailed characterization of small and intermediate scale clustering of galaxies* for classes defined by luminosity, color, and morphology, allowing strong tests of galaxy formation theories and statistical determination of the relation between galaxies and dark matter halos.

- *Discovery of many new companions of the Milky Way and Andromeda,* exceeding the number found in the previous 70 years, and providing critical new data for understanding galaxy formation in low mass halos.

- *Discovery of stars escaping the Galaxy,* ejected by gravitational interactions with the central black hole, providing information on the conditions at the Galactic Center and on the shape, mass, and total extent of the Galaxy's dark matter halo.

- *Discovery of acoustic oscillation signatures in the clustering of galaxies,* the first clear detection of a long-predicted cosmological signal, opening the door to a new method of cosmological measurement that is the key to the BOSS survey of SDSS-III.

- *Measurements of the clustering of quasars over a wide range of cosmic time,* providing critical constraints on the dark matter halos that host active black holes of different luminosities at different epochs.

Half of these achievements were among the original "design goals" of the SDSS, but the other half were either entirely unanticipated or not expected to be nearly as exciting or powerful as they turned out to be. The SDSS and SDSS-II have enabled systematic investigation and "discovery" science in nearly equal measure, and we expect that tradition to continue with SDSS-III.

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