AS2: Surveys with the APO 2.5m Telescope After SDSS-II

April 3, 2007

ABSTRACT

Building on the extraordinary legacy of the Sloan Digital Sky Survey (SDSS), we propose a six-year program (mid-2008 to mid-2014) that will use the wide-field 2.5m telescope at Apache Point Observatory to carry out four 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. The Baryon Oscillation Spectroscopic Survey (BOSS) will measure redshifts of 1.5 million luminous red galaxies and Lyman-α absorption towards 100,000 high redshift quasars. By using the baryon acoustic oscillation scale as a physically calibrated ruler, BOSS will determine the absolute cosmic distance scale with percent-level precision at $z = 0.35$, $z = 0.6$, and $z = 2.5$, achieving tight constraints on the equation of state of dark energy. The high-precision clustering measurements over a wide range of redshifts and length scales will also provide rich insights into the origin of cosmic structure and the matter contents of the universe. SEGUE-II will use the SDSS spectrographs to measure radial velocities, spectral types, and elemental abundances of 250,000 stars in numerous categories, probing the kinematics and chemical evolution of the outer Milky Way. The APO Galactic Evolution Experiment (APOGEE) will use high-resolution infrared spectroscopy ($R \sim 20,000$ at $\lambda \sim 1.6\mu$m) to penetrate the dust that obscures the inner Galaxy from our view, measuring radial velocities, spectral types, and elemental abundances of 100,000 stars across the full range of the Galactic bulge, bar, and disk. Together, SEGUE-II 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. The Multi-Object APO Radial Velocity Exoplanet Large-area Survey (MARVELS) will use fiber-fed interferometric spectrographs to monitor the radial velocities of 13,000 bright stars, with the precision and cadence needed to detect planets with orbital periods ranging from several hours to several years. With a unique combination of enormous numbers and well characterized sensitivity, MARVELS will provide the critical statistical data set for testing theories of the formation and dynamical evolution of planetary systems.

SEGUE-II will be the principal dark time project for the first year of AS2 ("After SDSS-II"). The Baryon Oscillation Spectroscopic Survey, which will use significantly upgraded versions of the SDSS spectrographs, will become the principal dark time project thereafter. MARVELS will be the sole bright time project through Spring 2011. Following completion of APOGEE's infrared spectrograph, APOGEE and MARVELS will share the bright time equally, observing common fields where possible to maximize overall observing efficiency. The cost for the full suite of surveys is estimated at $45-50 million, of which $10 million is for instrument development, $15 million is for mountain-top operations, and $20-25 million is for off-mountain operations including data processing and validation, creation of the public archive, and project management.

1. The SDSS Legacy

The Sloan Digital Sky Survey is one of the most ambitious and most successful projects in the history of astronomy. In its first five years of operation (2000 – 2005), the SDSS obtained five-band CCD imaging over 8,000 square degrees of the high Galactic latitude, Northern sky, detecting 217 million celestial objects. It obtained spectra of 675,000 galaxies, 90,000 quasars, and 215,000 stars, selected from 5,700 square degrees of this imaging. The cumulative, fully calibrated and reduced data have been made publicly available, beginning with an early release of commissioning data and continuing with a series of annual data releases. Object catalogs, imaging data, and spectra are all available through the SDSS web site `http://www.sdss.org`, along with detailed documentation and powerful search tools.

Beginning in July 2005, the SDSS entered a new phase, SDSS-II, which will continue through June 2008. SDSS-II is using the SDSS telescope, camera, and spectrographs to carry out three distinct surveys. The Sloan Legacy Survey is completing spectroscopic observations over the full 8,000 square degrees of SDSS-I. SEGUE, the Sloan Extension for Galactic Understanding and Exploration, is imaging 3,500 square degrees on a grid extending through the plane of the Galaxy and obtaining spectra of 240,000 stars to measure radial velocities and chemical abundances. The Sloan Supernova Survey repeatedly scans a 300 square degree area to detect and measure variable objects, with particular concentration on Type Ia supernovae to measure the expansion history of the universe; in two 3-month campaigns (with one more still to come) it has discovered more than 300 spectroscopically confirmed Type Ia supernovae. Finally, the "ubercalibration" component of SDSS-II uses auxiliary observations and a novel analysis of imaging overlaps to improve the global photometric fidelity to 1%, from its previous level of 2%.

The 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. As of February, 2007, there have been some 1400 refereed journal articles based on SDSS data, which cumulatively have more than 40,000 citations. Recent analyses by Madrid et al. (2006) and Madrid & Macchetto (2006) rate the SDSS as the most productive astronomical observatory in 2003 and 2004 based on citations to high-impact papers published in those years (their analysis does not run past 2004), ranking ahead of the European Southern Observatory, Hubble Space Telescope, the Wilkinson Microwave Anisotropy Probe, and the Keck Observatory. With the completion of SDSS-I and the broader scope of SDSS-II, this impact seems guaranteed to increase with time. The SDSS is a valuable resource for educators at many levels, and it has made it possible for investigators with even modest computing capabilities to carry out state of the art research.

When SDSS-II is completed in mid-2008, the SDSS facilities will remain a uniquely powerful resource for wide-field spectroscopic surveys. (The SDSS camera, while still among the world's most powerful, is no longer unique, which is why AS2 emphasizes spectroscopic programs.) While the telescope and instruments are extraordinary assets in themselves, the technical infrastructure and collaboration culture that transform raw observations into calibrated, accessible data and high-impact science are equally important. With the AS2 surveys, we aim to extend the legacy and leverage the accomplishments of the SDSS.

2. BOSS: Probing Dark Energy and Cosmological Physics

The discovery of the accelerating expansion of the universe is the biggest cosmological surprise of the last half century. Even the most prosaic explanations of cosmic acceleration demand the

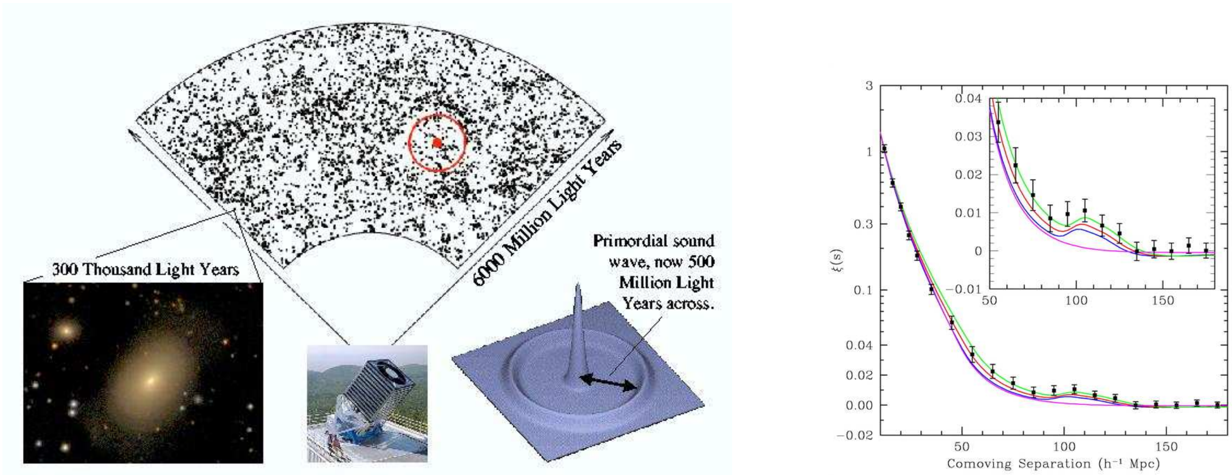

FIGURE 1. Illustrations of the baryon acoustic oscillation signature. Each dot in the wedge diagram (top left) is a luminous elliptical galaxy, similar to the one shown in the blow-up (far left). Measuring the clustering of these galaxies on large scales in the SDSS reveals the signature of the baryon acoustic oscillation (the bump at $100h^{-1}$ Mpc in the plot on the right; note that for $h = 0.7$, $100h^{-1}$ Mpc = 143 Mpc = 466 million light years). Density perturbations in the earliest times in the Universe throw off a pulse of sound that propagates outwards for about a million years after the Big Bang (middle bottom). Galaxies preferentially form both in the center region and at the final location of the sound waves, giving rise to the behavior that pairs of galaxies are more likely to be separated by 500 million light years than by 400 or 600 million light years. With AS2, we will measure the location of this peak to about 1% precision with the LRG survey and about 2.5% with the Lyman-α forest survey, thereby giving a robust measurement of the expansion history of the Universe.

existence of a pervasive and energetically dominant component of the universe with exotic physical properties. Once properly interpreted, cosmic acceleration could prove to be the essential clue to the physics of quantum gravity, or the first distinctive signature of string theory or extra spatial dimensions, or the symptom of a breakdown of General Relativity on cosmological scales. Whatever the explanation, the existence of cosmic acceleration implies a fundamental revision to our understanding of the cosmic energy contents, gravity, particle physics, or all of the above.

Many reports and articles have identified dark energy as the most pressing problem in fundamental physics. However, going beyond the detection of dark energy to informative constraints on its properties requires measurements of the cosmic expansion history with percent-level precision and correspondingly exquisite control of systematic uncertainties. At present, the baryon acoustic oscillation method is believed to have the smallest systematic biases of any dark energy probe. Sound waves that propagate in the opaque early universe imprint a characteristic scale in the clustering of dark matter, providing a "standard ruler" whose length, 150 megaparsecs, can be computed using straightforward physics and input parameters that are tightly constrained by cosmic microwave background observations. The detection of the acoustic oscillation scale in the clustering of Luminous Red Galaxies is one of the signature accomplishments of the SDSS (see Figure 1), and even this moderate signal-to-noise measurement substantially tightens the empirical constraints on cosmological parameters.

The Baryon Oscillation Spectroscopic Survey (BOSS) will survey the immense volume required to obtain a high-precision measurement of the acoustic oscillation scale. The main spectroscopic galaxy sample of the SDSS peters out by redshift $z \approx 0.2$, but the color-selected sample of Luminous Red Galaxies (LRGs) maintains nearly constant space density out to $z \approx 0.4$. With readily achievable improvements to the SDSS spectrographs and fiber system (reducing fiber size and replacing the gratings and CCDs to achieve higher throughput) and a slight increase of integration times, the SDSS telescope can measure LRG redshifts out to $z \approx 0.7$ with high completeness, with the spectroscopic targets being selected efficiently from standard SDSS photometry. During Fall 2008, BOSS will use the SDSS camera to carry out an additional 2,000 square degrees of imaging at high Galactic latitude in the southern Galactic cap, filling the gaps between the SDSS southern stripes. After the spectrograph upgrades are completed in Summer 2009, BOSS will carry out a redshift survey of 1.5 million LRGs selected from the 10,000 square degrees of AS2+SDSS imaging. For studies of structure on the largest scales, BOSS will have an effective volume eight times higher than that of the final SDSS-II sample.

To measure large scale structure and baryon oscillations at higher redshifts, BOSS will observe Lyman-α absorption in the spectra of 100,000 high-redshift quasars ($2.3 < z < 2.8$, at an apparent magnitude cut $g \approx 22$). Lyman-α forest measurements in a sample of ~ 3000 SDSS-I quasar spectra have already yielded some of the survey's most powerful cosmological constraints. The dense grid of quasar sightlines in BOSS will enable measurements that are effectively three-dimensional, instead of treating each sightline independently, so the gain in statistical power is much larger than the "mere" 33-fold increase of sample size would suggest. Our forecasts show that the LRG and Lyman-α surveys will yield absolute distance measurements with precision of 1.1% at $z = 0.35$, 0.9% at $z = 0.6$, and 2.5% at $z = 2.5$, greatly tightening the constraints on dark energy and the curvature of space. In terms of the figure of merit defined by the Dark Energy Task Force (see bibliography), BOSS will achieve more than a factor of three improvement over Stage II dark energy experiments (i.e., those currently underway). It will complement other Stage III experiments that use different observational probes, such as supernovae or weak lensing, and it will lay the groundwork for more expensive, future baryon oscillation experiments such as WFMOS, ADEPT, or the SKA galaxy redshift survey. No proposed Stage II or Stage III experiment will achieve comparable constraints on the baryon oscillation scale at $z < 0.7$, because no other experiment covers as much sky. Finally, the high precision, enormous dynamic range, and wide redshift span of the BOSS clustering measurements will greatly improve empirical constraints on neutrino masses, the physics of inflation, and the evolving relation between galaxies and dark matter.

3. SEGUE-II: Mining the Outer Milky Way

In addition to mapping the distant cosmos, SDSS-I made remarkable contributions to our understanding of the Milky Way and the stellar populations that comprise it. These successes inspired the SEGUE component of SDSS-II. Together, SDSS-I and SEGUE have discovered eight new dwarf galaxy companions of the Milky Way, detected and mapped huge streams of stars gravitationally stripped from merging satellite galaxies and globular star clusters, discovered thousands of the most primitive metal-poor stars, and demonstrated that the Galaxy's "inner" and "outer" stellar halos are chemically and kinematically distinct (see Figures 2 and 3). The ubiquitous substructure found by SDSS-I and SEGUE provides strong evidence for the hierarchical assembly of the outer Milky Way from smaller subsystems, as predicted by the cold dark matter scenario of galaxy formation.

The old stellar populations of the Milky Way were born during the heyday of its formation, when the Milky Way gained most of its mass through hierarchical merging and accretion. Whether they formed in the Milky Way proper or in smaller systems that later merged with the Galaxy, the velocities and chemical abundance distributions of old Galactic stars are the signature of its

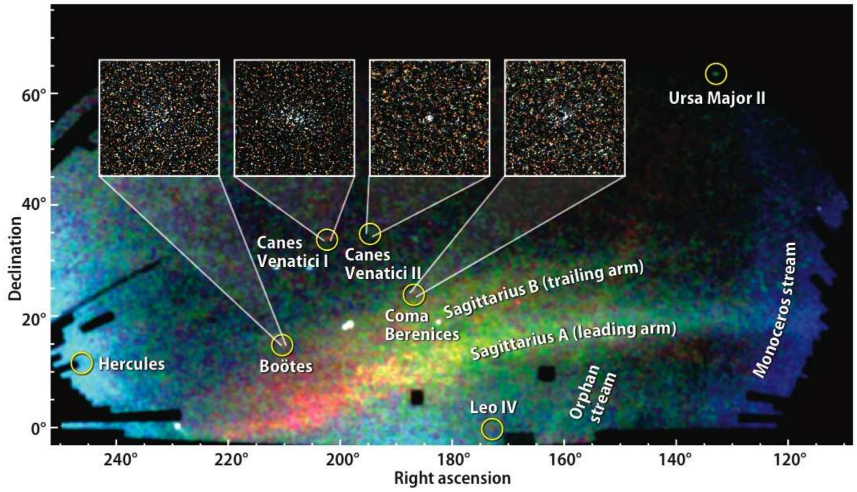

FIGURE 2. A map of stars in the outer regions of the Milky Way, covering about 1/5 of the sky, as observed by the SDSS. The trails and streams that cross the image are stars torn from disrupted Milky Way satellites. The inset panels show four of the surviving, but very faint, dwarf galaxies discovered by the SDSS. The color-coding represents distance, with red being the most distant and blue being the closest; the distances of stars are inferred from their colors and magnitudes in the 5-band SDSS images. This striking map, referred to as "The Field of Streams" in the paper that first presented it, demonstrates the complexity of structure in the outer Milky Way.

accretion and star formation history. The most recent studies from SDSS-I and SEGUE show that the inner halo of the Galaxy is dominated by stars on highly elongated prograde orbits with typical iron abundances about 2% of the solar value, while the outer halo is dominated by lower metallicity stars ($<$ 1% solar) on less eccentric, highly retrograde orbits.

Building on these accomplishments, SEGUE-II will obtain optical spectra of 250,000 stars in the Galactic halos and thick disk, using existing SDSS instruments and software. With one full year of dark time operation, SEGUE-II will double the spectroscopic sample from SEGUE, thereby doubling its statistical leverage and scientific payoff. SEGUE's combination of depth, precision, and massive number of targets is unique among the current and upcoming generation of stellar spectroscopic surveys, and it offers a powerful complement to the future astrometric space missions SIM and GAIA.

SEGUE-II will map the kinematics and chemical content of the newly delineated components of the Galaxy, and of the numerous structures visible in Figure 2. Many of these may be remnants of dwarf satellites disrupted by the Milky Way's gravitational tides. SEGUE-II will also target the Milky Way's thick disk, which may itself be the remnant of an accreted satellite or the signature of thin-disk stars heated by encounters with satellites and dark matter substructure. Finally, SEGUE and SEGUE-II will increase the sample of very metal poor stars (with less than 1% of the solar heavy element abundance) by more than an order of magnitude. These rare jewels, the subject of intensive follow-up campaigns with large-aperture telescopes, offer unique insights into the nucleosynthetic processes that forged the chemical elements. The archaeological evidence encoded in their abundance patterns allows powerful tests of the properties of the first stars, probing an epoch beyond the reach of even the deepest images from Hubble Space Telescope. SEGUE-II science operations will continue beyond 2009 by using calibration stars and stars targeted as quasar candidates in BOSS, and by using a small subset of the MARVELS fibers to monitor

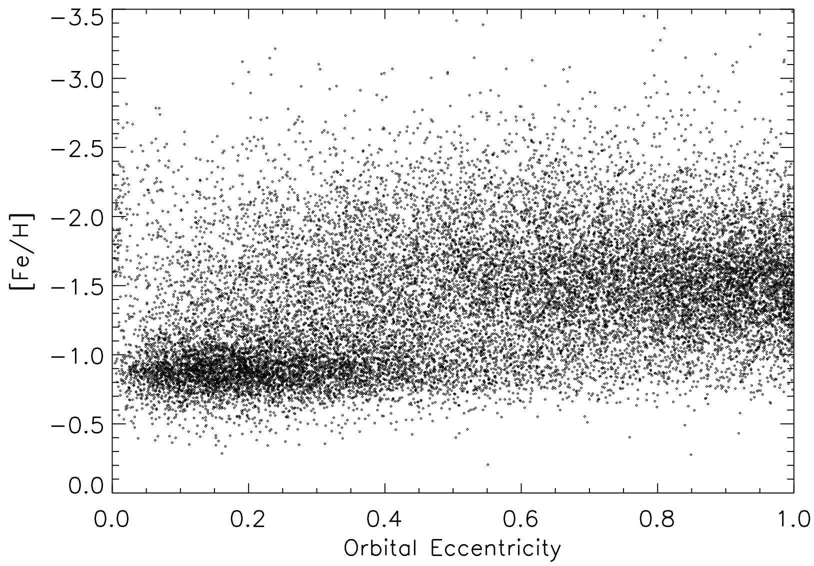

FIGURE 3. Structure in the Milky Way as measured by stellar spectroscopy, from SDSS-I and SEGUE. For each star, the logarithm of the iron abundance relative to the solar value (denoted [Fe/H]) is plotted against the eccentricity of its orbit around the center of the Milky Way. Note the clear separation between thick-disk stars, with low eccentricity and metallicity in the range $-1.0 < [Fe/H] < -0.6$, and the generally more metal-poor halo stars, which cover a wide range of eccentricity. The numerous high eccentricity stars with $[Fe/H] \sim -1.6$ are associated with the inner-halo population. Stars with $[Fe/H] < -1.6$ include objects from both the inner-halo and outer-halo populations, though more detailed views are needed to demonstrate the dichotomy between them.

low metallicity stars and investigate the role of binary interactions in driving their often peculiar abundance patterns.

4. APOGEE: Unveiling the Inner Milky Way

The core of the Galaxy — the inner disk, bar, and bulge — is largely obscured at visual wavelengths by interstellar dust (see Figure 4). The APOGEE survey will penetrate this veil of dust with a 300-fiber, cryogenic spectrograph operating in the near-infrared H-band (1.6μm), where extinction is much lower than in optical ($A_H = A_V/6$, a factor of 100 in flux at $A_H = 1$). The H-band window is coursed with numerous molecular lines of OH, CN, and CO, which can be used to obtain reliable abundances of carbon, nitrogen, and oxygen, the most abundant heavy elements. It also contains well defined atomic lines of iron, α-elements, and odd-Z elements up to and including the iron peak, thus probing nuclei produced by different physical processes operating in different types of stars. The high resolution ($R \sim 20,000$) and the high signal-to-noise ratio (typical $S/N \sim 100$) of APOGEE spectra will allow precise measurements of chemical abundance ratios, which encode critical clues to each star's nucleosynthetic ancestry.

To date, only a few hundred stars beyond the immediate solar neighborhood have been observed at such high spectral resolution and signal-to-noise ratio. APOGEE will observe $\sim 10^5$ red giants selected from 2MASS (the 2-Micron All-Sky Survey) to a magnitude limit $H \sim 13.5$, a revolutionary advance. APOGEE will be the first large-scale, systematic, chemical and kinematic study of the

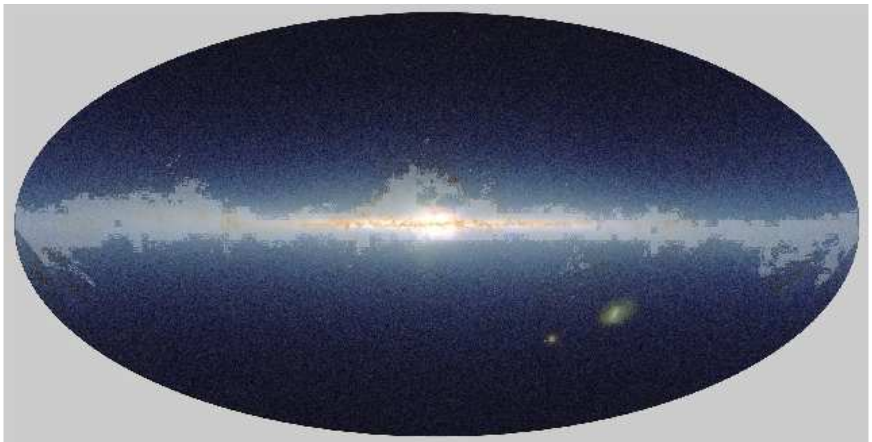

FIGURE 4. A panoramic view of the sky as seen by the Two Micron All-Sky Survey (2MASS), prominently showing the disk and bulge of the Milky Way. The gray overlay shows regions in which extinction at visual wavelengths exceeds 1 magnitude (a factor of 2.5 in flux), demonstrating the need for infrared spectroscopy to probe the inner Galaxy.

inner Milky Way. Even in fields with 15 magnitudes of visual extinction, APOGEE will probe to 25 kpc, allowing a thorough survey across the disk, bar, and bulge.

Hierarchical models of galaxy formation predict that the Galaxy's oldest stars lie buried in the inner bulge. APOGEE observations will extend the archaeological reach of SEGUE-II by constraining the population of stars that preceded and enriched this oldest surviving generation. By mapping the distribution functions of many chemical elements and probing the correlations between abundances and kinematics, APOGEE will reveal the history of star formation and interstellar gas mixing through the bulge and disk, and it will determine the relative contributions of *in situ* star formation and accretion of previously formed stellar populations. APOGEE will map the large scale dynamics of the bulge, bar, and disk, with radial velocity precision sufficient to measure subtle disturbances such as the perturbations of orbits by spiral arms. The combination of kinematic and abundance measurements for an enormous sample will make APOGEE a tremendous tool for identifying and probing low-latitude substructure, such as the Monoceros ring that appears to encircle the Galactic disk (see Figure 2). APOGEE will also carry out the largest systematic exploration of low latitude globular and open clusters, which will lend further insight to the evolution of these stellar systems and provide critical absolute age calibrations for the chemical evolution sequence established by abundance patterns.

Together, SEGUE, SEGUE-II, and APOGEE will provide the key data sets needed to understand our Galactic home in a fully cosmological context. Other cosmological observations have achieved tight constraints on the matter and energy contents of the universe and on the initial conditions for structure formation, but the physics of galaxy formation and the behavior of dark matter on sub-galactic scales remain topics of intense research and debate. Any successful theory of galaxy formation must account for the properties of the galaxy we know best, including its structure, the relative distributions of stars, gas, and dark matter, and the histories of star formation and chemical enrichment. By revealing the story of the Milky Way in unprecedented detail, the AS2 Galactic structure surveys will transform this vision of "near-field cosmology" into reality.

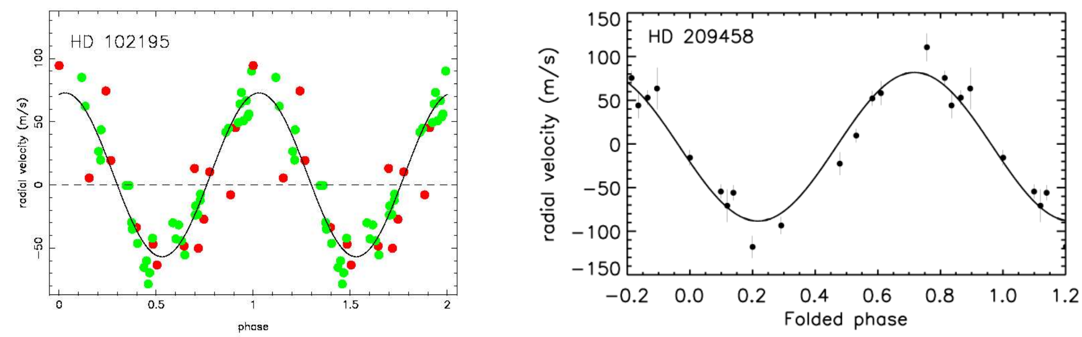

FIGURE 5. *Left:* The first planet discovered with a prototype of the MARVELS spectrograph, a single-fiber instrument operating on the Kitt Peak 2.1m telescope. Points show the measured radial velocity of the star (the reflex of the planetary orbit) against the orbital phase, with one repetition. The smooth curve shows the best-fit orbit, which is nearly circular with a period of 4.11 days. *Right:* Observations of the well known transiting planet system HD 209458 from the APO 2.5m, using the first MARVELS spectrograph. Points show the MARVELS radial velocity measurements, while the smooth curve is the prediction based on earlier observations from other telescopes.

5. MARVELS: Revealing the Architecture of Planetary Systems

With the possible exception of dark energy, the most extraordinary astronomical development of the last 15 years has been the discovery of an abundant population of extra-solar planets. Surveys to date have detected just over 200 planets, 90% of them found by radial velocity monitoring of ~ 3000 bright stars. Many of the discovered systems are radically different from our own solar system, with giant planets in close, short-period orbits or highly eccentric orbits. These discoveries have overturned many of the traditional theoretical ideas about planet formation, suggesting that complex dynamical interactions frequently rearrange the architecture of planetary systems.

The Multi-Object APO Radial Velocity Exoplanet Large-area Survey (MARVELS) will transform the study of extra-solar planets by using multi-fiber spectrographs to monitor radial velocities of a sample of stars much larger than that of all previous surveys combined. The key technical innovation is a combination of fixed-delay interferometers with moderate dispersion spectrographs, which allows simultaneous, high throughput, high velocity precision measurements of many objects with reasonable detector sizes. The 60-fiber, Keck ET I spectrograph has been operating at the APO 2.5-m since September 2006 (see Figure 5), and a second 60-fiber system will be installed in July, 2007. The baseline MARVELS survey will use these two spectrographs to monitor 13,000 stars in the apparent magnitude range $8 \leq V \leq 12$, each with ~ 30 observations over 18 months. For a $V = 10$ star, MARVELS would detect a Jupiter-mass planet out to an orbital radius of 1 AU (period of 1 year) with greater than 50% efficiency. MARVELS will be the sole AS2 bright time project until the APOGEE spectrograph is completed in 2011. After this, MARVELS and APOGEE will share the bright time, but since they target similar regions of the sky and can share the focal plane, the effective observing time may decline only slightly.

Moving from one-at-a-time observations to the highly multiplexed regime allows MARVELS to make a much more systematic census of extra-solar planets than previous surveys, investigating host stars with a diverse set of compositions, ages, rotational velocities, and evolutionary states. The large number of stellar targets will enable MARVELS to discover rare systems that are poorly represented in other studies. These include planets around low metallicity stars or red giants, planets in the mass "desert" between several Jupiter masses and the brown dwarf regime, and short-period, multi-planet systems that will be beautiful laboratories for studying dynamical interactions among extra-solar planets. The baseline survey is expected to detect roughly a dozen transiting planets around bright stars; these are Rosetta-Stone objects because follow-up observations on other telescopes can probe their radii, their atmospheric structure, and even the presence of large moons or rings. Above all, MARVELS will provide a clear, well quantified picture of the diversity of giant-planet systems, including the correlation of planet frequency with the properties of the host star, the joint distribution of planetary masses, orbital radii, and eccentricities, and the incidence of multi-planet systems. These data are exactly what is required to test theories of the formation and dynamical evolution of planetary systems.

6. Management and Budget

The AS2 collaboration will be modeled after the successful structure of SDSS-I and SDSS-II. Institutions will join the collaboration via contributions, both technical and financial. Scientists at these institutions will have data rights to some or all of the AS2 surveys. Scientists at other institutions who make direct work contributions to the project may also earn data rights.

The AS2 presently has a Director (Daniel Eisenstein), a Steering Committee with a representative from ARC and from each of the four surveys, and an extended management committee that includes a project manager, a project scientist, the four survey PIs, and several at-large members (see list below). The Steering Committee will eventually be replaced with an Advisory Committee that has representation from all of the participating institutions. This committee will operate under the aegis of the ARC Board of Governors and will have ultimate responsibility for direction of AS2.

The four survey PIs are David Schlegel (BOSS), Connie Rockosi (SEGUE-II), Steve Majewski (APOGEE), and Jian Ge (MARVELS). Each survey will also have a Project Scientist, and management support for hardware and software development as needed. Each survey already has a large and growing team of participating scientists, and the PIs and Project Scientists will organize these teams to handle the technical development for the survey and science analyses of the data. Although SEGUE-II and APOGEE explore common science themes, the hardware and software development are sufficiently disjoint that we treat them as two distinct surveys within the management structure.

Certain tasks require centralized approaches and do not fall under the survey teams. Observing operations will be centrally managed, likely with a structure similar to that of SDSS-II. The fiber and plug plate systems require a common design. Jim Gunn has been designated to oversee all hardware interfaces. Data processing will stay with the teams, but the data distribution system will be developed under central management. Survey planning and plate drilling will be similarly centralized.

We plan intermediate data releases from all the surveys. We anticipate that the first will be in summer 2010, releasing the SEGUE-II and BOSS data taken prior to summer 2009. Subsequent annual releases are planned, with the final release in December 2014. Because MARVELS is a monitoring survey, we expect that yearly releases are not the right unit of time, but we will have an intermediate release no later than summer 2011.

The detailed budget for the AS2 project is still under development, but we anticipate a cost of $45-$50 million US, of which $10 million is for instrument development, $15 million is for mountain-top operations, and $20-$25 million is for off-mountain operations including data processing and validation, creation of the public archive, and project management. For comparison, the SDSS-II project costs $15 million for three years of observations. The AS2 project is twice as long and involves the development or upgrade of three instruments and associated data analysis software.

We expect some savings on operations, data processing, and data distribution because the amount of new imaging data is quite small.

We hope to raise the funds from a partnership of institutions, including both US and foreign sources, US government agencies (NSF and DOE), and private foundations, most notably the Alfred P. Sloan Foundation, which made SDSS-I and SDSS-II possible.

Personnel

The program described here emerged out of a solicitation by the Astrophysical Research Corporation of proposals for use of the APO 2.5m and its instruments after the completion of SDSS-II. The proposal teams for the four surveys that comprise AS2 included 93 investigators from 47 institutions. We anticipate that many of these investigators and institutions will become members of the AS2 consortium.

This document, which draws heavily on these proposals and on input from the four survey teams, is submitted on behalf of the still-forming AS2 Consortium by the AS2 Management Committee and the AS2 Steering Committee. The current members of these committees are:

Management Committee

Daniel Eisenstein, University of Arizona (AS2 Director)

Jian Ge, University of Florida (MARVELS PI)

Bruce Gillespie, Apache Point Observatory (Program Manager)

James Gunn, Princeton University

Steven Majewski, University of Virginia (APOGEE PI)

Constance Rockosi, Lick Observatory (SEGUE-II PI)

David Schlegel, Lawrence Berkeley Laboratory (BOSS PI)

Michael Strauss, Princeton University

David Weinberg, Ohio State University (Project Scientist)

Steering Committee

Timothy Beers, Michigan State University

Holland Ford, Johns Hopkins University

Richard Kron, University of Chicago

Robert O'Connell, University of Virginia

Natalie Roe, Lawrence Berkeley Laboratory

Selective Bibliography

This bibliography lists a small fraction of the many papers relevant to AS2, with particular attention to SDSS-I and SDSS-II results that motivate the AS2 program.

THE SLOAN DIGITAL SKY SURVEY

Gunn, J. E., et al. 1998, “The Sloan Digital Sky Survey Photometric Camera,” AJ, 116, 3040

York, D.G., et al. 2000, “The Sloan Digital Sky Survey: Technical Summary”, AJ, 120, 1579

Stoughton, C., et al. 2002, “Sloan Digital Sky Survey: Early Data Release”, AJ, 123, 485

Blanton, M. R. et al. 2005, “New York University Value-Added Galaxy Catalog: A Galaxy Catalog Based on New Public Surveys,” AJ, 129, 2562

Strauss, M. A. & Knapp, G. R. 2005, “The Sloan Digital Sky Survey: 7000 square degrees, 700,000 spectra, and counting,” Sky and Telescope, February 2005, 34

Adelman-McCarthy, J.K., et al. 2007, “The Fifth Data Release of the Sloan Digital Sky Survey”, ApJS, in press

BARYON ACOUSTIC OSCILLATIONS AND BOSS

Eisenstein, D. J., et al. 2001, “Spectroscopic Target Selection for the Sloan Digital Sky Survey: The Luminous Red Galaxy Sample,” AJ, 122, 2267

Blake, C. & Glazebrook, K. 2003, “Probing Dark Energy Using Baryon Oscillations in the Galaxy Power Spectrum as a Cosmological Ruler,” ApJ, 594, 665

Seo, H.-J., & Eisenstein, D. J. 2003, “Probing Dark Energy with Baryon Acoustic Oscillations from Future Large Galaxy Redshift Surveys,” ApJ, 598, 720

Cole, S., et al. 2005, “The 2dF Galaxy Redshift Survey: power-spectrum analysis of the final data set and cosmological implications,” MNRAS, 362, 505

Eisenstein, D.J., et al. 2005, “Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies,” ApJ, 633, 560

Seljak, U. et al. 2005, “Cosmological parameter analysis including SDSS Lyα forest and galaxy bias: Constraints on the primordial spectrum of fluctuations, neutrino mass, and dark energy,” Phys Rev D, 71, 3515

Albrecht, A. et al 2006, “Report of the Dark Energy Task Force,” astro-ph/0609591

McDonald, P., & Eisenstein, D. 2006, “Dark energy and curvature from a future baryon acoustic oscillation survey using the Lyman-alpha forest,” astro-ph/0607122

Tegmark, M. et al. 2006, “Cosmological constraints from the SDSS luminous red galaxies,” Phys Rev D, 7413507

Percival, W. J. et al. 2007, “Measuring the Matter Density Using Baryon Oscillations in the SDSS,” ApJ, 657, 51

Padmanabhan, N. et al 2007, “The Clustering of Luminous Red Galaxies in the Sloan Digital Sky Survey Imaging Data,” MNRAS, in press, astro-ph/0605302

GALACTIC STRUCTURE, SEGUE-II, AND APOGEE

Majewski, S. R. 1993, “Galactic structure surveys and the evolution of the Milky Way,” ARA&A 31, 575

McWilliam, A. 1997, "Abundance Ratios and Galactic Chemical Evolution," ARA&A, 35, 503

Majewski, S. R., Ostheimer, J. C., Kunkel, W. E., & Patterson, R. J. 2000, "Exploring Halo Substructure with Giant Stars. I. Survey Description and Calibration of the Photometric Search Technique," AJ, 120, 2550

Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2001, "Hierarchical Galaxy Formation and Substructure in the Galaxy's Stellar Halo," ApJ, 548, 33

Freeman, K. & Bland-Hawthorn J. 2002, "The New Galaxy: Signatures of Its Formation," ARA&A, 40, 487

Newberg, H. J., et al. 2002, "The Ghost of Sagittarius and Lumps in the Halo of the Milky Way," ApJ, 588, 824

Yanny, B., et al. 2003, "A Low-Latitude Halo Stream Around the Milky Way," ApJ, 588, 824

Beers, T.C., & Christlieb, N. 2005, "The Identification and Analysis of Very Metal-Poor Stars in the Galaxy," ARA&A, 43, 531

Bullock,, J. S., & Johnston, K. V. 2005, "Tracing Galaxy Formation with Stellar Halos I: Basic Methods," ApJ, 635, 931

Odenkirchen, M. et al. 2005, "The Extended Talks of Palomar 5: A 10° Arc of Globular Cluster Tidal Debris," AJ, 126, 2385

Willman, B. et al. 2005, "A New Milky Way Dwarf Galaxy in Ursa Major," ApJL, 625, 85

Belokurov, V., et al. 2006, "The Field of Streams: Sagittarius and its Siblings," ApJL, 642, 137

Skrutskie, M. et al., 2006, "The Two Micron All Sky Survey (2MASS)," AJ, 131, 1163

Belokurov, V., et al. 2007, "Cats and Dogs, Hair and a Hero: A Quintet of New Milky Way Companions," ApJ, 564, 897

EXTRA-SOLAR PLANETS AND MARVELS

Mayor, M. & Queloz, D. 1995, "A Jupiter-Mass Companion to a Solar-Type Star," Nature, 378, 355

Marcy, G. W. & Butler, R. P. 1996, "A Planetary Companion to 70 Virginis," ApJL, 464, 147

Erskine D. & Ge, J. 2000, "Novel Interferometer-Spectrometer for Sensitive Stellar Radial Velocimetry," Proc. Imaging the Universe in Three Dimensions, ASP Conference Vol. 195. Eds. W. van Breugel and J. Bland-Hawthorn, p.501

Ge, J. 2002, "Fixed-delay Interferometry for Doppler Extra-Solar Planet Detection," ApJ Letters, 571, L165

Ge, J., Erskine, D.J., & Rushford, M. 2002, "An Externally Dispersed Interferometer for Sensitive Doppler Extra-solar Planet Searches," PASP, 114, 1016

Marcy, G., Butler, R.P., Fischer, D., Vogt, S., Wright, J.T., Tinney, C.G., & Hugh, R.A.J. 2005, "Observed Properties of Exoplanets: Masses, Orbits, and Metallicities," Prog Theor Phys Supp, 158, 24

Ge, J., et al. 2006, "The First Extrasolar Planet Discovered with a New-Generation High-Throughput Doppler Instrument," ApJ, 648, 683

Udry, S., Fischer, D. & Queloz, D. 2007, "A decade of radial-velocity discoveries in the exoplanet domain," in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil (eds.), University of Arizona Press, Tucson, 951 pp., 2007., p.685-699