MARVELS: Revealing the Formation and Dynamical Evolution of Giant Planet Systems

White Paper for the Astro2010 PSF Science Frontier Panel

Submitted by the SDSS-III Collaboration

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ABSTRACT

MARVELS, the Multi-Object APO Radial Velocity Exoplanet Large-area Survey, is a 6-year program to characterize the distribution of gas giant planets with orbital periods ranging from several hours to two years. MARVELS will use multi-fiber interferometric spectrographs on the wide-field, 2.5-meter Sloan Foundation telescope at Apache Point Observatory to monitor $\sim 11,000$ stars in the magnitude range $V = 8-12$, visiting each star ~ 30 times over an 18-month interval, with velocity precision of ≈ 14, 18, and $35\,\mathrm{m\,s^{-1}}$ at $V = 8$, 10, and 12. MARVELS will survey far more stars with a wider range of spectral types and metallicities than previous radial velocity searches, yielding a statistically well defined sample of ~ 150 giant planets drawn from a host sample with well understood selection biases. With a unique combination of large numbers and well characterized sensitivity, MARVELS will provide a critical data set for testing theories of the formation and dynamical evolution of giant planet systems. The MARVELS detections will also be an ideal sample for follow-up observations to identify multiple planet systems and understand the influence of giant planet migration on the formation and survival of less massive planets. MARVELS is one of four surveys that comprise SDSS-III (the Sloan Digital Sky Survey III), a 6-year program that will use highly multiplexed spectrographs on the Sloan Foundation Telescope to investigate cosmological parameters, the history and structure of the Milky Way galaxy, and the population of giant planet systems.

1. Introduction

The success of extra-solar planet searches has been one of the most remarkable astronomical developments of the last two decades. While a variety of search methods are now bearing fruit, most of the known planets have been discovered by radial velocity surveys, and these samples are the basis of most statistical characterizations of the exoplanet population. Exoplanets reveal an astonishing diversity of masses, semi-major axes and eccentricities, from the short period "hot Jupiters", to planets in very elongated orbits, to planetary systems with multiple Jupiter-mass planets, to the super-Earth-mass planets with orbital periods of a few days (see Udry & Santos 2007 for a review of the properties of known exoplanets). If any single statement captures the development of this field, it is that the observations have continually revealed unanticipated diversity of planetary systems.

The standard, core accretion scenario of giant planet formation (Pollack et al. 1996) predicts that planets like Jupiter form in nearly circular orbits, with periods of several years or more. Growth is initiated by coalescence of icy bodies, which cannot survive close to the parent star; once the solid core reaches $5 - 10$ Earth masses its gravity is strong enough to rapidly accrete surrounding gas and grow to Jupiter-like masses. The two greatest surprises of extra-solar planetary discoveries have been that many giant planets have periods below one year, sometimes as short as one day, and that many of these planets are on highly eccentric rather than circular orbits. The first finding suggests that many giant planets "migrate" inward after their formation. Several migration mechanisms have been proposed, including dynamical interactions between planets and their natal gas disks, and strong planet-planet gravitational scattering. The latter migration mechanism may also explain the origin of the high orbital eccentricities.

The Multi-Object APO Radial Velocity Exoplanet Large-area Survey (MARVELS) will use fiber-fed interferometric spectrographs to monitor the radial velocities of 11,000 bright stars, with the precision and cadence needed to detect giant planets with orbital periods ranging from several hours to two years. Our forecasts predict that MARVELS will discover ~ 150 new planets, mostly in the range of $0.5 - 10$ Jupiter masses. The large sample size, comprehensive coverage of stellar hosts, and well-defined statistical sensitivity will make MARVELS a critical data set for testing models of the origin and dynamical evolution of giant planet systems and the phenomenon of giant planet migration. MARVELS will complement other searches, which will be sensitive to lower-mass or longer-period planets but will not detect nearly as many 'dynamically evolved' giant planets, i.e., giant planets in the intermediate period regime where dynamical evolution was likely important in shaping the distribution of planet properties.

MARVELS is 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 fund-raising 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 data sets that will shape the environment for other activities. We also want 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 such proposals that may come forward in the next decade.

2. Description of MARVELS

The key technical innovation behind MARVELS is a multi-fiber instrument that combines a fixed-delay interferometer with moderate dispersion spectrographs (Erskine & Ge 2000; Ge 2002; Ge et al. 2002). This approach allows simultaneous, high throughput, high velocity precision measurements of many objects using reasonable detector sizes. This technology is well matched to the wide field (7 deg^2) spectroscopic capability of the Sloan Foundation 2.5-m telescope. The first MARVELS instrument is a 60-fiber spectrograph with a monolithic interferometer. We anticipate adding a second, similar instrument in late 2010.

[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`.

MARVELS operates during bright time, while other SDSS-III (BOSS and SEGUE-2) surveys operate in dark time; from 2011-2014 MARVELS will carry out simultaneous operations with the infrared Galactic structure survey APOGEE, sharing the focal plane. The SDSS optical spectrographs will be used to obtain optical spectra and stellar parameters of all program stars, so the properties of the full target population will be well characterized.

The first MARVELS instrument was commissioned in September 2008. With this instrument, we have demonstrated calibration lamp image stability equivalent to ~ 3 m s^{-1} RMS stellar RV precision. On-sky, even in the presence of higher-than-normal environmental disturbances during our commissioning observations, our first preliminary analysis achieved ~ 12 m s^{-1} RMS RV precision on the RV-stable star HD 9407 ($V = 6.5$) in 144 second exposures, only $\sim 30\%$ larger than the photon-noise limit of ~ 9 m s^{-1}. For the known planet-bearing star TrES-2 ($V = 11.4$), we achieved ~ 30 m s^{-1} RV precision in 40-60 minute exposures over ~ 6 commissioning nights. See Figure 1. Overall, in 50-minute exposures, the MARVELS spectrograph yields photon-noise limited radial velocity errors of approximately 3.5, 8.5, and 21.5 m s^{-1} at $V = 8$, 10, and 12. The minimum goal for velocity precision including all sources of systematic error is 14, 18, and 35 m s^{-1} at these magnitudes, though we expect improvements in the analysis pipeline and modest improvements in the instrument thermal control to bring the measurement precision closer to the photon-noise limit. Normal MARVELS survey operations commenced in Oct. 2008, and we have already detected several candidate radial velocity variables.

Detailed simulations of observing strategies prior to the survey commencement led to a design in which each program star is visited ~ 30 times over an 18-month period, with sampling that provides sensitivity on all period scales within this interval. Assuming that a second 60-fiber instrument is available for the final four years of the survey, MARVELS will search about 10,000 main sequence stars and 1,000 giant stars for planets. Figure 2 shows the projected sensitivity of MARVELS in different mass and period ranges, based on (conservative) estimates of radial velocity errors consistent with the initial survey data and given above. Forecasts based on currently known planet statistics predict that MARVELS will detect ~ 150 planets in the mass range $M \sin i \approx 0.5 - 10 M_{\rm Jup}$. In the mass and period range that MARVELS probes, it will provide a factor of several increase over the largest homogeneous and statistically complete samples currently available (Fischer & Valenti 2005; Cumming et al. 2008).

MARVELS will provide a powerful data set for testing the emerging, detailed models of planet formation, migration, and dynamical evolution (e.g., Ida & Lin 2004; Alibert et al. 2005; Kornet et al. 2005, Ford & Rasio 2008). These models incorporate different assumptions about initial conditions and about the physical mechanisms that govern planet growth and orbital evolution. They make quantitative statistical predictions for the joint distributions of planet mass, semi-major axis, and orbital eccentricity, and for the dependence of planet frequency and orbital properties on the mass and metallicity of the host star. The predictions can be tested by combining them with star-by-star efficiency calculations, and these tests can incorporate both detections and non-detections in a statistically rigorous fashion. The short- and intermediate-period systems probed by MARVELS are especially important for understanding the physics of planet migration and for testing theories that address the puzzling preponderance of planets with large eccentricities.

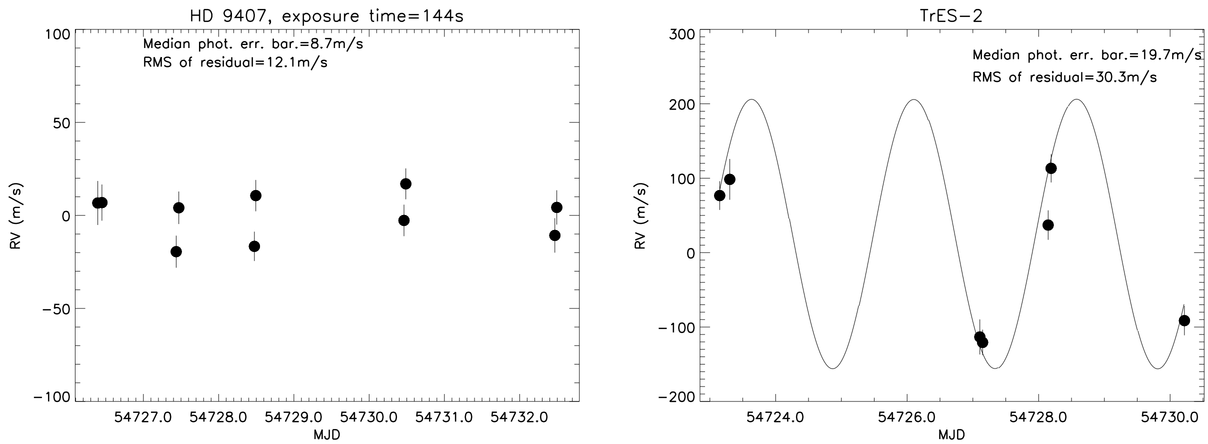

Figure 1: MARVELS Sep. 2008 commissioning observations of HD 9407 (left), a known RV-stable star with $V = 6.6$, and TrES-2, a known planet-hosting star with $V = 11.4$.

The broad selection of target stars will make MARVELS ideal for studying the correlation of planetary systems with stellar metallicity, mass, multiplicity, age, evolutionary stage, activity level, and rotation velocity. For example, the observed correlation of planet frequency with metallicity (Santos et al. 2004; Fischer & Valenti 2005) may favor the core accretion model of planet formation over the gravitational instability model (Boss 1997), or it may simply be a signature of a metallicity-dependent migration rate (Livio & Pringle 2003). By targeting a large number of lower metallicity stars, MARVELS will provide a more robust determination of the planet-metallicity correlation, and so provide important constraints on models that seek to explain it.

The host stars of the MARVELS planet detections will be valuable targets for longer term, higher precision radial velocity monitoring to detect longer period and/or lower mass companions. For example, we would like to know what fraction of systems with migrated giant planets have surviving lower mass planets at smaller separations, or massive long-period planets. With a well characterized primary survey and a well designed follow-up program, the two-stage selection effects of such a survey are straightforward to apply to predictive models. The large number of targets also makes MARVELS sensitive to rare classes of planetary systems that would be largely missed by smaller surveys: systems in the “brown dwarf desert,” massive hot Jupiters, rapidly interacting multiple planet systems, very-hot Jupiters, and/or planets with extremely high eccentricities.

Finally, a wide range of auxiliary science can also be extracted from the MARVELS dataset. For example, MARVELS will discover a large number of binary stars, which can be used to construct a relatively unbiased sample of binary orbital elements, as well as determine the close binary fraction as a function of primary mass and metallicity. Some fraction of these binary systems will also be eclipsing, and follow-up RV and photometric observations of particularly interesting eclipsing binary (EB) systems can be used to test models of low-mass stars and brown dwarfs. Double-lined eclipsing systems can be used to test stellar models by providing model-independent physical properties (i.e. masses, radii, gravities) for both stars, and eclipsing systems with very low-mass secondaries can be used

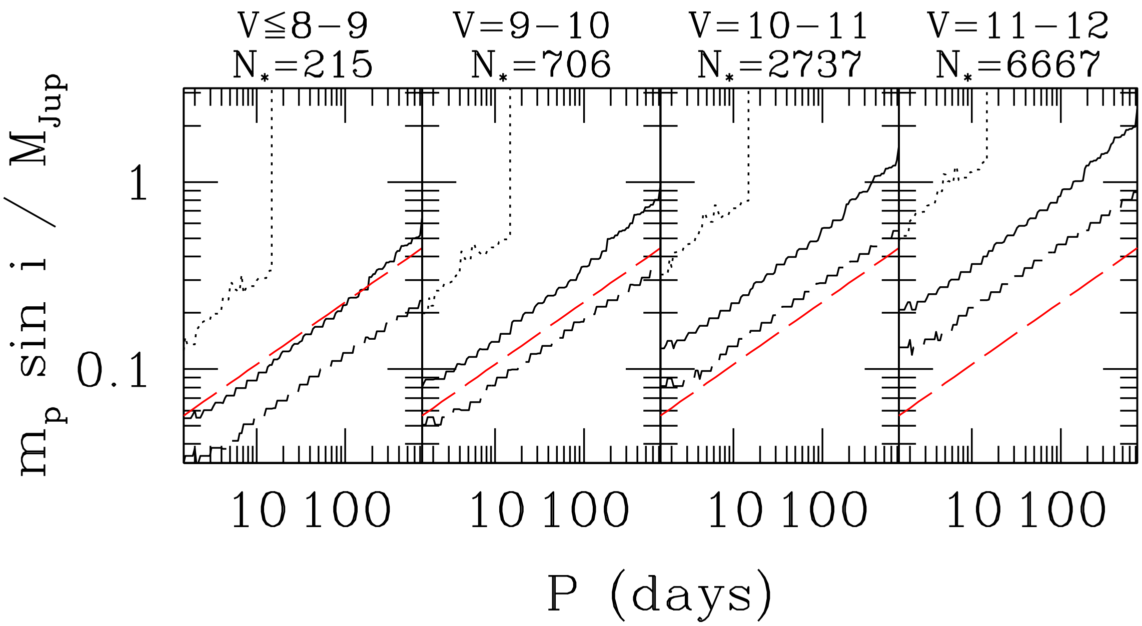

Figure 2: The efficiency of MARVELS planet detection for four different ranges of stellar apparent magnitude V. The number of stars in each magnitude range that would be monitored in the baseline survey is listed above each panel. Lines show contours of constant planet detection efficiency for host stars of the indicated brightness. At each period P, MARVELS would detect 95% of planets above the mass threshold $m_p \sin i$ indicated by the dotted line, 50% above the solid line, and 5% above the dashed line. Long-dashed lines show the locus of a planet with a 10 m/s orbital velocity in a circular orbit about a solar-mass star.

to study the mass-radius relationship of objects near or below the hydrogen burning limit.

3. Conclusions

The great scientific opportunities in the field of extra-solar planets have sparked an explosion of new instruments and new methods for planet searches. In terms of the range of planet masses and separations to which it is sensitive, MARVELS will complement ongoing and planned radial velocity, transit, microlensing, and astrometric surveys, which probe lower mass or longer period systems but will not yield a comparably large sample of 'dynamically evolved' giant planets. The regime probed by MARVELS is crucial to understanding the physics of giant planet migration and dynamical interaction, and thus important for understanding the overall physics of the formation and evolution of planetary systems. MARVELS will also set the stage for larger-scale, higher-precision multi-fiber radial velocity searches, which will likely be pursued in the second half of the decade. These future surveys will provide exoplanet samples vastly larger than those that exist today, with radial velocity precisions of ~ 1 m s^{-1}, similar to the best precisions available with current single-object RV instruments, and sufficient to detect planets with mass as low as several times the mass of the Earth.

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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