FERMILAB-PROPOSAL-0949

A PROPOSAL BY THE ASTROPHYSICAL RESEARCH CONSORTIUM TO THE ALFRED P. SLOAN FOUNDATION

February 2004

Period of Performance July 2005 to July 2008

I. Introduction

The scientific goals of the Sloan Digital Sky Survey (hereafter SDSS) focused on extragalactic themes, including the large-scale structure seen in the distribution of galaxies over very large volumes; a detailed characterization of galaxy properties and how these depend on galaxy clustering; and the quasar luminosity function and how it evolves. The observing and data systems were designed for such investigations. At the time, it was recognized that the excellent quality and enormous volume of the data produced by these systems would support a vast number of other scientific programs, and so it has turned out. In particular, the SDSS has made great progress in two other important areas, Galactic structure and time-domain studies.

The SDSS is funded to operate through mid-2005. All of the operations are working smoothly and with an efficiency limited only by the atmospheric conditions at the site, Apache Point Observatory (APO). In 2005 and for years thereafter, the hardware and software systems of the SDSS will still be unmatched by any other facility for large-scale survey observations, and much sky will remain to be explored.

The combination of significant impact on cosmological problems, the ability to make contributions to other major fields of astronomy, and the efficiency of current and future operations, impel us to seek new resources for continued operations. The outlook as we make this proposal to extend the SDSS is entirely different from several years ago, when we faced the challenges of getting SDSS up and running. We are now in full operations mode, have a well developed archive that has delivered our first major data release, and the SDSS data are having a major impact in many scientific fields.

This proposal covers the interval mid-2005 to mid-2008 (three years) and includes a combination of programs: a new systematic study of the stellar density, chemical, age and kinematic distributions in the halo and disk(s) of the Milky Way Galaxy (SEGUE); continued work on the large scale structure of the Universe, now aimed at constructing the largest possible single survey volumes (Legacy); and a survey to determine Type Ia supernova light curves with five-band photometry which will provide an important constraint on the rate of expansion of the Universe in the redshift interval $0.1 < z < 0.3$. Because of the complementary nature of these programs in their demands for observing time, their combination maximizes the effective exploitation of the facilities at APO. The programs also complement one another in terms of common overarching scientific goals and common efforts to maximize the data quality in support of those goals. They are summarized in this proposal and described more fully in documents available at http://www.sdss.org/extension/.

The SDSS Project Book (http://www.astro.princeton.edu/PBOOK/) describes the goal of covering a quarter of the sky in a contiguous area of π steradians (about 10,000 square degrees) in the North Galactic Cap (NGC). At about the time that SDSS began survey operations, the Five Year Baseline was developed to provide a metric against which actual progress could be evaluated. The Five Year Baseline was less ambitious than the Project Book goals, suggesting that only $\sim 70\%$ of the NGC area would be covered by mid-2005. The plan was to undertake imaging and spectroscopy for the first four years, and then dedicate the last year to spectroscopy so that the two (spectroscopic and imaging) aspects of the SDSS would finish with more-or-less the same footprint. If, instead, we continue to image at the maximum possible rate, then by mid-2005 we achieve the goals of the Five Year Baseline in the imaging survey. However, the spectroscopic rate continues to be lower than we had anticipated even with the more conservative assumptions of the Five Year Baseline. (The detailed reasons for the shortfall with respect to the baseline have been reviewed in our Quarterly Reports: http://tdserver1.fnal.gov/sdss/qtr-reports/qtrly-reports.htm). By mid-2005, we expect to have achieved 80% of the baseline spectroscopic goals, where the spectroscopic footprint will not form a single, contiguous area. Finishing the baseline and creating a contiguous map ("filling the gap") is one of the primary motivations for the Legacy survey described in Chapter III.

The mission of the SDSS is to create a data base of unprecedented size, quality and ease of access to support studies of the large scale structure of the Universe. Even in its present unfinished form, the SDSS has had a major impact on this and many other areas of science. SDSS participants have written more than 350 papers for the refereed journals and for conference proceedings. A very successful conference on SDSS contributions to the science of active galactic nuclei (AGN) has been held. More than 50 papers based on SDSS data from the Early Data Release (EDR) and the First Data Release (DR1) have been written by astronomers outside the SDSS. Among the highlights of SDSS contributions to cosmology are direct measurements of the masses of galaxies, galaxy clusters and the bias factor from weak and strong lensing; the detection of the integrated Sachs-Wolfe effect, in which the energies of photons from the Cosmic Microwave Background (CMB) are altered by passage through density lumps produced by clustered matter; measurement of the cosmological power spectrum and the cosmological density parameters; the discovery of the highest-redshift quasars and the epoch of re-ionization of the Universe; and the first clear detection of departures from a power law correlation at small scales. In addition, SDSS has made major contributions to other areas. The repeat imaging of the equatorial region of the South Galactic Cap (SGC) has produced time-variability studies of quasars and discovered hundreds of new variable stars. Tidal streams from the breakup of infalling satellites have been found, including the discovery of diffuse large-angle streams around the Galaxy, of tidal debris from the loosely bound globular cluster Pal 5, and the discovery of a possible ancient tidal stream around the Andromeda galaxy. A complete sequence of the lowest luminosity stars and the objects below the end of the main sequence, the brown dwarfs, has been established. New kinds of white dwarf stars have been found, including the coolest such object discovered to date. SDSS has produced by far the largest catalogue of multicolor photometry of asteroids, demonstrating the common origins of families of these objects. Some of these discoveries have inspired the new work described in this proposal.

II. SEGUE

We propose to use the SDSS hardware, software and infrastructure to undertake a major survey of the Galaxy aimed at a systematic study of its structure. This new imaging and spectroscopic survey, SEGUE (Sloan Extension for Galactic Underpinnings and Evolution) will image about 3,500 square degrees of the Galaxy at lower Galactic latitudes and measure spectra of a quarter of a million stars. The goal of SEGUE is to unravel the structure, formation history, kinematical and dynamical evolution, chemical evolution, and dark matter distribution of the Milky Way. These results will underpin our knowledge of the formation of the Milky Way Galaxy and will be the cornerstone of our understanding of galaxy formation processes in general. The data will enable discovery of all major halo substructures, including relic streams from merger events. Low Galactic latitude imaging and spectroscopy enable studies of the metal-rich Galactic thin disk, the vertical structures of the thin and thick disks, the disk-halo interface, and the warping and flaring of the Galactic disks. In this chapter we first summarize Galactic structure results obtained from the existing SDSS, and then describe how this new survey will be carried out.

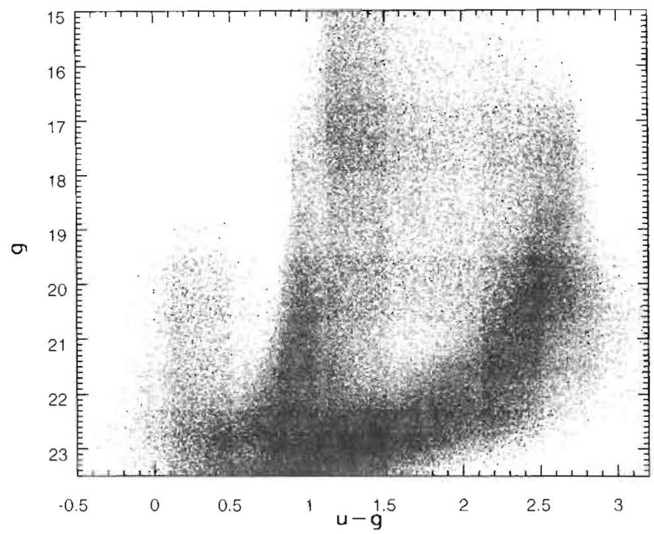

Figure 1. Example SDSS color-magnitude diagram for 220,000 point sources from 60 square degrees of co-added data in the SGC. These data allow the exploration of stellar halo substructure samples with well constrained absolute magnitudes (e.g. main sequence turnoff stars) and Galactic extinction using sharp features in color space, e.g. the "blue edge" or "blue tip" due to metal-poor halo turnoff F stars.

Some SDSS terminology is required for the following discussion. The SDSS camera contains an array of CCDs arranged in six columns of five CCDs, each column containing the SDSS *ugriz* filters. Data are taken in time-delay-and integrate (TDI) mode, and the camera produces six *scanlines* of data, separated by just under the width of the CCDs (about 13 minutes of arc on the sky), which together form an unfilled *strip*. A filled *stripe* is observed by repeating the scan with the camera offset. During data processing, the imaging data are divided into $9' \times 13'$*fields*. The spectroscopy is observed with 3° diameter plug plates obtaining 640 spectra simultaneously.

1. SDSS Stellar Data and Galaxy Science

Figure 1 shows a color-apparent magnitude diagram for point sources in part of the SDSS SGC survey; the sharp edges in the diagram demonstrate the high quality of the photometry. From such diagrams, one can color-select samples of stars which have a narrow range in absolute magnitude, allowing the halo to be mapped on large scales. Samples include the very numerous turnoff (or blue-tip) stars ($u-g \sim 0.9$), with absolute g magnitudes around 4.2; and the blue horizontal branch (BHB) stars ($u-g \sim 1.1$), and low metallicity G and K giants ($u-g \sim 3$), with $M_r \sim 0.6$. Apparent magnitude then serves a proxy for distance (Newberg et al. 2002) and maps the three-dimensional distribution of stars in the halo. The stellar halo is found to be far from smooth, and shows large features due to the Sagittarius dwarf tidal stream (Yanny et al. 2000; Ivezić et al. 2000), the tidal tails of Palomar 5 (Figure 2, Odenkirchen et al. 2001), and a new low-latitude stream, the Monoceros stream (Newberg et al. 2002; Yanny et al. 2003), as well as large-scale gradients suggesting a non-spherical halo. These results place the SDSS in the forefront of efforts to investigate the merger history of the Galaxy. In particular, the depth of the SDSS (stars can be separated from galaxies to about 21.5 magnitudes) means that the high-luminosity halo stars such as BHB stars can be identified to distances of 100 kpc (Newberg et al. 2003).

Proper motion data have also been obtained for many millions of stars by comparing SDSS positions with those of digitized photographic surveys such as USNO-B (Munn et al. 2004). These allow the measurement of the kinematic properties of the thick disk, the thin disk and the halo (Figure 3).

In addition, SDSS has acquired spectra of tens of thousands of stars. The radial velocities for the stars brighter than about g=18 can be determined to better than 10 km/sec, as shown by tests on cluster stars of known radial velocity. The halo streams are easily detected in radial velocity distributions (Yanny et al. 2000; Newberg et al. 2002), with velocity dispersion of about 20 km/sec. The spectra further allow discrimination between giant and dwarf stars (Yanny et al. 2000; Sirko et al. 2004) and metallicity determinations to about 0.25 dex. Figure 4 shows the distribution of metallicities for the sample of turnoff stars from SDSS DR1. About 1000 stars with 1% or less of the solar metallicity are found in this sample, equal to the sum total of such stars found in all other surveys to date.

2. Science Case

Our understanding of galaxy evolution has advanced considerably since the monolithic collapse model of Eggen, Lynden-Bell & Sandage (1962) was adopted as the standard. Most astronomers now believe that the Galaxy was built up through a series of mergers (Searle & Zinn 1978) although there is no agreement on the number and size of the merger events. These current models of galaxy formation are motivated by cold dark matter (CDM) simulations that show the outer halos of galaxies accreting over billions of years (Steinmetz & Navarro 2002) and from the discovery of substantial spatial and kinematic inhomogeneities due to tidal disruption of smaller stellar systems in the halo of the Galaxy (Irwin & Hatzidimitriou 1995; Grillmair et al. 1995; Ibata, Gilmore & Irwin 1995; Majewski, Munn & Hawley 1996; Helmi et al. 1999; Odenkirchen at el. 2001; Newberg et al. 2002; Majewski et al. 2003). Evidence of mergers is currently most apparent in the outer halo, where because of the long dynamical times, signatures of satellite accretion persist for many billions of years (Johnston, Spergel & Hernquist 1995). It is also possible

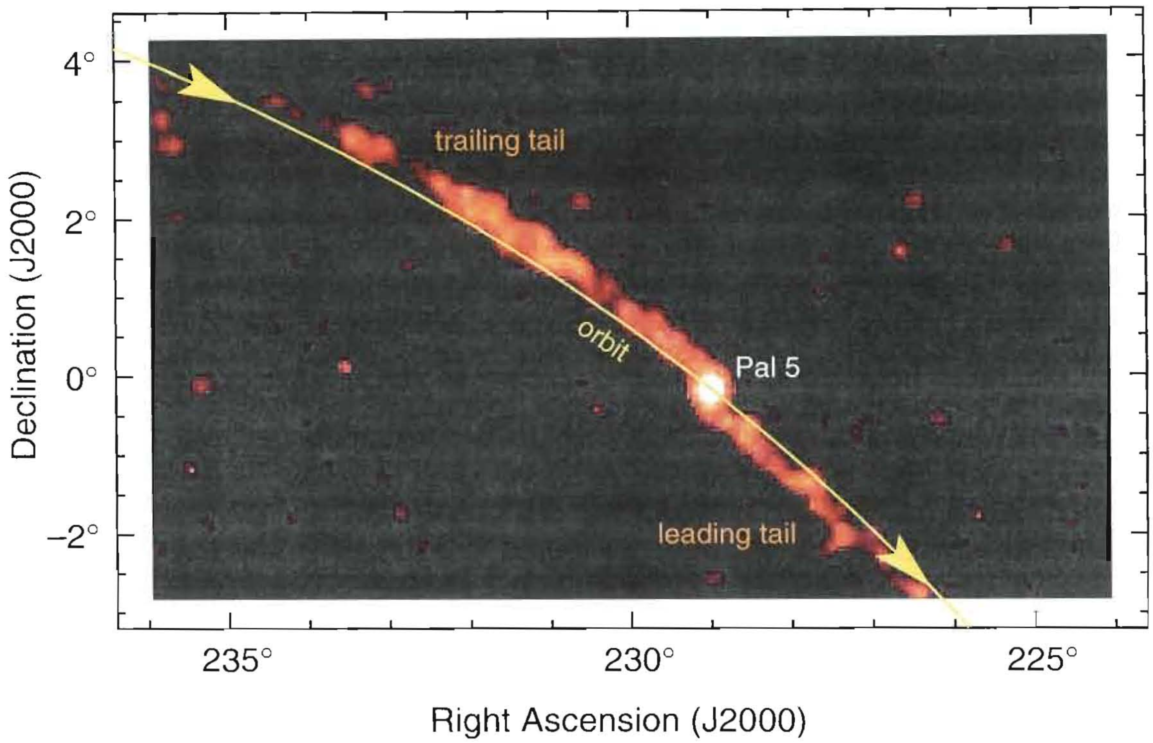

Figure 2. Surface density of stars associated with the globular cluster Pal 5. The tidal tails contain 1.2 times as much stellar mass as does the cluster, showing that it is in the process of being disrupted. The structure of such tidal tails is a sensitive probe of the structure of the dark matter halo.

that small dark matter lumps which do not contain stars exist in the outer halo and have not yet merged (Bullock, Kravtsov & Weinberg 2000); these could be detected by their perturbation of tidal tails and warping of disk structures.

Our own Milky Way is the only galaxy we can currently study at sufficiently high spatial and kinematic resolution, and to sufficient depth, to address many of the open questions in galaxy formation and structure at subgalactic masses. SEGUE will use its large data base to tackle key questions:

Halo substructure: Disentangling the structure of the halo requires that individual stellar associations can be separated by population (age and metallicity), kinematics, and spatial density. The SDSS and SEGUE photometry will give photometric parallaxes; isochrone fitting sorts the stars into rough age and metallicity bins. SEGUE spectroscopy and proper motions (available for the entire SEGUE area) will enable further separation of halo components by kinematics and chemical abundance. Observations of open clusters will be made to provide calibration of stellar physical and chemical properties. Dynamical analysis of stellar streams allows us to fit the Galactic potential's shape and orientation and constrain the lumpiness of the dark matter halo.

Disk Structure: SEGUE will use spectra (physical properties, chemical composition and radial velocities), photometry (stellar populations and spatial density) and proper motions

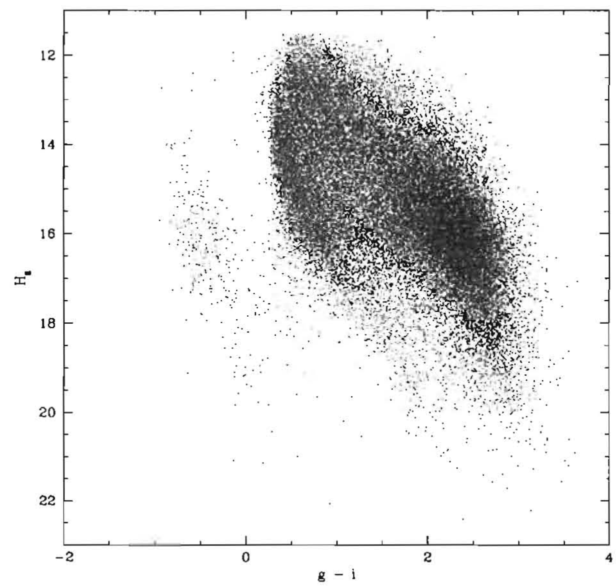

Figure 3. Reduced proper motion diagram (H = g + 5 + 5 log μ) for stars with 16<g<19.5 and μ > 20 mas/year for part of SDSS DR1. The three groups of stars are (from red to blue) the main-sequence disk, the high-velocity thick disk and the white dwarf sequence.

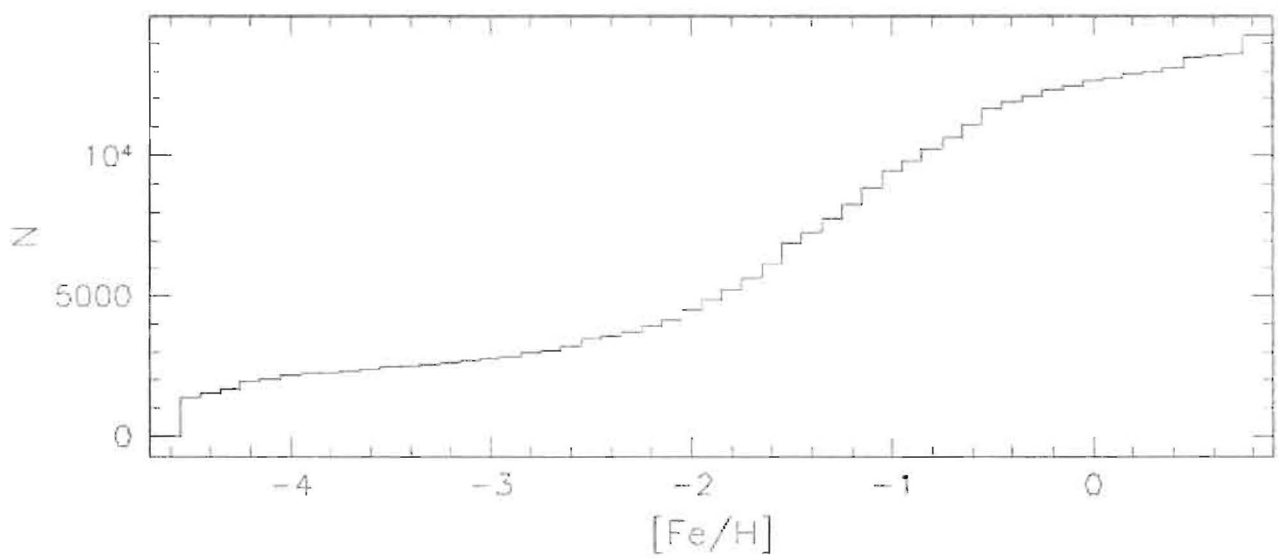

Figure 4. Cumulative metallicity distribution function for the DR1 turnoff stars. The total number of stars with [Fe/H] < −2.0 is about 1000.

to separate the Galactic components in the Solar neighborhood (see Figure 3). SEGUE data at low Galactic latitude will allow us to systematically study the space density, Galactocentric rotation velocity and velocity ellipsoid, chemical abundance and age of stars as a function of position in the Galaxy. This will be an ideal data set for tracing the transitions from thin disk to thick disk to inner halo (Chiba & Beers 2000; Gilmore, Wyse & Norris 2002).

Formation History and Chemical Evolution: SEGUE is an archaeological dig into the fossil record of galaxy evolution. We will search for the rare, extremely low metallicity stars which have abundances characteristic of the earliest stages of star formation in the Universe (an epoch that is currently being explored by SDSS's discovery of very high redshift quasars). We expect to identify many thousands of stars with [Fe/H] < -3.0, and hundreds with [Fe/H] < -4.0, providing an unprecedented probe of the chemical evolution of the early Galaxy.

The results obtained from the SDSS data have, so far, been confined to high Galactic latitudes. Mapping the very large structures in the halo, and investigating the interface between the halo and thick disk, requires observations at all Galactic latitudes. We propose an imaging survey extending to low latitudes, covering as much sky as is visible from APO and closely sampled enough to detect all large halo features. This includes imaging and spectroscopy of the Sgr stream. Spectral plates will be designed from SDSS and SEGUE photometry to trace all the large scale features and to reach a depth corresponding to the outer reaches of the halo, at 100 kpc.

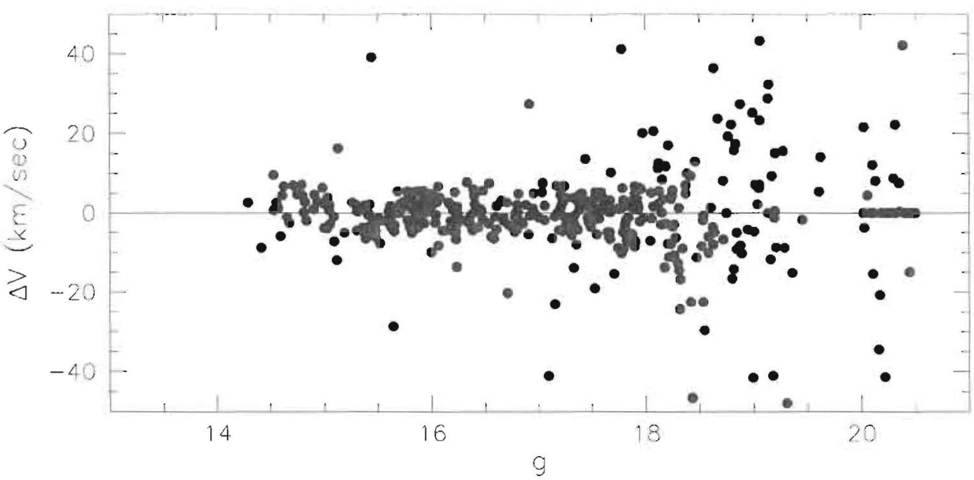

Figure 5. Radial velocity differences as a function of apparent g magnitude for independent observations of Plate 1664. The radial velocities have no systematic shift and an rms dispersion of 5 km/sec for the brighter stars (g<18.2).

3. The Proposed SEGUE Observing Strategy

SEGUE's imaging and spectroscopic surveys are designed to find and and characterize all large-scale components of the Galactic halo. The proposed sampling interval of approximately 10° is smaller than the scale of known halo streams and than the known variation in the global properties of the Galaxy's disks. We will survey in stripes which probe the Galaxy over the entire sky available from the APO (27,000 square degrees). The preliminary science plan is shown in Figure 6. The imaging consists of: (a) twelve constant-longitude stripes which go through the Galactic plane and extend into the SDSS NGC and SGC areas to help with photometric calibration. These stripes are roughly every 20° of longitude, but their exact locations are adjusted to pass through open clusters for use as calibrators; (b) three stripes on the SDSS system which interleave the SDSS SGC stripes and provide better coverage; (c) a strip along the great circle defined by the Sagittarius dwarf tidal stream; and (d) two low-latitude strips to aid in photometric cross-calibration and to follow low-latitude streams, including the newly-discovered Monoceros stream. The total area of new sky to be imaged is about 3,500 square degrees.

The spectroscopic targets will be selected from both SDSS and SEGUE imaging. The spectroscopic survey is a set of 3° fields in each of 200 sky directions, sampling closely enough to obtain several plates per expected coherent halo structure so that it can be followed around the sky, and covering Galactic latitudes down to 10° to examine the relationship between the disks and halo. Two plates will be observed in each field, one normal exposure plate for the brighter stars, and one double-length plate for the fainter stars. These are observed to a limit of $g = 20.3$, i.e., for turnoff and blue horizontal branch stars, to the edge of the Galaxy. An additional set of special plates will sample the Sgr stream and clusters with a range of metallicities for calibration.

4. Tests and Development

Rather little is needed in the way of further technical development. The existing SDSS spectroscopic pipelines do an adequate job of measuring radial velocities, even for faint (>18 mag) stars, as shown by both external tests (observations of clusters with known radial velocities) and internal tests (repeat independent observations; an example is shown in Figure 5). A small amount of further development, mostly to improve the templates and template fitting, and measure metallicity indicators (cf. Figure 4) is required.

5. Data at Low Galactic Latitudes

The proposed SEGUE imaging scans (Figure 6) pass through the Galactic plane. Our test data taken to date reveal several essential characteristics: (1) because of the TDI imaging mode, the SDSS camera is not strongly affected by transients and data overflow in the CCDs caused by very bright stars; (2) the areas affected by bright stars, within which other objects cannot be found, are only a few arcminutes across and affect less than 7% of the sky; and (3) the photometric pipeline can adequately reduce essentially all of the data required for SEGUE.

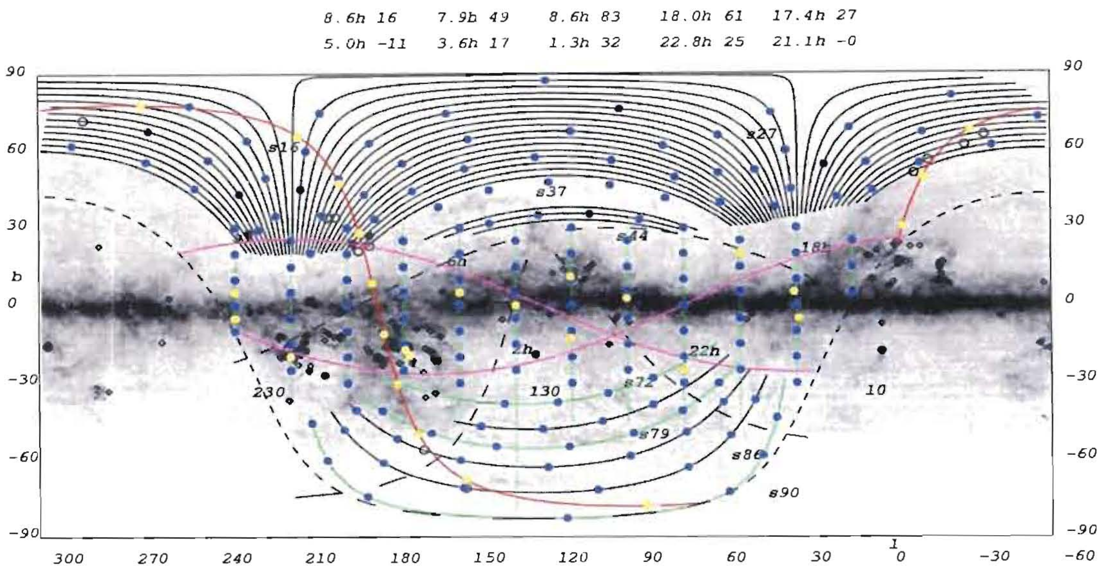

Figure 6. Preliminary low-latitude imaging and spectroscopic observing plan for SEGUE in Galactic coordinates, superposed on the dust emission/extinction map of Schlegel, Finkbeiner & Davis (1998) (grey scale). The solid black lines show the imaging scans already obtained or which will be obtained by the end of the SDSS baseline survey. The dotted black line shows δ = -20^o, the practical southern limit for observations from APO. The black dashed lines show for reference constant right ascensions of $\alpha = 18^h$, 22^h, 02^h and 06^h. Filled black circles show the positions of known Monoceros stream stars and open black diamonds the positions of Galactic open clusters.

The SEGUE targets are shown in color. The green lines show proposed new SEGUE imaging. The constant-longitude scans will probably be extended further into the SDSS area for calibration purposes. That at $\ell = 110^o$ has already been observed from b = -30^o to b = $+30^o$ as a test of the ability of the SDSS system to carry out SEGUE (see text). The magenta lines are half-filled strips at low Galactic latitude. The red line is the Sagittarius stream scan (see text). The blue circles show the locations of the proposed Galactic structure plate pairs, and the yellow circles the locations of special plates - along the Sgr stream and of star clusters for metallicity calibration.

6. Interstellar Extinction

Maps of the star distribution in the halo would be distorted if the extinction corrections were not properly made. As Figure 1 shows, there is a very well defined blue edge in color-magnitude diagrams for high latitude stars. The color of this blue edge is metallicity dependent, with thick disk stars being about 0.15 mag redder than halo stars, but these components are distinct. The variation in the color of the blue edge thus gives an excellent measure of the reddening and the form of the extinction law because these stars are so numerous, as we have found by checking the technique against the dust maps of Schlegel, Finkbeiner & Davis (1998). The three dimensional distribution of extinction, necessary for studies of the disk stars, can be measured using the lower luminosity, very numerous dwarf K and M stars. A well-defined absolute magnitude-color relationship has been established for these stars (Hawley et al. 2002), which enables the simultaneous investigation of their distribution and that of the interstellar dust.

III. The SDSS Legacy and Post-2005 Operations: Filling the Gap

While we expect to be close to imaging a contiguous area in the Northern Galactic Cap by mid-2005, the spectroscopy at that time will cover two disjoint regions with a substantial gap roughly 15 degrees wide. We argue here that the large-scale structure science goals of the SDSS, and the legacy of the SDSS database, require filling this gap.

1. The Power Spectrum

In the current cosmological standard model (now spectacularly solidified by the results of the WMAP satellite, Spergel et al. 2003), the initial density fluctuations laid down at the end of inflation have Fourier modes with random phases. To the extent that this is true, the resulting density field is exactly describable statistically by the power spectrum, in essence the squared amplitude of these Fourier modes as a function of scale. Moreover, in linear perturbation theory, the amplitude of the power spectrum increases with time independent of scale. This means that with some reasonable assumptions about the nature of large-scale bias, measurements of the present-day galaxy power spectrum can tell us directly about the nature of the fluctuations after inflation, as they were modified through the epoch of matter-radiation equality. As such, these are an absolutely crucial test of our cosmological framework.

The measurement of the galaxy power spectrum from the spectroscopic data has therefore been one of the most important scientific goals of the SDSS. The current state of the art is given by Tegmark et al. (2004ab) and Pope et al. (2004). A rough calculation shows that if the NGC survey is completed, the effective volume will increase by 50% over the Baseline survey. How much difference will this make in the measurement of the power spectrum? Tegmark and Vogeley have investigated this question and find that the error bars scale as the square root of area covered, almost independently of the geometry of the survey footprint. On this basis we expect error bars on the power spectrum to improve by 15%.

However, this is not the whole story. The Fourier Transform of the survey footprint convolves the measured power spectrum, with the consequence that the finest scale Δk with which one can measure $P(k)$ is given by the width of the convolving kernel, $2\pi/\Delta L$, where ΔL is the smallest dimension of the survey volume. Without the gap filled, the relevant smallest dimension is the width of each of the two contiguous pieces of the NGC. With the gap filled, this smallest dimension increases by a factor of three. *By filling the gap, we can measure the galaxy power spectrum with three times higher resolution in k space than we can do in June 2005.* A number of theoretical models have predicted sharp features in k space (cf., Wang, Spergel, & Strauss 1999); for example, the WMAP team (Peiris et al. 2003) have suggested such a sharp feature to explain the anomalously small quadrupole and octopole moments in the CMB sky. Such features would only be apparent in the SDSS data if the gap were filled. In particular, the power spectrum is expected to exhibit "baryon wiggles" which are due to acoustic oscillations in the photon-baryon fluid after matter-radiation equality. The amplitude of these wiggles depends on the ratio of Ω_b to the total mass density, while the wavelength scale on which these wiggles are seen is dependent on the geometry of the universe and the Hubble Constant. Thus measurement of these predicted wiggles allows a crucial consistency check with the results of WMAP and of the correctness of current cosmological models, and would allow an independent determination of the Hubble Constant. Due to non-linearities (see below), the wiggles should be washed out on small scales, and therefore should be visible *only* on the largest scales, where the baselines provided by filling the gap become crucial. There are hints of this in previous work on 2DF (Percival et al. 2001; Miller et al. 2001), but SDSS should be able to make the definitive measurement.

2. Higher-order Clustering

While the fluctuations which gave rise to the large-scale distribution of galaxies may have been random phase, clustering will not remain in the linear regime. In the random phase limit, the *skewness* of the density field (i.e., $\langle\delta^3\rangle$) is identically zero. However, non-linear clustering generates a non-zero skewness, that to *second* order scales as $\langle\delta^3\rangle = S_3\langle\delta^2\rangle^2$. The quantity S_3 depends on the galaxy *bias* (i.e., the ratio of amplitude of galaxy to dark matter fluctuations on a given scale), and therefore is of great interest to measure. In fact, measurement not of just the third moment of the density distribution $\langle\delta^3\rangle$, but the full scale and angular dependence of the three-point correlation function, (or its Fourier counterpart, the bispectrum) allows one to measure both the linear and second-order terms of the bias parameter, as well as to test gravitational perturbation theory. This has been done most recently for the 2dF survey by Verde et al. (2002), who found that the sample of galaxies they had were consistent with bias. With the full SDSS + Legacy, we should be able to measure this effect with substantially smaller error bars. Second, we know that the clustering of galaxies is dependent on luminosity, galaxy surface brightness, and color, and we can use this technique to explore the dependence of bias on galaxy type.

Higher-order quantities such as the three-point function are quite a bit more sensitive to the volume to surface area ratio. Scoccimarro (2003) has carried out simulations of the SDSS redshift survey both with and without the gap, and found that closing the gap will lead to an improvement in accuracy of 20% and 35% for the linear and quadratic bias parameters, and 45% for f_{NL}, which quantifies the non-Gaussian nature of the primordial fluctuations (an important test of inflationary cosmology models). This will allow f_{NL} to be constrained to an upper limit of 150. For reference, the recent WMAP data gives $-58 < f_{NL} < 134$ (Komatsu et al. 2003); thus SDSS will give independent constraints at somewhat smaller scales. SDSS therefore has the possibility of giving an independent check to one of the strongest tests of inflationary cosmology, namely the absence of primordial non-Gaussianity, and it is only with filling the gap that the limit becomes comparable to the larger-scale WMAP results.

3. Photometric Calibration

Since the SDSS camera saturates at magnitudes of 14-15, the survey cannot be directly calibrated by observations of fundamental standard stars, and a major part of the

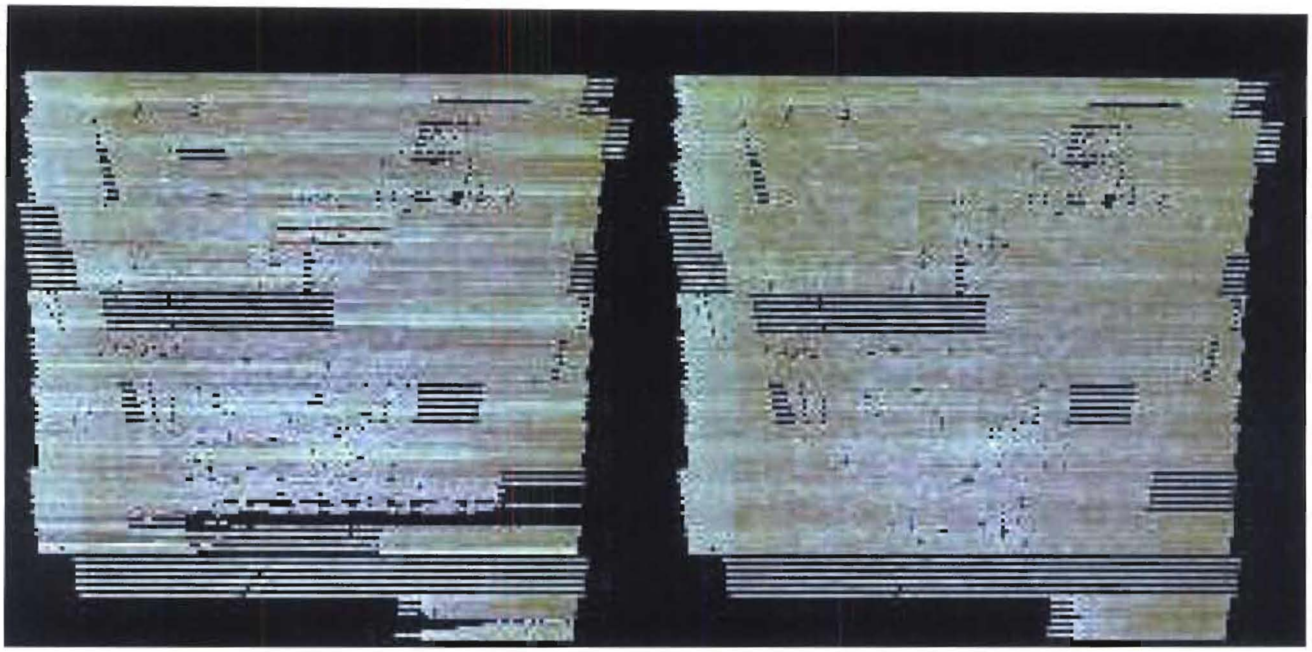

Figure 7. Comparison of the g-r colors of the stellar "blue tip" with regular SDSS photometric calibration (left panel) and with übercalibration (right panel) in a region $150° \times 30°$ in the NGC. Survey stripes are plotted horizontally; missing data are shown as black. Note that some poorly-calibrated and hence rejected data from the left panel have been recovered in the right. The rms error is decreased from 2% to 1% and the non-Gaussian errors eliminated. The Galactic color gradient of the blue tip can now be seen.

SDSS effort involved setting up a network of faint standards which calibrate the SDSS imaging using a small photometric telescope. After major effort by the SDSS team, the photometric calibration is accurate to 2% rms in the g, r, and i bands, a level of accuracy unprecedented for such a large survey and without which many of the SDSS science breakthroughs would not have been possible.

The "2%" number does not tell the whole story, however. The SDSS camera is a mosaic of 30 CCDs and filters, each of which needs to be calibrated separately for each imaging run. The result is that there are small but systematic variations of the photometric calibration across the imaged area. This is illustrated in Figure 7, where the g-r blue-tip color of stars is shown across the northern part of the NGC survey, the largest contiguous area obtained so far. In the absence of photometric errors, this quantity should be uniform (except for the effect of the Galactic metallicity gradient) over the survey area. These figures show that the color variations on large scales are dominated *not by random noise but by systematic photometric calibration offsets.* Though at a low level, these effects dominate statistical calculations of large scale structure at long wavelengths over the largest volumes.

Accordingly, we have begun an effort to work in the native system of the SDSS camera by using crossing scans to calibrate every SDSS CCD/filter with respect to every other and every area of the survey with respect to every other. The results of these preliminary efforts are shown on the right-hand side of Figure 7. The stripe-to-stripe offsets have almost disappeared. Formally, the photometry is now 1% accurate, but the real improvement lies in the reduction of systematic effects.

We propose to carry out this effort (übercalibration) throughout the survey's duration. The results of a globally calibrated, filled NGC survey will be that an object in one part of the sky can be compared with one 100° away to an accuracy of 1%. This enables the measurement of the power spectrum on the largest scales (smallest k values) for both the galaxies and the SEGUE stars. Preliminary studies of the power spectrum for the most luminous galaxies obtained from photometric redshifts show the redshift evolution of the power spectrum slope, the turnover at long wavelengths, and give tantalizing hints of the presence of baryon wiggles (Schlegel et al. 2003). This brings the possibility of major new scientific investigations using the SDSS.

4. Overlap with Surveys in Other Bands

Present-day astronomy increasingly focuses on multi-epoch and multi-wavelength investigations. With its high photometric accuracy and large spectral data base, SDSS will be the survey of choice for providing optical data for these studies. Major studies have been made using SDSS and digitized photographic surveys to measure proper motions and characterize variability; using SDSS and 2MASS imaging to find high redshift quasars, brown dwarfs and dust-reddened quasars; using radio and Xray surveys plus SDSS to investigate the nature of AGNs; comparing SDSS colors of asteroids with their dynamics to establish the origins of asteroid families; and comparing WMAP and SDSS maps of the sky to closely constrain the basic cosmological parameters. These are only a small number among many examples, and such work will only increase as other surveys come on line, such as GALEX, a UV imaging survey: UKIDSS, a deep near-infrared survey: SWIRE a deep mid-infrared survey: and HIPASS and HIJASS, HI surveys to z = 0.03. The science that this synergy enables is maximized by the area of sky covered by the SDSS, both photometrically and spectroscopically.

5. SDSS as an Astrometric and Photometric Calibration Survey

The SDSS also provides utilitarian data which greatly increase the operating efficiency of large telescopes. Photometric observations with an imaging camera on a large telescope require repeated exposures of standard star fields for photometric calibration, and the observations must be made under photometric conditions. But in any region of sky which the SDSS has already surveyed, deep images will always contain at least a few objects which the SDSS has already measured to an accuracy of 1% and whose positions are known to better than $0.1''$, thereby calibrating the astrometry and photometry, and allowing non-photometric time to be used. This argument is strictly correct only for observations done in the SDSS filter set, *ugriz*, although there exist quite accurate transformations (e.g., Fukugita et al. 1996) to other broad-band optical photometric systems. An increasing number of projects on large telescopes are using this approach (for example, Tonry et al. 2003; Wirth et al. 2004).

The SDSS photometry is already having a huge impact on the design of forefront imaging cameras on a variety of telescopes, largely because of the availability of this dense network of calibrating stars. In particular, the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope includes an SDSS filter set among its complement, as do the GMOS imaging spectrographs on the national Gemini North and South telescopes.

All this of course only works in the region of sky covered, arguing again for obtaining the largest possible area with the proposed continued operations.

IV. A Supernova and Time Domain Survey with the SDSS 2.5m Telescope

In this section, we motivate and describe a program of repeated imaging over three three-month periods that will enable the SDSS 2.5m telescope and camera system to obtain 150 – 200 *high-quality* type Ia supernova light curves in the redshift range $0.05 < z < 0.4$. The SDSS system can provide densely sampled, multiband SNe light curves with much better photometric calibration and spectral coverage than are generally available currently. These supernovae will fill in an important gap in redshift space, providing unique foundational knowledge of both intrinsic supernova properties and an important part of the Hubble diagram, including new constraints on the nature of the dark energy. The SN survey will follow standard SDSS imaging procedures and make use of existing photometric reduction and subtraction software. Rapid data reduction on the mountain will allow follow-up of the SN candidates with spectroscopy and NIR imaging near peak—we plan to use the ARC 3.5m telescope (for brighter candidates) and to collaborate with interested teams with access to other telescopes, with the aim of complete follow-up of the sample. In addition, we will rapidly release IAU circulars for candidates passing reasonable quality criteria, so that all interested groups can observe these objects. Since this 2.5m imaging data will be useful for a variety of other time-domain studies, we will make the corrected frames and photometric catalogs available to the public as soon as they are processed and calibrated.

1. Probing the Accelerating Universe

The recent discovery of the accelerating Universe, and the implication that some as yet mysterious form of Dark Energy dominates the cosmos, provides a compelling motivation to map out in detail the recent history of the cosmological scale factor. Type Ia supernovae (SN Ia) are well established as the method of choice for accurate relative distance determination. The joint analysis of an improved SN Ia Hubble diagram with other complementary cosmological constraints (including the cosmic microwave background (CMB), large-scale structure, and weak lensing) will provide insight into the physics that gives rise to the accelerating expansion. Some have called determining the nature of the dark energy one of the most important problems in science today.

With the evidence from the CMB that the spatial geometry of the Universe is nearly flat, attention in the field has shifted to determination of the effective equation of state parameter, w, that relates the pressure to the energy density of the dark energy, $P = w\rho$. In a flat Universe, two parameters determine the evolution of the luminosity distance D_L with redshift: w and the contribution $\Omega_{\rm DE}$ of the dark energy to $\Omega_{total} = 1$,

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \left[(1-\Omega_{\rm DE})(1+z')^3 + \Omega_{\rm DE}(1+z')^{3(1+w)}\right]^{-1/2} dz',$$

where, for simplicity, we have assumed w is constant at recent epochs. There is a surprising amount of dark energy leverage at modest redshift: for the WMAP value of $\Omega_{DE} = 0.73$, the difference in distance modulus between $w = -1.0$ and $w = -0.8$ models grows from 0 to about 0.05 magnitudes between redshifts $z = 0$ and 0.3, about the same as the growth between $z = 0.3$ and 0.8. While the latter redshift range is being targeted by the on-going CFHT Supernova Legacy Survey (SNLS, Pain et al. 2003) and the NOAO ESSENCE supernova survey (Kirshner et al. 2003), the regime $0.05 < z < 0.4$ is ideally suited to SN observations with the SDSS 2.5m telescope and will not be targeted by other facilities in the next few years.

The SN Ia cosmology observations can be considered comparisons of the expansion rate at different epochs. Present constraints come from constructing a Hubble diagram that uses heterogeneous low-z and high-z SN samples, drawn from different telescopes with different photometric passbands. The SDSS system is currently unique in its ability to bridge between $z < 0.1$ surveys, which rely on small, automated wide-field telescopes for discovery, and $z > 0.3$ surveys carried out on $4 - 8$m telescopes with narrow fields of view.

To obtain precise constraints on dark energy, the next generation of SN cosmology experiments must reduce sources of systematic error to the level of a few percent. The uniformity of the 2.5m photometric instrumentation, in conjunction with in-situ photometric standards *from the same telescope*, will allow us to minimize systematic errors arising from instrumental color terms, multi-stage transfer of photometric standards, and inadequate extinction information. The SDSS photometric calibration has been demonstrated to be accurate to 2% in r and can be made 1% accurate, as described above. The number of "fully characterized" type Ia supernovae light curves (with multicolor data before peak, IR photometry, and densely-sampled, well-calibrated light curves) is less than a few dozen (Tonry et al. 2003); the SDSS SN survey will increase this by a substantial factor.

The viability of detecting and following SNe from SDSS imaging data has been convincingly demonstrated (Miknaitis et al. 2001). In Fall 2002, 77 SNe candidates were detected in several SDSS scans; 39 of them were subjected to follow-up spectroscopic observation, resulting in 18 confirmed SNe Ia out to $z \simeq 0.4$ and 8 SNe of other types (this is not a statement about our expected detection efficiency, just a demonstration of the technique). This analysis used the University of Washington frame subtraction pipeline; Figure 8 shows its performance in detecting a SN near the core of a host galaxy. A modified version of this pipeline is being used by the ESSENCE project and will be developed further for the SDSS SN search.

Finally, although recent SN observations have focused largely on type Ia supernovae, there is increasing evidence (Hamuy & Pinto 2002) that type II supernovae may also prove to be useful cosmological probes. The SDSS search will produce the first comprehensive and homogeneous set of multiband full-coverage SN II light curves.

2. Science Empowered By Quality Supernova Light Curves

Our plan is to obtain $150 - 200$ high-quality Ia light curves between $0.05 < z < 0.4$, out of a much larger sample of detected SNe Ia, in order to achieve the following science

Figure 8. Detection of supernova 2001eu from SDSS r band images (showing two epochs and difference image).

goals:

Science Goal 1: Cosmological Parameters from the SN Ia Hubble diagram

We will fill in the SN Ia Hubble diagram with $\sim 40 - 70$ SNe Ia in each of the three $\Delta z = 0.1$ bins spanning the redshift range $0.05 < z < 0.35$. These distances and redshifts will provide important information on the evolution of the cosmic scale factor that is not accessible to any competing system. Assuming the intrinsic SN Ia distance modulus dispersion is 0.13 mag (in V band, Phillips et al. 1999), this survey should determine the distance modulus with statistical and systematic uncertainty less than 0.02 mag per redshift bin.

Figure 9 shows constraints in the $w - \Omega_m$ plane expected from several model surveys (SNe assumed uniformly spread over the indicated redshift range). The SDSS SN survey proposed here (200 SNe, $0 < z < 0.4$) is modeled approximately by the black region; the blue region approximates the expectations from the ESSENCE survey (200 SNe, $0.4 < z < 0.8$), and the red region indicates the combination of the two. While the parameter constraint region is broader at lower SN redshift, this is compensated by the fact that it is more nearly orthogonal to the constraints from the CMB or from prior knowledge of Ω_m (Frieman et al. 2003, Spergel & Starkman 2002). The SDSS SN survey, in conjunction with an external determination of Ω_m to within 0.03 (1σ), will determine w with a statistical precision of about 10% (at 1σ, assuming $w = -1$); the precision for ESSENCE is about the same. Although the statistical precision is comparable, the systematic errors in the SDSS survey, building on years of effort at reducing photometric calibration errors, will arguably be under better control than for ESSENCE and CFHTLS. Also, of all SN-based dark energy programs, the SDSS SN survey, by virtue of being at the lowest redshift, will suffer the least from evolution, another source of systematic error.

Science Goal 2: Evaluate systematics

Systematic errors are the main limitation in SN cosmology; the quality of the SDSS photometric data and the attributes of the 2.5m and its camera system reduce these better than any other currently available system. We can partition the large number of light curves into subsets at common redshift, to search for potential sources of systematic error that may afflict the SN Ia distance measurements. We can search for correlations between

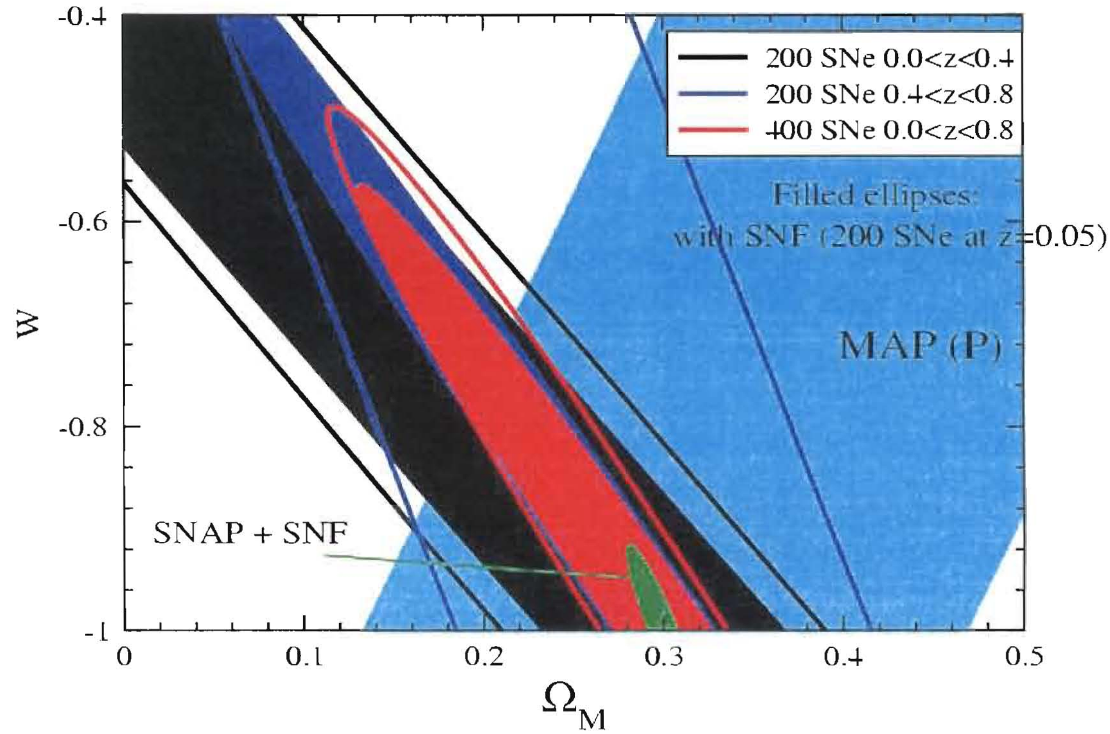

Figure 9. Forecast constraints in the w-Ω_m plane from model SN Ia surveys, assuming $\Omega_m = 0.3, w = -1$. Open ellipses: results from these SN surveys alone; filled ellipses: the Hubble diagram zeropoint has been determined by 200 SN Ia around $z = 0.05$, e.g. from the SN Factory (SNF). Black: SDSS SN survey; blue: ESSENCE; red: SDSS+ESSENCE; green: SNAP. Turquoise: constraints from 4-year WMAP data including polarization. (D. Huterer, private communication).

Hubble diagram residuals and host galaxy morphology, metallicity, or extinction.

Science Goal 3: SN phenomenology and second parameter effects

This large sample of supernova light curves, obtained on the uniform SDSS multicolor photometric system, will provide an unprecedented opportunity to study in detail the color/peak brightness/decline-rate relationship, and to search for any second parameters that may further reduce the scatter in the Hubble diagram. In particular, we will be able to explore in detail recent indications of a brightness/decline-rate relationship in the restframe u-band wavelength range.

Science Goal 4: Rest-frame u-band light-curve templates for High-z SN Surveys

Ultimately, the strongest constraints on w and its possible time evolution will come from future SN surveys that extend to $z > 1$. A number of HST pilot programs in this regime are on-going or recently completed, including GOODs, SCP, HZSST, SNaZ, and GTO, while the proposed SNAP mission aims to measure $\sim$ 2000 SNe out to $z = 1.7$. To reduce systematic errors, these high-redshift SN light-curves must be matched to a set of low-redshift templates. The $z \sim 0.3$ range is needed to garner the rest-frame u-band templates to match these distant SNe.

Science Goal 5: SN Cosmology from multi-band photometry

Future wide-field surveys, such as PanSTARRS and LSST, will measure optical, multi-band light-curves for thousands of supernovae, but the resources do not exist to obtain spectra for the vast majority of them to distinguish SN types. As they evolve, SNe Ia trace out a distinct locus in color space that, along with host-galaxy colors, provides information on SN type, redshift, and age (Poznanski et al. 2002, Vanden Berk et al. 2001). Particularly with g band photometry, the SDSS should be able to identify SNe Ia from their intrinsic UV-deficit. This technique has been used with HST to successfully identify SNe Ia at $z > 1$, but the SDSS will be the first to do it from the ground. It is not yet clear to what extent photometric information alone can be used for precision SN cosmology, given degeneracies among SN types and photometric redshift errors. With a large, well-calibrated, multi-band sample spanning a range of redshifts and SN types with spectroscopic follow-up, the SDSS SN survey will provide an excellent proving ground for this idea. We also note that this will be the first large SN survey carried out in the SDSS filter bands, which are becoming standard for wide-area imaging surveys.

3. Observing Strategy, Simulations, and Tests

Although a variety of SN survey strategies with the 2.5m telescope have been considered, the most promising one involves drift-scanning at the normal (sidereal) SDSS survey rate, yielding 55-second integrated exposures, alternating between the two interleaving strips of a 2.5-degree-wide stripe (defined by the camera FOV and CCD gaps) about 120 degrees long. In addition to being nearly optimal for SNe, this strategy benefits from many years of survey operations and data processing experience. The actual survey geometry will be determined by observing season, the desire to keep the fields at low airmass, and access of the fields to follow-up telescopes. For example, for Fall campaigns, the SDSS southern celestial equator stripe is one natural choice: it has been scanned repeatedly during the SDSS, with excellent co-added template images—searching a well-scanned field allows one to go deeper in the difference frame—and it is readily accessible to southern hemisphere telescopes during that season.

We used a supernova simulation program developed by Philip Pinto. With the help of Gajus Miknaitis, we modified the program for the SDSS telescope and included APO weather records and accounted for sky background light from the moon. We simulated a 3-month Fall observing season on the SDSS equatorial stripe. The program assumes a standard SN Ia rate (Cappellaro et al. 1999), draws from observed SN distributions of brightness, color, and correlated decline rate (Phillips 1993), and includes host galaxy extinction and K corrections. A distance modulus, extinction, and SN color are extracted from each SN light curve that meets a number of quality criteria, which include at least one observation on the rise at least 1 mag below peak, at least 7 data points with S/N > 5 in a particular waveband, at least one point with S/N > 10 in each of 3 bands, and a good fit to template lightcurves. Only a small number of extant supernova light curves meet these criteria: the SDSS SN survey will set the standard for high quality data in this arena.

We find that a 3-month campaign typically yields about 65 SNe Ia that meet our stringent quality criteria, with a very broad redshift distribution centered at $z = 0.2$, or nearly 200 high-quality SNe Ia over 3 quarters. The recent compilation of all SN Ia to which distances have been determined to date (Tonry et al. 2003) shows a large gap just in this redshift interval, for reasons noted earlier. The SDSS SN survey is uniquely placed to fill this gap with high-quality data.

The major operational differences between the SDSS SN survey and previous SDSS imaging operations will be: (i) the SN survey will require imaging in non-photometric and non-dark conditions to obtain densely sampled lightcurves, and (ii) the imaging data must be processed through the photometric pipeline and frame subtraction software in near real time on the mountain to enable follow-up observations. We are currently testing the reduction and subtraction software on extant non-photometric SDSS data to determine their performance and the resulting photometric accuracy in these conditions. To extend those tests to cover a broader variety of conditions and to demonstrate our ability to rapidly process the data on the mountain, identify candidates, and carry out follow-up, we expect to carry out a one-month end-to-end test campaign in Fall 2004.

4. Follow-up Spectroscopy and NIR Imaging

We plan to obtain follow-up spectra and NIR imaging near peak of all high-quality candidates in order to identify SN types, obtain redshifts, and constrain host galaxy extinction. At $z = 0.1(0.3)$, the SN Ia peak magnitude is $b \simeq 19$ ($r \simeq 21.3$). The low-redshift portion of the sample will be accessible to the ARC 3.5m and other 2-4m class telescopes, and we will partner with other groups to ensure follow-up of the entire sample. So far, we have received positive expressions of interest and willingness to collaborate on follow-up from the Carnegie Supernova Group (via W. Freedman), which uses the 1, 2.5, and 6m telescopes at Las Campanas, from A. Filippenko (U. C. Berkeley), who has active SN programs at Lick and Keck Observatories, and from R. Kirshner, whose group has extensive SN spectroscopy experience at Mt. Hopkins, MMT, and Magellan. We will continue to develop these and other contacts with the aim of forging a broad-based collaboration.

V. Integrated Observing Plan

Our three proposed observing projects: SEGUE, Legacy, and the supernova survey, are complementary both in science goals, and in their requirements for telescope time. We will see that the three fit together well within a three-year observing plan.

The Supernova survey requires exclusive blocks of time: time that would normally be used for spectroscopy is allocated to imaging. We estimate that 10 months of time for this project would achieve the science goals. This time should be available in three years of operations if Legacy and SEGUE are finished as expected. Legacy may require no further imaging after mid-2005. Our past rate of collecting new imaging data is 2400 square degrees per year. On this basis, there is more than sufficient time to achieve the SEGUE imaging goals.

Our past rate of collecting new spectroscopic data is 360 plates per year with the standard (SDSS) exposures. We estimate that Legacy may require 480 plates beyond mid-2005 to fill the gap in the NGC. The SEGUE science case supports 200 tiles, each of which is observed with two exposures, one of which is twice as long as the standard SDSS exposure, for an equivalent of 520 standard-length plates. Thus the demands are for the order of 1000 plates worth of spectroscopic time, whereas we would expect to be able to acquire 780 plates in the time available.

There are two ways to address this apparent shortfall. First, we can start to obtain SEGUE spectroscopic data and Supernova imaging data as early as Fall 2004. Second, at least some of the time in 2007 and 2008 that would normally have been used to obtain new imaging scans will not be needed for imaging, and can instead be used for spectroscopy. Each of these approaches yields an additional $\sim$100 plates, for a total close to 1000, as required. We emphasize that the rates quoted above are averages, but variations in weather introduce considerable scatter, amounting to $\pm 50\%$ in the rate from year to year.

Legacy's seasonal demands are in the Spring - essentially all for spectroscopy. SEGUE also needs spectroscopic observations in the North Galactic Cap, and this is the main circumstance where there is potential difficulty in scheduling. The distribution of SEGUE spectroscopic tiles is approximately uniform around the sky. The seasonal demands for Supernovae are having dedicated blocks of time with available high-latitude sky. Since the SEGUE spectroscopic observations in the Fall sky may be finished by the end of 2005, the plan is to undertake the Supernovae program in the Fall seasons of 2006 and 2007, with additional time for Supernovae in the Spring of 2008 if that time is available.

We do not yet have a detailed understanding of how the separate demands for spectroscopic time for SEGUE and for Legacy in the Spring seasons will work out. When the spectroscopic footprint of the SDSS from the Spring 2004 and 2005 seasons is known, we will know which tiles remain for Legacy. Since the tiles for SEGUE are defined beforehand, we will optimize both programs together, where the order of the selection of tiles depends on availability and minimizing any end-game inefficiencies. This balancing of the two programs will continue throughout the new survey. Given that there is some flexibility in the location of the tiles for SEGUE, it is reasonable to expect that we can devise a way to both complete the Legacy footprint and to address the critical spectroscopic requirements for SEGUE. The scheduling plan is summarized in Table 1.

Table 1. Scheduling Plan, 2004–2008 (I=imaging, S=spectroscopy)

Year	Spring season	Fall season
2004	SDSS I,S	SEGUE I,S; SNe I
2005	SDSS I,S	SEGUE I,S
2006	Legacy/SEGUE S	SNe I
2007	Legacy/SEGUE S	SNe I
2008	Legacy/SEGUE S (+SNe)	

VI. Operations Plan

1. Mountaintop Operations

No major changes to operations procedures at Apache Point Observatory are anticipated in the transition from current operations to the future survey, other than the implementation of a system for fast identification of supernovae. Some hardware systems may require increased maintenance or may require replacement; in particular, we will undertake a review of the data-acquisition system in June 2004.

2. Plate Drilling Operations

The spectroscopic plug plates have been produced at the University of Washington for the SDSS. This system is working well and we plan to continue the same arrangement. About 1000 plates will be needed for the new survey, which can be compared to 490 drilled plates within just the 2003 reporting period - hence the load will not be any heavier than for current operations.

3. Data Processing Operations

The Early Data Release (EDR), Data Release 1 (DR1), and upcoming Data Release 2 (DR2) for the SDSS have been accomplished in the Fermilab production environment. The present team has a substantial body of experience that will translate directly to the needs of the new survey. However, the new survey will require some additional development of data processing pipelines, target selection code, databases, survey planning infrastructure, and procedures.

The data processing for the Legacy observations will be identical to that of the SDSS, and data distribution will follow the SDSS model of incremental releases after scientific validation within the Collaboration. Similarly, the new SEGUE stripes will be processed in the same way as for Legacy and for SDSS. Frames that cannot be processed (for example, because of high stellar density or strongly varying background) may not be included in the survey data products and may not be used for selection of spectroscopic targets. The core science goals of SEGUE are not impacted by the loss of this small amount of data.

The version of the spectroscopic pipeline for SEGUE will provide for better stellar spectral classification and radial velocities, as well as stellar parameters like atmospheric effective temperature, surface gravity, and chemical abundances. Spectroscopic target selection will be done at Fermilab using a single automated algorithm. The SEGUE spectroscopic data will be processed at Princeton University using an existing automated reduction system, which is the most significant proposed change from current operations. This change will help off-load work from the Fermilab data processing group. The distribution of data products for SEGUE will, as for SDSS, be undertaken from Fermilab.

The Supernova survey will have two data processing systems: one will be at Apache Point Observatory and is designed to identify candidate supernovae within a day of observation. The other will be at Fermilab and is designed to apply photometric calibrations to produce accurate multi-band light curves for the supernovae. There is some redundancy between these systems: in both cases a version of the imaging pipeline that handles data from non-photometric conditions is run, and the outputs are used by code that does frame-subtraction. This code was developed more than a year ago and is currently being tested at Fermilab.

VII. Management Plan

Despite the expanded scientific agenda of new survey with its three components, it is both possible and efficient to operate the new survey in the same way as for the SDSS: one management structure, and one operations system for data acquisition, data processing, and data distribution. A feature new to the proposed survey is that separate demands for observing time need to be balanced so that the scientific goals of all of the surveys are optimized together, and so that the observing systems are always used with full efficiency. Weather patterns introduce an unavoidable and important element of uncertainty into the planning process. As each component survey progresses, priorities for the acquisition of new data may change. The optimization is thus necessarily a dynamic process.

As for the SDSS, the new management structure will comprise an Advisory Council that advises the ARC Board of Governors. The Advisory Council consists of representatives of the invested participating institutions; it oversees the work of the Management Committee. The Management Committee consists of the Director (currently Richard Kron), the Project Scientist (James Gunn), the Project Manager (Bill Boroski), and the Scientific Spokesperson (Michael Strauss). The Director reports to the Advisory Council and is charged with conducting the survey and expending resources according to specific goals. The Director will prepare a baseline plan for the observations for the Extension Survey for approval by the Advisory Council, and will periodically report actual progress with respect to that baseline. The Project Scientist oversees the survey data stream end-to-end and is responsible for the integrity of the data products. The Project Manager oversees the day-to-day operations of the various project components (Observing Systems, Data Processing and Distribution, Observatory Support, and Survey Coordination), plans the general application of resources on an annual basis, and reacts to immediate needs of the survey. The Scientific Spokesperson is responsible for Collaboration Affairs, which relates to the research productivity of the scientists at the participating institutions. Activities of the Spokesperson include implementing policies related to publications and projects, organizing scientific meetings, and overseeing the activities of the Working Groups.

The Working Groups facilitate the work on the science goals of the Survey. They are organized around scientific themes and provide a mechanism whereby the Collaboration can organize research on the respective topics. Discussions within the Working Groups can enhance the overall effectiveness of the effort by enabling information to be exchanged on what projects are being undertaken, and by providing a framework for individuals to join projects.

Operation of the new survey will require efforts like monitoring spectroscopic targeting and plate design, and undertaking work related to calibrations. To organize this work we will appoint "Teams", one for each new component (Legacy, SEGUE, and Supernova). The Teams serve as centers of expertise to advise on matters of the optimal observing strategy, necessary systems or software development, and the specific content of the periodic data releases. Survey progress (for each dark run and cumulative-to-date) will be reviewed cooperatively by the Teams and the Management Committee. Based on this discussion, guidance will be given to the Head of Survey Coordination concerning the design of the observing plan for the following month.

VIII. Cost Plan

The interval of time to be funded is 1 July 2005 through June 2008 for observatory operations, with an additional five months for final data processing and distribution and project close-out. Operations will use the same hardware on the mountaintop as currently used for the SDSS, and similar processing and data-distribution procedures. (The most significant new operations element may be a processing system to detect transient objects in near-real-time, but we already have experience in implementing such a system and can estimate its cost.) Therefore, the experience we have gained concerning costs for operating the SDSS is directly applicable to the new survey. These operations costs total $14.9M and include close-out costs at the end of the project. Of this amount, we anticipate $1.6M as in-kind contributions, and thus we require $13.2M in cash. The cash covers the salaries of the Observers, engineers and other technical staff, some of the data-processing and distribution team, some academic staff who support the data systems, and support staff. The cash also supports the production of the spectroscopic plug plates and the acquisition of computers and disks, and procurements as required to repair and maintain the hardware systems on the mountain.

Appendix B provides a much more detailed budget for the new survey. It includes some new elements, such as a replacement of the data-acquisition system at APO, but in general the budget was evolved from the current SDSS budget, assuming inflation at 4%. Again, the current SDSS budget has closely matched our actual expenditures over the last three years, and so is known to be realistic. We are in fact planning a detailed external cost review for operations for the new survey. The main thrust of this review will be to look for possible added savings and improved efficiencies, and thus the sense of any small change to the budget would be downwards.

The SDSS is funded from a combination of resources from the A.P. Sloan Foundation, the National Science Foundation, the National Aeronautics and Space Administration, the U.S. Department of Energy, the Japanese Monbukagakusho, the Max Planck Society, and the Participating Institutions. This partnership has served all of us well, and we propose to fund the new survey in the same way. Also as before, the administrative entity is the Astrophysical Research Consortium. The SDSS institutions that are members of ARC are The University of Chicago, The Johns Hopkins University, New Mexico State University, Princeton University, and The University of Washington. The other SDSS institutions participate via memoranda of understanding with ARC; in the new survey we will include non-ARC partners in the same way.

The SDSS institutions have each expressed interest in pursuing the scientific goals of the new survey, and are in the process of exploring what resources they can contribute. In parallel, we are seeking new institutional partners, ones who can strengthen the scientific Collaboration and who can provide cash resources. Offers of in-kind resources, either from within the current group of partners or from new partners, must address critical operations needs (as detailed in the Addendum) so as to reduce the cash requirements.

Given NASA's interest and expertise in handling large astronomical databases, and given the leverage that the new survey will bring to the analysis of data from space missions, we have made an informal approach to explore the fundability from NASA of the costs related to data archiving and distribution. It would be logical for NASA to take on the long-term archiving of the SDSS and the new survey. Such a request would go to a standing committee that reviews NASA's support for data archives, and we will prepare a proposal accordingly. However, we are not sanguine about the likelihood of obtaining funds from NASA. The present plan shows the costs for data archiving and distribution shared between the Sloan Foundation and the NSF. In the event that we are successful in obtaining these funds from NASA, then the total amounts requested of the Sloan Foundation and the NSF will be lower by approximately \$2.3M.

We are requesting support from the A.P. Sloan Foundation and from NSF in equal amounts to support the operations, exclusive of the data archiving and distribution effort. The cash request is \$5.4M from each agency, or \$1.8M per year for three years. We have submitted letters of intent to the A.P. Sloan Foundation and to NSF's Division of Astronomical Sciences.

The final part of the funding plan is to cover the remaining \$2.5M cash requirements from contributions from the participating institutions. We expect to have specific agreements by May of 2004.

In summary:

Funds from A.P. Sloan Foundation	\$5.4M
Funds from National Science Foundation	\$5.4M
Funds from Participating Institutions	\$2.5M
In-kind contributions from Participating Institutions	\$1.6M
Total (three years)	\$14.9M

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Appendix A. Relation between the Extension Survey and Other Surveys

Partly inspired by the scientific and technical success of the SDSS, the rest of the world has not sat idle, but has been planning a variety of wide-field surveys of their own, and there are a number of on-going and planned surveys which potentially compete with the SDSS extension. For example, the planned Legacy survey on the CFHT will image 1300 square degrees in three bands, going 1–2.5 magnitudes fainter than SDSS (and will go substantially deeper in more bands over smaller areas of sky).

The VST ("VLT Survey Telescope") is a 2.5m telescope at La Silla which will carry out SDSS-like multi-band imaging in the Southern Hemisphere, mostly to feed the Very Large Telescope at Paranal in Northern Chile. VISTA is led by a British consortium, and will carry out a near-infrared wide-field survey on a 4-meter-class telescope, with weak lensing science in mind. Pan-STARRS is an array of four 1.8-m telescopes to be placed on the summit of Mauna Kea. With wide-field optics and gigapixel arrays, it will be able to survey the full sky to 23-24 mag several times per month. Its science is driven by variable object science, in particular Near Earth Asteroids, and variable Galactic and extragalactic objects. Pan-STARRS, which already has substantial funding, plans first light for their first telescope in 2006, with the other three coming on line over the following two years. Pan-STARRS will have the SDSS filter complement, except u. On a longer timescale, the Large Synoptic Survey Telescope (LSST), is planned to have an étendue (i.e., collecting area times field of view) five times larger than Pan-STARRS. This could be achieved with a single wide-field telescope of effective 6.9-m diameter, or perhaps a "super Pan-STARRS", involving of order 20 1.8-m telescopes. In any case, the LSST is not likely to see first light in much less than a decade.

There are quite a few on-going and planned ambitious supernova search projects underway. On the longest timescale is the Supernova Acceleration Probe (SNAP; sometimes also known as the Joint Dark Energy Mission, JDEM), which will be a dedicated satellite mission to find and photometer the most distant supernovae; it is at least a decade away. There are of order a dozen on-going and ground-based supernova surveys; *none combine the depth, photometric accuracy, and sky coverage* of the SDSS. This means that they either probe only to modest redshifts ($z < 0.1$), or only get appreciable numbers of supernovae at quite substantial redshifts. The SDSS is unique in its ability to discover and obtain accurate well-sampled multi-color light curves in the crucial redshift range $0.1 < z < 0.3$, where the effects of dark energy are maximized.

On the spectroscopic side, multi-object wide-field fiber-fed spectrographs are being built for a variety of telescopes, such as Hectospec at the MMT, Echidna on the AAT, and 6DF on the UK Schmidt at Siding Springs. However, none of these instruments is close to matching the SDSS in the combination of field of view, sensitivity and resolution of spectrograph, number of fibers and size of telescope. The 2dF instrument on the AAT is the current closest competitor, but it works at substantially lower resolution and smaller spectral coverage than does SDSS, is lower in throughput, and is not capable of proper spectrophotometric calibration. Hectospec, and large multi-slit spectrographs on Keck (DEIMOS) and the VLT (Virmos) are oriented to very deep spectroscopic surveys over relatively small areas of sky, and will not venture to compete with SDSS in getting complete samples of relatively bright objects over thousands of square degrees. LAMOST (a Chinese collaboration with a 4000-object spectrograph fed by a 4-meter Schmidt telescope) is scheduled to see first light at the end of 2004, but it will have substantially worse spectral resolution and spectral coverage than does SDSS. KAOS (the Kilo-Aperture Optical Spectrograph) is a proposed instrument for the Gemini telescopes. With its superior resolution ($R = 20,000$) and 4000–5000 fibers on a substantially larger telescope (albeit with 1/4 the field of view), it will replace the SDSS spectroscopic system as the state of the art. However, it currently only exists as a proposal; it is unlikely to see first light before 2009, by which time the science program proposed here should be completed and can be used to help define the KAOS strategy.

RAVE is a ground-based all-sky radial velocity project with the ultimate goal of obtaining medium-resolution spectroscopy of ~50,000,000 Galactic stars to V = 16 (remember that we are proposing to probe four magnitudes fainter). During its first phase (2003–2005), RAVE will obtain 100,000 moderate-resolution spectra (R=4,000) of southern stars up to a limiting magnitude of V=12 (*much* shallower than we propose here). using the 6dF facility on the UK Schmidt Telescope. The projected starting date for the main survey is 2006. Moreover, RAVE observes only the region around the near-infrared Ca II triplet.

RVS on GAIA (Launch 2010?) will also obtain spectroscopy to about $V = 16$. The RVS is an $R = 11,500$ spectrometer that will take spectra of "everything", since the spectrometer is always on as GAIA sweeps the sky. GAIA imaging (5-7 broad-band, 11 medium-band filters) will be complete to V = 20, with good distance and tangential motion information for a significant fraction of the stars to V~ 18 (Perryman 2002). GAIA will have a 5-year lifetime, and may be extended up to 10 years. With the proposed SDSS extension, we would obtain deeper data over a smaller area almost a decade earlier than GAIA, fill in a crucial missing part of parameter space for radial velocities, and greatly help to focus the scientific questions to be addressed with such missions in the future.

Unlike essentially all the systems mentioned here, SDSS combines imaging and spectroscopy in a single facility *dedicated* to the survey, allowing maximally efficient use of telescope resources. Moreover, SDSS has created not just a system to collect data. but a system to make those data available in an effective and efficient way to the entire astronomical community. On roughly the timescale that SDSS will end, new surveys such as Pan-STARRS will just start to come on line with superior imaging capabilities. Furthermore, the SDSS spectroscopic system (from the target selection from our imaging data, through the efficient plate plugging/mapping operations, to the superb spectra themselves) will find no direct competition for at least the next 7-8 years. While we can imagine Pan-STARRS or a facility like it carrying out an SDSS-like imaging survey in roughly five years, if we don't finish the SDSS spectroscopic survey, no-one will do it for us!

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Dorothea Klumpke-Roberts Prize (1975)
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Selected Publications

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Dannie B. Heinemann Prize, American Astronomical Society (1988)
Gold Medal, Royal Astronomical Society, London (1993)
Petrie Prize, Canadian Astronomical Society (2001)
Distinguished Alumnus, California Institute of Technology (2003)
Joseph Weber Award, American Astronomical Society (2003)

Selected Publications

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3-year Extension Survey Cost Projection

(as of 02/21/04)

Total Cost - Organized by WBS

(in $000s)

Calendar Year	2005	2006	2007	2008	Total
1.1 Survey Management					
1.1.1 ARC Administration	38	78	81	86	284
1.1.2 Office of the Director	60	92	95	38	285
1.1.3 Office of the Project Scientist	78	103	107	58	346
1.1.4 Office of the Project Manager	109	220	229	211	769
1.1.5. Office of the Scientific Spokesperson	32	65	57	50	204
ARC Support for Project Spokesperson	5	9	10	9	32
ARC Support for Collaboration Affairs	8	11	11	11	41
ARC Support for Public Affairs	10	24	14	19	67
Public Information Officer	9	21	22	11	64
Survey Management Sub-total	316	559	571	443	1,889
1.2 Survey Operations					
1.2.1 Observing Systems	822	930	949	522	3,222
Technical Support at APO	172	352	367	298	1,189
Off-mountain Technical Support	112	230	239	121	702
Plug Plate Production	101	181	172	35	488
ARC Support for Observing Systems	437	166	172	68	844
1.2.2 Data Processing	399	817	841	555	2,612
Core Data Processing Operations	287	577	600	410	1,874
Software and Data Processing Support	113	240	241	145	738
1.2.3. Data Distribution	219	364	379	246	1,209
Core Data Distribution Operations	163	245	255	180	842
Data Archive Development and Support	57	120	124	67	367
1.2.4. Observatory Operations	745	1,534	1,595	994	4,868
1.2.5. ARC Support for Survey Operations	60	125	130	54	369
Survey Operations Sub-total	2,246	3,770	3,894	2,371	12,280
1.3. ARC Corporate Support	44	50	52	37	182
1.4 Management Reserve	100	170	170	109	549
Total	2,706	4,549	4,686	2,959	14,900

NOTES

1) The CY2005 budget covers the period Jul-Dec, 2005.
2) The CY2008 budget covers full operations from Jan-Jun 2008 and closeout activities from Jul-Nov 2008
3) An inflation factor of 4% per year was used to prepare this forecast.
4) Closeout costs are included in this cost forecast

3-year Extension Survey Cost Projection
(as of 02/21/04)

Cash Budget - Organized by WBS
(in $000s)

Calendar Year	2005	2006	2007	2008	Total
1.1 Survey Management					
1.1.1 ARC Administration	38	78	81	86	284
1.1.2 Office of the Director	60	92	95	38	285
1.1.3 Office of the Project Scientist	78	103	107	58	346
1.1.4. Office of the Project Manager	43	89	92	51	274
1.1.5. Office of the Scientific Spokesperson	32	65	57	50	204
ARC Support for Project Spokesperson	5	9	10	9	32
ARC Support for Collaboration Affairs	8	11	11	11	41
ARC Support for Public Affairs	10	24	14	19	67
Public Information Officer	9	21	22	11	64
Survey Management Sub-total	250	427	434	283	1,394
1.2. Survey Operations					
1.2.1. Observing Systems	795	876	892	491	3,054
Technical Support at APO	172	352	367	298	1,189
Off-mountain Technical Support	85	176	182	90	534
Plug Plate Production	101	181	172	35	488
ARC Support for Observing Systems	437	166	172	68	844
1.2.2. Data Processing	327	668	687	450	2,133
Core Data Processing Operations	241	483	502	336	1,563
Software and Data Processing Support	86	185	184	114	570
1.2.3. Data Distribution	159	239	248	148	794
Core Data Distribution Operations	102	119	124	81	427
Data Archive Development and Support	57	120	124	67	367
1.2.4. Observatory Operations	745	1,534	1,595	994	4,868
1.2.5 ARC Support for Survey Operations	60	125	130	54	369
Survey Operations Sub-total	2,087	3,441	3,552	2,138	11,217
1.3 ARC Corporate Support	44	50	52	37	182
1.4 Management Reserve	100	170	170	109	549
Total	2,480	4,088	4,207	2,567	13,342

NOTES
1) The CY2005 budget covers the period Jul-Dec, 2005.
2) The CY2008 budget covers full operations from Jan-Jun 2008 and closeout activities from Jul-Nov 2008.
3) An inflation factor of 4% per year was used to prepare this forecast
4) Closeout costs are included in this cost forecast.

3-year Extension Survey Cost Projection
(as of 02/21/04)

Anticipated In-Kind Contributions - Organized by WBS
(in $000s)

Calendar Year	2005	2006	2007	2008	Total
1.1 Survey Management					
1.1.1 ARC Administration	0	0	0	0	0
1.1.2 Office of the Director	0	0	0	0	0
1.1.3 Office of the Project Scientist	0	0	0	0	0
1.1.4. Office of the Project Manager	66	132	137	160	495
1.1.5. Office of the Scientific Spokesperson	0	0	0	0	0
Survey Management Sub-total	66	132	137	160	495
1.2. Survey Operations					
1.2.1. Observing Systems	27	54	57	31	168
Technical Support at APO	0	0	0	0	0
Off-mountain Technical Support	27	54	57	31	168
Plug Plate Production	0	0	0	0	0
ARC Support for Observing Systems	0	0	0	0	0
1.2.2. Data Processing	72	149	155	104	480
Core Data Processing Operations	45	94	98	74	312
Software and Data Processing Support	27	54	57	31	168
1.2.3. Data Distribution	60	126	131	98	415
Core Data Distribution Operations	60	126	131	98	415
Data Archive Development and Support	0	0	0	0	0
1.2.4 Observatory Operations	0	0	0	0	0
1.2.5 ARC Support for Survey Operations	0	0	0	0	0
Survey Operations Sub-total	159	329	342	233	1,063
1.3 ARC Corporate Support	0	0	0	0	0
1.4 Management Reserve	0	0	0	0	0
Total	226	461	479	393	1,558

NOTES
1) The CY2005 budget covers the period Jul-Dec, 2005
2) The CY2008 budget covers full operations from Jan-Jun 2008 and closeout activities from Jul-Nov 2008
3) An inflation factor of 4% per year was used to prepare this forecast.
4) Closeout costs are included in this cost forecast.

3-year Extension Survey Cost Projection

(as of 02/21/04)

Level of Effort Profile - Organized by WBS

Calendar Year	2005	2006	2007	2008
1.1. Survey Management				
1.1.1 ARC Administration	0.74	0.74	0.74	0.74
1.1.2 Office of the Director	0.00	0.00	0.00	0.00
1.1.3 Office of the Project Scientist	0.00	0.00	0.00	0.00
1.1.4. Office of the Project Manager	1.90	1.90	1.90	1.90
1.1.5. Office of the Scientific Spokesperson	0.50	0.50	0.50	0.50
Survey Management Sub-total	3.14	3.14	3.14	3.14
1.2. Survey Operations				
1.2.1. Observing Systems	6.75	6.75	6.75	6.75
Technical Support at APO	4.00	4.00	4.00	4.00
Off-mountain Technical Support	2.00	2.00	2.00	2.00
Plug Plate Production	0.75	0.75	0.75	0.75
1.2.2. Data Processing	6.95	6.95	6.95	6.95
Core Data Processing Operations	4.95	4.95	4.95	4.95
Software and Data Processing Support	2.00	2.00	2.00	2.00
1.2.3. Data Distribution	2.75	2.75	2.75	2.75
Core Data Distribution Operations	1.50	1.50	1.50	1.50
Data Archive Development and Support	1.25	1.25	1.25	1.25
1.2.4. Observatory Operations	14.35	14.35	14.35	14.35
Observers	8.00	8.00	8.00	8.00
APO technical support	2.25	2.25	2.25	2.25
APO infrastructure support	4.10	4.10	4.10	4.10
1.2.5. ARC Support for Survey Operations	2.00	2.00	2.00	2.00
Survey Operations Sub-total	32.80	32.80	32.80	32.80
Total FTE Support	35.94	35.94	35.94	35.94

NOTES

1) The CY2005 budget covers the period Jul-Dec, 2005
2) The CY2008 budget covers full operations from Jan-Jun 2008 and closeout activities from Jul-Nov 2008.
3) An inflation factor of 4% per year was used to prepare this forecast.
4) Closeout effort is not included in this table

The EAG Balancing Act

Here are the FTE counts in EAG: We have 8 scientists, 3.5 CPs currently in EAG that are FNAL funded and are committed to astrophysics. (I am excluding Marriner for this exercise).

The following shows the expected breakdown in the next couple of years if we pursue SDSS, SNAP, and DECAM.

SDSS 3 Scientists 2.5 CPs
SNAP 1.25 Scientist 1 CP
DECAM 1.5 Scientist 0 CP
Research 2.25 Scientist

The remaining people needed for SDSS are either existing non-EAG scientists from PPD, existing CD people not in EAG, or existing or planned CPs in EAG funded by ARC.