Sloan Extension for Galactic Underpinnings and Evolution (SEGUE)

Segue (v.): To proceed to what follows without pause

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I. Project Summary

A. Science Goals

We propose an imaging and spectroscopic survey to unravel the structure, formation history, kinematics, dynamical evolution, chemical evolution, and dark matter distribution of the Milky Way. These results underpin our knowledge of the formation of the Milky Way Galaxy and of formation processes within the Milky Way, and will be the cornerstone of our understanding of galaxy formation processes in general. Cosmology is entering a precision era, facilitated by new work on the Cosmic Microwave Background by the Wilkinson Microwave Anisotropy Probe (WMAP) and on the distribution of galaxies by the Sloan Digital Sky Survey (SDSS) and by smaller, deeper large-telescope surveys. Galaxy formation and evolution, however, is still as data-starved as cosmology was twenty years ago. The Milky Way is the only galaxy in which we can hope to kinematically and spatially resolve the fossil record of evolution, since here the geometry is relatively unambiguous and intrinsically faint stars can be readily observed.

Two key projects which focus on Galactic history and dynamics are: (1) detection of substructure in the Galactic halo, and (2) defining and refining our knowledge of the Milky Way's Galactic disks. Other projects that will be necessary to realize the full potential of the key projects include understanding the relationship between SDSS photometry and the physical properties of stars, mapping the interstellar extinction in three dimensions, and studying the chemical evolution of the earliest Milky Way stars.

To accomplish these goals, the existing SDSS hardware and software will be used to image (in five SDSS passbands) four thousand square degrees of the Milky Way at low Galactic latitude and to sample the stars in this new region and in the existing high-latitude SDSS survey to target and obtain spectra of 240,000 stars. These spectra will allow determinations of radial velocities and chemical abundances, which will allow us to study kinematics, dynamics, and the chemical history of the Galaxy.

Key Project 1: Halo Substructure

SDSS data have already been used to trace the tidal stream from the Sagittarius dwarf galaxy, and to discover a second large tidal stream in the plane of the Milky Way. The structure of the Milky Way's halo is sufficiently lumpy that it has so far defied a consistent global fit to the smooth component of the spheroid stars. The halo may contain a (possibly flattened) power law component, a flattened inner halo, at least two large tidal streams, a dozen dwarf galaxies and a hundred globular clusters. Some of the dwarf galaxies and globular clusters are currently being pulled apart by tidal forces. Some of the stars in the components that appear to be smooth in density may retain kinematics of the stellar associations in which they were born.

Disentangling the structure of the Milky Way halo requires that individual stellar associations can be separated by population (age and metallicity), kinematics, and spatial density. The SDSS and SEGUE photometry can be used for photometric parallax (spatial density) and isochrone fitting to stellar components (into rough age and metallicity bins). Galaxy components can be separated kinematically with radial velocities. The stellar physical properties determined from spectroscopy and from imaging of open clusters serve as a check on the isochrones and further serve to illuminate the chemical composition of each component.

The dynamics of stellar streams allow us to fit the Galactic potential's shape and orientation, and constrain parameters characterizing the lumpiness of the halo dark matter. The dark matter itself could accrete with time as the stars do; knowledge of the Galactic merger history and gravitational potential place important constraints on N-body models of galaxy formation and on the expected velocity distribution of dark matter particles. The velocity distribution of dark matter particles can affect both the energy spectrum and annual modulation of the expected signal in dark matter direct detection experiments on the Earth.

Key Project 2: Disk structure

Imaging at low Galactic latitude will allow us to study the transition from thin disk to thick disk to flattened inner halo. There is general agreement on the number and exponential form of the Milky Way stellar disks, but little agreement on the exact parameters of each. This situation is similar to the state of our knowledge of the halo several years ago, when there was general agreement that the spheroidal population of stars was well modeled by a power law, but with no agreement on the flattening parameter (measurements range from $c/a = 0.4 - 1.0$). As the current generation of precise data is beginning to show, the Milky Way's disks are not as simple as the present models suggest. The fact that the stars associated with the large tidal stream in the plane of the Milky Way were initially widely attributed to an extended thick disk of stars underlines how little we know for sure about the number and detailed form of the Milky Way's disks.

SEGUE will use spectra (physical properties and radial velocities), photometry (stellar population and spatial density), and proper motions from outside catalogs to separate and normalize the Galactic components in the solar neighborhood. Additionally, the disk components will be traced using stars as close as five or ten degrees from the Galactic plane, using techniques similar to those for finding halo substructure. We do not expect to be able to trace all the spiral substructure of the young thin disk, as that is best studied at longer wavelengths, but we will be able to trace the structure, kinematics, and compositions of the other disks as a function of position in the Galaxy. This latter goal will require that we understand the three dimensional structure of the Interstellar Medium (ISM), including independent measures of dust from SEGUE observations, and its effects on our stellar photometry.

Formation History

The identification and characterization of the Milky Way components can be utilized as an archaeological "dig" illuminating the fossil record of galaxy evolution. We will study how many mergers and of what size and time series must have occurred to make the Milky Way. We will begin to be able to pick apart the chemical and dynamical evolution of the Galaxy as a whole. We will search for rare, especially low metallicity, stars that 'freeze-in' the state of the ISM during the earliest stages of star formation in the Universe. The rare stellar objects identified in this survey will provide followup targets of high scientific interest for the world's largest telescopes.

B. Survey Data

Approximately four thousand square degrees of new imaging data, at moderate to low Galactic latitude, and spectra of 240,000 Galactic stars will be acquired. The imaging footprint was designed so that no part of the sky (above $\delta = -20°$ observable from the Apache Point Observatory) is more than $10°$ from either an SDSS or a SEGUE imaging stripe. In the Galactic caps, no part of the sky is more than $5°$ from an imaging stripe. In addition, the scans are designed to tie the photometric calibration from the SDSS north Galactic cap to the scans in the south, and to cross each other a sufficient number of times to reduce systematic uncertainties in the overall photometric calibration. The positions of the spectroscopic plates are chosen to sample the Galaxy in all directions, so that no part of the observable sky is more than about ten degrees from a spectroscopic plate, and to target well-studied open clusters. Figure 1 shows the approximate layout of the SEGUE imaging stripes and spectroscopic plates on the sky.

The low Galactic latitude imaging enables studies of the metal-rich Galactic thin disk, the vertical structure of the thin and the thick disks, the Galactic warp and flaring, the three dimensional structure of the ISM, and present star forming regions. The imaging will be taken in similar weather conditions, at the same scanning rate (which translates to the same exposure time), and with the same instruments and filters as the SDSS. Each stripe is $2.5°$ wide and requires two interleaved scans with the SDSS imaging camera, on separate nights, to complete. The imaging includes twelve constant Galactic longitude stripes which go through the Galactic plane and typically extend thirty-five degrees on either side (dashed green lines in Figure 1). These stripes are separated by about $20°$ of Galactic longitude, varying somewhat to pass through known open clusters, SIRTF legacy fields, and patches of low extinction near the Galactic plane. The constant Galactic longitude stripes connect and overlap SDSS imaging of the Galactic caps to facilitate the photometric calibration of both old and new data.

In addition, three new SDSS stripes (72, 79, and 90, shown as solid green lines in Figure 1) will be imaged in the South Galactic Cap. Only three stripes were imaged in the South Galactic Cap during the SDSS survey, and the additional stripes are needed to sample that part of the sky about every ten degrees. One stripe (red line in Figure 1) follows the Sagittarius dwarf tidal stream across the northern sky. Two long (half-filled) strips (magenta lines in Figure 1) cross the remaining SEGUE stripes, and will be used to cross-calibrate the stellar photometry to a level of at least 2% (systematic+rms), and will trace low latitude structures, including the newly discovered tidal stream in the Galactic plane. The SDSS camera must scan along great circles, so all of these stripes describe great circles on the Celestial Sphere.

The spectroscopic observations include 1200 spectra in each of 200 individual sky directions. The plate positions were chosen to sample the sky in all observable directions, and spectra will be selected to sample stars from one to 100 kpc from the Sun and from as many Galactic substructures as possible. Additional observations target regions of high interest such as open clusters, star formation regions, and known tidal streams in the halo. Each plate position is $3°$ in diameter. We will design two 640-fiber plates in each plate position, with a total of about 1200 stellar targets

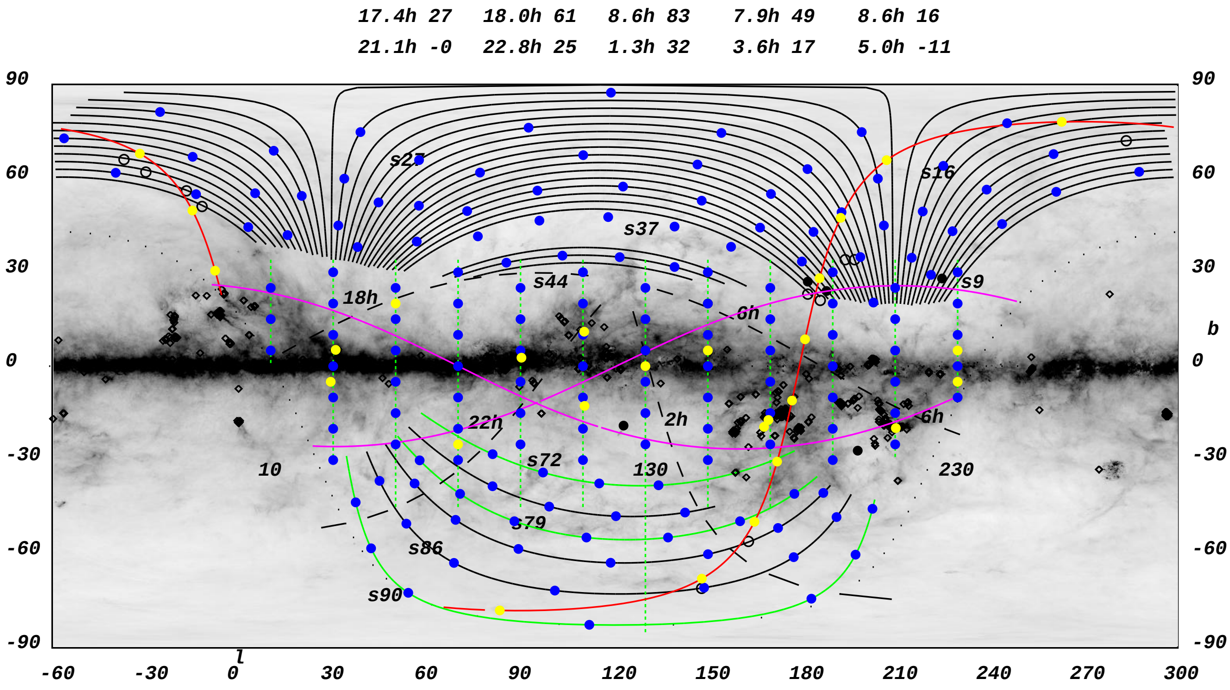

Figure 1. Low Latitude Imaging and Spectroscopy Plan. The SFD (1998) reddening map is shown in Galactic coordinates; note the center is shifted to $(l, b) = (120°, 0°)$. Green, red, magenta (purple) lines indicate new SEGUE scans to be obtained. SEGUE Imaging at $l = 110$ degrees from $-30° < b < 30°$ has already been obtained as of Nov 2003 (SDSS runs 4134, 4135, 4144, 4152). The red line along the great circle with (node, incl) = $(32°, 35°)$ follows the Sagittarius dwarf tidal stream. Magenta lines indicate half-filled "strips" in portions of the sky at low Galactic latitude, and cross the constant longitude stripes for better calibration; the great circles arcs are defined by (node,incl) = $(259.9°, 43.6°), (311.0°, 66.7°)$. The total SEGUE imaging area is about 4000 sq. degrees, of which 200 sq. degrees has already been obtained. Black lines indicate existing or planned SDSS regular imaging. Black dotted reference lines are at $b = 0°$ and declination (DEC) = $-20°$ (no SEGUE imaging or spectroscopy occurs at a DEC of $< -20°$ from Apache Point Observatory in the Northern hemisphere). Black long dashed lines mark constant Right Ascensions (RAs) of (18, 22, 2, and 6) hours. Labels above the top of the figure indicate RA, DEC start and end for a vertical SEGUE imaging stripe. Open black circles indicate positions of known Sagittarius dwarf tidal stream stars. Filled black circles indicate positions of known Monoceros stream stars. Open black diamonds indicate positions of known Galactic open clusters. The blue circles indicate individual 3-degree diameter positions of Galactic structure plate pairs (bright plate: 45 min exposure, plus faint plate: 90 min exposure), 168 blue plate pairs. Yellow circles indicate positions of 'special plates,' landing on a known open cluster, the Sag. dwarf stream, or the Monoceros Ring structure. 29 blue plate pairs. Total: 197 plate pairs and about 240,000 stellar spectra with resolving power $R \sim 2000$, and $3 < S/N < 100$ for objects with $20.3 > g > 14.5$.

plus calibration objects. One plate will have the SDSS standard 45 minute exposure time, and the other will be exposed for twice as long, allowing us to reach stellar targets as faint as $g \sim 20.3$. Spectroscopic targets will include halo giants, metal-poor dwarfs, G disk and halo dwarfs, white dwarfs, and a large variety of rare stars. At low latitudes, targets within star-forming regions will be selected.

II. Scientific Case

Our understanding of Galaxy evolution has advanced considerably since the monolithic collapse model of Eggen, Lynden-Bell and Sandage (1962) was adopted as the standard. Most experts now believe that the Galaxy was built up through a series of mergers (Searle & Zinn 1978), though there is no agreement on the number and size of the merger events. These current models of galaxy formation stem from cold dark matter (CDM) simulations that show the outer halos accreting over billions of years (Steinmetz & Navarro 2002), and from the increasing number of examples of moving groups and tidal disruption discovered in the halo of our galaxy (Majewski et al. 2003; Newberg et al. 2002; Odenkirchen et al. 2001a; Irwin & Helmi et al. 1999; Ibata, Gilmore, & Irwin 1995; Grillmair et al. 1995; Irwin & Hatzidimitriou 1995), M31 (Ferguson et al. 2002), and other external galaxies (Shang et al. 1998, Zucker et al. 2004).

It is possible that the hierarchical merging process is most important in the dark matter dominated galactic halos, while disks might form from the (angular momentum conserving) collapse of the gas within the stellar spheroid. However, Λ cold dark matter simulations suggest merging may significantly affect the formation of disks as well (Abadi et al. 2003). Evidence of mergers is currently most apparent in the outer halo where signatures of satellite accretion persist for many gigayears (Johnston, Spergel, & Hernquist 1995). Dwarf galaxies and globular clusters are among the outer halo objects which are merging at the current epoch. It is also possible that there exist some lumps of dark matter in the outer halo that have not yet merged, and which do not contain stars (e.g., Bullock, Kravtsov, & Weinberg 2001). These latter structures could be evident by their perturbation of tidal tails and warping of disk structures.

Our own Milky Way is the only galaxy that we can presently study at sufficiently high spatial and kinematical resolution, and at sufficient depth, to address many of the open questions of galaxy formation and small-scale structure evolution in sub-halos. Our goal is to obtain the spectroscopic and photometric data required to unravel the structure, the formation history, the kinematic and dynamical evolution, the chemical evolution, and the distribution of the dark matter within and around the Milky Way.

We propose two key projects, which contribute to our knowledge of the Galactic mass assembly and disk formation models. These projects are: (1) detection of substructure in the Galactic halo, and (2) defining the structures of the Galactic disks. These are really two parts of the one key project to define the major components of the Milky Way galaxy, but are listed separately since they may require different data sets and analysis methods. One may think of this proposed project as providing a large homogeneous input data set to a 21st century model of the Galaxy – one which involves not only accurate multi-color photometry such as has gone into earlier models (Bahcall & Soneira 1984), but large amounts of kinematic velocity and proper motion data which can be used to complete the dynamical and evolutionary picture. This technique is most similar to that used to construct the Besancon model of the Galaxy (Robin et al. 2003), but with more input data.

Detection of substructure in the Galactic halo requires photometry and radial velocities in as many directions as possible. The large tidal streams that have already been discovered are more than 4 kpc across, setting the scale over which we must sample the sky to find all large tidal structures. Characterizing the Galactic disks requires data collection primarily at low latitudes, and within a few kpc of the Galactic plane. The goal is to separate disk components by their stellar content, and then measure the global properties.

These projects will separate and describe components using radial velocities, proper motions, chemical composition, photometric parallax, and isochrone fitting to photometry. In some sense, our survey is concentrated on the “big picture” of our galaxy. We will identify and constrain all of the largest components, paving the way for future inquiries which will find finer substructure,

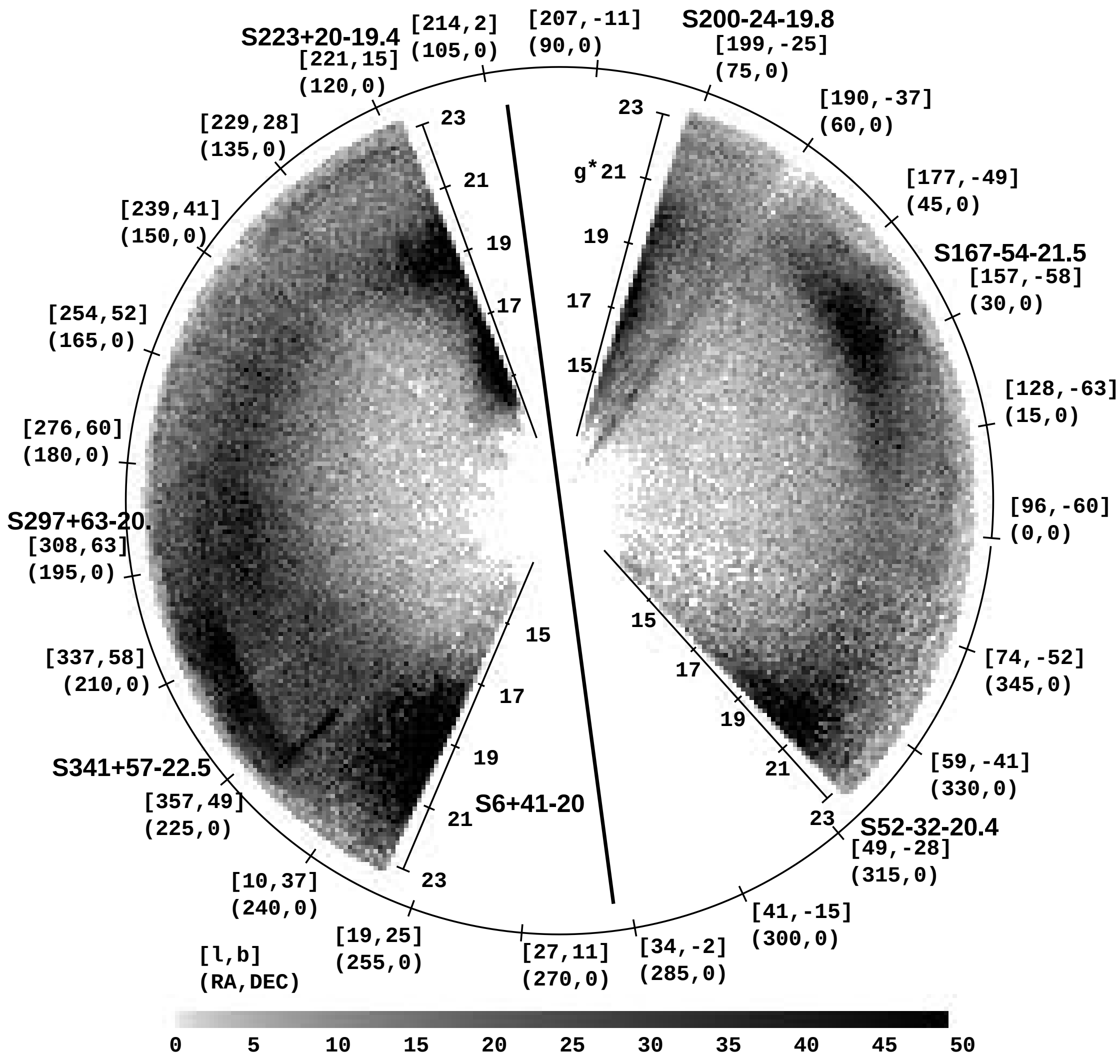

Figure 2. Polar histogram of color-selected turnoff stars on the celestial equator. This data was obtained with the Sloan Digital Sky Survey. The radial distance gives the apparent dereddened g^* magnitude. The angular position gives the RA. Galactic coordinates are labeled for reference. The shading of each cell indicates the relative number of counts of stars in each $(r,\theta) = (g^*, \alpha)$ bin. A typical absolute magnitude for stars with these colors is $M_{g^*} = 4.2$. The feature at $\alpha = 60^\circ$ is an artifact from imperfect reddening correction of a large dust cloud at this position. The streak at $\alpha = 229^\circ$ represents stars in the globular cluster Palomar 5. The boldface labels indicate our names for identified structures of halo stars. S341+57-22.5 at $g^* \sim 22.5$, and S167-54-21.5 at $g^* \sim 21.5$ are cross sections of the Sagittarius dwarf galaxy tidal stream.

more accurately determine the chemical evolution, and measure proper motions for a large fraction of the stars in the Milky Way.

A calibrated catalog of images, spectra, and associated derived quantities, will be the primary product of this survey. These will be generated in nearly real time, to be used for rapid follow-up work or as input targets to space-based or large aperture telescopes.

The need for this global picture of our galaxy is well illustrated by the results of Newberg et al. (2000; Figure 2). In this figure, there are seven marked concentrations of stars. Concentrations S341+57-22.5 and S167-54-21.5 have been identified as cross sections through the tidal stream of the Sagittarius dwarf spheroidal galaxy, which is currently in the process of tidal disruption. The overdensities S223+20-19.4 and S200-24-19.8 are thought to be pieces of another tidal disrupting stream in the plane of the Milky Way galaxy. The concentrations in this region near the Galactic plane, at 15th and 17th magnitude near the anticenter are not named, but also are not understood in any global picture of the Milky Way. The overdensity S297+63-20. is thought to be another tidal stream, possibly associated with the Sagittarius dwarf galaxy, though this has not been confirmed and remains controversial. The concentrations S6+41-20 and S52-32-20.4 are thought to be portions of the stellar spheroid, though their density distributions do not fit standard spheroidal models within the errors of our density measurements.

One sees in Figure 2 a strong argument for a global view of the whole Milky Way, including low Galactic latitudes, since one cannot identify substructure without understanding the major Galactic components in which that substructure is embedded, and properly accounting for interstellar extinction. Many of the scientific analyses that we anticipate will be based on these data have counterparts in the much smaller-scale efforts of individuals or groups, which, unavoidably, dilute their impact by acquiring data in a piecemeal and non-uniform fashion. A uniform survey creates a synergy which allows more global questions to be addressed and leaves behind a legacy data set against which future data sets will be compared.

A better understanding of the Milky Way's structure and evolution is already a "cornerstone" project in ESA's science planning, through the GAIA satellite mission, and plays an important role in the definition of the science goals for NASA's SIM and TPF missions, which are "key elements in NASA's Origins Program." We demonstrate here how a deep imaging and spectroscopic optical survey will complement as well as lay the groundwork for these ambitious satellite projects. Furthermore, SEGUE will fill a unique and vital niche complementing ongoing and planned large ground based Galactic structure programs such as RAVE and K.A.O.S.

A. Characterization of the Component Stellar Structures in the Milky Way

The fossil record of galaxy evolution (star formation and mass assembly) is written in the chemical, kinematic, and spatial distribution of Galactic stars. The main recognized components of the Galaxy are the thin disk, the thick disk, the bulge, and the stellar spheroid. Recently many groups of astronomers have identified examples of Galactic structure that either requires additional components or an increase in the complexity of the traditional components. Kinematic studies show the existence of moving groups and coherent streams (numerous studies), and a group of stars (Gilmore, Wyse, & Norris 2002) that may be part of the merger that puffed up the thick disk. Overdensities of stars over the Galactic bar (Parker, Humphreys, & Larsen 2002) have been found in photometry. Also, a new metal-weak thick disk component has been proposed (see Norris 1994, Beers et al. 2002 and references therein).

Clearly, even the basic stellar components of the Milky Way are not yet understood in depth. The complex substructure now being identified has undoubtedly biased the previous limited studies of thick disk structure, contributing to our present imprecise knowledge of the thick disk; study of many lines of sight over much of the sky will be necessary to unravel the substructure and obtain a more complete picture.

This survey would specifically target the thick disk/halo boundary and substructure. The structures would be studied in stellar density from statistical photometric parallaxes, and in kinematics through statistics of the radial velocities/metallicities in each component. We use the term "statistical photometric parallax" to describe the method of using photometry to determine distance (photometric parallax) in cases where the number of stars is large, so that statistics can be used to estimate the underlying spatial structure of the group. We will have a unique opportunity to study the stellar Metallicity Distribution Function (MDF), especially in the region where the thick disk and spheroid populations overlap. Figure 3 demonstrates preliminary results from SDSS

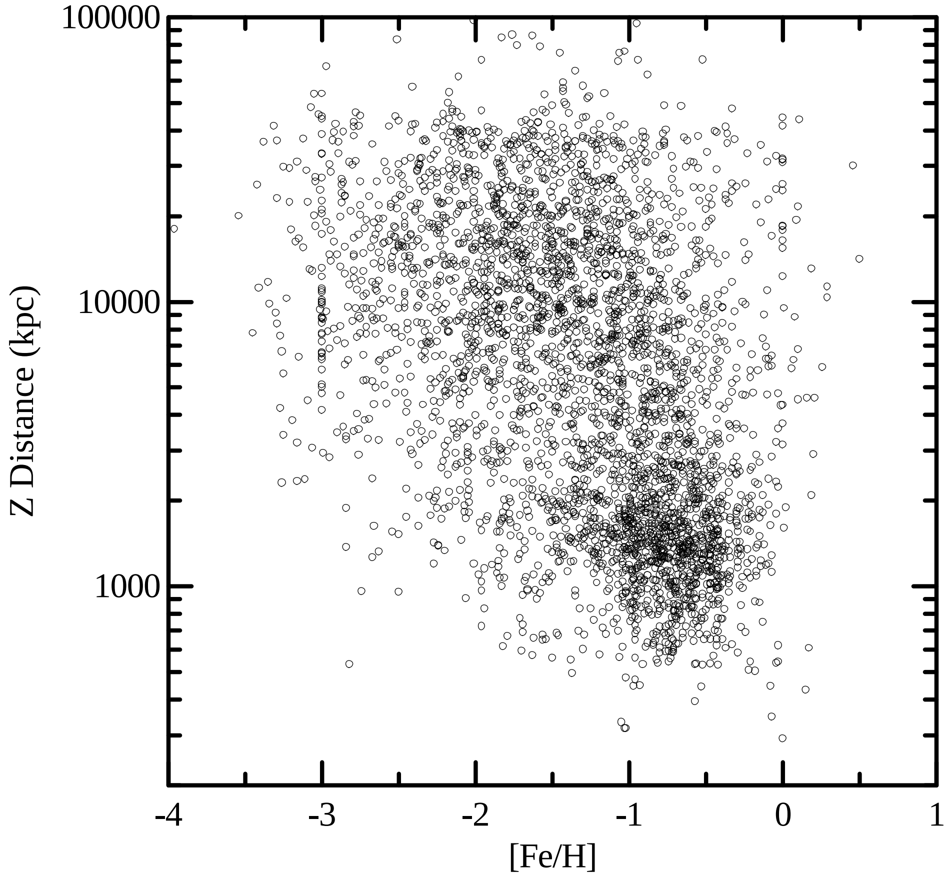

Figure 3. The distance and metallicity distribution of EDR stars. The distance distribution of ~ 4000 stars from the SDSS Early Data Release (EDR) as a function of metallicity [Fe/H]. One can clearly discriminate the presence of thick-disk stars with metallicities in the range -1.0 $<$ [Fe/H] < 0 and locations within a few kpc of the Sun, from the halo objects at large distances that extend to much lower metallicities.

EDR spectra.

Flaring and Warping of the Galactic Plane

The disks of many galaxies both flare and warp in their outer regions. Flaring is attributed to an increasing ratio of spherically distributed dark mass to disk mass with increasing distance from the center of the galaxy, and provides one of the few available methods of measuring the three-dimensional distribution of dark matter within a galaxy. The origin of Galactic warps is still something of a mystery. Tidal interactions with satellites and neighbors is an obvious cause; for example, the warp in the Galaxy is often attributed to the tidal influence of the Magellanic Clouds (e.g., Weinberg and Nikolaev 2001; Garcia-Ruiz et al. 2002) or of the Sagittarius dwarf spheroidal galaxy (Bailin 2003). However, not all warped galaxies appear to have (presently detected) neighbors.

The warp and flare in the outer Galactic disk has been studied primarily using (radio) observations of neutral hydrogen. The depth and color sensitivity of SDSS will allow the 3-D structure of the northern warp in the Galaxy to be traced to distances beyond the entire known extent of the warp (20 kpc, Binney 1992), using photometrically identified giants, carbon stars (especially when combined with 2MASS data) and red clump stars (e.g., Margon et al. 2002; Helmi et al. 2003).

The Structure of the Thick Disk

Hawley et al. (2002) show that early M dwarfs can be traced to distances of up to 1 kpc above the Galactic plane, well into the domain where the thick disk population dominates that of the thin disk. Since the stars of the thick disk are more metal-deficient (typically by at least 0.3-0.5 dex) than the thin disk stars, their colors, especially $g-r$, diverge from those of the metal-rich disk stars. One can therefore, at least in a statistical sense, separate the two populations. A first look at the vertical structure of the thick disk from SDSS data has been carried out by Chen et al. (2001). Star counts in the thin and thick disks can be used to determine the initial mass function, and in particular the counts of lower-metallicity stars must be understood (see the recent discussion by Zheng et al. 2001 and Chabrier 2003).

The current SDSS imaging data provide star counts at high Galactic latitude only; understanding and disentangling the vertical structure of both the thick and thin disks requires data covering the whole range of Galactic latitude at many longitudes.

The Structure of the Galactic Halo

SDSS data have already demonstrated the presence of very large structures in the Galactic halo (Yanny et al. 2000; Ivezic et al. 2000; Odenkirchen et al. 2001a,b; Newberg et al. 2002; Rave et al. 2003; Yanny et al. 2003). These structures include extra-tidal features around globular clusters and vast comoving stellar streams from accreted dwarf galaxies. These structures, and similar more tenuous analogues, may cover a significant fraction of the sky. Imaging more sky allows such structures to be traced to larger angular sizes, and allows structures which do not completely fill a great circle on the sky to be detected. Furthermore, high-metallicity globular clusters tend to be found at lower Galactic latitudes; there may be streamers and tails of different color (metallicity) at lower latitudes. Indeed, recently Frinchaboy et al. 2004 showed that many low latitude open and globular star clusters are likely to be associated with a single large tidal stream in the Galactic plane.

There is increasing evidence that even "globally recognized" structures, such as "the halo," change dramatically with increasing Galactocentric distance. An inner, "flattened" halo component, for example, has been indicated by many recent studies (Lemon et al. 2003, Chiba & Beers 2000). Preston, Shectman & Beers (1991) have used the mean colors of blue horizontal-branch stars to indicate a possible decrease in the ages of stars with increasing Galactocentric distance. Sirko et al. (2004) use an analysis of the spectra of high-latitude A stars to demonstrate a change in the velocity ellipsoid of the halo with distance from the Galactic center. Both of these represent key results for understanding the formation of the Milky Way, which could be readily refined and extended using our proposed survey effort.

Complexity of Galactic spheroid populations in other galaxies is traced by their globular cluster systems (at least in early-type galaxies with populous cluster systems that can be studied). Typically the globular cluster systems are bimodal, with bluer (lower metallicity) clusters making up a more extended and dynamically hotter system, and redder (higher metallicity) clusters comprising a system more centrally concentrated and sometimes rotating (e.g. many papers in IAU Symposium 207, ed. Geisler, Grebel & Minniti 2002). Typically the field-star populations have color and spatial distributions suggesting properties more similar to (and perhaps having a common origin with) the redder globular clusters. The Milky Way has only a sparse system of metal-rich globular clusters, which are mainly found in the Galactic bulge and which are too sparse to give information on substructure. Studying field stars will provide good statistical information on both lower- and higher-metallicity components (the "blue horizontal branch" and the little-studied "red horizontal branch" components, if we consider metallicity as the primary culprit of the second-parameter effect). Then, a comparison to the tracer globular clusters may provide insight into the origin of the dichotomy seen in the extragalactic cluster systems.

Estimating the Mass of the Galaxy

Although it is perhaps obvious, it is worth noting that kinematics of the distant stars in the proposed SDSS extension will provide definitive estimates of the mass of the Galaxy, a fundamental parameter that at present has errors of determination (arising from methods that rely on the motions of the globular clusters and nearby satellite galaxies) of 50% to 100%. Sakamoto, Chiba, & Beers (2003) show how even the relatively nearby field horizontal-branch stars in the HK survey can be used to dramatically reduce the errors in the mass estimate of the Milky Way. The ~ 1000 horizontal-branch stars contained in the EDR will reduce these errors even further (Li et al. 2002). The clear advantage of distant mass tracers derives from the fact that the escape velocity from the Galaxy decreases to the point that a halo population with dispersion on the order of 100-150 km/s populates the velocity space of targets with velocities that would exceed this escape velocity ($>$ 400-450 km/s) if they were not gravitationally bound. A sharp "edge" in the velocity distribution of tracers is a good indicator of the total enclosed mass. A sufficiently large number of tracers would enable one to directly estimate the variation of enclosed mass with distance, which is a necessary ingredient, for example, in fully exploiting past and future microlensing surveys. Making these robust density estimates requires good distance estimates, which we will be able to find in multiple ways. SDSS spectroscopy allows BHB stars to be distinguished from blue stragglers, variability measurements identify RR Lyrae stars, and SEGUE spectroscopy can also be used to distinguish carbon 'R' stars, which also have a common absolute magnitude, from other types of carbon stars, especially N stars and dwarf carbon stars.

B. The Merger History of the Galaxy

The detailed merger history of galaxies is crucial to our understanding of the evolution of the Universe from early times until the present. Wyse (2001) argues that no more than 20% (by mass) of the Milky Way was assembled from mergers within the last 10-12 Gyr, which is not "typical" for CDM models. By looking for galaxy substructure with density contrasts, as well as with radial velocity structure, and possibly correlated chemical inhomogeneities, we can unravel at least the general outlines of the merger history of the Milky Way.

We hope to identify streams as spatial overdensities, moving groups, and as star groupings with similar metallicities/ages as determined from spectroscopic classifications of stars. The ages (or ranges of ages) of the stars in the identified groups can be determined from isochrone fitting of the stellar populations and from direct measurements of the stellar spectra (coupled with model atmosphere analysis) with uncertainties of several gigayears. The number and inferred extent of identified substructures will be used to constrain the total number of mergers and typical sizes of the merged structures. One would have to account for the fact that if larger structures containing smaller structures merged (for instance a dwarf galaxy containing globular clusters), then we would probably observe two or more separate stellar populations, perhaps exhibiting similar space positions and motions (as is nicely demonstrated by the Sagittarius dwarf spheroidal galaxy with its distinctive, wide range of ages and metallicities in its field populations and its distinctly different globular clusters). Statistical fits to the existing stellar position and velocity data already show promise for identification of the merger events from which (at least a portion of) the halo and possibly the thick disk of the Milky Way were created. These approaches will benefit far more data, some of which will be obtained in the SEGUE survey.

Photometric detection of Streams from SDSS Data

The SDSS camera obtains multi-color photometry of objects to faint magnitudes with a color accuracy of 2% (0.02 magnitudes) down to the spectroscopic limit (g $\sim$ 20th magnitude). The attainment of this accuracy to this depth, with absolute calibrations uniform over a vast area of sky (thousands of square degrees), is unprecedented. The large number of stars and the high photometric accuracy, allow us to trace coherent structures across the Galaxy using classic photometric parallax techniques for determining distances to stars. This has been shown (see below) to be an unexpectedly powerful observational technique, now being adopted by a broad community of astronomers (e.g., Majewski et al. 2003).

It has already been demonstrated that merger events can be identified in SDSS data. Figure 4 shows the primary result of Yanny, Newberg, et al. (2000), which identified tidal debris from photometrically selected A-type stars. The stars in the Sagittarius dwarf tidal stream dominate our original sample of blue Galactic stars, making it impossible to generate a reliable fit to the smooth (relaxed) Galactic halo. Even though the blue stars turned out to be 'bi-modal' standard candles (consisting of a mix of BHBs and blue stragglers), they are extremely useful for tracing structures in the Galactic halo.

Techniques for mining the SDSS data for Galactic structure were further developed in Newberg, Yanny, et al. (2002). Figure 5 shows a color-magnitude Hess diagram (CMD) of a region of the sky towards (ℓ, b) = (341°, 57°), one of the directions in which SDSS blue stars trace the tidal tails of the Sagittarius dwarf galaxy. The diagram bears striking resemblance to the CMD of the Sagittarius dwarf, including similar clumps of red stars. From this figure we demonstrate that, at least for high-contrast structures, we can measure the turnoff color of the stars in that stellar concentration. Both of the overdensities identified in Figure 4 have the same color turnoff stars as the Sagittarius dwarf galaxy, when transformed to SDSS colors. Once the diagram is made, it becomes clear that we can use turnoff stars to trace the structure of the Sagittarius dwarf tidal stream. The stars in Figure 4 were selected with -0.3 < $g^* - r^*$ < 0.0; from Figure 5, it is apparent that more Sagittarius stars would be selected with a color selection of 0.1 < $g^* - r^*$ < 0.3. This technique of isolating F turnoff stars to trace halo structure at distances of 1.5-50 kpc from the Sun was pursued by Newberg et al. (2002). The results are shown in Figure 2. The redder stars sample the stellar density distribution to only 20% of the distance sampled by BHB stars at the same apparent magnitude, but there are orders of magnitude more stars with which to sample the density function.

From this analysis we identified at least five additional overdensities of stars. Darker, higher density regions are labeled in Figure 2 as $S\ell\ell\ell \pm bb - mm.m$, where $\ell\ell\ell$ is the Galactic longitude in degrees, bb is the Galactic latitude in degrees, and mm.m is the approximate g^* magnitude of the selected stars. Four of these may be pieces of the same halo structure, which could be a new (tidally disrupting) dwarf satellite of the Milky Way, partially hidden in the Galactic plane, or part of a metal-poor, disk-like structure with larger scale lengths than have been previously proposed. A fifth overdensity is not associated with any known structure, and might be a new tidal stream or a separate piece of the Sagittarius dwarf galaxy stream.

As shown in the above example, once we identify a clumped stellar population in the halo, we will use color–magnitude diagrams for the stars in the structure to study its stellar density, metallicity, and age. If the structure has a low density contrast, we can measure the turnoff color. If the structure has a high density contrast, we can (at least sometimes) identify the turnoff, giant branch, and structure of the horizontal branch. In the Sagittarius dwarf tidal stream, a giant branch can be discerned and is shown in Figure 5. We will use color-magnitude Hess diagrams to

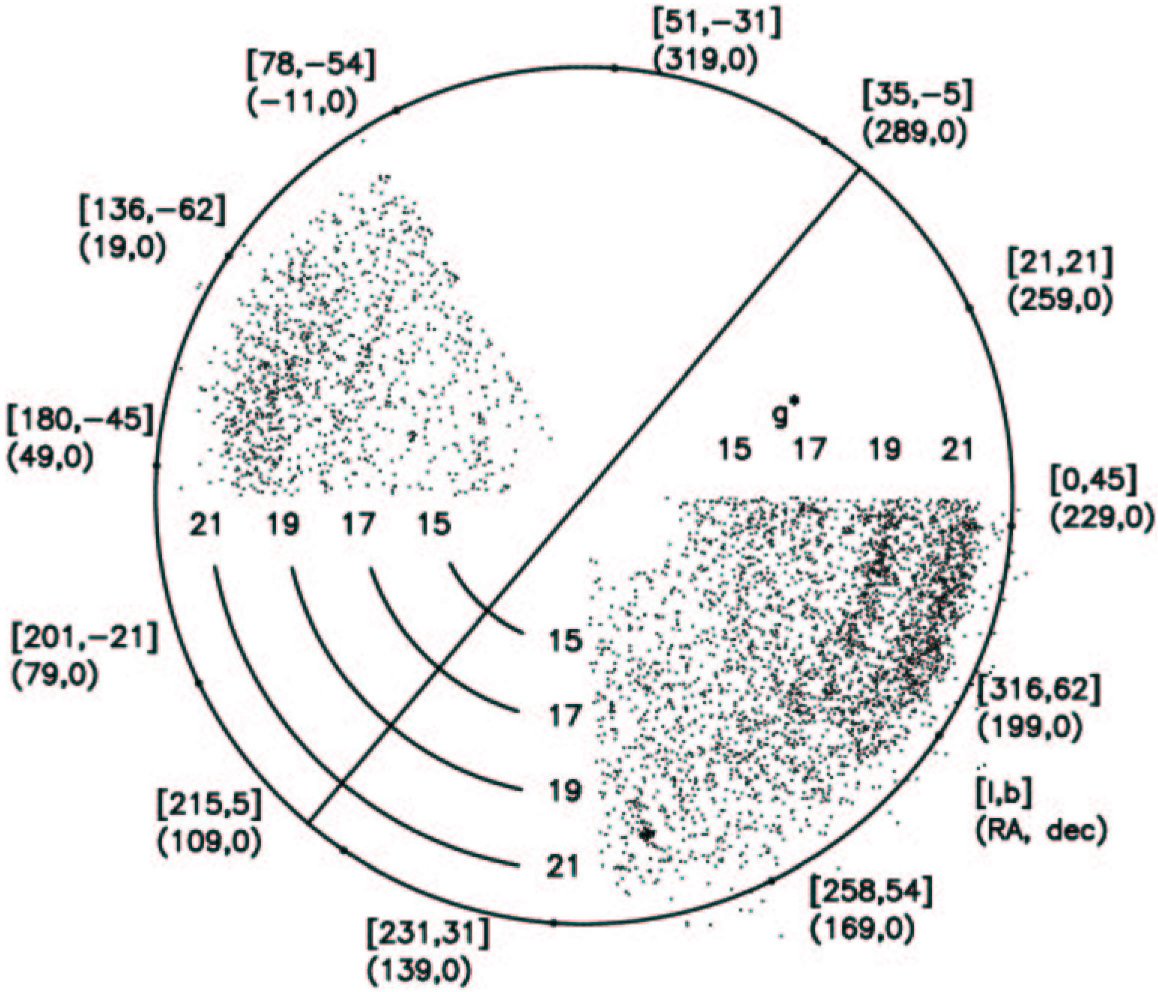

Figure 4. Two dimensional (g^* magnitude versus right ascension) polar plot of blue (-0.3 $< g^* - r^* <$ 0.0) stars on the Celestial Equator. Right ascension and declination are indicated by numbers in round brackets, whereas Galactic longitude and latitude are given in square brackets. The intersection of the plane with the celestial equator and the plane of the Galaxy is indicated by a dark line. The Sextans dwarf galaxy is at $\alpha = 153°$, $g^* = 20.5$. Notice the parallel arcs at $195° < \alpha < 230°$ and the large structure at $20° < \alpha < 40°$. The parallel arcs are the blue horizontal branch stars (BHB, inner arc) and blue stragglers (BS, outer arc) in the tidal stream of the Sagittarius dwarf galaxy. The arc of BHB stars and corresponding arc of blue stragglers represent stars at the same distance, but which appear at different apparent magnitudes due to a two-magnitude difference in the average absolute magnitudes of the two populations.

study the stellar populations as a function of position along each stream.

The more general technique of using the turnoff color (accurate to 2% with SDSS photometry) of a collection of stars in the halo or in a stream is a quite powerful marker which can be used to identify groups of stars with the same metallicity and age, even when spread diffusely across the sky.

We believe we can study stellar population evolution along streams – a mixed probe of stellar evolution and morphology of the host galaxy (e.g., Oh, Lin, & Aarseth 1995; Piatek & Pryor 1995; Johnston, Sigurdsson, & Hernquist 1999). It will be important to also estimate metallicity/age information for each component, as a function of position within the component. Without estimates

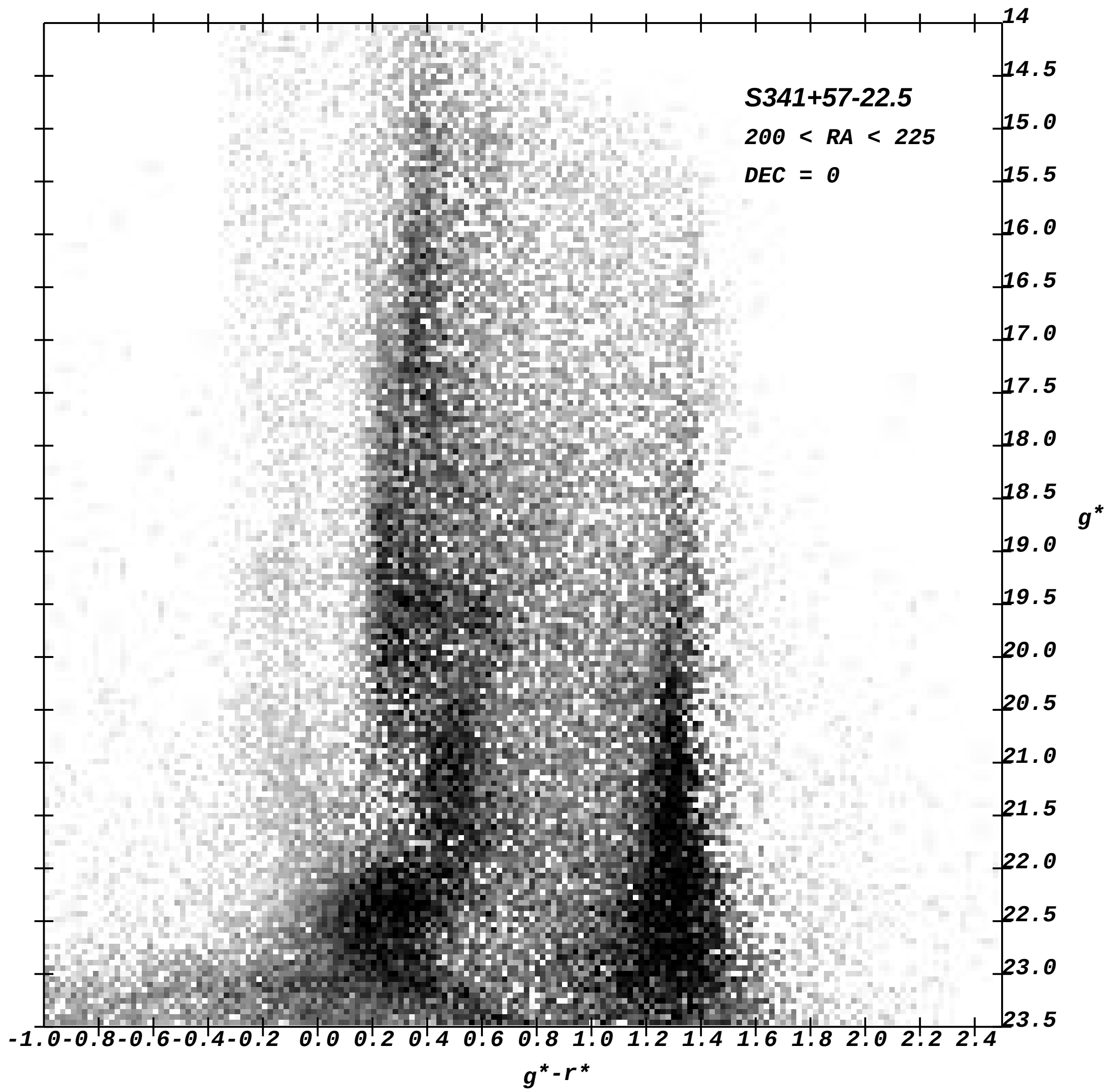

Figure 5. Color-magnitude image of S341+57-22.5 (Sagittarius stream. This shows stars in the equatorial region $200^\circ < \alpha < 225^\circ$. Capturing the color-magnitude diagram as an image allowed us to subtract off images of other parts of the sky which do not contain the Sagittarius dwarf streamer. The image clearly shows a turnoff at about $g^* = 22.5$, a giant branch extending to a clump of red stars at $g^* = 19.7$, a blue horizontal branch extending from the clump to as blue as $g^* - r^*$ = -0.1, and blue stragglers which extend from the turnoff up through the horizontal branch.

of these quantities, the number count data are difficult to interpret, since the age and metallicity affects the luminosity function of color-selected stellar samples. These determinations will be much easier since the Padua isochrones have recently been transformed to the SDSS photometric system (Girardi et al. 2004) The spectral data will also be important in characterizing the stellar content as a function of position within each stream.

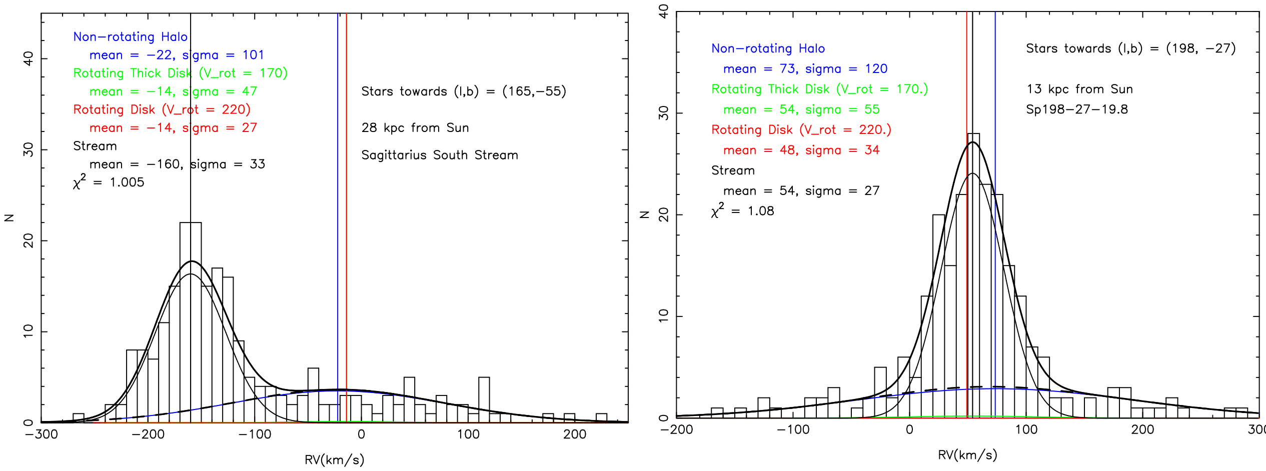

Figure 6. Kinematics of the Sagittarius dwarf tidal stream and tidal stream in the Galactic plane. The left panel shows a histogram of the radial velocities of stars with colors, magnitude and position on the sky consistent with membership of the Sagittarius dwarf tidal stream. These spectra were obtained during normal operations of the SDSS. The dashed line shows the distribution of stars expected, based on our selection criteria, from a power-law spheroid population. The heavy black line shows the sum of the power-law distribution and a best-fit Gaussian stream with dispersion 33 km/sec. Subtracting an instrumental dispersion of 25 km/sec for A-type stars, we estimate the intrinsic dispersion of the stream at 22 km/sec. The right panel shows a histogram of the radial velocities of stars selected by color, magnitude and sky position to coincide with our previously identified substructure near the Galactic anticenter. Again, the dashed line indicates our expected distribution from a power law spheroid population, and the dark line shows the sum of that distribution with a best-fit Gaussian. Subtracting and instrumental dispersion of 20 km/s for F-type stars, we estimate the intrinsic dispersion of this population is 18 km/s.

Kinematics of Individual Streams

It is obvious that useful constraints on the nature of individual streams will come from specification of their kinematics – we have only begun to mine our spectral resources for such information. Figure 6 (left panel) shows a histogram of 306 SDSS spectra selected to be likely members of the Sagittarius dwarf tidal stream ($10^\circ < \alpha < 45^\circ$, $-1.5^\circ < \delta < 1.5^\circ$, $17.8 < g < 20.2$, $-0.3 < g - r < 0.2$). Also shown is our model fit to a power-law spheroid Galactic component, and our maximum likelihood fit to the Sagittarius stream. The minimum reduced χ^2 of 1.005 was achieved with a mean radial velocity in the stream of −160 km/sec, and a velocity dispersion in the stream of 33 km/sec Removing an instrumental radial velocity dispersion of 25 km/sec, we estimate the radial velocity dispersion of the Sagittarius stream in this direction to be 22 km/sec. The mean radial velocity is an excellent match to the Sagittarius stream models of Ibata et al. (2001), and the dispersion of the stars is similar to (or a little smaller than) measurements in the literature at other stream locations (Majewski et al. 1999; Dohm-Palmer et al. 2001).

Normal operations of the SDSS survey will not image any more of the "ring" structure below 30 degrees Galactic latitude, and in particular, will not trace it anywhere near the Galactic center. One of the science drivers of our proposed extension is to explore this structure in far more detail. The proposed low-latitude imaging will allow us to trace the stream around the Galaxy, study its stellar dynamics, and obtain information on the chemical abundances of its constituent stars.

Recently, Helmi et al. (2003, astro-ph/0303305) have shown how different scenarios related to the nature of the apparent ring of stars in Newberg, Yanny et al. (2002), Yanny, Newberg et al. (2003), and Ibata et al. (2003) may be distinguished. Their prescription requires both more photometric information at low latitude, to see if the ring completely encircles the Galaxy (or if it is an arc), and more kinematic information. If the radial velocities as observed from our location in the Galaxy are uniform with Galactic longitude, then a shell is indicated, but if they show a gradient with Galactic longitude then they are more likely associated with an infalling dwarf. Recent 2MASS and spectroscopic observations by Crane et al. (2003, astro-ph/0307505)) and by Rocha-Pinto et al. (2003; astro-ph/0307258) support the disrupted dwarf galaxy hypothesis. The program of observations proposed here obtains just this required information to fully elucidate the nature of the feature, which may turn out to be the second substantial merger event experienced by our Milky Way following the discovery of Sagittarius a decade ago.

Streams and Mergers

There is a growing body of evidence which shows that at least part of the halo of the Milky Way Galaxy was formed through the accretion of smaller satellite galaxies, and is not a relic of the initial collapse of the Milky Way. The evidence includes not only that described above from the SDSS, but also by identification of moving groups of stars and theoretical simulations of structure formation. The data we propose to obtain will address the question of how many mergers occurred in the formation of our galaxy, through photometric and kinematic searches for substructure. The mergers not only contribute to the content of our Galactic stellar populations, but also can affect the structure of the Galactic disk. It is possible that the “ring” discovered around the Galaxy, for example, is the remnant of an ancient merger which puffed up the thick disk.

Stellar metallicity (and age) determinations, and the distribution of the evolutionary status of stars in the more populated streams can be used to estimate merger ages. Presumably, star formation halted at or before the time of merging, which puts an upper limit on the time since the merger. We can also use the results of analytic and N-body simulations to estimate the time since the merger occurred. This comparison is tied to a clearer understanding of the mass distribution in the Milky Way and the dark matter content of the merging galaxy. The disentangling of these effects would lead to a rich data collection with which one might study a wide range of astrophysical problems, from CDM models to the nature of star formation and evolution.

These studies would complement present and future proper motion (and parallax) studies that will allow us to draw a much more complete picture from examination of the full phase space of kinematics, and importantly, draw attention to the most significant unanswered questions.

C. Chemical Evolution of the Milky Way

Elemental abundances of stars are crucial for the identification of stellar populations, characterization of the chemical history of the Milky Way, and ultimately for constraining the formation of the Milky Way. The α- and iron-peak elements are of particular importance, since they are not transported to the outer atmospheres of stars during their lifetimes, and hence provide a window to the the pre-stellar nebulae from which the stars formed. Astronomers have yet to identify low-mass examples of the elusive low-metallicity population III stars which are believed to have provided the metals found in the extreme population II stars, though we are getting close (see below).

Extensive, wide-field objective prism surveys, such as the HK survey (e. g., Beers, Preston, & Shectman 1992) and the Hamburg/ESO Survey (e.g., Christlieb & Beers 2000) have produced many thousands of candidate metal-poor (and other interesting) stars in the Milky Way. Other directed surveys, such as the “Spaghetti Survey” (Morrison et al. 2000), and the Grid Giant Stellar Survey (Majewski et al. 2000) have probed a limited fraction of the sky in a “pencil beam” approach. Already these surveys have revealed the possible lower limit of stellar metallicity in

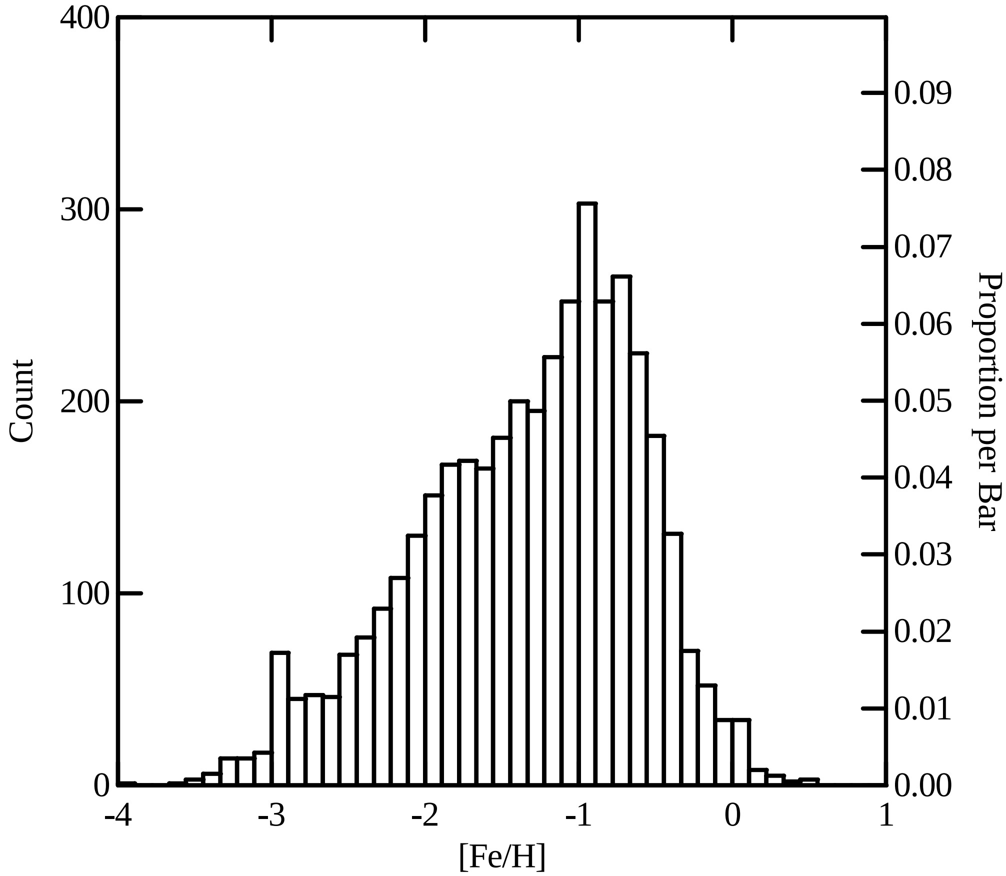

Figure 7. Distribution of derived stellar metallicities for 4000 stars in the SDSS EDR (Li et al. 2002). Although the targets included in this diagram represent a complex amalgamation of stellar sources chosen for reasons OTHER than their potentially low iron abundance (e.g. photometric calibration sources, reddening determination, ROSAT sources, misidentified QSOs, etc.), there are nearly as many stars with [Fe/H] $<$ -2.0 as have been discovered by ALL previous studies of the Galactic halo combined. Clearly, a targeted survey for metal-deficient stars is likely to be highly successful.

the Galaxy (at [Fe/H] $\sim$ -4.0), the existence of a class of r-process and s-process enhanced metal-poor stars, the likely operation of processes involving carbon enhancement in the evolution of early generation stars, and provided the identification of a sufficiently large number of very low metallicity stars ([Fe/H] $<$ -2.0) to enable high-resolution spectroscopic studies of the evolution of elemental abundances in the early Galaxy. The recent discovery of HE 0107-5240, a halo giant carbon-enhanced star with [Fe/H] = -5.3 (Christlieb et al. 2002), is yet another example of an unanticipated return from a large survey. This survey will also provide the observational counterpart to fundamental physics experiments such as those underway at the Los Alamos Neutron Science Center where the neutron capture cross-sections for s-process isotopes are being determined

(Reifarth et al. 2003).

However, even after several decades of ongoing spectroscopic follow-up effort, these surveys have only scratched the surface of the information content that can be extracted from a dedicated effort such as would be realized in the proposed SDSS extension. As noted above, Li et al. (2002) have demonstrated the ability to extract accurate estimates of the important stellar physical parameters, $T_{\rm eff}$, log g, and [Fe/H] (with errors on the order of $\sigma(T_{\rm eff}) = 200$ K, $\sigma(\log g) = 0.4$ dex, $\sigma([Fe/H]) = 0.3$ dex), using the combination of stellar photometry and flux-calibrated spectroscopy obtained from previous SDSS data (the EDR in this case). These efforts are presently being refined in order to decrease the errors, and to obtain additional elemental abundance measurements, such as should be feasible for C, Ca, Mg, and Na.

A subset of stars in the sample we assemble for spectroscopic follow-up could be photometrically selected from the SDSS imaging data using techniques similar to those described by Helmi et al. (2003). For example, if one were to identify a total of some 100,000 F- and G-type stars that are likely to have [Fe/H] $<$ -1.0, this might be expected to include over 10000 stars with [Fe/H] $<$ -2.0, 1000 with [Fe/H] $<$ -3.0, 100 with [Fe/H] $<$ -4.0, and so on. The distribution for the smaller set of SDSS EDR stars is shown in Figure 7. Not only would such a database provide unprecedented detail on the nature of the Metallicity Distribution Function (MDF) of the halo population, it would also enable detailed tests of whether or not the MDF changes with Galactocentric distance, as has been suggested from inspection of preliminary results from the EDR, as well as from the HK and HES surveys. If the MDF of the outer halo contains primarily stars of much lower metallicity than the inner halo (which dominates present samples of low metallicity stars), one might hope to identify even larger numbers of the lowest metallicity stars than indicated above.

D. Dark Matter Clumpiness and the Galactic Potential

Elucidation of the nature of the dark matter in the Galaxy (and throughout the Universe) is one of the most important quests of modern astronomy. The dark matter profile of our own Milky Way galaxy has recently been the subject of a series of controversies. The "dwarf satellite problem" (Moore et al. 1999; Klypin et al. 1999; Bullock, Kravtsov, & Weinberg 2001), wherein $N-$body simulations predict more satellites than are observed in the halos of galaxies like the Milky Way, could be solved if there were dwarf lumps of dark matter the size of dwarf galaxies, but containing no stars, outside of about 10 kpc from the Galactic center (Stoehr et al. 2002). This solution has yet to be verified by experiment, however.

Most recently, measurements of the flattening of the Galactic potential through dynamical analysis of the tidal tails of the Sagittarius dwarf galaxy have indicated an almost spherical potential (Ibata et al. 2001; Law, Majewski, & Skrutskie 2004). However, simulation of the creation of dark matter halos (e.g. Jing & Suto 2002) find a negligibly small probability of producing so spherical a distribution of dark matter.

Constraints on Dark Matter from Sagittarius tidal debris

By tracing the structure and kinematics of stars in our own galaxy, we will increase the available observational data with which we will attempt to identify and characterize any existing structure in the dark matter distribution in our Galaxy. It is feasible that, since halo star streams have relatively narrow velocity dispersions and are coherent over large arc-lengths, we could use them to measure the clumpiness of the dark matter halo (Johnston, Spergel, & Haydn 2002). Since the infalling streams themselves could harbor dark matter, and the dark matter probably does not interact strongly with itself, it is possible that there exist as-yet-undiscovered substructures of dark matter lurking throughout the Galaxy.

Ibata et al. (2002) showed how the kinematic information from streams of visible stars might be used to explore the clumpiness of the dark matter halo. Specifically, they argued that by plotting various integrals of the motion (L, L_z, and E) for groups of stream stars in the halo (proper motions are clearly required), one can distinguish a flattened halo from a halo that is smooth or composed of dark matter lumps. The Sagittarius dwarf tidal stream itself will be a powerful tool with which to study the dark matter halo of the Milky Way (Martinez-Delgado et al. 2003).

Freese et al. 2004 showed that dark matter associated with the leading tail of the Sagittarius dwarf spheroidal galaxy could significantly affect the signature expected in WIMP dark matter detectors on the Earth. More than twenty collaborations workwide are developing detectors designed to search for these WIMPs, which are generally assumed to have an isothermal velocity dispersion. Tidal streams which contribute only a few percent of the local dark matter density can have a large effect on these detectors – both in the expected energy spectrum of the dark matter particles and in the annual modulation of the strength of the WIMP signal. If WIMPs are the primary source of dark matter, we could be approaching the day when local dark matter streams can be correlated with stellar moving groups in the Galactic halo, found in surveys such as we propose.

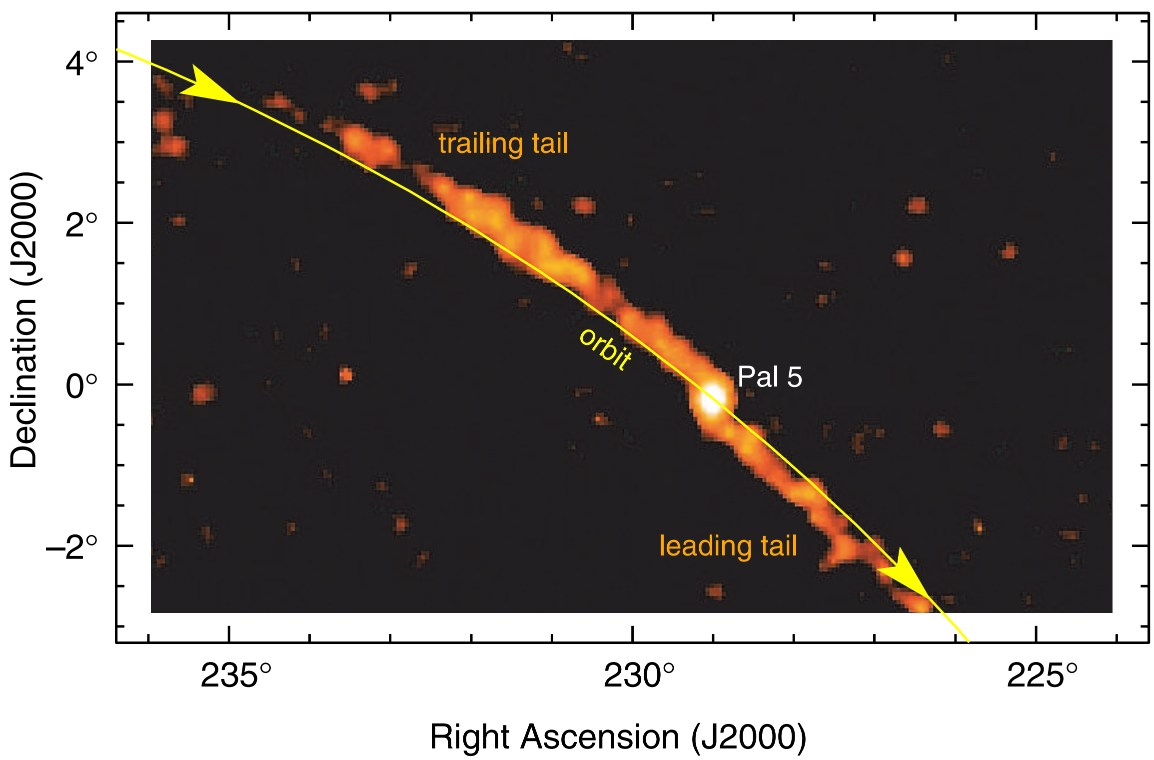

Figure 8. Color-coded map of the surface density of stars from the globular cluster Palomar 5. Using wide-field photometry from the SDSS, this cluster was discovered to have two long tidal tails of stars that spread out along its Galactic orbit. These tails comprise about 1.2 times as much stellar mass as retained in the cluster, showing that Palomar 5 is in the process of being tidally disrupted.

Constraining the Galactic Potential from Globular Cluster Tidal Streams

The disruption of globular clusters in the tidal field of the Milky Way can produce stellar streams that are kinematically cold, therefore narrow and potentially long-lived. An excellent example of such a stream was discovered around the low-mass cluster Palomar 5 (Odenkirchen et al. 2001a, 2003). Deep, wide-field photometry from the SDSS revealed the existence of two long and massive tails of tidal debris, which are leading and trailing the cluster on its Galactic orbit (Figure 8). These tails, which subtend an angle of at least 10 degrees on the sky, corresponding to a projected length of 4 kpc in space, provide a new and unique possibility to trace the orbit of the cluster in the Galactic halo. It has thus, for the first time, become possible to directly observe the orbital path of a distant star cluster on the sky and to measure the curvature of this path. By combining the geometric information with spectroscopic measurements of stellar radial velocities in such streams one can determine the orbits of clusters in the Galactic halo without any dependence on a model for the Galactic potential. Where they are available, proper motions of stripped stars can provide additional valuable constraints. In return, these orbits will provide probes of the gravitational acceleration in the Galactic halo and thus help to map the Galactic potential and the underlying distribution of mass.

In this way, tidal streams from globular clusters provide an important key to the fundamental problem of quantifying the dark matter content of our Galaxy. Numerical simulations suggest that the system of globular clusters in the Milky Way was originally much larger and that most clusters have already been disrupted, perhaps in the process providing a substantial amount of the presently observed stellar material in the inner halo of the Galaxy (e.g., Gnedin & Ostriker 1997). A number of the surviving globular clusters have orbits, masses, and half-light radii that makes them likely candidates for ongoing or future disruption.

Thus it is likely that more stellar streams from the decay of globular clusters can be detected through systematic searches with deep and homogenous wide-field photometry, as well as from spectroscopy and even coherence of their proper motions. Streams should be found even if their parent clusters have already been completely dissolved. It is of great interest to identify as many globular cluster tidal streams as possible since this will probe the halo potential at various Galactocentric radii.

The Importance of Proper Motions for Stars Throughout the Galaxy

The USNO-B catalog of proper motions (Monet et al. 2003) from scanned Palomar plates combined with SDSS astrometry will be available for detecting coherent groups of objects (i.e., stream stars or nearby disk-component stars) with motions better than 2-3 mas/yr rms errors for individual stars. This may be achieved by averaging over many stars in a coherent structure with common proper motions (see Section IV.D below). This will enable reliable detection of proper motions for coherent star structures out to 10 kpc from the Sun, opening up the thick disk and inner halo to complete six dimensional phase space component kinematic analysis.

E. Star Formation

Star formation plays a crucial and on-going role in the formation of the Milky Way. If we are to understand Galactic origins and chemical evolution of the Galaxy, we must understand the processes which govern the formation of stars. The stellar nurseries and associations in the Milky Way provide a window to this process. Both open and globular clusters provide important tests of star formation and stellar evolution models which we will use to characterize the stellar populations in all Galactic components. In particular, we seek a better understanding of the initial mass function, and stronger constraints on stellar isochrones in SDSS filters.

Star formation investigations have made huge strides in the last ten years or so (Lada & Lada 2003) due to deep wide-field imaging at near infrared wavelengths, necessary to penetrate the dense dust clouds. Accurate wide field optical images, some of which will be provided by our survey, do not exist for most of the well-studied molecular clouds and star formation regions. What can we learn? Optical and infrared imaging together reveal the relationships among young stars, Herbig-Haro objects, and the density and composition of the surrounding dust (extinction curves only diverge at blue and shorter wavelengths). These studies also lead to measurements of the current stellar Initial Mass Function (IMF) in molecular clouds, which can be compared with the IMFs derived from the field – in the disk, thick disk and halo – measured by the very large statistical data base which SEGUE will deliver.

Together with the temporal variation of the star formation rate, the IMF determines the evolution and fate of star clusters and galaxies. The dependence of chemical evolution on the IMF is therefore a fundamental issue in stellar population theory (Larson 1998; Worthey 1994). The form and variation of the stellar IMF has an impact on cosmological studies and on the measurement of the relative amount of dark matter in galaxies and clusters.

For stars more massive than a few $M_{\odot}$, the present-day IMF is well fitted by the classic Salpeter (1955) power-law ($\alpha = 2.35$). However, significant deviations have been found in areas of current star formation. Kroupa & Weidner (2003) find that the local embedded cluster mass function has a power-law exponent of $\beta = 2.0$, which implies that the mass distribution of massive stars has a steeper exponent, $\alpha_{field} = 2.8$, and suggests a different mode of star formation in isolated molecular clouds, possibly due to changes in the ISM equation of state.

In higher metalicity regions, relatively more low mass stars are produced (Kroupa 2001, 2002). The effect of metalicity has been evaluated by comparing the observed IMFs for globular clusters, field stars, and young clusters. For $m < 0.7M_{\odot}$, the power-law slope of the IMF is found to be $\alpha \sim 1.3 + 0.5[Fe/H]$. The data also suggest that chemical composition gradients may exist within individual molecular clouds due to opacity variations brought about by the larger dust grains, and thus higher R_V, found within dense cores, and that these may affect the IMF within an individual cluster (Casu, Cecchi-Pestellini, & Aiello 2001).

Further evidence for variability in the IMF includes the scarcity of low-mass Population III stars, and differences in the spectral type distributions between young stars in high density clouds (IC 348, Trapezium) and in low density clouds such as the Taurus molecular clouds (Luhman et al. 2003; Briceno et al. 2002; Muench et al. 2002).

Star formation occurs as a dynamic and complex process. Chabrier (2003) points out that turbulent shocks appear to generate local non-equilibrium structures, which produce scatter in the Jeans mass. Environmental effects are clearly evident in high density regions such as the Orion Nebula Cluster, where the formation of high mass stars terminates local star formation due to photoevaporation and winds (Palla & Stahler 1999) and skews the IMF in favor of high mass stars.

Determination of the relative number of stars as a function of mass within specific young clusters and associations will provide the data required to help identify systematic variations in the IMF with different star formation environments. Understanding of the physics driving these variations will enable us to gain indirect information on what affects the star formation process, and on what might have been the IMF at early cosmological times.

Because of the large extinctions in star formation regions, most current work is carried out at infrared, millimeter, and radio wavelengths. Among the current and new missions devoted largely or wholly to star formation studies are 2MASS, UKIDSS, SMA, ALMA, SOFIA and SPITZER. Nevertheless, optical work is important or even crucial to understanding star formation, especially if the observations can be carried out over wide areas, and with high precision. Such observations reveal the distributions of stars, dust and outflow regions (Herbig-Haro objects), where mechanical energy is imparted to the ambient dense clouds by stellar winds. They also allow much better determinations of interstellar extinction than do infrared observations alone, as well as measurements of the scattering properties of dust. The wide-field optical observations described herein, with their excellent five-color photometry, show the large-scale relationship between star formation regions over a wide range of ages and the molecular clouds from which they formed. There is no modern optical imaging or spectroscopic survey at low Galactic latitude either underway or planned. The SDSS apparatus can be used to address this need by providing deep imaging and spectroscopy over very large areas of star-forming sky.

The Galactic plane, especially well outside the solar circle, contains many large, nearby, star-forming regions. SDSS and 2MASS JHK imaging provide crucial information for characterizing these stellar birthplaces. Such information includes the properties and distribution of dust and ionized gas in the star-forming regions, the dependence of these properties on the highest-mass stars being formed in the region, the extension of the IMF to substellar masses (because brown dwarfs are brighter when newly formed), and information on circumstellar matter.

SEGUE spectra will enable us to constrain the age and activity of young stars and brown dwarfs via spectral typing, study of emission lines and surface gravity, and possible Lithium detection (Koenig, in preparation).

In this section we describe several topics in star formation which the SEGUE imaging and spectroscopic data will address: the history of star formation from surveys of white dwarf stars; the properties of young and old open clusters, star formation in molecular clouds, the behavior of the IMF in different regions, the dynamics of Herbig-Haro objects and their relationship to the molecular clouds and clusters in which they occur, the accretion physics of T Tauri stars, and the origins of brown dwarfs.

Star Formation History from White Dwarfs

Most of the stars in the Galaxy, more than 95% for a Salpeter (1955) initial mass function, have initial masses less than 8 $M_\odot$ and will therefore end their evolution as white dwarfs (with much mass loss during the preceding red giant phases). The oldest observed populations in the Galaxy, the globular clusters, have main-sequence turnoff masses of about 0.8 $M_\odot$. Thus white dwarfs have been produced by progenitor stars with masses between about 8 and 0.8 $M_\odot$ over the lifetime of the Galaxy. The possible exception to this is the first stars, "Population III", for which star formation in metal-deficient gas may have produced only high mass stars (Abel et al. 2002). For Populations I and II, however, white dwarfs can provide important tracers for the star formation history of the Galaxy. Although white dwarfs are numerous in any volume-limited sample - 8% of the stars within 8 pc of the Sun are white dwarfs, for example (Kirkpatrick 2001) - their intrinsic faintness makes them difficult to find, identify, and observe, especially the cool, faint objects.Likewise, the luminous precursor objects to white dwarfs, the central stars of planetary nebulae and the O-type subdwarfs, represent a very brief phase in a star's evolution and are therefore rare. The detailed study of the Galactic populations of these objects requires the wide-area, multi-color, sensitive imaging which can be provided by the SDSS facility.

The hotter (>12,000 K) white dwarfs and subdwarfs separate fairly cleanly from other stellar populations and quasars in SDSS colors. Sampling 190 square degrees of the Sloan Digital Sky Survey, Harris et al. (2003) find 269 white dwarfs and 56 hot subdwarfs, with spectral types confirmed by SDSS spectroscopy. This discovery rate, roughly 2 stars per square degree brighter than $g = 20$, will be higher for imaging at lower Galactic latitudes and with longer exposure times. Spectra to this magnitude can be obtained with the SDSS spectrographs and provide classifications and radial velocities.

A well-defined white dwarf luminosity function can place important constraints upon the associated star formation history (Winget et al. 1987, Iben & Laughlin 1989). The local luminosity function constrains the age of the oldest disk population (Liebert, Dahn, & Monet, 1988; Oswalt et al. 1996; Smith 1997; Leggett, Ruiz, & Bergeron 1998), and the roles of mass inflows and outflows associated with star formation and evolution (Greenstein 1986; Wood & Oswalt 1990). Radial velocity measurements, particularly if supplemented with proper motion data and photometrically determined distances, can define the spatial and kinematic properties of white dwarf populations (Silvestri et al. 2001), and thereby constrain their parent populations.

The nature and distribution of the halo white dwarf population has been quite controversial

(Oppenheimer et al. 2001; Nelson et al. 2002; Reid et al. 2001; Flynn et al. 2003). The large SDSS/SEGUE data base should allow significant progress in this important area. For example, the distribution of white dwarf radial velocities clearly shows the dipole due to the solar orbital motion around the Galactic center (Figure 9, Ivezić et al. 2004, in preparation), showing that it is possible to find large numbers of halo and thick disk white dwarfs.

Open Clusters

Open clusters provide a convenient source of large numbers of stars for studies of stellar evolution and chemical enrichment in the galaxy. Each cluster provides an assortment of stars of varying masses and stages of evolution yet all members of the cluster can be assumed to be the same age and have the same metalicity. Although open clusters may be large in angular extent, the large field of the SDSS telescope easily enables mapping of entire clusters. The SEGUE imaging and spectroscopy will expand the observed areas around well-studied clusters, use the data on well-known clusters to calibrate SDSS photometry in terms of stellar metalicity and cluster age, measure stars further down the main sequence in many of these clusters, and produce a sample of well-observed clusters about five times larger than that which currently exists.

A current major effort on measuring the detailed properties of open clusters, the WIYN Open Cluster Survey (WOCS - see Mathieu 2000) seeks to expand the well characterized group of fundamental open clusters (Hyades, Pleiades, M67, NGC-752) to a set of 16; these four as references and an additional 12. The WOCS uses photometry, astrometry, and spectroscopy to study radial velocities, chemical abundances, membership, colors and magnitudes of the stars in these clusters. While the SDSS spectrographs do not have the resolution to match the WOCS for abundance or radial velocity work, the SDSS imaging capability is comparable to that of the WOCS in terms of the quality of the astrometry and photometry. However, the SDSS telescope has a much larger field of view, and can image clusters and their surrounding areas much more rapidly. The SDSS data will thus be complementary to WOCS, providing large-area maps of the fundamental clusters and their surroundings, plus imaging data of comparable quality for a much larger sample of clusters.

Well characterized clusters can be used as calibration tools when combined with appropriate evolutionary models (cf. Girardi et al. 2002; 2004). Rider et al. (2004), using SDSS photometry for NGC 2548, show that good fits of evolutionary models to the SDSS filter system data are possible and result in accurate age and metalicity determinations. While clusters currently used for age and distance indicators are bright, the SDSS imaging data will be sufficiently deep enough to allow the study of the lower main sequence in these clusters and of H-R diagrams in more distant, fainter, clusters.

Slight adjustments of the locations of six or seven of the SEGUE low-latitude scans will allow the imaging of approximately 25 clusters with known metalicities and ages (these range from $<$ 10 Myr to $>$ 10 Gyr). In addition, several more clusters have been imaged during regular SDSS operations. While most of these data will be used for calibration purposes and to verify previously determined values, the large quantity of deep, accurate photometry will be useful in refining the evolutionary models for the SDSS filter system. The primary gain to the astronomical community will be in the number of stars with observations in multiple filter systems.

The sky imaging in SEGUE will also map some 50-70 additional clusters which currently have little, if any, modern data - what is known about them is based on the photographic surveys made almost 50 years ago. As demonstrated by Rider et al. (2004), the SDSS imaging data will provide fairly accurate ages, metalicities and determinations of the IMF for these additional clusters.

Targeted spectroscopic followup will allow verification of the cluster metalicities, turnoff age, and reddening: the radial velocity data will yield probable membership information to aid the photometric fitting to provide a second estimate of age. Further, these new observations will

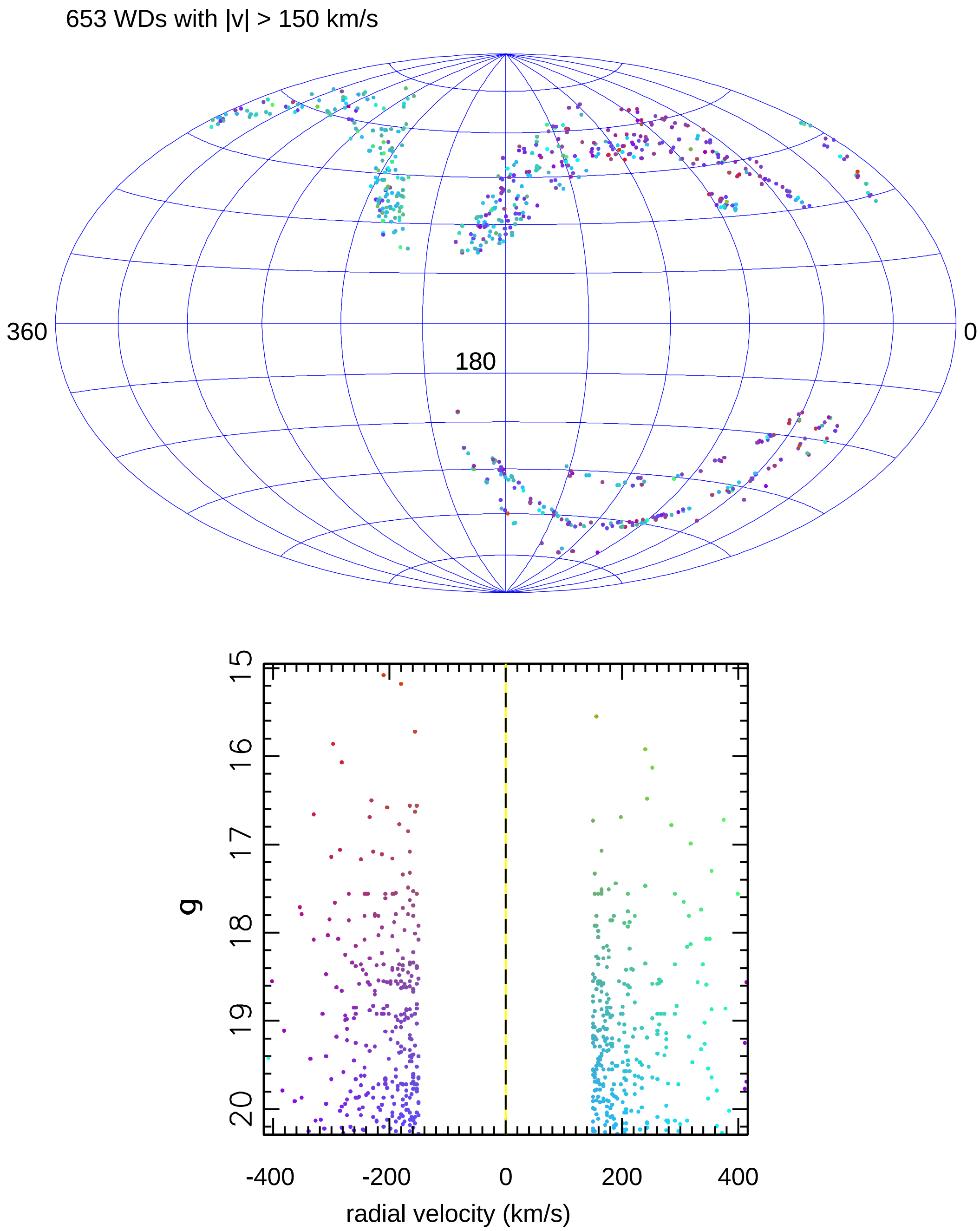

Figure 9. Sky distribution of white dwarf velocities. Distribution on the sky, in Galactic coordinates, of white dwarfs with large heliocentric velocities. The points are color-coded by velocity, and the dipole due to Galactic rotation is clearly seen (from Ivezić et al. 2004, in preparation).

provide target lists for high resolution spectroscopic programs for followup of interesting stars using other telescopes.

IMF Studies in Young Clusters

Star forming regions and young clusters are favorable targets to determine the IMF for three principal reasons. First, all objects in the cluster are likely to be roughly coeval, with an age spread comparable to the age of the cluster. Second, young objects are brighter for a given mass, making detection of very low mass objects easier. And, third, young clusters, with ages less than 100 Myr, are less dynamically evolved than older open clusters, and more likely to retain a representative mass spectrum. As well as being essential for determining the IMF, complete membership lists are also necessary for the study of circumstellar disks, X-ray emission, multiplicity, rotation, and kinematics. While photometric signatures of youth include location above the main sequence and excess emission in the blue/near-UV and/or near-IR, robust identification of young stars requires spectroscopy. Determination of the spectral type is necessary for the measure of local extinction, blue/near-UV and/or near-IR excess emission, Hα emission above that measured for active field dwarfs, Brγ emission, and spectral features (e.g. K I, Na I, CaH) implying low gravity. The observations proposed as part of SEGUE use the very efficient photometric, astrometric and spectroscopic data gathering power of the SDSS apparatus.

Previous studies of the IMF in young systems have relied on three techniques: creation of a luminosity function (LF), mass and age determination by comparison of photometric observations against theoretical models, and mass and age determination by comparison of spectroscopically derived indicators against theoretical models.

IMF determinations in the absence of spectroscopic data are subject to uncertainties in IMF slope measurements and contamination. As shown by Megeath (1996), non-power-law luminosity functions are significantly distorted by the relatively high extinction typically found near star-forming regions. In addition, all techniques based solely on photometry are affected by contamination by foreground and background stars. However, comprehensive studies of diverse star formation environments have been hindered by the need to perform both photometric and spectroscopic surveys of the targeted regions, and the majority of IMF studies to date have relied exclusively on photometry. The three Orion Nebula Cluster papers cited by Kroupa (2002) are representative examples of IMF determination based solely on imaging data. Palla & Stahler (1999) utilized an empirical bolometric luminosity function from Hillenbrand (1997) which is based on a Main Sequence bolometric correction to dereddened I band fluxes. The study by Muench, Lada, & Lada (2000) analyzed the K-band Luminosity Function. No correction was made for unresolved binaries, disk emission, or differential extinction, so that the luminosity function can be determined only in quite coarse bins. Hillenbrand & Carpenter (2000) compute the mass probability distribution for stars based on H and K photometry given a range of near-IR excess and extinction. While simulations show that slightly rising (α = +0.35) and falling (α = -0.35) IMFs can be distinguished, this technique is not as accurate as one that includes spectroscopy. Only limited spectroscopic surveys have been conducted to date, most notably by Briceno et al. (2002) and Luhman et al. (2003), and are focused on the Taurus, IC 348, Ophiuchus, and Trapezium clusters. The SEGUE data, together with 2MASS photometric data, will provide comprehensive eight-band photometry and spectroscopy of thousands of members in each of several tens of young clusters.

Selection and Observations of Young Clusters

We use the Porras et al. (2003) catalog of nearby young stellar groups and clusters to provide potential targets within this component of the SEGUE program. As seen in Figure 10, these are predominately found at low Galactic latitudes and with Galactic longitudes between 60 and 270. This bias in l is largely due to the Sun's interarm location. SEGUE can potentially observe 60 out of 73 or 82% of the identified regions.

Open clusters younger than 100 Myr are extracted from the on-line WEBDA catalog of Mermilliod (1998). These are more tightly clustered around the Galactic mid-plane than the star formation regions. 185 out of the 297 low Galactic latitude young clusters (62%) are potentially observable from our northern observatory.

The relative impact of the young cluster observations on SEGUE spectroscopy is assessed by computing the fraction of 3 degree square fields that include a group in either catalog. The fraction of pointings that include a star formation region is between 4% and 8% for $|b| < 30°$. Young open clusters are predominately found at $|b| < 5°$ where they are included in nearly 50% of all possible pointings. Figure 10 shows the fraction of pointings that include either a young open cluster or a nearby star formation region as a function of Galactic latitude. The number of plates and fibers required per pointing is dependent on the density and extent of each star formation region and cluster.

To determine the SDSS spectroscopic plate and fiber requirements within star formation regions, we compare several published surveys that cover a variety of association angular sizes and stellar densities. These range from large (100deg^2) and sparse complexes (Taurus-Auriga: Briceno et al. 2002; Orion OB1: Briceno et al. 2001) to compact ($<$ 5deg^2) cores including the region around the Orion Nebula Cluster (Rebull et al. 2000) and the Serpens cloud core (Giovannetti et al. 1998). The spatial densities range over four orders of magnitude from 1 to 10^4 stars/pc^3.

The survey areas have target densities varying from 12 deg^{-2} to 940 deg^{-2} with the higher densities associated with more compact groups. The larger complexes, i.e. Taurus-Auriga and Orion OB1b, require 60% or fewer of the fibers on any specific SDSS plate while the dense cores need multiple plates for a single pointing to target all of the association members.

Spectroscopic Target Selection in Star Formation Regions

Spectroscopic observations in support of the IMF project will be made of both star formation regions and in young open clusters. Only star formation regions that contain candidates for SDSS spectroscopy, including classical T Tauri, weak-lined T Tauri, and older (β Pic-like) systems are considered here.

Palla and Stahler (1999) show that for stars exceeding 2 M$_\odot$, the Zero Age Main Sequence (ZAMS) is reached within 10 Myr. Furthermore, stars more massive than 4 M$_\odot$ arrive on the ZAMS in less than 1 Myr. Consequently, in all but the youngest star formation regions, we expect that stars more massive than a few solar masses will already be found on the main sequence.

In the low mass ($< 1.2M_\odot$) models of Baraffe et al. (1998), the effective temperatures extend to 6000 °K for field populations aged 5 Gyr. For the range of ages found within active star formation regions, the maximum temperatures are much lower, having limits of 4300 °K at 10 Myr and 4000 °K at 1 Myr. For this reason, the initial target list will include only stars whose colors indicate a spectral type later than K5.

Data Analysis

Spectra of young cluster members will be used to determine photospheric parameters (temperature, surface gravity, metalicity). This information will be combined with theoretical pre main sequence models to characterize the cluster IMF.

The TiO5 and CaH3 spectral indices defined by Gizis (1997) for spectral type determination and for identification of low surface gravity (pre main sequence) have been used to categorize pre main sequence star candidates in SDSS spectra obtained in the Orion and Taurus star formation regions. These indices are defined in terms of the flux ratio between an absorption feature and a nearby pseudo-continuum. These two indices use the wavelength range 6960 to 7135 Angstroms and are used to obtain spectral types expressed in M subclasses (M0 = 0.0, M1 = 1.0, etc):

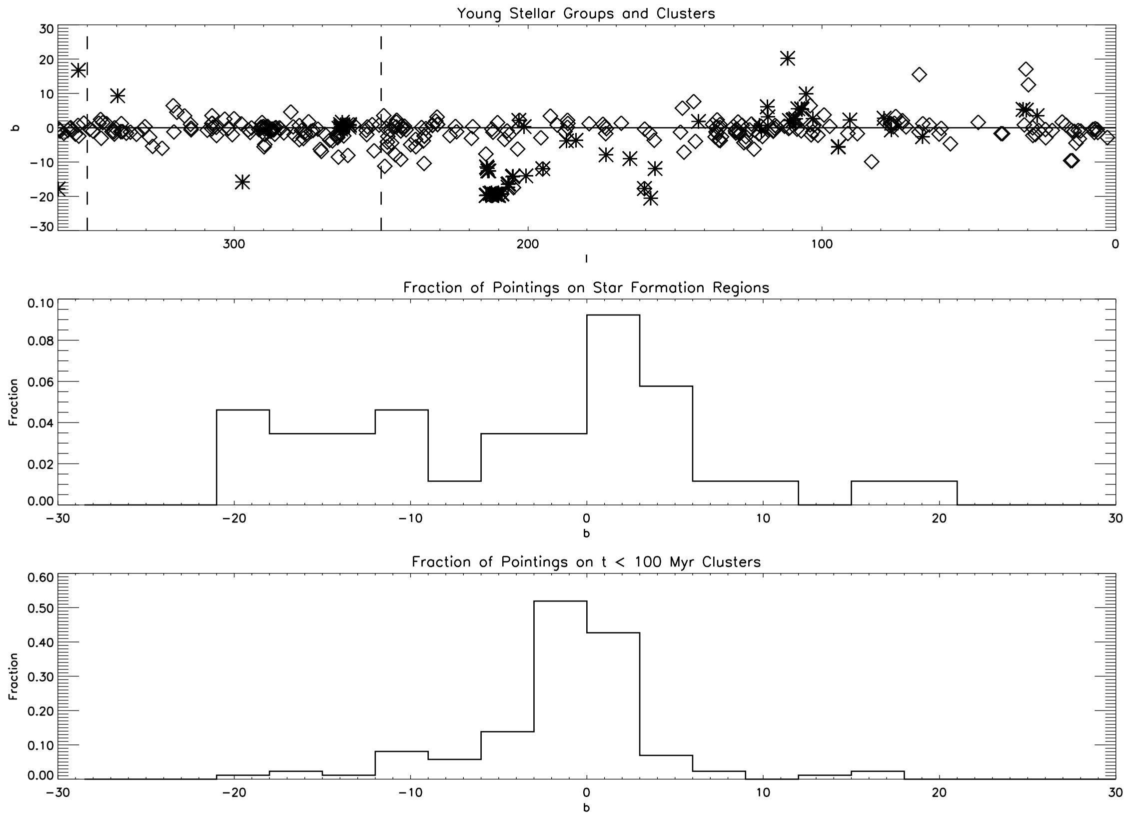

Figure 10. Nearby Young Stellar Groups. The upper plot shows the distribution of nearby young stellar groups (asterisks; t < 10 Myr; Porras et al. 2003) and open clusters (diamonds; t < 100 Myr; Mermilliod 1998) in Galactic coordinates. The dashed lines indicate the unaccessible region ($240 < l < 350$) due to the northern location of Apache Point Observatory. The impact of this program on SEGUE spectroscopic observations is estimated by identifying the number of possible pointings defined along a uniform 3 degree by 3 degree grid that include a young group. This fraction is shown for the active star formation regions and for the young open clusters in the lower two panels as a function of Galactic latitude.

SpT(TiO5) = -9.64 * TiO5 + 7.76

SpT(CaH3) = -18.00 * CaH3 + 15.80

As the relative CaH absorption is weakened with lower gravity, the CaH3 index becomes stronger, with the result that SpT(CaH3) <SpT(TiO5) for pre main sequence stars and giants. Figure 11 illustrates the spectral index errors computed for the SDSS Orion plates obtained in January 2003. These were observed at high signal-to-noise ratio, so have errors about 30% less than will be reached by normal SEGUE plates.

Observational estimates of the IMF are subject to several uncertainties: the finite number of stars in sample, dynamical evolution effects, incorrect number and mass estimates from unresolved binaries and high-order multiple systems, errors in stellar evolution and structure models (including the effect of rapid rotation), and errors in the observational stellar parameters due to uncertainties in the extinction, adopted distance, and magnitude errors.

The studies of Briceno et al. (2002) illustrate the procedure necessary to deduce a stellar IMF from observations of nearby Galactic star formation regions. This technique makes use of optical photometry, near-IR photometry, and optical spectra. For SEGUE work the optical photometry

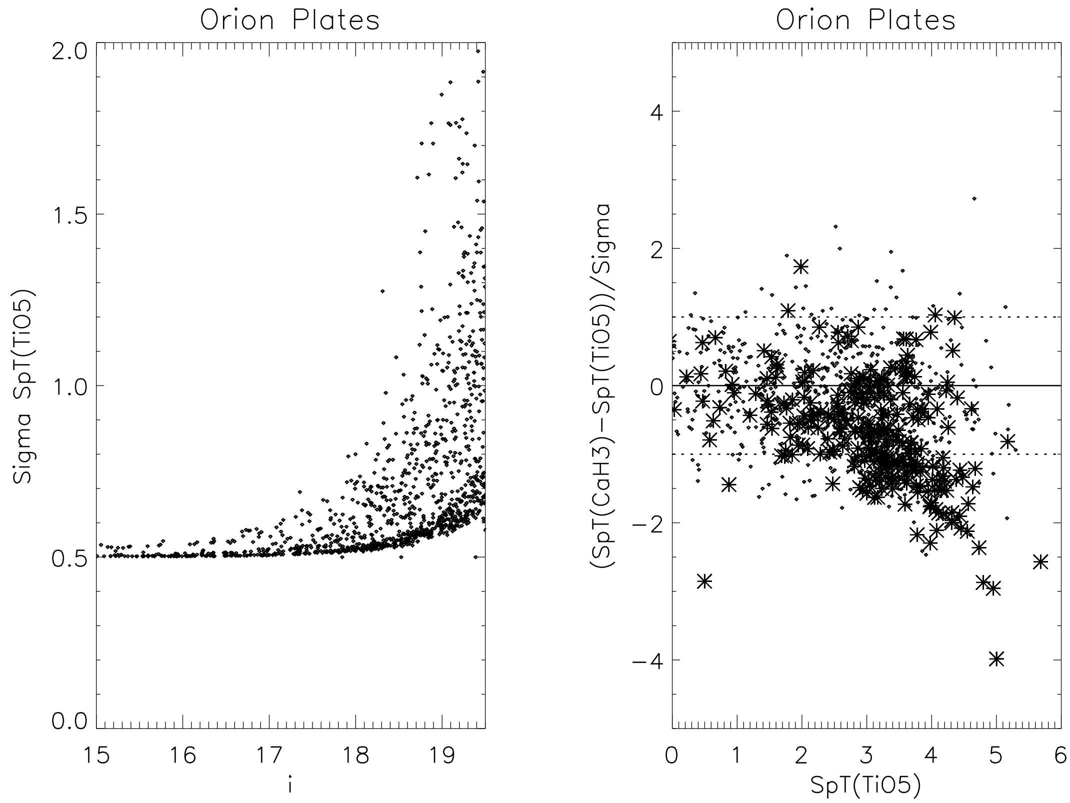

Figure 11. Spectral index errors in the SDSS Orion plates. This figure illustrates the errors in spectral type and low gravity determination. The left hand plot depicts the RMS error in spectral type assignment (via TiO5) measured in M subclasses as a function of the SDSS i band magnitude which incorporates the 0.5 subclass intrinsic dispersion in each index (Gizis 1997). On the right is shown the difference between the SpT(CaH3) and SpT(TiO5) values scaled by its RMS error shown as a function of SpT(TiO5). The horizontal lines trace the M dwarf locus (delta SpT = 0) and the ± 1 sigma variations. Note the population of PMS candidates between SpT(TiO5) = 2.5 and 6.0. Bright objects ($i < 18.0$) are highlighted with asterisks.

and spectra will be supplemented with near-IR (J,H, K_S) data acquired from the 2MASS public release.

Binaries in the Field and in Star Forming Regions

The distribution of stellar masses in close binary systems is still unknown. Is this distribution consistent with the hypothesis that the two components of a binary are independently drawn from the same IMF? If not, the implication is that star formation proceeds differently during the formation of binaries and that of single stars. To investigate this, the huge SDSS imaging data set, combined with the 2MASS data set to greatly increase the wavelength baseline, can be searched for stellar objects with composite colors. Wide latitude coverage is needed to allow the low- and high-metalicity stars to be separated. Kroupa and Bouvier (2003) note the different binary proportions between the Taurus and Orion star formation regions. The SEGUE data will be used to address the mechanisms responsible for these differences.

Herbig Haro Objects

Herbig-Haro objects (Reipurth 1999) are emission-line objects formed by the interaction of a

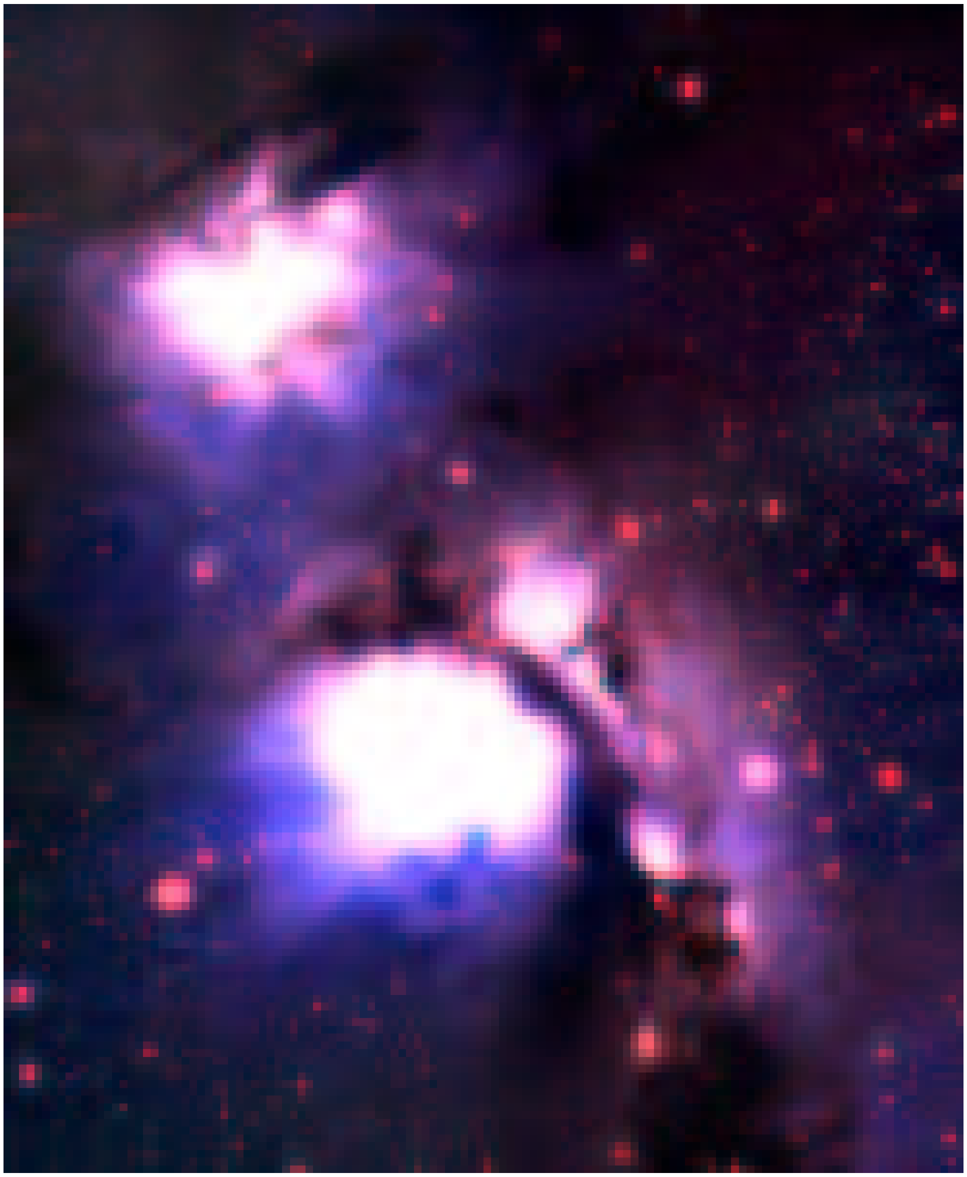

Figure 12. Star formation in Orion An SDSS gri color composite about $40' \times 40'$ of NGC 2071, NGC 2068 and HH24-26. The image is binned to a spatial resolution of $4''$.

protostellar jet with the local interstellar medium. They have typical linear scales of 0.1 to 0.5 pc, outflow velocities of order 200 to 400 km/sec, and exhibit a variety of features including the [SII], [OI], and the Hydrogen Balmer lines (Baccioti, Chiuderi, and Oliva 1995). The SEGUE depth and color discrimination will likely allow the discovery of many more Herbig-Haro objects in dark clouds. Examples are shown in Figures 12 NGC 2068, NGC 2071 and HH24-6) and 13, a region of the Taurus Dark Cloud containing HH 276. The characteristic green color of the HH nebulosity in Figure 13 is due to very bright Hα (the color planes used for these pictures correspond to the SDSS g, r, and i filters). HH objects show up as extended r-band-only objects. It is already clear from examining SDSS test images of the Orion and Taurus clouds that the surface density of HH objects is different in these two regions. Comparison of these images with 2MASS data and molecular line maps will locate, map, and measure the sites of low mass star formation in these two clouds.

Counts and spectra of HH objects are important for understanding low-mass star formation and the input of turbulence into dark clouds.

It is worth keeping in mind that the existing SDSS images of dark/bright nebulosity in star forming regions are breathtaking. These pictures are likely to form an important part of SDSS outreach, which clearly could be expanded based on the extension of the imaging survey as proposed here.

Figure 13. Bright and dark nebulosity in Taurus This SDSS gri color composite covering an $40' \times 40'$ region shows HH276 in the Taurus dark cloud.

T Tauris and Magnetospheric Accretion Physics

SDSS photometry is effective at identifying pre-main-sequence objects and low-mass chromospherically active stars (dMe) on the basis of intrinsic ultraviolet excess. This extends the technique originated by Haro (1953) and Haro & Herbig (1955) which is effective in selecting actively accreting Classical T Tauri stars (see, for example, Rebull et al. 2000). In addition, we can identify

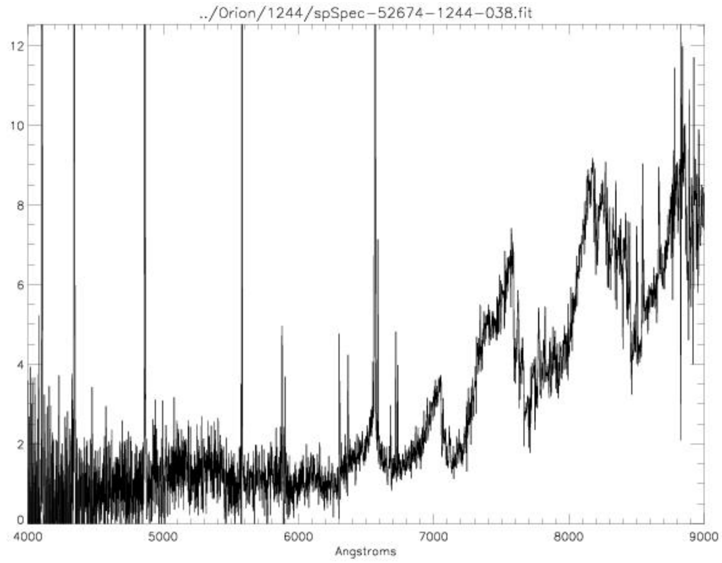

Figure 14. T Tauri spectrum. This spectrum, from an SDSS spectroscopic plate targeting low mass stars in Orion, is of a low-mass classical T Tauri star found within the Orion OB1 association. The estimated spectral type is about M4 and the Hα equivalent width is 110 Å.

the non-accreting yet still magnetically active Weak-lined T Tauri stars (WTTS) that have similar colors to the dMe stars.

Detailed surveys of nearby star formation regions will permit characterization of magnetic activity and accretion processes of young objects at and below the Hydrogen Burning Limit (McGehee, Hawley, & Covey 2003), which will aid in the understanding of the magnetic field strength evolution of very low mass stars and will address the formation processes for proto brown dwarfs (Feigelson 2003; Feigelson & Montmerle 1999). Figure 14 shows the SDSS spectrum of a low mass Classical T Tauri found in the Orion OB1b association in one low latitude test scan.

Connection with SPITZER Legacy Proposals

The SDSS imager and spectrographs will target the star formation regions to be studied by the SPITZER cores to disks [c2d] Legacy Proposal (Evans et al. 2003), which will use 400 hours of SPITZER time to map 5 nearby molecular clouds, including 150 compact molecular cores, photometry of 190 stars with ages up to 10 Myr, and spectroscopy of 170 objects. SEGUE will obtain data for three of the cloud complexes (Persus, Serpens, and Rho Ophiuchi) and the Taurus Weak-Lined T Tauri [WTTS] sample. SEGUE will add u,g,r photometry to the planned R,i,z observations by the CFHT12K and Megacam instruments at CFHT and additional spectra supplementing those planned with the KPNO echelle. The KPNO observations only target the Taurus WTTS population, not the entire source list, so the comprehensive set of SDSS spectra would represent a significant addition to the c2d project.

GLIMPSE (Benjamin et al. 2003) is a fully sampled image of the inner Galactic plane (longitudes $\pm[10^\circ$ to $60^\circ]$, latitude $\pm 10^\circ$ at 3.6, 4.5, 5.8, and 8.0 microns. This survey is aimed at the inner structure of the Galaxy. It is likely that it will be more useful to SEGUE than vice versa, but it will enable the identifications of red giant and supergiant stars in the inner galaxy in the SEGUE data, and may make it possible to measure extinctions along these lines of sight.

F. The Interstellar Medium

Modern dust maps are two-dimensional on the sky (but note that Drimmel & Spergel 2001 match the two-dimensional observations with a three-dimensional parametric model). Many researchers, both inside and outside the SDSS collaboration, are currently working on ways to turn information from large survey databases into a three dimensional map of the dust distribution. Techniques include statistical number counts/reddening analysis of large numbers of stars of various types (from F-M) and reddening determinations from stellar spectroscopy. The early results from these efforts appear to indicate that the present state of the art reddening maps (such as those of Schlegel, Finkbeiner, and Davis 1998, SFD) can be improved, both in terms of spatial resolution and accuracy. We will combine the optical catalogues produced in the extension with the 2MASS point-source catalog, which will aid in determination of reddening for the brighter stars in our extension, and help resolve ambiguities in the stellar identifications.

Determination of Extinction and Reddening

The background population that resides in the "blue tip" of the stellar color distribution provides an excellent measure of the total wavelength-dependent extinction. The SDSS camera saturates at about 14th magnitude, so these unsaturated stars (absolute magnitudes about +3) lie at very large distances and can be assumed to be behind all the Galactic plane dust. These are the turnoff stars in the old halo and thick disk populations and are the bluest stars at high Galactic latitudes except for white dwarfs. The color of the blue tip is easily measured because these turnoff stars are much more numerous than are the quasars and white dwarfs. Finkbeiner et al. (2003) show that the extinction measured by this method agrees very well with the extinctions predicted by SFD, as shown in Figure 15.

Measurements of the color of the blue tip can give the total extinction in each of the five SDSS bands. The SDSS data themselves can be used to measure the blue tip color, but by design the SDSS area is chosen to lie in the areas of minimum extinction in the north and south Galactic polar caps, so the actual extinction is small and its measurement by any method uncertain. The SDSS uses the dust map of SFD, derived from maps of the infrared emission from dust across the sky, to predict the extinction in each of the five SDSS bands, assuming a constant ratio of the total to selective extinction. The resulting extinction maps are used to correct the observed magnitudes of quasars and galaxies before spectroscopic target selection.

Checking the SFD map is important because it is the fundamental source for correcting observations of extragalactic objects for extinction; because it measures an important CMB "foreground"; and because it checks the assumed dust model and extinction curve and the dust masses and compositions derived from the model. SDSS photometry from the SEGUE scans, which cover a wide range of Galactic latitudes, provides an excellent check on the extinction model and a lot of valuable information on possible variations in the dust reddening curve. There are early indications in the small amount of SDSS data have so far been gathered at low Galactic latitudes that the value of R ($=A_V/E_{B-V}$) is constant throughout the ISM on large scales, but this needs to be further investigated with data covering a much larger area of sky.

Spatial Mapping of the Local ISM

Stars in the blue tip are not useful for mapping the three-dimensional distribution of the ISM in the solar neighborhood because of the saturation limits of the SDSS. For this, we need to use stars of intrinsically much lower luminosity. Since M dwarf g-r colors have a narrow locus about g-r=1.4 and there is a quite well-defined color-absolute magnitude relation for these very numerous objects (Hawley et al. 2002), SEGUE will probe the three dimensional structure of the local dust at distances ranging from 100 to 1000 pc (following Neckel and Klare 1980, see Figure 16), where the bulk of the extinction is expected to occur. The spatial variation of M dwarf g-r colors can be transformed into a map of cloud locations using techniques such as maximum entropy reconstruction (Arabadjis and Bregman 2000).

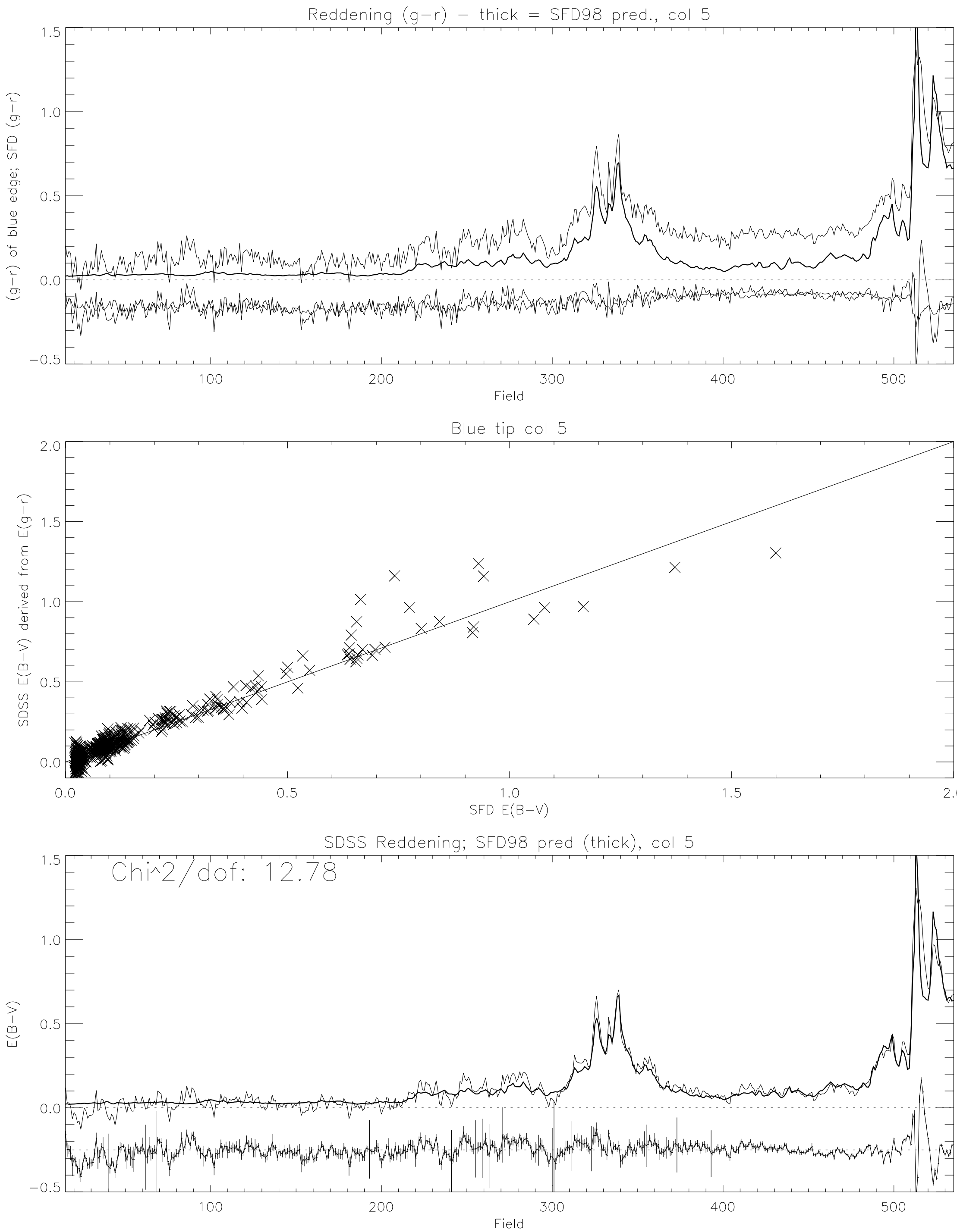

Figure 15. Measurement of reddening using blue-tip colors Top panel: run of blue tip g-r color and SFD extinction versus distance along the imaging stripe. The Galactic latitude decreases from about 60 degrees at the lest to 10 degrees at the right. Center panel: scatter plot of E(B-V) from blue tip data versus E(B-V) from SFD. Bottom panel: Run of E(B-V) from blue tip data (light line) and E(B-V) from SFD (heavy line) versus position along the imaging stripe.

Recent FUSE observations (Sonnentrucker et al. 2002) suggest that many objects that appear as distinct clouds in the ISM are actually multiple layers of Galactic cirrus that are superimposed along the line of sight. The proposed survey will distinguish between separate structures that contribute to the net extinction. The relative abundance of low mass stars will permit a finer resolution both along the sky and in distance. A reddening of 0.05 magnitudes in g-r corresponds to $A_V = 0.16$, equivalent to a HI column density of 3×10^{20} cm^{-2} (Magnani, Blitz, and Mundy 1985), enabling the mapping of diffuse clouds and Galactic cirrus in addition to the translucent (A_V = 1 to 5) and dark clouds.

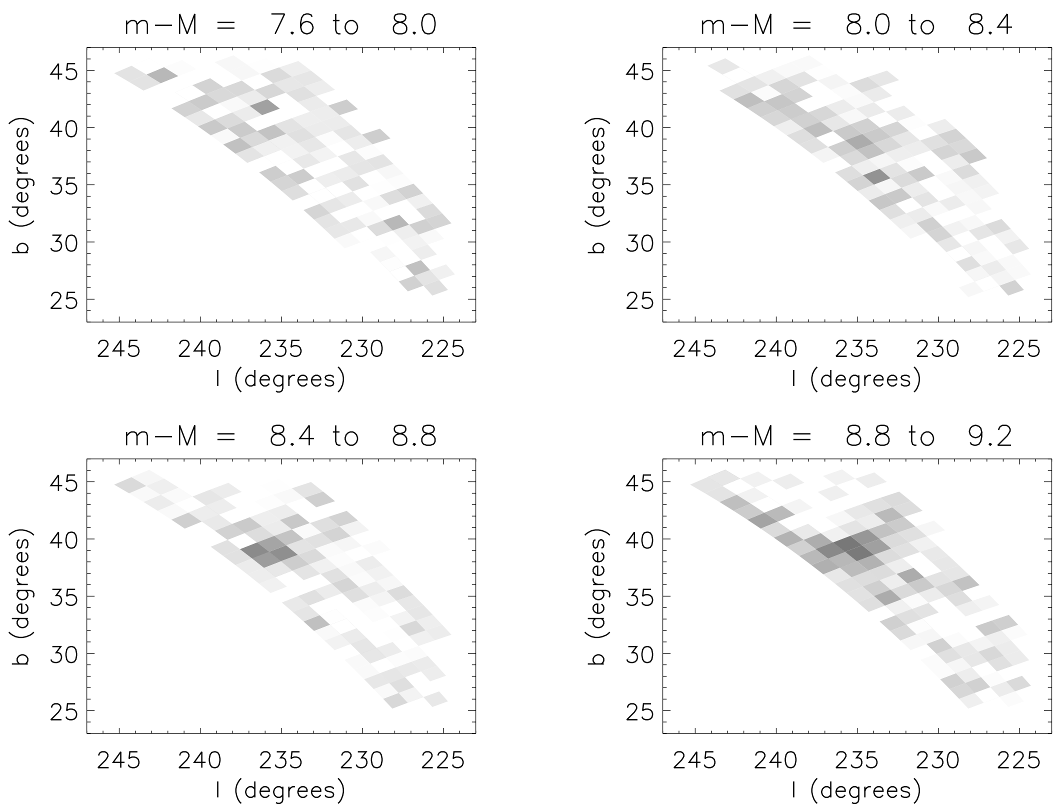

Figure 16. Detection of an Isolated Diffuse Cloud. This figure shows the HRK 236+39 diffuse cloud ($A_V = 0.68$ or $E(g-r) = 0.22$) detected in the m-M = 8.4 to 8.8 magnitudes mean $g-r$ map. The persistence of reddened stars farther along the line of sight at m-M = 8.8 to 9.2 magnitudes confirms the presence of the cloud.

Red Emission from Dust

Figure 13 clearly shows glowing red emission from the edges of the dust lanes. This figure represents a small portion of the SDSS imaging of dust clouds in the Orion, Taurus and Cygnus regions, taken during testing and calibration observations, and the emission is seen to be widespread. These color composite images are made using the SDSS g, r and i images, so that the red color in Figure 13 corresponds to light in the SDSS i filter (which is centered at 7700Å). This diffuse red glow may very well be related to the diffuse extended red emission (ERE), a broad emission band centered near 7000 Å and attributed to photoluminescence from carbon nanoparticles (cf. Gordon et al. 1998; Smith & Witt 2002). Five-band imaging by SDSS over large areas containing a wide range of dust densities and starlight illumination offers the possibility of establishing the origin of this feature and evaluating the size range and composition variations of dust particles in different environments in the ISM.

G. Rare Objects

More sky coverage means the discovery of more rare objects, such as brown dwarfs (e.g., Geballe et al. 2002), KBOs (Ivezić et al. 2001), etc. Because they are not in equilibrium, brown dwarfs cool after formation and their spectral properties depend on mass, age and metallicity. The SDSS is currently within a factor of three of providing enough of these objects to characterize the spectra and work back to an IMF below 0.08 solar masses.

Other rare objects include cool white dwarfs and white dwarf-white dwarf pairs. These data provide a census (with the use of proper motions) of disk and halo white dwarfs and a measurement of the age of the Galactic disk.

Perhaps the rarest of all halo objects are the stars with metallicities [Fe/H] < -5.0 (only one of which is presently known!). We anticipate that additional examples of such stars, or even stars of lower iron abundance, may be discovered during the proposed SEGUE extension. These stars provide the most direct means of deciphering the metal content and chemistry of the early Universe, and hence are of enormous interest. In a recent issue of Nature (April 24, 2003), for example, four separate articles presented discussions of the impact of the discovery of HE 0107-5240 (Christlieb et al. 2002), a halo giant with [Fe/H] = -5.3.

III. Technical Feasibility

We will use radial velocities and spectroscopic as well as photometric stellar properties to identify and study the kinematics and stellar evolution history of the primary structural components of the Galaxy. Stellar parameters derived from SDSS spectra will be a powerful complement to the photometry in constraining the age/metallicity of each component, from which we construct the evolutionary history of the Galaxy. Studies of the coherent streaming motions of stars in accreting dwarf galaxies will further illuminate the distribution of dark matter, and allow us to constrain the clumpiness of the dark matter component. These goals place requirements on the imaging, spectroscopy, and survey software.

A. Imaging

The technical feasibility of finding tidal debris and densities of Galactic disk components in SDSS data has been well established by the many discoveries of Galactic substructure with SDSS photometry (Chen et al. 2001, Yanny et al. 2000, Ivezic et al. 2000, Odenkirchen et al. 2001, Rockosi et al. 2002, Newberg et al. 2002, Yanny et al. 2003). Some of these results have been outlined in Section I. Two technical points require some further clarification: the accuracy with which the statistical photometric parallax determines distances to Galactic substructure, and the ability to separate populations photometrically.

Our technique for finding substructure from photometry involves first selecting a target population by color, and then looking for density contrasts in plots of sky position and apparent magnitude. In the future, we will use maximum likelihood techniques to search in color/magnitude/position simultaneously.

When a tidal stream is identified in a narrow distance range an dominates the starcounts, there is no ambiguity in the type of star that has been identified. This is because one can generate a color magnitude diagram of the stars, and observe at what magnitude the turnoff, horizontal branch, etc. occur (see Figure 5). In extended components such as disks, or when a concentrated component does not dominate, there is a significant ambiguity in the distance to each star, and we will need to apply models that include a probability in distance for each color star. For dominant streams such as the Sagittarius dwarf tidal stream and the probable stream in the Galactic plane, the statistical error in the mean magnitude of the turnoff or horizontal branch can be determined to within 1-2 tenths of a magnitude, corresponding to a 5-10% error in the distance.

In addition to the statistical error, there is also a systematic error, as one does not know the mean absolute magnitude of the stellar populations. We will need to establish the distance to at least one distance indicator in a concentrated structure in order to set the distance scale for the rest of the stars. Figure 17 (left panel) shows detections of the Sagittarius dwarf tidal debris using 2MASS stars (Majewski et al. 2003) along with detections of the same stream in SDSS data (Newberg et al. 2003). There is about a 13% discrepancy in the distances using these two stellar populations, and the difference is not statistical in nature. Although it is possible that these populations trace stars that are actually at different distances, it is more likely that there is a systematic error in the assumed absolute magnitudes of one or both stellar types.

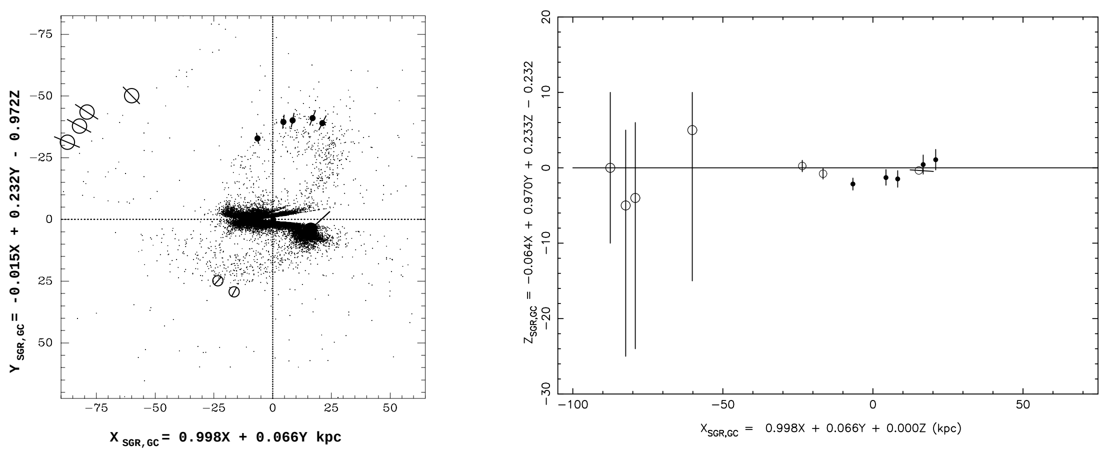

Figure 17. The plane of the Sagittarius dwarf tidal debris. In the left panel, 2MASS M giants from Figure 11 of Majewski et al. (2003) are reproduced, and overlaid with SDSS detections of the Sagittarius stream in A-colored stars. The panel shows the trailing tidal tail reaching out to 90 kpc from the Galactic center, and the leading tidal tail turning down towards the solar position. In our adopted Galactic coordinates, the Sun is at (X,Y,Z) = (-8.5,0.0) kpc. There is a 13% discrepancy in distance scale between the two data sets, reflecting uncertainties in the distance to Sagittarius and in the absolute magnitudes of A-colored stars and M giants. The right panel shows the positions of SDSS A-colored stars perpendicular to the Sagittarius dwarf orbital plane. This shows evidence that the tidal tails are twisted slightly out of the plane.

In an ideal world, we would be able to color select stars that have high probability of being in each stellar component of the Galaxy, and from this subset of stars we could map the individual component separately from all other components. In Figure 5 one sees several populations with different turnoffs - the Sagittarius dwarf at $g - r = 0.2$, another component at $g - r = 0.3$, and yet another brighter component at $g - r = 0.38$. This gives us some hope that components can be separated by color and apparent magnitude range. However, the results in Figure 2 temper that conclusion. Even though we selected stars that should include only the bluest component, we find a concentration of stars at $g = 15$ near the Galactic anticenter (RA = 120°). These may be stars of the thick disk leaking into the sample either due to a metallicity gradient or the shear numbers of stars in that component.

If the identified population includes turnoff stars, Newberg et al. 2002 showed that the color of the turnoff can be determined to a few hundredths of a magnitude. Observations of stellar clusters will enable another method for verifying the calibrations of the survey. Fitting isochrones and metallicity curves (Girardi et al. 2000; 2001; 2002; 2003) to the observations will allow determination of ages and metallicities for the observed star clusters. These can be compared to results in the literature for the well observed clusters, and new results obtained for those clusters with few or no observations (Rider et al. 2003). Determination of age and metallicity values for the clusters is currently limited by the models for our photometric uncertainties, although variations in the interstellar dust will degrade the results somewhat. These results will in turn be used to determine the metallicities and ages of stars in tidal streams.

B. Spectroscopy

The spectroscopic exposure time is driven by our need to accurately measure the strengths of key spectral features. For warmer stars, the Ca II H and K lines, Ca I 4226, the CH G-band, Hδ, Hγ, and other Balmer lines, the Mg I b lines, the Na D lines, and the Ca triplet, will be measured; for cooler stars, the molecular bands that dominate their spectra are of primary importance. It is also driven by the need to obtain radial velocities with 20 km/s precision for stars as faint as g$\sim$ 20. A sample SDSS spectrum is shown in Figure 18.

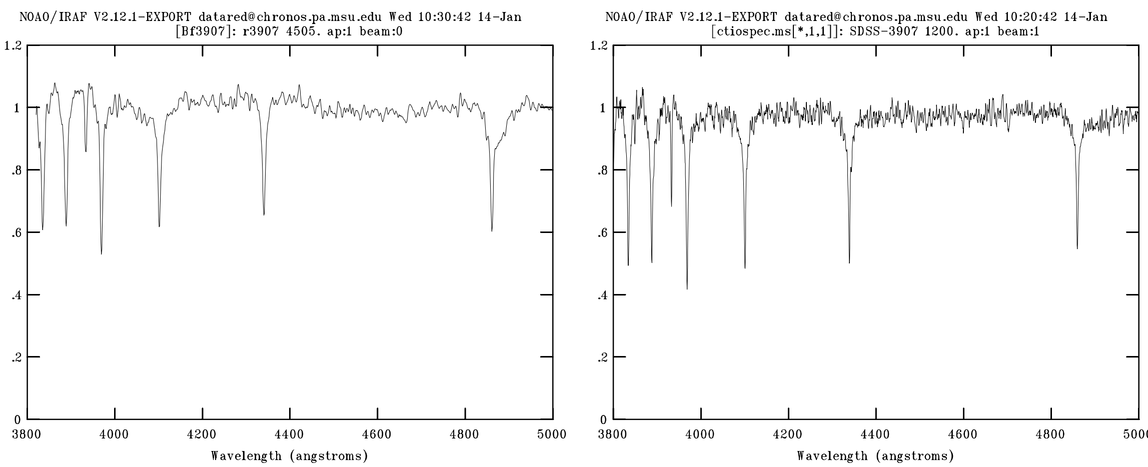

Figure 18. Sample Spectrum. The star EDR-3907 (left), a main-sequence turnoff star with [Fe/H] = -3.3, originally selected and observed by the SDSS, is shown on the left, while a CTIO 4m spectrum (1.5 Åresolution, 20 minute integration) spectrum is shown on the right.

Radial Velocity Precision

As part of the Fall 2003 SDSS observing season, several SEGUE feasibility tests of the SDSS spectrographs were performed.

To determine the reproducibility of the instrumental radial velocities, a special plate of about 400 SEGUE-target stars, reaching to magnitude $r_{\rm PSF} \sim 20.0$, with extra sky fibers for accurate sky subtraction on faint objects, was designed and observed in the following fashion:

1. First the plate was plugged with fibers, fiber-mapped, and observed for about 2 hours, this yielded $S/N \sim 5$ for the faintest objects, and $S/N > 50$ for the brightest stars.

2. Then the plate was unplugged and replugged on a different cartridge of fibers, scrambling the fiber-object associations. It was then remapped and re-observed, this time for about 6 hours, yielding $S/N > 15$ for the faintest objects and $S/N > 100$ for the brightest.

The two observations of this plate of 400 stars were processed independently, and then the measured radial velocities (as determined from fits to ELODIE high resolution, high S/N spectral templates) of the same stars were compared as a function of magnitude and stellar color. The results are presented in Figure 19 and Table 1.

Table 1 – Radial Velocity accuracy for SEGUE				
r_{PSF} mag	S/N	$N_{spectra}$	offset(km/s)	RV σ(km/s)
14 – 16	100	100	-0.3	4.2
16 – 17	60	71	-0.3	4.2
17 – 18	40	92	-0.5	6.6
18 – 19	22	82	-0.2	11.5
19 – 20	10	44	2.8	23.5

Ensemble velocities and dispersions

The above test demonstrated that we will be able to quite satisfactorily meet our radial velocity requirements for individual objects nearly down to our magnitude limit. When searching for and characterizing streams of stars, we can take the ensemble average and dispersion of their individual velocities, and obtain mean stream velocities with absolute systematic errors of no more than ~ 5 km/s, and the dispersions of faint streams may be determined if they have $\sigma \sim 20$ km/s or larger. Narrower dispersions (to about $\sigma \sim 10$ km/s) can be obtained if the associated stars are brighter than $r \sim 18.2$.

In order to characterize the mean velocity and dispersion of stars in a particular component, we require about one hundred radial velocities. Success in kinematically isolating streams of stars has been demonstrated by measurement of the velocity and dispersion of the stars in the Sagittarius dwarf spheroidal tidal stream and the planar "ring" (Figure 6) using spectra identical to those we will obtain with SEGUE.

Using ensemble velocities of a similar population of stars is also crucial not only for halo stream studies, but for studying structure within and at the boundaries between the Milky Way's disks and halo. A large sample of spectra is currently in hand from various special SDSS southern survey plates designed for this study.

Figure 20 displays the radial velocity distributions, binned by photometric parallax out to 4 kpc, for all stars redder than $i - z > 0.06$ from all currently observed plates in the "Kinematics of Main-Sequence Turnoff Stars" (J. Munn, PI) and "Kinematics of the Thick and Thin Disks" (C. Rockosi, PI) southern survey projects. A Gaussian is fit to each distribution (no attempt has yet been made to fit multiple components). The smoothly varying kinematics is evident, with monotonically increasing dispersion and increasing lag in the mean velocity with increasing distance above the Galactic plane (the line of sight is $\ell = 114°$, b $= -62°$), conventionally interpreted as the changing contribution from thin disk, thick disk, and halo stars. Of particular interest is the distance bin 1750 pc $<$ d $<$ 2000 pc, where a clear non-Gaussian distribution of objects is indicated. This figure demonstrates the effectiveness of our target selection strategy (see below), which aims to sample multiple Galactic components in many distance bins.

Although a single Gaussian is fit to each distribution in Figure 20, it is clear that with between 100 and 200 spectra (bottom four panels), more than one component can be identified. With more than 1000 stellar spectra in each chosen direction, we will constrain well the kinematics of ten populations. In this usage, a population is one stellar component at one distance range. If there is only one component it can be sampled at ten distances, but if there are three components (thin disk, thick disk, spheroid) that are significant at a particular distance, then that would count as three "populations."

With our heavy sampling of the velocity field we hope to go beyond the characterization of the velocity distribution of any sub-sample as being drawn from a Gaussian parent population.

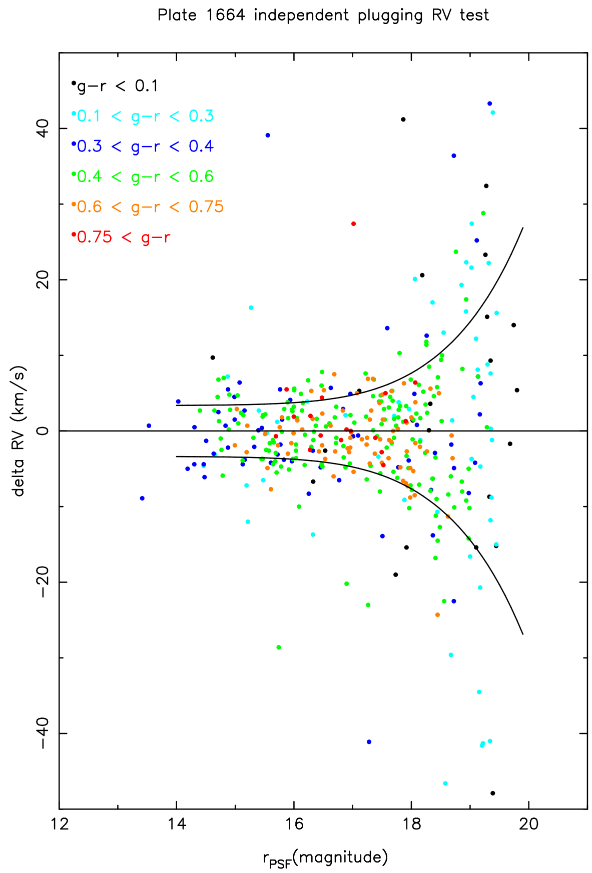

Figure 19. Plate 1664 Radial Velocity Reproducibility Test. Radial velocity differences from two independent observations of plate 1664, one with SEGUE S/N, the other with significantly higher S/N. For bright objects ($r < 18.2$) the errors in RVs have no systematic shift and a remarkably small rms dispersion of $\sigma = 5$ km/s. For fainter objects, the errors rise to $\sigma \sim 25$ km/s at $r = 20.0$. The black curves show a standard error curve: $\sigma^2 = 11.3 + 10^{0.62(r-15.3)}$.

Establishing the reality of substructure in the F/G dwarfs, for example, requires several tens of stars in any one velocity bin. Such data will provide for an unprecedented exploration and characterization of the velocity distribution functions for stars in the dominant populations of the Galaxy. Radial velocities, combined with proper motions and photometric parallaxes (when available) provide all six kinematic phase space coordinates. This opens up the possibility of conducting a detailed exploration of the velocity ellipsoids of the components of the Galaxy (e.g., Chiba & Beers 2000), and examination of their possible change with Galactocentric distance, as is expected in some models of galaxy formation.

Metallicity accuracy and other spectroscopic parameters

In addition to radial velocities, we will use the spectroscopy to constrain the physical properties of individual stars.

From a first-pass analysis of EDR data (Beers 2002; Li et al. 2002), we estimate that the surface temperature, surface gravity, and metallicities of stars in the range of temperature 4,000 K < $T_{\rm eff}$ < 10,000 K can be determined to an accuracy of $\sigma(T_{\rm eff}) \sim 200$ K, $\sigma(\log g) \sim 0.4$ dex, and $\sigma([Fe/H]) \sim 0.3$ dex. Additionally, the spectra can be used to estimate $[\alpha/Fe]$, at least down to metallicities as low as [Fe/H] $\sim$ -2 (Allende Prieto et al. 2003), which straddles the important regime between the halo and disk populations, where the change in this ratio places fundamental

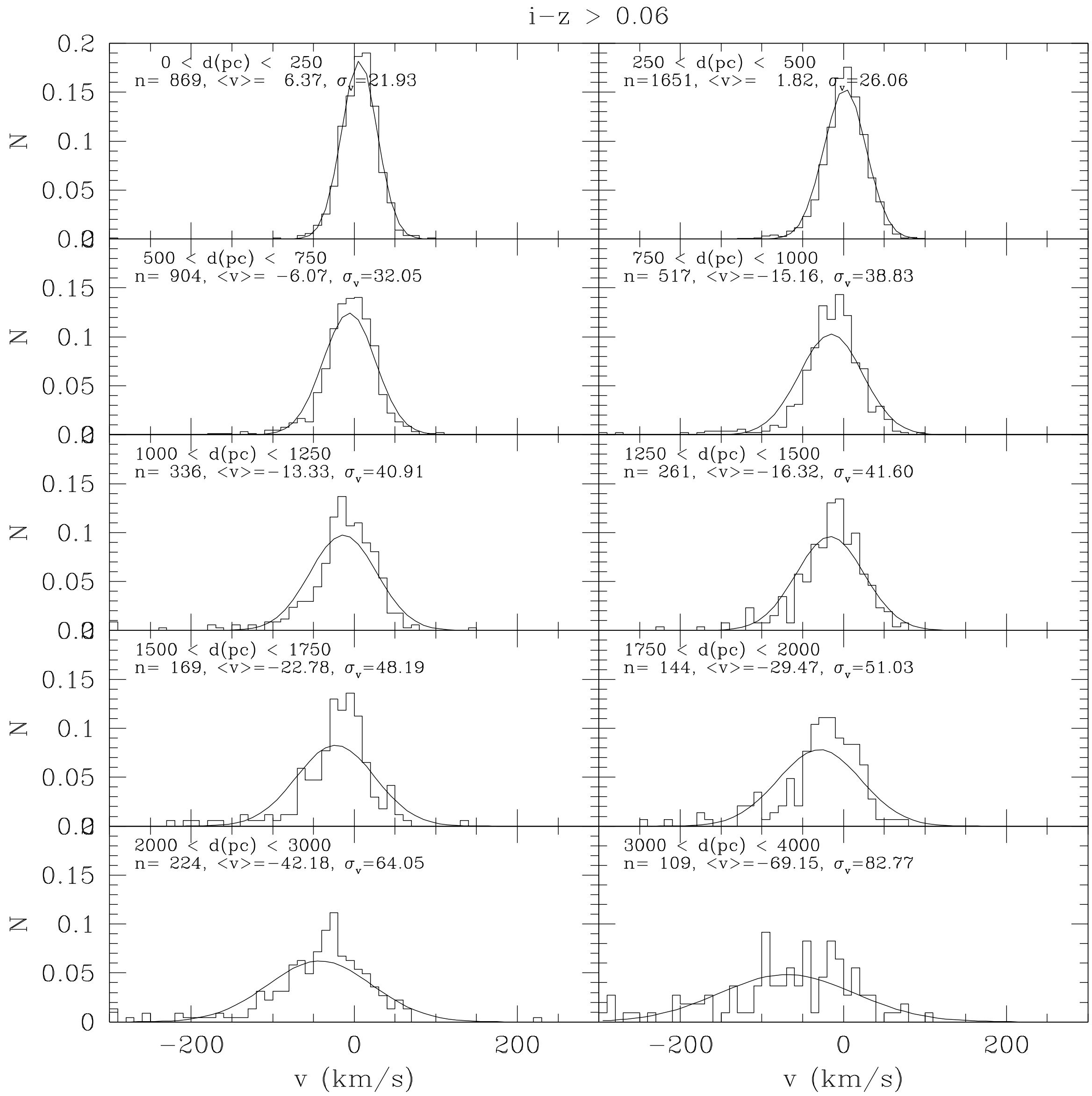

Figure 20. Sample radial velocity distributions. Radial velocity distributions, binned by photometric parallax out to 4 kpc, for all stars redder than $i-z > 0.06$ from all currently observed plates in the "Kinematics of Main-Sequence Turnoff Stars" and "Kinematics of the Thick and Thin Disks" southern survey projects. A Gaussian is fit to each distribution.

constraints on the chemical evolution of these populations.

To assess how these determinations depend on S/N, a detailed look at a set of approximately 6,000 stellar spectra from the SDSS EDR sample yielded estimates of metallicity, effective temperature and log gravity for each spectrum, based on least-squares fitting to a grid of model atmospheres. The internally determined errors from this grid-fitting exercise, as it relates to the precision with which these parameters can be extracted from SEGUE spectra, are summarized in Table 2. We note that for most of the brighter stars in the sample ($r < 18.2$), where we will have

$S/N > 30$ spectra, we will be able to determine metallicity for stars with metallicity $[Fe/H] > -2$ to an accuracy of 0.3 dex or better. For the stars of very low metallicity $[Fe/H] < -2$, the accuracy with which one can determine precise metallicities is diminished. However, there is no difficulty in recognizing these rare and very interesting objects as such, and they may then be followed up individually with larger telescopes in the future.

The above results are based on estimated errors based *solely* on application of our fully automated procedures, and do not take into account the advantages which are realized from inclusion of alternative approaches, such as the abundance calibration of Beers et al. (1999) and physical parameter estimates based on the techniques of Wilhelm, Beers, & Gray (1999). Although for determinations of surface gravity higher S/N is clearly desirable, estimates of [Fe/H] from the alternative procedures are capable of reducing the errors indicated above to on the order of δ[Fe/H] $\sim 0.2 - 0.3$ dex for stars with [Fe/H] ≤ -2.0 and spectra with S/N of $\geq 15/1$.

Table 2 – Projected accuracy of [Fe/H], $T_{\rm eff}$, and *logg* determinations

S/N	$T_{\rm star}$(K)	$\sigma([Fe/H])^1_{\rm hi\ met}$	$\sigma([Fe/H])^2_{\rm lo\ met}$	$\sigma(T_{\rm eff})$	σ(logg)
100	4500-5500	0.01	0.15	20	0.2
100	5500-7000	0.04	0.20	25	0.1
100	7000-10000	0.05	0.25	20	0.1
30	4500-5500	0.05	0.40	75	1.0
30	5500-7000	0.30	0.70	100	0.3
30	7000-10000	0.20	1.00	80	0.2
10	4500-5500	0.30	2.00	300	3.0
10	5500-7000	1.40	3.00	700	2.0
10	7000-10000	1.50	3.00	700	1.0

[1] Accuracy of metallicities for stars with $-2 <$ [Fe/H] < 0.

[2] Accuracy of metallicities for stars with $-4.5 <$ [Fe/H] < -2.

Additional tests have been applied to existing SDSS data. Some 10,000 spectra of F/G turnoff stars, sparsely but uniformly distributed across the SDSS area have been obtained. Spectra of sixteen of these stars per plate (brighter than g = 18.5) are observed as spectrophotometric and reddening standards. There are also duplicate observations (useful for assessing the radial velocity accuracy) of several hundred stars. Since all of these stars are bright enough to be detected by the Palomar photographic surveys, proper motion information is available and the full power of the statistical/secular parallax analysis methods can be brought to bear. A first crude analysis easily separates the disk, thick disk, and halo stars; finds correlations of the metallicity with the kinematic components; and finds many examples of the carbon-enhanced (CH) stars in the low metallicity population (Knapp et al. 2003).

Spectroscopic target selection algorithm

Figure 20 gives a good sense of how the stellar targets will be selected to explore the kinematics of the Milky Way's disks and halo populations as a function of distance from the sun or Galactic center. The SEGUE target selection algorithm is similar to this, targeting roughly 100 stars in 1 kpc slices out to 5 kpc to sample well the thin and thick disks, and 100 stars per 5 kpc slice from 5 kpc to 50 kpc to sample the halo. Adjacent lines of sight may be binned to provide better sampling per distance bin. The halo and streams target selection algorithm will be similar to this toward lines of sight with no obvious structure apparent in the photometry (other halo lines of sight will specifically target stream detections of interest to obtain kinematic information).

It has already been demonstrated that A-type stars (including both field horizontal-branch and blue stragglers), F-type main-sequence turnoff stars, and photometrically selected G- and K-type giant stars are excellent tracers of Galactic structure from 2 to 100 kpc from the Sun. There are about 500 F-type turnoff stars ($0.1 < g{-}r < 0.3$) per square degree in an average SDSS field at intermediate latitude (Newberg, Yanny, et al., 2002), of which about half are brighter than 20th magnitude in g. To include thick-disk turnoff stars, the color range will need to be extended towards the red, which may double the overall stellar density of turnoff stars. There are about 10 A-type stars per square degree (Yanny, Newberg, et al., 2000), and about 20 K-giant candidates per square degree (of which at least 50% are actually halo K giants, Helmi et al. 2003; others are dwarf members of the thick-disk population). The SDSS spectra have sufficient wavelength resolution to allow the separation of the two groups of A stars (Figure 4) – the blue horizontal branch stars and the blue stragglers which are two magnitudes fainter (Yanny, Newberg et al. 2000; Sirko et al. 2004). Statistically sampling the F-turnoff stars by a factor of about one in five would provide an areal density of targets on the sky that is well matched to the spectrograph fiber spacing (assuming two plates per pointing). Inclusion of a random sample of cooler M/L/T stars and K dwarfs will include stars over the entire spectral range, and give us sensitivity to the nearest disk populations. Photometric colors and proper motions, which when available can distinguish main sequence from giant populations, will be used to select spectroscopic targets.

The target selection algorithm will be designed to produce a statistical sample of stars at a variety of distances along each line of sight. We will include all of the intrinsically luminous stars available in our target patches, which sample the Galaxy to a distance of up to 200 kpc. We will randomly sample the fainter populations, which will allow us to study the transition from the thin disk to the thick disk to the inner and outer spheroid stellar populations, as well as their local normalizations. The spectral data, combined with the much more abundant photometric data, will constrain the spatial, kinematical, chemical, and age substructure of each component. Confident selection of the optimal sample stars to be included in the spectroscopic portion of this survey is, of course, crucial.

Note that it is not necessary to know the distance to each of the target stars ahead of spectroscopy, as long as the final targets are spread in distance and do not avoid components based on chemistry or age. Although we use photometry to guess the distance to the spectroscopic target, we will use the spectrum to refine our guess. If we can constrain the stellar atmospheres of each star as we have begun to demonstrate in the EDR data, then in the final analysis we will have a better estimate of the absolute magnitude of each star, and will not be subject to the spread in derived distances that could arise from the brightening on the main sequence with age for F dwarfs, for example, or the ambiguity in distance when we do not know if a star is a K giant or a K dwarf. If we can identify from photometry a population that contains 50% K giants, as is suggested from the work of Helmi et al. 2003, then after the spectroscopy we will know which are which, and assign their kinematics and physical characteristics to the populations at the correct distances.

The target selection will depend on Galactic latitude (within 30° of the Galactic plane), as different stars and different components will dominate at lower Galactic latitude. At high latitude, the selection will concentrate on the thick disk/inner halo/outer halo stellar separation; at low latitude we will probe primarily the connection between the Galactic disks.

The goal here is to provide ~ 200 directions (see Figure 1) in which we have spectroscopy of a well understood subset of the stars, which can then be used to interpret the more voluminous photometric data set. Since the photometric data set contains virtually all stars within our magnitude limits, the global models based on this data will not be affected by selection biases in our choice of spectroscopic targets, though care will be taken to assure that we target a range of chemical compositions and ages.

C. Software Considerations

The SDSS software systems: data acquisition, operations, imaging data reduction, target selection, spectroscopic analysis and data bases, could be run in very much the same way as the current SDSS. This is a tremendous cost and effort savings.

We have altered the code that runs the data acquisition (DA) on the mountaintop so that scans at constant Galactic longitude can be observed seamlessly. The modifications to the DA code took only a couple of weeks of effort for our observing team, and were tested on the $\ell = 110^\circ$ strip alluded to above this fall as a test. The imaging and data reduction software systems have already been run successfully on this test scan (all the way down to b = 0°).

To date, data have been obtained for some 470 square degrees of low-latitude sky (called hereafter the Orion data, and, as a test, for one SEGUE strip at $\ell = 110^\circ$), and successfully reduced using the latest versions of the photometric pipelines (Finkbeiner et al., in prep). Of particular note is that the low-latitude data have been reduced at the same time, on the same computer systems, and with exactly the same set-up, as have the high-latitude main survey data. Thus we already know that data taken in all of the proposed imaging modes: high latitude sidereal rate, low latitude sidereal rate, great circles in several different coordinate systems, can be reduced with the current SDSS imaging software in a straightforward way.

The photometric pipeline is *not* designed as a crowded-field code, nor is it tuned optimally for crowded fields, and some straightforward development will be required for it to produce accurate results at low latitudes. We will cover this and discuss how well it does in section V below.

Stellar studies using SDSS spectra processed through spectroscopic data reduction pipelines (2D and 1D) show that the pipeline which extracts the one-dimensional spectra from the CCD frames performs adequately at high latitudes, though some work will be required for its sky-subtraction accuracy to be adequate in regions where background nebulosity is present. This is discussed in more detail in Section V. The 1-D spectral analysis program used in the SDSS is designed to perform well on galaxies and quasars and does not currently handle stellar spectra optimally. An alternate SDSS pipeline (developed by D. Schlegel) is optimized for stellar spectra, with a much larger and finer set of stellar templates and fitting code, has been used for several stellar spectral studies. However, even this template library does not give us the optimal radial velocities and type information allowed by the spectra themselves.

As SEGUE progresses, we will collect very large numbers of stars of the types of interest for this survey, and the template library can be easily updated. The discussion in (B) above indicates that the radial velocity error floor, determined probably by flexure, sampling considerations, and such, is in the neighborhood of 3 km/s, and the errors even at $r = 19.5$ are of the order of 20km/s. This magnitude corresponds to a bright halo giant at 250 kpc, a horizontal branch star at 60 kpc, and a turnoff subdwarf at about 13 kpc. These errors do not include template errors, since they are derived from repeat observations, but independent studies indicate that with the current templates, the floor set by all systematics is about 5-7 km/s, and will be improved as the templates improve.

A new spectroscopic target selection algorithm will need to be defined. This is a task more of testing than of coding and algorithm development. We are quite experienced with the machinery of selecting targets, but are faced here with a very different scientific goal. The technical implementation of target selection (described in detail above) requires only the definition of criteria for selecting new types of targets and the re-assignment of priorities. The scientific basis on which targets are selected, from color, magnitude, proper motion, or cross-correlation with other catalogs, needs to be worked out in detail and will require some experience to properly adjust the parameters, so that all components and distances are properly sampled.

IV. Observational Strategy

A. Overview

The observations in this proposal include both imaging and spectroscopy. The imaging survey will be carried out under identical weather conditions and scan rates as the current survey, and extends the sky coverage of the SDSS survey in a completely seamless fashion. The spectroscopic observations will be obtained at approximately the same rate and with the same weather constraints as the current survey, so survey operations will remain much the same as they are now.

B. SEGUE Imaging Plan

The imaging survey is designed to identify and trace photometrically all stellar components of the Galaxy, including the major debris streams. Previously identified Galactic structures and halo sub-structures (with the exception of high surface brightness features such as globular clusters and undisrupted dwarf galaxies) have characteristic angular sizes of several tens of degrees or more. Major components such as disks and spheroid populations are also well sampled at ten degree intervals.

Our goal is to sample the entire sky available from Apache Point Observatory, with gaps of no more than about 10 degrees between observations at high Galactic latitude ($|b| > 30°$), and no more than 20 degrees at low Galactic latitude ($|b| < 30°$), so that all major structures will be sampled.

Assuming that the imaging of the North Galactic Cap is completed before, or in conjunction with, this proposed extension, we need only add imaging coverage in the Galactic Plane and in the South Galactic Cap. The area of sky sampled is the 27,000 square degrees with declination $\delta > -20°$ that is visible from this northern hemisphere site. While this will not be completely imaged, it will be completely sampled. Additional proposals could be developed to complete imaging of the entire northern sky. The proposed strategy is to aim at optimal sampling and coverage of areas of special interest.

The imaging proposed here will be designed to cover as wide a range of Galactic latitude and longitude as possible. Due to the large areal extent of the halo star streams and substructures already identified, even sparse sampling should allow us to detect similar new streams intersected by the scans. In the South Galactic Cap, we propose to image stripes 72, 79, and 90 (about 700 square degrees). This will supplement the data already obtained from stripes 76, 82, and 86. Since the stripes are 2.5 degrees wide, a sampling of every fourth stripe results in a maximum stripe separation of ten degrees.

Additional imaging close to the Galactic plane ($|b| < 30°$) over as large a range of Galactic longitude as is feasible will allow us to explore structures like the Gilmore, Wyse, & Norris (2002) sample, the proposed "Ring around the Galaxy" (Yanny, Newberg, et al., 2003, Ibata et al 2003), the scale height and the structure of the thin and thick disks, asymmetries (off-center, tri-axial, higher-order moments) of the thick-disk population(s), the possibly-flattened inner halo population, the Galactic warp and flaring, the column density and three dimensional structure of the ISM, and the nature of star formation in young stellar populations.

The positions of the proposed scans are shown in Figure 1, and described in section I.B. The exact longitudes of the stripes will be adjusted to include Galactic regions of special interest, including those targeted by SIRTF legacy projects, those with more complete astrometric coverage, the regions to be imaged by the ESO/UKIRT Deep Infrared Sky Survey, and young open clusters. Every stripe should contain at least one target of special interest.

C. SEGUE Spectroscopic Observing Plan

In order to sample the global properties of all large structures, we will sample the stars in ~ 200 directions in the Galaxy (see Figure 1 for a sense of how they will be distributed – the actual positions will be adjusted as our program develops) . Our imaging data samples about 27,000 square degrees (three quarters of the sky). Each of the ~ 170 pointings shown in blue in Figure 1 represents the stars in a 160 square degree patch of sky. In each of these directions, we will sample the kinematics and metallicities of the stars from 2 to 150 kpc from the Sun, as extinction allows. Because we can only observe stars in the apparent magnitude range $14 < g < 20.3$, we will sample different types of stars at each distance (M-type stars will only be sampled near the Sun, whereas A-type stars and K giants will be sampled to the edge of the known Galaxy).

In each of these 200 directions, we will expose two plates (400 plates total). One of the two plates will be exposed for about 45-minutes, similar in length to the current SDSS survey, and the other will be exposed for about 1.5 hours, a double-length plate. In general, the fainter half of the targets will be observed on the deeper plate, though there may be special cases in which we would like a longer exposure of some of the brighter objects - particularly for quality assurance. The deeper plates will yield S/N ~ 10 for objects as faint as g ~ 20.3, and S/N > 50 for g ~ 18.0. We need this signal-to-noise to increase the accuracy of the metallicity (and radial velocity) determinations for the fainter stars in each of the pointings. We will measure the radial velocities with errors of 5–25 km/s for our program stars, depending on the apparent magnitude, $14.5 < g < 20.3$.

D. Using the best available astrometry

The exact positions of the pointings will be shifted to include areas with the best first epoch astrometry available. Combining SDSS positions with USNO-B yields proper motions with rms errors of roughly 3 mas/year, complete for stars brighter than g = 20. This corresponds to tangential velocity errors of 30 km/s at a distance of 2 kpc. The errors are dominated by the error in the first epoch position, based on 2 POSS-I plates in USNO-B. Figure 21 shows that about half of the sky is covered by at least 4 POSS I plates. In that survey, plates with defects were re-imaged to obtain more uniform coverage, and these plates have been scanned at USNO to increase the accuracy of the first epoch astrometry. The accuracy of the first-epoch astrometry roughly varies as the (210 mas)/$\sqrt{\mathrm{N}}$, where N is the number of plates observed. A careful selection of spectroscopic fields to overlap areas of sky with 4 - 8 POSS-I plates should yield rms errors in tangential velocities of 30 km/s out to distances of 3 - 4 kpc, enabling a complete six dimensional phase space kinematic analysis out to the thick disk/inner halo interface.

The impact of the science in this proposal will be leveraged by including approximately 30 spectroscopic pointings in directions of special interest, primarily young clusters and star forming regions near the Galactic plane (though a few probe the velocity distribution in the Sagittarius dwarf tidal stream). These spectroscopic observations will be tied together by the network of photometric observations to create the global picture of the Galaxy.

Because we already have imaging data from the main SDSS survey, we will be able to begin spectroscopic observations immediately at the start of SEGUE observations, and will not have to wait for high quality imaging data to be acquired. The data in stripes 76 and 82, as well as previous imaging of the Orion star formation regions, will be used for early target selection in the summer and fall months at the beginning of the survey.

E. Observing constraints in light of a combined extension proposal

SEGUE is requesting roughly 4000 square degrees of new imaging data and 200 tiles of spectroscopic data, which are equivalent to about 520 “standard” SDSS spectroscopic exposures. The distribution extends around the sky, such that data can be, and needs to be, collected in each quarter. Since the SDSS imaging data cover much of the available sky in the Spring, there is less demand for imaging time for SEGUE in March and April.

The observation plan attempts to obtain as many of these data as possible within a three-year

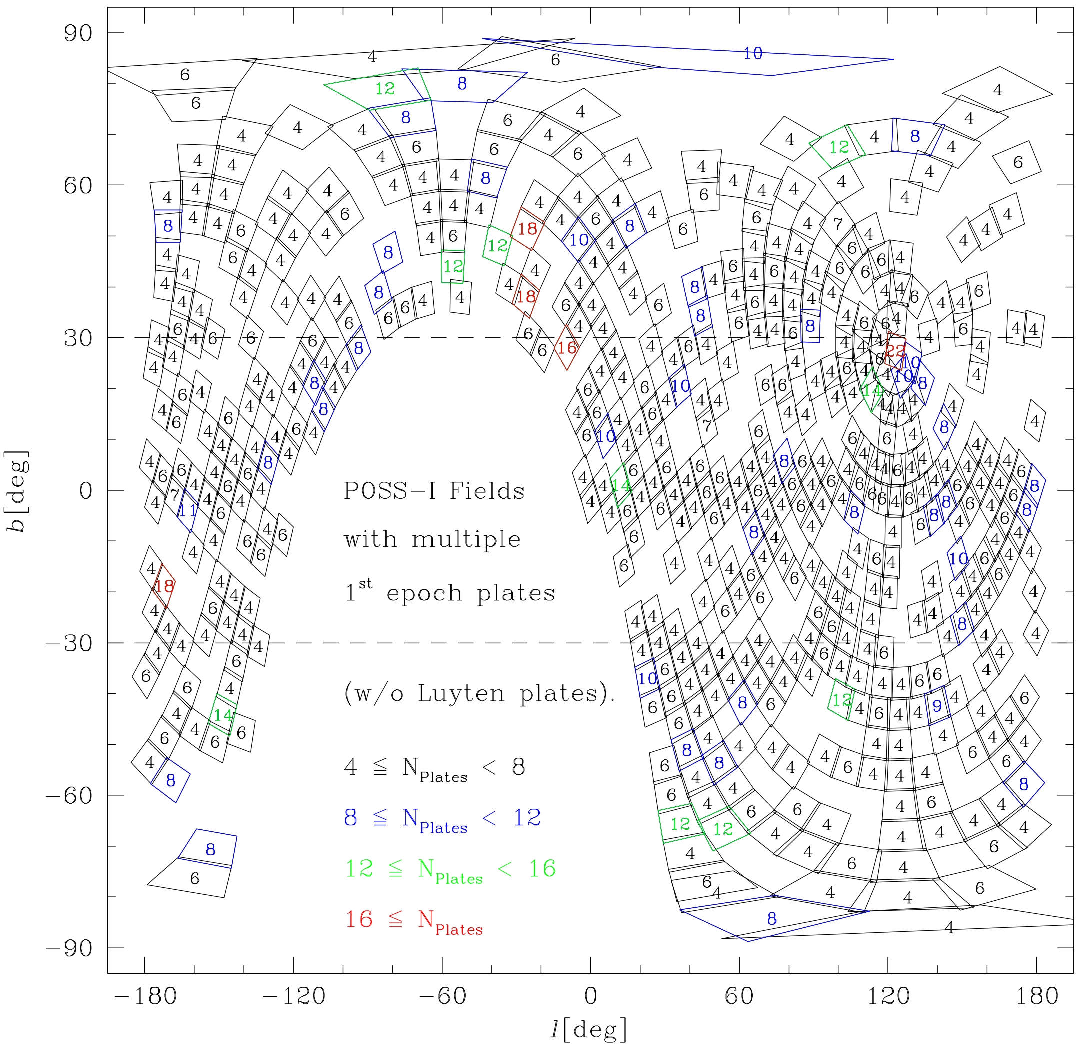

Figure 21. Available POSS I astrometry. Distribution of the POSS-I first epoch fields (those with at least four first-epoch plates). The plates are roughly $6.4° \times 6.4°$. The fields are color coded in the ranges N=4-7 (black), 8-11 (blue), 12-15 (green), and 16 (red) plates taken of the field, with the actual number written inside the field boundaries.

interval starting in mid-2005. (Some of the data have already been obtained, and more may be obtained in Fall 2004.) There are also two other surveys (Supernovae and Legacy) that need to be integrated into a single coherent observing plan.

While we cannot forecast with any accuracy the sky coverage of the SDSS as of mid-2005, and we cannot forecast in detail the progress of the new surveys during the three subsequent years, we can at least ask whether the demands from the three surveys are consistent with the rate of collecting data for the SDSS.

The rate of collecting survey-quality imaging data has been 2400 square degrees per year. The Legacy imaging may well have been finished, or nearly finished, by mid-2005. The Supernova survey requires blocks of time, each block at least two months long. If a total of ten months were dedicated to the Supernova program, and if there were no further demand from Legacy, then 2.2 years could be allocated to SEGUE. By this reckoning, there is more than adequate photometric time to obtain the 4000 square degrees.

After mid-2005, there may remain about 480 plates that need to be observed for Legacy, that is, to complete the contiguous area in the North Galactic Cap. As indicated above, SEGUE is asking for about 520 standard-plate equivalents worth of observing time, for a combined total of 1000 plates. Our rate of collecting spectroscopic data for the SDSS has been 360 plates per year. Given the 2.2 years available, we can obtain 780 plates. If the photometric time not used for imaging were used instead for spectroscopy, we would be able to obtain an additional 80 plates or so, for a total of 860 plates, which is reasonably close to the estimate of 1000 plates. The difference could be made up by obtaining data before mid-2005 for either SEGUE or for Supernovae.

The challenging aspect is not so much the total time available for spectroscopy, but the time available in the Spring, since both Legacy and SEGUE require time then. Without specific knowledge of the footprint that will need to be completed for Legacy, it is impossible to evaluate how serious a scheduling problem this will be. 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.

V. Required Development

As discussed above, the SDSS software tools are, for the most part, adequate for the task at hand, but it is clear that SEGUE would benefit from some tuning and a small amount of development.

A. Imaging

We expect that some algorithmic development will be needed within the photometric data processing pipelines to deal optimally with the results of the increased star density, the much larger numbers of bright stars (read saturated stars with bright diffraction spikes), and the varying bright and dark background at low Galactic latitudes. This code is currently being developed. This development will not be a large intiative, but instead a careful adaptation of current code, methods, and parameters. It is to be stressed that the photometric pipeline is not a crowded-field code, nor do we intend to make it so; the development effort would, we believe, be prohibitive.

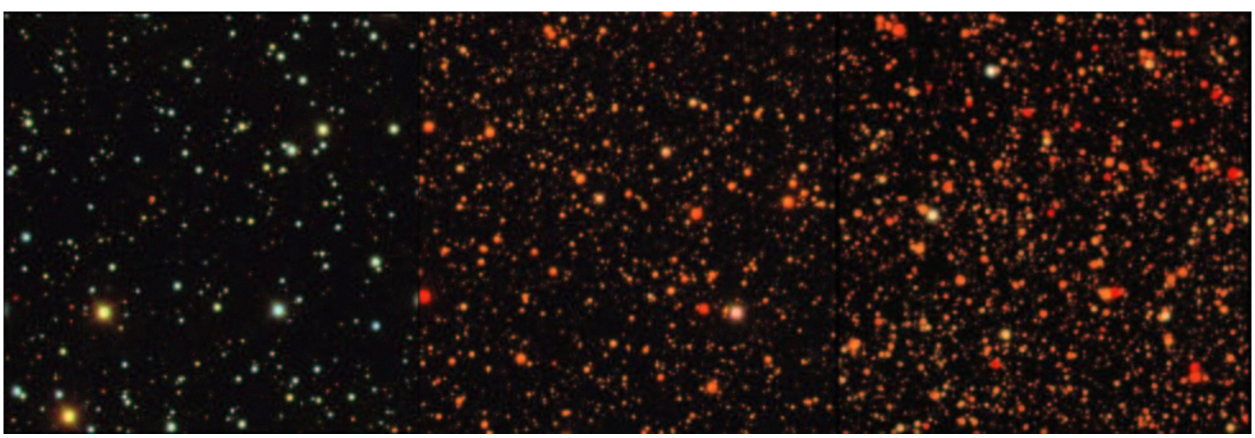

Figure 22. A mosaic of fields along the $\ell = 110$ SEGUE stripe The three fields shown are 320 arcseconds square, and are, from left to right, at b=20.3, 6.8, and 2.3. The stellar density in the center field is about 120,000 stars per square degree brighter than $r = 20$, and represents roughly the limit to which the photometric pipelines in their current configuration perform well.

That said the existing code does reasonably well, as shown in Figure 22. At longitudes greater than about 60 degrees, it runs through the plane without trouble. The reductions for stellar densities less than about 5000 stars per field brighter than $r = 20$ (about 130,000 objects per square degree) are reasonably good. This corresponds to Galactic latitudes of about 6 degrees most of the way around the plane. There are several parameters in the existing pipelines which can be tuned to optimize performance and allow working to higher densities, including simply allowing more "children" in the object deblender (which in crowded fields lumps many stars into one "parent" object that is then deblended – a maximum number of children per object limits the processing time required per image), making the psf fitting code work over somewhat smaller radii so it is less confused by nearby stars, and tuning the PSF determining code so the set of stars accepted for PSF determination is better adapted to crowded fields. Some algorithmic development to enhance the speed of the peak-finding code in the deblender would make the pipeline much faster under crowded conditions, and it is likely that a fairly substantial reduction in processing speed could be achieved.

The question of dealing with variable backgrounds is somewhat tricky. The code as developed assumes that the sky is flat, and interpolates in various sky-related quantities on fairly short scales to deal with atmospheric brightness fluctuations. It is not even terribly clear what one wants to do when dealing with real varying backgrounds, since the sky does vary in time and even, in the i and z bands at least, substantially spatially over the field of the camera. The stellar photometry is not affected very much, since local sky values are used, but surface photometry is rendered very difficult. It would appear at first glance that the only way to deal adequately with this problem is an ancillary program of repeated (to average out the sky variations) very-wide-field imaging with a small instrument to calibrate the SEGUE data, but such an effort is somewhat outside the scope of this proposal.

B. Spectroscopy and Spectrophotometry

It is clear that the present spectroscopic algorithms can deal adequately with the SEGUE data, but a number of enhancements to the pipelines need to be made to make the determinations of stellar parameters automatic, and a number of small bookkeeping enhancements need to be made to deal adequately with spectra taken in regions of variable background.

As of now, the pipeline does classification and measures radial velocity, and we have seen that the radial velocity accuracy is adequate with the current set of templates. As the template set is augmented, it is in principle possible to refine the classification to include gravity and composition. It may, however, be better or easier to put in explicit code to perform these measurements, which are currently done externally by code which could be incorporated into the pipeline. It is in any case doubtful that straight maximum-likelihood template fitting will ever rival more focussed techniques for parameter determination, but it might well be that fitting with suitable wavelength-(and color-) dependent weight functions is equivalent to or at least as good as existing techniques. Since the external code exists and is being used, this development is not crucial, but fully automatic routines which process all the data quickly and uniformly are clearly desirable.

As in the case of the photometric reductions, dealing with variable sky backgrounds needs some work, and here some real algorithmic development is probably necessary. Currently the 2D pipeline uses a few (16-20) fibers placed on empty sky to construct a master sky spectrum which is then scaled to allow for variable fiber throughput and airmass-related gradients across the field and subtracted from the individual spectra. This does not work, clearly, if there is significant variable astronomical background over the field. In this case, it will be necessary to use many more sky fibers, in the worst case one per object displaced a common distance from each object so that one can chop. The method for handling the sky is in this case quite different from the standard one. It is not simply a bookkeeping issue because the master sky is a superresolved version of the sky making use of the slightly different sampling on the CCD of each sky spectrum. Dealing with the chopping case is conceptually simple; dealing with many more sky fibers than currently used (but not associated with any object in particular) and associating the skies so determined with objects in a given area on the plate is harder, and how the whole question is to be tackled is not yet completely clear. It is clear that the chopping case can be handled and *is* essentially a bookkeeping issue, and probably the intermediate case of determining a variable master sky can be reduced to one–but it may well be that the two modes of standard- constant-sky and chopping will cover our needs adequately, and the development to deal with chopping is minimal.

It is clear for all of this that the sky spectrum used to process each object must be exported, indeed even for high-latitude objects. It is not currently done, and is a major shortcoming in the present data archival scheme. This will hopefully be addressed by the time of the final data release for SDSS.

The SDSS spectrograph fibers are too small to allow accurate spectrophotometry to be done blindly, because differential refraction attenuates the ends of the spectra by moving the image at the extreme wavelengths off the fiber. This loss is not uniform because of drilling errors, guiding errors, astrometric errors, PSF variations, use of the plate at elevations different from the design one, etc, etc. Various techniques have been tried to calibrate the spectra, none of them very successfully. Recent work has shown, however, that the broadband colors (the system responses of g,r, and i are contained almost completely in the spectroscopic free spectral range) can be used to remove the differential refraction losses quite accurately. The spectra can be on the spectrophotometric scale with an RMS accuracy only about 1.5 times worse than the photometric errors. at least if the spectra are taken at airmasses above about 1.5, which is always the case except for the very lowest declinations. A part of the extension effort, though not specifically a SEGUE project, is to improve the photometric errors to the floor allowed by the site, which appears to be about one percent. So we will be able to achieve spectrophotometric errors of between 1.5 and 3 percent, which will aid the classification effort substantially.

VI. Complementary Survey Efforts

K.A.O.S. is a proposed prime focus wide-field multi-object fiber spectrograph for one of the Gemini Observatory telescopes. K.A.O.S. is conceived as a facility instrument that will enable the next generation of spectroscopic surveys, and has many proposed science drivers including formation of the thick disk and halo of the Milky Way. The proposed field of view is 1.5 degrees in diameter, with 4000-5000 fibers in the field. Although we might be able to constrain the fraction of alpha-process elements in our survey, the higher resolution attained in this survey (R=20,000) is vastly superior. They will also obtain radial velocities to 3 km/s, which could prove useful for very cold, low dispersion components. The scientific program for Galactic structure requires 10^6 stellar spectra to a limiting magnitude of $V = 17$. Our proposed survey will select a fainter set of stars, and thus better sample the outer halo. There is no timeline or cost estimate for this facility instrument.

RAVE (see http://www.aip.de/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. Observations for RAVE began in April 2003 with the 6dF facility on the UK Schmidt Telescope in Australia. 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, including Hipparchos and Tycho stars. intention of obtaining 100,000 moderate resolution spectroscopic observations (R = 4000) of Hipparcos and Tycho stars, using the 6dF facility on the UK Schmidt Telescope. The projected starting date for the main survey is 2006, but the ∼ $6 million in funding this project requires in order to build two advanced wide-field multi-fiber spectrographs for the southern and northern hemisphere is not in place yet. The SDSS extension is not considered to be a direct competitor for this project, since the magnitudes targeted are so different and because RAVE does not currently include a northern component. In addition, RAVE observes only the region around the near-infrared Ca II triplet. Note also that RAVE does not include an imaging component; hence it will not be able to color- select the most interesting targets, as we will be able to with the SDSS extension. With the planned larger dispersion (R $\sim$ 10,000), the future RAVE project will have an advantage in measuring chemical abundances. Some of the members of this proposal are also members of the RAVE project, which should facilitate cooperation between the projects.

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$\sim$ 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.

The Chinese LAMOST project, advertised to start at the end of 2004, will include a 4000 fiber optical spectrograph on a 4-meter telescope with a five degree field of view. The spectrograph has similar resolution to what we obtain with SDSS, on the order of 2.5 Å. We were unable to find specific information on whether this is still projected to actually begin observing in 2004. We have also found no concrete science plan; informal conversations indicate that the primary goal of LAMOST is spectroscopy of a million quasars. This instrument would clearly be useful for stellar science, especially for stars fainter than the SDSS limit, and if LAMOST is to include a stellar research component, we could provide targets and collaboration on mutually interesting science.

The repeat photometric survey pan-STARRs (http://www.ifa.hawaii.edu/pan-starrs/) project is expected to begin operations roughly in 2006. This survey should ultimately provide deeper photometry and variability information, as well as better astrometry (better PSF and multiple epochs) than our proposed SDSS extension. Combining our unique spectroscopic data with pan-STARRS would also be clearly advantageous.

Like pan-STARRs, the recently funded Large Synoptic Survey Telescope (aka the Dark Matter Telescope) will image only. With as wide a field of view as SDSS but with a larger telescope and repeat scanning, this telescope will eventually provide a much deeper photometric survey of the sky and much more multi-epoch data. Several SDSS scientists are members of the LSST team.

NOAO is investigating a wide-field spectroscopic telescope, SWIFT, to make spectroscopic follow-up observations of faint objects in regions of deep imaging using slitlets. This project has a science component on faint stars in the halo of the Galaxy, and if built will both complement and compete with SEGUE.

The UKIRT Infrared Deep Sky Survey (UKIDSS) (http://www.ukidss.org/) will image 7500 square degrees of the Northern sky, extending over both high and low Galactic latitudes, in JHK to K=18.5. UKIDSS complements the SDSS low and high latitude imaging surveys. VISTA in the Southern hemisphere might overlap with some of the SDSS area as well. Both UKIDSS and VISTA include imaging only; hence it will not compete with the spectroscopic component of our proposed SDSS extension. UKIDSS data will become public 18 months after they are obtained (and even faster for people within the ESO community), so they could easily be incorporated into derived reddening maps, etc. We are unable at present to ascertain the areas of sky to be covered by UKIDSS, but will make sure that we overlap as much as possible if the SDSS extension becomes reality.

SEGUE, this proposed extension of the SDSS to study the Galaxy, is truly unique among the ongoing and planned projects. It is the only survey that would combine imaging and subsequent spectroscopy, thus ensuring that photometrically detected structure can be confirmed kinematically and chemically. It uses fully established instruments, reduction pipelines, and experienced personnel. Furthermore, it studies wavelength ranges and apparent magnitudes not covered in ongoing surveys, hence it will supplement surveys that will not come online until after the extension is finished.

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