Contents

Taking Measure of the Milky Way

A Key Project for the Space Interferometry Mission

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Executive Summary

We plan to undertake fundamental measurements of the gravitational potential (mass distribution) and dynamical structure of the Milky Way. Among our goals will be:

1. The determination of two fundamental parameters that play a central role in virtually every problem in Galactic astronomy, namely
   (a) the solar distance to the center of the Milky Way, R_0
   (b) the solar angular velocity around the Galactic center, ω_0
2. The measurement of fundamental dynamical properties of the Milky Way, among them
   (a) the pattern speed of the central bar
   (b) the rotation field and velocity-dispersion tensor in the disk
   (c) the kinematics (mean rotational velocity and velocity dispersion tensor) of the halo as a function of position
3. The definition of the mass distribution of the Galaxy, which is dominated by the presence of dark matter. We intend to measure
   (a) the relative contribution of the disk and halo to the gravitational potential
   (b) the local volume and surface mass density of the disk
   (c) the shape, mass and extent of the dark halo of the Milky Way out to 250 kpc

To the greatest extent possible, we will take advantage of the data already being obtained for sub-solar metallicity K giants in the SIM Astrometric Grid. These data, produced as part of the mission's baseline operations, will be supplemented by SIM observations of other targets, among them: (1) counterparts to the

Astrometric Grid stars at greater distances, (2) a sample of disk Mira and Cepheid variables, (3) a sample of disk open clusters, (4) the brightest few stars in every Galactic globular cluster and satellite dwarf galaxy, and (5) stars in tidal tails of disrupted satellite galaxies and globular clusters.

While the primary goal of our Key Project is focused on the global spatio-dynamical properties of the Milky Way, and this goal dictates strictly the selection of our intended targets, we also intend to address the wealth of information these data will yield on Galactic stellar populations and the insight provided into the formation history of the Milky Way. Therefore, we intend to supplement the astrometric data with ground-based observations of abundances, radial velocities, and other properties, to maximize the benefits of the SIM data for analyses of stellar populations. Several of our proposed SIM experiments lend themselves to early release of mission results.

Our project includes co-I's from six U.S. and three foreign institutions that provide numerous opportunities for student involvement. While the proposers are committed to participate in E/PO activities organized by NASA, in the "Education/Public Outreach Statement of Participation" we propose several additional opportunities for E/PO activities that are specifically related to the topic of this proposal. The PI is involved in the creation of an observatory museum in Virginia specifically focused on the science of astrometry. Other co-I's are working with the Hayden Planetarium to develop a new museum model of the Milky Way. Both museum efforts have the potential to bring new SIM results to a wide audience rapidly.

Scientific Investigation and Technical Description

1. Introduction

We intend to use SIM to make legacy-definitive measurements of fundamental structural and dynamical parameters of the Milky Way. The important niche in dynamical parameter space afforded by SIM can be exploited to resolve, with unprecedented precision, a number of classical problems of Galactic astronomy, such as our distance from (R_0) and the local motion about ($\Theta_{\rm LSR}$) the Galactic Center, the measurement of the Oort limit, and determining the mass of the Galaxy via the motions of test particles in the halo. In addition, we have developed new tests of the Galactic mass distribution specifically designed for data with the special properties of SIM products. Our proposed suite of experiments will utilize the SIM Astrometric Grid as well as complementary observations of star clusters and other strategically-selected, distant "test particles" for a definitive characterization of the major components (bulge, disk, halo, satellite system) of the Milky Way. Although we have divided the Key Project into several distinct projects, we stress that these projects are closely related and cannot be solved in isolation. For example, an accurate measurement of the Oort limit strongly constrains models of the spatial distribution of mass in the disk and the total mass of the inner halo, while an accurate determination of R_0 and $\Theta_{\rm LSR}$ is needed to interpret the phase-space distribution of halo tracers and the kinematics of tidal tails. While the proposed SIM observations are meant specifically to address the definition of the fundamental structure and dynamics of the Galaxy, they also permit fecund inroads into numerous ancillary problems regarding stellar populations and the evolution of the Milky Way.

We outline in §2 our proposed resolution to longstanding questions regarding the fundamental **distance** and **velocity** scale of the Galaxy with reference to solar values. §3 addresses the establishment of the fundamental Galactic **mass** scale referenced to the mass density of the solar neighborhood. §4 details the characterization of the disk mass potential, while §5 discusses our exploration of the halo and outer limits of the Galaxy, culminating in a measurement of the total mass of the Milky Way within several hundred kpc. We conclude by summarizing our pre-launch activities (§7), our Key Project capabilities in the event of reduced SIM performance (§8), the relation of our project to capabilities of other missions (§9), potential early release results (§10), and our access to relevant data and telescopes (§11).

2. Fundamental Galactic Parameters

Despite decades of efforts by astronomers, the size and rotation rate of our Galaxy remain poorly known. Water masers yield absolute solar Galactocentric distances that range from $R_0 = 6.5 \pm 1.5$ kpc (Reid et al. 1988b) to 8.1 ± 1.1 kpc (Gwinn et al. 1992), while techniques using various stellar populations yield distances that range from 7.8 ± 0.4 to 8.4 ± 0.4 kpc (Reid 1993; Binney & Merrifield 1998). HIPPARCOS proper motions (Feast & Whitelock 1997) suggest that the velocity of the Local Standard of Rest (defined as the velocity of a closed orbit at R_0) is $\Theta_{\rm LSR} = (218 \pm 8)(R_0/8)\,{\rm km\,s^{-1}}$, consistent with measurements of the proper motion (Reid et al. 1999) of Sgr A* that yield $\Theta_{\rm LSR} = (219 \pm 20)(R_0/8)\,{\rm km\,s^{-1}}$. On the other hand, Olling & Merrifield (1998) suggest $\Theta_{\rm LSR}$ is as low as $184 \pm 8\,{\rm km\,s^{-1}}$. With roughly 400 hours of SIM observing we can accurately determine R_0 and make an independent measurement of the solar angular velocity, ω_0, from which we may derive $\Theta_{\rm LSR}$ (in §4 we discuss how to derive the *circular* velocity at R_0, which differs from $\Theta_{\rm LSR}$ in non-axisymmetric disks and requires additional SIM measurements). These fundamental parameters are not only essential for determining the mass of the Milky Way (a 3% error in both R_0 and $\Theta_{\rm LSR}$ leads to a 5% error in the mass scale) but are important for virtually every problem in Galactic astronomy.

We plan to determine the distances to stars in low extinction windows close to Sgr A*, the kinematical center of the Galaxy. Blum et al. (1994, 1995) have identified 120 M giants at projected distances of 160–300 pc from the Galactic center in three low extinction windows ($A_I = 1.3 - 3.5$). Since the inner stellar density profile falls as $r^{-2.2}$, over half of these giants are within 400 pc of the Galactic center. The M giants should have $I \sim 10 - 13$ in these windows and are our primary targets for determining R_0. With 6.25 μas SIM astrometry, we can obtain uncertainties in individual bulge star distances of ∼500 pc. Thus, if we obtain the distance to 30 stars per window, we can determine the centroid of the stellar distribution in each window to an accuracy of 90 pc. By comparing the distances derived from these three windows, we should be able to measure R_0 to better than 1%. Since the windows are on either side of $l = 0^\circ$ and probe to past R_0, we can also locate the *kinematical* center of the Galaxy via the distance at which the mean proper motion along a line of sight switches sign. Since almost all of the absorption towards the windows at $b > 0.5^\circ$ is due to foreground dust in the nearby Galactic disk, we expect minimal variation in extinction with position in the window. However, we will be able to verify this assumption by looking at correlations between reddening and distance in our sample.

We will also measure the distances for 100 bright Baade's window M giants drawn from the Blanco (1986) sample, which is at a projected distance of 550 pc from the Galactic center and supplemented with stars from Frogel & Whitford (1987). The low absorption should enable us to be confident that we sample to the other side of the Galactic center. We should be able to determine the centroid of the stars in Baade's window to within 60 pc, which yields another determination of R_0 better than 1%.

We are currently obtaining third epoch HST images of Baade's window that will enable us to obtain accurate relative proper motions for ∼10,000 Galactic bulge stars. Calibration to the absolute frame with SIM proper motions for a 100 star subsample will yield absolute proper motions for the entire sample with individual accuracies $\sim$ 100 μas yr^{-1} (4 km s^{-1} at R_0). We can then determine the motion of the LSR relative to Baade's window to within 1% and make an independent measurement of ω_0 (and $\Theta_{\rm LSR}$).

This sample will also allow us to constrain the properties (shape, mass and pattern speed) and history of the Galactic bar. Apart from the intrinsic interest, knowing the bar properties is important for interpreting disk dynamics (see §4). The history of the Galactic bar has wider implications since the origin and evolution of galactic bars are not understood. After complementing our astrometric measurements with ∼10 km s^{-1} radial velocities and 0.2 dex abundances, we will be able to compute orbits for stars and measure correlations between kinematics and metallicity. Eggen et al. (1962) were able to make powerful inferences about galaxy formation from observations of only 221 well-measured stars in the local neighborhood; we will have a much larger sample with better kinematics with which to study the Galactic bulge. For example, if the bar formed out of a pre-existing metal rich disk population, then only metal rich stars will be on bar-supporting orbits. On the other hand, if the Galaxy oscillates between states with and without a bar, then both metal rich and metal poor stars should be on similar orbits. Analysis of astrometric data for a small sample of only 62 K giants in Baade's window (Zhao et al. 1994) suggests that metal rich stars occupy prograde orbits with boxy shapes that align with and support the bar, while the metal poor stars occupy retrograde, bar-opposing orbits. Our more than 150 times larger Baade's window sample will settle this question definitively.

3. The Oort Limit

Using K giant stars, the Key Project will measure values for the local disk mass volume and column densities, with a precision and accuracy that is consistent with the measurements proposed here for other dynamical Galactic parameters. A key step will be to determine the dependence of K giant number density upon distance above the plane. SIM will uniquely make possible the measurement of individual K giant distances to an accuracy of better than 2% throughout the region (up to 2 kpc) in which the Galactic potential is dominated by the disk mass. Since the work of Oort (1932), efforts to determine the local mass density have been severely limited by our lack of knowledge of the distances to a homogeneous and well-mixed tracer population. Disk K giants are bright (M_V peaks sharply at about 0.8 mag), well understood, and well-mixed. K giants have been used in several previous attempts to measure the local mass density, beginning with the study of Bahcall (1984), who used an approximate luminosity function to determine photometric parallaxes, and culminating in the work of Holmberg & Flynn (2000) who used HIPPARCOS parallaxes (see also Creze et al. 1998). With these studies, it is now generally believed that we know the local mass density and column density to an accuracy variously estimated in the range 30–50%.

We propose to measure precise parallaxes and proper motions for 500 K giants within 20° of the Galactic poles. Using the same techniques (and some of the same data) that the PI has developed for selecting K giants for the SIM Astrometric Grid (Majewski et al. 2000c), we will obtain new ground-based observations for ∼4000 disk K giants with $V \lesssim 13$. These stars will be studied carefully with precise ground-based photometry, spectroscopic abundances, and radial velocities. A homogeneous subset will be selected for determining the velocity distribution and a representative subset of this ground-based sample will be used for the SIM parallax sample that will calibrate precisely the density distribution as a function of height above the plane to ∼2 kpc.

We expect to achieve an overall accuracy of 10% in the local volume density and slightly better accuracy in the total column density. Using precise distances and *three dimensional* velocities for the full sample of stars, we can include, for the first time, important corrections to the vertical equations of motion. These corrections arise because the potential cannot be separated *exactly* into vertical and planar dependences; this leads to a correction term proportional to $\langle v_z v_R \rangle$ (of order a few $\mathrm{km\,s^{-1}}$). Thus, a key improvement over classical attempts at the Oort limit will be to account for off-diagonal elements in the velocity correlation tensor. Moreover, we will not need to make the conventional assumption of isothermality, but instead can measure the velocity dispersion in different, well-defined distance bins. SIM proper motions will also be used to eliminate tangential contributions to the velocity dispersion from off-pole stars. To exploit the full power of the data set, we plan to make maximum likelihood fits to expectations from different assumed Galactic potentials, including three dimensional velocities and positions of the entire K giant sample. Systematic biases, including Malmquist, Eddington and Lutz-Kelker, will be evaluated using Monte Carlo simulations.

4. Probing the Potential with Disk Stars

As a cold population, whose kinematical response to disturbances is well understood (e.g., Binney & Tremaine 1987), disk stars provide excellent tracers of the underlying potential. Past measurements of disk kinematics have been plagued by the inability to measure direct distances to stars beyond 1 kpc, systematic and random errors in proper motions, and our uncertain knowledge of the solar motion and position with respect to the Galactic center (see §2). Inside the Solar Circle, the rotation curve has been traced with some accuracy using H I tangent-point data. However, this technique can neither be used outside R_0 (for $|l| > 90°$) nor applied to regions on the opposite side of the Galaxy with $|l| < 90°$ (e.g., to check for biases due to the presence of global non-axisymmetries). As a result, our knowledge of the Galactic rotation curve – particularly outside the Solar Circle (see Olling & Merrifield 1998, and references therein) – and our constraints on the amplitude and phase of non-axisymmetries in the Galaxy (e.g., Blitz & Spergel 1991a,b; Kuijken & Tremaine 1994) – are much worse than for many external galaxies.

With SIM we have the first opportunity to measure distances to and proper motions of a sample of stars spread across the entire Galactic disk *directly.* Combined with the SIM assessment of our position and velocity in the Galaxy (see §2) we will be able to measure: (1) the rotation curve of the Milky Way; (2) the amplitude and phase of large scale asymmetries such as open spiral arms or the Galactic warp; and (3) the kinematic properties of different age populations. The first of these will tell us the underlying mass distribution in the inner Galaxy and complements our study of the mass distribution from halo kinematics (see §5); the second will provide detailed probes of disk dynamics and the interaction of the disk with other Galactic components; and the last will allow us to study disk formation and evolution.

4.1. Assessment of SIM Capabilities

Motions in the Disk Plane

We have investigated SIM's capabilities to interpret disk motions by "observing" particle realizations of disks using a realistic tracer sample size and appropriate errors and then attempting to recover the disk potential using a minimum χ^2 approach. Our base model is an axisymmetric, thin disk population moving in a rigid Hernquist halo potential. This model is allowed to respond to rotating potentials, either in the form of a 2-armed spiral with radial wavelength $\lambda_R = 4.6$ kpc (which induces oscillation of order 10–20 $\mathrm{km\,s^{-1}}$ about mean motion) or in the form of a Galactic bar (corresponding to the "default" model of Dehnen 2000). To mimic SIM observations of the Mira and Cepheid variable star samples described in §4.2, the Galactic longitude l, parallax π, proper motion μ and line-of-sight velocity v of 400 particles in each disk distribution are observed from a viewpoint at a distance and velocity similar to the Sun. Gaussian errors in each quantity (with dispersions chosen to match the expected error distributions of the tracers described in §4.2) are added to find $(\pi_{\rm obs}, \mu_{\rm obs}, v_{\rm obs})$. The minimum χ^2 routine seeks the best fit to the observed mean motion at each position in the disk by varying the circular velocity $v_{\rm circ}(R)$ and radial velocity dispersion $\sigma_R(R)$ of the disk and the amplitude, phase and radial wavelength λ_R of the overlaid spiral.

Figure 1 illustrates example results of these experiments from an ongoing detailed numerical study (Johnston et al. 2000). In the analysis we calculated an analytical correction to remove systematic biases as

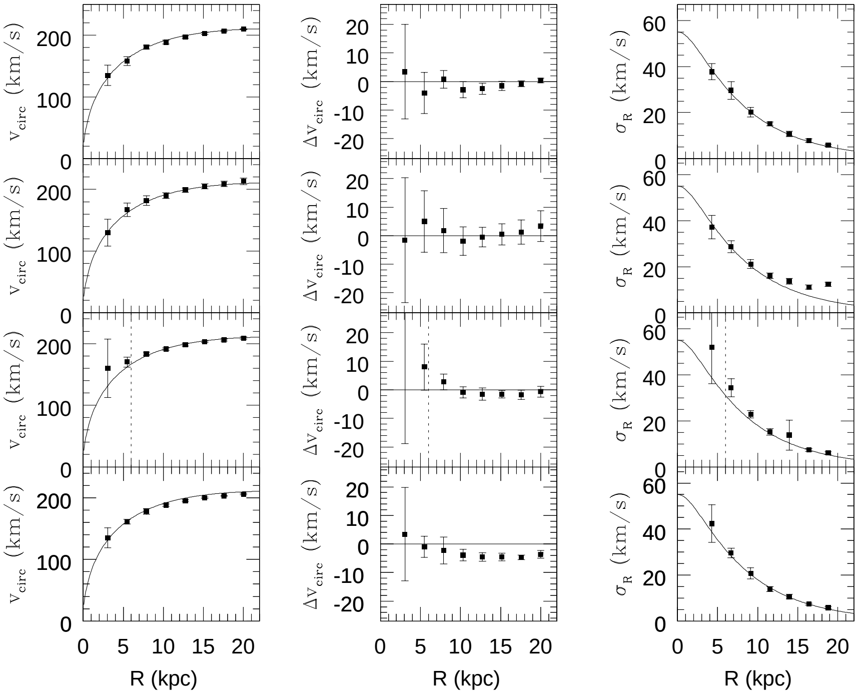

Fig. 1.— Recovered circular velocity (*left hand panels*), the uncertainties in $v_{\rm circ}$ (*middle panels*) and velocity dispersion profile (*right hand panels*) for our disk models. The solid curves represent the underlying model and the dots and error-bars are the average and dispersion from 10 different samples (each of 400 particles). The panels show axisymmetric disks (*top panels*), spiral arm forced disks (*second row of panels*) and bar forced disks (*third row of panels*), assuming we know our distance to and motion around the Galactic center perfectly. The location of the OLR is indicated by the dotted line (see text). The bottom panels repeat the axisymmetric disk calculation, but assuming we have underestimated both our distance and motion by 1%.

large as $20\,\mathrm{km\,s^{-1}}$ introduced by the interaction of observational distance errors with our sample selection function. The success of this correction is amply demonstrated by the small random and systematic errors for the axisymmetric disk (top panels). The bottom panels show that viewing the same disk, but assuming 1% errors in R_0 and ω_0 leads to errors of a few $\mathrm{km\,s^{-1}}$ in v_{circ}. Additional systematic biases are apparent for the different disk distributions: (i) *Spiral arm forcing (second row of panels)*: Although we do typically recover the wavelength (to within 10%) and phase (to within 20°) of the spiral arms, measurement errors cause us to underestimate their amplitude and, in turn, overestimate σ_R and v_{circ} in the outer disk. We expect this to improve once we also account for the combination of distance errors with the velocity gradient along each line of sight. (ii) *Bar forcing (third row of panels)*: The Galactic bar is expected to contribute less than 1% to accelerations beyond the Solar Circle yet can still have a significant effect on stars trapped in orbits resonant with it (see Weinberg 1994; Dehnen 2000). The location of the bar Outer Lindblad Resonance (OLR) in our model is shown as vertical dotted lines in the relevant panels. Our results suggest that, for our selected tracers, resonant orbits do cause both the dispersion and v_{circ} to be overestimated around the OLR, but have little effect on the outer disk. Obviously, the physical size and population of resonances depend on the pattern speed, shape and strength of the bar (e.g., Weinberg 1994); their effect will be taken into account in our final analysis after determination of the properties of the bar from §2.

We conclude that our proposed SIM observations should recover the disk potential, including the amplitude, phase and shape of large-scale non-axisymmetries, to within 2–3% out to $2R_0$, assuming that R_0 and ω_0 are determined to the accuracies expected from §2.

Vertical Kinematics

SIM stellar proper motions perpendicular to the plane will shed light on the following issues:

— *Radial dependence of the vertical velocity dispersion:* Observations of edge-on spiral galaxies show that the vertical scale height of the disk is nearly independent of radius; this implies that the vertical dispersion in a disk with an exponential surface-density distribution should also vary exponentially, with a scale length twice that of the surface density (e.g., Binney & Merrifield 1998, p. 727–8). Our observations will determine the radial dependence of the vertical dispersion over a significant fraction of the Galactic disk. Coupled with our Oort limit analysis, this will enable us to develop a consistent model of the radial variation of surface density and scale height.

— *The Galactic warp:* We will include distant stars in the $l = \pm 90°, 180°$ directions to probe the kinematics of the Galactic warp. In particular, we can (i) make a crude estimate of the surface density in the outer disk, analogous to the Oort limit; (ii) determine the pattern speed, Ω_p, of the warp: In a simple model where the vertical displacement of the disk is $z(l) = \epsilon\cos(l - l_0)$ then the vertical velocity is $v_z(l) = -\epsilon(\Omega - \Omega_p)\sin(l - l_0)$. Thus $\Omega - \Omega_p$ can be measured from the proper motions and distances; assuming we know Ω - from the horizontal motions of the same stars - we can find Ω_p.

— *Precession of the Galaxy:* Hierarchical formation models predict that the inner disk precesses, effectively as a rigid body, due to torques from distant substructure and infall of material with misaligned angular momentum (e.g., Ostriker & Binney 1989). The characteristic precession frequency is expected to be of order the Hubble constant H_0 (i.e. the inverse of the age of the Galaxy), which corresponds to a proper motion $20h\ \mu\mathrm{as\ yr^{-1}}$, where $h = H_0/100\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$. This proper motion is readily detectable by SIM, as a position-dependent mean proper motion perpendicular to the Galactic plane, and will provide a unique datum for comparison to models of cosmological structure formation.

4.2. Proposed Targets, Target Selection and Target Time Calculation

Ideal tracers of disk rotation should be luminous, easily recognizable, with known distance, and sufficiently old that the kinematics are well mixed. We propose making SIM measurements of:

Mira Variables: Miras are pulsating asymptotic giant branch stars with periods between 150 and 1000 days. The period is mass dependent, with $P = 220$ to 300^d stars descended from 1-2$M_\odot$ main-sequence progenitors, and therefore having ages of a few Gyr (Feast 1963). Miras follow a well-defined period-luminosity relation in the (M_K, log(P)) plane, (Reid et al. 1988a), with $\langle M_I \rangle = -4.5$ and amplitudes $\Delta I = \pm 0.7$ mag. As such, they represent a thin disk population that can easily be traced by SIM across the Galactic disk. We propose observations of 300 Miras.

Cepheid variables: With $-2 < M_V < -6$, Cepheids have been used to trace Galactic rotation since Joy's (1939) pioneering analysis. The most recent study (Metzger et al. 1998) includes variables up to 10 kpc from the Sun. As with Miras, pulsational variability provides both ready identification and a means of distance estimation. Descended from more massive progenitors than short-period Miras, Cepheids have typical ages of 50–300 Myr, and therefore may retain memories of the 10–20 $\mathrm{km\,s^{-1}}$ non-circular motions of the spiral arms. We will observe 300 Cepheids, providing both verification of the overall rotation curve deduced from the Miras, and allowing study of the extent of these non-axisymmetric features.

Open clusters: Open clusters are internally homogeneous, coeval systems that readily allow age determination. We will use observations of the three brightest stars in selected clusters to measure both spiral arm strength as a function of age (probing our dynamical models) and disk velocity dispersion as a function of age (as a probe of disk formation models). By combining the results with our findings from the Mira and Cepheid samples we can assess the dynamical evolution of the disk. Most old open clusters follow orbits inclined to the Plane, and we will take this bias into account in our analysis. This data set will also provide an invaluable resource for stellar population and cluster evolution studies.

Target selection: Both Mira and Cepheid variables will be identified from multiple-epoch CCD imaging surveys of low extinction windows within 2° of the Galactic Plane (i.e. within two thin disk scale heights at 20 kpc) up to 20 kpc from the Sun. Following Caldwell et al. (1991), we expect to detect a surface density of ∼4 Cepheids and ∼20 Miras per square degree, although only 10–20% of the latter variables are expected to have periods in the range 200 to 300 days. We will use the Schlegel et al. (1998) maps to select regions with extinctions of $A_I < 2$ mag (cf. Caldwell et al. 1991). Our targets will therefore have $I < 15$. We propose to integrate for the minimum recommended time on a sample of 600 variables, for a total cost of 360 SIM hours. For variables within 5 kpc of the Sun, SIM parallaxes will provide distances to better than 10%; beyond that, distances will be estimated to comparable accuracy from SIM-calibrated period-luminosity relations. The SIM proper motions for all stars will be such that the velocity precision will be set by distance errors alone.

Mermilliod's (1998) on-line open cluster database (WEBDA) lists measurements for over 200 open clusters (about half with some kind of membership study, 38 by proper motions) having photometric ages >0.1 Gyr. We plan to obtain SIM observations of 3 stars in each of these clusters whose distance can be determined to better than 3% using not more than one hour of SIM time. Extrapolating from a sub-sample of 72 of these clusters that we have looked at in detail, we expect approximately half of the 200 to satisfy the above criterion. These clusters are at distances 0.05–4.0 kpc (1.2 kpc median) and have ages in the range 0.1–7.0 Gyr (1.2 Gyr median). All SIM targets will be verified as radial velocity cluster members before scheduling observations. We anticipate observing ∼100 clusters for a total cost of about 250 SIM hours.

5. The Mass of the Galaxy to Large Radii

The nature of the dark matter that comprises most of the Galactic mass is not understood. Different cosmological models make varied predictions for the radial distribution of mass in galaxies: Cold Dark Matter (CDM) models predict that the dark matter is highly centrally concentrated, and while the CDM (+ Λ) model has been remarkably successful on scales larger than 1 Mpc (Bahcall et al. 1999), there appears to be a conflict on galactic scales. Alternative models, for example warm (Hogan & Dalcanton 2000) or strongly self-interacting (Spergel & Steinhardt 2000) dark matter models predict a less concentrated halo.

Ours is the only galaxy for which a detailed, three-dimensional profile of the mass distribution may be determined. With SIM, this is possible to radii of at least 100 kpc. We intend to apply two tests to measure the Galactic potential at large radii. The first (§5.1) traces the halo with virialized test particles, a classical experiment that is only possible to the outer limits of the Galaxy in the era of SIM. A second technique exploiting the dynamical coherence of stars in tidal tails (§5.2) has the potential for much greater precision with a smaller number of stars. These two approaches are complementary. There is increasing evidence (see below) that the outer halo (at distances greater than 20 kpc) contains numerous families of tidal tail stars suitable for the latter experiment. If true, however, this raises the specter that the hoped-for virialized tracers for the classical test may be insufficiently mixed to provide a secure potential measure at the largest distances. The reverse situation occurs in the inner halo, where dynamical timescales are short and debris streams quickly become spatially incoherent; finding suitable tidal tails in this region may prove a challenge. Hence, we feel it is prudent at this point to insure a legacy SIM result by contemplating *both* the classical *and* the potentially more powerful tidal tail, halo experiments.

5.1. Probing the Dark Halo with Dynamically Old Test Particles

The relation between halo star kinematics and the Galactic potential can be described by the Jeans equation, which for a steady state reads (Binney & Tremaine 1987)

$$\frac{\partial \Phi}{\partial x_j} = -\overline{v}_i \frac{\partial \overline{v}_j}{\partial x_i} - \frac{1}{\nu} \frac{\partial (\nu \sigma_{ij}^2)}{\partial x_i}; \tag{1}$$

here $\nu(\mathbf{x})$ is the spatial density of a tracer population, $\overline{\mathbf{v}}(\mathbf{x})$ is the mean velocity, and $\sigma_{ij}^2(\mathbf{x})$ is the velocity-dispersion tensor.

Studies of Galactic dynamics using halo stars offer the possibility of determining (1) the overall mass distribution in the Galaxy, (2) the shape and extent of the dark halo, and (3) the relative contribution of the halo and disk to the gravitational potential. The kinematics of the distant halo and the implications for the Galactic potential have been analyzed by many authors (see Kochanek 1996, and references therein) Most recent analyses agree that the data are roughly consistent with an isothermal potential $\Phi(r) = v_c^2 \ln r$, with circular speed v_c in the range 180–220 $\mathrm{km\,s^{-1}}$, extending to at least 200 kpc (e.g., Wilkinson & Evans 1999, hereafter WE99). However, existing studies have been hamstrung by three limitations:

1. Ground-based proper-motion studies are not accurate enough to measure transverse velocities of stars beyond the solar neighborhood, so that our knowledge of $\overline{\mathbf{v}}$ and σ_{ij}^2 is restricted to line of sight components. The most recent analysis of halo kinematics (WE99) uses proper motions for six globular clusters and satellite galaxies and finds that proper motions dramatically increase the reliability of mass estimates; but ground-based proper motions have disturbingly large error bars (and since the P.I. on this proposal is responsible for several of these proper motions we can confidently state that even these large error bars generally exclude likely remaining systematic errors). For the first time, SIM offers the possibility of measuring accurate proper motions and hence determining *all* components of the mean velocity vector and velocity-dispersion tensor throughout the Galaxy.
2. The sample of distant halo tracers is too small. For example, WE99 use only 27 test particles at Galactocentric distances $R_{\mathrm{GC}} > 20$ kpc (globular clusters, dwarf spheroidal galaxies, Magellanic Clouds). This situation is improving rapidly as a result of new surveys. The APM halo carbon star survey has found 75 new carbon stars at distances between 10 and 100 kpc (Ibata et al. 2000a), and the first 1% of the Sloan Digital Sky Survey has discovered ∼150 new RR Lyrae stars at > 30 kpc, an order of magnitude increase over all previous surveys combined (Ivezić et al. 2000).

3. Theoretical studies of hierarchical galaxy formation suggest that both the dark halo and its stellar counterpart have a complex phase-space structure. Not only is the halo likely to be strongly triaxial (Warren et al. 1992; Hartwick 1999), so that simple spherical models are a serious oversimplification, but phase mixing in the halo is probably incomplete, so that much of the halo material is in a web of tidal tails (Tremaine 1993; Johnston 1998). We describe below how selected tidal tails can be used as powerful probes of the Galactic potential, but their effect on the Jeans equations is an unavoidable enhancement of the statistical noise, which can only be beaten down with a large sample of tracers.

The kinematic structure of the nearby halo (distance $\lesssim$7 kpc) will be well sampled by the SIM Astrometric Grid, which will provide high-accuracy proper motions and parallaxes for ~3000 metal poor K giants uniformly distributed over the celestial sphere. Majewski et al. have been funded by two SIM Preparatory Science Program grants to conduct the Grid Giant Star Survey (GGSS) for Astrometric Grid stars in 1300 evenly spaced fields around the sky. The typical metal poor K giant has $M_V = -1$, so the typical Grid star will be at a distance of 4 kpc if the Grid is limited to V=12, but the mean distance of the Grid will be increased if NASA raises the acceptable magnitude limit for these stars (a question yet undetermined).

At distances larger than those sampled by the Astrometric Grid, our survey will be designed around a set of "selected areas" in strategic directions. This approach helps to disentangle velocity-space structure from spatial gradients in the kinematics, simplifies ground-based surveys to detect suitable tracers, and minimizes SIM overhead by placing as many targets as possible in a few astrometric tiles. Our mission time budget is based on ten selected areas: one plausible set would include two at the North and South Galactic Pole ($b = \pm 90°$), four at $l = 90°, 270°$, $b = \pm 45°$, two near the anticenter ($l = 180°$, $b = \pm 15°$, and two above and below the Galactic center ($l = 0$, $b = \pm 45°$). These areas will be coordinated with already existing data from the PI's GGSS, which actually probes some 5 mags fainter than the present V=12 limit of the Astrometric Grid. Available GGSS targets include not only metal-poor red giants, but horizontal branch stars. In each selected area we would choose three samples of 30 tracer stars specified by apparent magnitude and thus concentrated at a given distance (e.g., 10 kpc, 30 kpc, 100 kpc). The measurements near the anticenter may also detect a flared outer disk.

For Poisson statistics, the expected fractional accuracy of the velocity components would be $\sim N^{-1/2}$, although the accuracy in the force field will be lower for several reasons: (i) the force field depends on the derivative of the velocity and velocity dispersion in equation (1); (ii) there will be some uncertainty in the tracer density ν determined from star counts; (iii) the halo stars are not fully phase-mixed, especially at large distances; (iv) we will not have 100% accurate distances to the halo giant stars (assuming that SIM pins down the globular cluster distance scale, distance errors arising from uncertainties in field star abundances and ages will probably remain at about 5%).

We plan to observe 900 halo field giants plus all globular clusters and dwarf spheroidal galaxies (see §5.2 below). The sample size is driven mainly by our own ranking of the importance of this project relative to other components of the Key Project: while a denser sampling of phase space will always yield more accurate results, we believe that the proposed sample is sufficient to provide a legacy result from SIM, since the proposed target list not only represents a factor of seven increase over existing halo samples, but we will have 3-D motions for each object instead of only radial velocities.

5.2. Proper Motions of Milky Way Globular Clusters and Dwarf Satellites

Globular clusters, which span the dimensions of the Milky Way and readily lend themselves to abundance and age assessments, have long served as a cornerstone stellar population for understanding galaxy evolution. Yet only a small fraction ($\lesssim$20%) of Galactic globular clusters and dwarf satellite galaxies have had *any* attempt at a measured proper motion, and reliable data exist only for those closest to the Sun. Even in the rare cases when appropriate data for proper motion measurements exist, analyses are hampered by critical systematic errors, notably the tie-in to an inertial reference frame: galaxies yield unreliable centroids and QSOs have too low of a sky density. SIM will immediately resolve these problems.

We will reserve ∼300 of our measurements to determine proper motions for most or all of the Galactic globular clusters (∼150 clusters at 2–3 stars each) and dwarf spheroidal galaxies within 250 kpc. In addition to serving as valuable test particles for determining the halo potential (e.g., Frenk & White 1980; Thomas 1989), these cluster data will also play an essential role in understanding clusters and dwarf galaxies as stellar systems. The dynamical evolution of small stellar systems is largely determined by external influences such as disk and bulge shocks (e.g., Gnedin et al. 1999), so determining cluster and satellite orbits by measuring their proper motions will dramatically improve our understanding of their evolution and address the long-standing issue of whether the present population of these systems is the surviving remnant of a much larger initial population. The formation of globular clusters remains a mystery, and understanding cluster orbits will strongly constrain formation models. Other SIM projects may concentrate on studying the internal dynamics of a few clusters. However, only by obtaining orbital data for the entire sample, as we propose, can one assess the impact of the full range of cluster/satellite dynamical histories on the evolution of the Galactic ensemble.

5.3. Studying the Dark Halo with Dynamically Young Tidal Streams

We will use SIM to measure the motions of stars in tidal streams from the Milky Way's satellite population. These measurements will enable us to determine accurately both the mass of the satellites (which will solve the outstanding problem of the mass-to-light ratio of dwarf spheroidal galaxies) and the mass distribution of the Milky Way to $R_{\rm GC}$ ∼250 kpc. The strengths of this method include: (i) there is solid evidence that such debris exists and can in many instances be associated with a particular Galactic satellite; (ii) the dynamical properties of such debris are well-understood and make them uniquely sensitive as potential probes; and (iii) the required accuracies are easily within SIM's performance specifications but impossible with any previous ground-based or space-based study. This novel approach complements the more conventional Jeans analysis outlined in the §5.1.

Outline of the Method and Theoretical Expectations.

Both simulations and analytical arguments (Tremaine 1993; Johnston et al. 1996; Johnston 1998) demonstrate that stars tidally torn from Galactic satellites remain concentrated in thin streamers trailing/leading the satellite along its orbit. Over the lifetime of the Galaxy, tidal streamers in the inner halo become spatially incoherent due to the short mixing timescales (Helmi & White 1999), but in the outer halo streamers are likely to remain spatially distinct. This suggests that outer halo streams can be identifiable as phase-space clumps, associated with their parent satellites by the similarity of their orbital (and chemical) properties. If we could observe the full phase-space coordinates of such a population of stars, we can strongly constrain the Galactic potential: integrating the orbits of both stars and satellite backwards, the "best" potential recombines the largest number of stars with the parent satellite. We refer to this as the JZSH algorithm (Johnston et al. 1999). If we find a coherent stream but not the associated satellite, the same idea applies but with the parent satellite's position and velocity as additional free parameters.

We have tested the JZSH algorithm by "observing" debris stars at the end of an N-body simulation of Galactic satellite destruction (Johnston et al. 1999). We can recover parameters such as the circular velocity and ellipticity of the Galactic potential to within a few percent given perfect knowledge of the mass and phase-space position of the parent satellite and using proper motion (but not parallax) measurements of just 100 stars within an associated tidal stream. In real life, we lack that perfect knowledge, but thorough simulations (see Johnston & Spergel 2000) show the limitations and requirements of this technique:

— *Satellite distance:* Errors in the distance ultimately affect only the scaling of the potential, not the details of its 3-D distribution.

— *Proper motion uncertainties:* We need to know the proper motions with sufficient accuracy to distinguish between debris and satellite orbits. Required values range from $\sigma_v \sim 30\,\mathrm{km\,s^{-1}}$ for Sgr and the LMC/SMC ($\sigma_\mu \approx 120$ μas yr^{-1}), to $\sigma_v \sim 4\,\mathrm{km\,s^{-1}}$ ($\sigma_\mu \approx 20$ μas yr^{-1}) for small and/or distant satellites such as Carina, Leo I and Leo II.

— *Tidal tail length:* Sampling the Galactic potential over an entire orbit demands measurements of stars that left the parent satellite at least one orbit ago ($N_{\rm orb} > 1$). However, we gain little accuracy in sampling $N_{\rm orb} > 3$ orbits. This means we can restrict stellar debris samples to be within a mere $\sim 30^\circ$ of all satellites except Sgr and the LMC/SMC, which require samples encircling the Galaxy.

— *Smoothness of the Galactic potential:* Current cosmological simulations find ~10% of a typical halo is in the form of lumps larger than $\sim 10^8 M_\odot$ (Klypin et al. 1999; Moore et al. 1999) and these lumps would cause dispersal of tidal tails by scattering the orbits of debris stars. However, a simple impulse approximation calculation suggests that, if our halo has the same degree of lumpiness, the scattering over the last $N_{\rm orb} = 3$ will be much less than the expected range in the energies of debris stars associated with each of the Galactic satellites. Hence this effect is not important.

— *Dynamical friction:* is unimportant if the change in the energy of the satellite's orbit in $N_{\rm orb}$ orbits is less than the range in the energies of debris particles. For $N_{\rm orb} = 3$, this condition is met for all satellites except the LMC/SMC and Sgr.

— *Evolution of the Galactic potential:* Orbits of stars in evolving potentials also evolve (e.g., Zhao et al. 1999). However, the cold state of the $> 7 \times 10^9$ year-old disk population suggests that the Galaxy has not evolved significantly over 3 halo orbits (3–6 Gyr). Hence, tidal tails should be accurate potential probes.

The analytical estimates on which the last three assertions are based will be tested quantitatively in future work by examining the evolution of tidal tails in cosmological N-body simulations.

Evidence for Tidal Tail Populations.

The most famous (if controversial) example of a tidal tail is the 110°-long, H I Magellanic Stream. Efforts have already been made to use the Stream to probe the Galactic potential (Lin et al. 1995), although it remains uncertain whether it is appropriate to assume that gas in the Stream is unaffected by ram pressure forces (Moore & Davis 1994). We have recently found and are actively studying moving groups of giant stars spread over $> 40^\circ$ in fields around the Large and Small Magellanic Clouds (Majewski et al. 2000b). These potential LMC/SMC-escapees are promising candidates for measuring the potential at large $R_{\rm GC}$.

The Sagittarius (Sgr) dwarf galaxy currently provides the best example of a satellite with clearly associated stellar tidal tail populations. With the recent announcement by the Sloan group (Ibata et al. 2000b) of the discovery of Sgr-associated RR Lyraes at the celestial equator, Sgr is now established to have a continuous trail of material stretching over $\sim 100^\circ$ along its orbit (e.g., Ibata et al. 1994, 1997; Mateo et al. 1998; Majewski et al. 1999; Cseresnjes et al. 2000; Dinescu et al. 2000). Recently, Ibata et al. (2000a) have found a set of ~40 distant high latitude carbon stars completely encircling the Galaxy that appear to be aligned with Sgr's orbit. Radial velocities to $\sim 5\,\mathrm{km\,s^{-1}}$ accuracy and JHK photometric distances to ~10% accuracy demonstrate that the carbon stars aligned along the orbit were once part of Sgr since they occupy a restricted phase-space location characteristic of its tidal stream. With this population alone Ibata et al. (2000a) are able to place strong limits on the flattening of the Milky Way's dark matter halo.

Evidence for "extra-tidal" populations of stars have also been identified photometrically around several Galactic dwarf spheroidals (Irwin & Hatzidimitriou 1995; Kuhn et al. 1996; Majewski et al. 2000a). We have undertaken an extensive program to search for these populations around the Galactic dwarf satellites, with data already in hand for eight and positive results for the first three objects analyzed (Carina, Sculptor, Leo II). Tidal tails are also being found around globular clusters (Grillmair et al. 1995; Meylan et al. 1999; Testa et al. 2000), and we have begun an extensive survey of the halo globular clusters to increase the pool of interesting candidates.

Finally, recent work is dramatically increasing the depth to which halo stars have been observed in random fields and in all cases cold clumps of stars have been found that support the notion that the halo is far from well-mixed but, instead, is filled with numerous tidal streamers (Majewski 1993; Yanny et al. 2000; Majewski et al. 2000b). Thus, we have confidence that multiple stream populations will be available for exploitation by SIM. Expanding the stream analysis to three velocity dimensions vastly enhances the power of the technique over all previous related efforts using one-dimensional, radial velocity data.

Desired Target Properties

We propose to observe target stars chosen from four classes of tidal tail populations:

— *LMC/SMC and Sgr:* Samples of ∼200 K giant and carbon stars associated with each satellite, drawn from the full great circle. The SIM minimum integration times will provide motions accurate to $< 40\mu$as yr^{-1}, equivalent to velocities $< 10\,\mathrm{km\,s^{-1}}$ for stars within 50 kpc. The target stars can be used both to probe the Milky Way potential and to reconstruct the dynamical history (tidal stripping) of each satellite.

— *Sextans, Draco, Sculptor and Ursa Minor:* Samples of ∼50 K giant stars within ∼30° of the parent satellite, with proper motions measured with sufficient accuracy (of order 20μas yr^{-1} in all cases) to apply the JZSH algorithm. The cost is between 1.0 and 3.5 hours per star assuming stars at the current distance (typically about 80 kpc) of the satellites.

— *Carina, Fornax, Leo I and Leo II:* Samples of 10–20 of the brightest stars associated with these very distant (100–250 kpc) satellites, measured with the highest possible accuracy. It is unlikely that these observations will achieve sufficient accuracy for application of the full JZSH algorithm, but simple orbit-fitting techniques can constrain the Galactic potential (e.g., Murali & Dubinski 1999).

— *Globular clusters:* Extratidal stars associated with globular clusters will be added to the target list. These samples typically only need to be within ±10 degrees of a cluster to be useful. However, because globular clusters are lower mass than satellites and demand higher accuracy velocities to apply JZSH we may have to use the orbit-fitting technique to recover the potential.

In total, ∼600 hours are required for these observations. Our combined measurements will map the 3-D structure of the Galactic potential to better than 5% to $R_{\mathrm{GC}} \sim 100$ kpc, and will measure the total mass enclosed by the orbits of the outer satellites ($R_{\mathrm{GC}} < 250$ kpc) to an accuracy of ∼10%.

Identifying the Target Stars

Observations to date (including many by our team) suggest that extra-tidal phenomena are ubiquitous, and we anticipate that sufficient individual targets for these experiments will become available in the near future from our own survey efforts and those of the community at large. At minimum we will have hundreds of stars drawn from the full 360° tidal stream of Sgr, in the form of already known carbon star members supplemented by observations of luminous giant stars and Sgr globular clusters. The clusters are particularly useful probes because their distances will be determined. For the LMC/SMC we will continue to extend our observations of the giants identified as potential members of the Magellanic Stream by Majewski et al. In both cases, our continuing survey for distant giants in selected regions along the predicted great circle distributions will yield new candidate members, as will the Grid Giant Star and Sloan Surveys, both of which already are yielding new Sgr candidates where the surveys intersect its orbital plane.

We also have well underway concentrated ground-based surveys of the full complement of dwarf spheroidal and high-latitude globular cluster satellites of the Milky Way. In each case, our observations, using both photographic data and wide-field CCD imaging, extend to a minimum of several tidal radii. Follow-up spectroscopic observations are being used to verify the potential tidal tail stars. Within a few years we expect to have at least several substantial tails mapped (e.g., Carina appears to be losing 1/3 of its mass per Gyr; Majewski et al. 2000a). In the end, our approach will be to take the lists of candidate extratidal stars spatially and dynamically associated with each dwarf galaxy or cluster, and then winnow to the best target list using semi-analytical and N-body modeling to: (i) assess both the plausibility of association and the informational leverage on a star-by-star basis; and (ii) evaluate the ensemble of all available tail data to optimize targets for net informational content on the Galactic potential.

6. Summary of Requested SIM Observations

Time Requested

Table 1 summarizes the estimated SIM time requirements for this Key Project proposal. The proposed suite of experiments aims to establish the fundamental distance, velocity and mass scales of the Galaxy from the solar neighborhood to the greatest reaches accessible with stellar tracers at the $V \approx 19$ SIM limit (to the dwarf spheroidals at $R_{\rm GC} \gtrsim 200$ kpc, as traced by their brightest giant/carbon stars). The observations are approximately evenly divided between samples of disk and halo tracers.

Our calculations of SIM integration time for stars of varying spectral energy distribution are based on the total *photon* flux across the 0.4–0.9 μm sensitivity of SIM, since fringe signal-to-noise will depend on Poisson statistics of photoelectron counts. Thus we adopt the 5700° K blackbody (G2V star) assumed in the SIM V-band exposure time calculator as a baseline and set $m_{\rm SIM}({\rm G2V}) = {\rm V(G2V)}$, where $m_{\rm SIM}$ is the SIM magnitude (calculated in photons, not ergs) in a 0.4–0.9 μm passband assuming a flat instrument response. Utilizing B, V, R, I colors (Drilling & Landolt 2000) to benchmark the photon flux distributions relative to that for a G2V star, and passband flux definitions from (Bessell et al. 1998), we establish that, *for stars of the same V magnitude*, $V({\rm G2V}) = m_{\rm SIM}({\rm G2V}) = m_{\rm SIM}({\rm K5III}) + 0.35 = m_{\rm SIM}({\rm M4.5III}) + 1.09$. Thus, evolved stars redder than G2V yield higher net SIM photon fluxes at the same V magnitude.

Potential Observational Overlaps with Other Key Projects

We anticipate mutually beneficial interactions with any “Extra-Galactic Distance Scale” and “Internal Dynamics of Small Satellite Systems” Key Projects including, for example, Cepheid calibrations, and measuring distances and proper motions of Galactic clusters and satellites. We also intend to make full use of the K giant stars selected to be part of the SIM Astrometric Grid wherever possible (e.g., §5).

Other Potential Improvements in Observing Efficiency

The Oort, disk and random halo studies involve large samples in selected areas. We will choose targets to encompass as few individual “tiles” as possible to maximize the efficiency of SIM's observing pattern.

If several Grid stars are chosen to be near the Galactic center (e.g., by the PI's Grid Giant Star Survey), then the astrometric measurements in Baade's window and other low extinction windows can be done with small angular separation between the Grid and target stars. This should reduce both the error per observation and the observing time.

There are some additional tricks that are currently against SIM time calculation rules but that could improve the observing efficiency. For example, for all of our outer halo work parallaxes are not needed for our targets, only proper motions; since we do not need to solve for as many parameters (the value for the parallax derived from the SIM data will be inferior to that which we can input from other techniques), we do not need to observe these targets as frequently. This would give the freedom to either cut time from the scheduled ∼1300 hours or (the preferable option!) to observe more halo targets.

Table 1. SIM Time Summary

Project	Targets	d (kpc)	m_{SIM}[a]	Data from SIM	Required[b] accuracy of error	Required SIM accuracy (μas)	KP time[c] per star (hours)	Number of Stars	Total KP time (hours)
Galactic Center									
Blum field 2, $A_I = 3.5$	M giants	8	14.4–15.4	π, μ	5% in d	6.25	$\sim$3.4	30	108
Blum field 3, $A_I = 1.3$	M giants	8	12.0–13.0	π, μ	5% in d	6.25	$\sim$1.2	30	36
Blum field 4, $A_I = 2.8$	M giants	8	13.7–14.7	π, μ	5% in d	6.25	$\sim$2.3	30	72
Baade's Win, $A_I = 1.0$	M giants	8	10.6–14.6	π, μ	5% in d	6.25	0.8–2.9	100	200
Oort Limit									
field	K giants	0–2	< 12	π, μ	$< 2\%$ in d	8–9	0.6	500	300
Disk Potential									
field, $A_I = 2$	Miras	0–20	< 16	π, μ	$< 2\,\mathrm{km\,s^{-1}}$	8–24	0.6	300	180
field, $A_I = 2$	Cepheids	0–20	< 15	π, μ	$< 1\,\mathrm{km\,s^{-1}}$	8–15	0.6	300	180
open clusters	brightest	0–4	< 16	π, μ	3% in d	7.5-75	0.6–1.0	3×100	250
Random Halo									
field	K giants	20–100	15–18.5	μ	1–25 $\mathrm{km\,s^{-1}}$	15–80	0.6	900	540
dSph	RGB tip	20–200	14–20	μ	5–20 $\mathrm{km\,s^{-1}}$	12–30	0.6–5	3×9	45
globulars	RGB tip	0–120	10–18.6	μ	0–20 $\mathrm{km\,s^{-1}}$	12–50	0.6	2×150	180
Astrometric Grid Stars	K giants	< 7	< 12	π, μ	N/A	4	0	3000	0
Tidal Tails									
Sgr/LMC/SMC	K giants	20–100	15–18.5	μ	1–25 $\mathrm{km\,s^{-1}}$	15–80	0.6	400	240
Dra/Sex/Umin/Scul	K giants	20–100	15–18.5	μ	6–9 $\mathrm{km\,s^{-1}}$	20–40	0.6–2.5	150	230
Car/For/LeoI/LeoII	K giants	100–200	< 19	μ	10–20 $\mathrm{km\,s^{-1}}$	30	< 2.7	50	130
globulars	K giants	20–100	15–18.5	μ	1–25 $\mathrm{km\,s^{-1}}$	15–80	0.6	150	90
Total									2781

[a] Effective SIM magnitude, including extinction. See text for the definition of m_{SIM}.

[b] Corresponding error in physical quantities, expressed as a percentage in d or in $\mathrm{km\,s^{-1}}$ for tangential velocity error due to the proper motion error. (Assuming $\epsilon = 4\mu$as over the course of the mission translates into a proper motion accuracy of 2.8μas/yr, as described in the AO Support WWW pages "FAQ".)

[c] Total time, including overhead, calculated from description in AO Support WWW pages.

7. Summary of Activities

Each of the programs outlined in this proposal requires substantial preparatory observations with a reduced load of follow-up observations once the mission is launched. In accordance with the AO, we anticipate sending a postdoc for several month-long visits from UVa to ISDC to facilitate the production and transfer of SIM data products to/from the Key Project Team. This postdoc will also be in charge of converting the Level 4 SIM positional data to astrometric quantities required by the Key Project team. Theoretical studies developing analysis techniques will be conducted in tandem with the observational program. Additional details of all aspects are given in the appendix on "Individual Duties and Responsibilities" with a short summary and the relevant individuals indicated below by their initials.

R_0, ω_0 We will measure proper motions of ~10,000 Baade's window stars using HST (CG), select the Baade's window sample, obtain high-resolution spectroscopy for the bulge SIM targets (CG) and 10 $\mathrm{km\,s^{-1}}$ velocities for a larger sample of the HST stars (CG,DG,WG). We will obtain Washington photometry abundances (to 0.2 dex) for the entire HST bulge sample (DG). Theoretical work will include construction of a dynamical model of the bulge/bar consistent with the measured kinematics (DNS).

Oort Limit We will construct photometric catalogues to $V \sim 13$ at the northern and southern Galactic caps to identify disk K giants and measure their *relative* density with height above the Galactic Plane. Follow-up spectroscopic observations of at least 4000 candidates will be used to determine radial velocities and more detailed metallicity estimates (SRM, RJP, INR). Monte Carlo simulations will be used to develop analysis techniques (JNB, ST).

Disk We will combine 2MASS and photographic data to identify candidate variables in the Galactic Plane. Follow-up CCD observations will be used to confirm variability and identify short-period Miras and Cepheids (INR, WG). Radial velocity studies will be conducted to confirm the membership of the brightest stars in our open cluster sample (DG). Our simulations will be extended to examine the effect of resonances on our analysis and determine the sensitivity to the disk potential for different age populations (KVJ, ST, DNS).

Random halo Distant metal-poor halo giants will be identified in selected areas from deep, wide-field CCD images using the same techniques employed to select Astrometric Grid stars. We will obtain spectra and radial velocity measurements of ~1000 of these giants selected as SIM targets (SRM, RJP, DG, WG). Analysis techniques for our specific program of selected areas will be developed (ST).

Globular clusters and satellite proper motions We will continue our program of imaging, designed to identify the brightest cluster and satellite giants as well as tidal tails (SRM, RJP, DG).

Tidal tails An extensive campaign is currently underway using both photographic and CCD imaging and multi-object spectroscopy to identify stars in tidal tails of known Galactic satellites and globular clusters, and as well as orphaned star streams in the Galactic halo (SRM, RJP, CG, EG, MO, MI). Theoretical work includes examining tidal tail evolution in cosmological simulations and providing modeling support for target selection (KVJ, DNS).

8. Science Goals for Reduced Mission Performance

We consider two benchmark cases for degraded SIM performance impacting our proposed science:

Reduced Astrometric Performance to Mission Floor (30 μas)

— *Fundamental Parameters:* So long as 30 μas represents a statistical rather than systematic error, this simply increases the error in measurements of distances to individual stars to 24% and of R_0 to 3–4%; this would still be a factor of four improvement from present determinations.

— *Oort Limit:* The most valuable and precise information would be obtained within 1 kpc, where the bound on individual stellar distance errors would still be <3%. While this would require very careful control of the other systematics, it would not reduce significantly the ultimate accuracy obtainable with 500 well-measured tracer stars.

— *Disk Potential:* In this case, distances will be derived entirely from SIM/FAME calibrations of pulsational variables and open cluster main sequence fitting rather than using SIM parallaxes. However, proper motion errors will still be of order a few $\mathrm{km\,s^{-1}}$. With use of non-SIM distances, the study will be largely unaffected.

— *Jeans Equation and Tidal Tail Halo Experiments:* All of the halo work can still be done, since proper motion accuracies need only be at the mission floor and distance information from SIM is not needed. Our accuracy in the very distant halo (>100 kpc) may be slightly reduced.

Reduced SIM Magnitude Limit by Two Magnitudes

— *Fundamental Parameters*, *Oort Limit* and *Disk Potential:* No effect on our scientific goals.

— *Jeans Equation and Tidal Tail Halo Experiments:* There will be a factor of 3 reduction in the radius to which the potential can be measured with 5–10% accuracy ($\lesssim$80 kpc). Only the LMC/SMC, Sagittarius, and other nearby tidal tails may be exploitable.

9. Science Goals in Relation to Other Astrometric Satellites

The limits of the FAME (50 μas at V=9) and GAIA (160 μas at V=20) missions of course translate to substantial reductions in astrometric capability to a given $R_{\rm GC}$ limit compared to SIM. (DIVA has a similar magnitude limit but lower astrometric accuracy than FAME so we do not include it in our discussion.) Even at the SIM astrometric floor, our Key Project science will encompass legacy results that cannot be matched by these other missions. Among our unique results will be analysis of the proper motions for all targets in the distant (> 10 kpc) Galaxy, and the measurement of the potential in this regime.

The only aspects of our proposal with potential overlap with FAME and GAIA are our studies of the nearby Milky Way, where the other missions may make up somewhat by sheer number of targets what they lack in precision. For example, improving on the current distance uncertainties (10%) in Baade's window requires measuring parallaxes with a systematic uncertainty of 12.5 μas. FAME will achieve only 500 μas at V=15 and its systematic uncertainties are too large to be able to reduce the distance uncertainties by measuring the distances to several thousand stars in Baade's window; However, GAIA (which flies after SIM) can beat down the error with four times as many V=15 targets, as long as the systematic errors are comparable to SIM. Our studies of the more distant, heavily dust-extinguished disk are beyond the faint-end limit of V=15 FAME, so it will not be sensitive to non-axisymmetric features in the disk. However, if the FAME mission is successful, one of our collaboration (Bahcall) will participate in using that satellite to make a preliminary measurement of the nearby mass density. We will select the SIM sample so as to obtain an independent test of the FAME result and to use the greater accuracy of the SIM astrometry in an independent and more precise measurement of both the local column density and the local volume density.

10. Potential Early Release Data

Our Key Project group will implement a policy of only releasing results as soon as they can be regarded as a significant improvement over existing studies. Nevertheless, we understand the importance to NASA of early release results. Fortunately, several of our experiments – specifically, those we have discussed above (§8) as still doable with a final, degraded mission performance delivering only 30 μas – lend themselves to early release results as soon as the mission lifetime of a non-degraded SIM reaches allows delivered performance at the 30 μas level.

Thus, for example, the novel nature of the tidal tails experiment will allow astrophysically interesting results to be obtained at an early stage in the SIM mission. Minimum time integrations on stars in the LMC/SMC and Sgr tidal streams will achieve proper motion accuracies exceeding 30 μas yr^{-1} after only 2–3 years, permitting initial solutions for the Galactic potential. A full five years is required to achieve the necessary accuracy for analysis of the Milky Way potential using the tidal tails of the other, more distant satellites; however, lower-accuracy initial solutions can be obtained using the orbit-fitting techniques. Similarly, the Jeans equation solutions can be attempted once 30 μas proper motions are available. These measurements would provide the first determination of the mass distribution of the Galaxy at radii between 75 and 250 kpc. By virtue of the proximity of the stars in the Oort and Galactic center distance experiments, we should, again, be able to achieve a significantly improved (though not our final) result within a few years.

11. Resources Available to the Key Project

The suite of experiments we have detailed in this Key Project proposal is only possible with reliance on the substantial observational resources available to undertake the substantial effort to select and characterize optimal target sets. Co-Is of this proposal have access to databases from the Grid Giant Star Survey for the SIM Astrometric Grid, the Sloan Digital Sky Survey, the optical $u'g'r'i'z$ wide field survey in selected areas being carried out on the 2.5-m INT, Irwin's extensive carbon star and Sgr tracking surveys, and Geisler's extensive Washington photometry surveys on open and globular clusters. Co-Is on this proposal have direct access to the ARC 3.5-m, the Sloan 2.5-m, and Fan Mtn. Observatory telescopes. Chilean co-I's have abundant access to telescopes through the guaranteed 10% time on all Chilean telescopes. Grebel has access to ESO facilities, including the VLT on a competitive basis, and privileged access to MPI's 2.2-m telescope in Chile as well as MPI's 2.2-m and 3.5-m telescopes at Calar Alto Observatory, Spain. Irwin has access to UK facilities, and the American co-I's to NOAO facilities through competitive proposal. The University of Virginia is presently negotiating 20% access to a 2-m class telescope effective 2001; this access will be a significant help to the ground-based efforts of this proposal.

REFERENCES

Bahcall, J. N. 1984, ApJ, 287, 926

Bahcall, N. A., Ostriker, J. P., Perlmutter, S. & Steinhardt, P. J. 1999, Science, 284, 1481

Bessell, M. S., Castelli, F. & Plez, B. 1998, A&A, 333, 231

Binney, J. & Merrifield, M. 1998, *Galactic Astronomy* (Princeton: Princeton University Press)

Binney, J. & Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton University Press)

Blanco, V.M. 1986, AJ, 91, 290

Blitz, L. & Spergel, D. N. 1991a, ApJ, 370, 205

Blitz, L. & Spergel, D. N. 1991b, ApJ, 379, 631

Blum, R. D., Carr, J. S., Depoy, D. L., Sellgren, K. & Terndrup, D. M. 1994, ApJ, 422, 111

Blum, R. D., Carr, J. S., Sellgren, K. & Terndrup, D. M. 1995, ApJ, 449, 623

Caldwell, J.A.R., Keane, M.J. & Schechter, P.L. 1991, AJ, 101, 1763

Creze, M., Chereul, E., Bienayme, O. & Pichon, C., 1998 A&A, 329, 920

Cseresnjes, P., Alard, C. & Guibert, J. 2000, astro-ph/0002157

Dehnen, W. 2000, AJ, 119, 800

Dinescu, D.I, Majewski, S.R., Girard, T.M. & Cudworth, K.M. 2000, AJ, 120, 1892

Drilling, J. S. & Landolt, A. U. 2000, in *Allen's Astrophysical Quantities,* 4th ed, ed. A. N. Cox (New York: Springer-Verlag)

Eggen, O. J., Lynden-Bell, D. & Sandage, A. R. 1962, ApJ, 136, 748

Feast, M.W. 1963, MNRAS, 125, 367

Feast, M. W. & Whitelock, P. 1997, MNRAS, 291, 683

REFERENCES

Frenk, C. S. & White, S.D.M. 1980, MNRAS, 193, 295

Frogel, J. A. & Whitford, A. E., 1987 ApJ, 320, 199

Gnedin, O. Y., Lee, H.-M. & Ostriker, J. P. 1999, ApJ, 522, 935

Grillmair, C. J., Freeman, K. C., Irwin, M. & Quinn, P. J. 1995, AJ, 109, 2553

Gwinn, C. R., Moran, J. M. & Reid, M. J. 1992, ApJ, 393, 149

Hartwick, F. D. A. 1999, astro-ph/9912083

Helmi, A. & White, S.D. 1999, MNRAS, 307,495

Hogan, C. & Dalcanton, J. J., 2000, astro-ph/0002330.

Holmberg, J. & Flynn, C. 2000, MNRAS, 313, 209

Ibata. R., Lewis, G. F., Irwin, M., Totten, E. & Quinn, T. 2000a, astro-ph/0004011

Ibata, R., Irwin, M., Lewis, G.F. & Stolte, A. 2000b, astro-ph/0004255

Ibata, R. A., Gilmore, G. & Irwin, M. J. 1994, Nature, 370, 194

Ibata, R. A., Wyse, R. F. G., Gilmore, G., Irwin, M. J. & Suntzeff, N. B. 1997, AJ, 113, 634

Irwin, M. J. & Hatzidimitriou, D. 1995, MNRAS, 277, 1354

Ivezić, Z. et al. 2000, astro-ph/0004130.

Johnston, K.V. 1998, ApJ, 495, 297

Johnston, K. V., Hernquist, L. & Bolte, M. 1996, ApJ, 465, 278

Johnston, K. V. & Spergel, D. N. 2000 ApJ, *submitted*

Johnston, K. V., Tremaine, S. & Spergel, D. N. 2000 *in preparation*

Johnston, K. V., Zhao, H. S., Spergel, D. N. & Hernquist, L. 1999, ApJL, 512, L49

Joy, A.H. 1939, ApJ, 89, 356

Klypin, A. A., Kravtsov, A. V., Valenzuela, O. & Prada, F. 1999, ApJ, *submitted*

Kochanek, C. S. 1996, ApJ, 457, 228

Kuhn, J. R., Smith, H. A. & Hawley, S. L. 1996, ApJL, 469, L93

Kuijken, K. & Tremaine, S. 1994 ApJ, 421, 178

Lin, D. N. C., Jones, B. F. & Klemola, A. R. 1995, ApJ, 439, 652

Majewski, S. R. 1993, ARA&A, 31, 575

Majewski, S. R., Ostheimer, J. C., Patterson, R. J., Kunkel, W. E., Johnston, K. V. & Geisler, D. 2000a, AJ, 119, 760

Majewski, S. R., Ostheimer, J. C., Kunkel, W. E., Johnston, K. V. & Patterson, R. J. 2000b, *in preparation*

Majewski, S. R., Ostheimer, J. C., Kunkel, W. E. & Patterson, R. J. 2000c, AJ, 120, 2550

Majewski, S. R., Siegel, M. H., Kunkel, W. E., Reid, I. N., Johnston, K. V., Thompson, I. B. & Landolt, A. U. 1999, AJ, 118, 1719

Mateo, M., Olszewski, E. W. & Morrison, H. L. 1998, ApJL, 508, L55

Mermilliod, J.-C. 1998, in *Dynamical Studies of Star Clusters and Galaxies*, eds. P. Kroupa, J. Palous & R. Spurzem (Noordwijk: ESA) (http://obswww.unige.ch/webda/)

Metzger, M.R., Caldwell, J.A.R. & Schechter, P.L. 1998, AJ, 115, 635

Meylan, G., Leon, S. & Combes, F. 1999, astro-ph/9912041

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. & Tozzi, P. 1999, ApJL, 524, L19

Moore, B. & Davis, M. 1994, MNRAS, 270, 209

Murali, C. & Dubinski, J. 1999, AJ, 118, 911

Olling, R. P. & Merrifield, M. R. 1998, MNRAS, 297, 943

Oort, J. 1932, Bull. Astron. Inst. Netherlands, 6, 249

Ostriker, E. C. & Binney, J. J. 1989, MNRAS, 237, 785

Reid, M. J., 1993, ARA&A, 31, 345

Reid, I.N., Glass, I.S. & Catchpole, R.M. 1988a, MNRAS, 232, 53

Reid, M. J., Gwinn, C. R., Moran, J. M. & Matthews, A. 1988b, BAAS, 20, 1017

Reid, M. J., Readhead, A. C. S., Vermeulen, R. C. & Treuhaft, R. N. 1999, ApJ, 524, 816

Schlegel, D. J., Finkbeiner, D. P. & Davis, M. 1998, ApJ, 500, 525

Spergel, D.N. & Steinhardt, P. J. 2000, Phys. Rev. Lett., *in press*

Testa, V., Zaggio, S. R., Andreon, S., Longo, G., Scaramella, R., Djorgovski, S.G. & de Carvalho, R. 2000, astroph/0002280

Thomas, P. 1989, MNRAS, 238, 1319

Tremaine, S. 1993, in *Back to the Galaxy*, eds. S. S. Holt & F. Verter (New York: AIP), p. 599

Warren, M. S., Quinn, P. J., Salmon, J. K., & Zurek, W. H. 1992, ApJ, 399, 405

Weinberg, M. D. 1994, ApJ, 420, 597

Wilkinson, M. E. & Evans, N. W. 1999, MNRAS, 310, 645 [WE99]

Yanny, B. et al. 2000, astro-ph/0004128

Zhao, H. S., Johnston, K. V., Spergel, D. N. & Hernquist, L. 1999, ApJL, 512, L109

Zhao, H., Spergel, D. N., Rich, R. M. 1994, AJ, 108, 2154

12. Education/Public Outreach Statement of Participation and Outline of Special Opportunities for this Key Project

While the proposers are committed to participate in E/PO activities organized by NASA, we outline several additional opportunities for E/PO activities specifically related to the topic of this proposal and unique venues available to the proposers.

Our project includes co-I's from six U.S. and three foreign institutions that provides numerous opportunities for student involvement (even our non-university institutions are either affiliated with universities or have a mechanism for and tradition of taking on student researchers). Moreover, because our Key Project encompasses a suite of multiple distinct, but interrelated experiments, it is particularly well suited to packaging into a number of self-contained, interesting student projects from the undergraduate level to the Ph.D. thesis. For example, this year at the University of Virginia, the PI will have mentored five undergraduate students and five graduate students doing individual research projects directly related to this Key Project proposal, while at Wesleyan University, Johnston will have mentored two undergraduates and one graduate student.

Among the foreign institutions is the University of Concepción, which has just formed a doctoral program in physics and astronomy, and also grants degrees at the undergraduate and Masters level. Students at Concepción stand to benefit greatly from the participation of their institution in this project. A large share of preparatory observing projects will take advantage of Chilean facilities, and these students have already been active participants in these projects. This assistance to a new Chilean astronomy educational center comes at a critical time for the U.S. astronomical community: with our growing stake in observational facilities located in Chile (with, for example, the new Gemini, ALMA, Magellan, and SOAR telescopes already underway, and new telescopes, like the Cornell 15-m, being considered), the need for Chileans trained in, or at least familiar with, the technical and scientific aspects of astronomical observing is becoming ever greater (and Chilean technical support people are already considered in short supply by some of the above-named projects).

The PI is currently involved in the creation of a museum at the Leander McCormick Observatory at the University of Virginia specifically focused on the science of astrometry, in keeping with the century-long tradition of astrometry at that institution. Public access to the Observatory averages some 4000 visitors a year, but this number can be expected to double, as we have implemented a doubling of available public hours to accommodate special tours. New exhibit space has already been created for the proposed endeavor, and the Department of Astronomy is currently advertising a new faculty line for an Education and Public Outreach position with duties partly focused on this effort. It is our plan to cover the entire history of astrometry including the latest developments with SIM. In addition, Spergel has strong connections with the Hayden Planetarium, which is currently developing a three dimensional computer simulation of the Milky Way. The results from our Key Project will be incorporated in the continuing updates of that model. Both museum efforts have the potential to bring new SIM results to a wide audience rapidly.

13. Individual Duties and Responsibilities

Here we describe the experience (relevant to the proposal), duties and responsibilities of the primary collaborators and co-I's on this project. We discuss here only those individuals known at the present time, not individuals (e.g., postdocs) who will be part of the Key Project, but at present are only planned for in the proposal.

John Bahcall (Professor, Institute for Advanced Study) will lead the Oort Limit project analysis. Bahcall has done extensive work on using disk giants as tracers of the local mass distribution and in the development of the Bahcall-Soniera model for the stellar distribution in our Galaxy. Bahcall is participating in the Oort Limit analysis for the FAME mission. During the pre-launch period, Bahcall will develop a Monte-Carlo program for simulating the SIM observations of disk stars, and work with Majewski's group on developing and characterizing the proposed Oort limit target samples described in this proposal.

Doug Geisler (Research Scientist, NOAO) will be part of the program of identifying halo K giants using the Washington + DDO51 photometry system. Geisler developed and calibrated this filter system (via numerous papers), and has been the most extensive user of it. Geisler is also a co-I in the Grid Giant Star Survey for the SIM Astrometric Grid, and is the PI of a SIM preparatory grant to do follow-up monitoring (photometry and high resolution spectroscopy) of Grid stars. Because of his extensive experience with observing globular clusters in the Washington system, Geisler will play a key role in the effort to identify the brightest giants in both the open and globular clusters for SIM. He will also participate in efforts to find tidal tails and apply his calibration of the Washington photometry system for metal-rich giants to the measurement of abundances of giants in our bulge fields. Geisler will organize and mentor students for Chilean contributions to this project.

Wolfgang Gieren (Professor, Universidad de Concepción) is an expert in Cepheid and other variable stars and will play an important role in establishing the Cepheid target list and characterization thereof. He will assist with the spectroscopy of bulge stars. Gieren is also involved with the creation of the Grid Giant Star Survey for the SIM Astrometric Grid, and so will be involved with the creation of the halo K giant sample. He will also mentor Chilean students contributing to this project.

Eva Grebel (Associate Astronomer, Max Planck Institut für Astronomie, Heidelberg) is an expert in the study of stellar populations and dwarf galaxies. She is playing an active role in the search for tidal tails around dwarf satellites and globular clusters. She provides privileged access to wide-field imagers through MPIA's telescope facilities and has hired a postdoc (Michael Odenkirchen) to work exclusively on SIM preparatory science. In addition, she has been leading the extensive search of the open cluster literature to identify brightest member stars.

Carl Grillmair (Staff Scientist, SIRTF Science Center) has been part of the HST program to study galactic nuclei and massive black holes. He is leading our associated program to obtain Hubble Space Telescope astrometry to complement the SIM measurements of the Galactic bulge and bar populations. With his extensive experience in locating tidal streams around globular clusters, and Hubble investigations of stellar populations in dwarf galaxies, Grillmair will play a key role in the pre-launch search for tidal streams associated with dwarf galaxies and globular clusters.

Michael Irwin (Institute of Astronomy, Cambridge, UK) has long played an important role in studies of the Milky Way and associated dwarf galaxies. He will be part of the effort for identifying candidate stars in tidal tails. Irwin has played a major role in the following: discovering the last two additions to the exclusive club of satellite galaxies that orbit the Milky Way – one of which, Sgr, has become the "smoking gun" of galactic merger hypotheses; discovered two new Local Group galaxies; finding the only new outer Galactic Halo globular cluster discovered since 1980; finding and investigating the first compelling direct evidence for tidally disrupted dwarf galaxy entrails, in the form of giant arcs of stellar streams in the Galactic Halo; identified the Sagittarius dwarf and has traced its tail across the sky using carbon stars. Irwin is currently extending his previous work using plate scans for detecting tidal streams in globular clusters and dwarf galaxies.

Kathryn Johnston (Assistant Professor, Wesleyan University) will be responsible for theoretical aspects of the disk and tidal tail studies. She has already developed a Monte Carlo code that simulates the analysis of SIM observations of the Galactic disk. She also has been studying the practical application of the JZSH algorithm to SIM observations of tidal tail stars. Her pre-launch activities include: extending the disk study to look at the effect of resonances on the analysis (with Tremaine and Spergel); modeling support for selection of tidal tail candidates (with Majewski); and examining the evolution of tidal tails in cosmological simulations of galaxy formation (with Spergel). Johnston has been one of the primary leaders in the theoretical understanding of tidal tails in Milky Way-like contexts and their use as halo tracers. She is a Co-I on the Grid Giant Star Survey and a recipient of a Long Term Space Astrophysics Grant awarded to study the use of SIM for Galactic astronomy.

Steven Majewski (Associate Professor, University of Virginia) will be the Principal Investigator for the project. He has been involved in numerous studies of the structure and kinematics of stellar populations in the Milky Way utilizing deep surveys of astrometry, photometry and spectroscopy, and was the author of a 1993 article in Annual Reviews of Astronomy and Astrophysics on these topics. Majewski was asked to participate in the activities of the SIM Science Working Group in 1998. He has been active in the search for tidal tails around dwarf satellites and, more recently, globular clusters, and will lead the team's pre-launch efforts to identify tidal streams using the Washington/DDO51 filter technique, and will work with Johnston, Spergel and other team members on the SIM tidal tail data. Majewski is also leading the Grid Giant Star Survey, a survey (funded by two SIM preparatory science grants) to identify the K giants for the SIM Astrometric Grid. As an extension of this effort, Majewski, together with his students and postdocs, will identify the disk giant sample for the Oort limit analysis and the halo giant sample for the Jeans equation analysis. He is the advisor for a student who has already declared the creation of the Oort limit sample for this Key Project as a Ph.D. thesis. For the past decade Majewski has been leading a ground-based effort (in collaboration with K. Cudworth, U. Chicago) to measure the proper motions of globular clusters (focusing primarily on the most distant clusters possible) and Milky Way dwarf spheroidal galaxies and he will also take an active role in that part of the Key Project analysis. Majewski's group will therefore participate in the selection of stellar targets for the globular clusters and dwarf spheroidals.

The University of Virginia (with Majewski as PI) will serve as the principal point of contact and managing center for Key Project activities. Virginia will take a primary role in the planning of observational activities related to target selection and characterization, as well as post-launch reduction of the Level 4 SIM data to astrometric quantities required by the Key Project. Virginia will also serve as a "clearing house" for all pooled Key Project resources, including funds for Key Project meetings, publication costs, most observing travel support, and some FTE manpower.

Michael Odenkirchen (Postdoctoral Fellow, Max Planck Institut für Astronomie, Heidelberg) is assisting with tidal tail identification around dwarf spheroidal satellites and globular clusters by photometric and spectroscopic means. He has extensive experience in Galactic structure, kinematics, and astrometry. In addition, he continues to collaborate with astrometrists at the Observatoire de Bordeaux and at Bonn University in ongoing studies of radial velocities and proper motions of open and globular clusters.

Richard Patterson (Research Professor, University of Virginia) is an expert in both astrometry (he is a co-I of the Virginia Parallax Program) and dwarf galaxies. He has collaborated with Majewski in the search for tidal tails around clusters and satellites, and is a co-I of the Grid Giant Star Survey. He will play a key role in conducting the ground-based observational activities for the project, including organizing the day-to-day operations of the many observational programs. He will be involved scientifically in the K giant samples for the halo and Oort surveys, the project to determine the proper motion of globular clusters and dwarf galaxies, and the search for tidal tails.

Neill Reid (Associate Astronomer, moving to Space Telescope Science Institute in autumn 2000) will lead the observational program to identify Cepheid and Mira variables suitable for probing the potential of the Galactic disk. He will collaborate in the Oort limit determination, both analyzing the photometric catalogue and obtaining follow-up spectroscopy of candidate K giants. Reid has extensive experience in Galactic structure studies, with particular expertise in the analysis and interpretation of starcount data. He was on the SIM Science Working Group, has undertaken ground-based astrometric analyses, and was the first to exploit HIPPARCOS data to redetermine distances to globular clusters. Reid has two decades of experience analyzing large-scale photometric catalogues, including over 14 years working on POSS II. More recently, he has been intimately involved in exploiting data from the 2MASS near-infrared survey.

David Spergel (Professor, Princeton University) will be leading the analysis of R_0 and the study of the bulge kinematics. He will construct a dynamical model for the bar consistent with measured stellar kinematics and explore implications for the formation of the bar. He will also be part of the disk analysis and the tidal tail analysis effort. Spergel will develop cosmological simulations of the formation history of the Galaxy as inputs for the tidal tail analysis. Spergel is the new President of IAU Commission #33 (The Galaxy) and was a member of the SIM Science Working Group. Spergel has made a number of contributions to Galactic astronomy: Blitz and Spergel used the COBE data to show that the Milky Way is a barred galaxy; Spergel and his collaborators showed that the bar has a significant effect on the predicted rate and number of microlensing events towards the Galactic bulge; Spergel and his collaborators proposed that the High Velocity Clouds are extragalactic and are part of the on-going formation of the Milky Way. Spergel has been active in the search for dark matter: In his thesis work, he showed that the Earth's motion around the Sun produces an annual modulation in the event rate in dark matter detectors. All of the current generation of dark matter detectors aim to detect this modulation effect. Recently, Spergel and Steinhardt proposed that the dark matter has strong self-interactions. This model predicts that the Galactic halo is nearly spherical and that the infalling dwarf satellites experience both collisional and dynamical friction: Our observations of tidal tails will test this hypothesis.

Scott Tremaine (Professor, Princeton University): Tremaine is the co-author with Binney of *Galactic Dynamics*, the standard graduate textbook on the theory of stellar systems. He has worked extensively on many aspects of galactic structure, including the use of halo tracers to measure the mass distribution, evidence for non-axisymmetry in the Galactic disk, galactic warps, phase-space substructure in the Galactic halo, bar and spiral structure dynamics, techniques for modeling spherical stellar systems, and structure and evolution of galactic nuclei. He has participated in a large HST collaboration to study the centers of elliptical galaxies and the evidence for massive black holes in nearby galaxies. He was a member of the SIM Science Working Group.

Tremaine will lead the analysis of the hot halo tracers. Initially this effort will involve the development of statistical techniques to measure the mass distribution of spherical stellar systems from tracer populations; the novel feature is that all three velocity components—not just radial velocities—will be determined by SIM. For practice, these techniques can be applied to the globular clusters with known proper motions. He will also investigate phase-mixing in galaxies formed by hierarchical merging to determine the influence of incomplete mixing on halo tracers. Tremaine will also continue to work with Johnston and Spergel on simulations of SIM observations of disk parameters, and with Bahcall on analysis of the Oort limit.