Space Interferometry Mission Dynamical Observations of Galaxies (SIMDOG) Key Project

Executive Summary

Space Interferometry Mission (SIM) will be used to obtain proper motions for a sample of 27 galaxies; the first proper motion measurements of galaxies beyond the satellite system of the Milky Way. SIM measurements lead to knowledge of the full 6-dimensional position and velocity vector of each galaxy. In conjunction with new gravitational flow models, the result will be the first total mass measurements of individual galaxies. The project includes development of powerful theoretical methods for orbital calculations. **This SIM study will lead to vastly improved determinations of individual galaxy masses, halo sizes, and the fractional contribution of dark matter.**

Astronomers have struggled to calculate the orbits of galaxies with only position and redshift information. Traditional N-body techniques are unsuitable for an analysis backward in time from a present distribution if any components of velocity or position are not very precisely known. Co-I Peebles made a major advance in this field when he introduced numerical action methods (NAM) to cosmology. Peebles noted that six components of phase space are accurately known: right ascensions, declinations, and redshifts of galaxies today and the initial condition of effectively zero peculiar velocities. At early times, the mass parcels that would eventually turn into galaxies simply followed the Hubble Law of expansion for that epoch. The NAM provide explicit numerical procedures that transforms cosmological N-body orbit calculations into a non-chaotic boundary value problem.

SIM offers an exciting prospect — access to three more elements of phase-space for each galaxy. These extra constraints are vital since the dynamical gravitation problem naturally leads to several families of solutions for orbits and masses. SIM measurements will discriminate between orbit families, which will strongly constrain total masses and make a locally determined estimate of the global mass density of the Universe. We will have sufficient information to measure dark matter mass to the outermost edges of galaxies, and to discern the sizes of extended halos. These halos may extend far beyond the stars and gas of the observable galaxies.

Accurate distances are needed to complement proper motions and will be obtained through a parallel program of observations. Through other Key Projects, SIM will determine precise distances to Cepheid variable stars and the red giant and horizontal branch stars that serve as standard candles. Bootstrapping on these calibrations, and in the course of a program of support observations for SIM, our team will derive distances at the level of 7 percent for all our target galaxies from two methods: from the luminosity of the tip of the red giant branch of old metal-poor stars and from the

Balmer line equivalent widths of A,B supergiants, the very stars used for the SIM proper motion studies. With this anticipated level of accuracy, we will locate galaxies to better than 300 kpc across the ∼4 Mpc region of interest. This galaxy localization uncertainty is comparable to the anticipated dimensions of halos. One can expect to resolve the mass of groups into the masses of individual galaxies.

We are planning an observing campaign prior to the launch of SIM in order to select target stars. Color–magnitude information about many of the brightest candidate stars have already been published, although usually only parts of the host galaxies have been surveyed. In a small minority of cases there are spectroscopic studies that confirm that the candidates from photometric studies are evolved supergiants in the host galaxies, the kinds of stars needed for SIM observations. **Hence, the practicality of this SIM Key Project is established, but there will have to be spectroscopic and photometric monitoring of several hundred stars before we can make the final selection of program targets.**

A range of analytical techniques will be applied to the set of SIM proper motions, including N-body simulation statistics, the cosmic virial theorem, Zel'dovich approximations, and numerical action methods. Over the next decade, we will advance these techniques and adapt them to the special case of our Local Group and neighboring groups. Within the vicinity of the Local Group, gravity perturbations are large so orbits have evolved into the non-linear domain. Most dynamical studies in cosmology avoid this regime. Our team initiated, and has been closely involved in the development of NAM, **the Numerical Action Method, the only mathematical tool that solves for orbits in the fully non-linear regime.**

The investigators are experienced in data handling, format issues, and data reduction. The PI and a Co-I are contracted managers at the Astronomical Data Center at GSFC and are experienced in archival data issues. The PI heads a research project on XML for astronomical data and has been developing advanced scientific data formats based on XML. A Co-I is the director of the U. of Maryland BIMA group and brings experience, as well as an infrastructure, for the development of software for interferometric analysis. Three Co-I's work at major observatories with the facilities to carry out the extensive pre-launch observational programs.

An unusual amount of pre-launch preparation is required because of the SIM requirement of a complete specification of targets before flight. The budget expenses are overwhelmingly for personnel – students, postdoctoral fellows, and partial summer salaries – for observational, theoretical, and analysis preparatory work.

This research should excite the interest of the public and our team members will continue their current aggressive activities in the area of outreach. This Key Project directly addresses the first and second fundamental questions of the NASA OSS Strategic Plan for “Origins, Evolution, and Destiny”: 1. How did the Universe begin and what is its ultimate fate? And, 2. How do galaxies, stars, and planetary systems form and evolve? **On large scales, these processes are controlled by dark matter.** Full 3-dimensional information on the orbits of galaxies, albeit initially only for the nearest galaxies, leads to an understanding of the mass composition and evolution of galaxies and large-scale structure. We also learn about the future paths of galaxies, which tells us how rapidly galaxies in groups are merging into fewer, more massive systems and, specifically, when the Andromeda galaxy will collide with the Milky Way.

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1. Introduction

There is compelling evidence that the universe is primarily composed of an unknown and invisible substance. The gravitational field of galaxies, outside of the central few kiloparsecs, is significantly stronger than expected from the contributions of all the known objects (stars, remnants, planets, gas, and dust). Rotation velocities in spiral galaxies indicate that galaxies are embedded in halos with masses that increase roughly linearly with radius (Faber & Gallagher 1979). Dynamics of globular clusters and satellite galaxies indicate that the mass of the Milky Way Galaxy extends to at least 200 kpc (Zaritsky *et al.* 1989, Kochanek 1996; Wilkinson and Evans 1999) and reaches at least $\sim 1.4 \times 10^{12} M_\odot$, about 14 times the mass in known material. The temperature and gradients of the X-ray gas of clusters indicate total mass $12 h_{75}^{1.5}$ times greater than the ordinary (baryonic) material measured to be there (Fukugita, Hogan, & Peebles 1998). The source of the excess gravitation has been dubbed "dark matter" because this material has defied detection at all wavelengths.

Interestingly, the theory of structure formation requires that a significant fraction of the total mass resides in a material that does not couple to photons. The paradigm that fits current observations posits that the Big Bang began with a period of rapid inflation, that the energy density of the inflation field decayed into the thermal energy of the early universe, and that quantum fluctuations from the epoch of inflation became frozen into the irregularities that seeded the growth of galaxies. *These irregularities, observed by COBE/DMR (Bennett et al. 1996), were too small to have grown into the present-day high density contrasts in the time available, unless there was a significant mass density in non-baryonic particles.* Baryonic plasma could not gravitationally collapse because of the large resistance from the intense photon field, but non-baryonic particles were not coupled to the photon field and could self-attract. When the temperature dropped sufficiently for the plasma to become atomic gas, it decoupled from the photon field and quickly slipped into the pre-formed potential wells of the non-baryons.

On the largest scales, a suite of observations suggests that the global matter density is $\Omega_M \sim 0.3$ and that the cosmological constant is $\Omega_\Lambda \sim 0.7$ (Bahcall *et al.* 1999; Schmidt *et al.* 1998; Balbi *et al.* 2000; de Bernadis *et al.* 2000). More accurate measurements will be made in the next decade by the NASA MAP and the ESA Planck satellites. *The matter density is many times the contribution from known baryonic components* $\Omega_B = .02 h_{75}^{-1}$, (Fukugita *et al.* 1998), or the factor of two larger baryonic density derived from the observed deuterium abundance (Burles & Tytler 1997). Direct evidence of the distribution of similarly large amounts of dark matter comes from studies of large scale flows (Shaya, Peebles & Tully 1995; Willick & Strauss 1998).

Despite some progress in understanding the dark matter distribution, there is a wide gap from scales of tens of kpc where the stars and gas respond to the distribution of matter to the 4 Mpc scale where large scale peculiar velocity flow studies begin to be effective. It is toward these missing scales that the most important structure formation questions are posed. We have yet to detect the edges of dark matter halos. We only know that the Milky Way halo extends to at least 200 kpc. Are groups dominated by a common dark matter envelope as recently suggested by a study of poor groups (Zabludoff & Mulchaey 1998). Are there totally unbound particles, as one finds in CDM simulations? Is there evidence for flattening of the potential which might be evidence of dissipational processes?

Our SIM measurements will allow these questions to be directly addressed. A complementary SIM Key Project on the Stellar Dynamics of the Galaxy will examine dark matter distribution in detail out to a few hundred kpc for our own galaxy. For our SIM Key Project, observations of proper motions of many galaxies in the Local Group and in the nearest groups can be used to constrain the mass distribution on scales from 100 kpc to 2 Mpc for a range of galaxy sizes and types. In so doing, SIM will provide insight regarding basic cosmological issues. What are the total masses of galaxies? What fraction of the dark matter is baryonic? How does the mass-to-light ratio vary with other parameters of a galaxy? Are there galaxies composed nearly entirely of dark matter? How important were mergers? Do galaxies move through a sea of particles and thereby lose energy by dynamical friction? What is the origin of the rotation of galaxies? What is the history of galaxy formation? What is the origin of the elliptical/spiral dichotomy?

Clues on new stable massed particles could lead to important refinements in theories of the forces of nature. *The clumping scale size of dark matter is a measure of its particle mass* because, for particles in thermal equilibrium in the early universe, mass governs the epoch when the particles became non-relativistic.

SIM has the potential to make the first observations of the proper motions of galaxies at distances beyond the immediate halo of the Milky Way. The Local Group has about 40 known members within 1.5 Mpc. Within 4 Mpc of the Milky Way there are more than 100 galaxies. Therefore, the gravitational potential within 4 Mpc is very well sampled. A good dynamical model for the motions of these galaxies should provide a wealth of information on how the mass is distributed on this crucial scale. The proper motions that SIM will provide are the crucial ingredient that can take the Local Group dynamical models to a higher level of sophistication such that accurate individual masses and mass distributions can be calculated and *unique* orbit solutions can be determined for most of the galaxies.

Orbit calculations from the observed galaxy flows is particularly complex in collapsed or nearly collapsed regions. Difficulties stem from lack of knowledge of the mass distribution, the availability of only the radial component of velocities, and the current poor distance measures. The most advanced method for solving for the flow of galaxies in high density regions is the Numerical Action Methods (NAM), invented by Peebles (1989) and used to create full dynamical models of the flow of galaxies from early epochs to the present. For any set of redshifts, sky coordinates, and mass-to-light ratio, there are usually multiple solutions. This is a natural by-product of the mixed boundary conditions inherent to the problem, which can not be resolved with the available data today. *SIM will provide two additional components of velocity for certain galaxies, and with more and better distance measures, the degeneracy in NAM solutions will be unambiguously broken and a detailed model of the mass distribution can be built.*

We therefore propose a 3-pronged strategy on these issues: 1) Make advancements to the NAM method to take maximum advantage of SIM proper motion measurements as described in Section 3 and 4. This theoretical study is a major share of the work because the field of mass determinations from dynamics of galaxy motions is not fully developed, and the inclusion of proper motions represents a tremendous advance. 2) Obtain proper motions of a carefully selected sample of nearby galaxies with SIM, as described in Section 5. 3) Obtain high-quality distance measures for all of the galaxies within 4 Mpc, described in Section 6.

2. Numerical Action Methods

The Numerical Action Methods were developed specifically to overcome the incompleteness of phase-space information for galaxies needed to do cosmological N-body calculations backward in time from the present galaxy distribution. NAM has been extensively applied to the Local Group in a series of papers by Peebles (1989, 1990, 1994, 1995) and to the Local Supercluster (Shaya, Peebles, & Tully 1995). It has undergone extensive testing and improvements (Phelps 2000; Susperregi 2000; Nusser & Branchini 2000).

The partial dynamical information available in present galaxy catalogs (angular positions, redshifts, and some distances), combined with the reasonable assumption that the early-time peculiar velocities of galaxies were insignificant, comprises a mixed boundary condition problem that is especially well suited to an integral formulation of the equations of motion, called the action,

$$\delta S = \delta \int_0^{t_0} dt \sum_{i=1}^{N} [K_i - V_i] = 0 \qquad (1)$$

where K_i and V_i are the kinematic and potential energies of the N individual mass tracer. V_i includes contributions from each of the other mass tracers in the sample plus a component from the background potential. Solutions are found by iteratively relaxing the set of galaxy orbit trajectories from a random initial configuration.

In the simplest form of the code, the present positions are fixed, and the minimization code solves for the positions at all other time steps and for the velocities at all time steps except at $t_0 = 0$. Recently, alternative action variational principles have been developed (Schmoldt *et al.* 1998, Phelps and Peebles 2000) in which redshift constraints are substituted for distance constraints. The solutions are in general non-unique, and information on galaxy distances is used to partially lift this degeneracy.

NAM solutions are no different in principle from conventional solutions by numerical integration of the motions forward in time of gravitationally interacting matter: both are approximate solutions to the equation of motion. The action methods cannot describe the details in the formation of an extended dark mass halo. However to the extent that the galaxy is a useful tracer of the center of mass of its dark halo, one can obtain a useful description of the dynamical motion of galaxy plus halo. The ratio of halo mass to galaxy luminosity is a parameter to be adjusted since the problem is overconstrained when one has galaxy distances as well as redshifts[1]. When one has proper motions, the problem is so heavily overconstrained that the halo mass and size of each galaxy can become free parameters.

2.1. Past Work on the Local Group

For the sample of galaxies in this project, the time scale for interactions is roughly of order of the age of the universe. Galaxies with large separations in an environment like the Local Group have simple orbits. The relatively uncomplicated regime of our sample can be constrained by the minimum number of phase-space sampling, unlike most other dynamical problems in astronomy.

Previous applications of NAM to the Local Group galaxies, including several dwarf spheroidal companions of the Milky Way, have found orbits consistent with the observed redshifts when mass-to-light ratios were set to $\sim 150 h M_\odot / L_\odot$. In general, the orbits are rather simple curves that mostly infall toward the center of mass of the group. A few galaxies have undergone perhaps an orbit or so around a neighbor. The mass of the Milky Way is then $\sim 3h \times 10^{12} M_\odot$, a value not much greater than the Milky Way mass within a radius of 200 kpc found in other studies. Such a small mass and halo size is in conflict with CDM simulations.

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[1] Neglect of this consideration, that one must consider the ratio of observed to total mass belonging to each mass tracer, caused the failure of Dunn and Laflamme (1995) to reproduce orbits.

However, the distance determinations are very poor, and it is possible that the assumption of a constant mass-to-light ratio is leading us astray. The availability of proper motions will allow us to drop that assumption.

2.2. Evaluation of Model Results

There are a number of ways to evaluate how well a NAM model represents reality. A goodness of fit can be based on differences between model and observed distances after the redshifts are made to agree. We also check that the predicted distances are statistically better than Hubble Flow predicted distances. Most of our experience with model evaluations comes from studies of a sample within redshifts 3000 km/s with a large sample of distance measurements from the Tully-Fisher (1977) technique. At present, distance uncertainties are typically 25%, while peculiar velocity flows are only 10% at redshifts of 1000 km/s. Therefore, evaluation of models is somewhat hampered by the fact that observational errors dominate. In the Local Group region, this could be reversed; *distance errors could be reduced to less than 10% with a moderate effort and peculiar flows are, of course,* $\geq$ 100% *of Hubble Flow.*

2.3. Evaluation of the Methods

2.3.1. High-Order Zel'dovich Approximations

A family of convenient approximations (Nusser et. al. 1991, Buchert 1992, Gramann 1993) to gravitational instability is based on the Zel'dovich approximation (Zel'dovich 1970). These approximations are a significant improvement over linear theory and provide a reasonable description of the gravitational evolution in regions where the density is a few times the mean density. Although not as accurate as the NAM, these approximations are useful for monitoring the complicated machinery of NAM; they are easily implemented and provide a convenient framework for the analysis of systematic errors. *They clearly demonstrate that the present velocity and density fields are tightly related independent of the merger history of the large scale structure.*

2.3.2. N-body Evaluation of the Method

Recently, we have tested the ability of the NAM to correctly recover cosmological parameters with a set of high resolution N-body simulations from Gross (1998). These large-scale particle-mesh simulations were used to create mock observational catalogs for input to the action code. The catalogs are comprised of "galaxy halos" defined by a particle overdensity criterion. There is substantial matter in the simulation between the identified halos, so this tests the response of the NAM code to complex environments. The velocity dispersion of particles in the simulated catalogs was often substantially greater than that in the real universe, so the test turned out to be especially challenging. Even so, NAM recovered Ω_0 and t_0 (with $<$ 20% rms errors in distances), produced by the N-body simulations, for four out of five paradigmatic scenarios (Phelps 2000): standard cold dark matter (SCDM), open CDM, cold plus hot dark matter, and a tilted initial spectrum CDM. In the tilted Λ initial spectrum CDM simulation, there were excessive rms peculiar velocities which is due to a numerical issue pertaining to the creation of the simulation as discussed by Gross *et al.* (1998). The amplitude of the rms errors from NAM are about at the level expected given the assumption of a constant total mass to particle mass and the multiplicity of solutions resulting from the high velocity dispersions. An independent study was similarly successful (Susperregi 2000).

3. Proper Motion Analyses

In recent work by Ph.D. candidate Phelps (supervised by Peebles), a fixed redshift NAM code was applied to individual galaxies and groups out to 6 Mpc in distance. A total of 52 objects were included in the analysis. A large number of runs were made in which the parameters $\Omega_\Lambda = .7, \Omega_M = .3, H_0 = 75$ were fixed. A range of M/L was considered, but all mass tracers (i.e., galaxies and groups) for a given solution shared the same M/L. In Figure 1 the orthogonal components of proper motions for several galaxies are presented for solutions that meet a goodness-of-fit constraint. There are often three families (tight clusters) of solutions for each individual mass tracer. A proper motion observation that restricts a galaxy to a particular family results in a substantial reduction of solutions and thus restricts the set of possible families for *all* galaxies. Almost all of the proper motion amplitudes and most of the differences between solutions are well within the detection range of SIM.

Figure 1 and plots like it reveal that changes in the mass of a major galaxy by 50% can result in proper motion changes of ~ 40 km/s for adjacent galaxies (see, Shaya *et al.* 1999). Some galaxies cease to have reasonable solutions when the mass of a neighbor is out of a restricted range. The determination of total masses of major galaxies to 25% is quite feasible. There can be discrimination between families of models with only 25 μas/yr proper motion accuracy. Therefore, a performance degradation of SIM of a factor of ~ 10 in positional accuracy from goals would still leave much of the science intact.

The tidal forces from structures beyond the Local Group proper also play a *significant* role in the dynamics. Local Group models require inclusion of the effects of the surrounding environment out to fairly large distances. The proposing team has two decades of experience doing just that. Our continuously updated galaxy catalog that maps the density field currently consists of **35,000 galaxies within 10,000 km/s**.

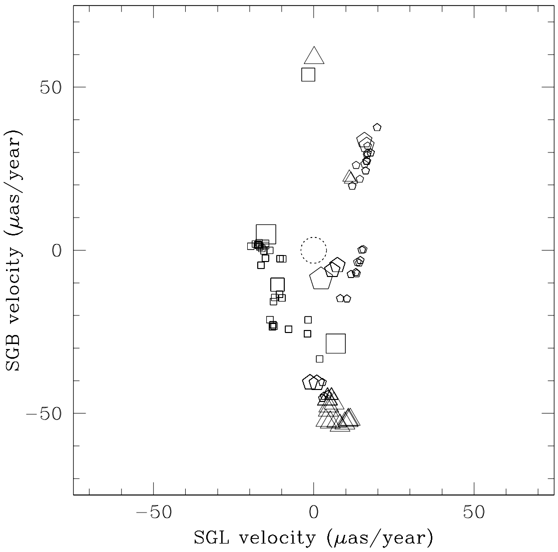

Fig. 1.— Proper motion predictions from NAM calculations involving 52 nearby galaxies. Results are shown for three galaxies, M31 (triangles), WLM (squares) , and Leo A (pentagons), in supergalactic coordinates. Many trials lead to the population of ~ 3 families of good solutions for each system. Quality of solutions are judged by a comparison of model and measured positions. Size of symbols are proportional to the M/L of the model: 50, 100, or 150. A proper motion uncertainty of 4 μas/yr is indicated by the dotted circle at the origin. SIM observations would cleanly discriminate between the separate families of solutions allowed by present information on positions and redshifts.

3.1. Individual Mass Determinations

With accurate distances and redshifts, one has a total of seven constraints per galaxy (or group): right ascension, declination, distance, redshift, and the three components of early time peculiar velocity set to zero. Solutions are overconstrained by one variable, which formally allows one to solve for total masses for each galaxy. *Recently, we have invented a technique that solves for individual total masses.* The procedure is to adjust each mass estimate by a fixed percentage (first upward, solve for orbits, and if distances are not predicted better, then downward). One cycles through each of the dominant galaxies until one finds no substantial improvement in predicted distances. The entire procedure must be repeated many times with different random initial orbit guesses and different mass ratios. With 52 galaxies, about two dozen families of solutions are discovered (each distinguished by at least one galaxy taking a radically different route to near its present position).

We have been running timing tests of this procedure using processors at the Maui High Performance Computing Center (IBM RS/6000 SP2s). To find 48 sets of local minimum in distance errors by varying 14 masses in a 14 particle sample, takes roughly 30 minutes. Only two or three of the 48 solutions have acceptably low distance errors (rms 10%). However, to ensure finding the particular solution with both correct distances and proper motion might take over 100 attempts, 5 hours on an 8 processor machine. The largest massed galaxies are estimated to about 20% accuracy and the galaxies an order of magnitude less massive are estimated to 40% accuracy. The mass estimates scale linearly with assumed value of H_0. If the global mass density is not well determined, separate sets of solutions need to be found for a range of values of Ω_M. Because the systems span a wide density range, from near Hubble flow to non-linear collapse, acceptable solutions will exist only for a very narrow range of Ω_M.

At present, most real galaxies within 5 Mpc do not have adequate distance determinations for this inversion for masses. Nevertheless we have forged ahead and tried this technique for illustrative purposes only. The orbits from one such solution, with the nearest 52 galaxies and groups, is shown in Figure 2. The differences between model and observed distances are shown in Figure 3. Much of the remaining residual errors are due to the poor distance measurements available and to the lack of forces from any matter outside of the sample volume.

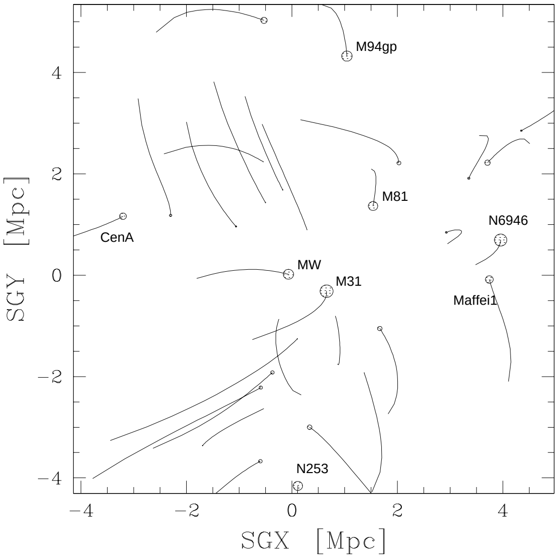

Fig. 2.— The trajectories within 5 Mpc of the Milky Way. The 52 orbits are from solutions with 12 masses adjusted to best fit the present distances. Present positions are circles. The sizes of the circles are proportional to masses. Distance measurements for 37 galaxies were available and guided the mass solutions. Note that the crossing times are comparable to the age of the universe so the orbits are relatively simple.

4. Proposed Work on Theory

Most of the proper motion measurements will not exist until nearly the end of the 5.5 year mission, but in the meantime we propose to advance the theoretical machinery to be prepared for most reasonable outcomes. Over the next few years the cosmological parameters will probably be constrained by the microwave background experiments, and N-body simulations will narrow in on a set of likely scenarios for structure formation. *One of our jobs is to hone NAM techniques with these*

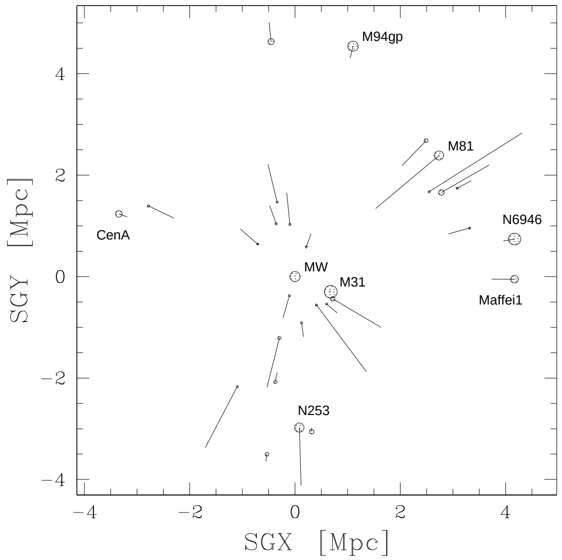

Fig. 3.— Comparison of observations with model positions. Model was the same as previous figure. Positions projected onto the supergalactic plane are shown (dots are observations, end of lines are model predictions) for a catalog of 52 galaxies. The residual errors are dominated by distance uncertainties and the neglect of tidal fields from external sources.

simulations. First, it has to be demonstrated that NAM recovers the known parameters of any reasonable simulation and, second, there must be an understanding of the constraints of sample variance since we only get to sample one $\sim$ 4 Mpc radius region around the Milky Way.

4.1. Statistics of Velocities

When we have obtained substantial proper motion data from SIM, it would be a good idea to run some sanity checks with the best N-body simulations. If our basic assumptions of cosmology and gravitational formation of structure are correct, measured statistics of total velocities should be roughly predicted by some simulations. *We will extract statistics on Local Group like entities from a best set of these simulations to test for agreement with observations on basic statistical properties.* Some useful statistics to investigate are ratios of radial-to-tangential velocity with respect to group centers of mass, velocity ellipsoid shape, pairwise velocity statistics, and velocity-velocity correlations.

Correlations between galaxy peculiar velocities and the potential field from neighboring galaxies (see Fig. 4) follow from the cosmic virial theorem (Peebles 1976). and can be applied to SIM total velocities to put rough constraints on the masses (Nusser *et al.* 1991). *One can assign mass (potential) estimates to those galaxies with lightweight neighbors, provided the neighbors have 3-D velocity measurements.* The cosmic virial theorem has only limited utility if only radial velocities are available because peculiar velocities can only be extricated from the Hubble expansion on a statistical basis, through coupling with the 2-point angular correlation function. Proper motions are orthogonal to the expansion so they provide a direct measure of peculiar velocities.

4.2. Backward N-body Calculations

If one knew all six present phase-space coordinates and masses of all of the major galaxies in a volume limited region of space, then one could calculate galaxy motions, starting with the present distribution, backward in time to when the mass distribution was nearly homogeneous. However, In addition, distances and proper motions will, for the foreseeable future, have significant uncertainties, so ranges in each of these parameters will have to be explored. Therefore, one would needs to develop an iterative technique to find solutions that satisfy the additional three early time constraints such that each of the components of peculiar velocity were small.

Investigation of the large parameter space will require long computation times. However, in certain restricted problems this procedure is reasonable. It can be aided by the analytical

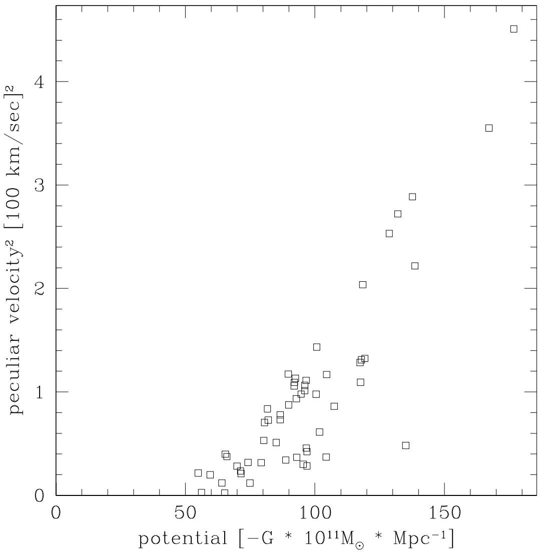

Fig. 4.— Peculiar 3-D velocity versus amplitude of local gravitational potential. These results are based on 52-particle N-body simulations with varying M/L, designed to recover the conditions around the Local Group.

solutions for the restricted 3-body problem (Mishra & Agrawal 1985). For instance, we expect to have excellent distance and proper motion measurements for the three most massive objects (Milky Way, M31, and M33). This technique should work well for solving just the orbits of these three. It is warranted here because M33 may have made two or threee orbits about M31 which requires many time steps to properly simulate. Other Local Group galaxies with measurements of similarly high accuracy could be included in this computation. We therefore propose to adapt N-body routines to include an iterative "shoot-through" technique to the early time constraints. The Zel'dovich (1970) approximation can be used to set the early time constraints.

However, when the number of objects to calculate gets large and some galaxies have large distance uncertainties or no proper motion measurents, this technique of hunting for parameters is too cumbersome and one must resort to NAM-type calculations.

4.3. Reconstructing Initial Perturbations

Information on the initial fluctuations can be recovered by transforming the Zel'dovich approximation into a time evolution equation for the velocity potential, $\Phi_v(\mathbf{x}, t)$, in Eulerian space. This equation is reminiscent of the Bernoulli equation and is consequently termed the Zel'dovich-Bernoulli equation (Nusser & Dekel 1992). It is expressed as $\dot{\Phi}_v - \dot{D}/2\Phi_v^2 = 0$, where D is the amplitude of the growing mode of linear perturbations. This equation can be integrated backward in time to yield the Φ_v at recombination, which can then be derived to obtain the anisotropies δ using the linear theory relation. It should be possible to use NAM to reconstruct the mass distribution back to a time when the dynamics is well represented by linear perturbation theory, and then switch to Zel'dovich approximations to give an accurate evaluation of the small-scale inhomogeneities at recombination.

4.4. Dynamical Friction

In some CDM and HCDM simulations, there is a lot of matter at rather high velocities that is not gravitationally bound to any system, even at the present epoch. In these cases, the galaxies would undergo moderate kinetic energy loss due to dynamical friction as they travel through this swarm of orphaned particles. The addition of a dissipation term, that would be a simple function of an assumed density of unbound matter and galaxy peculiar velocity, could simulate the dynamical friction losses. This will also be useful when we attempt to follow galaxy mergers or close interactions.

4.5. Dark Objects

An object at, or just beyond, turnaround may not yet be bright with stars, but could exert a substantial gravitational influence. Conceivably, there could be nearby systems composed nearly entirely of dark matter. One cannot *a priori* add these into the calculations, but their existence could be deduced from organized discrepancies between observations and best-fit models. Predicted distances will tend to be in error by a shift toward the invisible object. Predicted velocities, at a position specified by distance measurements, will be in error by a vector pointing away from the object.

4.6. Many Particles per Mass Tracer

A legitimate concern for the NAM, as it is presently coded, is that it follows the center of mass of the atoms and particles that comprise each present-day galaxy. If the major phase of assembly of matter into bound protogalactic objects happened at $z > 3$, then NAM should provide accurate orbits. However, if the assembly of galaxies was mostly at $z < 3$, and the subcomponents were not neighbors, but independent group members that only recently got caught in each other's potential, then NAM could have substantial errors.

We will develop a more advanced NAM code that allows each galaxy today to be represented by many equal-mass subunits that are nearly co-spatial. This will be a hybrid of traditional N-body calculations and NAM that can be used to study effects of late-time merging. Dynamical friction simulated in the NAM code would allow the subunits to merge and remain merged. The mean binding energy of these subunits could be altered to explore different merging rates. The early-time mass distribution would be more detailed, because of the use of many more mass points.

5. SIM Observations

The SIM wide-angle mode goal of a proper motion measurement of 2μas/yr corresponds to a transverse velocity of $10d$ km/s, where d is the distance in megaparsecs. One-dimensional proper motions are anticipated to be on the order of 100–200 km/s and should be an order of magnitude higher in the vicinity of the Virgo Cluster. Hence, from the standpoint of proper motions alone, there would be targets of acceptable amplitude in the general field out to distances of $\sim$ 10 Mpc and targets throughout the Virgo infall region, extending to roughly 20 Mpc.

The SIM magnitude limit of V$\sim 20^m$ is considerably more restrictive. The brightest individual stars in galaxies with very recent star formation have magnitudes $M_V \sim -10^m$. Such stars could be observed with SIM out to a distance modulus of 30, or $d = 10$ Mpc. However, stars this bright are uncommon. The brightest Population II stars at $M_V = -3^m$ can only be observed within 400 kpc, so systems with just old stars are inaccessible beyond the immediate confines of the Milky Way. Hence SIM targets are restricted to galaxies with recent star formation.

5.1. Criteria for Galaxy Selection

The nearby galaxies that are accessible to SIM reside in a flattened cloud with four principal clumps. This cloud is part of a filamentary structure that can be followed all the way to the Virgo Cluster, but the local components that concern this experiment are the M81, Maffei, Local, and Sculptor groups. Seven galaxies in this region contain 80% of the light and are suspected to trace the dominant gravitational potential wells. The Local Group is itself a bound system congregated about the M31 and Milky Way giants. A smattering of galaxies reside about the Local Group but apparently are not bound units. This smattering extends to the Sculptor structure, which contains one big galaxy, NGC 253. This entire region is relatively uncomplicated, and SIM will provide good phase-space information for the reconstruction of orbits. At the edge of the domain accessible to SIM are the M81 and Maffei groups, with four big galaxies between them (M81, IC 342, and Maffei I, II). This region is confusing because it is intersected by the zone of obscuration. This Key Project will concentrate on the dynamics of the bound Local Group and the relatively simple Sculptor region and make whatever headway is possible with the M81/Maffei complex. The local gravitational field will be probed by the study of 27-29 galaxies with SIM.

The list of galaxies with stars sufficiently bright to be viewed by SIM is sufficiently small (29), so that it is quite reasonable to attempt to observe almost all of them. As many "test particles" as feasible should be observed, since we can only draw from the sprinkling of phase space where nature gives us objects. Certain galaxies are more providently located than others as probes of the dark matter halos around big galaxies. But all contribute to a better understanding of the tidal field exerted by larger structures, the mean overdensity of the sample, and the reality of unseen clumped matter. The random motions of gas and the young stars born from this gas have typical values of ~ 10 km/s (van der Kruit & Shostak 1984). The mean rotation in galaxies can be determined from either HI synthesis or optical spectroscopic observations to 10 km/s in favorable cases, degrading to 20 km/s in less favorable cases. The situation is more complicated in massive galaxies with large rotation amplitudes and simpler in dwarfs with rotation as low as ~ 10 km/s for the smallest systems. The proper motion of a dwarf may be constrained by only a couple of stars, while five stars might be needed in a big galaxy.

5.2. Criteria for Star Selection

The details of star selection will motivate extensive observations before the launch of SIM. Stars in confused star formation regions, some binaries, and variable stars will be inappropriate. Spectra will be obtained of all candidate stars prior to inclusion in the program. Binaries with motions > 10 km/s and stars with symbiotic spectra can be distinguished. Photometric monitoring will reveal variables. An effort will be made to obtain Hubble Space Telescope images of target regions to cull out objects with structure at the $0\farcs02$ level. Issues to do with crowded fields are discussed in section 5.6.

Presently, the information on the brightest stars in nearby galaxies is extremely sparse, though the observations necessary to correct the situation are straightforward with current instrumentation. The Key Project team has adequate access to facilities to carry out the pre-launch observations. Tonry and Tully at the University of Hawaii have access to the four 8–10 m class telescopes on Mauna Kea as well as smaller telescopes, and Zaritsky has access to the 6 m MMT, the two 6.5 m Magellan telescopes, and the twin 8.4 m Large Binocular Telescope.

Serendipitously, the most favorable stars for SIM observations have luminosity-dependent characteristics that provide an indication of their distances. The brightest stars at V-band tend to be type-B and A supergiants with Balmer series equivalent widths that are strongly dependent on intrinsic luminosity. Spectroscopy intended for star selection will simultaneously provide accurate distances to the host galaxies. The importance of good distances is discussed in section 6.

5.3. Exposure Times

All conceivable galaxy targets (*i.e.*, those with $V < 20^m$ stars) were inventoried. Then, with a

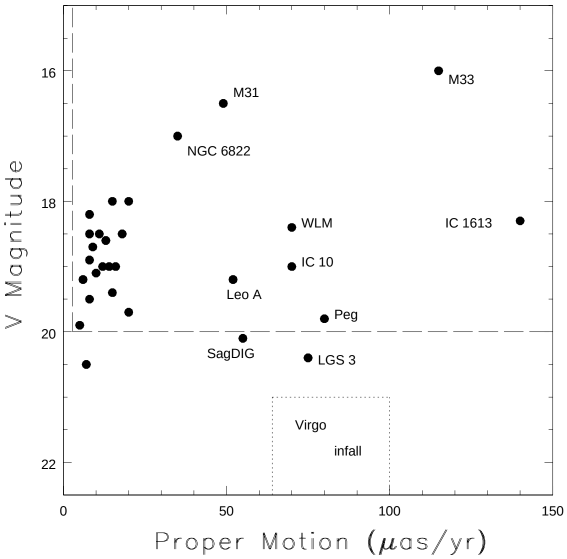

Fig. 5.— The principal observing constraints: anticipated proper motions and brightness of stars. The V-band magnitude of the 5th brightest candidate star in each galaxy is plotted. The nominal SIM observing limits are delineated by dashed lines: $V = 20^m$ and 4 μas. The anticipated proper motions are determined from NAM calculations involving 52 nearby galaxies (Phelps 2000). The values plotted are 1-D proper motions representative of the mean of many trials. Proper motions more than an order of magnitude above the SIM limit are expected in 10 cases. For 7 of these, the brightest stars are at least 1^m brighter than the SIM sensitivity limit. A region in the figure is labelled 'Virgo infall'. Galaxies falling into the Virgo Cluster at 1500 km/s would have easily detectable proper motions but their brightest stars are too faint. It remains to be determined if the centroid of an active nucleus can be used to determine the proper motion of any galaxies in the Virgo region.

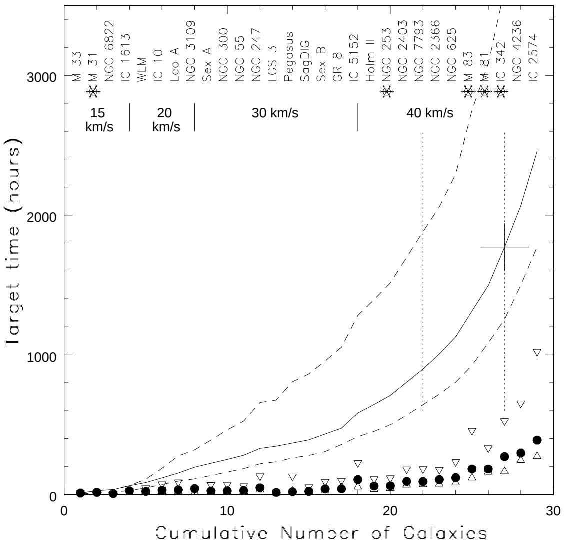

Fig. 6.— Cumulative target time. SIM observing time required per galaxy is indicated by the filled circles. Lower triangles give time requirements for a 100% acceptability rate for candidate stars. Filled dots and upper triangles use a 50% acceptability rate, but the upper triangles reflect 10 km/s accuracy. The targets are ordered from the easiest cases at the left to the more difficult cases at the right. Cumulative time requirements are given by the solid and dashed curves. Anticipated rms velocity accuracies degrade as indicated below the galaxy identifications. The five giant galaxies that should track the dominant halos are indicated by snowflakes. The 5% and 10% allocation of SIM time are shown as the vertical dotted lines. The observing time allocation requested, 1770 hrs, is indicated by the large cross.

list of brightest candidate stars in hand, Table 2 in the SIM Wide Angle Astrometry Timeline was consulted for estimates of mission time per visit to each star for a specified astrometric accuracy. The stars are toward the faint limit of the SIM capability, so there would be an exposure time penalty for extreme precision per star. Fortunately, we will require a typical precision no better than 40 km/s per star.

Target integrations are based on the following considerations:

$$\Delta v_s = \sqrt{2} \cdot 5 d \Delta\alpha / \Delta t$$

where Δv_s is the proper motion error in km/s resulting from two measurements of the positions of a star each of accuracy $\Delta\alpha$ in μas for a galaxy at d Mpc and observations separated by Δt years. Observations of N stars in a galaxy combine to give an overall 1-D proper motion accuracy of Δv_g where

$$\Delta v_g^2 = (\Delta v_s^2 + \Delta v_d^2)/N.$$

Here, the deviant motion, Δv_d, from the rotation-corrected systemic velocity is conservatively taken to be $\Delta v_d = 20$ km/s. The baseline between observations is taken to be $\Delta t = 4$ years. For purposes of trial calculations, $N = 5$ stars/galaxy. Hence, a required accuracy $\Delta\alpha$ is defined for a specified $\Delta v_g/d$.

For the nearest galaxies with bright stars, we are in the domain of minimal mission time/target and it is efficient to push to small $\Delta\alpha$, such that $\Delta v_g \sim 15$ km/s. Galaxies with large d and faint stars are only tractable if Δv_g is allowed to degrade.

Our observing strategy is summarized in Figure 5, Figure 6, and Table 1. There are 29 feasible galaxies. Fig. 5 shows the locations of the potential targets in the domain of the two principal selection considerations, anticipated proper motions and brightness of stars. See the figure caption for details. Fig. 6 summarizes the observing time requirements. The order from left to right in the figure is basically from easiest to hardest for SIM observations. The targeted accuracy is allowed to degrade from 15 km/s to as poor as 40 km/s proceeding to the more difficult cases. The solid curve tracks the cumulative target time for our expectation scenario. The lower dashed curve tracks the cumulative required time with an optimistic list of candidate stars (which requires that most of our initially identified stars not be binaries with separations $< 0\rlap{.}''04$). The solid curve accepts a more conservative return of useable stars off the candidates list. The upper dashed curve uses the conservative return of useable stars and entertains target accuracies 10 km/s better. The penalty for better accuracies is severe. The uncertainties associated with the yield of useful stars are much smaller.

5.4. Priorities and Sample Cut

The five giant galaxies in our sample are tagged with snowflakes in Fig. 6. Unfortunately, three of these are at positions 25, 26, and 27 in the order of difficulty. Still, they are tractable as SIM targets. The giant galaxies are the most probable tracers of the dark matter potential wells, so they are of particular interest.

Nearby galaxies are strongly constrained to a flattened plane, and Figure 7 illustrates the distribution of local galaxies in supergalactic coordinates. Galaxies in this plot are all within ±2 Mpc of the supergalactic equator. The 29 galaxies on our target list are represented by filled circles. Galaxies with $L_B > 10^{10}\ L_\odot$ are given large symbols. All large galaxies in the volume under consideration are included; it is exceedingly unlikely that any other nearby giant galaxy lies undetected in the zone of obscuration. Not all dwarf galaxies are plotted. Many dwarfs are known or suspected to be associated with the groups seen in this figure, though distances are poorly known for most.

The filled circles in Fig. 7 predominantly sample three domains:

1. There are the nine galaxies within 1 Mpc of the Milky Way and with $SGY < 0$, the traditional region of the Local Group. M 31 and the Milky Way (MW) dominate this region. The halos of these large systems are probed by 8 small galaxies on scales of 200 kpc to 1 Mpc.

2. There are 12 more galaxies drawn from a structure that extends the Local Group into a cloud confined to $-3.5 < SGY < 1.5$ with $SGX \sim 0$. The only large galaxy in addition to M31/MW in this extended region is NGC 253, the

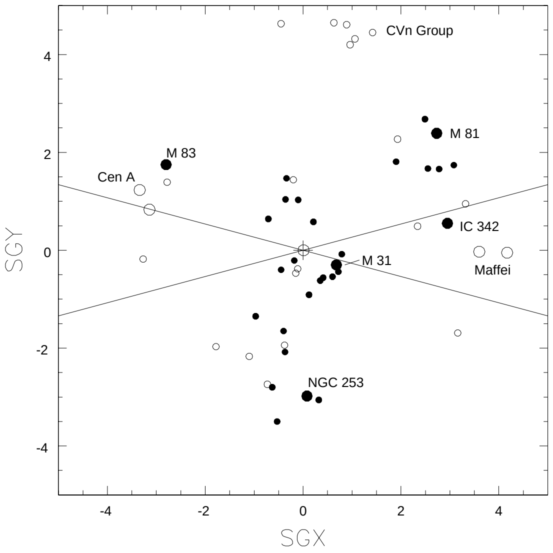

Fig. 7.— Location of galaxies in supergalactic coordinates centered on the Milky Way. The zone of obscuration ($\mid b \mid < 15$) is identified by the horizontal wedges. Galaxies with $\mid SGZ \mid < 2$ Mpc are plotted. Big symbols: $\log L_B > 10$. Filled symbols: 29 potential SIM targets.

heart of what has been called the Sculptor Group. This region is reasonably uncomplicated. There are no issues of obscuration and no large objects lurking in the immediate background.

3. Seven more galaxies are associated with the M 81 and IC 342/Maffei groups. The dominant galaxy scale perturbations on the Local Group are expected to arise from IC 342, then the two Maffei galaxies, then M 81. Hence, this region is important to understand. Unfortunately, it is cut by the zone of obscuration. We sample as nature allows.

The only other major galaxy in our sample is M 83. It is a member of the next group out, the Centaurus Group. In addition to M 83, this group contains Centaurus A, NGC 4945, and many small systems. It is a complicated region and extends into the zone of obscuration. Fortunately for our purposes it is set off from us by a fair gap. A serious study of this region is beyond the capability of SIM.

Returning to Fig. 6, we draw attention to the large cross at galaxy 27 and 1770 target hours. This mark identifies our requested allocation for this Key Project. With this allocation:

- All five giant galaxies that are accessible in the region extending from the Sculptor Group to the M 81 group will be observed (only the Maffei galaxies cannot be observed).
- Proper motions for eight galaxies within 1 Mpc will be obtained with an rms accuracy of ±20 km/s. For ten additional galaxies mostly within 2 Mpc, proper motions will be measured to ±30 km/s. For nine more galaxies extending out to 4 Mpc, proper motions will be obtained good to ±40 km/s.

5.5. Galaxy Kinematic Parallax Key Project

Our team has had discussions with Deane Peterson, PI of a Key Project proposal to determine the kinematic parallax distances of galaxies. The attention of that proposal is on M31 and M33, with possible consideration of one or two other systems. If that Key Project goes ahead, then it will provide data, for those few galaxies, that is more than adequate for our purposes. Peterson has offered to us the use of a restricted set of their SIM data to avoid a duplication of effort. Similarly, pre-launch target star investigations will be coordinated for the few galaxies of common interest.

5.6. Dealing With Crowded Fields

Some target fields will be crowded and will require special observation and analysis techniques. For example, a second star 1% as bright as the target can alter the phase by as much as 0.01 rad, leading to position errors as large as 20 μas. Fortunately, steps can be taken to greatly reduce problems associated with the complex fields likely to be encountered by this project. The optimum strategy depends on the brightness, number, and distribution of stars, and on the observing modes and capabilities that ultimately are available with SIM. The preliminary conclusions presented here are based in part on simulations using the MIRIAD interferometric suite of programs (Sault, Teuben, and Wright 1995). Programs were modified to simulate and fit the effects of broad optical bandwidths. The simulations included scaling HST LMC stellar fields (Zaritsky *et al.* 1997) to distances of 1 Mpc and 3 Mpc; we refer to these as the "LMC-1Mpc" and "LMC-3Mpc" simulations. Fields centered on the dozen brightest stars in an 8′ LMC region were selected. The LMC-3Mpc fields had up to 4 stars within five magnitudes of the target star lie within a 2″ diameter field of view. Below we briefly discuss several strategies for identifying and reducing the errors associated with crowded fields.

The strategy that will work for most targets is to select baseline orientations that attenuate secondary stars. Also, the large fractional bandwidth can result in significant attenuation, provided the secondaries are several resolution elements from the delay center. The key to attenuation is to avoid baseline angles perpendicular to the separation vector between the target and the secondary; such orientations can be predetermined from high resolution imaging. Most simulations were with rectangular passbands, although more tapered bands would result in less systematic error. For all but one of the 12 LMC-1Mpc fields, *wide orientation ranges are available over which the secondaries cause insignificant error (rms < 1 μas) in the position.* Even for the more crowded LMC-3Mpc fields, half of the targets can be observed with insignificant error. An example with eight stars is shown in Figure 8.

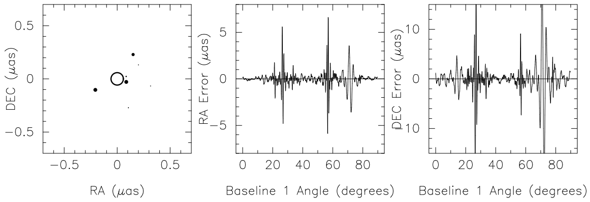

Fig. 8.— (Left) LMC field scaled to a distance of 3 Mpc. In addition to the target, seven stars 4 to 7 magnitude fainter are present. (Middle and Right) Error in the RA and DEC derived from single-star fit to data in left panel using two perpendicular 10-m baselines, as a function of the orientation of baseline 1. Baseline angles with large errors correspond to position angles of secondary stars.

Multiple baseline orientations or multiple spectral channels also have advantages. Either will help identify secondaries unresolved by pre-flight imaging which distort the astrometry. Also, either may enable astrometric fitting of multiple stars. The choice will depend on tradeoffs, such as overhead in obtaining multiple baselines versus possible increased read noise with multiple channels. The spectral approach requires either fitting the colors of each star, or determining them from other observations.

Fitting multiple unresolved stars is difficult. Another strategy to mitigate effects of such close binaries is to repeat the baseline orientations, pointing center, and delay center as closely as possible from epoch to epoch. If these could be set sufficiently close, *systematic errors would be reduced, again to insignificant levels, by using the difference in derived position or other differential techniques.* The baseline angle would have to be repeated within 1° to allow significant reduction in the proper motion error due to a secondary located within $0\overset{''}{.}01$ of the target. Brightness variations (most likely to occur in the luminous target star) could cause difficulties with differential techniques, so the flux at the two epochs should be compared either using the visibility amplitude or ground-based monitoring.

In summary, for most target fields, a simple strategy of careful selection of baseline orientation should reduce the errors associated with crowded fields to an insignificant level. Close binaries and more complicated fields can be dropped from the target list or will require more complex methods; the precise methods will depend on the ultimate configuration and capabilities of SIM. Factors that would help in this regard include 1) a field stop at the smaller end of the size range considered; 2) accurate measurement of complex visibilities; 3) reproducible baseline orientations, pointing, and delay centers; 4) ability to select baseline orientation tailored to target; and 5) multiple spectral channels (allowing bandpass taper and more complex fitting) while minimizing S/N degradation.

6. Independent Distances

It is anticipated that other observations with SIM and FAME will greatly improve the calibration of methods to determine distances to galaxies. For example, precision should be added to the methods that relies on the period–luminosity relation of Cepheid stars and RR-Lyrae stars. In addition, SIM has the capability to directly measure the distances to nearby galaxies by combining information on the proper motions of stars with rotation curve information. A complementary Key Project proposal promises to make these measurements.

Distances are a critical component in the modeling of galaxy orbits. Our Key Project team proposes to engage in a campaign to determine distances to all our targets and all other accessible galaxies within 5 Mpc. Two independent methods will be pursued that are both intimately connected to the programs that must be undertaken in any event to select SIM target stars. We must obtain the highest possible resolution images of the fields of candidate stars. With HST images, we can look for complexity at the level of $0\farcs02$. Comparable accuracy can be achieved with adaptive optics and K-band observations with the Gemini Telescope. These same observations can be used to obtain distances to the host galaxies by making use of the known stability of luminosity of the TRGB for metal–poor stars (Lee *et al.* 1993). We must also take spectra of candidate stars to ascertain if they are symbiotic or binaries with substantial motions. The most favorable stars for our program, A,B supergiants, have strongly luminosity-dependent spectral signatures. The equivalent widths of the Balmer series of Hydrogen become increasingly narrow in absorption in the low effective gravity envelopes of the most massive supergiants (Tully and Wolff 1984; Kudritzki *et al.* 1999). Both the TRGB and supergiant wind–momentum methods are capable of giving distances at the 10% level of accuracy. The dual nature of our observing programs will make it more assured that ground-based and HST facilities will be put at our disposal for observations necessary for SIM.

7. Summary

Other SIM projects will focus on the dynamics of our Galaxy and its entourage of companions. For our Galaxy and its satellites dynamical times are much less than the age of the Universe, while the interactions between galaxies in our sample are occurring with dynamical times comparable with the age of the Universe. Objects in and around our Galaxy follow orbits that are complex while galaxies with large separations in an environment like the Local Group have simple orbits. The relatively uncomplicated regime of our sample can be constrained by phase-space sampling that is coarse compared with the requirements of the Galactic problems.

Measurements of proper motions of just a few nearby galaxies will strongly overconstrain solutions for the current set of dynamical models of the Local Group of galaxies. Combined with improved distances to the nearby dwarf galaxies that serve as "test particles", these observations will provide stringent constraints on the distribution of mass in and near the Local Group. The results will be a guide to the nature of the elusive dark matter and to the processes of structure formation since the Big Bang.

If the mass of the Local Group proves to be dominated by an extended halo component, as anticipated by the adiabatic CDM theory for structure formation, the challenge would be to understand why the nearby dwarfs cluster so strongly around the large galaxies or, conversely, why there are so few dwarf galaxies at-large in the groups. If the dynamics demonstrate the presence of a nearby massive dark galaxy, it would be a dramatic addition to our concept of structure on the scale of galaxies. If the mass is found to be concentrated tightly around the observed galaxies, it could be indicating that the dark matter is self-interacting, or behaves as matter described by a self-interacting classical field, or perhaps it is even baryonic matter now hidden in compact objects. Because the Local Group is so close, we can and must examine it in the exceptional detail needed to improve our understanding of the nature of mass and structure.

The issue of dark matter is one of the fundamental problems of astronomy and it is not evident that we will ever do better than infer the properties of this material from its gravitational influence. The scale of dark matter clustering is greater than the size of visible galaxies but, apparently, smaller than megaparsecs. For the forseeable future, it is a scale that can only be probed by SIM. It would be wonderful if a modest fraction of SIM observing time leads to important constraints on the nature of dark matter.

Table 1

Information about Target Galaxies

ID[a]	Name[b]	$\log(L/L_{M31})$[c]	d[d] (Mpc)	Δv_g[e] (km/s)	$\Delta\alpha$[f] (μas)	V_1[g] (mag)	V_5[h] (mag)	V_{10}[i] (mag)	time[j] (hrs)	$\sum$ time[k] (hrs)	flag[l]
1	M 33	−0.9	0.8	15	19	15.5	16.0	16.5	12	12	1
2	M 31	0	0.8	15	19	16.0	16.5	17.0	17	29	1, big
3	NGC 6822	−2.4	0.5	15	30	16.6	17.0	17.6	7	37	1
4	IC 1613	−2.6	0.7	15	21	17.2	18.3	18.4	27	64	1
5	WLM	−2.7	0.9	20	26	17.9	18.4	18.6	23	87	1
6	IC 10	−1.7	0.8	20	29	18.6	19.0	19.5	32	119	1
7	Leo A	−3.6	0.7	20	33	18.8	19.2	19.8	35	155	1
8	NGC 3109	−1.9	1.3	20	18	17.3	18.5	18.8	43	197	2*a*
9	Sex A	−2.7	1.4	30	26	17.5	18.6	18.9	27	224	2*a*
10	NGC 300	−1.1	2.1	30	17	17.0	18.0	18.2	28	252	2*b*
11	NGC 55	−0.9	1.7	30	21	17.5	18.5	18.8	30	282	2*b*
12	NGC 247	−0.8	2.5	30	14	17.0	18.0	18.4	50	332	2*b*
13	LGS 3	−4.5	0.8	20	29	18.6	20.4	21.4	16	348	1
14	Peg DIG	−3.5	1.0	30	36	18.4	19.8	20.5	21	369	1
15	Sag DIG	−3.3	1.0	30	36	19.5	20.1	20.4	24	392	1
16	Sex B	−2.8	1.3	30	28	18.7	19.0	19.6	42	434	2*a*
17	GR 8	−3.8	1.6	30	22	18.8	19.1	20.7	42	476	2*a*
18	IC 5152	−2.4	1.7	30	21	18.3	19.4	20.0	108	584	2*b*
19	Holm II	−1.7	3.0	40	16	17.4	18.2	19.0	62	646	3
20	NGC 253	−0.3	2.8	40	17	17.0	18.7	18.9	63	709	2*b*, big
21	NGC 2403	−0.7	3.2	40	15	17.8	18.9	19.5	95	804	3
22	NGC 7793	−1.0	3.3	40	15	18.0	19.0	19.2	94	899	2*b*
23	NGC 2366	−1.5	3.4	40	14	18.3	18.5	19.2	108	1007	3
24	NGC 625	−2.0	3.3	40	15	18.0	19.2	19.5	122	1129	2*b*
25	M 83	−0.5	4.0	40	12	18.0	19.0	19.5	184	1313	4, big
26	M 81	−0.2	3.6	40	14	18.7	19.5	19.6	184	1497	3, big
27	IC 342	−0.1	3.5	40	14	18.5	19.7	20.1	272	1769	3, big
28	NGC 4236	−1.0	3.5	40	14	19.1	19.9	20.4	298	2067	3
29	IC 2574	−1.8	3.5	40	14	19.1	20.5	20.5	390	2457	3

[a] Running number. Galaxies roughly in order of increasing difficulty for SIM observations. First 2 may overlap with another Key Project.

[b] Common name.

[c] Logarithm of luminosity compared to the largest galaxy, M 31.

[d] Distance. Current *relative* uncertainties ±10% (best) to ±70% (worst). *Absolute* scale uncertain by ±10%.

[e] Target rms accuracy of 1-D tangential velocity measurement for galaxy (km/s).

[f] Required accuracy of angular displacement measurement per star (μas).

[g] V magnitude of brightest candidate star.

[h] V magnitude of 5th brightest candidate star.

[i] V magnitude of 10th brightest candidate star.

[j] Required mission time for galaxy.

[k] Running sum of required mission time.

[l] 1: member of Local Group; 2*a*: vicinity Local Group at +SGY; 2*b*: vicinity Local Group toward Sculptor Group; 3: Maffei/M 81 groups; 4: Centaurus Group. Five biggest galaxies are noted.

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1984: PhD, Astronomy, Institute for Astronomy/University of Hawaii
1980: MA, Astrophysics, University of Chicago
1976: BA, magna cum laude, Astrophysics, Princeton University

Positions:

1997–: Chief Scientist, RTSC & Astrophysics Data Facility/NASA/GSFC

Duties - Lead a small software development group at the Astrophysics Data Facility. The group has produced: a generalized code to automatically archive High Energy Astrophysics space based mission data, a central web site (http://tarantella.gsfc.nasa.gov/impress/) for graphical interface to distributed archives of NASA astrophysics data, browsing, subsetting, and visualization tools for web based perusal of all ADC holdings of data tables (http://tarantella.gsfc.nasa.gov/viewer/). Principle Investigator on AISRP/NASA grant to investigate use of advanced XML technology at data centers. Design an eXtensible Data Format (XDF) for cross-disciplinary interchange of scientifc data.

1997–: Adjunct Research Associate, University of Maryland

1990–1997: Research Associate, University of Maryland

Duties - Analysis of Hubble Space Telescope WFPC-1 and WFPC-2 data obtained by the WFPC-1 Instrument Definition team. Attend monthly meetings at STScI to represent the WFPC-1 IDT during the calibration period.

1986–1990: Assistant Professor, Columbia University

Teaching Experience:

Graduate Level: "Extragalactic Astronomy"
Senior Level: "Astrophysics for Scientists and Engineers"
Junior Level: "Planetary Atmospheres and Interiors"
Freshman Level: "Introductory Astronomy"

1984–1986: Bantrell Research Fellow, Caltech
1983: Astronomy Instructor, U. of Hawaii
1979–1980: Graduate student tour guide of Yerkes Observatory.
1976: Programmer, Princeton U.

Created the database package for the Copernicus UV Satellite.

Honors, Prizes, and Fellowships:

1994: NASA Group Achievement Award for the Wide Field/Planetary Camera-2 Science Team.
1993: JPL Award in Recognition of Significant Contribution to the Wide Field/Planetary Camera-2 Project.
1991: NASA Group Achievement Award for the Wide Field/Planetary Camera-I Science Team.

1984–1986: Bantrell Fellowship at Caltech.
1984: Commendation of Science from the House of Representatives of the State of Hawaii.
1983: "ARCS Scholar of the Year" Award.
1982: Achievement Reward for College Scientists Award.
1976–1980: Shirley Farr Research Fellow, U. of Chicago

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Awards, Honors, and Prizes:

1994: STScI Group Achievement Award for ST-DADS (Archive) Project
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1983–1985: Carnegie Fellowship, Carnegie Institution of Washington
1978: Outstanding Teaching Assistance, Caltech
1975–1978: National Science Foundation Graduate Fellowship, Caltech
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Professional Service:

1999–: Publications Committee, Astronomical Society of the Pacific (ASP)
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Selected Recent Publications:

- Borne, K. D., Bushouse, H., Colina, L., & Lucas, R. A., "Evidence for Multiple Mergers among Ultraluminous Infrared Galaxies: Remnants of Compact Groups?", 2000, ApJ Letters, 529, L77.
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- On the Least Action Principle in Cosmology, Nusser, A. & Branchini, E. 2000, MNRAS, 313, 587
- Large-Scale Motions in Superclusters: Their Imprint in the Cosmic Microwave Background, Diaferio, A., Sunyaev, R. A. & Nusser, A. 2000, ApJ, 533, L71
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1964–1965: Research Staff Member, Princeton
1962–1964: Research Associate, Princeton
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Awards, Prizes, and Fellowships:

1977: A.C. Morrison Award in National Science, NY Academy of Sciences
1981: Eddington Medal, Royal Astronomical Society
1982: Heineman Prize, American Astronomical Society
1986: Doctor of Science, U. of Toronto
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1989: Doctor of Science, McMaster U.
1992: Robinson Prize, University of Newcastle upon Tyne
1992: Henry Norris Russell Lectureship of the AAS
1994: Feshback Lectureship, MIT

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Books:

- Principles of Physical Cosmology, Peebles, P. J. E. 1993, Princeton Series in Physics, Princeton, NJ: Princeton University Press
- Quantum Mechanics, Peebles, P. J. E. 1992, Princeton, N.J.: Princeton University Press
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Positions:
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1996: Full Professor, MIT
1990–1996: Associate Professor, MIT
1985–1990: Assistant Professor, MIT
1982–1985: Bantrell Research Fellow, California Institute of Technology
1980–1982: Member, Institute for Advanced Study
1978–1980: Research Assistant (with M. Davis), Harvard University
1975–1977: Teaching Assistant, Harvard University

Fellowships and Awards:
1991: MIT Buechner Teaching Prize
1989–1994: Presidential Young Investigator Award
1986–1988: Alfred P. Sloan Fellowship
1982–1985: Caltech Bantrell Fellowship
1975–1978: NSF Graduate Fellowship

Professional Service:
1995–1996: AURA Committee: "HST and Beyond"
1995–: U.S. Gemini SAC
1992–: MDM Observatory Consortium Representative
1987–1989: NOAO visiting committee

Selected Recent Publications:

- The Surface Brightness Fluctuation Survey of Galaxy Distances. II. Local and Large-Scale Flows, Tonry, J. L., Blakeslee, J. P., Ajhar, E. A. and Dressler, A. 2000, ApJ, 530, 625

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1975-78: Assistant Astronomer, University of Hawaii (UH), Honolulu, USA.
1973-75: Postdoctoral Research Fellow, Marseille Observatory, Marseille, France

Public Service:
1979–1982: Scientific Advisory Committee, Canada-France-Hawaii Telescope
1986: Director, NATO Workshop "Galaxy Distances and Deviations from Universal Expansion"
1987: Scientific Organizing Committee, "A Life for Astronomy: Gerard de Vaucouleurs," Paris
1987–1988: Steering Committee, Keck Telescope
1992: Scientific Organizing Committee, "Physical Cosmology," National Academy of Sciences, Irvine
1994: Scientific Organizing Committee, "Tridimensional Optical Spectroscopic Methods in Astrophysics," Marseille
1994: Scientific Organizing Committee, "The World of Galaxies II," Lyon
1995–1996: Warner/Pierce Prize Committee

Ph.D Theses Supervised: 10

Books:
1987: Atlas and Catalog of Nearby Galaxies (Atlas w. J.R. Fisher), Cambridge U. Press
1986: Galaxy Distances and Deviations from Universal Expansion, NATO ASI Series, ed. with B.F. Madore

Recent Publications Relevant to this Proposal

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- H-alpha Fabry-Perot Observations of the Density-Wave Pattern in M51, Vogel, S. N., Rand, R. J., Gruendl, R. A. & Teuben, P. J. 1993, PASP, 105, 666
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- The Tip of the Red Giant Branch Distance to the Large Magellanic Cloud, Sakai, S., Zaritsky, D. and Kennicutt, R. C. 2000, AJ, 119, 1197

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Phelps, S., & Peebles, P.J.E. 2000, in preparation (see Dissertation: Phelps 2000).

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B. Acronyms and Symbols List

BIMA - Berkeley-Illinois-Maryland (Millimeter) Array
CCD - Charge Coupled Device
CDM - Cold Dark Matter
CMBR - Cosmic Microwave Background Radiation
ISDC - Interferometry Science Data Center
kpc - 10^3 parsecs
$L_\odot$ - Luminosity of the sun
LMC - Large Magellanic Cloud
Mpc - 10^6 parsecs
M/L - Mass-to-light ratio in units of $M_\odot/L_\odot$
$M_\odot$ - Mass of the sun
HST - Hubble Space Telescope
MMT - Multi-Mirror Telescope
NAM - Numerical Action Methods
RTSC - Raytheon Technical Services Company
SCDM - Standard Cold Dark Matter
SIM - Space Interferometry Mission
TRGB - Tip of the Red Giant Branch distance indicator
UH - University of Hawaii
χ^2 - Goodness of fit merit
H_0 - Hubble Constant, Expansion Rate of the Universe
h - $H_0/100$, h_{75} - $H_0/75$
Λ - The cosmological constant of gravitation
Ω_M - ratio of univeral mass density to closure mass density
Ω_Λ - The cosmological constant in dimensionless units
t_0 - The age of the universe