6 Luminosity-Independent Extragalactic Distances

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ABSTRACT

SIM Lite can provide astrometric data of such high quality that it will be possible to determine geometric (luminosity-independent) distances to the nearest spiral galaxies, even though these systems are too far away for direct trigonometric parallax determination. Instead, the method to use is that of rotational parallax (RP). Percent-level distances to M31 and M33 are within reach of a SIM Lite observing program. Such accurate geometric distances will be required for many projects, such as: (1) to establish a small external error on the Hubble constant, H_0*, (2) double-check on the "determination" of* H_0 *from cosmological data sets, (3) obtain six-dimensional phase-space coordinates for galaxy-dynamics studies with unprecedented accuracies, and 4) establish a uniform comparison between the many stellar populations (and their formation histories) among Local Group galaxies. The RP method extends the 1 percent distance limit of SIM Lite by a factor of over 300, from 2.5 kpc to about 770 kpc.*

6.1 An Independent Yardstick

Why are SIM Lite–based extragalactic distances needed if Gaia will calibrate almost every conceivable standard candle, and if the Joint Dark Energy Mission (JDEM) determines the redshift dependence of the Hubble constant? The answer is that an independent determination of the extragalactic distance scale gives us confidence in the external errors. Since small external errors (<1 percent) are required for future applications, it is unwise to rely on a single calibrator (e.g., the LMC or NGC4258) or even a single method. SIM Lite–based rotational parallax (RP) distances can provide such checks. SIM Lite's RP distances will be essentially bias free, so that SIM Lite's RP galaxies provide independent, absolute anchors for most distance indicators, including Cepheids.

Some areas of astrophysical research that would benefit from accurate extragalactic distances are:

- Cosmology and dark energy
- The internal dynamics of disk galaxies
- Star-formation histories of nearby galaxies
- Any other field that requires absolute distances

The aim of this chapter is to illustrate the power of SIM Lite in the area of extragalactic distances. More details can be found elsewhere (Olling and Peterson 2000, hereafter OP2000; Olling 2007, hereafter O2007; Olling 2008, hereafter O2008; and OPO for the combined works).

6.2 H_0, Cosmology, and Dark Energy

There is a growing realization that a 1 percent level determination of the Hubble constant (H_0) is important for cosmology, dark energy (Hu 2005, hereafter H2005; O2007; Macri et al. 2006; Braatz et al. 2007; Ichikawa and Takahashi 2008), and the determination of the critical density,

$$\rho_{CRIT} = 3H_0^2 / (8\pi G)$$

H_0 is important for cosmology because the cosmic microwave background (CMB) data are the most accurate of the various methods (SNe, baryon acoustic oscillations, weak lensing, galaxy clustering, and so on) that probe cosmological evolution and that the CMB data really measure the physical matter densities (H2005). To figure out whether the Universe is open, closed, or flat, one works with relative densities: $\Omega = \rho / \rho_{CRIT}$, which introduces the dependence on H_0.

Measuring the equation of state (w) of dark energy is one of the biggest efforts in observational cosmology today. The accuracy to which w can be determined depends strongly on the uncertainty in the Hubble constant (Figure 6-1). In fact, Hu (2005) states that "…the Hubble constant is the single most useful complement to CMB parameters for dark energy studies ... (if H_0 is) ... accurate to the percent level." A simple analysis (O2007) indicates that the CMB data and H_0 currently contribute in about equal proportion to the error of the equation of state (EOS) and how this proportionality changes for the various stages considered by the Dark Energy Task Force (DETF). Planck's CMB errors will be 8 times smaller than those of WMAP, so it is imperative to reduce the H_0 errors commensurately, to ~1 percent. For DETF-Stage-I data and with the current uncertainties of H_0, the EOS is known to about 9 percent. Decreasing the error on H_0 by a factor of 10 will decrease the error on the EOS by a factor 3.9 to 2.3 percent. Likewise, with DETF-Stage-IV data, a 1 percent error on H_0 would decrease the error on the EOS by the square root of two to 0.9 percent. DETF-stage-I data roughly correspond to the state of the art in DE research, while DETF-Stage-IV represents the *expected* state of the art attainable *after* completion of the JWST *and* LSST *and* the Square Kilometer Array.

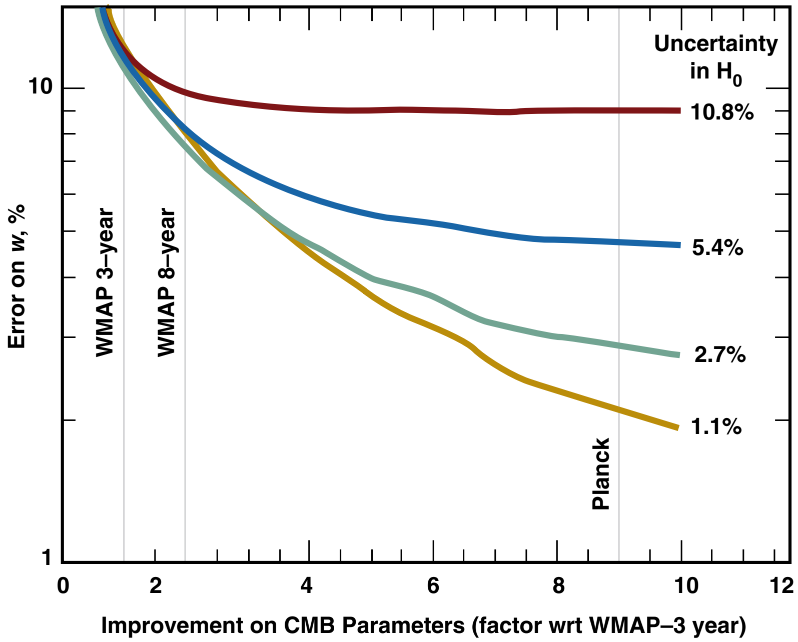

Figure 6-1. Measuring the equation of state (*w*) of dark energy is one of the biggest efforts in observational cosmology today. The accuracy with which *w* can be determined depends on the uncertainties in the CMB parameters and the Hubble constant, H_0. SIM Lite will be capable of reducing the uncertainty in H_0 by almost an order of magnitude. This result, when combined with improved CMB parameters from WMAP and Planck, will result in a significant improvement in our determination of *w*. This figure shows how the uncertainty in *w* depends on the uncertainties in the CMB and in H_0. Four curves are shown corresponding to four different uncertainties in H_0, ranging from the current value (10.8 percent) down to the value expected from SIM Lite (1.1 percent). With Planck-like CMB parameters (right-most vertical line) and the current uncertainty in H_0, *w* can be determined with an accuracy of 8.9 percent. Including SIM Lite's result for H_0, the accuracy in *w* will improve to 2.3 percent.

6.3 A Luminosity-Independent Zero-Point for the Distance Scale

6.3.1 Background and Current Problems

Significant progress has been made on the calibration of the extragalactic distance scale, and the determination of H_0 with methods such as Type Ia SNe, the Tully-Fisher relation, surface brightness fluctuations, the Tip of the Red-Giant Branch, and the Fundamental Plane. The primary calibration usually relies on the period-luminosity relation for Cepheids.

While the zero-point of the Cepheid distance scale in the LMC and in the Milky Way is still debated, steady progress is being made in the calibration of Galactic Cepheids' distances (e.g., HST parallaxes and the interferometric calibration of the Baade-Wesselink method).

There is currently a shift to use NGC4258 as a zero-point rather than the LMC, because NGC4258 is much more similar to galaxies that are used to determine H_0 than is the LMC. Currently, the nuclear water-maser distance of NGC4258 (Humphreys et al. 2005) provides a Cepheid zero-point calibration to 3 percent (Macri et al. 2006; Riess and Macri 2007). The search is "on" to find more distant water-maser sources for direct H_0 determination (Braatz et al. 2007, 2008). Also, the Cepheid period-luminosity relation in the near/mid-infrared is much more reliable than the ones based on optical photometry (Freedman et al. 2008).

With standard candle methods, many problems exist that are basically due to the fact that the physical properties of stars are determined only at the 1 to 10 percent level for a small number of stars. Even the metallicity of the Sun is defined rather than measured (Kurucz 2002). Gaia and SIM Lite will provide a large number of high-accuracy calibrators to determine mass, luminosity, radius, temperature, and metallicity, although not necessarily all for the same objects.

6.3.2 Potential Problems with Existing Measurements

The history of the luminosity calibration of standard candles indicates that “ultimate answers” are hard to obtain. Furthermore, even “geometric” methods may be subject to significant uncertainty. See O2007 for an extended discussion.

The Case of the Pleiades: The distance to the Pleiades cluster has been derived by a number of methods. Pinsonneault et al. (1998), Pan, Shao, and Kulkarni (2004), and Soderblom et al. (2005) (see Section 7.2) indicate that the geometric Hipparcos distance is “wrong.” Similar discrepancies are found for four other clusters (Kaltcheva and Makarov 2007).

The Case of SN1987A: The “light echo” of SN1987A has been analyzed by several groups to determine the distance to the LMC. However, there is a systematic difference between the groups at the 10 percent level. It appears that this gap cannot be bridged (Gould 2000).

Interferometric Baade-Wesselink Method: Recently, the interferometric Baade-Wesselink calibration of the Cepheid PL relation changed significantly due to a cross-check with independent data (Gieren et al. 2005). However, this result is also disputed (Groenewegen 2007).

Extragalactic Water Masers: There is a renewed effort to improve Cepheid distances based on the VLBI-based water maser zero-point. However, the water maser method samples only parts of the major and minor axes, so that “more complicated models” are difficult to rule out. For example, the derived distances will be systematically off by twice the intrinsic eccentricity (e = 0.01 yields a 2 percent distance error [O2007]). Such small eccentricities might well exist in AGN accretion disks (Armitage 2008), but are not satisfactorily included in the distance determinations.

6.3.3 Potential Solutions with SIM Lite

As discussed earlier, the most important reason to undertake the SIM Lite RP project is to obtain independent data to corroborate the existing, ongoing, and future distance-scale projects. Because the proposed RP method samples large areas of the galaxy disks, the method is not sensitive to sampling effects as is the case for the water maser method. The distance determination will be very robust because four of the six phase space coordinates are measured (per star), while the remaining two can be adequately modeled (OPO). Any “standard candle” present in the RP galaxies will thus have a zero-point determined, also allowing for many essential cross-checks with their counterparts in the Milky Way.

6.4 The Rotational Parallax Method

The rotational parallax method employs the fact that velocity (V), distance (D), and proper motion (μ) are related via $\mu = V / (\kappa D)$, where κ is a constant related to the choice of units. We illustrate (Figure 6-2) the RP method for a toy galaxy model with only circular motion and the rotation speed (V_c) and inclination known (from the HI). Then, a star on the minor axis directly yields the distance $D = V_c / (\kappa\mu)$. The distance can also be recovered from a star at an arbitrary location since there are three unknowns (D, V_c, and inclination) and three observables (the radial velocity and the two proper motions).

For a realistic galaxy, we split the total observed velocity (V_{TOT}) into components that are intrinsic to the galaxy and ones that may vary from star to star: $V_{TOT} = V_{SYS} + V_C + V_P + V_\sigma$, where V_{SYS} is the systemic

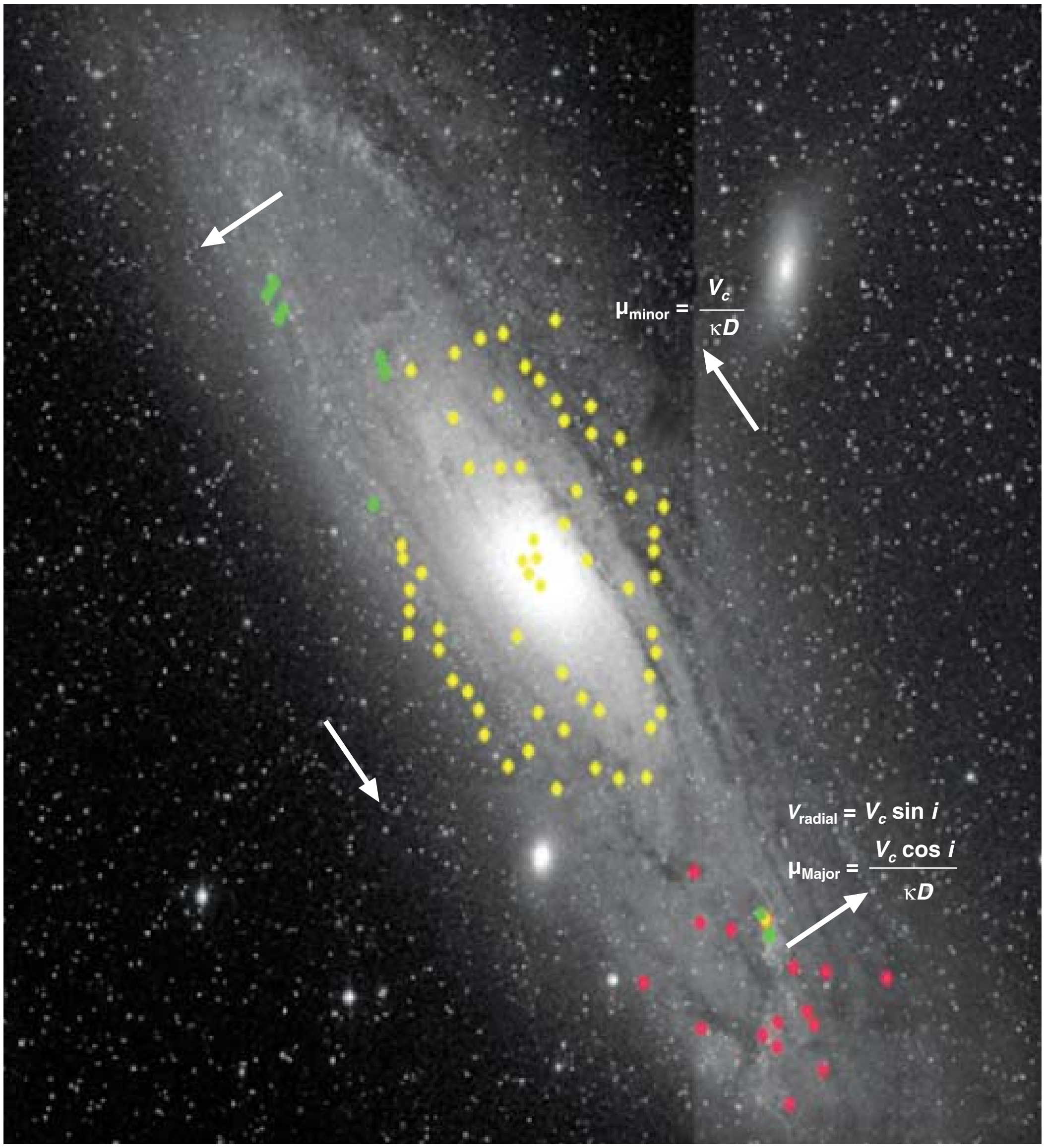

Figure 6-2. This figure illustrates the rotational parallax method for a model galaxy with no systemic motion and with only circular internal motion. (The application of this method to a realistic galaxy is given in the text.) When applied to nearby galaxies, RP will provide a luminosity-independent estimate of the extragalactic distance scale, with an absolute accuracy of <1 percent. At the same time, it will serve as a check on estimates using the standard candle indicators, such as Cepheids. Here is a DSS image of M31 showing the relationships between distance (D), inclination (i), velocity from rotation (V_c), radial velocity (V_{radial}) and proper motion (μ_{Major}) for stars on the major axis; it also shows the relationship between D, V_c, and proper motion (μ_{minor}) for stars on the minor axes. The constant κ is related to the choice of units. The colored dots denote bright AB supergiants already identified in M31 (courtesy D. Peterson). Their distances from and rotation about the galactic center cause them to move toward (green) or recede from (red) Earth; stars near the galactic center (yellow) may have relatively little radial velocity from rotation. SIM Lite will make measurements of μ_{Major} and μ_{minor}. When these are combined with ground-based measurements of V_{radial}, distance D can be estimated.

motion of the galaxy, V_σ is the random motion, and V_P is the peculiar velocity due to spiral-arm perturbations, tidal interactions, bar-induced elliptical motions, and so forth, or a combination thereof.

The equation above involves 18 unknowns: three components for V_{SYS}, V_P, and V_σ, the (x,y,z) position of the star, the center of the coordinate system and position angle of the major axis (+3), the circular velocity, distance, and inclination. Only five measurements are taken per star: the three components of the stars' space velocity and two positions. Thus, there appears to be no solution as we have 18 unknowns and five observables, per star.

However, when considering ensembles of several stars, a robust solution can be found. First, the velocity-dispersion values are only required for the group as a whole: 15 unknowns remain and three unknowns shared by all objects. Similarly, the systemic motion, coordinate system parameters, rotation speed, inclination, and distance are shared between stars (at the same galactocentric radius). Thus, the number of shared variables equals 12 ($N_{SV} = 12$). This leaves six star-dependent unknowns (V_P, [x,y,z]) and five observables per star. To solve this problem, OP2000 assumed co-planarity — that $z = 0$ and $V_P(z) = 0$ — so that only four star-dependent unknowns remain and a solution is possible.

This solution can be generalized (O2007) because the peculiar motions are due to some large-scale perturbation (see above). If this were not the case, V_P would be a random velocity instead. Thus, because gravity is a long-range force, the peculiar velocities are correlated from star to star, and V_P can be expressed as a Fourier series that adds ($N_{FS} \geq 0$) shared variables to N_{SV}, but, crucially, eliminates star-based unknowns. Likewise, disk-warping or a radially varying rotation curve will add shared variable ($N_{WRC} \geq 0$). Thus, from first principles, we know that the number of stars (N_{STR}) that needs to be observed must exceed the number of shared variables: $N_{STR} > 12 + N_{FS} + N_{WRC}$.

Our error estimates do not fully include the effects of non-circular motions, and we estimate that a safety margin of about a factor of two is required with respect to OP2000's distance-error relation [their equation (25)]. However, this margin is not included in any of the quoted accuracies below.

With rotational velocities of 270, 97, and 55 km/s, the rotation-induced proper motions for M31, M33, and the LMC are 74, 24, and 192 μas/year, respectively; all easily detectable by SIM Lite. In fact, the achievable distance errors are dominated by the internal velocity dispersions of the stellar population and increase linearly with the per-star proper motion accuracy. We adjust integration time with apparent magnitude to achieve about 8 μas/yr across our magnitude range. We find that, with 300 stars per galaxy (down to V = 16.5), the distance errors will be 0.56 percent for M31. M33 has 300 stars down to V = 17.1 and yields a distance accuracy of 1 percent. Our target stars will be among the most luminous stars with masses over 20 $M_{\odot}$. For M31, we computed the expected errors based on the true magnitude distribution of M31 stars (Massey et al. 2006) as well as the guide-star catalog (Lasker et al., 2008), both corrected for foreground stars. We find enough bright stars in M31 to achieve the goal of subpercent distance errors in a reasonable time: 0.36 percent (0.52 percent) errors in 32 (16) days of SIM Lite time. M33 is expected to have roughly three times fewer stars, with a commensurate reduction in achievable accuracies.

A similar analysis indicates that Gaia's best-possible accuracy would be as good as for a 32-day SIM Lite program for M31. However, the Gaia-based project would employ 10,000 stars as faint as V = 20. An RP project also needs ground-based radial velocities (RVs) with accuracies of 1–2 km/s for all program stars.* The SIM Lite program needs fewer than than 300 stars (V ≤ 17), requiring several 100 times less observing time than the Gaia-based project. A more realistic Gaia project could read 0.5 percent distance error and would use five times fewer stars (2,000 at V ≤ 18.6) and 30 times more RV observing time than for SIM Lite. Such a Gaia program would be comparable to a modest 16-day SIM Lite project.

Both SIM Lite and Gaia can in principle achieve the goal of subpercent distance errors for M31 based on the rotational parallax method. This result is predicated on the assumption that the data allow for $1 / \sqrt{N}$ accuracy improvements. This may in fact be the case; an absolute reference frame is not required, as the physics of the RP method allow one to measure (and take out) linear and rotation motions of the local astrometric grid. Since it is of paramount importance to have confidence in the derived distances, and their errors, the Gaia/SIM Lite comparison provides a crucial cross-check of procedures.

The LMC stars are relatively bright and have large internal (random) motions, so the LMC requires many thousands of stars: Gaia can probably get a rotational parallax to this system.

** Note that one might consider using radial velocities from other sources such as the HI, or from averaging a number of nearby stars at lower RV accuracy. However, that would decrease the robustness of the method.*

6.5 Internal Dynamics of Nearby Galaxies

To date, the understanding of the dynamics of the Milky Way has been hampered strongly by the absence of a large sample of stars for which six-dimensional phase space information is available. For example, the vertical force law can only be studied in the immediate solar neighborhood, and is derived from the vertical density and vertical velocity distribution functions. Gaia is designed to solve these kinds of problems for the Milky Way.

Since the peculiar motions of individual stars can be determined with the RP technique, SIM Lite RP studies enable the same kind of dynamical studies of M31 and M33 that Gaia enables for the Milky Way. Such six-dimensional information will only be available for the Milky Way and the RP targets, and can be used to study in great detail the dynamics of bars, warps, spiral-arm streaming motions, tidal encounters, and so forth. These systems will be the laboratories for galactic dynamic studies of spirals for many decades.

The proper motion accuracy (~8.0 µas/yr at V = 16.5) is an *absolute* measure. Important for the internal dynamics are the *relative* motions, which are determined at the 6.7 µas/yr level (25 km/s). At this magnitude, Gaia's accuracy is about four times worse. However, the SIM Lite error has the potential for further reduction: for a 10-year data set, the errors reduce by about a factor of three to 8.2 km/s (2.2 µas/yr), which is below the expected velocity dispersion of the target population.

Finally, it might even be possible to unravel the time dependency of the perturbing force. Some SIM Lite RP targets have well-defined ages, such as Cepheids. By choosing targets with a suitable range of ages, it may be possible to determine their "birth velocities" and whether the perturbing forces have changed over time.

6.6 Stellar Content, Star Formation, and Assembly Histories of Nearby Galaxies

A 1 percent distance for the rotational parallax galaxies would also allow for an accurate age determination (from accurate luminosities) of all stars in those galaxies (10^{11} stellar ages per distance measurement). Although current estimates for stellar ages are not limited by distance uncertainties, the Gaia data are expected to change this situation dramatically. It will determine masses for over 17,000 astrometric binaries to better than 1 percent (Lebreton 2008). Furthermore, distances of about 21 million stars will be measured to ~1 percent. Since about 0.85 percent of stars are detached eclipsing binaries (DEBs), radii can be determined for ~357,000 stars in DEB systems with distance uncertainties ≤1 percent. Masses for these systems will be determined employing Gaia's radial-velocity data supplemented with ground-based spectroscopy and/or SIM Lite astrometry to provide proper sampling of these short-period systems. SIM Lite should contribute significantly to this calibration by getting subpercent distances for the slowly evolving (low-mass) systems that are crucial for the determination of the star-formation history of the Milky Way.

Already, star-formation histories (and, hence, galaxy assembly histories) are inferred from deep star-counts in Local Group galaxies. SIM Lite rotational parallax distances would allow for the direct transfer of these new Gaia-based age calibrations from the Milky Way to the RP galaxies.

While Gaia might get a good rotational parallax for M31, SIM Lite will excel at it. By using all stars down to V = 20, Gaia can just about attain 1 percent distance error for M31, while SIM Lite can easily reach 1 percent distance error for a five-year mission.

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