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SIM PLANETQUEST, LUMINOSITY-INDEPENDENT EXTRA-GALACTIC DISTANCES

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ABSTRACT

The Space Interferometry Mission (SIM PlanetQuest) 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 the "Rotational Parallax" [RP; Peterson & Shao (1997); Olling & Peterson (2000) and Olling (2007)]. *Percent-level* distances from M 31 and M 33 are within reach of a SIMPQ-based observing program. Such accurate geometric distances will be required for many projects such as: 1) to establish a small systematic error on the Hubble constant, 2) double-check on the "determination" of H_0 from cosmological data sets, 3) obtain 5D 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) between Local Group galaxies.

Subject headings: galaxies: distances and redshifts, Local Group — galaxies: individual (LMC, M 31, M 33) – cosmology: cosmological parameters, dark energy and distance scale – astrometry and celestial mechanics: astrometry

1. INTRODUCTION

Why are SIMPQ-based extra-galactic distances needed if *Gaia* will calibrate almost every conceivable standard candle, and if JDEM determines the redshift dependence of the Hubble constant? The answer is that an *independent* determination of the extra-galactic distance scale give us confidence that the *systematic* errors on these measurements are realistic. The latter is required in the era of precision astrophysics where small internal errors are required but not sufficient. Small systematic errors can be provided by SIMPQ-based RP galaxy distances.

There are many areas of astrophysical research that would benefit enormously from accurate extra-galactic distances, some of these include:

- Cosmology & dark energy research.
- Securing a luminosity-independent zero-point of the extra-galactic distance scale.
- The internal dynamics of disk galaxies.
- The stellar contents & star-formation and assembly histories of galaxies with uniform age scales.

2. H_0, COSMOLOGY & DARK ENERGY

2.1. *Background & Current Problems*

There is a growing realization that a percent-level determination of the Hubble constant (H_0) is important for cosmology, dark energy (Hu 2005); O2007; Macri et al. (2006); Braatz et al. (2007); Ichikawa & Takahashi (2008) and the determination of the critical density [$\rho_{crit} \equiv 3H_0^2/(8\,\pi\,G)$]. However, when small systematic errors are required, it is unwise to rely on a single calibrator (e.g., the LMC or NGC 4258) or even a single method. Currently, the nuclear water-maser distance of NGC 4258 (Humphreys et al. 2005) provides a Cepheid calibration (Macri et al. 2006; Riess & Macri 2007) that is accurate to about 3%.

H_0 is important for cosmology because the cosmic microwave background (CMB) data is the most accurate of the various methods (SNe, baryon acoustic oscillations, weak lensing, galaxy clustering ...) that probe cosmological evolution and that the CMB data really measures the *physical* matter densities [ω_i in kg/m^3; Hu (2005)]. Of interest to cosmology are the *normalized* densities ($\Omega_i = \omega_i/\rho_{crit} \propto \omega_i/H_0^2$), so that H_0-errors are *four* times as important as errors on ω_i (Olling 2007).

It is well known that the total amount of dark energy (Ω_Λ) and the matter density (Ω_m) are strongly correlated, especially in a flat universe. This correlation is nicely illustrated by the analysis of WMAP data [Spergel et al. (2007), their Fig. 21; Komatsu et al. (2008), their Fig. 19]. Furthermore, our knowledge of the equation of state (EOS) of dark energy (w) is strongly affected by the uncertainty of the Hubble constant [Olling (2007); hereafter O2007]. 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

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equal proportion to the error of the EOS, and how this proportionality changes for the various stages considered by the Dark Energy Task Force [DETF; Albrecht et al. (2006)]. *Planck*'s CMB errors will be ∼8x smaller than those of WMAP, so it is imperative to reduce the H_0 errors commensurately, to $\lesssim$ 1%. In each panel of Fig. 1 we show that the errors on the EOS decrease for smaller errors on H_0 (drawn curves), especially when *Planck*-data are available. In summary, for DETF-Stage-I data and with the current uncertainties of H_0, the EOS is known to about 9% (top panel, top curve). Decreasing the error on H_0 by a factor of ten will decrease the error on the EOS by a factor 3.9 to 2.3% (top panel, bottom curve). Likewise, with DETF-Stage-IV data, a 1% error on H_0 would decrease the error on the EOS by a factor of about $\sqrt{2}$ to 0.9% (bottom panel, bottom curve).

2.2. *Potential Solutions with* SIMPQ

SIMPQ's RP distances will be essentially bias-free, so that SIM's RP galaxies provide *independent,* absolute anchors for most distance indicators, including Cepheids. See §3 below.

3. A LUMINOSITY-INDEPENDENT ZERO-POINT FOR THE DISTANCE SCALE

3.1. *Background & Current Problems*

During the past decades significant progress has been made on the calibration of the extra-galactic distance scale, and the determination of the Hubble constant with new methods such as type Ia Supernovas, the Tully-Fisher relation, surface brightness fluctuations, the Tip of the Red-Giant Branch and the Fundamental Plane. The primary calibration is the period-luminosity relation for Cepheid variables. The discussion below is a summary of the presentation in O2007.

However, the zero-point of the Cepheid distance scale is still debated, especially the zero-points based on Cepheids in the Large Magellanic Cloud (LMC) and those in the Milky Way. Because just two of the Cepheids with *HIPPARCOS* measurements have parallax errors better than 20%, the Cepheid period–luminosity relation relies on Galactic Cepheids in open clusters, and is therefore tied to main-sequence fitting. However, steady progress is being made in the calibration of Galactic Cepheids distances via *HST* trigonometric parallaxes, interferometric calibration of the Baade-Wesselink method and a re-calibration of *HIPPARCOS.*

Because of uncertainties in the Galactic calibration, most extra-galactic distance scale studies have been calibrated relative to the nearby LMC. However, the metallicity of the LMC is substantially below that of those distant galaxies (and the Milky Way [MW]) that are used to calibrate the Supernova Ia distance scale onto the Cepheid distance scale, while there are also strong indications that the Period-Luminosity (-Color) relation is non-linear and dependent on metallicity.

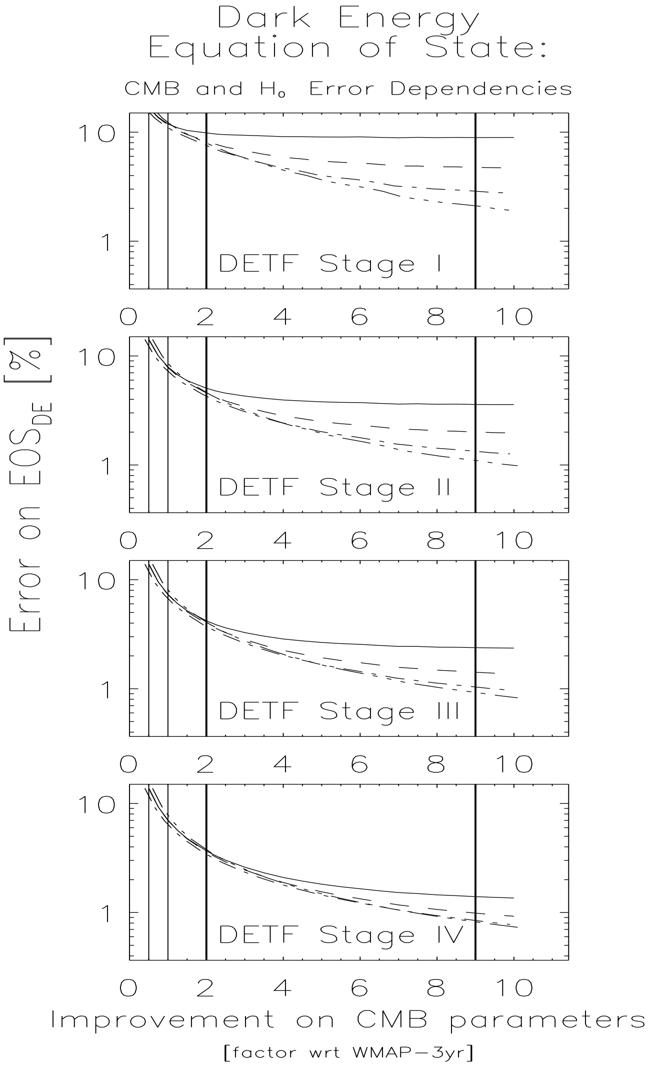

FIG. 1.— In each panel we present the accuracy with which the EOS of Dark Energy can be determined (ϵ_w) as a function of the accuracy of the CMB data (abscissa), and the accuracy in H_0 (ϵ_{H_0}; curved lines). The vertical lines correspond to accuracies of the WMAP-1-year data (left), WMAP-3yr data, WMAP-8yr data and *Planck* (right). The difference between the four panels is the accuracy with which the "other" data sets are determined. From top to bottom, these correspond to stages I, II, III and IV as defined by the Dark Energy Task Force, respectively. In each of the panels, the four lines correspond to the same errors on H_0: ϵ_{H_0}=8/1, 8/2, 8/4 and 8/10 km s^{-1} Mpc^{-1}, from top to bottom. The attainable errors with *Planck* data are: ϵ_w= 8.90%, 4.81%, 3.02% and 2.27% for Stage I (ϵ_w= 3.60%, 2.06%, 1.43% and 1.20% for Stage II; ϵ_w= 2.41%, 1.48%, 1.14% and 1.02% for Stage III; ϵ_w=1.45%, 1.07%, 0.95% and 0.91% for Stage IV.

Thus, there is currently a shift to use NGC 4258 as a zero-point rather than the LMC, because NGC 4258 is much more similar to galaxies that are used to determine H_0 than the LMC (Macri et al. 2006; Riess & Macri 2007). The zero-point distance for NGC 4258 is provided by the geometric nuclear water-maser distance (Humphreys et al. 2005), while the search is "on" to find more distant water-maser sources for direct H_0 determination (Braatz et al. 2007; Braatz & Gugliucci 2008). Also, the Cepheid PL relation in the near/mid-infrared is much more reliable than the ones based on optical photometry (Freedman et al. 2008).

Many problems exist with standard candle methods that are basically due to the fact that many of the physical properties of stars are determined only at the 1 – 10% level, and only for a small number of stars. This is mostly due to the lack of well-measured calibrators, but even the metallicity of the Sun is *defined* rather than measured (Kurucz 2002). *Gaia* and SIMPQ will provide a large number of new calibrators to determine mass, luminosity, radius, temperature and metallicity, although not necessarily all parameters for the same objects (Unwin et al. 2008).

3.2. *Potential Problems*

The history of the luminosity calibration of standard candles indicates that "ultimate answers" are hard to come by, because the problem is really hard. Furthermore, it is well-known that astronomers suffer from a herding instinct and that results tend to cluster around popular values, with too small errors (Schaefer 2008). Even "geometric" methods are subject to significant uncertainty. Several examples are discussed in the next subsections. O2007 present some more detail and other examples.

The Case of the Pleiades

The distance to the Pleiades cluster has been derived by a number of methods that include ground-based-, *HST* - and *HIPPARCOS* parallaxes, orbital parallaxes and main-sequence fitting. Soderblom et al. (2005) indicate that the geometric *HIPPARCOS* distance is wrong (about 4-σ too large). Similar discrepancies are found for four other open clusters [e.g., Kaltcheva & Makarov (2007)]. Reanalysis of the *HIPPARCOS* data (Makarov 2002) yields concordant results.

The Case of SN1987a

The "light echo" of SN 1987A 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% level. It appears that this gap can not be bridged (Gould 2000).

Interferometric Baade-Wesselink Method

Recently, the interferometric Baade-Wesselink calibration of the Cepheid PL relation changed significantly (by an average 0.095 mag) due to a cross-check with independent data (Gieren et al. 2005). However, in good distance-scale tradition, this result has also been disputed (Groenewegen 2007).

Extra-galactic Water Masers

There is also a renewed effort to get better Cepheid distances (Macri et al. 2006; Riess & Macri 2007) based on the VLBI-supplied zero point (Braatz et al. 2007; Braatz & Gugliucci 2008). 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, O2007 finds that the derived distances can be systematically off by twice the intrinsic eccentricity ($e = 0.01 \longrightarrow 2\%$ distance error). Such small eccentricities might well exist in AGN accretion disks (Armitage 2008), but are not satisfactorily included in the distance determination process (to date).

3.3. *Potential Solutions with* SIMPQ

As discussed in the Introduction, the most important reason to undertake another distance scale project is to obtain *independent* data that can corroborate the existing, on-going and *Gaia*- and SIMPQ-based distance-scale projects.

The rotational parallax (RP) method summarized below is likely to be essentially free from biases, and will thus provide robust extra-galactic distances [see Olling & Peterson (2000), hereafter OP2000; O2007; OPO for the combined works]. Because the proposed RP method samples large areas of the galaxy disks, the method is not sensitive to sampling effects such as the water-maser method. Furthermore, since the SIMPQ- and radial velocity (RV) data provide five of the six phase-space coordinates per star (two proper motions, one radial velocity and two coordinates), one can imagine that the distance determination will be robust (OPO).

Any "standard candle" present in the RP galaxies will thus have a zero-point determined for each RP galaxy, also allowing for the essential cross checks.

The Rotational Parallax Method

The RP 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 for unit conversion: $\kappa \approx 4.74$ if distances are expressed in Mpc, proper motions in μas/yr and velocities in km/s. Variations of this geometric+Newton-gravity method have been applied in diverse environments such as: 1) binary stars 2) stars orbiting the Galactic center, 3) the nuclear water maser of NGC 4258, or 4) galaxies as a whole: see O2007 for a review.

We illustrate the RP method for a toy galaxy model with only circular motion and the rotation speed (V_c) and inclination (i) known from the H I velocity field. In that case, the proper motion of a star on the *minor* axis directly yields the distance: $D = V_c/(\kappa\mu)$ (see Fig. 2). At arbitrary location, the *three* unknowns (D, i and V_c) are solved from the *three* observables [radial velocity (V_r) and two proper motions].

For a realistic galaxy, we break apart the total observed velocity ($\overline{V}_{tot}$) into components that are intrinsic to the galaxy and ones that may vary from star to star: $\overline{V}_{tot} = \overline{V}_{sys} + \overline{V}_c + \overline{V}_p + \overline{V}_\sigma$, where $\overline{V}_{sys}$ is the systemic motion of the galaxy, $\overline{V}_\sigma$ is the random motion and $\overline{V}_p$ is the peculiar veloc-

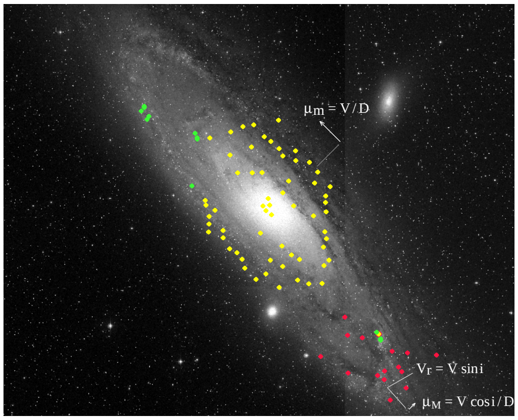

FIG. 2.— A DSS image of M31 showing the relationship among proper motions and radial velocity for objects on the major and minor axes. Also shown are the bright AB supergiants already identified in M31 (courtesy: Deane Peterson).

ity. The latter term may be due to spiral-arm perturbations, tidal interactions, bar-induced elliptical motions and so forth, or a combination thereof.

This relation seems impossible to solve: there are only 3 observables (left-hand side) and 4 times three unknowns. However, 12 unknowns are actually "shared" between stars: distance, V_c, $\overline{V}_{sys}$, the origin (2x) and orientation (2x) of the coordinate system, while the random terms average out [the shape of the velocity-dispersion ellipsoid (3x) is needed for χ^2 evaluation]. We end up with 6 star-based unknowns [$\overline{V}_{p,*}$ and $(x, y, z)_*$], 12 shared variables and 5 observables (3 velocities and 2 positions): still no unique solution.

However, we can eliminate two of the star-based unknowns: if the shared variables are known, then the star-based (x, y) values are also known. (If the target stars scatter randomly around the mid-plane, then z_* averages to zero). Because, we have good initial estimates for the distance and origin/orientation from either external information (H I) or from $V_r - \mu$ correlations (OP2000), a small amount of iteration will lead to the correct determination of the remaining star-based unknowns: $\overline{V}_{p,*}$. In summary, the number of stars (N_*) must exceed the number of shared variables (N_{SV}). Other "complications" may arise. For example, the inclination and/or position angles may may depend on radius (warp), or the galaxy may be lopsided. Because those effects are felt by all stars in the relevant radial/azimuthal range, more shared variables need to be determined, while N_* must always exceed N_{SV}.

Expected Accuracies

The rotation-induced proper motions for M 31, M 33 and the LMC are 74, 24 and 192 μas yr^{-1}, respectively: all easily detectable by SIMPQ. The achievable distance errors are dominated by the internal velocity dispersions (σ) of the stellar population. Our recent analysis shows that with 200 stars per galaxy, and with 7μas yr^{-1} proper motion accuracies and a total of 1,200 hours of SIMPQ time, we can reach distance errors of 0.56% and 2.1% for M 31, and M 33, respectively. From the 2MASS catalog, we estimate that there are enough stars to achieve this goal: ∼1,100 and ∼300 stars brighter than V=17.5 in M 31 and M 33, respectively. The LMC stars are relatively bright and large internal (random) motions, so the LMC requires thousands of stars: this system will be done by *Gaia*.

4. 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 6D phase-space information is available. *Gaia* is designed to solve this problem for the Milky Way. For example, studies of the vertical force law can only be performed in the immediate solar neighborhood where the vertical velocity component is radial.

Since the peculiar motions of individual stars can be determined with the RP technique, SIMPQ RP studies enable the same kind of dynamical studies of nearby galaxies that *Gaia* enables for the Milky Way. Such 6D 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.

Especially for the extended SIMPQ mission, many such studies can be undertaken with samples that are designed for the specific problem at hand.

4.1. *Potential Solutions with* SIMPQ

Since the observational accuracies will be roughly limited to the velocity dispersion, the per-star accuracy of the peculiar component will be ∼10 km/s. The accuracy with which these perturbations can be determined depends on the number of stars that can be "averaged" while retaining enough resolution to study the physical process responsible for the peculiar velocities. Depending on the application, the interpretation of the perturbations may require substantially more stars scattered more widely across the galaxy than for the distance-only analysis.

Finally, it might even be possible to unravel the time dependency of the perturbing force. Some SIMPQ-RP targets may be Cepheids (which have a period-age relation) or other stars with well-defined ages. By choosing targets with a suitable range of ages, it may be possible to determine their "birth velocities," and whether the perturbing force has changed over time.

5. THE STELLAR CONTENTS & STAR-FORMATION AND ASSEMBLY HISTORIES OF NEARBY GALAXIES

Absolute luminosity (from distance) correlates very strongly with stellar age, a 1% distance for the RP galaxies would also allow for an accurate luminosity determination of *all* stars in those galaxies

(100 billion stellar ages per "shot"). For example, one could determine on a group-by-group basis (e.g., Cepheids, RR Lyrae, RGB stars, etc.) the stars in the RP galaxies with those in the Milky Way with approximately equal luminosity errors. Such would allow thorough checks on the robustness of the various standard-candle methods.

Already star-formation histories (and hence galaxy assembly histories) are inferred from deep (HST) star-counts in Local Group galaxies (Brown et al. 2006). SIMPQ-RP distances would allow for the direct transfer of the new and very much improved *Gaia*/SIMPQ-based calibrations of stellar ages from the Milky Way to the RP galaxies.

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