Extragalactic Water Masers, Geometric Estimation of $H_\circ$, and Characterization of Dark Energy

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High precision estimation of the equation of state of dark energy depends on constraints external to analyses of Cosmic Microwave Background fluctuations. A geometric estimation of the local expansion rate, $H_\circ$, would provide the most direct and robust constraint. Traditional techniques to estimate $H_\circ$ have depended on observations of standard candles for which systematic effects can be 10% or more. Observations of water maser sources in the accretion disks that feed the central engines of active galaxies enable simplified, robust, and largely geometric analyses. Many thousand maser sources will be discovered in studies with the SKA, owing to its great sensitivity. Spectroscopic monitoring and interferometric mapping - with intercontinental baselines - will allow estimation of $H_\circ$ to $\sim 1\%$ and possibly better.

1. CMB Fluctuations and $H_\circ$

Analyses of cosmic microwave background (CMB) fluctuations in the context of power-law ΛCDM models are powerful means for estimation of cosmological parameters, such as flatness, e.g., [3]. However, estimation of some parameters, such as the equation of state for dark energy, described by w_0 and $\dot{w}$, requires external constraint, such as measurement of expansion rate. Studies of large scale structure, lensing, and the Sunyaev-Zeldovich effect are being pursued with this in mind. However, estimation of the local Hubble constant, $H_\circ$, directly from a sample of galaxies for which geometric estimates of distances are available provides the most direct independent constraint (Figures 1 & 2). Overall, estimates of $H_\circ$ with uncertainties on the order of 1% are desirable to resolve degeneracies in CMB analyses among ΛCDM parameters [13].

Analysis of CMB data has been used to predict $H_\circ$ [27] in good agreement with the value obtained from analysis of standard candles (i.e., Cepheid variable stars) by the *HST* Key Project on the Extragalactic Distance Scale (EDS). However, there are two limitations to this CMB analysis: the equation of state for dark energy (w) was assumed to be -1, and there is no independent check of the reference value of $H_\circ$ that can be used realistically to detect deviations from -1. The total reported uncertainty in the reference value of $H_\circ$ is 10%, for analysis of 889 Cepheids in 31 galaxies [9], but control over sources of systematic uncertainty was difficult and two significant sources stand out.

First, the best present estimate of $H_\circ$ is underpinned by the distance to the Large Magellanic Cloud (LMC), because that galaxy is used to establish the zero point of the Cepheid PL relation. This affects the calibration of all other standard candles and thus *the entire EDS*. However, the suitability of the LMC as an "anchor" is problematic due to (1) poorly understood internal structure, e.g., [21,1], and (2) controversy concerning the LMC distance, values for which obtained with different methods and analysis techniques disagree beyond formal errors. On one side a "short" distance modulus ($\mu_{LMC} \simeq 18.2$ mag) is obtained with analyses of red clump stars, e.g., [28,29] and some detached eclipsing binaries, e.g., [11,8]. On the other side some estimates yield $\mu_{LMC} \simeq 18.7$, e.g., [6]. Confusion is worsened because other standard candles, such as RR Lyrae variables, support conflicting distances, again de-

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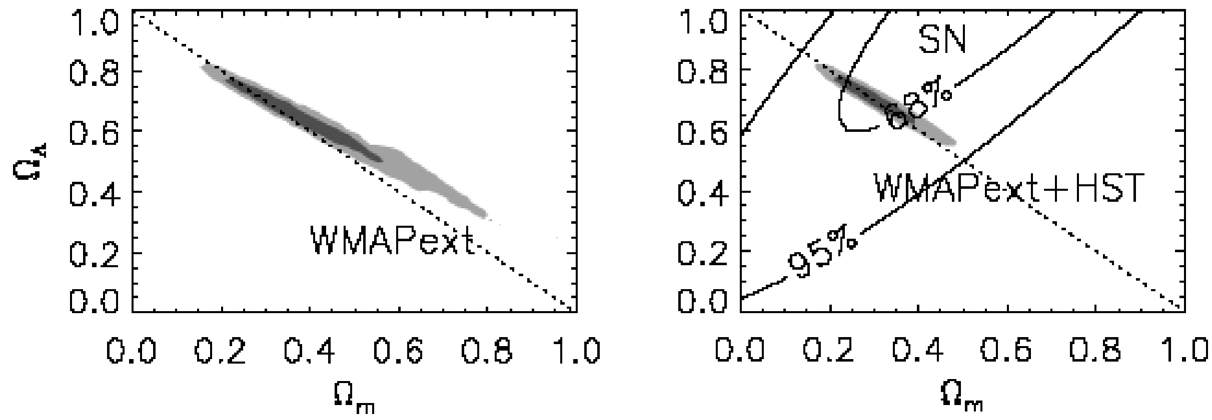

Figure 1. Two-dimensional likelihood surfaces for Ω_m and Ω_Λ, from [27], Figure 13. *(left)*– Likelihood for a combination of several CMB experiments, the so-called "WMAPext" set: WMAP [2], CBI [22], and ACBAR [18]. *(right)*– WMAPext likelihood surfaces in light of independent determination of $H_\circ$ obtained by the *HST* Key Project on the Extragalactic Distance Scale, e.g., [9], demonstrating the importance of external constraint on CMB data. Separate likelihoods for analysis of supernova data are also shown. The dashed line denotes a flat universe.

pending on calibration and analysis method. It is possible the distance is different by ± 0.2 mag ($\pm 10\%$), twice what is assumed in Key Project analyses.

Second, the effect of metallicity on the PL relation is controversial. Intense debate among observers, e.g., [26,16,15,25] has not led to broad agreement as to the sign and magnitude of the effect, while recent theoretical work suggests sensitivity to Helium as well as metal content [7,24, and references therein]. Although the Key Project adopted the results of [15], with a 0.08 mag uncertainty in their error budget [9], using VI-band photometry alone, they could not disentangle the effects of reddening and metallicity. This adds uncertainty particularly because LMC Cepheids are metal poor compared to Cepheids in our Galaxy and in most galaxies studied by the Key Project. The effect of metallicity could be at least as large as 0.2 mag.

Conceptually, the weakest link in calibration of the EDS is that it is anchored to a distance measurement for a single metal poor galaxy (the LMC), which remains controversial despite the application of much effort over many years. In principal, *the EDS should be tied to a sample of "reference" galaxies, broadly distributed in recessional velocity and for which robust geometric distances are available. SKA mapping of water maser sources that lie in the accretion disks of massive black holes within active galactic nuclei will make this possible.*

2. "Geometric Anchors" for the EDS

For an accretion disk that is relatively edge-on, well ordered kinematically, and heated as by X-ray irradiation or spiral shocks, conditions favor H_2O maser emission (1) in a narrow sector on the near side and (2) close to the disk- diameter perpendicular to our line of sight or "midline," e.g., [23,19]. The former masers correspond to spectral features close to the systemic velocity of the central engine. The latter group of masers traces the rotation curve of the disk when mapped with interferometers. Wherever the emission originates, it is highly anisotropic and beamed parallel to the local plane of the disk. In the case of a warped disk, the observed loci of emission mark a com-

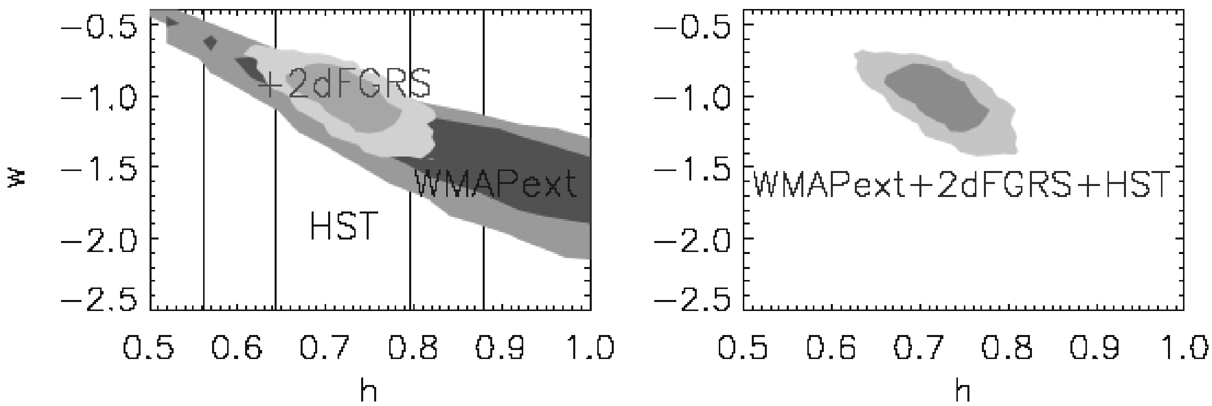

Figure 2. Two-dimensional likelihood surfaces for w and h ($H_\circ/100$), from [27], Figure 11. *(left)*– The outer contours are 68% and 95% confidence limits obtained from for three CMB experiments shown in Figure 1, combined. The tighter inner contours show 68% and 95% limits for CMB data combined with data on large scale structure from the 2°-field galaxy redshift survey [5]. Confidence limits for Key Project determination of the Hubble constant, $H_\circ$, are indicated by vertical lines. *(right)*– The joint likelihood for the equation of state of dark energy. Key Project estimates of $H_\circ$ have a modest impact, owing to an estimated uncertainty of 10%. Reduction in that uncertainty by factors of a few would substantially improve estimates of w.

promise between where the line of sight is tangent to the disk and where gradients in the line-of-sight component of orbital velocities (projected along the line of sight) is close to zero.

Two largely independent geometric estimates of distance may be obtained from measurements of the gravitational (centripetal) acceleration and separately from measurements of the proper motion of masers on the near side of the disk. The acceleration is obtained from the secular change of maser line-of-sight velocities (observed in spectra), and the proper motion is obtained from the changes in angular position (observed in interferometer images). Successful estimation of distance depends on a disk exhibiting emission from the near side of the disk, to enable measurement of acceleration or proper motion, and emission from the midline, to enable modeling of the disk geometry (e.g., inclination) and central mass.

To date, a geometric distance has been estimated for one galaxy, NGC 4258, and the example is a pathfinder for future work involving other galaxies. Herrnstein et al. [12] reported acceleration and proper motion distances that agree to $< 1\%$, and they obtained random and systematic uncertainties of 4% and 6%, respectively. The systematic uncertainty arises largely from unmodeled substructure and a 0.1 upper limit on the eccentricity of orbits in the 0.56 pc diameter disk. An increase in the number of observing epochs from 6 to 24, extension of the time baseline of monitoring from 3 to 6 years, and incorporation of eccentricity into the geometric model may ultimately reduce the total uncertainty in the geometric distance to $\sim 3\%$ [14].

However, using the distance to NGC 4258 to estimate $H_\circ$ is complicated because the galaxy is nearby and its peculiar motion above and beyond the Hubble expansion is large. A geometric distance for NGC 4258 is most appropriately used to recalibrate Cepheids PL relations independent of the LMC distance and sub-solar metallicity. As a result, uncertainty in a new estimate of $H_\circ$ would combine error budgets for maser and Cepheid analyses. Ultimately, the best results will be achieved for galaxies distant enough that

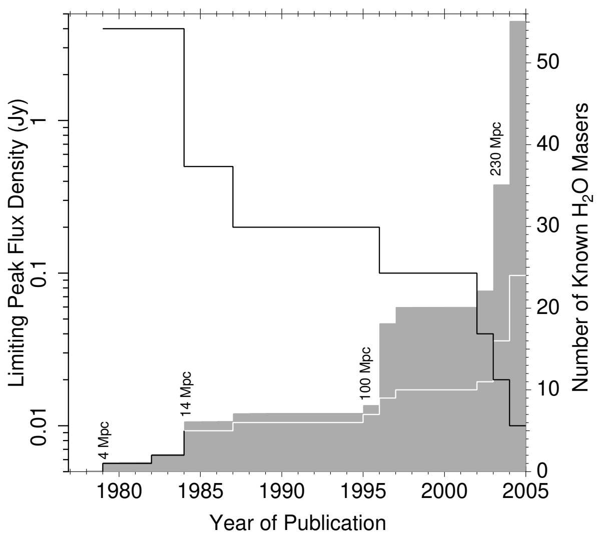

Figure 3. Growth over time in the number of known megamaser sources *(shading)* and the concomitant decline in peak flux density for the weakest source at each epoch *(black line)*. The increase over time in the maximum distance at which maser emission has been recognized is also marked. The white line indicates the subset of sources believed to be associated with edge-on accretion disks, judging from spectroscopic signatures and/or interferometer maps.

their peculiar motions are a small fraction of their total motions, and $H_\circ$ may be estimated directly from maser distances and recessional velocities.

3. SKA Measurement of $H_\circ$

The sensitivity of the SKA will be critical to assembling a large sample of maser-host galaxies and estimating their distances. Somewhat more than 50 masers are known at flux densities above $\sim$ 10 mJy and distances of $\sim$ 4 to 230 Mpc. This count is strongly sensitivity limited. Larger and more efficient apertures detect more masers, and rapid growth in the number of known masers since 2000 is primarily a consequence of improving instrument sensitivity (Figure 3). The best detection rates achieved thus far are for the Green Bank Telescope (GBT), $\sim$ 30% for Seyfert-2 galaxies with $cz < 5000$ km s^{-1}, of which there are 34 masers [4,17]. The SKA will be $\sim 80\times$ more sensitive than the GBT at λ1.3cm. Judging from the larger volume of space that the SKA will explore with at least comparable sensitivity, it may be expected to increase the number of known H_2O masers by two to three orders of magnitude [20].

Estimating distances for galaxies beyond a few tens of megaparsecs is best accomplished by measurement of centripetal accelerations through monitoring of spectra, and by measurement of angular structure via interferometric mapping. For a zero order model disk (i.e., flat, effectively massless, and otherwise similar to NGC 4258), $D = a^{-1}(\theta_h V_{rot}^2|_{\theta_h})^{\frac{1}{3}}\Omega^{\frac{4}{3}}$, where D is distance, a is centripetal acceleration, $V_{rot}|_{\theta_h}$ is rotation speed at angular radius θ_h (estimated from a measured rotation curve), and Ω is orbit curvature estimated for material along the near side of the disk (obtained to first order from position-velocity plots of interferometer data).

The overall factional uncertainty for an individual distance measurement, $\frac{\sigma_D}{D}$, is approximately

$$\frac{1}{3}\sqrt{4(\frac{\sigma_{V_{rot}}}{V_{rot}})^2 + (\frac{\sigma_{\theta_h}}{\theta_h})^2 + 9(\frac{\sigma_a}{a})^2 + 16(\frac{\sigma_\Omega}{\Omega})^2} \quad (1)$$

where σ is used to indicate measurement uncertainty. Consider a nominal 10 mJy maser source that is observed with the SKA for one hour to construct images with sub-milliarcsecond resolution and whose spectrum is monitored with one minute snapshots every two months for one year. A spectral line width of 3 km s^{-1}, which is typical, is assumed for the following calculations. Adopting a sensitivity of $\sim$ 1 mJy hr$^{-0.5}$ for very long baseline imaging (i.e., for the core of the SKA operating in tandem with outrigger antennas that provide intercontinental baselines) [20] and a sensitivity for spectroscopy corresponding to $A_e/T_{sys} \sim 10^4$ m^2 K^{-1} (at λ1.3 cm), one obtains $\frac{\sigma_D}{D} < 10\%$ for a wide range of central engine mass, disk radius, and distance (Figure 4). In principle, actual measurements may be affected by systematics, as may be introduced by blending of spectral lines, nonKeperlian rotation curves or substructure within the disk (e.g., the Circinus maser; [10]), but it is difficult to assess their magnitude in advance. If the case of NGC4258 is typical of the subsample that will be studied in detail to obtain $H_\odot$, then the systematic and random errors will be the same order of magnitude, and this may suggest an upper limit of $< 20\%$ on σ_D/D for individual galaxies.

As discussed by Morganti et al., the SKA is expected to detect many thousand water maser sources in the accretion disks of massive black holes. Conservatively, on the order of 10% will be useful for the estimation of distances, based on expectations developed in light of the source sample known today. (The actual fraction could turn out to be substantially larger.) The systematic uncertainties that affect individual distance measurements will be largely uncorrelated. Overall uncertainty in $H_\circ$ will scale inversely with $\sqrt{N}$, where N is the number of distance measurements (assuming peculiar motions are small), and a 1% factional uncertainty on $H_\circ$ will be achievable with no more than just a few hundred "maser galaxies," an order of magnitude improvement over current best estimates obtained by the study of standard candles. The impact on parameter estimation for ΛCDM or other precision cosmological models will be substantial (e.g., [13]) and would be difficult to obtain by other means, because the maser studies will rely primarily on geometry and the results will be largely model independent.

The critical elements that will enable high accuracy measurement of $H_\circ$ are (1) a short wavelength capable SKA (λ1.3 cm), (2) outrigger antennas that contribute substantial collecting area on intercontinental baselines (A_e/T_{sys} on the order of 10^3 $m^2\,K^{-1}$), (3) high spectral resolutions and broad instantaneous bandwidths ($\frac{\Delta\nu}{\nu} \sim 10^{-6}$) to resolve lines distributed over of order 2000 $km\,s^{-1}$, (4) time to observe tens of thousands of active galactic nuclei with the goal of identifying new maser sources and (5) follow-up imaging and spectroscopic monitoring of the hundred or thousands of new maser sources, keeping in mind that long synthesis tracks will be required to achieve adequate sensitivity with the highest angular resolutions.

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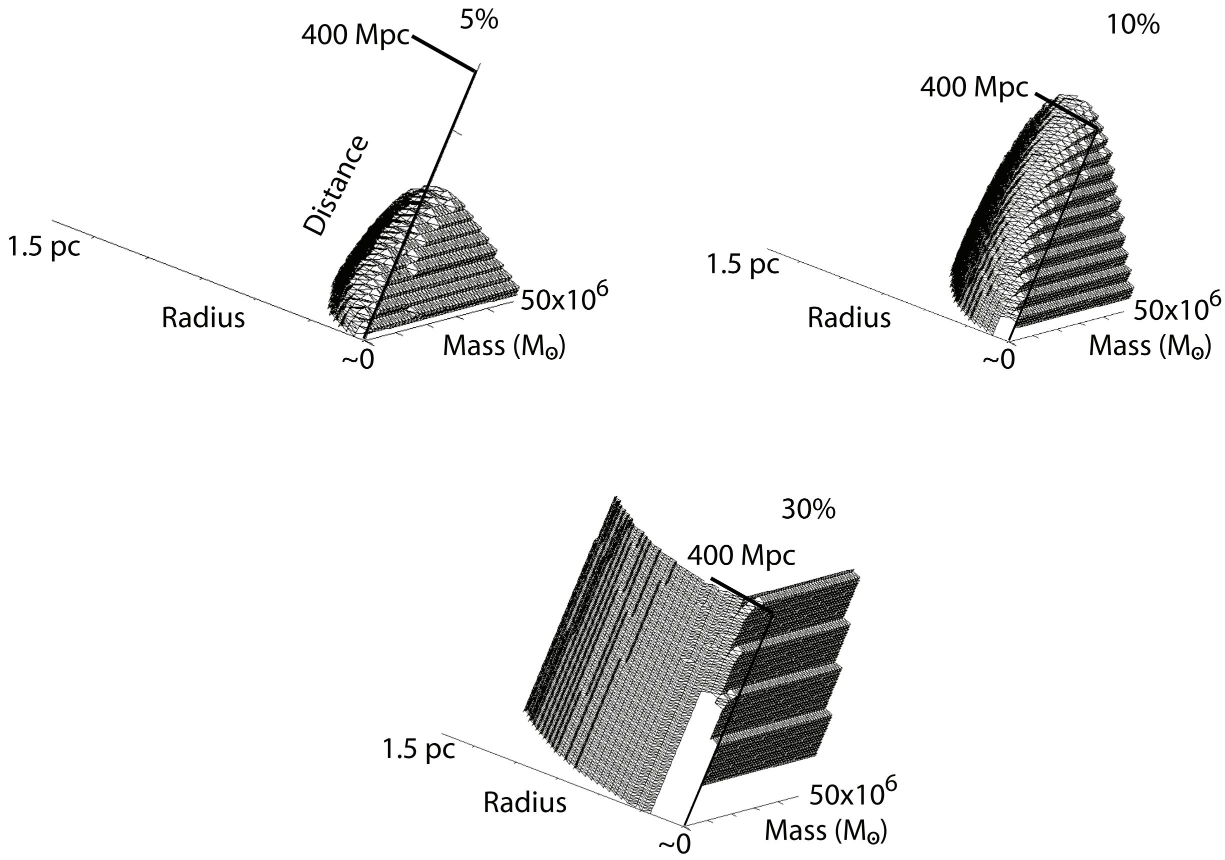

Figure 4. Surfaces that represent fractional uncertainties in estimated distance of 5%, 10%, and 30% (for an individual galaxy) as functions of central engine mass, accretion disk radius, and true distance. The effects of systematic uncertainties are not included, but in the case of NGC 4258, random and systematic uncertainties in estimated distance are about the same magnitude.