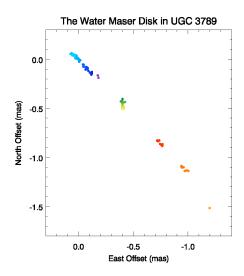# Cosmology with Water-vapor Megamasers

A White Paper for the Astro2010 Survey

J. A. Braatz[1] (NRAO), J. J. Condon (NRAO), C. Henkel (MPIfR), K.-Y. Lo (NRAO), and M. J. Reid (CfA)

The Water Maser Disk in UGC 3789

[1]Contact Author:

James Braatz
National Radio Astronomy Observatory
520 Edgemont Road
Charlottesville, VA 22903
(434) 296-0251
jbraatz@nrao.edu

Abstract

Dark Energy (DE) accounts for 74% of the mass of the universe, dominates its present expansion and ultimate fate, and retards the formation of large-scale structure. Understanding DE may be the most important problem in all of physics today.

Complementing the exquisite cosmic microwave background radiation (CMBR) data from redshift $z \approx 1100$, when DE was negligible, an independent measurement of the Hubble constant H_0 at $z \approx 0$ to within 3% would provide the best single constraint on the nature of DE (Hu 2005). An accurate H_0 would also constrain other critical cosmological parameters, including the geometry (open, closed, or flat) of the universe and the fraction Ω_m of the critical density contributed by matter.

The Hubble Space Telescope (HST) Key Project measurement of H_0 is indirect, based on Cepheid variables within 25 Mpc used as standard candles in a distance ladder limited by systematic errors at the 10% level. Baryon Acoustic Oscillations (BAOs) measure the Hubble parameter $H(z)$ directly but statistically and only at $z \geq 0.3$, where H is less sensitive to DE by factors of two to four. The best prospect for measuring the Hubble constant at $z = 0$ with 3% or better accuracy involves direct, angular diameter distance measurements to circumnuclear H_2O megamasers in galaxies at distances 50–200 Mpc. Measuring such maser distances requires both Very Long Baseline Interferometry (VLBI) and single-dish observations, using the technique pioneered on the nearby galaxy NGC 4258 (Herrnstein et al. 1999).

The Megamaser Cosmology Project (MCP) is a large project to develop the maser distance technique and measure H_0 using the best telescopes available for this task—the Green Bank Telescope (GBT), Very Long Baseline Array (VLBA), and Effelsberg 100 m. Progress is encouraging but clearly limited by sensitivity, especially in the VLBI observations. To measure H_0 within 3%, we should double the VLBI sensitivity at 22 GHz. For the next decade, we endorse continued support for the GBT, VLBA, Effelsberg 100 m, and Expanded Very Large Array (EVLA). We recommend equipping the 50 m Large Millimeter Telescope (LMT) for VLBI at 22 GHz, thereby adding sensitivity and critical N-S baselines. We also endorse increasing the collecting area at VLBA sites through a program such as the North American Array (http://www.nrao.edu/nio/naa). These upgrades would double VLBI sensitivity at 22 GHz. The ultimate application of the maser distance technique, achieving a ~1% accuracy, would require a Square Kilometer Array (SKA) telescope capable of observing at 22 GHz. We endorse development of the SKA-high for this long-term goal.

Scientific Background: Dark Energy, Concordance Cosmology, and *H_0*

"It is difficult for physicists to attack this problem [the nature of dark energy] without knowing just what it is that needs to be explained, a cosmological constant or a dark energy that changes with time as the universe evolves; and for this they must rely on new observations by astronomers. Until it is solved, the problem of the dark energy will be a roadblock on our path to a comprehensive fundamental physical theory"—Steven Weinberg

Dark Energy is called is called "dark" because it does not interact with photons and "energy" because its pressure p is comparable with its energy density ρ. Matter, by contrast, has $p \ll \rho$.
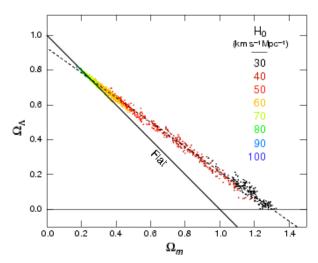
Pressure and energy density are the only properties of the constituents of the universe that enter into the Friedmann equations for the expansion of the universal scale length $a \propto (1+z)^{-1}$:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho - k\frac{c^2}{a^2} \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p).$$

The superscript dots denote time derivatives, G is the gravitational constant, c is the speed of light, and k is the curvature parameter (0 for a flat universe). Both p and ρ are sources of gravity. Energy density is always positive, so matter (defined by $p = 0$) only produces deceleration. Radiation has positive pressure $p = \rho/3$ and also decelerates the expansion of the universe. However, an energy source having negative pressure may cause gravitational acceleration. The observed acceleration requires an energy component whose equation-of-state parameter $w \equiv p/\rho$ is < -1/3. A cosmological constant Λ whose energy density is independent of a has $w = -1$ and hence may accelerate the expansion. A leading candidate for the cosmological constant is the quantum vacuum, but physical estimates of its energy density are many orders of magnitude too high (Weinberg 1989). DE might also be a variable "quintessence" (Wetterick 1988, Ratra and Peebles 1988) having -1 < w < -1/3.

The "concordance" cosmological model *assumes* a flat ($k = 0$) ΛCDM universe composed of baryons, cold dark matter (CDM), and DE in the form of a cosmological constant Λ (Spergel et al. 2003). The *absolute* size (that is, the size independent of the Hubble constant H_0) of the density fluctuations that produce the first peak in the angular power spectrum of the CMBR at the decoupling redshift $z \approx 1100$ may be calculated from basic physics, so the observed angular size of the first spectral peak determines the absolute angular-size distance to the surface of last scattering.

Although the absolute angular-size distance to the surface of last scattering is known, this distance does not determine H_0 by itself. It depends on three parameters: the amount and nature of DE, the geometry of the universe (flat, open, or closed), and the current expansion rate H_0. Only when two parameters are eliminated by assuming that (1) the universe is flat and (2) DE is a cosmological constant can CMBR data yield an estimate of H_0. Thus Spergel et al. (2007) stress that WMAP data are consistent with a wide range of H_0 (Figure 1), so an *independent* measurement of H_0 is needed to justify these assumptions.

Figure 1: Each point marks a model and H_0 consistent with WMAP data without the flatness assumption. The WMAP data are consistent with a wide range of H_0 (Spergel et al. 2007).

In his analysis of DE probes, Hu (2005) concluded that the single most important complement to CMBR data for constraining DE is an accurate (< 3%) measurement of H_0. The long lever arm between $z \approx 0$ and $z \approx 1100$ means that determining H_0 to 3% locally constrains the DE equation-of-state parameter w more effectively than a 1% measurement of H at redshifts $z > 0.3$ (Hu 2005). In addition, an accurate H_0 is essential for converting between relative (depending on H_0) and absolute cosmological quantities. For example, the angular power spectrum of the CMBR constrains the

absolute density of matter ω_m, which is proportional to $\Omega_m H_0^2$, where Ω_m is the fraction of the closure density contributed by matter. However, it is the density parameter Ω_m that affects the expansion of the universe, so the uncertainty in Ω_m is still dominated by the uncertainty in H_0.

There are other probes constraining DE in different ways: improving the magnitude–redshift relation of SNe Ia and extending its redshift range, measuring baryon acoustic oscillations at moderate redshifts, and weak lensing. Each has its own strengths, weaknesses, and systematic errors. The DE problem is so important that major efforts should be developed to exploit all of them simultaneously.

The State of H_0

The most widely accepted value of the Hubble constant, independent of a cosmological model, is still $H_0 = 72 \pm 3_r \pm 7_s$ km s^{-1} Mpc^{-1} (random and systematic uncertainties listed separately) from the HST Key Project (Freedman et al. 2001) and is based on the "extragalactic distance ladder" using the Large Magellanic Cloud (LMC) to calibrate Cepheid variables treated as "standard candles." The 10% total uncertainty is dominated by systematic errors. The Cepheid metallicity correction is controversial, as highlighted by Sandage et al. (2006), who used similar methods but a different metallicity correction to obtain $H_0 = 62 \pm 1.3_r \pm 5.0_s$ km s^{-1} Mpc^{-1}. Note that $H_0 = 72$ km s^{-1} Mpc^{-1} is consistent with the flatness assumption while $H_0 = 62$ km s^{-1} Mpc^{-1} challenges it. Figure 2 demonstrates how reducing the uncertainty in H_0 improves constraints on the cosmological model. The value of w can be determined with uncertainty < 0.1 by reducing the H_0 uncertainty to 3%. The bottom right panel of Figure 2 shows that measuring $H_0 = 62 \pm 3\%$ would eliminate the cosmological constant ($w = -1$) as the explanation of DE with a confidence level $> 96\%$. A measurement of $H_0 = 72 \pm 3\%$ would eliminate many quintessence models.
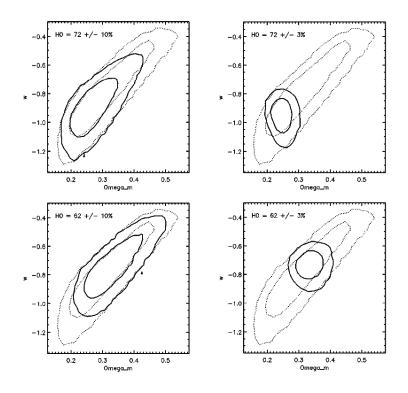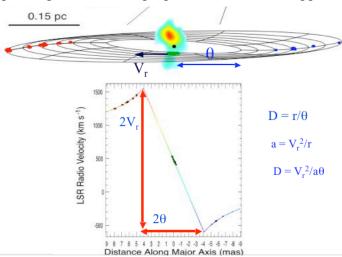

Figure 2: WMAP 1σ and 2σ likelihood surfaces for w vs. Ω_m given two priors on H_0. The dotted lines represent the "wcdm + no perturbations" model from Spergel et al. (2007) while the solid lines show the improvements given by independent values of $H_0 = 72$ km s^{-1} Mpc^{-1} (top) and $H_0 = 62$ km s^{-1} Mpc^{-1} (bottom) with 10% (left) and 3% (right) errors.

Measuring geometric distances to galaxies in the Hubble flow eliminates the systematic errors associated with standard candles. Several methods provide important, independent tests, for example

gravitational lens time delays and the Sunyaev-Zel'dovich (SZ) effect. However, both of these methods are complex in their own right. Lens measurements typically give $H_0 \approx 60 \pm 25\%$ (e.g. Treu & Koopmans, 2002; Cardone et al. 2002). A recent, large SZ survey determined $H_0 = 77 \pm 4_r \pm 10_s$ (Bonamente et al. 2006). Another important method involves observations of the Baryon Acoustic Oscillations. The SDSS-III BOSS experiment, for example, aims in the next decade to measure the Hubble parameter to 1% uncertainty at $z = 0.3$ and beyond. However, to gain the longest "lever arm" from the CMB observations, and to measure DE where its effect is greatest, requires measuring the Hubble parameter at $z = 0$. A measurement of H_0 based on distances to individual galaxies also provides an essential test of the cosmological model using independent and straightforward methods. *To achieve a 3% or better measurement of H_0, the most promising technique involves observations of H_2O megamasers in AGN accretion disks.*

The Maser Distance to NGC 4258

VLBA observations of the H_2O megamaser in the nearby ($D = 7.2 \pm 0.5$ Mpc) Seyfert 2 galaxy NGC 4258 determine its distance geometrically, thereby bypassing the problems of standard candles (Herrnstein et al. 1999). The H_2O masers reside in a thin, edge-on, gaseous annulus (Figure 3) at distances $r \approx 0.14$–0.28 pc from the central black hole. Emission near the systemic velocity comes from the near side of the disk, and "satellite lines" with velocities $V \approx \pm 1100$ km s^{-1} come from the two tangent points. The Keplerian rotation curve of the satellite lines imply a central mass of $3.9 \times 10^7 \, M_\odot$. The recession velocities of individual systemic features are increasing by ~ 9 km s^{-1} yr^{-1} (Haschick, Baan, & Peng 1994; Greenhill et al. 1995a), the centripetal acceleration $a = V^2/R$ of clouds moving across our line of sight (Watson & Wallin 1994; Haschick, Baan, & Peng 1994; Greenhill et al. 1995a,b). The distance D to NGC 4258 can be measured in two independent ways: (1) from proper motions $\dot{\vartheta}$ via the relation $V = D\dot{\vartheta}$ or (2) from accelerations via the relation $a = V_r^2/r = V_r^2/(D\vartheta)$, where V_r, a, ϑ, and $\dot{\vartheta}$ are measured from either monitoring or VLBI observations. Herrnstein et al. (1999) give a detailed explanation. The second method, not depending on measured proper motions, can be applied in principle to galaxies at distances much greater than 7 Mpc provided the disk can be mapped with sufficient precision.

$$D = r/\theta$$
$$a = V_r^2/r$$
$$D = V_r^2/a\theta$$

Figure 3: For the simplest disk model, the maser distance is determined by three parameters: $D = V_r^2 / a\vartheta$. The disk's angular size at the radius of the systemic features is given by ϑ, and it is measured from the rotation curve as shown. The velocity that corresponds to that radius is V_r, and the acceleration of systemic features, a, is measured by the secular velocity drift of the systemic masers, as determined by monitoring the spectrum. Note that the position-velocity distribution of systemic features defines a line that intersects the rotation curve at two loci and determines V_r and θ.

Measuring the Hubble Constant using Maser Distances

NGC 4258 is so close that its peculiar motion may be large compared to its recession velocity, so it cannot constrain H_0 directly. However, astronomers have used the sensitive GBT and Effelsberg radio telescopes to discover H_2O masers in galaxies well into the Hubble flow at $D \sim 50$–200 Mpc (e.g. Braatz et al. 2004, Kondratko et al. 2006, Braatz & Gugliucci 2008). Measuring the distance to each galaxy requires a sensitive VLBI map and a series of single-dish spectra over a couple of years to measure centripetal accelerations. The maser disk in each galaxy must then be modeled to account for any warp and radial structure in the maser distribution. With adequate data, systematic errors in disk modeling are expected to be $\sim 5\%$ and not likely to be correlated among different galaxies, so the uncertainty in H_0 determined from observations of N galaxies spread around the sky should fall nearly as $\sqrt{N}$. Measuring multiple galaxies with a wide sky distribution is important to reduce the impact of peculiar velocities and large-scale flows, even after corrections from models of the cosmic velocity field (e.g. Branchini et al. 1999). Therefore to measure H_0 with a total uncertainty $\sim 3\%$, for example, one could aim to measure $\sim 10\%$ distances (including systematic and random errors) to each of $N \approx 10$ galaxies (cf. Greenhill 2004); by measuring additional galaxies or more accurate distances, the uncertainty in H_0 could be further reduced.

Currently there are 120 galaxies detected as H_2O maser sources. Five have circumnuclear H_2O masers appropriate for distance measurements with current telescopes, and these are being studied in detail with the GBT, VLBA and Effelsberg. While progress is encouraging, it is clear that the effort is limited by sensitivity and would be greatly helped by doubling the VLBI sensitivity.
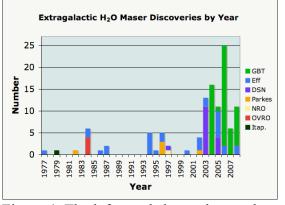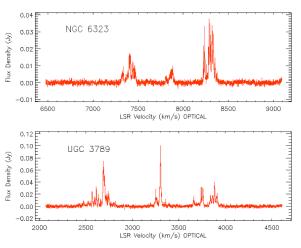

Figure 4: The left panel shows the number of extragalactic maser discoveries each year, color-coded by telescope, and demonstrates the significant progress of surveys recently. The exquisite sensitivity of the GBT makes it the best telescope for detecting these rare masers. The right panels show GBT spectra of the maser disks in NGC 6323 (top) and UGC 3789 (bottom), which are ideal for measuring distances. Each spectrum shows the characteristic triple-peaked profile. VLBI images of these masers are shown in Figures 5 and 6.

The Maser Distances to UGC 3789 and NGC 6323

Observations of water masers in the Seyfert 2 galaxy UGC 3789 clearly identify a parsec-scale, edge-on maser disk with a Keplerian rotation profile (Reid et al. 2009; Fig. 5). Accelerations measured with the GBT, combined with the VLBI map, provide the necessary data to measure a distance to this galaxy. A preliminary analysis gives a distance of 51 Mpc, corresponding to

$H_0 \sim 65$ km s^{-1} Mpc^{-1} (Braatz et al., in preparation). *These observations provide the first maser distance to a galaxy in the Hubble flow.* With future refinements in the acceleration modeling, and by applying 3-D disk fitting (see Humphreys et al. 2008), it should be possible to measure a 10% or better distance to this galaxy.

While the masers in UGC 3789 are bright enough for self-calibration and high-fidelity imaging using the existing suite of GBT+VLBA+EB telescopes, the masers in other galaxies are weaker and present a greater challenge. The maser in NGC 6323 (D $\approx$ 100 Mpc) pushes the limit of what can be observed with today's telescopes, but the prospect of measuring its angular diameter distance warrants the effort. The VLBI map shown in Fig. 6 demonstrates that sub-pc disks can be imaged with high fidelity even at these considerable distances. Disk substructure in the form of warping is evident in the map, and the rotation curve is consistent with Keplerian rotation. Nevertheless, a robust maser distance to this galaxy requires a significantly more sensitive map to measure the position-velocity gradient among systemic features; only a hint of it appears in the current best map. Observations of Mrk 1419, NGC 1194, and NGC 6264 are also being made. In each of these cases, sensitivity is a challenge, as in NGC 6323.
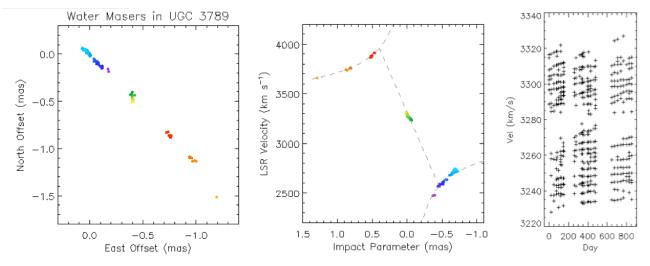

Figure 5: The left panel shows the distribution of maser spots in UGC 3789, delineating the thin, edge-on disk. Colors represent rotation velocity, with reds indicating motion away from the observer, blues toward the observer, and yellow/green representing the systemic lines. The middle panel shows the position-velocity diagram, identifying the Keplerian rotation profile and gradient in systemic features. The right panel shows velocities of systemic maser components measured with monthly GBT monitoring. The upward trend indicates the redward drift of these features, which have a mean acceleration of ~ 4 km s^{-1} yr^{-1}.

VLBI Sensitivity Requirements: There is an critical sensitivity threshold for mapping maser disks because the best maps require that the atmospheric phase be calibrated directly on the brightest lines of the maser itself (i.e. self-calibration), rather than using an external phase calibrator. The peak line flux density needed to calibrate on a single, narrow line with the current suite of telescopes is about 100 mJy. Improving the sensitivity of the array by a factor of ~ 2 would reduce this threshold commensurately, and enable self-calibration of masers such as NGC 6323 and Mrk 1419 without relying on fortuitous and sparse maser flares. An improvement in sensitivity by a factor of ~2 is thus an essential step in measuring 10% distances to these galaxies.
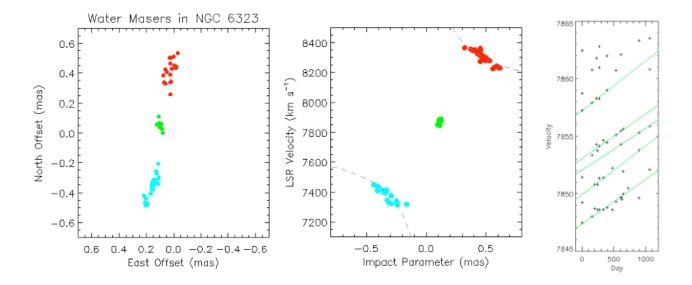
Figure 6: The left panel shows the distribution of masers in NGC 6323, and the middle panel shows its P-V diagram with a Keplerian fit to the high velocity lines. The right panel shows results of our GBT monitoring. The angular radius of the disk is ~ 0.5 mas.

The Future of Cosmology with H_2O Megamasers

The current effort to measure H_0 using water megamasers is sensitivity limited. To advance this effort it is essential to (1) maintain support of the VLBA, (2) continue support and development of the GBT, Effelsberg 100 m, and EVLA, and (3) instrument the LMT for 22 GHz VLBI, which would both add to the sensitivity of the global VLBI array and add critical N-S baselines. It would be possible to double the sensitivity of the VLBA by adding collecting area at VLBA sites, as is proposed in the North American Array, for example. To reach the ultimate potential of the megamaser distance technique and eventually measure a percent-level H_0 in later decades will require development of SKA-high, operational at 22 GHz.

References

Bonamente, M. et al. 2006, ApJ, 647, 25
Braatz, J. A., Henkel, C., Greenhill, L., Moran, J. & Wilson, A., 2004, ApJ, 617, L29
Braatz, J. A. & Gugliucci, N. 2008, ApJ, 678, 96
Branchini et al. 1999, MNRAS, 308, 1
Cardone, V. F. et al. 2002, A&A, 382, 792
Freedman, W. et al. 2001, ApJ, 553, 47
Greenhill, L. J. 2004, NewAR, 48, 1079
Greenhill, L.J., Henkel, C., Becker, R., Wilson, T.L. & Wouterloot, J.G.A., 1995a, A&A, 304, 21
Greenhill, L. J., Jiang, D. R., Moran, J. M., Reid, M. J., Lo, K. Y., & Claussen, M. J., 1995b, ApJ, 440, 619

Herrnstein, J. et al., 1999, Nature, 400, 539
Hu, W. 2005, ASP Conf Series Vol 339, Observing Dark Energy, ed. S. C. Wolff & T. R. Lauer (San Francisco: ASP), 215
Kondratko, P. T. et al. 2006, ApJ, 638, 100
Ratra, B. & Peebles, P. J. E. 1988, Phys. Rev. D, 37, 3406
Reid, M. J. et al. 2009, ApJ, in press
Sandage, A. et al. 2006, ApJ, 653, 843
Spergel, D. N. et al. 2003, ApJS, 148, 175
Spergel, D. N. et al. 2007, ApJS, 170, 377
Treu, T. & Koopmans, L. V. E. 2002, MNRAS, 337, L6
Watson, W. & Wallin, B. 1994, ApJ, 432, L35
Weinberg, S. 1989, Rev. Mod. Phys., 61, 1