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Measuring the Hubble constant with observations of water-vapor megamasers

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Abstract. To constrain models of dark energy, a precise measurement of the Hubble constant, H_0, provides a powerful complement to observations of the cosmic microwave background. Recent, precise measurements of H_0 have been based on the 'extragalactic distance ladder,' primarily using observations of Cepheid variables and Type Ia supernovae as standard candles. In the past, these methods have been limited by systematic errors, so independent methods of measuring H_0 are of high value. Direct geometric distance measurements to circumnuclear H_2O megamasers in the Hubble flow provide a promising new method to determine H_0. The Megamaser Cosmology Project (MCP) is a systematic effort to discover suitable H_2O megamasers and determine their distances, with the aim of measuring H_0 to a few percent. Based on observations of megamasers in UGC 3789 and NGC 6264, and preliminary results from Mrk 1419, the MCP has so far measured $H_0 = 68.0 \pm 4.8$ km s^{-1} Mpc^{-1}. This measurement will improve as distances to additional galaxies are incorporated. With the Green Bank Telescope, we recently discovered three more excellent candidates for distance measurements, and we are currently acquiring data to measure their distances.

Keywords. masers, distance scale

1. Introduction

As a complement to the exquisite observations of the cosmic microwave background, a measurement of the Hubble constant, H_0, provides strong constraints on several fundamental parameters of the Universe, including the equation of state for dark energy, the curvature of space, the mass of neutrinos, and the number of families of relativistic particles (e.g., Freedman & Madore, 2010). Consequently, measuring H_0 continues to be a critical focus of observational cosmology, with the aim of reaching a robust measurement with few-percent accuracy, or better. The most precise measurements of H_0 to date have been based on the 'extragalactic distance ladder,' using observations of relatively nearby (< 30 Mpc) Cepheid variable stars as standard candles. Cepheids are then tied to observations of Type Ia supernovae and other distance indicators that can be measured in the Hubble flow. The distance ladder is anchored by zero-point Cepheid calibrators in the Large Magellanic Cloud, the nearby maser galaxy NGC 4258, or a small number of

Galactic Cepheids for which parallaxes can be measured (e.g., Riess *et al.* 2011; Freedman *et al.* 2012).

Circumnuclear water-vapor megamasers provide an opportunity to obtain precise, direct geometric measurements of the distances to galaxies in the Hubble flow. These megamasers thus provide a one-step measurement of H_0 that is independent of standard candles and does not rely on distance ladders. The maser technique was pioneered by observations of the nearby galaxy NGC 4258 (Herrnstein *et al.* 1999). At 7.2 Mpc, NGC 4258 is too close to measure H_0 directly, but we have been discovering similar megamasers in galaxies 50–200 Mpc distant that are suitable for distance measurements.

The Megamaser Cosmology Project (MCP), a Key Project of the National Radio Astronomy Observatory, is a systematic effort to discover these megamasers and measure their distances. Using the Green Bank Telescope (GBT), the MCP searches for new megamasers primarily in type 2 active galaxies identified from the Sloan Digital Sky Survey, the 6dF galaxy survey, the 2MASS Redshift Survey, and other catalogs. So far, the MCP has discovered over 60 megamasers, about half of all megamasers known in active galactic nuclei. Not all megamasers show spectral profiles indicative of emission from a circumnuclear disk, but we have identified several from our survey that are excellent candidates for distance measurements. In this contribution we discuss the results of measuring maser distances to these galaxies, and we present three discoveries of maser disks that will be the focus of future efforts.

2. The Maser Method

In megamaser galaxies suitable for distance measurements, the masers originate in warm ($\sim$400 K), dense ($\sim 10^7$–10^9 cm^{-3}) gas in Keplerian rotation around the central supermassive black hole in active galaxies. The maser disk is typically a few tenths of a parsec in radius and is seen almost perfectly edge-on, an orientation that maximizes the maser gain length for observers near the plane of the disk. Because the masers reside directly in the black hole's sphere of influence, they provide strong evidence that the object at the dynamical center must be a black hole, and they provide 'gold-standard' masses of these black holes (e.g., Kuo *et al.* 2011).

In a maser disk, emission is detected from three distinct loci, i.e. directly in front of the black hole, and on each side of the disk near the mid-line, where the maser features are redshifted (relative to systemic) on one side and blueshifted on the other by their internal orbital motion. We refer to the redshifted and blueshifted masers as 'high-velocity' masers, and those on the front side of the disk as 'systemic' masers. Typical rotation velocities in maser disks are $\sim$500 km s^{-1}.

Conceptually, we measure the distance to a maser galaxy by comparing the observed angular radius of a maser orbit (from VLBI maps) to its measured linear distance from the black hole: $D = r/\theta$. In a simplified system, we can envision masers in a thin annulus that is part of a flat accretion disk, in a circular orbit around the black hole. Systemic masers on the front side of this annulus with radius r will be observed to accelerate with $A = v^2/r$. This acceleration could be measured by monitoring the spectral profile of the maser system and measuring the secular drift in velocity of each systemic maser component, as a function of time. High-velocity masers in the same annulus, which are near the midline, will be redshifted or blueshifted by the rotation velocity, v, and will have an observed acceleration near zero, because their acceleration vector is in the plane of the sky. Conceptually, then, for this thin annulus we can determine the distance by $D = v^2/A\theta$.

In practice, high-velocity masers are observed at a range of radii on the disk midline, and systemic masers occupy a range of radii on the front side of the disk, as well. In addition, maser disks are observed to be more complex than this conceptual model. They can have substructure such as a warp, they may not be precisely edge-on, the masers may not follow circular orbits, and some of the high-velocity masers may be displaced from the disk midline. Thus we can optimize our distance measurements by constructing a 3D model for the masers in the disk and adjusting the model to fit the observations. As in the conceptual scenario, we require two types of observations to determine the distance, a VLBI image to map the maser locations and measure velocities, and spectral-line monitoring to measure the accelerations of individual maser lines.

Reid *et al.* (2012) describe our model and technique in detail. We model the disk with a position-angle warp and an inclination warp. Initial tests to investigate eccentricity indicate that the maser orbits are nearly circular, so our current model uses circular orbits for simplicity. We fit the (x, y) position of the black hole with respect to reference masers, the recession velocity of the galaxy, and the mass of the central black hole. And finally, we can fit either the distance to the galaxy, D, or we can fit H_0 directly. In practice, we fit H_0 directly because of advantages in measuring the posteriori probability distribution function (PDF; for a discussion, see Reid *et al.* 2012). We evaluate each parameter's PDF with Markov-chain Monte Carlo trials, applying the Metropolis–Hastings algorithm to accept or reject each trial. Our model incorporates an estimate of the peculiar velocity of the galaxy and its uncertainty, when these are available from large-scale flow models. When unknown, we just apply a conservative uncertainty.

3. Results

Initial efforts by the MCP have concentrated on measuring maser distances to UGC 3789 (Braatz *et al.* 2010; Reid *et al.* 2012) and NGC 6264 (Kuo *et al.* 2012).

UGC 3789. In Fig. 1 we show a summary of the maser data for UGC 3789. The figure includes a spectrum from the GBT, showing the characteristic spectral profile of an edge-on maser disk. Above the spectrum are the VLBI map and the position–velocity (P–V) diagram. Overlaid on the latter is a Keplerian rotation curve. The high-velocity masers follow very nearly Keplerian orbits and the good fit to the curve indicates that they are close to the disk midline. Furthermore, the VLBI map shows that the systemic masers, near the origin in the plot, fall directly on the line defined by the redshifted and blueshifted masers, showing that the disk is nearly edge-on.

The panel on the right of Fig. 1 shows results of the GBT monitoring campaign for the systemic masers in this galaxy. The observing procedures are described in Braatz *et al.* (2010). Each mark on the plot shows the velocity of a distinct maser component, measured by eye. The evident positive slopes reveal the accelerations of maser clouds. All of the obvious trends exhibit positive slopes, indicating that the masers in the systemic spectrum originate on the front side of the maser disk. The individual maser components show a range of accelerations, from $\sim$0.9 to 8.4 km s^{-1} yr^{-1}, with the smaller accelerations near 3250 km s^{-1} and the larger accelerations near 3300 km s^{-1}.

Prior to modeling the disk, we determine the acceleration of each maser component using a global least-squares fit. The data in Fig. 1 show breaks on yearly intervals because our monitoring excludes the summer months when the weather in Green Bank is too warm and humid for K-band observations. It is natural, therefore, to fit one year of data at a time with the least-squares procedure. We find that the year-to-year accelerations are generally consistent with a single value, so we can bin and average the fitted accelerations from the yearly fits to arrive at our final acceleration results (Reid *et al.* 2012).

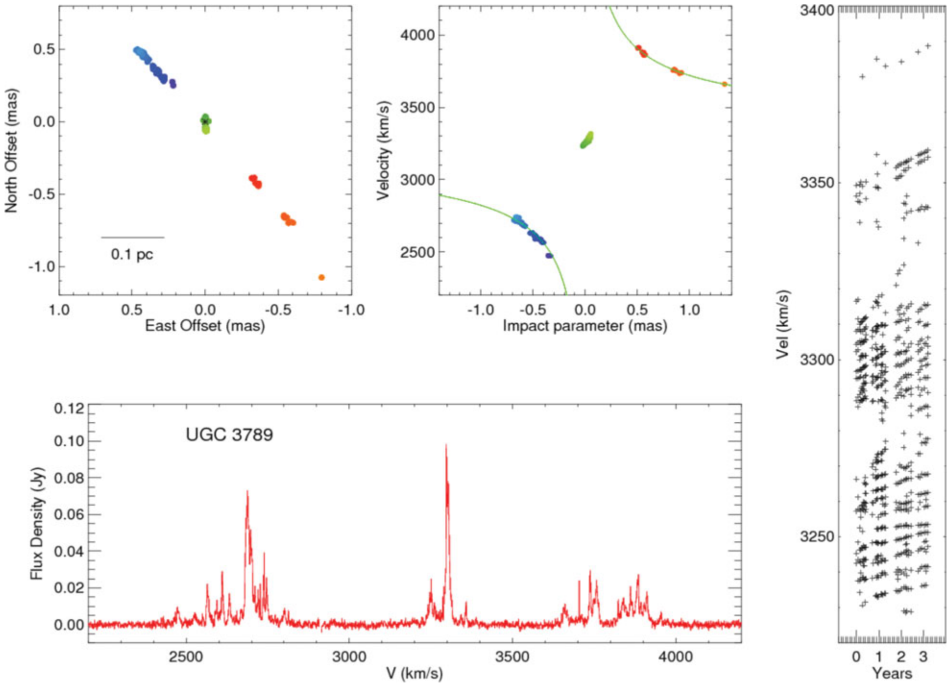

Figure 1. The megamaser in UGC 3789. The top left-hand panel shows a VLBI map. The points near the origin of the plot represent the systemic masers. The maser disk is viewed edge-on. The top middle panel is a position–velocity diagram derived from the VLBI map. The curves drawn through the high-velocity masers show a Keplerian fit. The bottom panel shows a representative GBT spectrum. The triple-peaked profile is characteristic of maser emission from an edge-on disk. The right-hand panel shows an acceleration plot. Each marker indicates the velocity of an individual maser component, measured by eye, from one spectrum. The upward slopes reveal the centripetal acceleration of systemic masers on the near side of the disk.

The posteriori PDF for the Hubble constant determined for the UGC 3789 maser disk is nearly Gaussian, and from it we determine $H_0 = 69 \pm 7$ km s^{-1} Mpc^{-1} (Reid *et al.* 2012). This measurement places the galaxy at an angular-diameter distance of 49.6 Mpc, and the fitted black hole mass is 1.16×10^7 $M_\odot$. Fig. 2 shows the distribution of maser spots as fitted by our disk model, first in a top-down view of the disk (left) and then as it is seen on the sky (right).

NGC 6264. Fig. 3 shows the VLBI map, P–V diagram, GBT spectrum, and GBT monitoring data for the megamaser in NGC 6264. Our analysis of this data follows the methods used for UGC 3789. Kuo *et al.* (2012) present our results for this galaxy.

Accelerations of systemic features in NGC 6264 range from $\sim$0.8 to 4.4 km s^{-1} yr^{-1}. In Fig. 4 we show the results of the disk model fitting. For this galaxy, we measure $H_0 = 68 \pm 9$ km s^{-1} Mpc^{-1} (Kuo *et al.* 2012). The corresponding angular-diameter distance is 150 Mpc, and the fitted black hole mass is 3.09×10^7 $M_\odot$.

4. Improving H_0 by Measuring Additional Galaxies

We can improve our determination of H_0 by measuring distances to additional galaxies. Systematic errors in disk modeling are $\lesssim 5\%$ 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 $\sqrt{N}$. 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. To reach the goal of measuring H_0 with a total uncertainty of ~3%, we could, for example, measure ~10% distances to each of 10 galaxies (cf. Greenhill 2004).

In addition to the two galaxies discussed above, we have already collected VLBI and GBT data to determine distances to several other galaxies, including Mrk 1419, NGC 6323, NGC 1194, and NGC 2273. The maser in Mrk 1419 is very well suited for a distance measurement, while the others present challenges that may limit their measurement accuracy. For example, the systemic masers in NGC 6323 became considerably fainter after their discovery.

Preliminary results of a distance measurement to Mrk 1419 are presented by Impellizzeri *et al.* (2012). They estimated the distance to the galaxy using an analysis of the P–V diagram (see also Braatz *et al.* 2010), and from Mrk 1419 we determine $H_0 = 66 \pm 10$ km s^{-1} Mpc^{-1}. Full disk modeling, currently underway, will improve the uncertainty in this measurement.

Finding new maser disks, like those in UGC 3789 and NGC 6264, remains a priority for the MCP, and GBT surveys by the MCP have been productive. In Fig. 5 we show spectra of three maser disks recently discovered with the GBT. We are currently acquiring the VLBI and spectral-line monitoring data necessary to measure distances to each of these.

5. Summary

The Megamaser Cosmology Project aims to determine H_0 by discovering water-vapor megamasers in galaxies 50 to 200 Mpc distant, and measuring their distances geometrically using the maser technique. The method measures H_0 in one step, and it is independent of standard candles.

The MCP has focused so far on measuring distances to UGC 3789 and NGC 6264. From these two galaxies, we determine $H_0 = 68.6 \pm 5.5$ km s^{-1} Mpc^{-1}. By further including our preliminary result from Mrk 1419, we determine $H_0 = 68.0 \pm 4.8$ km s^{-1} Mpc^{-1} (7%).

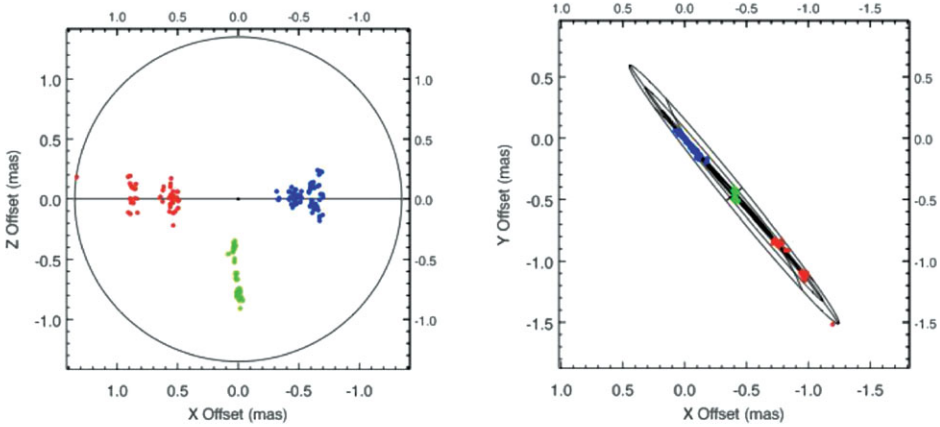

Figure 2. Disk model of the megamaser in UGC 3789. The left-hand panel shows a top-down view of the disk, with each spot representing the modeled position of the detected maser components. An observer views the maser from a large negative z offset (below the panel). The right-hand panel shows the distribution as we see it on the sky, with the model overlaid as a wire mesh. The disk has little warping in this case, and is very near to edge-on.

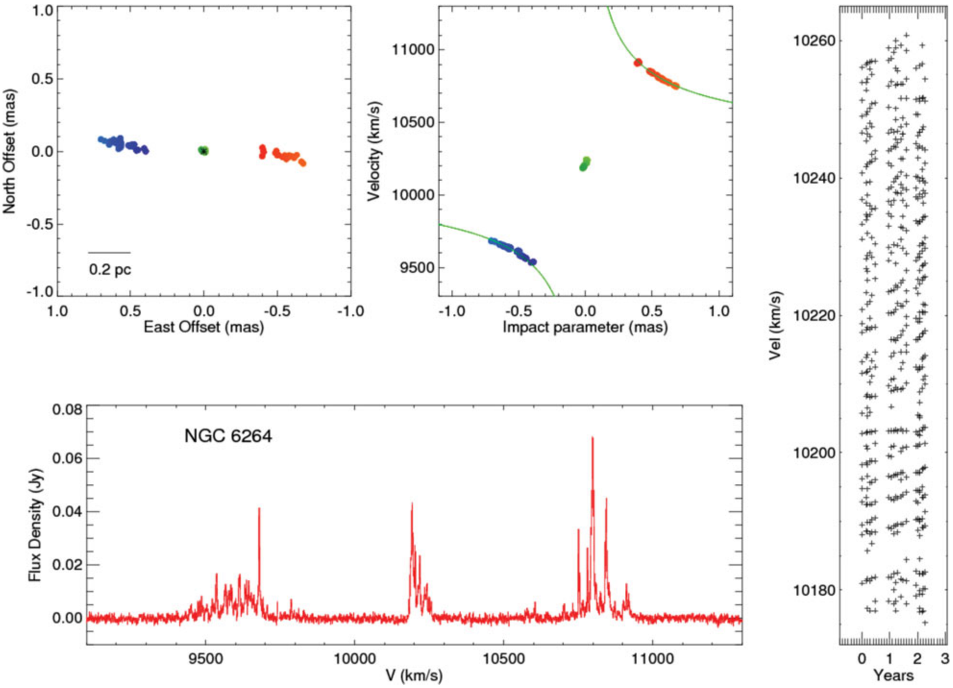

Figure 3. Megamaser in NGC 6264. The top left-hand panel shows a VLBI map of the maser and the top middle panel presents a P–V diagram. The curves drawn through the high-velocity masers show a Keplerian fit. The bottom panel has a representative GBT spectrum, and the right-hand panel shows an acceleration plot, as in Fig. 1.

The MCP is currently observing additional megamaser disk galaxies and will improve the measurement of H_0 by including these galaxies in later analysis. Our current focus is on obtaining the necessary observations for the distance candidates J0437+2456, ESO 558-G009, and NGC 5765b.

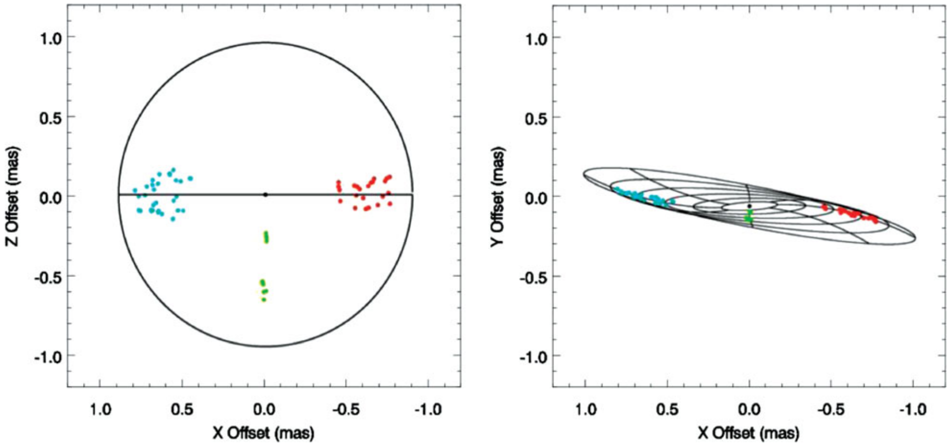

Figure 4. Disk model of the megamaser in NGC 6264. The left-hand panel shows a top-down view of the modeled maser positions. The right-hand panel shows the model and maser locations, this time tilted by 5° from our actual viewing angle to show the warping structure more clearly.

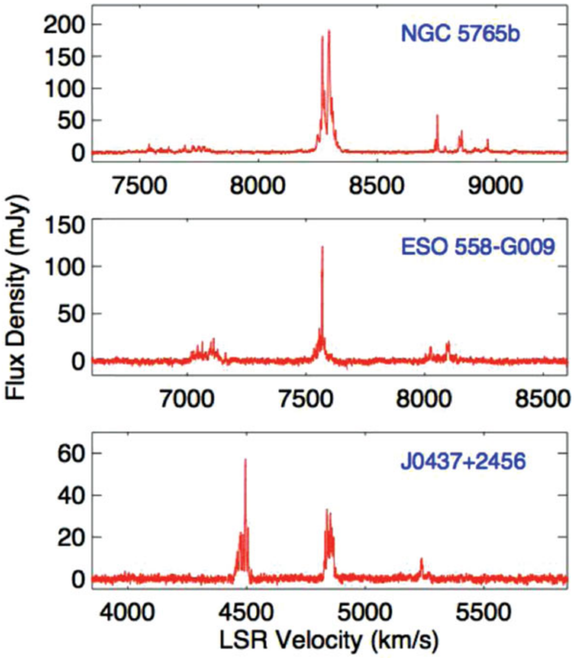

Figure 5. GBT surveys for new megamaser disks have resulted in discoveries of a number of excellent candidates appropriate for distance measurements. Here we show GBT spectra of three galaxies for which we are currently collecting data to determine their maser distances.

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