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A Measurement of the Hubble Constant by the Megamaser Cosmology Project

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Abstract. The Megamaser Cosmology Project (MCP) measures the Hubble Constant by determining geometric distances to circumnuclear 22 GHz H_2O megamasers in galaxies at low redshift ($z < 0.05$) but well into the Hubble flow. In combination with the recent, exquisite observations of the Cosmic Microwave Background by WMAP and Planck, these measurements provide a direct test of the standard cosmological model and constrain the equation of state of dark energy. The MCP is a multi-year project that has recently completed observations and is currently working on final analysis. Based on distance measurements to the first four published megamasers in the sample, the MCP currently determines $H_0 = 69.3 \pm 4.2$ km s^{-1} Mpc^{-1}. The project is finalizing analysis for five additional galaxies. When complete, we expect to achieve a $\sim$4% measurement. Given the tension between the Planck prediction of H_0 in the context of the standard cosmological model and astrophysical measurements based on standard candles, the MCP provides a critical and independent geometric measurement that does not rely on external calibrations or a distance ladder.

Keywords. masers, distance scale

1. Introduction

Exquisite observations of the Cosmic Microwave Background (CMB) at $z \simeq 1100$ by WMAP and Planck establish a framework for precision cosmology, but observations of the CMB on their own do not uniquely determine all fundamental cosmological parameters. Complementary observations in the local universe at $z \simeq 0$ can constrain critical parameters such as the equation of state for dark energy and the number of families of relativistic particles. Nevertheless, it is possible to use CMB results to *predict* certain observable cosmological parameters, including the Hubble Constant, but only in the context of a specific cosmological model. In this way, the base ΛCDM model of cosmology combined with Planck CMB observations makes the precise prediction: $H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1} (Planck Collaboration 2016). Astrophysical measurements of H_0 then make a powerful test of the model. Recent observations based on standard candles determine H_0 =73.24 ± 1.74 km s^{-1} Mpc^{-1} (Riess *et al.* 2016) and $H_0 = 74.3 \pm 2.6$ km s^{-1} Mpc^{-1} (Freedman *et al.* 2012), in tension with the Planck result. Meanwhile, measurements from BAO + SN Ia determine $H_0 = 67.3 \pm 1.0$ km s^{-1} Mpc^{-1} (Alam *et al.* 2017), in line with the Planck prediction, and observations of gravitational lensing determine H_0 $= 71.9\,^{+2.4}_{-3.0}$ km s^{-1} Mpc^{-1} (Bonvin *et al.* 2017). The tension between predicted values of H_0 from the CMB and observed values based on standard candles motivates a concerted effort in observational cosmology to measure H_0 using multiple, independent methods to minimize systematic uncertainties, with a current goal to achieve agreement at the $\sim 3\%$ level.

The Megamaser Cosmology Project (MCP) is an international, multi-year project to measure the Hubble Constant using observations of 22 GHz water vapor megamasers in the circumnuclear accretion disks of Active Galactic Nuclei (AGN). The MCP determines geometric distances to galaxies in the range ∼ 50-200 Mpc, directly in the Hubble Flow. The measurement of H_0 by the MCP is a one-step process that requires no external calibrations or distance ladders.

In addition to the determination of H_0, the MCP also measures gold-standard masses of supermassive black holes in AGNs, maps the geometry and orientation of the thin molecular accretion disk, and probes physical conditions of the disks on scales of tenths of a pc. Other contributions in this volume, including those by Henkel *et al.* and Pesce *et al.*, discuss aspects of these studies. In this paper, we focus on the progress of the MCP measurement of H_0.

2. A Survey for H_2O Disk Megamasers

Magnificent observations of the prototypical H_2O megamaser disk in NGC 4258 provide a precise distance to the galaxy (Humphreys *et al.* 2013) and make it an important anchor for the extragalactic distance scale, but at only 7.54 Mpc (Riess *et al.* 2016) it is too close for a direct measurement of H_0. However, the MCP has been conducting surveys to identify similar maser disks in the Hubble Flow. The MCP surveys target obscured AGNs, mainly Seyfert 2 galaxies, with $z < 0.05$ selected from SDSS, 6dF, and 2MRS optical spectroscopy. Additional smaller samples of galaxies have been included as survey targets based on X-ray or IR properties indicative of obscured AGN. The MCP and its pilot programs have surveyed about 2800 galaxies over nearly 10 years, and detected about 3%. The project then pursues followup studies for detections showing evidence of disk rotation.

Figure 1 shows the total number of extragalactic 22 GHz water masers detected each year. Altogether, there are 178 galaxies currently known to host 22 GHz H_2O masers. Of them, about 150 are in AGN and the others are associated with star formation in the host galaxies. About 37 of the megamasers in AGN show spectral profiles characteristic of edge-on disk masers, and 10 of those have been targeted for distance measurement observations.

MCP surveys use the sensitive Green Bank Telescope (GBT) to detect new masers. The survey strategy is to cover each candidate galaxy with a short 10-minute observation

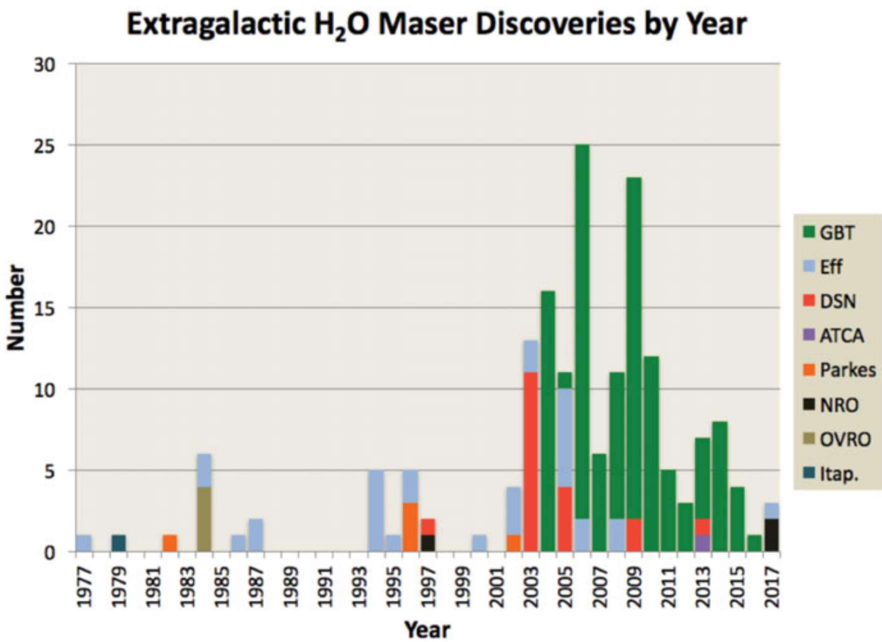

Figure 1. Extragalactic 22 GHz H_2O Maser detections, by year. The MCP used the Green Bank Telescope to conduct the large survey for new megamasers. About half of all known extragalactic 22 GHz water masers were discovered as part of the MCP or its pilot programs.

and, for detections and marginal cases, obtain a longer integration to better characterize the extent of the maser emission. The GBT has detected $\sim$ 65% of the known 22 GHz maser galaxies, most of those through the MCP surveys. The drop off in GBT detections since 2016, evident in Figure 1, reflects the end of the MCP surveys and refocusing of resources on observations needed to measure distances to the selected disk maser galaxies.

Masers originating in an edge-on accretion disk have a characteristic shape to the spectral profile, with 3 distinct sets of maser features grouped in velocity. Maser components in the central velocity group are termed systemic masers and form along the line of sight to the central black hole, while red- and blue-shifted "high-velocity" masers originate near the disk midline, rotating away from and toward the observer, respectively. Ideal candidates for distance measurements have at least one maser component bright enough ($\gtrsim$ 80 mJy) to enable VLBI self-calibration, clean Keplerian rotation profiles evident from the VLBI mapping, a large number of maser components within each group (red, blue, systemic) spread over a wide velocity range, bright and distinct systemic features that enable reliable tracking of accelerations, and accelerations in the systemic features sufficiently large ($\gtrsim 1$ km s^{-1} yr^{-1}) to track over $\sim$2 years of monitoring. The MCP web page† includes an online catalog of all known extragalactic 22 GHz water maser galaxies.

3. Spectral Monitoring and VLBI observations

Once a suitable maser disk is identified, two types of additional observations are required to determine the distance: spectral monitoring and VLBI imaging. Spectral monitoring is used to measure line-of-sight accelerations of individual maser components. For each galaxy targeted for a distance measurement, we require at least two years of

† https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

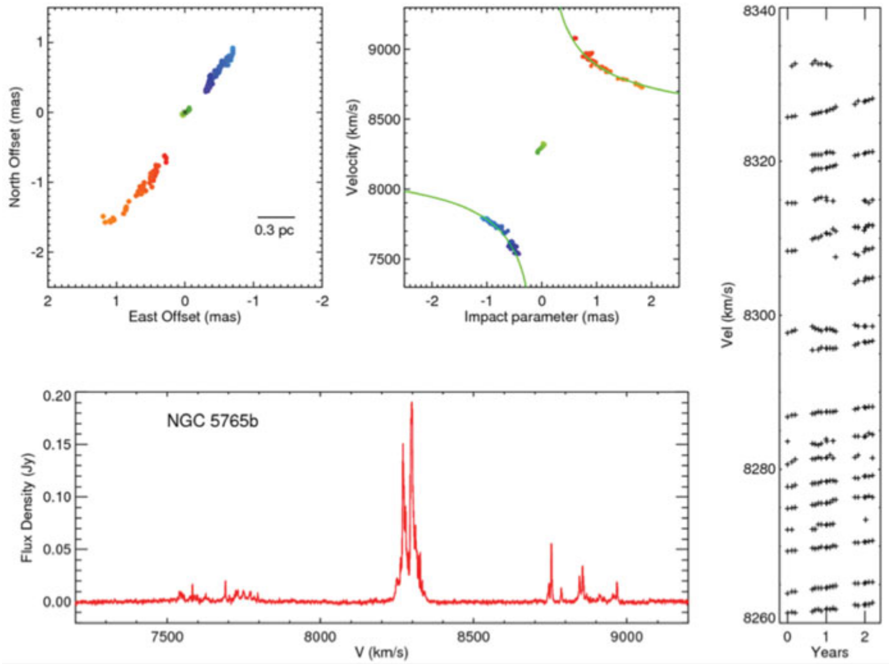

Figure 2. The H_2O Megamaser in NGC 5765b (also see Gao *et al.* 2016). The top left panel shows the VLBI maser map and the top center panel shows a P-V diagram. The solid lines on the P-V diagram represent a Keplerian fit to the rotation curve. The bottom panel shows a representative GBT spectrum, the three groups of maser features identifying the characteristic spectral profile of an edge-on maser disk. The right panel shows results of GBT spectral monitoring. Each symbol on the right-panel plot marks the velocity of a maser peak in the systemic part of the spectrum. The positive slopes evident in the evolution of the maser velocities represent the centripetal acceleration as maser clouds orbit the central supermassive black hole.

spectra, observed monthly. We use ∼3 hour integrations with the GBT to obtain each spectrum. The weather in Green Bank prohibits sensitive K-band data in the summer months, so most of our targets have a summer gap in the monitoring sequence. In one case, CGCG 074-064, we supplemented the GBT observations with VLA data taken during the summer. We determine accelerations of each individual maser feature using a global least-squares fit (e.g. see Reid *et al.* 2013 and Gao *et al.* 2016). Where possible we fit accelerations for the full time sequence of spectra, but variability and line blending force fitting to shorter time sequences in most cases.

In addition to the spectral monitoring, we obtain sensitive VLBI maps to measure the distribution of maser spots in the disk. We use the VLBA augmented by the GBT, phased VLA, and for high-declination targets also the Effelsberg telescope. We observe multiple tracks to reach the required sensitivity, and combine the data prior to imaging. When possible, we self-calibrate to the brightest maser component in the spectrum, thereby improving the efficiency of the observation.

4. An Example: the MCP Galaxy NGC 5765b

Figure 2 presents the set of observations for one of our MCP galaxies, NGC 5765b. See Gao *et al.* (2016) for a full presentation of the data and the determination of the distance to this megamaser system. The bottom left panel shows a representative GBT spectrum. The panel on the right highlights results from the ∼2 year spectral monitoring campaign. Each symbol on the plot marks the velocity of an individual maser peak in the systemic part of the spectrum. The positive slopes of the individual tracks mark the redward drift of each maser component, and the slope is equal to the acceleration of that maser cloud as it orbits the central supermassive black hole. In NGC 5765b, the bright systemic features enable precise tracking of individual maser drifts. While the velocity drifts in NGC 5765b are easily identifiable throughout the entire velocity range of the systemic group, in some other galaxies the fainter and blended systemic maser lines make acceleration measurements a challenge. For most galaxies in our sample, the measured accelerations of the systemic features is the limiting factor in the determination of the galaxy distance. We also measure the line-of-sight accelerations of the red- and blue-shifted high-velocity components (not shown). Those have measured values near zero since the acceleration is directed in the plane of the sky for maser clouds at tangential locations in the orbit, near the disk midline.

The top left panel in Figure 2 shows the VLBI map of maser positions, clearly presenting a thin, edge-on, rotating disk. The location of each spot in the map is determined with a 2D Gaussian fit to the unresolved maser detection in the corresponding VLBI spectral channel. The uncertainty of each maser position measurement is therefore approximately equal to the beam size divided by twice the signal-to-noise in that spectral channel. The top central panel shows the position-velocity diagram derived from the VLBI map. The solid lines represent a Keplerian fit to the rotation of high-velocity maser clouds, and demonstrate that the disk is in Keplerian rotation.

5. Model Fitting and Determination of H_0

For each megamaser system in our sample, we fit a warped disk model to the observed maser data to determine the distance, and H_0. We determine the probability density function for H_0 using a Markov Chain Monte Carlo (MCMC) method. In addition to H_0, the model fits for the mass of the black hole, the (x_0, y_0) position of the dynamical center, recession velocity of the dynamical center, the position angle and inclination of the disk, and up to 4 parameters to describe the warping in the position angle and inclination angle directions. The model fitting approach is described in Reid *et al.* (2013). We thus obtain an H_0 measurement individually for each maser galaxy in the sample. Systematic errors in disk modeling are not likely to be correlated among different galaxies, so the combined measurement of H_0 in this paper is determined by a weighted mean of the individual measurements.

The MCP has so far published distances to four galaxies. Here we update the published value to the first of these, UGC 3789 (Reid *et al.* 2013) by extending the MCMC run to 3 billion trials to reach convergence. Our updated measurement based on UGC 3789 is $H_0 = 76 \pm 8$ km s^{-1} Mpc^{-1}. The other measurements come directly from the published values: $H_0 = 68 \pm 9$ km s^{-1} Mpc^{-1} (Kuo *et al.* 2013), $H_0 = 73 \pm 26$ km s^{-1} Mpc^{-1} (Kuo *et al.* 2015), and $H_0 = 66 \pm 6$ km s^{-1} Mpc^{-1} (Gao *et al.* 2016). The weighted average of these values is our current best estimate: $H_0 = 69.3 \pm 4.2$ km s^{-1} Mpc^{-1}.

The MCP has completed all observations and is currently finalizing the processing and analysis on five additional megamaser galaxies that will contribute to the final result. When complete, we expect the final measurement to achieve a total uncertainty of ∼4%.

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