H$_2$O Megamaser Cosmology with the ngVLA

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1. Description of the problem

The expansion rate of the universe at $z \approx 0$, known as the Hubble Constant ($H_0$), is the most fundamental parameter in observational cosmology. Historically, measurements of $H_0$ have been sought to reveal basic properties of the universe, including its age and geometry. Measuring $H_0$ remains a primary focus of observational cosmology today. The goal of new studies with the ngVLA will be to determine $H_0$ to $\sim 1\%$ by measuring geometric distances to H$_2$O megamasers directly in the Hubble Flow. A measurement at this precision is required to improve our understanding of dark energy and to test the validity of the standard $\Lambda$CDM model of cosmology.

2. Scientific importance

The exquisite observations of the Cosmic Microwave Background (CMB) by the WMAP and Planck satellites set a powerful framework for precision cosmology. These observations determine the angular-size distance to the surface of last scattering at $z \approx 1100$ and constrain the geometry of the universe to be very nearly flat. The CMB, however, does not uniquely determine all fundamental cosmological parameters on its own. Observations at $z \approx 0$, when dark energy is dominant, provide complementary data that constrain critical parameters, including the dark energy equation of state, neutrino mass, and the number of families of relativistic particles. CMB observations can predict basic cosmological parameters, including $H_0$, but only in the context of a specific cosmological model. Comparing CMB predictions to astrophysical measurements of $H_0$ therefore provides a powerful test of cosmological models.

In the context of the standard model of cosmology, i.e. a geometrically flat $\Lambda$CDM universe, Planck measurements predict $H_0 = 67.8 \pm 0.9$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2016). Measurements from Baryon Acoustic Oscillations combined with 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. Measurements anchored at low redshift and based on standard candle techniques, however, are in tension with the BAO measurements and the Planck predictions: $H_0 = 73.24 \pm 1.74$ 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). Determinations based on observations of gravitationally lensed quasars, meanwhile, give $H_0 = 71.9^{+2.4}_{-3.0}$ km s$^{-1}$ Mpc$^{-1}$ (Bonvin et al. 2017).
The measurements of $H_0$ based on low-z observations and the predictions based on $\Lambda$CDM disagree at high significance, and understanding this discrepancy is of fundamental importance. Either the underlying observations suffer from unrecognized uncertainties, against all scrutiny, or adjustments are needed to the $\Lambda$CDM standard model of cosmology. A problem of such fundamental importance warrants new, independent, and percent-level measurements of $H_0$. The long-term goal for the observational cosmology community is to reach percent-level precision in $H_0$ with agreement across multiple, independent observational methods.

Measuring $H_0$ with H$_2$O megamasers is a powerful complement to standard candle methods because it is a one-step measurement, independent of distance ladders and calibrations, and it is a fundamentally geometric method that measures $H_0$ directly at $z \approx 0$.

3. Astronomical impact

Understanding the cosmological model and the nature of dark energy is perhaps the most important problem in fundamental physics. It is unclear whether dark energy is an intrinsic property of the universe (the cosmological constant), or related to a time-variant field with a yet-undiscovered particle. Modifications to General Relativity, the introduction of new relativistic particles, and identification of new modes of interaction between matter and radiation are all also viable options to resolve the outstanding tension between measurements and the standard model.

Refinements to the cosmological model would impact our understanding of all aspects of the universe on its largest scales, including remnant background radiation, the formation of structure, and galaxy and cluster evolution.

4. Anticipated results

An ngVLA measurement of $H_0$ can build on methods and results from the Megamaser Cosmology Project (MCP), a multi-year, international project to measure $H_0$ using the megamaser technique (Reid et al. 2013). The project measures distances to suitable megamaser systems by fitting a warped disk model to observations of 22 GHz water vapor megamasers in the nuclear accretion disk of the host AGNs. Figure 1 shows an example of observations of an edge-on accretion disk megamaser system in the nucleus of the Seyfert 2 galaxy NGC 5765b. Systematic errors in the disk modeling are not likely to be correlated among different galaxies, so the final measurement of $H_0$ is determined as a weighted mean of measurements to individual galaxies. With present-day instrumentation, the MCP has so far measured $H_0 = 69.3 \pm 4.2$ km s$^{-1}$ Mpc$^{-1}$ (Braatz et al. 2018). When complete, the project should achieve a $\sim$4% total uncertainty.

With the ngVLA, the megamaser-based measurement of $H_0$ will aim to reach $\sim$1% total uncertainty. If the ngVLA measurement of $H_0$ aligns with the standard-candle measurements, which are themselves improving, the evidence would become convincingly against the standard $\Lambda$CDM model. If it aligns with the Planck prediction, additional scrutiny would be warranted to search for systematics among the different astrophysical measurement methods.
5. Limitations of current astronomical instrumentation

Megamaser systems used to measure $H_0$ are faint, and the megamaser method is limited by the 22 GHz sensitivity of the telescopes available for their study. The MCP uses the most sensitive suite of telescopes working today at 22 GHz, including the GBT for surveys and spectral monitoring observations, and the High Sensitivity Array (the VLBA, GBT, VLA, and 100-m Effelsberg telescope) to map maser disk systems. The final measurement by the MCP will be based upon distances to nine maser disk systems bright enough to measure with these existing facilities. Targeted surveys of over 3000 galaxies were necessary to identify those nine.

6. Connection to unique ngVLA capabilities

Only the ngVLA, with its sensitivity approaching an order of magnitude increase over existing facilities, will make a 1% measurement of $H_0$ plausible using the megamaser method. The measurement, however, will require that the ngVLA meet certain design features to enable precision astrometry of faint masers. Importantly, the ngVLA must have a compact core of antennas containing a substantial fraction of the total collecting area. This core should be concentrated within $\sim$5 km to enable efficient phasing at 22 GHz.

The method also requires that the ngVLA include, or have coordinated access to, a number of VLBI stations on intercontinental baselines out to $\sim$5000 km, ideally with substantial collecting area of their own. Long baselines in both the E-W and N-S directions are required. Contiguous frequency coverage from 18-22 GHz within a single receiver band is also important to make surveys efficient for detection of high velocity maser emission. Furthermore, flexible subarray capabilities will be beneficial so that, for example, outer antennas can be utilized for other science while the phased core is operating in a VLBI mode.

7. Experimental layout

Measuring $H_0$ with the megamaser technique requires three types of observations. First is a survey to identify the rare, edge-on disk megamasers suitable for distance measurements. Second is sensitive spectral monitoring of those disk megamasers to measure secular drifts in maser lines, indicative of the centripetal accelerations of maser clouds as they orbit the central black hole. And third is sensitive VLBI observations to map the maser features and determine the rotation structure and angular size of the disk. For each megamaser disk being measured, the spectral monitoring would span 1-2 years and include observations on a roughly monthly cadence. Since each VLBI map includes the necessary spectral information needed to track line-of-sight accelerations, a strategy to map and monitor the maser disks simultaneously is feasible with the ngVLA.

The positions, velocities, and accelerations of the maser components are then used to constrain a model of a warped disk and determine the distance to the host galaxy.

The precision with which the distance to a megamaser disk can be measured depends on a number of factors, including the richness of its maser spectrum, the layout of observable masers within the disk, and the signal-to-noise of the measurements. For megamasers in the Hubble flow, higher signal-to-noise observations would equate to
more precise distances in all cases. So, the first stage of the experimental layout would be to measure distances to all known megamasers suitable for such measurements. The MCP surveys and others have discovered \( \sim 20 \) megamaser disk systems whose spectral profile indicates an edge-on disk suitable for a distance measurement. Although the MCP will already have measured distances to nine of those megamasers, those nine would have to be reobserved with the ngVLA to improve their individual measurement uncertainties.

The overall measurement of \( H_0 \) based on these \( \sim 20 \) megamasers is not likely to reach the 1% project goal, so new megamaser disks must be discovered. The ngVLA project could aim for 10% distances to \( \sim 100 \) megamasers, or 7% distances to \( \sim 50 \). In practice, the precision for each system is not well known until the disk is observed and modeled. The prototypical megamaser in NGC 4258, at a distance of \( 7.54 \pm 0.17 \pm 0.10 \) Mpc, demonstrates that systematics in an individual system can be < 3% with sufficient sensitivity and angular resolution (Riess et al. 2016).

Ultimately, to reach 1% the second stage of the experiment requires a survey. With a nearly order of magnitude advantage in sensitivity, the ngVLA would be able to discover \( \sim 30 \) times more megamasers than the GBT. It would also extend the practical distance to which megamasers can be measured to a few hundred Mpc, alleviating potential concerns about local variations in the Hubble parameter.

8. Complementarity

Dark energy is the most important unsolved problem in modern physics, and an accurate local measurement of \( H_0 \) is the most effective complement to CMB data for constraining the equation of state of dark energy. A number of future facilities, for example WFIRST, will continue to focus on investigations of dark energy and cosmology.

A precise and independent measurement of the Hubble constant also elevates the effectiveness of future CMB observations, such as the “Stage-4” ground-based experiment, CMB-S4. Besides dark energy, a percent-level prior on \( H_0 \) also provides the best complement to CMB-S4 experiments for constraining the neutrino mass (Manzotti, Dodelson & Park 2015).

The importance of the Hubble constant demands agreement and verification using several measurement techniques. The long-term goal for observational cosmology is to achieve percent-level measurements that are consistent across independent methods, to minimize the impact of systematic uncertainties.

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Figure 1. The H$_2$O Megamaser in NGC 5765b (also see Gao et al. (2016)). The maser observations in this galaxy determine its distance at 126.3 ± 11.6 Mpc. The top left panel shows the VLBI maser map, with colors of the maser spots representing the line-of-sight velocities. The top center panel shows a position-velocity (P-V) diagram. The impact parameter represented on the x-axis is the angular distance measured along the length of the edge-on disk. The solid green lines on the P-V diagram represent a Keplerian fit to the rotation curve. The bottom panel shows a representative GBT spectrum. Masers in edge-on AGN accretion disks have a characteristic profile with three groups of maser features, evident in this spectrum. The features centered near 8300 km s$^{-1}$ originate from the front side of the disk while those centered near 7650 km s$^{-1}$ and 8850 km s$^{-1}$ originate from the approaching and receding sides of the edge-on disk, respectively. The right panel shows results of GBT spectral monitoring. Each symbol on the plot marks the velocity of a maser peak in the systemic part of the spectrum. The maser velocities increase with time and represent the centripetal acceleration as maser clouds orbit the central supermassive black hole.