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H_2O Megamaser Cosmology with the ngVLA

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Abstract:
As a complement to observations of the Cosmic Microwave Background, a measurement of the Hubble Constant at $z \ll 0.5$ provides a powerful test of ΛCDM cosmology and constrains the equation of state of dark energy. Observations of circumnuclear water vapor megamasers at 22 GHz in nearby active galaxies can be used to measure distances to the host galaxies, geometrically, and thereby provide a direct, one step measurement of the Hubble Constant, independent of standard candles. Observations of megamasers with present-day instrumentation are expected to reach a $\sim$4% H_0 measurement. A long-term goal of the observational cosmology community is to attain a one percent measurement of H_0 in agreement across several independent methods to minimize the systematics. To reach such a measurement with the megamaser method requires an order of magnitude improvement in sensitivity at 22 GHz, as can be attained with the ngVLA.

1 A Fundamental Problem in Modern Cosmology

Observations of the Cosmic Microwave Background (CMB) by the WMAP and Planck satellites set a powerful framework for precision cosmology. On their own, CMB observations determine the angular-size distance to the surface of last scattering at $z \simeq 1100$ and constrain the geometry of the universe to be very nearly flat. However they do not uniquely determine all fundamental cosmological parameters. Direct observations of the Hubble Constant (H_0) provide the strongest complement to CMB observations for constraining critical cosmological parameters, including the dark energy equation of state, neutrino mass, and the number of families of relativistic particles. Indeed, to most effectively constrain models of dark energy, which has become dominant only at redshifts $\lesssim$0.5, it is best to measure H_0 directly at $z \ll 1$ [6]. 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 ΛCDM universe, Planck measurements predict $H_0 = 67.27 \pm 0.60$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [10]. Measurements from Baryon Acoustic Oscillations (BAOs) combined with SNe Ia determine $H_0 = 67.3 \pm 1.0$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [1], in line with the Planck prediction. Standard candle measurements anchored at low redshift are, however, in tension with the Planck predictions: $H_0 = 73.52 \pm 1.62$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [14]. Meanwhile, observations of gravitationally lensed quasars determine $H_0 = 71.9^{+2.4}_{-3.0}$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [2].

Resolving the discrepancy between measurements of H_0 anchored with low-z observations and the predictions based on ΛCDM has been a focus of recent efforts in observational cosmology, and the resolution will shed light on what is perhaps the most important problem in fundamental physics today: understanding the nature of dark energy. It is unclear whether dark energy is an intrinsic property of the universe (e.g., a cosmological constant), or related to a space- or time-variant field with a yet-undiscovered associated particle. Modifications to General Relativity, the introduction of new relativistic particles, and an identification of new modes of interaction between matter and radiation are also viable options to explain the tension between H_0 measurements and predictions from the standard model.

A long-term goal for the observational cosmology community is to reach a percent-level measurement of H_0 with agreement across multiple, independent observational methods. Measuring H_0 with H_2O megamasers is a powerful complement to standard candle methods because (1) the megamaser method is fundamentally geometric, and (2) the method uses direct distances to galaxies at low redshift but well into the Hubble Flow, measuring H_0 in a single step and requiring no external calibration. Improving the measurement of H_0 will 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.

2 Measuring H_0 Directly with the Megamaser Method

Water vapor masers emitting at a frequency of 22 GHz are often associated with active galactic nuclei (AGN), where they are called "megamasers" because of their apparently large luminosities. Very long baseline interferometric (VLBI) observations of these megamasers reveal that they reside in a thin, edge-on accretion disk orbiting the supermassive black hole (SMBH) at sub-parsec radii. The "megamaser method," pioneered on the archetypal megamaser disk galaxy in the nearby (7.5 Mpc) Seyfert 2 NGC 4258 [5, 7, 12], exploits the ordered geometry and simple kinematics of such megamaser systems to bypass the distance ladder and make one-step, geometric distance measurements to their host galaxies.

Efforts to measure H_0 directly with the megamaser technique have been coordinated by the Megamaser Cosmology Project (MCP) [11, 8, 9, 4]. The measurement 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. 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. Figure 1 shows an example of observations of the disk megamaser system in the nucleus of the Seyfert 2 galaxy NGC 5765b.

Systematic errors in the disk modeling are uncorrelated across different galaxies, so the final measurement of H_0 by the MCP is determined as a weighted mean of measurements to multiple galaxies. The MCP has so far measured $H_0 = 69.3 \pm 4.2\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ [3]. Observations for the project have concluded, and when final analysis is complete the project should achieve a $\sim$4% total uncertainty based on distance measurements to nine megamaser galaxies.

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 available at 22 GHz, including the GBT for surveys and spectral monitoring observations, and the High Sensitivity Array (the VLBA, GBT, phased VLA, and 100-m Effelsberg telescope) to map maser disk systems with VLBI. Targeted surveys of over 3000 galaxies were necessary to identify the nine galaxies bright enough for MCP distance measurements using present-day instrumentation.

3 Attaining a 1% Measurement of H_0 with the ngVLA

The ngVLA reference design[1] contains 244 18-meter antennas covering a frequency range from 1.6–116 GHz, with a long-baseline component providing baseline lengths of up to ∼9000 km. At an observing frequency of 22 GHz the ngVLA will be ∼10 times more sensitive than any existing facility, achieving a ∼0.1 mJy noise level per 1 km s^{-1} spectral bandwidth in a $\lesssim$1 mas beam with an hour of integration time. Based on the reference design specifications, the ngVLA will provide the sensitivity necessary to enable a 1% measurement of H_0 using the megamaser method.

The ngVLA could reach a 1% H_0 measurement, for example, by measuring ∼7% distances to 50 galaxies, or ∼10% distances to 100. In practice, a range of measurement uncertainties will be attained, depending on the nature of each megamaser system. The exquisite observations of the nearby megamaser in NGC 4258 demonstrate that the systematics can be as small as a few percent for sufficiently high quality observations [7, 12].

The precision with which the distance to an individual 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. By reobserving known megamaser systems, the ngVLA will obtain better positions and accelerations for each of the maser components in the spectrum. The ngVLA will also see deeper into the spectra, detecting new, fainter masers well into the wings of the spectral profiles of the known megamaser systems, leading to better-constrained disk models and improved distance measurements.

The ngVLA will also be an efficient survey machine, capable of detecting hundreds of new disk megamaser systems that can subsequently be followed up for distance measurements. With a reference design sensitivity ∼10× that of either the GBT or the VLA, the ngVLA will enable megamaser detections within a volume ∼30 times larger than the present facilities can access.

The ngVLA will also open a pathway for measuring few-percent distances to new "anchor" galaxies used for distance ladder zero-point calibration. NGC 4258 is currently the only megamaser galaxy for which a few-percent distance is available and individual Cepheid variable stars can be resolved with current OIR facilities. JWST will resolve Cepheid variables at distances out to ∼50 Mpc [13], opening the possibility for additional megamaser galaxies to be used as anchors. By increasing the number of geometrically-calibrated Cepheid hosts and by varying the galactic environments in which they reside, both the statistical and systematic uncertainties associated with the distance ladder H_0 measurements will decrease.

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 ΛCDM model. If it aligns with the Planck prediction, additional scrutiny would be warranted to search for systematics among the different astrophysical measurement methods.

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[1] `http://ngvla.nrao.edu/page/refdesign`

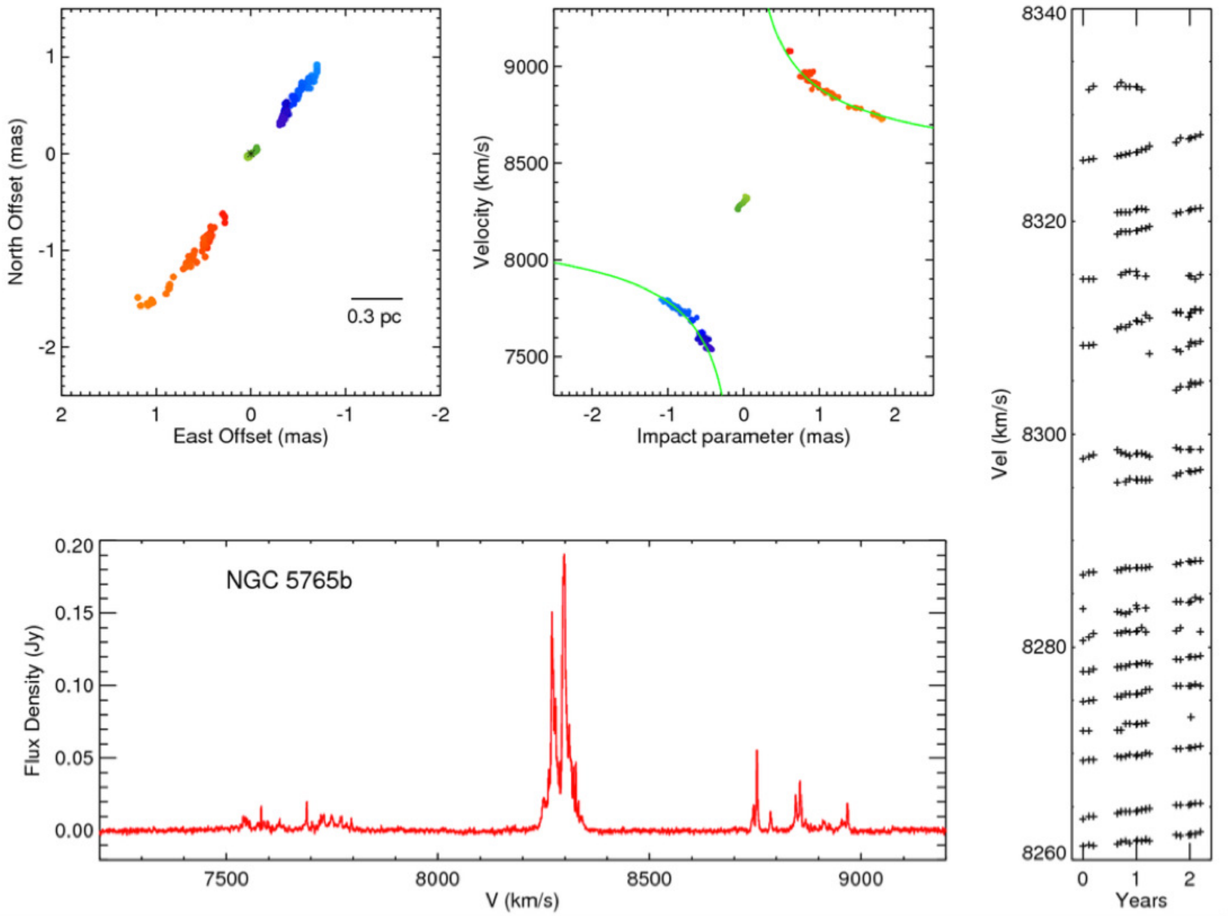

Figure 1: A summary of observations of the H_2O megamaser in NGC 5765b (also see [4]). These observations determine the galaxy's distance of 126.3 ± 11.6 Mpc. The top left panel shows the VLBI maser map, with colors of the maser spots representing the line-of-sight velocities. The top center panel shows 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 $\mathrm{km\,s^{-1}}$ originate from the front side of the edge-on disk while those centered near 7650 $\mathrm{km\,s^{-1}}$ and 8850 $\mathrm{km\,s^{-1}}$ originate from the midline of the disk on the approaching and receding sides, 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 according to the centripetal acceleration of maser clouds as they orbit the central supermassive black hole.

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