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Precision cosmology with H_2O megamasers: progress in measuring distances to galaxies in the Hubble flow

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Abstract. A determination of the Hubble Constant (H_0) to better than 3% would be the best complement to cosmic microwave background (CMB) data to constrain the equation of state of Dark Energy. Water vapor megamasers provide perhaps the best opportunity for measuring direct distances to galaxies out to about 200 Mpc. We have formed a team of astronomers in the Megamaser Cosmology Project to pursue the ambitious goal of making a precise measurement of H_0 by measuring such distances using the techniques pioneered on the disk maser in NGC 4258 by Herrnstein *et al* (1999). In recent surveys we have made significant progress identifying new maser systems analogous to that in NGC 4258, but more distant. Once the appropriate candidates are identified, two types of observations are necessary to ultimately measure a distance: single-dish monitoring to measure the acceleration of gas in the disk, and sensitive VLBI imaging in order to measure the angular size of the disk, measure the rotation curve, and model radial displacement of the systemic maser features. We have recently obtained preliminary VLBI maps of the masers in two systems, NGC 6323 and UGC 3789. The maser disks in both galaxies were discovered and monitored with the Green Bank Telescope (GBT) and subsequently imaged with the High Sensitivity Array (VLBA + GBT + Effelsberg). In this contribution we present a map of the maser distribution in one of those systems, NGC 6323. The map demonstrates that pc-scale maser disks as distant as ~ 100 Mpc can be imaged with existing telescopes. Results on UGC 3789 will be presented in a later publication.

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1. The megamaser cosmology project

The Megamaser Cosmology Project (MCP) aims to make a precise measurement of the Hubble Constant, an important complement to CMB data for constraining the nature of Dark Energy, the geometry (flatness) of the universe, and the fraction of the critical density contributed by matter. The measurement technique to be used by the MCP is based on observations of 22 GHz water vapor maser emission from AGNs with edge-on, nuclear accretion disks. The technique was first applied by Herrnstein *et al.* (1999) to determine the distance to NGC 4258. Because maser distances are independent of standard candle assumptions, they are not subject to the systematic uncertainties that currently limit the H_0 measurement based on standard candle techniques to about 10% precision.

In order to place a meaningful constraint on cosmological models, a measurement of H_0 to 3% or better is necessary. The precision in H_0 that can be achieved by measurements of maser disks depends on the quality of the individual measurements, the number of galaxies that can be measured, their distance distribution, and their distribution on the sky. A reasonable distribution on the sky is necessary to smooth over any local

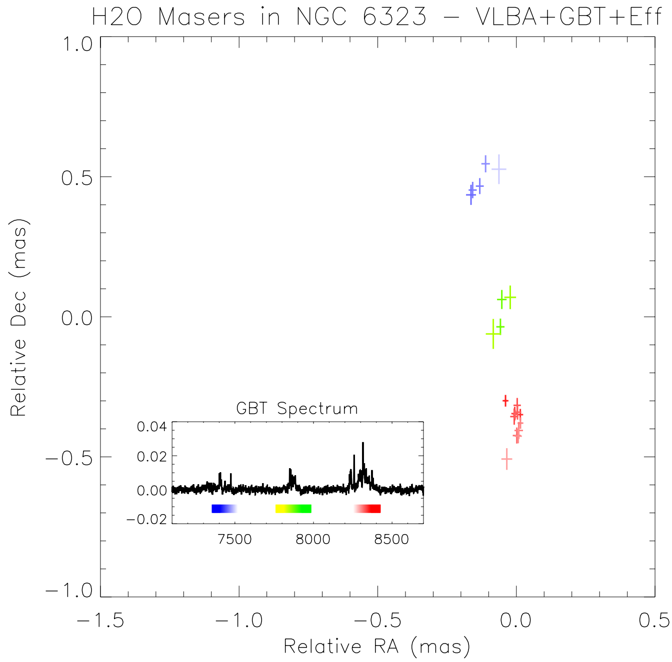

Figure 1. This preliminary VLBI map shows the distribution of maser emission toward the nucleus of the Seyfert 2 galaxy NGC 6323. The crosses in the figure represent the position of maser emission in each channel detected in the VLBI map, with the size of the cross proportional to the measured position uncertainty. The northernmost cluster of features are blueshifted with respect to the systemic recession velocity, the southernmost cluster of features are redshifted, and the features near the center of the map are near the recession velocity. The map is consistent with maser emission from an edge-on, sub-pc accretion disk in rotation about a central black hole with mass $\sim 10^7$ solar masses.

anomalies in the Hubble expansion rate. We could achieve an overall 3% precision in H_0, for example, by measuring the distances to 10 galaxies if each distance could be measured to 10% precision, assuming the individual distance measurements are uncorrelated.

NGC 4258 is the only galaxy with a 10% or better distance determination but it is too close to constrain H_0 directly. However, we have discovered H_2O masers in galaxies well into the Hubble flow (e.g. Braatz *et al.* 2004, Kondratko *et al.* 2006). Altogether, there are currently about 100 galaxies detected in water vapor maser emission. Of those, about one third show some evidence of disk origin. Currently about six of these galaxies are promising candidates for maser distance measurement. More are needed, and surveys are continuing to find additional candidates.

2. The maser disk in NGC 6323

An important milestone to the Megamaser Cosmology Project is the demonstration that maser disks in the Hubble flow can be imaged with high fidelity, given the faintness of the masers (a few tens of mJy at peak) and the need to apply external phase calibration techniques. We have recently made VLBI observations of several galaxies that have single-dish spectra consistent with edge-on disk maser emission. In Figure 1 we show a preliminary map of the maser distribution in the nucleus of one of these galaxies, NGC 6323, which has a recession velocity of 7772 km s^{-1} corresponding to a distance of

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110 Mpc for $H_0 = 72$ km s^{-1} Mpc^{-1}. The map was observed with the High Sensitivity Array, consisting of the VLBA, the GBT, and the Effelsberg 100 m telescope. A single track across the sky was used for this preliminary map. The maser system in the disk spans an angular radius of $\sim$0.5 mas and is aligned nearly N–S. The disk shows differential rotation, with orbital velocities increasing at smaller radii. The map demonstrates that it is possible to image maser disks at cosmological distances with high fidelity.

To ultimately determine a distance to the galaxy, it is necessary to measure an acceleration in the systemic features using long-term monitoring. Preliminary GBT monitoring of the maser spectrum in NGC 6323 reveals features with accelerations between 1.8 and 3.0 km s^{-1} yr^{-1}. A careful analysis of the monitoring data will improve these estimates and will be presented in a later publication.

In addition to measuring an acceleration and a rotation curve, a robust distance determination also depends on a measurement of the position-velocity gradient of the systemic features, which determines the radial velocity structure in the disk. The preliminary VLBI map shown in Figure 1 does not have sufficient sensitivity to make such a measurement, but more sensitive, multi-track VLBI observations of the maser in NGC 6323 are underway.

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