Cosmology With High-Redshift Water Masers

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Abstract. Multi-epoch VLBA observations of the maser in NGC 4258 have yielded a 4\% geometrical distance to the galaxy. The potential scientific payoffs of finding similar objects at large distances, in the Hubble flow, are considerable. In this contribution, I discuss the plausibility of detecting high-redshift water masers, and describe a search strategy that we have implemented to realize this objective.

1. Introduction – The Maser in NGC 4258

VLBA observations of the water masers in NGC 4258 reveal a nearly edge-on, slightly warped, extremely thin disk in nearly perfect Keplerian rotation around a central binding mass of $3.5 \times 10^7 M_\odot$ (Watson & Wallin 1994; Greenhill et al. 1995; Miyoshi et al. 1995; Moran et al. 1995; Herrnstein, Greenhill, & Moran 1996). The VLBA observations of the NGC 4258 maser provide insight into the structure and kinematics of the accretion disk, and NGC 4258 is an exceptional laboratory for the study of AGN accretion phenomenon and the connection between accretion disks and jet emission (Herrnstein et al. 1997; Herrnstein et al. 1998a). They can also be used to derive a precise geometric distance to NGC 4258.

The upper panel of Figure 1 is a schematic representation of the best-fitting NGC 4258 disk model, as derived from the positions and line-of-sight (LOS) velocities of the masers. As the disk rotates, the 'systemic' masers along the near edge of the disk drift in position and LOS velocity by about $30 \mu$as yr$^{-1}$ and 9 km s$^{-1}$, respectively, with respect to the apparently stationary 'high-velocity' masers in the plane of the sky (Herrnstein 1997a\&b). The expressions at the bottom of Figure 1 illustrate that both the LOS accelerations ($\dot{v}_{LOS}$) and the proper motions ($\dot{\theta}_x$) can be used to derive a purely geometric distance ($D$) to NGC 4258. Because the actual space velocities ($v_{\text{rad}}$) and angular radii ($\theta_R$) of the systemic masers cannot be measured directly, these acceleration and proper motion distances are model dependent. Fortunately, however, most of the model dependence resides in $\theta_R$, and the two distance estimates together provide a geometric distance estimate that is largely model independent. With this in mind, we have observed NGC 4258 with the VLBA at 3–4 month intervals for the last three years. The LOS accelerations and proper motions provided by the first five epochs of these data yield a geometric distance of $7.3 \pm 0.3$ Mpc (Herrnstein 1997a; Herrnstein et al. 1998b).
Figure 1. The top panel is a schematic representation of the sub-parsec molecular disk in NGC 4258. The bottom panels show the expected acceleration and proper motion vectors superposed on actual VLBA data of the systemic masers taken in May of 1995.
2. Masers and Cosmology?

Thus, the nuclear maser in NGC 4258 has yielded a purely geometrical distance with fractional uncertainty of 4% that is completely independent of all the usual rungs of the extragalactic distance ladder. While this result will undoubtedly play an important role in calibrating other primary and secondary distance indicators, it will be of limited utility in directly constraining any cosmological parameters due to the relative proximity of NGC 4258. The potential scientific payoffs from discovering an NGC 4258-like object at large distance, in the Hubble flow, are considerable: a 5% distance to such a maser could place significant constraints on both the Hubble constant and the deceleration parameter. In the remainder of this contribution, I describe why such high-redshift masers may, at least in principle, be detectable, and I discuss a program we have implemented to uncover them in practice.

The top portion of Figure 2 shows the inner 10 pc of a typical high-luminosity ($L \sim 10^{45-47}$ erg s$^{-1}$) AGN, as depicted in standard models. Between 0.1 and 1 pc lie the broad and intermediate line regions (BLR and ILR), characterized by forbidden optical line widths of $\sim 7000$ and $\sim 2000$ km s$^{-1}$ and number densities of $10^{12.5}$ and $10^{10}$ cm$^{-3}$, respectively (Baldwin 1997). This gas is both too hot and too dense to support water masers, which require number densities between $10^{8}$ and $10^{10}$ cm$^{-3}$ and temperatures between 200 and 1000 K. The outer edge of the ILR is probably caused by the formation of dust beyond 1 pc (Netzer & Laor 1993). This dust shields the gas from the central ionizing radiation and lowers the optical emissivity of the gas, resulting in the ‘dead zone’, which is largely devoid of optical emission lines, and hence remains essentially unstudied. However, the shielding of the dust tends to promote the creation of water outside of 1 pc. Furthermore, the presence of dust may help maintain an inverted population of water by absorbing the IR line photons that would otherwise tend to thermalize the population (Collison & Watson 1995). Finally, Rees, Netzer, & Ferland (1989) estimate a number density of $10^{8-9}$ cm$^{-3}$ at the outer edge of this zone (10 pc). Thus, the standard model for luminous AGN suggests that conditions suitable for water masers should exist between 1 and 10 pc from the central engine.

The proposed high-redshift masers achieve their enormous apparent luminosities through miniscule beaming angles, and an obvious concern is that they
Figure 2. Schematic representation of a high-luminosity active galactic nuclei. See text for details.
will be extremely difficult to find. However, if the maser-cloud filling factor in the 'dead zone' of Figure 2 is reasonably large, then such concerns may not be justified. The probability of realizing the necessary alignment between any one of the many foreground maser clouds and a background continuum source is much greater than is implied by the extremely narrow beam angle of any particular maser. Each maser cloud beams in a slightly different direction, and only one of these beams must lie along our LOS. We note that standard models for core-jet radio emission predict that the 22 GHz core can lie anywhere from 1 to 10 pc from the nucleus (Blandford & Königl 1979). This relatively large spread, combined with the considerable extent of the 'dead zone', indicates that detectable high-redshift masers may not be limited to AGN of any particular orientation.

The apparent luminosities of the proposed high-z masers are vastly larger than those of all known nearby megamasers, and it is natural to ask why we do not see any nearby apparently ultra-luminous masers. Essentially all of the ∼ 500 galaxies searched for masers to date have been nearby, relatively low-powered AGN such as LINERS or Seyfert 2s (Braatz 1996). As a result, the known, nearby masers invariably reside in relatively low-powered systems for which $D_m$, and therefore the saturation flux, is expected to be much smaller than in the high-powered, high-redshift systems. For example NGC 4258, with a bolometric luminosity of about $10^{42}$ erg s$^{-1}$ (Herrnstein et al. 1998a), is known to have a $D_m$ of about 0.15 pc (Herrnstein et al. 1997). In the context of the archetypal high-luminosity AGN of Figure 2, this result is consistent with the crude generalization that AGN sizes ought to scale as $\sim L^{1/2}$.

3. A High-Redshift Water Maser Search

This spring, we will use the VLBA to search for water masers in a sample of 114 moderate- and high-redshift AGN. This sample, generated using the NASA Extragalactic database (NED), is comprised mostly of QSOs and radio-loud AGN, and consists of all those sources in either the USNO geodesic survey or the VLBA calibrator survey above $-30^\circ$ dec with (1) redshifted 22 GHz water maser emission falling within the VLBA U-, X-, or C-bands, and (2) 5 GHz fluxes greater than 20 mJy. For the reasons described above, we will observe all sources that satisfy these criteria, irrespective of the likely orientation of the AGN. The breakdown of sources by redshift and band is shown in Table 1. We will spend approximately 10 minutes on each source, and cover the entire sky in a continuous 24-hour track, taking advantage of the excellent frequency agility of the VLBA.

Table 1 lists the velocity coverage and resolution in the rest frame of the host galaxy for each band. The large redshifts and 64-MHz bandwidth conspire to give extremely broad velocity coverage. The VLBA correlator also enables us to maintain adequate velocity resolution even for sources at $z = 3.5$. The combination of $> 1000$ km s$^{-1}$ bandwidths and $< 1$ km s$^{-1}$ resolutions is unique amongst maser searches, and is largely due to the VLBA correlator. We will self-calibrate on the continuum emission, and generate continuum snapshots for the entire sample. This collection of snapshots, unique in that they are at the same frequency in the rest frame of the objects, will be made available to the
public. The phases from the continuum self-calibration will be applied to the spectral data to stabilize the interferometer. Finally, we will generate image cubes (limited to several beams per spatial dimension) and search for maser emission in the synthesized spectra. The baseline-based thermal noises in the fifth column of the table confirm the feasibility of the continuum self-calibration. The sixth column gives the expected image thermal noises in ten minutes, and averaged across a 1 km s\(^{-1}\) maser feature. The anticipated 10-15 mJy thermal noises are as good or better than any previous water maser search performed to date. Furthermore, because the VLBA is a cross power instrument, we minimize the deleterious effects of standing waves on the detection of broadened maser emission.

Finally, we note that Barvainis and collaborators are also searching for high-redshift water masers using the Effelsberg 100-meter telescope. Preliminary results from this parallel effort are presented elsewhere in these proceedings.

| Band | f (GHz) | z | \(N^{(1)}\) | \(\Delta v^{(2)}\) (km/s) | \(v_s^{(3)}\) (km/s) | \(\Delta S_{2m}^{(4)}\) (mJy) | \(\Delta S_{512}^{(5)}\) (mJy) |
|------|--------|---|-------------|-----------------|-----------------|----------------|------------------|
| U    | 12.0 - 15.4 | 0.44-0.85 | 82 | 1400 | 0.35 | 6 | 15 |
| X    | 8.0 - 8.8  | 1.52-1.78 | 25 | 2300 | 0.56 | 4 | 10 |
| C    | 4.6 - 5.1  | 3.35-3.83 | 7  | 4000 | 1.0  | 4  | 15 |

1 Number of sources within specified range of z with: (1) \(F_{5GHz} > 20\) mJy, (2) \(\delta > -30^\circ\), and (3) VLBI position.
2 Velocity coverage in the host galaxy for 64 MHz total bandwidth.
3 Velocity resolution in the host galaxy for 512 channel spectra.
4 Continuum sensitivity along a single VLBA baseline in 2 minutes (64 MHz, 1 bit sampling).
5 Image sensitivity in maser line, for a 10-minute integration and assuming 1 km s\(^{-1}\) linewidth.

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