Supermassive Black Holes
And Precision Cosmology with Megamasers

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Most every large galaxy with a nucleus and a bulge has, at its center, a supermassive black hole. When the black hole is actively accreting matter, it releases a tremendous amount of energy, and the galaxy is said to have an active nucleus.

Buffered by the dust in the accretion flow, molecules can survive there and get energized by collisions with other molecules and dust particles. Water molecules are common in this environment, and they can emit **maser** radiation. Masers are the radio-frequency equivalent of lasers. A water maser therefore can shine a beamed ray of radio waves at a very specific frequency, 22,235 MHz, which corresponds to radio waves about 1 cm in wavelength.

When water masers are detected in the accretion disks of external galaxies they are called megamasers. These megamasers are valuable tools, but they are rare, difficult to find, and often faint because of the large distance from Earth. Currently about 150 galaxies have been detected with maser emission, and of these about 30 appear to arise in the well-ordered gas of an accretion disk, viewed edge-on, in the immediate vicinity of the central black hole.

While water masers are interesting in their own right, the primary reason they have been studied in detail is that they make excellent tools to help us understand the environment in which they reside. Small changes in the detected frequency of the masers, owing to the Doppler effect, mean that we can determine the line-of-sight velocity of maser clouds very precisely. Furthermore, masers can be imaged with amazingly high resolution using the technique of Very Long Baseline Interferometry (VLBI). The telescope of choice for imaging masers is the **Very Long Baseline Array**, operated by the National Radio Astronomy Observatory (NRAO). We combine this telescope with the NRAO Green Bank Telescope and the Max-Planck Institute's Effelsberg radio telescope to image the water megamasers with very high sensitivity and resolution. We can pinpoint the location of each individual maser cloud to a precision of about 10 **microarcseconds**, or about 1000 times better than the resolution of the Hubble Space Telescope.

One important application of this tool is that we can measure the mass of the black hole in the center of each galaxy, with a precision that far exceeds what other methods can do in external galaxies. We measure masses so precisely because our measurements are based on the motion of gas very close to the black hole, less than a light-year in many cases. Compared to techniques using optical telescopes, where the black hole mass can only be determined within a factor of 2 or so in the best cases, here we can measure black hole masses accurate to better than 10%. Not only that, but we are also measuring black hole masses in galaxies where it would be impossible using optical techniques, because the galaxies we are measuring tend to be spiral galaxies rich with gas and dust. Optical measurements of black holes work best on elliptical galaxies that are mostly transparent down to their nuclei.

With precise, maser-based black hole masses for about 15 galaxies now in hand, we can begin to investigate important relationships, such as comparing the black-hole mass to the mass of stars in the galactic bulge, or to the velocity dispersion of stars in the bulge. It is comparisons like these that lead to a better understanding of how galaxies evolve.

The primary science goal that we can address with studies of water megamasers is measuring distances to galaxies. Measuring distances is a notoriously difficult problem in astronomy, and one of the most important. By analyzing the internal dynamics of water maser systems, we can calculate the linear size of the accretion disks. Specifically, we can measure the rotation velocity, v, of maser clouds as they orbit the black hole from the Doppler shift of the maser lines, and we can measure the centripetal acceleration, a, of maser lines by observing how the Doppler shift velocity changes over time. Using the simple relation for centripetal acceleration, $a = v^2/r$, we can then calculate the size of the accretion disk in light-years.

From the VLBI maps, we also have the angular size of the accretion disk measured in milliarcseconds. Given the angular size (theta) and the linear size, r, of the accretion disk, we can simply triangulate to get the distance to the galaxy. $D = r/theta$. The simplicity of this method is remarkable, especially when compared to distance-measuring methods based on Cepheid variables or supernovae, the “standard candles” that historically have been subject to troublesome uncertainties.

The trick to measuring distances to galaxies using the megamaser method is to find the best megamasers for which the method can be applied. To date, only three have been measured precisely using this method. With the Green Bank Telescope, we are actively searching for more galaxies hosting megamasers that will work with this method.

We use these measured distances to galaxies to determine the expansion rate of the Universe, the famous “Hubble Constant,” H_0 =

v_r/D. In this equation, v_r is the recession velocity of the galaxy, easily determined from spectroscopy, and D is its distance. When combined with studies of the cosmic microwave background, a precise Hubble Constant can eventually lead us to a better understanding of the mysterious "dark energy" that seems to pervade the Universe and causes its expansion to accelerate.

Of the three galaxies for which the megamaser method has been applied to measure the distance, two are of particular interest because they are far enough to measure the expansion rate of the Universe directly. These are UGC 3789 and NGC 6264. The results from these galaxies, whose distances are 50 Mpc and 141 Mpc, lead to a Hubble constant of 72 km/s/Mpc with a precision of about 8%. The result for NGC 6264 is preliminary, and unpublished. As we continue to improve these measurements and apply the technique to additional galaxies, we will improve the uncertainty in this measurement.

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