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AGN accretion disk physics using H_2O megamasers

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Abstract. Many accretion disks surrounding supermassive black holes in nearby AGN are observed to host 22 GHz water maser activity. We have analyzed single-dish 22 GHz spectra taken with the GBT to identify 32 such "Keplerian disk systems," which we used to investigate maser excitation and explore the possibility of disk reverberation. Our results do not support a spiral shock model for population inversion in these disks, and we find that any reverberating signal propagating radially outwards from the AGN must constitute <10% of the total observed maser variability. Additionally, we have used ALMA to begin exploring the variety of sub-mm water megamasers that are also predicted, and in the case of the 321 GHz transition found, to be present in these accretion disks. By observing multiple masing transitions within a single system, we can better constrain the physical conditions (e.g., gas temperature and density) in the accretion disk.

Keywords. accretion disks, masers, galaxies: active

1. Introduction

The Megamaser Cosmology Project (MCP) is an effort to make geometric distance measurements to H_2O megamaser-hosting galaxies in the Hubble flow to constrain H_0 to a precision of several percent (Braatz *et al.* 2013). Using the "megamaser technique," first employed by Herrnstein *et al.* (1999) on the galaxy NGC 4258, the MCP has published distances to the galaxies UGC 3789 (Reid *et al.* 2013), NGC 6264 (Kuo *et al.* 2013), NGC 6323 (Kuo *et al.* 2015), and NGC 5765b (Gao *et al.* 2016), and additional distance measurements are under way.

The MCP has conducted a large single-dish survey of Seyfert 2 galaxies using the Robert C. Byrd Green Bank Telescope (GBT)†, with the goal of discovering suitable

† The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

megamaser candidates for distance measurements. In Pesce *et al.* (2015; hereafter P15) we identified a list of 32 "clean" megamaser disk systems from the MCP survey and the literature. Dynamically "clean" disk megamaser systems are those for which the gravitational potential acting on the maser clouds is dominated by the central SMBH (i.e., there are no outflow or jet components), and all such masers have characteristic single-dish spectral profiles marked by three distinct groups of maser features centered around the systemic velocity of the host galaxy ("triple-peaked" profiles). The central group ("systemic masers") coincides roughly with the recession velocity of the galaxy, and the masing arises along a line of sight through the disk to the central AGN. The two sets of "high-velocity" features, redshifted and blueshifted from the galaxy recession velocity, arise from the midline of the accretion disk along lines of sight that are tangent to the orbital motion.

2. Testing a spiral shock model

Maoz & McKee (1998; hereafter MM98) developed a model for maser excitation that sought primarily to explain two seemingly unusual properties of the high-velocity maser features in NGC 4258: (1) the features show periodic radial placement within the disk (see, e.g., Argon *et al.* 2007), and (2) the redshifted features are stronger by roughly an order of magnitude than the blueshifted features (see, e.g., Humphreys *et al.* 2008). In the MM98 model, the only regions of the disk that exhibit masing are the trailing edges of spiral shock waves (i.e., the post-shock regions behind the spiral shocks). We then observe high-velocity features wherever the line of sight is tangent to a spiral shock, because this geometry maximizes the gain path for maser amplification.

The MM98 model makes two testable predictions for the behavior of the high-velocity maser features in disk systems: (1) the redshifted features should appear systematically stronger than the blueshifted features, and (2) all high-velocity features should exhibit velocity drifts towards lower orbital velocities. Both of these predictions stem from the geometrical configuration of spiral shocks in a disk, which cause the redshifted features to originate from a region of the disk that lies in front of the midline while the reverse is true for the blueshifted features (see Figure 1 in MM98). Because the majority of the disk contains noninverted gas, the blueshifted photons pass through a region of velocity-coherent material that presents an absorption opportunity not seen by the redshifted photons. This preferential absorption of blueshifted photons then explains the observed red-blue flux asymmetry. As the (trailing) spiral shock rotates through the disk, the segment of the spiral that lies tangent to the line of sight (and thus the region of masing gas) moves radially outward with time. In a Keplerian disk, the orbital velocity is a monotonically decreasing function of radius, so the rotation of the spiral shock causes the observed maser feature velocities to drift with time. Specifically, the redshifted features are predicted to exhibit a negative velocity drift while the blueshifted features show a positive velocity drift.

Both Bragg *et al.* (2000) and Humphreys *et al.* (2008) found that the accelerations of high-velocity maser features in NGC 4258 are inconsistent with the MM98 model. We have further tested whether the model holds for disk maser systems in general by measuring the flux asymmetry and velocity drifts of high-velocity features in the MCP sample. Figure 1 shows a histogram of the redshifted-to-blueshifted flux ratios for all disk maser systems in our sample; a detailed description of the analysis is presented in P15. We can see that the mean of the flux ratio distribution shows no statistically significant deviation from unity, and that NGC 4258 is a clear outlier. In Table 2 of P15 we list the

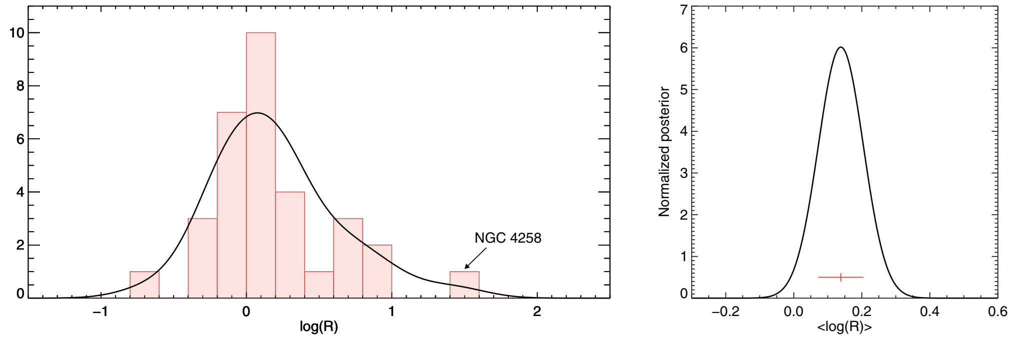

Figure 1. *Left*: a histogram of $\log(R)$ for the disk maser sample, where $R \equiv F_{\rm red}/F_{\rm blue}$ is the ratio of the redshifted to blueshifted flux. The bin containing NGC 4258 is marked, and we can see that it lies off to one side of the bulk distribution. The overplotted black curve shows the histogram smoothed using a Gaussian kernel; see P15 for details. *Right*: The normalized posterior distribution for the mean of $\log(R)$, computed as described in P15. The best-fit value of 0.136 ± 0.07 (1σ uncertainty), which is consistent with the parent distribution having a mean flux ratio of unity, is marked.

velocity drifts measured from the 11 most well-monitored maser systems in our sample; we found no evidence for the systematic velocity drifts predicted by the MM98 model.

3. A search for disk reverberation

The unique geometry and simple dynamics of Keplerian disk systems enable us to convert spectral information (i.e., velocity of a maser feature) directly into spatial information (i.e., radial location within the disk), without requiring a high-resolution VLBI map to spatially resolve the maser distribution. If a signal of some sort that affects the maser intensity is propagating radially through the disk at a fixed velocity – such as might be expected if, e.g., a flare from the AGN causes a change in the maser pumping efficiency – we can thus track the progress of that signal using spectral monitoring observations alone. Furthermore, by measuring the progression of that signal through the maser spectrum we could potentially make an independent measurement of the SMBH mass. For a signal propagating with a speed $v_{\rm s}$ through the disk, corresponding to a drift $\dot{v}$ through the maser spectrum, the SMBH mass can be obtained using

$$M_{\rm BH} = -\frac{v_{\rm s}\left(v - v_0\right)^3}{2G\dot{v}}. \qquad (3.1)$$

Here, v_0 is the recession velocity of the dynamic center and v is the observed velocity of the signal (i.e., the velocity that one would read off of the spectrum). If we know the value of $v_{\rm s}$ – such as would be the case for a signal propagating at c, for instance – then we can measure the quantities v_0, v, and $\dot{v}$ from the spectral monitoring and thereby derive the mass of the SMBH. Such a mass measurement can then further be combined with VLBI data to determine an independent distance to the system.

We have searched for a radially-propagating signal using the time-series spectra for our 6 most well-monitored sources. The details of our signal-extraction procedure are given in P15, and we put upper limits on the strength of any such propagating signal at a typical 3σ level of $\sim$1-2 mJy. Because the high-velocity features in these maser spectra typically display variability at the $\sim$tens of mJy level, we can therefore say that any contribution to this variability from radially-propagating signals must occur at the $\lesssim$10% level. The

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variability that we see is therefore most likely dominated by local processes, rather than some global influence from the central engine.

4. (Sub)millimeter H_2O megamasers

Water megamasers emitting at 22 GHz have proven to be powerful tools for studying AGN, cosmology, and SMBHs. Population inversion of the 22 GHz transition occurs under a range of physical conditions (i.e., gas temperature, gas density, dust temperature) that are also predicted to invert a number of other transitions (Neufeld & Melnick 1991; Yates *et al.* 1997). Many of these transitions emit at (sub)millimeter wavelengths, and several are expected to have line luminosities comparable to or greater than what is observed at 22 GHz (see, e.g., Gray *et al.* 2016). By observing multiple masing transitions in a single Keplerian disk system, we can constrain the physical conditions in the accretion disk as a function of orbital radius.

In Pesce *et al.* (2016), we presented an ALMA detection of 321 GHz water megamaser emission towards NGC 4945 and an updated calibration of the previously-discovered (see Hagiwara *et al.* 2013) 321 GHz water megamaser in Circinus. The 321 GHz masers in Circinus are about an order of magnitude weaker in flux density than the 22 GHz masers, though the isotropic luminosity is actually $\sim$4 times stronger at 321 GHz. In NGC 4945 the 321 GHz masers are down in flux density by about two orders of magnitude from their 22 GHz counterparts, with an isotropic luminosity that is smaller by roughly one order of magnitude. Though neither of these systems contains a “clean” Keplerian disk, they serve to illustrate the feasibility of extending megamaser science to the (sub)millimeter regime. Future ALMA observations will seek to map out these systems and to discover many more.

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