H_2O MEGAMASERS AND BLACK HOLES

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Abstract. Twenty-one H_2O masers have been identified in the nuclei of active galaxies. The detection rate is about 7 percent. Very Long Baseline Interferometric data of four of these maser systems (NGC 4258, NGC 1068, NGC 4945, and NGC 3079) show evidence of Keplerian disks on a subparsec scale. The best example is NGC 4258. There the masers trace a thin warped disk in nearly perfect circular Keplerian motion. If the apparent thinness is indicative of hydrostatic equilibrium, then the kinetic temperature must be less than 1000K, the magnetic field less than 200 mG, and the mass accretion rate less than about $\alpha 10^{-3}$ $M_{\odot}$/yr, where α is the viscosity parameter. From direct Zeeman measurements the toroidal magnetic field strength is less than 300 mG. The proper motions of the systemic maser feature imply a distance to the galaxy of 7.3 $\pm$ 0.3 Mpc . The high-velocity features show no detectable proper motions or accelerations, which confirms the model of circular Keplerian motion, and puts severe constraints on any alternative model. A feature in the systemic group flared to 20 Jy, offering opportunities to study the physics of the maser emission.

1. Introduction

Water vapor masers have been known for almost 20 years to exist in the centers of active galaxies, and early on, were suspected of being associated with accretion disks around black holes (e.g. Claussen & Lo 1986). However it was not until the masers in NGC 4258 were imaged with the VLBA, revealing a Keplerian disk in unprecedented clarity (Miyoshi et al. 1995, Greenhill et al. 1995, Moran et al. 1995), that the hypothesis gained wide acceptance.

About 350 galaxies have been searched for water vapor masers and as of October 1997, 21 have been detected. These include: NGC 315, Mrk 1, NGC 613, NGC 1052, NGC 1068, NGC 1386, Mrk 1210, NGC 2639, NGC 3079, IC 2560, NGC 3735, NGC 4258, NGC 4945, M51, NGC 5347, Circinus, NGC 5506, NGC 5793, ESO 103-G35, TXFS 2226-184, and IC 1481. Most of these galaxies are classified as Seyfert 2 galaxies or LINERs. The detection rate is only about 7%, probably because of the requirement for the disk to be viewed nearly edge-on, and because of the sensitivity threshold. Cases can be made from VLBI observations for 4 Keplerian accretion disk systems. The properties of these 4 systems are listed in the Table by galaxy, in order of the believability and clarity of evidence. Other galaxies for which VLBI images have been made include: NGC 1386 (linear structure over 0.5 pc; Braatz et al. 1997), NGC 1052 (masers associated with jet structure; Claussen et al. 1997), and IC 2560 (linear structure over 0.1 pc with a velocity gradient suggestive of rotation; Nakai et al. 1997). Velocity drifts in NGC 2639 are suggestive of centripetal acceleration. VLBI data have been acquired for Circinus, NGC 5506, NGC 5793, and TXFS 2226-184, but no results are available at this time. Most of the 10 remaining examples have flux densities less than 0.3 Jy. They are very difficult to image with VLBI because of the necessity of either detecting a reference feature within the natural atmospherically limited coherence time of the interferometer at 1.3 cm wavelength, or extending the coherence time by phase referencing to a nearby continuum source.

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TABLE 1. Properties of molecular disks in AGN

Galaxy	D Mpc	V km/s	R_i/R_o pc	M 10^6 $M_\odot$	ρ 10^7 $M_\odot/pc^3$	L_x 10^{42} erg/s	Ref
NGC 4258	6	1100	0.13/0.26	35	400	0.04	1
NGC 1068	15	330	0.6/1.2	17	3	40	2,3
NGC 4945	4	200	0.2/0.4	1	2	1	4
NGC 3079	16	150	0.5/1.0	1	0.2	0.02	5,6

Symbols: D = distance, V = systemic velocity, R_i/R_o = inner/outer radius of disk, M = central mass, ρ = central mass density, L_x = x-ray luminosity.
Ref: (1) Miyoshi et al. 1995, (2) Greenhill et al. 1996, (3) Greenhill 1997, (4) Greenhill, Moran & Herrnstein 1997a, (5) Trotter et al. 1998, (6) Satoh et al. 1997.

2. Properties of the Masers and Associated Continuum Emission in NGC 4258

2.1. THE WARP

The masers delineate a thin warped disk. The filling factor of masers in the disk is extremely small, since the masers are only detected along the line through the center of the disk perpendicular to the line-of-sight and in a thin annular region in front of the nucleus. However, the general character of the warp is clear and it offers a plausible explanation for the dominance of the red-shifted high-velocity features over the blue-shifted ones (Herrnstein, Greenhill & Moran 1996).

2.2. THINNESS

The maser disk cannot be resolved in the vertical direction with current observations, and is less than 0.0003 parsec in thickness, giving a height to radius ratio of less than 0.3 percent. The disk appears to be in hydrostatic equilibrium at a kinetic temperature of less than 1000K or a magnetic pressure from a magnetic field of less than 200 mG. However, it is possible the masers occur in a thin surface of a thicker accretion disk. For the simple thin-disk model, and with reasonable assumptions for parameters, the implied accretion rate is less than $\alpha 10^{-3}$ $M_\odot$/yr (Moran et al. 1995).

2.3. MAGNETIC FIELD

In principle, the longitudinal magnetic field in the condensations causing the maser emission can be measure by the Zeeman effect. Unfortunately, H_2O is a non-paramagnetic molecule and the Zeeman splitting is only about 1.4 Hz/mG, whereas the linewidths are about 1 km/s. However, very precise measurements of the difference between emission profiles in left-circular and right-circular polarization can be made, so that the effects of very small Zeeman frequency shifts can be detected. Furthermore, because the masers are so small in angular extent compared to the primary beams of the array antennas, this measurement technique is not affected by systematic errors such as beam squint that plague measurements of extended molecular clouds (e.g. Goodman et al. 1989). VLA observations of the isolated high-velocity feature at 1306 km/s show that the fractional circular polarization is less than about 1 percent. This result implies that the line-of-sight (i.e. toroidal) magnetic field is less than 300 mG in the particular cloudlet that gives rise to this maser, which is about 0.2 pc from the central engine (Herrnstein et al. 1998). The limit is set by the signal-to-noise ratio of the measurements, and could be substantially improved by longer observations and inclusion of more features. A positive detection would be important in assessing the importance of magnetic pressure in the disk and estimating the mass accretion rate.

2.4. ACCELERATION OF HIGH-VELOCITY FEATURES

Careful study of the high-velocity feature at 1306 km/s shows that its acceleration is very small, formally 0.07 ± 0.05 km/s/yr, or less than about 1 percent of the acceleration typical of systemic features (CfA group, unpublished data). The natural explanation of this small acceleration is that the condensation responsible for this maser lies slightly off the midline by about 0.5 degrees. The

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lack of detectable acceleration in the high-velocity features provides a crucial contraint for any dynamical model other than pure circular Keplerian motion.

2.5. PROPER MOTIONS

The rotational period of the molecular disk is predicted to be about 800 years at its inner radius of 0.13 pc. Careful tracking of the relative positions of the maser features over a period of two years shows that the motion of the systemic features is about 30 μas/yr. On the assumption of circular orbits, this gives a distance to the galaxy of 7.3 ± 0.3 Mpc (Herrnstein 1997; Herrnstein et al. 1997a). A similar distance has been obtained from precise analysis of the acceleration measurements of the systemic features. The relative motions of the high-velocity features are undetectable and entirely consistent with their being on the midline of a rotating disk.

2.6. CONTINUUM EMISSION

The use of a maser feature as a phase reference for VLBI observations allows the coherence of the interferometer to be extended indefinitely and provides a precise positional reference. With these techniques, continuum emission has been detected from the core of NGC 4258 (Herrnstein et al. 1997b). The emission comes from two jet-like components situated on opposite sides of the molecular disk along its axis. The emission is variable by up to 100 percent on the timescale of weeks. The offset of the northern jet component from the central engine, as marked by the dynamical center of the molecular disk, has always been larger than or about 0.01 pc (0.4 mas), which suggests that the bulk Lorentz factor is about 2. Careful analysis of the continuum emission reveals that there is no emission from the position of the central engine at a level of 0.2 mJy (3 σ) (Herrnstein 1998). This limit has significant implications for the size of a putative advection disk lying inside the accretion disk, i.e., such an advection zone must be smaller than about 100 Schwarzschild radii (Narayan, private communication).

2.7. FLARE

A strong flaring component was detected among the systemic group of masers in NGC 4258 at a velocity of 492 km/s (epoch 1997.2) (Greenhill et al. 1997b). The flare reached a peak intensity of about 20 Jy (10 times the normal maximum) in February 1997. It drifted at a rate of about 8 km/s/yr, close to the average canonical rate, which means that it originated within the normal thin annulus of maser emission at 0.13 pc radius. The analysis of this flare may lead to a better understanding of the physics of the maser process in the disk.

3. Non-Keplerian Models for NGC 4258

The dynamical information about the maser in NGC 4258 is extensive. The relative positions of the masers (x, y coordinates) have been measured to an accuracy of a few microarcseconds. The transverse velocities (v_x and v_y) have been measured to an accuracy of a few microarcseconds/yr. In addition, the longitudinal accelerations of the masers (a_z) have been measured to an accuracy of less than 1 km/s/yr. However, the line-of-sight positions with respect to the center of the system (z) cannot be directly measured. Even without this coordinate, the model for the Keplerian disk is highly overconstrained. Hence, we believe that the suggestion (Burbidge & Burbidge 1997) that the masers might trace an outflow is unsupportable. A detailed discussion of this issue can be found in the paper by Moran (1997).

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