VLBI IMAGING OF WATER MASER EMISSION FROM THE NUCLEAR TORUS OF NGC 1068

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ABSTRACT

We have made the first VLBI synthesis images of the H$_2$O maser emission associated with the central engine of the Seyfert galaxy NGC 1068. Emission extends about $\pm 300$ km s$^{-1}$ from the systemic velocity. Images with sub-milliarcsecond angular resolution show that the redshifted emission lies along an arc toward the northwest of the systemic emission. (The blueshifted emission has not yet been imaged with VLBI.) Based on the maser velocities and the relative orientation of the known radio jet, we propose that the maser emission arises on the surface of a nearly edge-on torus, where physical conditions are conducive to maser action. The visible part of the torus is axially thick, with comparable height and radius. The velocity field indicates sub-Keplerian differential rotation around a central mass of $\sim 1 \times 10^7 M_\odot$ that lies within a cylindrical radius of about 0.65 pc. The estimated luminosity of the central engine is about 0.5 of the Eddington limit. There is no detectable compact radio continuum emission near the proposed center of the torus ($T_A < 5 \times 10^8$ K on size scales of $\sim 0.1$ pc), so that the observed flat-spectrum core cannot be direct self-absorbed synchrotron radiation.

Subject headings: galaxies: individual (NGC 1068) — galaxies: kinematics and dynamics — galaxies: nuclei — masers

1. INTRODUCTION

The galaxy NGC 1068 is widely believed to harbor a Seyfert 1 nucleus that is obscured by a dusty edge-on torus (Antonucci 1993, and references therein). X-rays of energies up to 10 keV from the central engine of the active galactic nucleus (AGN) are blocked by an atomic column density of at least $10^{23}$ cm$^{-2}$ (Mulchaey, Mushotzky, & Weaver 1992). The inferred axis of the torus is nearly north-south, and broad-line optical and ultraviolet emission is scattered into the line of sight on angular scales as small as 0.1 mas. The H$_2$O maser emission subtends 0.1 mas. The H$_2$O maser emission marks the presence of warm ($\sim 400$ K), high-density ($n_{H_2} \sim 10^8$–$10^{10}$ cm$^{-3}$) molecular gas (Elitzur 1992, chap. 10). The line-of-sight velocity field also must be coherent (with respect to the sound speed) on size scales $\gg 10^3$ cm to achieve significant amplification (Reid & Moran 1988). The maser emission extends about $\pm 300$ km s$^{-1}$ from the galactic systemic velocity of 1150 km s$^{-1}$ adopted by Gallimore et al. (1996b). (Velocities throughout are heliocentric and assume the optical astronomical definition of Doppler shift.) Gallimore et al. (1996b) used the Very Large Array (VLA) of the NRAO$^1$ to partially resolve the source structure on scales of 40 mas, or about one-third of the synthesized beamwidth, and they inferred that the maser traces the midplane of the nuclear torus. Preliminary VLBI measurements also detected a position-velocity gradient in the maser on angular scales of 0.4 mas (Gwinn et al. 1993). We present the first VLBI synthesis images of the maser emission and at redward of the systemic velocity.

2. OBSERVATIONS AND DATA

We observed the H$_2$O maser emission in NGC 1068 for about 8 hours on 1994 November 5 with the Very Long Baseline Array (VLBA), and the VLA operating as a phased 132 m aperture. The sensitivity of the VLA was critical to the observations because of the low peak flux density of the maser, $\sim 0.6$ Jy. We recorded bandpasses tuned to bandcenter heliocentric velocities of 1438, 1134, 17, and 1165 km s$^{-1}$. The velocity range 1210–1285 km s$^{-1}$ was not observed. Figure 1 shows the velocity coverage of the observations in the context of the maser spectrum. The channel spacing in each band was...

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0.45 km s\(^{-1}\). We tracked variations in atmospheric phase using the maser feature at 1462 km s\(^{-1}\) as a reference and subtracted them from the data for other features.

Calibration and imaging relied upon standard spectral line VLBI techniques. We fitted a two-dimensional Gaussian model to the brightness distribution of every statistically significant peak in the images for each velocity channel. The centroid positions, measured with respect to the reference, are sensitive to calibration errors caused by uncertainties in the station clocks and positions, Earth orientation parameters, and astrometric maser position. Only uncertainties in the last two items are significant. These cause position errors that are linearly proportional to the velocity offset from the reference. For the emission at 1325 km s\(^{-1}\) and 1135 km s\(^{-1}\), the errors are \(\approx 50 \mu \text{as} \) and \(\approx 100 \mu \text{as} \), respectively.

### 3. SPECTRAL LINE IMAGES

Five dominant clumps of maser emission are distributed almost linearly on the sky, with pronounced velocity gradients (Fig. 2). The emission close to the systemic velocity (hereafter “systemic emission”) is extended roughly east-west and lies to the southeast of the redshifted emission. It displays a velocity gradient of about 50 km s\(^{-1}\) mas\(^{-1}\), with the higher velocity emission in the west (Fig. 3). The emission between about 1315 and 1465 km s\(^{-1}\) (hereafter “redshifted emission”) is distributed roughly in an arc about 0.6 pc long, at a position angle of about \(-45^\circ\). The redshifted emission is separable into clumps whose velocities and velocity spreads increase with decreasing separation from the systemic emission. Clump 4, which lies closest to the systemic emission, has the greatest velocity spread (\(\approx 100 \text{ km s}^{-1}\)) but a reduced average velocity. The uncertainties in measured positions after the data calibration are typically 100 times less than the characteristic size scale of the maser source. The 0.4 mas gradient reported earlier by Gwinn et al. (1993), along a position angle of 75\(^\circ\) (note correction of earlier typographical error), between 1391 and 1415 km s\(^{-1}\), is consistent with the current observations.

No radio continuum emission was detected in our observations. An average of all spectral channels redward of 1290 km s\(^{-1}\) shows no statistically significant emission other than that which is related to the maser. The limiting flux density is 0.45 mJy (1 \(\sigma\)), corresponding to a brightness temperature of \(<5 \times 10^6\) K for a tapered beamwidth of 1.4 \(\times\) 1.0 mas. (We note that continuum emission coincident with clumps 1–4 is only excluded at the 0.8 mJy level.)

### 4. THE MOLECULAR TORUS AND THE CENTRAL ENGINE

We propose that the observed redshifted maser emission traces part of the limb of an edge-on rotating torus, rather than the midplane (see Gallimore et al. 1996b). This torus is thick in both radial and axial directions and has an opening angle on the order of 90\(^\circ\). Along the limb, the orbital motion is parallel to the line of sight and produces a substantial amplification along a velocity-coherent path. Where the mo-
tion is transverse to the line of sight, the limited thickness of the maser layer precludes significant amplification except near the equatorial plane, where maser emission is visible perhaps because it amplifies the 22 GHz continuum flux associated with the central engine or radio jet. Observations that support this model are (1) the position angle of the redshifted emission relative to the radio jet axis; (2) a falling rotation curve for cylindrical radii beyond \( \sim 0.4 \) pc; (3) the position-velocity gradient of the systemic maser features; and (4) the location of redshifted maser emission, observed by us, with respect to the blueshifted emission, observed by Gallimore et al. (1996b).

(The cylindrical radius is defined with respect to an axis passing through the maser emission that lies at the adopted systemic velocity, with a position angle of approximately 0°; Antonucci et al. 1994, Gallimore et al. 1996a.)

The model in Figure 4 (Plate L4) shows the observed emission and the proposed location of the blueshifted emission. In the VLA map of the maser (Gallimore et al. 1996b), the weighted average centroid of the blueshifted emission between 800 and 850 km s\(^{-1}\) lies 42 mas due east of the redshifted emission at about 1425 km s\(^{-1}\), with 8 mas formal uncertainty in right ascension and declination. Based on this and the intrinsic symmetry of an edge-on torus, we hypothetically reflect the red emission in velocity about the systemic velocity and in space about the axis of the torus to obtain a V-shaped structure.

A thick torus requires vertical support, possibly from internal velocities, radiation forces, or magnetic fields. The ratio of internal motions to orbital velocity, \( v_i / v_o \), is approximately equal to the ratio of height to radius \( h / R \) (Krolik & Begelman 1988). The requisite velocity \( v_i \) is the order of 100 km s\(^{-1}\) corresponding to temperatures at which molecular gas could not survive if the motions were thermal. However, the spread of velocities in clumps 1–4 approaches 100 km s\(^{-1}\). The source of the supersonic turbulence is unclear, although our data show that internal motions increase dramatically close to the central engine, suggesting that it could drive these motions. Pier & Krolik (1992) show that radiation forces acting on dust grains close to the inner radius may be comparable to gravitational forces. Also, gas densities of \( 10^{10} \) cm\(^{-3}\) and magnetic field strengths of a few Gauss result in equipartition of rotational and magnetic energy. Emmering, Blandford, & Shlosman (1992) and Königl & Kartje (1994) model centrifugally driven flows from thin magnetized accretion disks. At sufficiently large radii the flow may be dusty, which is favorable to maser emission, though the model molecular gas density is too small.

The maser emission may arise from clouds that move in a warmer or more turbulent medium. Amplification occurs in gas with thermal motions of less than a few km s\(^{-1}\), but the turbulent velocities of the redshifted emission are at least an order of magnitude greater. The maser clouds may be the inward extension of a system of molecular cloud cores that lie close to the galactic plane at radii of at least 30 pc, with turbulent velocities of \( \sim 100 \) km s\(^{-1}\) (Tacconi et al. 1994; see also Jackson et al. 1993), although the maser torus is misaligned with respect to the galactic plane by approximately 65°.

The minimum radius at which maser emission is observed, \( \sim 0.4 \) pc, is close to the radius at which dust sublimates (Barvainis 1987; Laor & Draine 1993). Graphite grains smaller than 0.05 \( \mu \)m sublimate within a radius of \( r_{\text{sub}} \sim 0.4 \) L\(_{25}\) pc, where L\(_{25}\) is ultraviolet luminosity in units of \( 10^{35} \) ergs s\(^{-1}\) (Barvainis 1987). Most of the intrinsic bolometric luminosity is radiated at ultraviolet wavelengths. Hence, we adopt \( L_{25} = 0.6 \) (Pier et al. 1994), for which \( r_{\text{sub}} \sim 0.4 \) pc. Pier & Krolik (1993) find that the model infrared spectrum of a dusty torus fits best the observed spectrum of NGC 1068 for a 0.5 pc inner radius and 800 K effective temperature, somewhat less than the sublimation temperature of silicate dust. The agreement of \( r_{\text{sub}} \) with the maser observations may be related to the important role that dust can play in the thermodynamics of the maser pump cycle (e.g., Collison & Watson 1995) and in obscuring the nuclear continuum. Ablation of the component clouds of the torus by photons from the central engine (Krolik & Begelman 1986, 1988; Pier & Voit 1995) also fixes the inner radius to be on the order of 1 pc.

The radial extent of maser emission is probably governed by limitations in the maser excitation mechanism operating in the torus clouds. Emission can be driven by wind or jet-induced shocks (Elitzur, Hollenbach, & McKee 1989; Kaufman & Neufeld 1996), or by collisional heating associated with X-ray illumination by the central engine, as proposed for NGC 4258 and NGC 1068 (Neufeld, Maloney, & Conger 1994). Both mechanisms excite only a thin layer of material. Also, curvature of the torus may block direct mechanical interaction or X-ray illumination at large radii.

The maser torus model suggests that there should be redshifted emission visible from the southern half of the torus and systemic emission superposed along some length of the jet. The absence of southern emission may be related to the absence of strong southern jet emission, on scales smaller than about 10 pc (e.g., Ulvestad et al. 1987). Alternatively, southern radio emission may be preferentially obscured, especially if the torus is not strictly edge-on. The presence of systemic maser emission near the equator alone is consistent with the jet having a steep spectrum and a rapid decline with radius of the frequency at which it becomes optically thin. In NGC 4258, the 22 GHz jet emission is localized to radii on the order 0.2 mas scaled to a distance of 15 Mpc (Herrnstein et al. 1996). Since background continuum emission has not been observed directly by us, the relatively flat-spectrum nuclear source seen on angular scales of \( \sim 0.1 ' \) (Gallimore et al. 1996a; Muxlow et al. 1996) cannot be entirely a self-absorbed synchrotron source. The emission is not limited to a point source; it could represent thermal emission or possibly Thomson-scattered radiation (Gallimore et al. 1996a). Background amplification may still give rise to the systemic maser features because they are relatively weak. The limit on continuum strength implies that the gain is at least 40, which is modest.

From the rotation curve in Figure 3, we estimate that the total mass enclosed within a radius of 0.65 pc is \( \sim 1 \times 10^7 M_\odot \), assuming a circular orbital velocity of \( \sim 250 \) km s\(^{-1}\). The luminosity of the central engine (Pier et al. 1994) is \( \sim 0.5 \) times the corresponding Eddington luminosity. The mass is less than the approximately \( 2 \times 10^7 M_\odot \) implied by the motions of the molecular cloud cores beyond a radius of 30 pc (Tacconi et al. 1994). From VLA observations of the maser, Gallimore et al. (1996b) estimate a mass of \( 3 \times 10^7 M_\odot \) (scaled to 15 Mpc), though the VLBA observations provide a more accurate determination of the rotation curve. The VLBA mass estimate is uncertain by factors of order unity because the best-fit rotation curve is sub-Keplerian, \( v \propto R^{-0.31 \pm 0.02} \) for \( 0.65 > R > 0.40 \) pc. Self-gravity of the torus or substantial nearby stellar mass could be responsible. Alternatively, outwardly directed radiation pressure may reduce orbital velocities close to the inner edge of the torus (Pier & Krolik 1992).
This proposed force and the known dispersion in maser velocities is smallest for 0.65 pc radius, at which we estimate the central mass.

If the *systemic* masers are restricted to the inner surface of the torus, then the systemic emission arises over a narrow range of radii. The changing line-of-sight projection of the orbital velocity causes a gradient in line-of-sight velocity (as a function of impact parameter in the equatorial plane), 
\[ \frac{dV}{db} = 0.3M_b^2 r_{pc}^{-1.5} D_{bpc} \text{ km s}^{-1} \ \text{mas}^{-1}, \]
where \( M_b \) is the central mass in units of \( 10^5 \) M_\odot, \( r_{pc} \) is the radius in units of parsecs, and \( D_{bpc} \) is the distance in units of Mpc. For parameters estimated previously from the redshifted emission, \( M_b = 10, \ r_{pc} = 0.4, \) and \( D_{bpc} = 15, \) we predict a gradient of 60 km s\(^{-1}\) mas\(^{-1}\), in reasonable agreement with observation (Fig. 3). Greenhill et al. (1995b) apply similar arguments to the maser disk in NGC 4258. This interpretation of the systemic emission would be bolstered if the line-of-sight velocities of individual systemic maser features are observed to drift in time, corresponding to the line-of-sight centripetal acceleration while the red- and blueshifted maser features remain fixed (see Greenhill et al. 1995a and Nakai et al. 1995 for NGC 4258). The large velocity dispersion of the innermost maser clump (no. 4) may reflect in part a turnover in the rotation curve. We are grateful to O. Blaes, J. Gallimore, and J. Krolik for helpful comments and discussions. M. Eubanks and J. R. Herrnstein provided antenna positions. We thank P. Diamond and J. Benson for assistance with an early version of the correlator model. This work was supported in part by the National Science Foundation (AST92-17784).

REFERENCES

Antonucci, R. R. J. 1993, ARA&A, 31, 473
Antonucci, R. R. J., Hurt, T., & Miller, J. S. 1994, ApJ, 430, 210
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 476
Barvainis, R. 1987, ApJ, 320, 337
Capetti, A., Macchetto, F., Axon, D. J., Sparks, W. B., & Boksenberg, A. 1995, ApJ, 452, L87
Claussen, M. J., Heiligman, G. M., & Lo, K.-Y. 1984, Nature, 310, 298
Claussen, M. J., & Lo, K.-Y. 1986, ApJ, 308, 592
Collison, A. J., & Watson, W. D. 1995, ApJ, 452, 103
Elitzur, M. 1992, Astronomical Masers (Dordrecht: Kluwer)
Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, ApJ, 346, 983
Emmering, R. T., Blandford, R. D., & Shlosman, I. 1992, ApJ, 385, 460
Evans, I. N., Ford, H. C., Kinney, A. L., Antonucci, R. R. J., Armus, L., & Cagnonoff, S. 1991, ApJ, 369, L27
Gallimore, J. F., Baum, S. A., & O’Dea, C. P. 1996a, ApJ, 464, 198
Gallimore, J. F., Baum, S. A., & O’Dea, C. P., Brinks, E., & Pedlar, A. 1996b, ApJ, 462, 740
Greenhill, L. J., Henkel, C., Becker, R., Wilson, T. L., & Wouterloot, J. G. A. 1995a, A&A, 304, 21
Greenhill, L. J., Jiang, D. R., Moran, J. M., Reid, M. J., Lo, K.-Y., & Claussen, M. J. 1995b, ApJ, 440, 619
Gwinn, C. R., Antonucci, R. R. J., Barvainis, R., Ulvestad, J., & Neff, S. 1993, in Sub-arcsecond Radio Astronomy, ed. R. J. Davis & R. S. Booth (Cambridge: Cambridge Univ. Press), 331
Herrnstein, J. R., Moran, J. M., Greenhill, L. J., Diamond, P. J., Miyoshi, M., Nakai, N., & Inoue, M. 1996, in preparation
Jackson, J. M., Paglione, T. A. D., Ishizuki, S., & Nguyen-Q Rieu. 1993, ApJ, 418, L13
Kaufman, M. J., & Neufeld, D. A. 1996, ApJ, 456, 250
Königl, A., & Kartje, J. F. 1994, ApJ, 434, 446
Krolik, J. H., & Begelman, M. C. 1986, ApJ, 308, L55
Krolik, J. H., & Begelman, M. C. 1988, ApJ, 329, 702
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Macchetto, F., Capetti, S., Sparks, W. B., Axon, D. J., & Boksenberg, A. 1994, ApJ, 435, L15
Mulchaey, J. S., Mushotzky, R. F., & Weaver, K. A. 1992, ApJ, 390, 69
Muxlow, T. W. B., Pedlar, A., Holloway, A., Gallimore, J. F., & Antonucci, R. R. J. 1996, MNRAS, 278, 854
Nakai, N., Inoue, M., Miyazawa, K., Miyoshi, M., & Hall, P. 1995, PASJ, 47, 771
Neufeld, D. A., Maloney, P. R., & Conger, S. 1994, ApJ, 436, L127
Pier, E. A., Antonucci, R. R. J., Hurt, T., Kriss, G., & Krolik, J. 1994, ApJ, 428, 124
Pier, E. A., & Krolik, J. H. 1992, ApJ, 401, 99
Pier, E. A., & Voit, G. M. 1995, ApJ, 450, 637
Reid, M. J., & Moran, J. M. 1988, in Galactic and Extragalactic Radio Astronomy, 2nd ed., ed. G. L. Verschuur & K. I. Kellermann (Berlin: Springer), 255
Tacconi, L. J., Genzel, R., Blietz, M., Cameron, M., Harris, A. I., & Madden, S. 1994, ApJ, 426, L77
Ulvestad, J. S., Neff, S. G., & Wilson, A. S. 1987, AJ, 93, 22

5. SUMMARY

We have mapped the brightness distribution of H_2O maser emission at and redward of the systemic velocity in the Seyfert nucleus of NGC 1068, with sub-milliarcsecond resolution. The linear structure of the maser is misaligned with respect to the axes of the radio synchrotron jet and associated optical ionization cone. The observed maser emission can be reflected about the systemic velocity and jet axis to yield a V-shaped structure on the sky, and this may be interpreted as tracing the limb of a thick torus. Observations of the blueshifted maser emission, with lower angular resolution, are consistent with this interpretation. Velocity dispersions up to ~100 km s\(^{-1}\) may indicate that the torus probably consists of individual maser clouds immersed in a warmer, more turbulent medium.

The enclosed mass within a radius of 0.65 pc is \( \sim 1 \times 10^7 \) M_\odot, and the rotation curve is sub-Keplerian. The position-velocity gradient in the systemic maser emission is consistent with what would be expected if the emission arises on the inner edge of the torus at a radius of 0.4 pc. For this mass, the central engine of NGC 1068 radiates about 0.5 times its Eddington luminosity. No radio continuum source was detected toward the center of the torus, which argues that the flat-spectrum continuum emission observed on larger scales is not the by-product of a self-absorbed synchrotron source.
FIG. 4.—Model showing the location of the observed maser emission, as in Fig. 2, and the anticipated location of the emission blueshifted with respect to the systemic velocity. Color indicates line-of-sight velocity. Vertical line indicates the axis of the radio jet. The maser emission traces the limb of the upper half of an axially thick torus for radii between about 0.4 and 0.65 pc.

GREENHILL et al. (see 472, L23)