WATER MEGAMASERS AS A PROBE OF A CIRCUMNUCLEAR ACCRETION DISK IN AN ACTIVE GALAXY

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Abstract. In the past three years, observations of extragalactic water masers have demonstrated the extraordinary power of spectral line radio interferometry to probe the inner regions of active galaxies on subparsec scales. In the case of the active galaxy NGC 4258, the observations of Miyoshi et al. (1995) have established the presence of a thin, slightly warped, and Keplerian circumnuclear accretion disk that orbits a central object of mass 3.6×10^7 $M_\odot$. In addition to their immense value as kinematic probes, extragalactic water masers also provide valuable constraints upon the physical and chemical conditions in the masing circumnuclear gas, yielding an estimate of the mass accretion rate through the circumnuclear disk of NGC 4258. These recent observational and theoretical developments are reviewed here.

1. Introduction

Recent observations of extragalactic water masers have allowed the nuclear regions of active galaxies to be probed at unprecedented angular resolution. In this article, I will review some of the most important observational developments – without any attempt to be comprehensive – along with theoretical efforts that my collaborators and I have undertaken in an attempt to understand the microphysics of the maser emission process, and thereby to constrain the physical conditions in the emission region. These efforts have been described more fully in the papers of Neufeld, Maloney & Conger (1994) and of Neufeld & Maloney (1995).

In §2 below, I give a very brief observational overview of water megamasers. In §3, I discuss our suggestion that X-ray heating is the ultimate energy source that powers the water maser emission, and our conclusion

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that the standard collisional pump scheme invoked to explain Galactic water masers can also account adequately for the fluxes observed from extragalactic water megamasers. In §4, I review the beautiful observations of water megamaser emission that have been carried out over the past three years toward the source NGC 4258. In §5, I discuss how our interpretation of those observations may provide useful estimates of the density of the circumnuclear gas in NGC 4258 and the mass accretion rate through the circumnuclear disk.

2. Observational overview

Luminous maser emission in the $6_{16} - 5_{23}$ line of water near 22 GHz has now been detected from at least 16 active galaxies, with apparent luminosities[1] in the range 35 to 6000 $L_\odot$ (Koekemoer et al. 1995). These sources have been dubbed "megamasers", to indicate that they are very much more luminous than typical Galactic water maser sources. The extragalactic water megamasers are invariably associated with active galaxies, specifically Seyfert 2 galaxies and LINERs. A large systematic survey of Seyfert galaxies and LINERs by Braatz, Wilson & Henkel (1996) indicates that $\sim 5\%$ of Seyfert 2 galaxies (and no Seyfert 1 galaxies) show detectable water maser emission.

The spectra of extragalactic water megamasers typically show a large number of narrow features of individual width 1 – few $\mathrm{km\,s^{-1}}$ which cover a total velocity extent of several hundred $\mathrm{km\,s^{-1}}$. The spectra show time variability on timescales of months or less (e.g. Claussen & Lo 1986), implying by the usual light travel time arguments that the emission region is very small and the corresponding brightness temperatures extremely high. Maser amplification is therefore the only plausible emission mechanism. The small sizes of the emitting regions were confirmed by VLA observations of the active galaxies NGC 4258 and NGC 1068 (Claussen & Lo 1986), which showed that most of the $6_{16} - 5_{23}$ flux observed in these sources originates in unresolved regions of size smaller than 1 and 3.5 pc respectively that are spatially coincident with the active nuclei. This led Claussen & Lo to suggest that the maser radiation might be generated within a dusty molecular torus such as had been invoked by Antonucci & Miller (1985) to explain the polarization properties of Seyfert galaxies.

[1] These are the luminosities that are inferred under the assumption that the radiation is emitted isotropically; since the non-linear amplification of maser radiation typically leads to beaming, the true luminosities of *those sources from which maser radiation is observed* are likely to be less than the "apparent" luminosities, due to selection effects.

3. How is the water megamaser radiation generated?

The spatial coincidence of water megamasers with active galactic nuclei, and the fact that water megamasers are invariably associated with active galaxies (Braatz et al. 1996), suggests strongly that the physical process responsible for the excitation of water megamasers is intimately connected with nuclear activity. Noting that AGN are typically strong sources of hard X-rays, Neufeld, Maloney & Conger (1994) investigated whether the physical and chemical conditions in X-irradiated gas were conducive to the excitation of water maser emission; since the X-ray luminosities in AGN are typically as large as 10^{10} $L_{\odot}$, only a very small efficiency for the conversion of X-radiation to maser radiation would be required. We found that water maser radiation of the luminosity required to explain the observations is indeed expected from dense X-irradiated gas over a wide range of physical parameters.

Figure 1, from the paper of Neufeld et al. (1994), shows the physical and chemical structure of an isobaric slab of pressure $p/k = 10^{11}\,\mathrm{K\,km\,s^{-1}}$ that is irradiated by a hard X-ray source of luminosity 10^{43} erg s^{-1} located at a distance of 1 pc from the slab surface. Our model includes a careful consideration of the thermal balance, chemical equilibrium, and water excitation within the X-irradiated gas, full details of which have appeared elsewhere (Neufeld et al. 1994; Maloney, Hollenbach & Tielens 1996). Close to the slab surface, the X-ray heating rate is large, and the gas is too hot ($T \sim 8000$ K) to permit the existence of molecules. The X-ray heating rate diminishes with increasing depth into the slab, however, due to photoelectric absorption of the lower energy X-rays. Eventually, the heating rate drops below the critical value needed to maintain the gas temperature at 8000 K, and the gas undergoes a transition to a cooler ($T \sim 700$ K), mainly molecular phase.

As long as the gas temperature remains above ~ 400 K, water molecules are extremely abundant in the molecular gas, achieving an abundance relative to H nuclei in excess of 10^{-4}. Water production is driven by the sequence of neutral-neutral reactions

$$\mathrm{O + H_2 \rightarrow OH + H}$$

$$\mathrm{OH + H_2 \rightarrow H_2O + H,}$$

which are rapid for $T \geq 400$ K but slow at lower temperatures. The physical and chemical conditions within the region of high water abundance are well suited to the excitation of water maser emission. The lower panel in Figure 1 shows the predicted rate at which maser photons are produced by means of the standard collisional pump scheme that has been successful in explaining Galactic water masers.

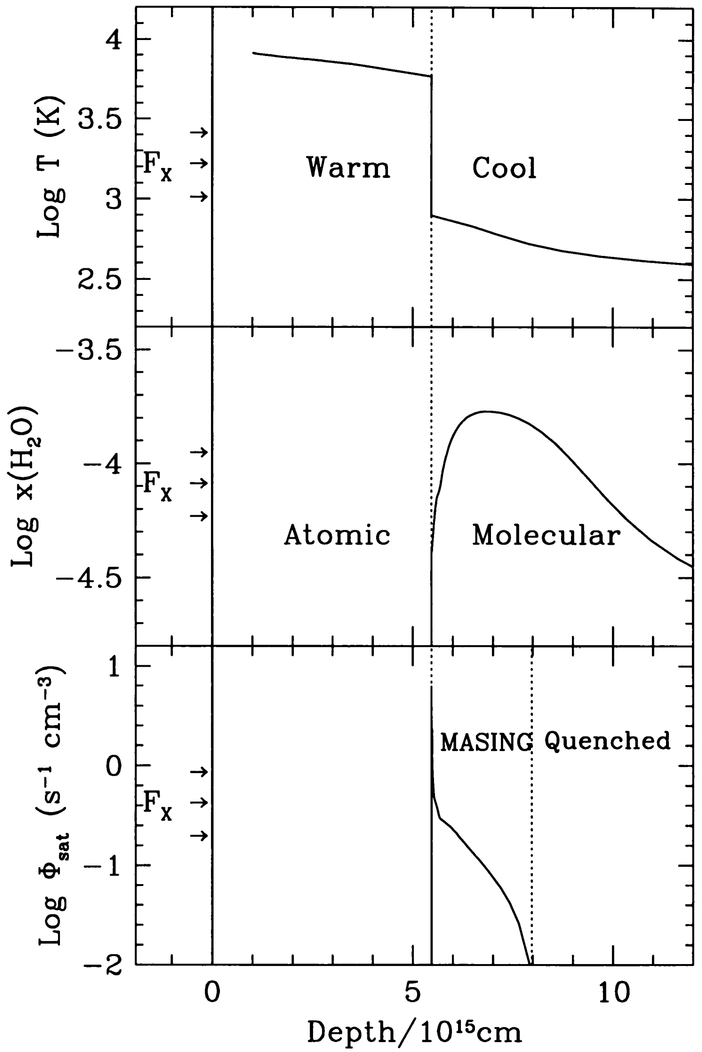

Figure 1. Structure of an X-ray illuminated slab, from the paper of Neufeld et al. (1994). The gas temperature, T, the water abundance relative to H nuclei, $x(H_2O) = n(H_2O)/n_H$, and the rate of production of maser photons, Φ_{sat}, are shown as a function of depth into the slab. Results apply to an isobaric slab of pressure $p/k = 10^{11}\,\mathrm{K\,km\,s^{-1}}$ that is irradiated by a hard X-ray source of luminosity $10^{43}\,\mathrm{erg\,s^{-1}}$ located at a distance of 1 pc from the slab surface.

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A general parameter study (Neufeld et al. 1994) showed that over a wide of range of values for the incident X-ray flux and for the gas pressure in the slab, the predicted maser luminosity lies in the range $10^{2\pm0.5}\,L_\odot$ per pc^2 of X-irradiated surface area[2], implying that the fluxes observed from typical megamaser sources can be accounted for by X-irradiated regions of area only $\sim 0.1\,pc^2$.

4. Detailed observations of NGC 4258

The past three years have seen enormous observational advances in the study of water megamasers, most importantly in the case of megamasers in the galaxy NGC 4258. An incomplete and very brief summary of these advances is given below.

Recent progress in the study of water megamasers in NGC 4258 began with the discovery by Nakai, Inoue & Miyoshi (1993) of high-velocity "satellite" maser features lying at velocity shifts of up to $\pm 1000\,km\,s^{-1}$ from the systemic velocity of the galaxy. This observation suggested that the emission might be arising in a differentially rotating disk, the features close to the galaxy's systemic velocity being beamed radially toward the observer, and the satellite features being beamed tangentially. In the absence of spatial information, however, the disk interpretation was non-unique. Emission from a jet could not be ruled out (Nakai et al. 1993), and it was not even clear that the frequency shift of the satellite features was kinematic in nature (Deguchi 1994).

A second important advance involved obtaining spatial information about the low velocity maser features. Using the powerful technique of spectral line Very Long Baseline Interferometry (VLBI) to observe the low velocity maser features, Greenhill et al. (1995b) discovered that their line-of-sight velocities varied linearly with the projected position on the sky, exactly as expected for a rotating disk. This interpretation was further strengthened by a third important observational development: the discovery of a secular redwards shift in all the low velocity maser features (Haschick, Baan & Peng 1994; Greenhill et al. 1995b). This shift could be understood quantitatively as a centripetal acceleration associated with the circular motion of masing material on the near side of the disk (Watson & Wallin 1994; Haschick et al. 1994; Greenhill et al. 1995a).

Most recently, in one of the first observations carried out using the Very Long Baseline Array (VLBA), Miyoshi et al. (1995) succeeded in locating the high velocity satellite features. Their velocities and projected positions

[2]This is a conservative estimate, which could be increased as a result of velocity gradients, of microturbulence, or - as pointed out by Collison & Watson (1995) - due to the effects of the absorption of non-masing infrared water line radiation by dust.

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showed excellent agreement with Kepler's law, yielding an estimate of 3.6×10^7 $M_\odot$ for the mass enclosed within the inner radius of the masing gas. The maser features appear to trace a geometrically-thin, and slightly warped Keplerian disk, which we view nearly edge-on at an inclination angle of 83 degrees. The inner radius of the masing annulus is 0.13 pc and the outer radius is 0.25 pc. By comparing the observed angular size scale of the disk with the linear size scale implied by the centripetal acceleration of the low velocity maser features, Miyoshi et al. were able to obtain a distance estimate to the source of 6.4 ± 1 Mpc.

The beautiful observations of NGC 4258 that have been reported in the past three years have demonstrated the extraordinary power of megamaser observations to probe the inner regions of active galaxies on subparsec scales. Such observations have yielded (1) the most compelling evidence to date for the existence of a supermassive black hole; (2) the first direct imaging of a circumnuclear disk in an active galaxy; (3) the first indication of a warp in such a disk; (4) the first evidence that such a disk is Keplerian; and (5) an accurate geometrical distance indicator which does not involve the usual chain of arguments needed to calibrate the extragalactic distance scale.

5. Models for a thin, warped accretion disk

We had originally envisaged the X-irradiated isobaric slab modeled by Neufeld et al. (1994) as representing the inner edge of a geometrically thick torus that was illuminated directly by X-rays from a central source. Although that geometry may indeed apply in some megamaser sources, the emitting region in NGC 4258 appears to be a thin disk that emits maser radiation over a range of radii. Thus the observations of NGC 4258 by Miyoshi et al. (1995) prompted us to change our thinking, if not by 180 degrees then by 90 degrees. Because the disk is warped, we may expect its surface to be illuminated obliquely by X-rays from a central source, so that the slab models we constructed might apply to surface layers of the disk itself. Given an intrinsic luminosity for NGC 4258 that was estimated by Miyoshi et al. (1995) as ~ 10 $L_\odot$, and a surface area of $0.15\,\mathrm{pc}^2$ for the masing annulus, the required maser luminosity per unit illuminated surface area is ~ 60 $L_\odot$, in line with typical values predicted in the models of Neufeld et al. (1994).[3]

In light of the detailed information available from recent observations of NGC 4258, we attempted to place constraints upon the physical condi-

[3] Although these models applied strictly to slabs that were illuminated by X-rays at normal incidence, we would expect only minor differences in the case of oblique illumination.

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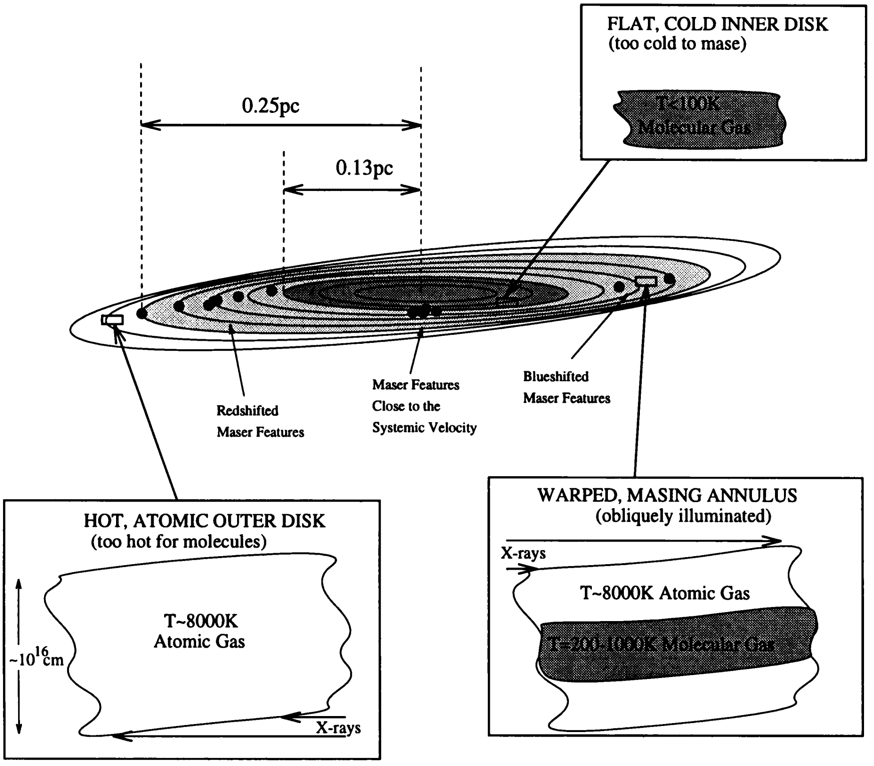

Figure 2. Model for the warped, masing circumnuclear disk in NGC 4258, from the paper of Neufeld & Maloney (1995).

tions in the disk (Neufeld & Maloney 1995). In particular, we considered the constraints imposed by the presence of water close to an X-ray source; the very existence of molecules places an upper limit upon the ionization parameter within the disk. Modeling the system as a steady accretion disk with a constant value of the dimensionless viscosity parameter α, we found that the density in the disk midplane declines roughly as r^{-3}, where r is the radial coordinate, whereas the incident X-ray flux declines as r^{-2}. The ionization parameter is therefore a *increasing* function of r, and the conditions become *less* favorable for the existence of molecules with increasing r.

The critical ionization parameter therefore imposes a maximum radius, r_{cr}, beyond which the disk is purely atomic. Inside the critical radius, molecules may exist at least at the disk midplane where the density is highest. The structure of the disk in this picture is shown in Figure 2, reproduced from the paper of Neufeld & Maloney (1995). Assuming that the observed outer radius of the masing annulus represents the critical radius beyond which molecules may not exist, we estimate the midplane density in the disk as $n(\mathrm{H_2}) = 2 \times 10^7\,\mathrm{cm^{-3}}$ at the assumed critical radius of 0.25 pc. This implies a mass accretion rate of $7 \times 10^{-5} \alpha\, M_\odot\,\mathrm{yr^{-1}}$. In deriving these parameters we assumed the X-ray properties inferred from ASCA observations by Makishima et al. (1995). We speculated that the *inner radius* of the masing annulus represented the point at which the warp flattens out and the disk can no longer be heated by obliquely-incident X-rays. Allowing ourselves the assumption that the accretion rate has remained roughly constant over the several million year timescale on which material is transported from radius r_{cr} to the active nucleus, we obtained an estimate of $\sim 1\alpha^{-1}\%$ for the efficiency with which the central engine converts rest mass energy into X-rays.

Acknowledgements

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References

Antonucci, R.J., Miller, J.S. 1985, ApJ, 297, 621
Braatz, J.A., Wilson, A.S., and Henkel, C. 1996, Vistas in Astronomy, 40, 83
Claussen, M.J., Lo, K.-Y. 1986, ApJ, 308, 592
Collison, A, Watson, W.D. 1995, 452, L103
Deguchi, S. 1994, ApJ, 420, 551
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
Haschick, A.D., Baan, W.A., Peng, E.W. 1994, ApJ, 437, L35
Koekemoer, A.M., Henkel, C., Greenhill, L.J., Dey, A., van Breugel, W., Codella, C., Antonucci, R. 1995, Nature, 378, 697
Maloney, P.R., Hollenbach, D.J., Tielens, A.G.G.M. 1996, ApJ, 466, 561
Makishima, K., Fujimoto, R., Ishisaki, Y., Kii, T., Loewenstein, M., Mushotzky, R., Serlemitsos, P., Sonobe, T., Tashiro, M., Yaqoob, T. 1994, PASJ, 46, L77
Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., Inoue, M. 1995, Nature 373, 127
Nakai, N., Inoue, M., Miyoshi, M. 1993, Nature, 361, 45
Neufeld, D.A., Maloney, P.R., Conger, S. 1994, ApJ, 436, L127
Neufeld, D.A., Maloney, P.R. 1995, ApJ, 477, L17
Watson, W.D., Wallin, B.K. 1994, ApJ, 432, L35

Discussion

Scappini: Can you put constraints upon the H_2 density for the maser action to take place, before water is thermalized?
Neufeld: In the standard collisional pump scheme — where the level populations are determined by the combined effects of spontaneous radiative decay and collisional excitation by H_2 — the level populations are driven by collisions to local thermodynamic equilibrium and the maser action is quenched for H_2 densities above $\sim 10^{12}\,\mathrm{cm}^{-3}$. That value applies at 400 K and is an increasing function of temperature. The maximum allowed density can be reduced below $10^{12}\,\mathrm{cm}^{-3}$ due to the effects of radiative trapping in non-masing infrared transitions.

Ellingsen: My understanding is that the geometry required for OH megamaser emission is similar to that for H_2O. Could you comment on why there is no overlap between those galaxies detected as OH megamasers and those detected as H_2O megamasers?
Neufeld: As you point out, the OH and H_2O megamaser galaxies appear to form two non-overlapping sets (except for the case of the H_2O megamaser source NGC 1068, from which Gallimore and collaborators have recently detected OH maser emission). I don't think a satisfactory explanation for this has yet been advanced. It is true that the required excitation conditions are somewhat different — in particular OH masers are collisionally quenched at lower densities than H_2O masers — but since a wide range of gas densities are present within a given galaxy, it is not clear why megamaser emission from both molecules from a single galaxy should be so unusual.

Hjalmarson: Since masers are known to be unstable and variable, it seems rather brave to determine the rate of centripetal acceleration from a time sequence of observations. Perhaps whole maser patterns were moving. Could you elaborate on this?
Neufeld: Indeed, not every maser feature persists long enough for an acceleration to be determined. But most spectral features can be tracked long enough to permit a systematic redwards shift to be detected and measured. In interpreting this shift as a centripetal acceleration, Miyoshi et al. are indeed making certain assumptions about the nature of the maser emission. In particular, they assume the velocity shifts to be kinematic in nature and that individual features are generated within clumps — or at least regions of enhanced velocity coherence — that are in circular motion about the center of the masing disk.

Pecker: Does the distance determination for NGC 4258 provide a useful measurement of the Hubble constant?
Neufeld: Unfortunately, NGC 4258 is too close to serve as a useful probe of the Hubble flow, and thus a substantial fraction of its redshift ($\sim$ 500 kms^{-1}) is probably contributed by random motions (i.e. peculiar velocities). What one would like to find - of course - is a larger, more luminous analog to NGC 4258 located at much larger redshift; such an object could make a very useful contribution in constraining the extragalactic distance scale.

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