AGN DISK DIAGNOSTICS

R. D. BLANDFORD
130-33 Caltech
Pasadena, CA 91125, USA

1. Introduction

The discovery of megamasers in nearby active galactic nuclei (AGN) is an unexpected boon for AGN researchers. The most immediate benefit, brought out in observations of NGC4258 (Miyoshi *et al* 1995, Moran, these proceedings) is that it allows an accurate mass measurement for the central black hole, in this case of 3.6×10^7 $M_\odot$, with unprecedented accuracy. (I shall not belabor the point that we have not proven rigorously that it is a black hole because this is surely on much firmer footing than what follows!) Masers also allow us to discover second order features of the kinematics, specifically that the disk is warped. Thirdly, and this is what I have been asked to review here, it should enable us to choose between several possible accretion modes by treating masers as diagnostic probes of physical conditions in the disk.

2. NGC 4258

A prominent model for maser emission from NGC 4258 (Watson & Wallin 1994, Myoshi *et al* 1995), is due to Neufeld, Maloney & Conger (1994) and Neufeld & Maloney (1995), who argued that the masing gas was X-ray heated so that the molecular gas is unusually hot ($T \sim 600$ K) and water forms readily and is efficiently pumped by hydrogen collisions. The molecular chemistry invoked seems quite robust and able to account for the large incidence of powerful masers. They derive an empirical relation connecting the X-ray radiation pressure, to the gas pressure and the surface density of atomic hydrogen that shields the molecular layer. These authors proposed that there are three distinct zones in the disk, a "hot" zone for $R > 0.25$ pc ($\equiv 1.5 \times 10^5 m$ in relativistic units), comprising atomic hydrogen at a temperature ~ 8000 K, a "wet" zone with $0.25\text{pc} < R < 0.13\text{pc}$ comprising a dense and cool molecular disk, sandwiched between two hotter, coronae of atomic hydrogen, and a "cold" zone, (somewhat parodoxically), at smaller radii, $R < 0.13$ pc, where the shielding is too strong to pump the maser. We view this disk with a mean inclination $i = 83°$.

The physical conditions are best defined at the transition radius $R \sim 0.25$ pc. In a standard, α disk, angular momentum conservation requires that $4\pi\alpha P s r^2/\Omega \sim \dot{M} r^2 \Omega$, where s is the sound speed and $\dot{M} = 10^{20}\dot{M}_{20}$ g s^{-1} $\sim 3\pi\alpha\Sigma s^2/\Omega$ is the mass accretion rate. Now the 2-10 keV X-ray luminosity is 4×10^{40} erg s^{-1}, and this allows us to derive a relationship between the gas pressure and the column density of shielding atomic hydrogen - $P \sim 2 \times 10^{-5}\Sigma^{-0.9}$ dyne cm^{-2}. We can then solve for the accretion rate obtaining $\dot{M} \sim 10^{21}\alpha$ g s^{-1}, $\Sigma \sim 0.2$ g cm^{-2}. (This is slightly lower than the value given by Neufeld & Maloney presumably due to my making slightly different assumptions.)

There is a further constraint associated with requiring the disk not to be so dense that self-gravity causes it to become unstable. This requires $\dot{M} < 3\pi\alpha s^3/G \sim 5 \times 10^{24}\alpha$g s^{-1} in the molecular gas. This does not affect the Neufeld-Maloney estimate of the accretion rate at the transition radius, but may be responsible for limiting the inner molecular disk.

Now, the near infrared luminosity is reported to be $\sim 10^{41}$ erg s^{-1} (Chary & Becklin 1997) and it is reasonable to suppose that the bolometric luminosity is at least three times this.. This would then require a radiative efficiency of $\sim 3 \times 10^{20}\alpha^{-1}$ erg g^{-1}. An additional demand upon the accretion process is the powering of the jet. Now Herrnstein et al (1997, private communication) report that the brightness temperature of the inner jet is $\sim 5 \times 10^6$ K at a frequency 22 GHz and a

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projected distance of $\sim 2\times10^{16}$ cm from the geometrical center of the accretion disk. This translates to a minimum pressure $P_{\rm min} \sim 2\times10^{-5}$ dyne cm^{-2}, where equality requires equipartition and no additional forms of energy. If the jet is relativistic with a Mach number given by the reciprocal of the opening angle, about the best that can be hoped, then it (together with its counterjet) carries a power $L_j > 2\times10^{41}$erg s^{-1}. Clearly, this further strains the efficiency. In fact the problem may be even greater. Jets have been observed by Cecil *et al* (1995) in radio, optical emission lines and X-rays. Although the bolometric luminosity of these jets is only $\sim 3\times10^{40}$ erg s^{-1}, the power they carry can be much larger. Again adopting the minimum pressure at a radius $r\sim 5$ kpc, which is comparable with the external pressure, we can estimate the jet power to be $\sim 3\times10^{41}\mathcal{M}^2V_8$erg s^{-1}, where $\mathcal{M}$ is the jet Mach number and $1000V_8$ km s^{-1} is the jet speed.

The net conclusion of this is that the Neufeld-Maloney estimate of the mass flowing through the disk can only barely supply the minimum power if $\alpha\sim1$ and is probably inadequate because α is generally argued to be much smaller than unity in neutral gas. It may be possible that a more sophisticated model of disk accretion can reconcile these two quantities. It is also possible that the accretion rate is strongly time-dependent and the current rate of supply of molecular gas is much smaller than in the past. A third, possibility is that Neufeld & Maloney are correct and that the jets and X-ray emission are powered by the spin of the central black hole.

In an alternative approach, Lasota *et al* (1996) have argued that NGC 4258 is an example of an advection-dominated accretion flow in which a high rate of angular momentum transport (presumably due to magnetic torque), allows quasi-spherical accretion. Only the ions are heated directly, (through a combination of ion cyclotron and transit time damping) and direct electron heating is limited to Coulomb scattering and synchrotron absorption. Under these circumstances, the radiative efficiency is low and most of the dissipated energy is advected across the event horizon. (If, as on phenomenological grounds, there is reason to suppose may be the case, this is a good description of the accretion process at rates significantly below the Eddington rate, then it is very suprising that more of the energy, does not find its way into electron heating, particularly if there is magnetic reconnection *cf* Gruzinov, 1997, preprint). Lasota *et al*'s baseline model had a mass accretion rate of 7×10^{22}g s^{-1} and $\alpha=0.1$. They predicted a 22 GHz radio flux roughly 10 times larger than the observed upper limit from the location of the black hole, $S<0.2$ mJy. Nevertheless, a revised model incorporating improved physics is able to accommodate the radio upper limit while postulating a significantly larger accretion rate $\sim10^{24}$ g s^{-1} (Narayan, private communication).

There is a more direct, model-independent implication of the observed radio upper limit. Let us first define an Eddington density and pressure, $n_E=(mm_p\kappa_T)^{-1}(r/m)^{-3/2}\sim3\times10^{11}(r/m)^{-3/2}$ cm^{-3}, $P_E=(m\kappa_T/c^2)^{-1}(r/m)^{-5/2}\sim5\times10^8$dyne cm^{-2}. These are fiducial values for gas accreting spherically at the Eddington rate. The 22 GHz flux upper limit translates into a lower bound on the brightness temperature, $T_B(22\text{GHz})<10^{10}(r/300m)^{-2}$ K. If this is a self-absorbed synchrotron source of photospheric radius r, then this becomes a condition on the field strength $200(r/300m)^4<B<3000$ G. The first inequality then becomes $r<300m(P_m/P_E)^{0.1}$, where P_m is the magnetic pressure and the second inequality is almost surely satisfied. Locating the photosphere at r requires that the synchrotron optical depth be unity, or, if we associate a pressure $P_\gamma(\gamma)$ with the relativistic electrons with energy $>\gamma m_ec^2$, then

$$P_\gamma[6(r/300m)^{-2}]/P_E\sim10^{-9}(P_m/P_E)^{-1}(r/300m)^4<10^{-9}(P_m/P_E)^{-0.6} \qquad (1)$$

Unless the magnetic energy density is extremely low, this places a surprisingly low bound on the efficiency of acceleration of mildly relativistic electrons.

There are some processes which can suppress radio synchrotron emission. The Razin effect is important at densities above $\sim10^{12}(B/1000\text{G})$ cm^{-3}, conditions that are unlikely to be present. Secondly, electron-electron Coulomb collisions may diminish the relativistic electron population. This happens on a timescale $t_{ee}\sim5\times10^4\gamma(r/300m)^{3/2}(n/n_E)^{-1}$, typically somewhat longer than the synchrotron cooling timescale and comparable with the infall timescale. Thirdly, extrinsic free-free absorption may extinguish the radio source if it is occulted by a dense gas phase, (eg a warped disk), with density satisfying

$$n>0.03n_E(T/10^4\text{K})^{0.7}(r/300m)f^{-1/2} \qquad (2)$$

where $f=<n_e^2>/<n_e>^2$ is the clumping factor. This seems the most reasonable possibility, but any model is subject to the constraints that the southern jet can be observed through the accreting gas at a projected radius $\sim 6000m$ and that the total gas column density be compatible with the X-ray observations, specifically that $\Sigma < 0.02$ g cm^{-2}. Free-free absorption is not excluded by existing observations but may not be consistent with an advection-dominated flow. Clearly, additional radio observations to measure the spectrum and to monitor the variablity are in order.

3. NGC 1068

Water masers have also been discovered associated with the Type 2 Seyfert galaxy, NGC 1068. Here the inferred black hole mass is $\sim 1.5 \times 10^7$ $M_\odot$, although there is a much greater uncertainty than for NGC 4258. Again the inclination is high, $i \sim 80°$ and the bolometric luminosity is at least $\sim 10^{44}$ erg s^{-1}. Gallimore, Baum & O'Dea (1997, preprint) have used observations of this source to develop yet another view of the accretion process. They also propose, "hot", "wet" and "cold" zones this time in increasing radial order. The water masers are located at $\sim 0.7 - 1$ pc and they observe the smaller hot zone using VLBI. What they find is an inhomogenous source with characteristic brightness temperature $T_B \sim 6 \times 10^6$ K. They attribute the radio emission to scattered synchrotron radiation from an occulted, central core or free-free emission from hot gas. In the latter case, as the radiopower $\sim 10^{37}$ erg s^{-1}, the total free-free power (mostly as soft X-rays) must be $\sim 10^{44}$ erg s^{-1} and the gas must be maintained at this high temperature at this a radius $\sim 10^6$ m. Perhaps the least unlikely way for this to happen is if the cloud is Compton heated by the central source. However this requires postulating an X-ray power at least an order of magnitude greater than we observe.

4. Future Observations

It is apparent that radically different views of accretion onto central, massive black holes can be supported by contemporary observations of megamaser sources. Future observations may limit the options. For example, we can use Zeeman observations of the maser line to limit the magnetic field strength (Moran, this meeting). The field is expected to have two components. The first is a reversing internal field, probably regenerated by the Balbus-Hawley (1991) instability. Adopting the Neufeld-Maloney pressure estimate gives a value $\sim 5\alpha^{1/2}$ mG, detectable in linear polarization. The second is a vertical component passing through the disk generating an external, non-dissipative torque If this is responsible for carrying away a fraction f_T of the liberated angular momentum, the vertical field strength is estimated to be $\sim 2 f_T^{1/2} \dot{M}_{20}^{1/2}$ mG detectable in circular polarization.

Another important diagnostic concerns the origin of the warps in NGC4258. These are well measured directly and cleverly integrated into an expanation of the blue-red asymmetry in the maser spots (Herrnstein et al 1996). Understanding the dynamics of warping may help us to understand the details of disk accretion. In an interesting suggestion, Maloney *et al* (1996) have suggested that the warp is due to radiation pressure. To order of magnitude, if the warping angle is θ and there is complete reflection, then there will be a net torque, $\sim LR\theta/c$ which may be responsible for unstable motion of the disk. If correct, this has important implications for AGN taxonomy, the shapes of radio jets and the formation of ionization cones. However, there could be stronger torques operating. For example, suppose a fraction f_W of the incident power is carried off in a wind of speed V_W, the ablative torque will exceed the radiative torque if $f_W > V_W/c \sim 0.003$. Similarly, if this outflow is hydromagnetic, as might reasonably be expected, the total, non-radiative torque will be even larger. In addition, the models are predicated on an assumption that the gravitational potential is spherically symmetric. If there is a central star cluster this may well not be the case and this may cause the precessional motion to be damped out. NGC 4258 provides a splendid laboratory to enable us to see what happens in practice.

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