Physical Conditions in Obscuring Tori and Molecular Accretion Disks, and Are They Really the Same Thing?

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Abstract. The nature of the obscuring material in active galactic nuclei is still uncertain. Although some sources, such as Cygnus A, show evidence for a geometrically thick “torus” as originally suggested, recent work on the radiation-driven warping instability discovered by Pringle suggests that obscuration by thin, warped disks may play a crucial role in AGN.

1. Introduction

In the currently popular and attractive “unified model” for active galactic nuclei, all AGN are surrounded by a geometrically and optically thick “torus” of obscuring material (see Conway, this volume, for the proper definition); the orientation of this torus with respect to our line of sight determines whether the AGN is classified as a Type I (Seyfert 1 or quasar) or Type II (Sy 2 or radio galaxy) object. Excellent reviews of unification are given by Antonucci (1993) and Urry & Padovani (1995). Following the pioneering theoretical work of Krolik & Begelman (1986, 1988), it has been generally assumed that the tori are composed of dusty molecular clouds; the geometric thickness of the torus is the consequence of a large cloud velocity dispersion. How such an assemblage could be maintained (i.e., preventing collisional dissipation of the random cloud motions) is still an unsolved theoretical problem (Krolik & Begelman 1988; Pier & Krolik 1992). However, there is indisputable evidence for the presence of obscuring material in many Type II AGN, and it is clear that this plays a major role in the classification of AGN.

There are a number of unanswered questions, however, and in the remainder of this paper I will focus on two of them: (1) Are “molecular tori” molecular, and (2) are they tori? As I will argue below, in the one object currently known where the obscuration appears to arise in a geometrically thick structure as originally envisaged, the torus is probably atomic rather than molecular, whereas in the two cases where we have information on the spatial distribution of molecular gas at $r \lesssim 1$ pc from the nucleus, the material appears to lie in a thin warped disk. Warped accretion disks are likely to be common in AGN, and may account for much of the phenomenology ascribed to “tori”.

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2. Physical Conditions in Obscuring Tori

By definition, the inner face of the torus sees the intense radiation field from the central source. For a given radius and source luminosity, the gas in the torus will only be molecular if its pressure exceeds a critical value, given by

\[ \tilde{P}_{cr} = P_{cr}/k \simeq 1.3 \times 10^{11} \frac{L_{44}}{r_{pc}^2 N_{24}} \text{ cm}^{-3} \text{ K} \]  

(1)

where \(10^{44}L_{44} \text{ erg s}^{-1}\) is the 1–100 keV luminosity, the distance from the luminosity source is \(r_{pc} \text{ pc}\), and \(N_{\text{att}} = 10^{24}N_{24} \text{ cm}^{-2}\) is the attenuating column density between the X-ray source and the point of interest in the torus. (The value of the column density exponent depends weakly on the spectral shape; see Maloney, Hollenbach & Tielens 1996 for details.) For \(\tilde{P} > \tilde{P}_{cr}\), the gas is molecular, with \(T < \sim 10^3 \text{ K}\), while for \(\tilde{P} < \tilde{P}_{cr}\), the gas is atomic, warm (\(T \sim 10^4 \text{ K}\)), and weakly ionized (\(x_e \sim 0.01\)). Thus, for a given X-ray luminosity and torus column density, the torus will be atomic only if its pressure exceeds a critical value; this pressure can be very large, even if the column density through the torus is itself very high. (Note also that in steady-state, the pressure in the torus must be at least equal to the pressure of the radiation which is absorbed close to the inner face of the torus, i.e., in a region of thickness \(\Delta r \ll \) the radial width of the torus.) Equivalently, for a fixed luminosity and pressure, the entire torus will be atomic unless the total column density exceeds a critical value also given by equation (1).

What diagnostics do we have for the physical conditions in the torus? Due to the small spatial scale for \(\sim \text{ pc-size tori}\), detection of emission lines is prohibitively difficult. However, detection of absorption lines, especially at millimeter and centimeter wavelengths where dust extinction is not a problem, is much more promising. For atomic tori, the best probes are (1) the 21-cm hyperfine transition of atomic hydrogen, and (2) free-free absorption at GHz frequencies. For molecular tori, both (1) and (2) are also potentially useful, while in addition (3) a wide variety of molecular transitions could in principle be seen in absorption.

Expressions for the 21-cm and free-free optical depths of tori are given in Maloney (1996). The first detection of 21-cm absorption in a “torus” was toward the nucleus of the relatively nearby, luminous radio galaxy Cygnus A (Conway & Blanco 1995). The large linewidth (\(\Delta V \approx 270 \text{ km s}^{-1}\)) argues against this absorption arising at large (\(r \sim \text{kpc}\)) distances from the nucleus; furthermore, such a large velocity dispersion (with random velocities comparable to rotation velocities) is necessary to maintain a geometrically thick torus. However, the absorption also cannot arise too close to the nucleus: as pointed out in Maloney (1996), a torus which is too near the luminosity source will have a large free-free optical depth at 21 cm, making the radio continuum source undetectable. This constraint requires that the absorbing gas is at \(r \gtrsim 30 – 40 \text{ pc}\), for either an atomic or molecular torus. (However, this estimate ignores the effects of stimulated emission due to the incident radio continuum on the free-free absorption coefficient; in some cases this may be significant.) The 21-cm absorption has now been mapped by Conway (this volume), using the VLBA; the results indicate that the absorption arises in a ring or thick disk with an inner radius of about
50 pc. If the spin temperature of the hydrogen is $T \sim 10^4$ K, then the neutral hydrogen column is comparable to that inferred from the X-ray spectrum (Koyama 1992). In this case, although the scale is much larger than originally envisaged, it appears that the nuclear obscuration does arise in a geometrically thick torus.

Searches for molecular absorption from the Cygnus A torus have proven unsuccessful (Barvainis & Antonucci 1994, 1996; Conway & Blanco 1995). The simplest explanation for this is that the torus is not molecular; if the torus pressure is less than the critical pressure, the X-ray ionization and heating rates will be high enough to maintain the entire column in a warm atomic state. However, the observed HI absorption could also arise in a molecular torus: the molecular gas could be too warm or turbulent, or the covering factor of clouds at a single velocity too small, for absorption to be detectable. An additional, interesting possibility, first suggested by M.J. Rees (see Barvainis & Antonucci 1994) is that radiative excitation of molecules by the nonthermal radio continuum is important. This possibility was explored in detail for CO molecules in a torus in Cygnus A by Maloney, Begelman & Rees (1994). The basic idea is quite simple: the incident radio continuum attempts to drive the excitation temperatures characterizing the rotational levels to the brightness temperature $T_b$ of the radiation field at the relevant frequency; generally $T_b \gg T_k$, the gas kinetic temperature. This acts to reduce the optical depth to absorption in two ways, by increasing the partition function (spreading the population of the rotational levels over a larger number of states) and by reducing the absorption coefficient through the correction for stimulated emission. Including the effect of radiative excitation, the excitation temperature of a rotational level is given approximately by

$$T_{ex} \approx T_k (1 + \gamma)$$

where $\gamma$ is the ratio of radiative to collisional rates. Hence, if $\gamma$ is large, the excitation temperature can be much larger than the gas kinetic temperature, greatly reducing the absorption optical depth.

Maloney et al. (1994) showed that this process could plausibly be important in the Cygnus A torus. A more detailed investigation of radiative excitation has been carried out by Black (1998), including non-LTE effects and examining the influence of the nonthermal continuum on the excitation of additional species such as OH, H$_2$CO and HCN. Radiative excitation by the nonthermal radio continuum is quite likely to be important in the class of radio sources known as “Compact Symmetric Sources” (Readhead et al. 1995), because of their large ratio of radio to X-ray luminosities. However, the simplest explanation for the absence of any molecular absorption is that the “torus” is atomic, rather than molecular. VLBI observations of 21-cm absorption in a number of other sources, discussed elsewhere in this volume in the contributions of Conway and Pedlar, show the tremendous potential of this technique as a probe of the structure and kinematics of near-nuclear gas in objects with extended radio emission.

### 3. Maser Emission and Warped Accretion Disks in AGN

Although the obscuring material in Cygnus A appears to lie in a geometrically thick torus as originally envisaged, albeit on considerably larger scale, it seems
likely that it is an atomic, rather than a molecular torus. However, there are a number of AGN where we know that there is molecular gas lying within \( r \sim 1 \) pc or less from the nucleus. These are the water “megamaser” sources, which are exclusively associated with AGN, either Seyfert 2 or LINER galaxies (see Braatz, Wilson, & Henkel 1994, 1996; Maloney 1997). These sources have (isotropic) luminosities in the 22 GHz water line of \( L_{\text{H}_2\text{O}} \sim 30 - 6000 \, L_\odot \); the emission is always centered on the nucleus. Roughly 10% of Seyfert 2 and LINER galaxies show water megamaser emission (Braatz et al. 1996), and the fact that no water megamasers are seen in Type 1 Seyferts (in which our line of sight by definition lies within the opening angle of the obscuring torus) suggests that the maser emission is directly associated with the obscuring material. Neufeld, Maloney, & Conger (1994) showed that the association of water megamasers with AGN could be understood in the context of obscuring torus models as the consequence of irradiation of the inner face of the torus by X-rays from the central source: as noted earlier, at some depth into the torus (depending on the pressure) the gas will undergo a phase transition from atomic to molecular. Across this phase transition, the water abundance jumps from negligible values to \( x_{\text{H}_2\text{O}} \sim 10^{-4} \), while the temperature drops from \( T \sim 10^4 \) K to \( T \lesssim 10^3 \) K (Figure 1). These conditions are ideal for producing maser emission in the 22 GHz line, provided that the torus pressure \( P \lesssim 10^{13} \, \text{cm}^{-3} \, \text{K} \), and substantial maser luminosities
\( L_{\text{H}_2\text{O}} \sim 10^2 \, L_\odot \) per \( \text{pc}^2 \) of irradiated area) are possible. The maser emission is eventually quenched by photon trapping, although photon absorption by dust may inhibit quenching, as pointed out by Collison & Watson (1995) (although the importance of this process depends on the torus pressure).

However, VLBI observations of several megamaser sources showed that the spatial distribution of maser emission is very different than expected from a geometrically thick torus. Mapping of the maser emission from the LINER galaxy NGC 4258 (which provided the first definitive evidence for the existence of a massive black hole in a galactic nucleus [Miyoshi et al. 1995], and is discussed in detail by Herrnstein elsewhere in this volume) revealed not the inner face of a torus but a thin, warped disk. A similar geometry is seen in NGC 1068 (Greenhill et al. 1996; Greenhill & Gwinn 1997), except that the disk as traced by the maser features makes a large angle with the radio jet axis (approximately \( 40^\circ \) at the outer edge of the maser distribution); one interpretation of this is that the maser disk in NGC 1068 is considerably more warped than that in NGC 4258. The maser emission is still powered by X-ray irradiation; due to the warping of the disk, the disk is obliquely illuminated by the central source. The maser emission can be used to derive the mass accretion rate through the disk (Neufeld & Maloney 1995).

There is little doubt in the case of NGC 4258 that it is the warped accretion disk itself, as traced by the maser emission, which obscures our line of sight to the central source. This may also be the case in NGC 1068. Are warped accretion disks generally present in AGN, and do they play a major role in obscuring the central source? Since the presence of the warp is also crucial for the production of the maser emission, as it allows the central source to illuminate the disk, the origin of the warp is a question of considerable importance. In fact, this problem considerably predates the discovery of the warped disk in NGC 4258. Evidence for warped, precessing disks in X-ray binary systems dates to the early 1970s, and the origin of these warps stood as an unsolved theoretical problem for nearly a quarter of a century.

Recently, however, a natural mechanism for producing warps in accretion disks has been discovered by Pringle (1996). The basis of Pringle’s instability is really quite simple, and in fact the key feature of the instability was pointed out nearly twenty years earlier by Petterson (1977). Consider a ring of an accretion disk that is optically thick to both absorption and emission, orbiting a point source of radiation. If we now warp this ring (i.e., make it non-planar), then portions of the ring will be illuminated by the central source. The pressure exerted by the incident radiation cannot exert any torque on the ring, since the incident flux is in the purely radial direction. However, since the ring is optically thick to re-emission of the absorbed radiation, the re-radiated flux will be normal to the local plane of the disk. When integrated over the surface of the ring, the pressure from this re-emitted radiation will exert a non-zero torque, since the inclination (the tilt of the ring with respect to the original rotation axis) will not be constant with azimuth, since the ring is warped. This torque will alter the angular momentum of the ring; in general this will lead to both precession of the ring and a change in the ring inclination. The warp modes all have \( m = 1 \) symmetry, i.e., they are antisymmetric.
Further work on Pringle’s instability has been done by Maloney, Begelman, & Pringle (1996), Maloney, Begelman, & Nowak (1997), Maloney & Begelman (1997), and Pringle (1997). One of the key features of the instability is that it is an inherently global mode: the disk twists itself up in such a way that the precession rate is the same at every radius. The evolution of an accretion disk subject to the instability is determined by the competition between viscosity, which acts to flatten the disk, and radiation torque, which acts to warp the disk. Because viscosity becomes relatively more important compared to the radiation torque as radius decreases, there is a minimum radius for instability: this critical radius is approximately where the viscous and warping timescales become equal. The actual value of the critical radius is not very sensitive to the scaling of disk surface density $\Sigma$ with radius: for power-law disks, with $\Sigma \propto R^{-\delta}$, the critical radius can be written (Maloney, Begelman & Nowak 1997)

$$R_{\text{cr}} = \frac{1}{2} \frac{x_{\text{cr}}^2}{\epsilon^2} R_s$$

(3)

where $R_s$ is the Schwarzschild radius, $\epsilon$ is the efficiency with which rest-mass energy is converted to radiation (of order 10% for accretion onto black holes), and $x_{\text{cr}} = 2\pi$ for $\delta = 3/2$ and $x_{\text{cr}} \approx 4.89\pi$ for $\delta = -3/2$. Thus accretion disks will be unstable to radiation-driven warping provided the disk radius exceeds a few thousand Schwarzschild radii (assuming $\epsilon \sim 0.1$). This condition is easily satisfied by the maser disks in NGC 4258 and NGC 1068, for which the inner edge of the maser emission occurs at $R \approx 3.7 \times 10^4 R_s$ and $R \approx 4 \times 10^5 R_s$, respectively.

Since, as noted above, the radiation torque becomes more important relative to viscosity as radius increases, the warp always grows from the outside inward. As the disk warps due to the instability, the illumination of the disk will become non-uniform, since the finite amplitude of the warp will cause shadowing of portions of the disk. If the accretion disk lives long enough for the warp to propagate to the center, then feedback between the warping and the irradiation can occur: since the angular momentum density of the disk increases outward, the behavior of the innermost regions of the disk is always dominated by the advection of tilted angular momentum from the outer portions of the disk. The change of the inner disk orientation in turn alters the irradiation of the outer disk, as a result of shadowing. As shown in the remarkable calculations of the nonlinear evolution of Pringle (1997), this can lead to chaotic behavior; this is not actually surprising, given that the governing equation is nonlinear with a built-in time delay (the time for twist angular momentum to propagate through the disk).

In Figure 2 I have plotted the inclination of the innermost ring of an accretion disk under the action of Pringle’s instability as a function of time; this was calculated using the code described in Pringle (1997). The inclination $\beta$ smoothly increases for a few hundred $t_0$, where $t_0$ is the viscous timescale for this inner ring, until $\beta \approx \pi$. At this point the innermost part of the disk has flipped completely over from its original orientation, i.e., the inner part of the disk has completely folded over. From this time on the behavior of the inclination is chaotic. The changes in inclination are of large amplitude, with drastic consequences for the escape of radiation from the central source. As shown in
Inclination $\beta$ of the innermost ring of an accretion disk subject to radiation torque, plotted as a function of dimensionless time $t/t_0$.

Pringle (1997), the obscuration of the central source by the warped disk leads to patterns of illumination which bear a striking resemblance to the ionization cones seen in some Seyferts, which have usually been interpreted in the context of obscuration by a geometrically thick torus.

Is the source of obscuration in AGN a radiation-warped disk, rather than a geometrically thick torus? Whether accretion disks in AGN ever reach the chaotic state exhibited by Pringle’s simulations depends on whether they are sufficiently long-lived. The timescale for the warp to propagate in to small radii (a few hundred times $t_0$ in the simulation shown in Figure 2, which is typical) will be $t \sim 10^7 - 10^8$ years in real accretion disks. It is not clear whether individual accretion disks actually live this long; fueling of AGN may be dominated by episodic accretion of material (e.g., molecular clouds), in which the disk is drained by viscous accretion on a timescale comparable to the above. However, Pringle’s instability should be generic in accretion disks around black holes, and obscuration by a thin, warped disk alleviates many of the difficulties of maintaining a geometrically thick torus. The simulations of Pringle (1997) are remarkably suggestive; additional work, both theoretical and observational, is necessary to better understand the role played by warped disks in AGN.

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