Dusty AGN Tori

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ABSTRACT

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1. AGN unification and the role to the Dusty torus

AGNs come in many types, and these types often seem like completely different objects. For Seyfert galaxies, for example, Broad & narrow lines are seen in Seyfert type 1, but only narrow ones in type 2’s. According to the AGN unification scheme, different types of AGNs are the result of orientation effect, i.e. looking at the same type of object from different angles (see figure 1). In order for this approach to succeed, an obscuring structure is needed, and hence the idea of a dusty torus. The torus absorbs UV photons from the central source and re-emits them in the infrared. It is optically thick in order to hide the core, and it also has an opening of some sort so that the broad line region can be seen directly.

1.1. relative numbers of Seyfert 1/2 galaxies and the torus

If the unification scheme is correct, then the number of Seyfert 2 nuclei should exceed that of type 1, since most lines of sight will nor offer an unobscured view to the core. The relative number of Seyfert 1/2, then, can tell us about the opening angle of such a torus (and its h/r ratio), although it has no implications on its actual size (figure 2).

In the simplest scheme, the fraction of Seyfert 2s, \( F_{II} \), is related to the opening angle as \( F_{II} = \cos \theta \). More complicated models allow for the \( \theta \) of be a function of the luminosity etc. Current evidence suggest that the ratio of height over radius for these tori is \( h/r \approx 0.6 - 1 \).

2. Indirect evidence for the existence of tori

2.1. Spectropolarimetric observations of hidden broad lines

NGC 1068 is the prototypical Seyfert two galaxy, and therefore its spectrum does not show any broad lines. Spectropolarimetric observations of its nucleus reveal a hidden Seyfert 1 nucleus through looking only at polarized light. The polarized light, which account to 16% of the flux independent of wavelength is identical with that of a Seyfert one, as shown in figure 3. This indicates that the polarization has to result from reflection (scattering) of the light from a hidden Seyfert 1 nucleus into our line of sight. The scattering cannot
2. AGN SED’s

The near-IR νFν distributions of most AGN’s show two features that are very suggestive of emission by hot dust: 3 – 5μm

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2.3. Other evidence

without going into details, other indirect evidence for tori include:

- characteristic asymmetries in [OIII] 5007 profiles indicate that dust obscures part of the narrow lines region (Vrtilek 1985)
- Extended ionization cones seen in some Seyfert galaxies (Pogge 1989)

3. Direct evidence

Direct evidence for tori comes from interferometric observations of NGC 1068 with the MIDI instrument at the VLTI.
Fig. 6. model emission from NGC 1068 by Jaffe et al. (2004)

Fig. 7. model fits to total and correlated flux of NGC 1068 (Jaffe et al. 2004)

4. Physics of dust

4.1. Formation

The theory of homogeneous nucleation deals with original material that is almost in complete thermal equilibrium at temperature $T$ and pressure $P$, but $T$ is lowered at a very slow, predetermined rate. As can be seen from Figure 8, higher pressures allow condensation of dust at higher temperatures. A typical dust grain is made out of a core and a mantle.

4.2. Grain-Grain collisions, Sputtering and UV effects

when two grains collide with relative velocity $\Delta V$, four different outcomes are possible: elastic scattering, coalescence, evaporation and shattering. Coalescence is more likely for $\Delta V < 1 \text{km/s}$, and shattering or evaporation for $\Delta V > 20 \text{km/s}$ (for refractory grains such as silicates or graphite); quantitative details depend not only on $\Delta V$ and binding energy of the solid but also on temperature and the shape of the grain.

The sputtering of a surface atom or molecule on a grain by the impact of a fast gas atom depends mainly on the ratio $M_p M_f (M_p + M_f)^{-2} E_p B_f^{-1}$, where $M_p$ and $E_p$ are the mass and kinetic energy of the gas-atom projectile, $M_f$ and $B_f$ are the mass and binding energy of a surface atom of the grain. For a silicate (or graphite) grain, velocities of order 200 km/s relative to the gas are required for efficient sputtering.

3.1. Results from MIDI observations

1. model fits clearly indicate a compact torus, as opposed to the size of the torus is a few hundred parsecs.
2. model points to an unusual type of dust
3. Warped structure is excluded, rather a ‘fat doughnut’ seems to be the case.

(Jaffe et al. 2004) with two baselines. The simplest model that accounts well for the spectra of both the total and the interferometric flux in our measurements requires only two gaussian components of different temperature, size and foreground dust absorption. The first is a hot ($T=800 \text{K}$) compact component. Its length along the source axis is resolved, and well constrained to 0.7 pc. The interferometric measurement sets only an upper limit (1 pc) to its orthogonal width. The second is a warm, well resolved component with best-fit temperature of 320 K. Its size is well constrained by the observations with two baselines. See figure 6. Fig. 6 shows the total a correlated fluxed of NGC 1068, and the model fits.
The most obvious destructive effect of radiation on a grain is heating and evaporation. Calculations of grain temperatures depend on the optical properties of the solid, but thermal evaporation is likely to be unimportant even in HII regions except close to the exiting star. For a foreign atom or molecule absorbed on grain surface the efficiency of photodestruction by UV photons of energy \( \sim 10eV \) is quite high, but the same photons do very little damage to atoms in a good crystal. A fully grown grain can survive the radiation field even in an HII region, whereas the build-up of molecules to form a grain mantle is prevented even by the milder radiation field in typical HI regions.

4.3. Optical properties of grains

The spectral luminosity of an individual grain in the infrared is given by:

\[
L_{\text{gr,IR}}^g = 4\pi a^2 \pi Q \rho_\text{IR} \left( T_{\text{gr}} \right) \text{ergs/s Hz}^{-1}
\]

where \( a \) is the size of the grain and \( Q \), the absorption efficiency. When exposed to a UV radiation field of energy density \( \mu_e \), a grain will come into equilibrium when the rate at which energy is absorbed equals the rate at which it is radiated,

\[
\pi a^2 \int u_e c Q_{UV} dv = \int L_{\text{gr,IR}}^g dv
\]

where \( Q_{UV} \) is the UV absorption efficiency of the grain. For most purposes it is sufficient to approximate \( Q_{UV} \) as constant with frequency and equal to one (i.e. the absorption cross-section equals the geometrical cross-section). With a power-law absorption efficiency in the IR, we an solve for the grain temperature:

\[
T_{\text{gr}} = 1650 \left( \frac{L_{\text{UV,46}}}{T_{\text{pc}}} \right)^{1/5.6} \exp - \tau_{UV}/5.6K
\]

where \( \tau_{UV} \) is the dust optical depth to UV radiation. Interior to some radius, \( r_1 \), grains exposed to the UV are destroyed by evaporation, and this evaporation radius is given by:

\[
r_1 = 1.3L_{\text{UV,46}}^{1/2} T_{\text{1500pc}}^{-2.8}
\]

4.3.1. 9.7 micron silicate feature

For wavelength in the mid-IR there is a striking feature in the interstellar extinction curve (see Fig. 10) at \( \sim 9.7\mu m \). This feature is a resonance arising from the stretching modes of silicate tetrahedra. The detection of this feature clearly indicates the presence of silicate dust. It turns out, however, that there is a problem with associating it with a dusty torus. To understand why, first we have to remind ourselves of some basic features of emission/absorption:

- An absorption feature is seen when viewing an optically thick object which has temperature increasing away from the observer.
5. Physics of dusty tori in AGNs

In order to have a hydrostatically supported geometrically thick torus around a supermassive black holes, random velocities \( \geq 100 \text{ km s}^{-1} \) are needed. If these motions where thermal, the corresponding temperature (~ \( 10^5 \text{K} \)) would be far too hot for dust to survive. With respect to gas temperatures low enough to permit dust, such motions are highly supersonic and can persist only if the rate of collisions between streams having different velocities is sufficiently low - hence the suggestion that the cool dust is organized into clouds.

5.1. Origin and velocity dispersion of clouds

The dusty clouds are produced by the stars at the core of the galaxy, and therefore take over their velocity dispersion. The relationship between the core radius and the central velocity dispersion of the stars is given by:

\[
\sigma_* \approx 200 \left( \frac{R_*}{75 \text{ pc}} \right)^{0.18} \text{ km s}^{-1}
\]

And so, as described in section 4.2, these velocities will cause rapid sputtering upon collision.

5.2. Environment of the clouds

The pressure in the hole of the torus is quite high by interstellar standarts: \( p \approx 10^{10} L_{\text{IS}} r_{\text{pc}}^2 K \text{ cm}^{-3} \) where \( p \) is the gas pressure divided by Boltzmann’s constant and \( L_{\text{IS}} \) the central luminosity in units of \( 10^{44} \text{ ergs/sec} \). Since the covering fraction, \( C \), of the clouds is close to unity, we expect this pressure effectively communicated into the torus.

5.3. Cloud lifetime

We can place an upper limit on the lifetime of a single cloud by comparing the gravitational collapse time in the absence of pressure, \( t_{\text{grav}} \), and the mean time between collision, \( t_{\text{col}} \), with the orbiting period of a cloud given the estimated pressure and temperature

\[
\frac{t_{\text{grav}}}{t_{\text{col}}} \approx 0.7 \left( \frac{v_{\text{orb}}}{200 \text{ km/s}} \right)
\]

On the other hand, the mean time between collisions is \( t_{\text{coll}} \approx (8Ch/r)^{-1} P_{\text{orb}} \sim P_{\text{col}} \) and so clouds will not survive more than a single orbit period without changing their structure.

5.4. Fixing the position of the inner edge of the torus

The radius of the innermost edge of the torus is determined by the balance between inward mass flow, \( M_{\text{in}} \) and ablation \( M_{\text{abl}} \). Exposed clouds are ablated rapidly and their material is either driven off in a wind or accreted by the black hole. If the rate of mass which is ablated to exceed \( m_{\text{in}} \), the position of the inner edge would recede. If \( M_{\text{abl}} < M_{\text{in}} \), the inner edge would move closer to the center. a necessary condition for steady state is \( M_{\text{abl}} = M_{\text{in}} \).

5.5. Spectroscopic constrains

Spectroscopic constrains on the size and shape of the grains leads to the following conclusions (Laor & Draine 1993):

1. Warm graphite+silicate dust (\( T > 200 \text{K} \)) with the MRN size distributions produce a prominent emission feature and therefore cannot be responsible for observed IR emission from AGNs
2. Increasing the size of the grains can better protect them from depletion by the incident radiation and also suppress the silicate feature in emission.
3. Dust cannot reside in the BLR could if their distance from the continuum source is smaller than \( 0.2L^{1/2} \text{pc} \). The innermost radius at which dust can survive is probably just outside the BLR
4. Dust can reside in the NLR clouds and will have a strong effect on the narrow line flux if the ionization parameter \( U \geq 0.01 \).
5. if the IR emission originates in clouds which are optically thick at \( 10 \mu \text{m} \) then \( U \geq 0.1 \) at the cloud surface.

6. Tori models

A successful AGN model should fulfill following three minimum requirements:

1. The predicted spectrum should be quite broad, at least for face-on views, and should peak in the mid-IR.
2. the model should predict absorption features at 10 micron for edge-one views, but featureless spectra on face-on views.
3. The above requirements must be satisfied for a range of torus models (i.e. no fine tuning)
4. In the case of thick tori, some explanation for its thickness is needed.

6.1. Ingredients of a model
To make a tori model, some basic ingredients are needed:

1. Input: Model inputs include the geometry of the torus, types of dust, grain sizes and distribution, luminosity and gravitational potential of the core.
2. Method: The method is the radiative transfer code and the physical assumptions it needs.
3. Output: model output is usually spectra and temperature distribution. These can then be fitted to known data. In the case of interferometric observations, additional output of the expected correlated flux from different angles can be used to fit the data (see section 3).

6.2. Detailed example: The model of Pier & Krolik, 1992
Model input: The geometry of the torus is that of a uniform density annular ring dust with inner radius $a$, outer radius $b$ and height $h$ \cite{1992ApJ...392..175P}. The dust extinction curve is that of Fig. 10. The central luminosity is assumed to be a power-law spectrum $L \propto \lambda^{-\beta}$ with $\beta > 0$. The four model parameters are: the inner aspect ratio $a/h$, the radial and vertical Thomson depths of the torus, $\tau_r$ and $\tau_z$, and the flux of illuminating radiation on the inner wall of the torus, expressed as an effective temperature $T_{\text{eff}} = (L/4\pi a^2 \sigma)^{1/4}$ where $\sigma$ is the Stephan Boltzmann constant.

Computational method: A 2 dimensional radiative transfer code using the lambda iteration method. The model neglects scattering effects.

Output: Temperature distribution as a function of $\tau_r$ and $\tau_z$, spectrum as a function of $\tau_r, \tau_z$ and the viewing angle $i$.

Results:
- As expected, a temperature profile of 200-1200 K is found, and it is steeper for tori with more obscurations. See Fig 12.
- Silicate emission feature can be suppressed for high optical depth of the clouds (Figs. 13,14).

Here is a brief summary of work that has been done on modeling tori:
- Pier & Krolik (1992): Most aspect of AGN SEDs can be produced by a cylindrical shape torus, small in size and thick (see Fig. 15).
- Efstathiou & Rowan-Robinson (1995) analyze three different geometrical configurations for the torus (a flared and a tapered disc and an anisotropic sphere) and found that a tapered disc (i.e. a disc whose height increases along with distance from the centre but flattens at a constant height in the outer parts) with an opening angle of 45 degrees was the most successful representation of what was observed. See Figures 16,17.
- Granato & Danese (1994): models of thick tori extending up to a few hundred parsecs in which physical processes such as shocks depletes the silicate grain abundance within the few tens of parsecs are fully consistent with data.
- Sanders et al. (1989) interpret the radiation between 5$\mu$m to 1 mm as re-radiation from dust in a warped disk extending from a few parsecs to a few kilo parsecs from the central source (see Fig. 18).
- Nenkova et al. (2002): clumpy model solves all the problems.
- Dullemond & van Bemmel (2005) find that the 10 $\mu$m emission feature of the clumpy models, when seen almost face-on, is not appreciably reduced compared to the equivalent smooth models. Some of the clumpy models have a
weak or even absent 10 $\mu$m feature, but so do some of the smooth models. On the whole the SEDs of clumpy and smooth tori are similar, but some details are different. The absorption feature seen at edge-on inclinations appears to be less deep in the clumpy models than in the smooth models, and the average flux in the near-infrared regime is stronger in the clumpy models. Moreover, at these inclinations the clumpy models have a slightly wider SED.

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**Turbulent torus model:** The dust density distribution and the geometrical shape of the torus model result from a hydrostatic equilibrium in which gravitational and centrifugal forces of the nuclear stellar distribution and the central black hole are balanced by pressure forces due to the turbulent motion of the clouds. Spectral energy distributions (SEDs) and surface brightness distributions are obtained by a fully three-dimensional treatment of the radiative transfer problem. They conclude that the stratification of dust grains, in terms of size and distribution, cannot be neglected.

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7. Proposed solutions to common problems

7.1. Solutions for the thickness problem

- Radiation pressure within the torus may be enough to support it (Pier & Krolik 1992).
- The torus is a slowly rotating free falling 'envelope' that circularizes at the centrifugal radius where it feeds the accretion disk. (Dopita et al. 1998).
- Nuclear starburst (Wada & Norman 2002).
- **Heating by stars:** Mechanical heating by local stellar winds and SN might naturally be thought to contribute to the cloud’s random motions. However, this form of heating is unable to maintain the large velocity dispersion. Heating by stellar radiation will not produce velocities greater than...
10 km/s and are therefore inadequate to account for the bulk of the stirring.

- **Viscous heating:** The same collisions which dissipate the energy of the clouds also produce viscous heating if there is any shear stress. When cooling exceeds heating the cloud will collapse into a thin disk. When heating exceeds cooling, the cloud thickens until limited by energy conservation to $\Delta v \lesssim v_{\text{orb}}$

- Warped disks ([Sanders et al. 1989](#))

### 7.2. Solution to silicate emission problem

- Clumpy material ([Nenkova et al. 2002](#))
- Large grains ([Laor & Draine 1993](#))

**References**