Infrared emission from the dusty veil around active galactic nuclei

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Dusty tori in the unified model of AGN

The unified model of AGN explains the difference between type 1 and type 2 AGN with aspect-angle-dependent obscuration by a dusty torus or thick disk:

- The model emerged from the interpretation of weak polarized broad emission lines hidden by strong narrow lines observed in the Seyfert 2 nucleus of NGC 1068 (Miller & Antonucci 1983).
- The observed ratio of type 1s to 2s, varies between 1:4 (Maiolino & Rieke 1995) and 1:1 (Lacy et al. 2004) depending on wavelength and luminosity range.
- In the simplest unification scheme all Seyfert 2 nuclei harbor a Seyfert 1 core.
- The ratio of type 1s to 2s measures the thickness of the obscuring torus $\Rightarrow H/R \sim 1$.
- Krolik & Begelman (1988) argued that these tori consist of a large number of dusty clouds.
- The relevance of clumpiness for the appearance of these tori in radiative transfer calculations was noticed by Nenkova et al. (2002).

We follow the programm of Nenkova et al., which developed a statistical scheme to account for clumpiness in radiative transfer calculations of the infrared emission from optically thick clouds. This approach resolves problems with the width of the spectral energy distribution (SED) and the weakness of the silicate feature at $10\mu m$ which appeared in earlier calculations.

Cloud distribution and cloud properties in the torus

The equilibrium model of cold, molecular and dusty clouds is different from the multi-phase medium in the ISM of a galaxy (Vollmer et al. 2004). The clouds in the torus are quasi-stable and experience frequent cloud-cloud collisions. The mass and size of the largest clouds in the torus is limited by tidal forces in the gravitational potential of the galactic nucleus and the internal pressure support against their own gravity. Their size and mass is derived from the Jeans and the shear limit. The important parameter of the torus in radiative transfer calculations is the vertical optical depth for intercepting a cloud

$$\tau = \int \frac{\mathrm{d}z}{l_{\mathrm{coll}}}, \qquad (1)$$

where l_{coll} is the mean free path of clouds in the torus. We use a modified isothermal distribution of cloud velocities in an external potential (Beckert & Duschl 2004), which includes a cut-off scale height x_H at which the density drops to zero. This leaves room for a wide polar outflow cavity. An example for the case of NGC 1068 is shown in Fig. 1. The radial structure is derived from a stationary accretion scenario.

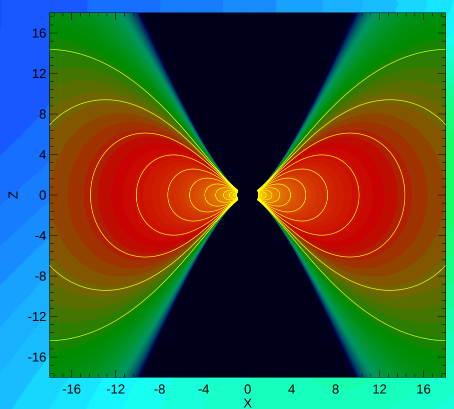

Figure 1: Meridional cut through the probability density distribution of finding a dusty cloud in the torus (red: high probability). The distribution leaves room for an outflow along the polar axis. The spatial scale is in units of the dust sublimation radius. The mean number of clouds along a line of sight to the center drops below unity for angles larger that $40°$ from the midplane ($Z = 0$).

The optical depth τ defined in Eq. (1) has to be $\tau \sim 1$ for obscuration of the AGN for line of sights through the torus. Because τ is also a dimensionless collision frequency $\tau \sim \omega_c/\Omega$, this implies that cloud-cloud collisions are frequent. A sufficient approximation for the effective viscosity was derived by Goldreich & Tremaine (1978)

$$\nu = \frac{\tau}{1+\tau^2} \frac{\sigma^2}{\Omega} \qquad (2)$$

for angular momentum redistribution. Like in ordinary accretion disks, the effective viscosity allows mass to be accreted towards the black hole. The inner boundary will be at the sublimation radius for dust ($R \sim 1$ pc) which depends on the AGN luminosity and dust chemistry.

The torus in NGC 1068

For a comparison of SED and surface brightness distribution or morphology of a particular AGN the mass distribution has to be known or modeled. For the case of NGC 1068 we collected the available data in Beckert & Duschl (2004). We note that:

- The rotation of the ring of H_2O-maser spots (Greenhill & Gwinn 1997) tends to underestimate the enclosed mass and this is likely to be the reason why the derived rotation does not follow a Kepler law for a central black hole.
- Only in a very thin disk like in NGC 4258 the projected radial velocities follow a Keplerian profile.
- The thickness of the the disk of free-free emission (component S1 of the radio jet) in NGC 1068 (Gallimore et al. 2004) and the intermediate orientation of the maser disk imply a large velocity dispersion of maser spots.
- Their projected radial velocities span a wide range of sub-Keplerian velocities.
- We suggest that the mass of the central black hole is larger than $10^7 M_\odot$.

Results of radiative transfer calculations

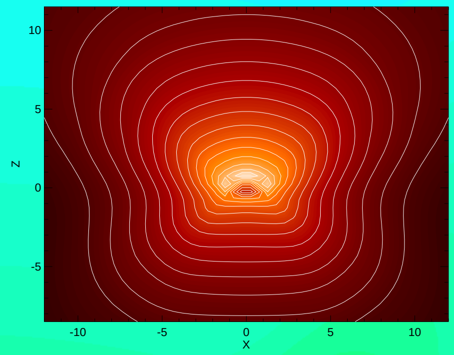

Figure 2: K-band brightness distribution of our radiative transfer calculations based on the method of Nenkova et al. (2002) and the scenario of Beckert & Duschl (2004) for an inclination of $55°$. The spatial scale is in units of the dust sublimation radius. The contour scale of the surface brightness is logarithmic with a dynamic range of 2^{14}.

We have used the model for individual clouds in a torus, and the cloud density distribution shown in Fig. 1 to derive a surface brightness distribution (Fig. 2) and SED (Fig. 3) for the dusty torus in NGC 1068. We find a size of 0.9 pc for the dust sublimation radius consistent with the size of the observed core component in K'-band speckle images (Weigelt et al. 2004; and poster here). The parameters of the model are

- inclination $i = 55°$,
- coefficient of restitution $\epsilon = 0.4$,
- required mass accretion rate through the torus: $6\,M_\odot\,\mathrm{yr}^{-1}$ and
- AGN luminosity: $L = 2.8 \pm 0.3\, 10^{45}$ erg s^{-1}.

The AGN luminosity is about twice the Eddington luminosity of a $10^7 M_\odot$ black hole.

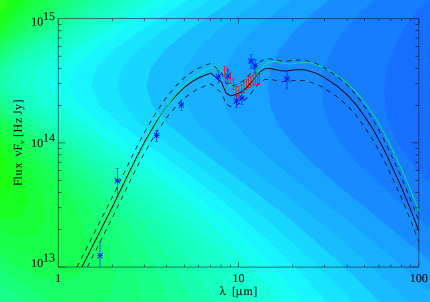

Figure 3: Spectrum of a clumpy torus model with normal interstellar dust composition adapted for NGC 1068. The black solid line shows the mean luminosity and the dash-dotted lines indicate the range of uncertainty. The silicate absorption feature as measured with MIDI (red data) (Jaffe et al. 2004) is not well fitted. An unacceptable modification, which does fit the data (green line), is achieved by an artificial redshift of $\Delta\lambda/\lambda = 0.1$.

Implications

- The overall shape of the model SED and the size of the sublimation radius agrees with observations.
- The shape of the silicate absorption feature measured by mid-infrared interferometry (Jaffe et al. 2004) is inconsistent with a normal interstellar dust mixture.
- Grain size distribution and/or dust composition is likely to be different close to the AGN in NGC 1068.
- The clumpiness of the torus can explain both the results of K'-band speckle images (see poster by Weigelt et al.) and the K-band long-baseline visibility ($b = 46$ m) of Wittkowski et al. (2004).
- The interferometry result can either set an upper limit to the size of individual clouds $R_{\mathrm{Cl}} < 0.4$ pc and super-resolves the separation between clouds, or it indicates a low-extinction view of the central accretion flow, which has a non-negligible probability for a clumpy torus.

The large mass accretion rate implies that only a small fraction of the mass accreted through the torus eventually reaches the black hole.

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