Monte Carlo radiative transfer modelling of clumpy tori around AGN

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Unification Scheme for AGN

The standard unification scheme for Active Galactic Nuclei (AGN) explains the differences between type 1 and type 2 AGN as angular-dependent obscuration by an optically and geometrically thick dust torus close to the central source:

- Scheme introduced by Miller & Antonucci (1983)
- Basic version: type 1 nucleus within all type 2 sources.
- Type 2 AGN show smooth silicate dust absorption around 10 μm (Jaffe et al. 2004), while from recent Spitzer spectra type 1 QSOs have been detected with the silicate feature in emission (Siebenmorgen et al. 2005; Hao et al. 2005).
- The observed ratio of type 1 AGN to type 2 varies between 1:4 (Maiolino & Rieke 1995) and 1:1 (Lacy et al. 2004), depending on wavelength range and luminosity ($\rightarrow H/r \sim 1$).
- Krolik & Begelman (1988) argue that the dust within the torus can survive only in clouds ($v \sim 100\,km\,s^{-1} \leftrightarrow T \sim 10^6\,K$).
- A physical accretion model for self-gravitating, optically thick dust clouds in the torus was introduced by Beckert & Duschl (2004) (see below).

Our goal is to find a method for 3-dimensional radiative transfer modelling of a clumpy torus. For that we developed a two step process: First we simulate individual dust clouds, and include them into the torus afterwards. With this method we want to model AGN Spectral Energy Distributions (SEDs) of type 1 and type 2 AGN and test current torus models.

Monte Carlo Simulation of Dust Clouds

For simulation of AGN dust clouds we utilize an already existing Monte Carlo radiative transfer code developed by Ohnaka et al. (2005). The code is based on the theory of Bjorkman & Wood (2001):

- spherically symmetric clouds irradiated by a central AGN
- central source emits photon packages according to a typical AGN spectrum
- absorption and scattering treated statistically $\rightarrow$ Mie theory

In the panels of Figure 1 we show spectra of four clouds with different optical depths. For all clouds we used the same central source with a luminosity of $10^{12}\ L_\odot$. Three of them were placed around the dust sublimation radius $r_{\rm subl}/{\rm pc} \approx L_{12}^{1/2}$, where L_{12} is the AGN luminosity in units of $10^{12}\ L_\odot$ and the dust sublimation temperature is in the order of 800–1 000 K. The fourth cloud was calculated at around $40 \times r_{\rm subl}$. These spectra were calculated using standard ISM dust with 53% silicates and 47% graphite and a grain size of 0.1 μm.

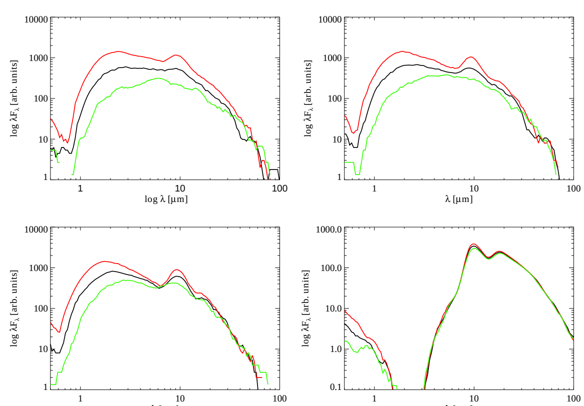

Figure 1: Spectra of spherical dust clouds calculated with our Monte Carlo code. From upper left to lower right the panels represent clouds with optical depths of $\tau_c = 400$, $\tau_c = 270$, $\tau_c = 70$ and $\tau_c = 10$, respectively. The first three clouds are placed around the sublimation radius $r_{\rm subl}$, while the lower left spectrum comes from a cloud at $40 \times r_{\rm subl}$ with $\tau_c = 10$ as a comparison. For each cloud its appearance at viewing angles of 20° (green), 70° (black) and 120° (red) is plotted.

Some results from the cloud simulations:

- cloud have cold back side with temperatures around 200–400 K, depending on τ_c and r
- hot front side of the clouds has relatively smooth, τ_c-dependent silicate feature in emission $\rightarrow$ large temperature gradient within the clouds with large τ_c
- cooler back side reveals no feature or slight absorption

The most striking result is that the strength of the emission feature is moderate. This is an important improvement since most of the smooth or disk-like, non-clumpy torus models end up with very strong emission or absorption, depending on aspect angle of the torus (e.g. Schartmann et al. 2005). Such strong silicate features, however, have never been observed.

$\Rightarrow$ cloud SED profiles surpress strong silicate feature and thus support idea of clumpiness

Reconstruction of the Torus

For the torus reconstruction we calculate the cloud spectra first and combine them to a torus afterwards. Compared to a one-step approach where Monte Carlo simulations are performed using the complete torus at once, this method has a lot of advantages, such as

- short calculation times of torus with several 10^4 clouds
- resolution of temperature gradients within clouds, also with high τ_c
- using a database with pre-calculated clouds

On the other hand, one has to be careful about geometric circumstances within the torus:

- directly illuminated by the AGN (First Order Clouds; FOCs)
- other clouds obscure AGN $\rightarrow$ Second Order Clouds (SOCs)
- SOCs have only minor contribution to torus spectrum in NIR and MIR (Nenkova et al. 2005)

Although we currently use only FOCs, we are working on calculating SOC spectra, either by directly simulating them with our Monte Carlo code and a FOC spectrum as central source, or via the averaging process introduced by Nenkova et al. (2005).

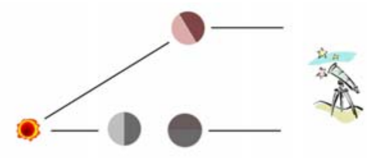

Figure 2: Explanation of First (FOC) and Second Order Cloud (SOC). A FOC (bright grey cloud) is directly enlighted by the AGN. The SOC (dark grey cloud) behind this FOC doesn't see the AGN directly. It may, however, be slightly enlighted by the hot side of surrounding FOCs (red cloud). Definition of the viewing angle: ϕ equals 180° minus angle from AGN to observer as seen from the cloud.

For reconstruction we currently use two different torus models

- *Free Model*: represents a set of free parameters. From observations one gets the Black Hole mass $M_{\rm BH}$ and AGN bolometric luminosity $L_{\rm bol}$. Powerlaws are fitted to the scale height $H(r)$, cloud size $R_c(r)$ and optical depth $\tau_c(r)$. N clouds are distributed via a distribution function $\eta \propto r^{-a}$.
- *Beckert-Duschl Model*: represents the accretion scenario of Beckert & Duschl (2004). Free parameters are basically determined by $M_{\rm BH}$, $L_{\rm bol}$, the Mass Accretion Rate through the torus $\dot{M}$ and the influence of a typical (isothermal) circumnuclear stellar cluster $M_{\rm SC}(r)$.

After distributing the clouds, a Line of View (LOV) is defined by introducing the inclination angle of the torus. Every cloud is checked for its viewing angle ϕ, and if it is a FOC or not. Then all FOC are associated with a model SED from the database, matching r, τ and ϕ. If another cloud cl$_k$ is located within the LOV from FOC cl$_i$ to the observer, the FOC spectrum of cl$_i$ is weakened by a factor $e^{\tau_{cl;k}(\lambda)}$. The resulting cloud spectrum is added to the torus spectrum. Once all FOCs are treated that way, the torus spectrum is complete.

First Results

In Figure 3 we present our model calculations for a typical free torus model at different inclination angles. One can see the moderate change from absorption to emission from low to high inclinations i, where $i = 0$ represents edge-on view. We used parameters $M_{\rm BH} = 10^7 M_\odot$ and $L_{12} = 1$.

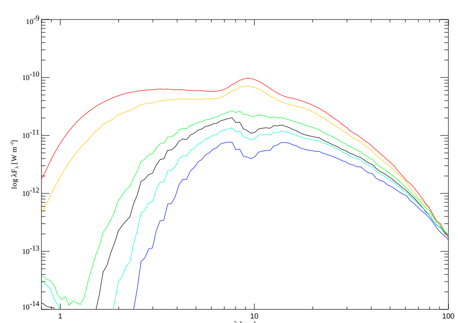

Figure 3: Torus spectra for different inclination angles.

Definitely, the smooth silicate feature is an improvement to current models. The next step is to fit our model SEDs to actually observed AGN.

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