RADIATIVE TRANSFER MODELING OF AGN DUSTY TORUS AS CLUMPY TWO-PHASE MEDIUM

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Problems:

- Survival of dust grains
- Dynamical stability

The torus consists of a large number of optically thick clumps orbiting around the central engine (Krolik & Begelman 1988).

Hydrodynamical simulations → ISM around AGN is a multiphase filamentary structure (Wada & Norman 2002; Wada 2009, 2012)
DUSTY TORUS EMISSION

Dust in the torus absorbs the incoming accretion disc radiation and re-emit it in the infrared

Mid- to far-IR bump

~ 10 μm silicate feature (Si – O ‘stretching’ mode) –
  - Window into dust distribution and chemical composition

In emission in type 1 AGN

In absorption in type 2 AGN

Siebenmorgen+ 2005
Lutz+ 2000
SOME OUTSTANDING ISSUES

- Intensity and position of the 10 μm silicate feature. Different chemical composition, emissivity properties, geometrical effects (Nikutta+ 2009)?
  - Clumpiness suppresses intensity (Nenkova+ 2008)

- NIR excess when fitting observed SEDs (Polletta+ 2008; Mor+ 2009; Ramos Almeida+ 2009; Alonso-Herrero+ 2011; Mor & Netzer, 2012; Deo+ 2011)
RADIIATIVE TRANSFER CODE SKIRT

(Baes et al, 2003, 2011)

- 3D Monte Carlo radiative transfer code
- Developed to investigate the effects of dust extinction on the photometry and kinematics of galaxies (Baes+ 2003)
- Over the years, the code evolved into a flexible tool that can model a variety of dusty systems, e.g:
  - Variety of galaxy types (Baes+ 2010; de Looze et al. 2010)
  - Post-AGB circumstellar discs (Vidal & Baes 2007)
  - AGN dusty torus (Stalevski+ 2012)
\[
\frac{dI_\lambda}{ds}(\mathbf{r}, \mathbf{k}) = j^*_\lambda(\mathbf{r}) - \sum_{j=1}^{N_{\text{pop}}} \int_{a_{\text{min},j}}^{a_{\text{max},j}} \frac{dn_j}{da}(\mathbf{r}, a) C_{\lambda,j}^{\text{ext}}(a) I_\lambda(\mathbf{r}, \mathbf{k}) \, da \\
+ \sum_{j=1}^{N_{\text{pop}}} \int_{a_{\text{min},j}}^{a_{\text{max},j}} \frac{dn_j}{da}(\mathbf{r}, a) C_{\lambda,j}^{\text{Sc}}(a) \left[ \int I_\lambda(\mathbf{r}, k') \Phi_{\lambda,j}(k, k', a) \frac{d\Omega'}{4\pi} \right] \, da \\
+ \sum_{j=1}^{N_{\text{pop}}} \int_{a_{\text{min},j}}^{a_{\text{max},j}} \frac{dn_j}{da}(\mathbf{r}, a) C_{\lambda,j}^{\text{abs}}(a) B_\lambda \left( T_{d,j}(\mathbf{r}, a) \right) \, da
\]

\[
\int_0^\infty C_{\lambda,j}^{\text{abs}}(a) B_\lambda \left( T_{d,j}(\mathbf{r}, a) \right) d\lambda = \int_0^\infty C_{\lambda,j}^{\text{abs}}(a) J_\lambda(\mathbf{r}) \, d\lambda
\]
Monte Carlo radiative transfer

A large number of photon packages are followed individually through the dusty medium.

The trajectory of each photon package is determined by (pseudo) random numbers.

Clever tricks to make MCRT simulations efficient
- continuous absorption
- immediate re-emission
- frequency distribution adjustment
- peeling-off technique
Approx: central point-like energy source with isotropic emission

\[
\lambda L(\lambda) \propto \begin{cases} 
\lambda^{1.2} & 0.001 < \lambda < 0.01 \\
\lambda^0 & 0.01 < \lambda < 0.1 \\
\lambda^{-0.5} & 0.1 < \lambda < 5 \\
\lambda^{-3} & 5 < \lambda < 1000
\end{cases} [\mu m]
\]

\[L = 10^{11} L_0\]
TORUS MODEL

- Dust mixture: silicate and graphite dust grains
- Dust grain size - MRN distribution:
  \[ dn(a) = C a^{-3.5} da \]
  \( a: 0.005 - 0.25 \, \mu m \)
- 3D Cartesian grid of cubic cells

\[ R_{\text{min}} \approx 1.3 \cdot \sqrt{L_{46}^{AGN} \cdot T_{1500}^{-2.8}} \, [pc], \]
CLUMPY TWO-PHASE MEDIUM:
High-density clumps + low-density dust between the clumps

Smooth dust distribution:
\[ \rho(r, \theta) = r^{-p} e^{-\gamma |\cos(\theta)|} \]

Filling factor & contrast

Two-phase medium

Very high contrast

Clumps-only

Dust density map (meridional plane)
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Two-phase medium

+ 

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Clumps-only

Dust density maps (meridional plane)

For different filling factors:

- \( ff = 0.15 \)
- \( ff = 0.25 \)
- \( ff = 0.35 \)
- \( ff = 0.45 \)

Contrast = 100
TORUS IMAGES

4.6 μm

9.7 μm

13.9 μm

30.7 μm
Degeneracy due to random arrangement of the clumps

Temperature map (meridional plane)
Silicate feature and NIR excess

- 10 μm silicate feature attenuated in the clumpy models. BUT smooth models are able to reproduce almost the same range of the silicate feature strength.

- Two-phase models: more pronounced NIR emission + attenuated silicate feature: a natural solution to the NIR excess problem?

- Roseboom+ 2012: observed \( \frac{L_{\text{NIR}}}{L_{\text{TOTIR}}} \) ratio easily achievable in two-phase models.

SKIRT4
(Stalevski et al. 2012, MNRAS)
https://sites.google.com/site/skirtorus/
ON-GOING WORK: SKIRT5

Adaptive octtree grid (Saftly et al. 2012)
ON-GOING WORK: SKIRT5

Map of optical depth
NEAR FUTURE WORK: SKIRT6

RT of multiphase, filamentary medium

Wada 2009
Observed polarization properties can constrain geometry of different scattering regions in AGN:

- Dusty torus
- Equatorial scattering region
- Polar outflows

Polarization studies of AGN and circumstellar discs based on Monte Carlo radiative transfer studies have been done before (e.g. Goosmann & Gaskell 2007, Marin+ 2012)

But not based on physically motivated clumpy 3D geometries...
FUTURE WORK: Polarization in SKIRT

Including polarization into a Monte Carlo radiative transfer code is relatively straightforward

• use all Stokes parameters \( S = (I,Q,U,V) \) instead of just the intensity

• it is usually assumed that radiation is unpolarized when emitted

• scattering by dust grains polarizes the radiation: use full Mueller matrix instead of scattering phase function

https://sites.google.com/site/skirtorus/
- Download model SEDs
- Images of torus (FITS) available upon request

SKIRT: http://users.ugent.be/~mbaes/SKIRT.html

9th Serbian Conference on Spectral Line Shapes in Astrophysics
Banja Koviljaca, Serbia, May 13-17, 2013
http://www.scslsa.matf.bg.ac.rs/