On donuts and crumbs

– a brief history of torus models –

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Overview

• Why do we need torus models?
  ‣ passively and actively contributing dust
  ‣ observational and physical constraints

• What is available on the market?
  ‣ smooth vs. clumpy
  ‣ radiative transfer vs. hydrodynamics
  ‣ differences in these models

• What challenges do current models face?
  ‣ Caveats and challenges
Why do we need torus models?
Unification and dust extinction

- type 2 AGN host type 1s nuclei *(Antonucci & Miller '85)*
- obscuration depends on **viewing angle** (e.g. Kinney et al. '00)
- **Fe Kα line equivalent widths** (e.g. Krolik & Kallman '87; Koyama et al '89)
- ...

Antonucci & Miller 1985
The infrared bump

- type 1s and type 2s show **IR bump** (e.g. Neugebauer et al. ’79,...)

- spectral **turn at 1\(\mu\)m** (~dust sublimation, ~pc scales) (e.g. Edelson & Malkan ’86; Barvainis ’87)

- IR power **correlates well with AGN power** (e.g. Keel et al. ’94, ..., Gandhi et al. ’09, Levenson et al. ’09, ..., Daniel’s talk)
1+1=...

• Direct and indirect evidence establish...
  ...the presence of **angle-dependent obscuring dust**
  on parsec scales

• Who called it the “**torus**”?
  ‣ Antonucci & Miller ’85: “very thick absorbing disk”
  ‣ Krolik & Begelman ’86: “obscuring torus”
    (referring to A&M ’85)
What models are on the market?
Obs. & phys. constraints

• basic framework: 
  dusty, obscuring ($\tau_v > 1$), geometrically-thick

• Further constraints:
  ‣ (sub-)parsec-scaled (dust radiative equilibrium)
  ‣ inhomogeneous (“clumpy”):
    → observational: e.g. velocity dispersion, CO emissivity, X-ray column variability, ...
    → theoretical: e.g. SG instability, shear, radiation pressure, ...

Krolik & Begelman 1986, 1988; Barvainis 1987; Pier & Krolik 1992a; Tacconi et al. 1994; Risaliti et al. 2002; ...
Radiative transfer models

- **Purpose:** provide **simulated SEDs (and images)** to be used to model data
- **Geometric model** inspired by observations and physics
- static

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Typical setups

vertical distribution
(opening angle, $\tau_v$(vert.), $\tau_{cl} \times N_{cl}$(vert.), flaring)

optical depth
(dust mass; $\tau_v$(eq.); $\tau_{cl} \times N_{cl}$(eq.); vol. filling factor; $R_{cl}$)

radial dust distribution

$R_{out}$ $R_{in}$ (or L) $R_{in}$ (or L) $R_{out}$
Fundamental strategy

• What goes in, comes out again (but reprocessed)
• radiative equilibrium calculations

\[
L_{\text{in}} = \int Q_{\text{abs};\nu} \times F_{\nu} \times A_{\text{dust}} \ \text{d}\nu
\]

incoming power = absorption efficiency \times incoming flux \times cross section

\[
L_{\text{out}} = \int Q_{\text{abs};\nu} \times \pi B_{\nu}(T) \times A_{\text{em}} \ \text{d}\nu
\]

outgoing power = absorption efficiency \times thermal emission \times emitting surface

• details depend on model setup and RT prescription
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- Smooth models: dust smoothly distributed
- Clumpy models: dust arranged in clouds
- Special purpose models:
  - Time-dependent models
  - X-ray scattering models
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Parameter space

- smooth models
  (Pier & Krolik, Loska+, Rowan-Robinson+, Granato & Danese, Schartmann+, Fritz+)

- CLUMPY
  (Nenkova+)

- CAT3D
  (Hoenig+)

- H&S

- Stalevski+

- RR95

- RADMC
  (D&vB)
## Model particulars

| Authors          | Details                                                                 |
|------------------|-------------------------------------------------------------------------|
| Nenkova+02,08a,08b | • analytic clumpy model (probabilistic)  
                   • low and high $\tau_v$ for low vol.fill.                     |
| Schartmann+05,08 | • considers RT for different grains  
                   • SEDs & images, smooth & clumpy                                 |
| Hoenig+06,10,11  | • clumpy model, MC and raytracing  
                   • SED & images (plus time resolved)                               |
| Kawaguchi & Mori 10,11 | • clumpy prescription for analytic RT  
                          • inner-rim model (SED + time-resolved)                    |
| Stalevski+12     | • 2-phase medium using MC  
                   • SED and images                                                    |
| Keating+12       | • smooth MC model  
                   • input from MHD wind model                                        |
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Hydrodynamic models

- **Purpose**: evolution of the *distribution of gas (and dust)* on parsec scales
- **Physical framework** suitable for the specific goal
- dynamic

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- Hydrodynamic models
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Wada 2012
What challenges do current models face?
Modeling caveats

• When modeling observations we observe the models
• **Parameter degeneracies** within models (e.g. Hoenig & Kishimoto10; Ramos-Almeida+11; Alonso-Herrero+11)
  → in particular parameters influencing **obscuration**
• Degeneracies and contradictions between **different models** (e.g. Schartmann+08; Feltre+12)
Modeling caveats

- When modeling observations, we observe the models.
- Parameter degeneracies within models (e.g. Hoenig & Kishimoto 2010; Ramos-Almeida et al. 2011) → in particular parameters influencing obscuration
- Degeneracies and contradictions between different models (e.g. Schartmann et al. 2008; Feltre et al. 2012)

Alonso-Herrero et al. 2011
Modeling caveats

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---

![CLUMPY](image1)

*Nenkova et al. 2008b*

![CAT3D](image2)

*Hoenig & Kishimoto 2010*
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![Graph showing clumpy and continuous models with varying obscurcation angles.](image-url)
Challenges for RT models

• Can we overcome degeneracies in SED fitting, e.g. using interferometry or optimized filters (e.g. Asensio-Ramos & Ramos-Almeida '12)

• Do current models accurately represent mass distribution?
  ‣ near-IR bump (e.g. Edelson & Malkan ’86; Mor+09; Mor+11)
  ‣ dust sublimation radius/composition (e.g. Roche+91; Kishimoto+07,11a)
  ‣ pc-scale mid-IR spatial distribution (e.g. Tristram+12; Hoenig+12; Kishimoto+13)
  ‣ (radiation-)hydrodynamic models
Summary

• **Torus models fundamentals**
  - radiative transfer models and hydrodynamic models
  - motivated by observations and fundamental physics
  - smooth and clumpy

• **Use of torus models**
  - RT models: reproduce SEDs and interferometry
  - HD models: self-consistently produce mass distribution

• **Things to keep in mind**
  - modeling means observing the model
  - different models can give different answers
  - recent observations show limits of current models