Time-resolved infrared emission from a radiation-driven dusty AGN torus

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3D Radiative Transfer models for Clumpy tori

- distribute clumps in a 3D geometry
- simultaneously account for high spatial resolution data as well as interferometric data
- good idea of torus structure

AMBIGUITIES
- toy models
- dynamical stability

NEED FOR PHYSICAL MODELS
Radiation-driven AGN tori

- self-gravitating gas disc \(10^6 \, M\odot\)
- central SMBH \(10^7 \, M\odot\)
- fixed DM and stellar potential
- X-ray heating, dust radiation pressure
- ray-tracing method
- 3 Eddington ratios: 0.01, 0.1, 0.2
- 0.125pc resolution
- \(32^3\) pc box

Wada 2012
Radiation-driven AGN tori

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Wada 2012
Radiation-driven AGN tori

- X-ray heating and radiation pressure
  - 0.01 \( L_{\text{Edd}} \)
    - thin disk
    - tenuous outflow
  - 0.10 \( L_{\text{Edd}} \)
    - dense, puffed-up structure
    - outflow ceases
  - 0.20 \( L_{\text{Edd}} \)
    - dense, puffed-up structure
    - tenuous outflow

**gas density distribution**

MIDI Science Group Meeting
Marc Schartmann
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“Radiation pressure driven fountain”

3-component obscuring structure replaces the classical “torus”:

- + hot, dusty, low density outflow
- + puffed-up “torus”
- + thin disk

Wada 2012
Dust Continuum Radiative Transfer & RADMC-3D

\[
\frac{1}{c} \frac{\partial I_\nu(\vec{x}, \hat{n})}{\partial t} + \hat{n} \cdot \vec{\nabla} I_\nu(\vec{x}, \hat{n}) = \frac{1}{4\pi} \rho_d(\vec{x}) j_\nu(\vec{x}, T) \\
- \rho_d(\vec{x}) \left\{ \kappa_{\nu, \text{abs}}(T) + \kappa_{\nu, \text{sca}}(T) \right\} I_\nu(\vec{x}, \hat{n}) \\
+ \rho_d(\vec{x}) \int \frac{d\Omega}{4\pi} \Phi(\hat{n}, \hat{n}') \kappa_{\nu, \text{sca}}(T) I_\nu(\vec{x}, \hat{n}')
\]

- solve radiative transfer equation with 3D Monte-Carlo code RADMC-3D (Dullemond et al.)
- primary source SED, point-like with \(\cos(\theta)\) radiation characteristic
Dust Continuum Radiative Transfer & RADMC-3D

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- solve radiative transfer equation with 3D Monte-Carlo code RADMC-3D (Dullemond et al.)
- primary source SED, point-like with \( \cos(\theta) \) radiation characteristic
- local ISM dust model:
  - 62.5% silicate, 37.5% graphite
- spectral features
- cut at \( r_{\text{in}} = 1 \text{pc} \)
Wavelength-dependent appearance

orders of magnitude different intensity levels

- scattered light within the cone
- cone edge
- inner disk rim
- clumpy disk in absorpt.
- cold filaments and clumpy disk

20% $L_{\text{Edd}}$
Time evolution of MIR images

- filamentary outflow
- wide opening angle
- ceasing outflow
- vert. elongation changes to spherical shape
- vertical elongation
- low density cone

12 micron
Spectral Energy Distributions

• “Big Blue Bump”, IR re-emission bump
• spectral features
• evolution for ~ 2 Myr

• 0,30 and 60 very similar
• large differences to edge-on view

typical for a thin disk
Spectral Energy Distributions

- much larger differences between inclination angles
- strong absorption in the visible
- deep silicate absorption features

- ceased wind
- (completely) dust enshrouded AGN

10% Eddington
Spectral Energy Distributions

• large differences between inclination angles
• large variety of absorption in the visible
• moderately deep abs. features in IR

three-component system: disk plus low density outflow plus puffed-up structure
Comparison to observed SEDs

- Seyfert galaxy templates (Prieto et al. 2010)
- type I - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity

• edge-on case: overall good agreement
• face-on case: reasonable agreement at short and long wavelengths
• too much flux at NIR wavelengths (outflow, resolution?)

20% Eddington
Comparison to observed SEDs

- Seyfert galaxy templates (Prieto et al. 2010)
- type 1 - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity

- edge-on case: similarly good agreement, but too strong silicate absorption
- face-on case: too much extinction at short wavelengths
Comparison to observed SEDs

- Seyfert galaxy templates (Prieto et al. 2010)
- type I - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity

• neither explains face-on nor edge-on case very well
Comparison with observations: silicate feature vs gas column density

- red line = Seyfert sub-sample
- black line = all objects
- NH probes single line of sight
- silicate feature = mixture of emission and absorption components within the beam
- linear relation found with large amount of scatter
- interpreted as being the result of clumpiness

Comparison with observations: silicate feature vs gas column density

ER20 - stars
• overall best match

ER01 - squares
• too little scatter

ER10 - triangles
• 90: compactness problem

too strong silicate feature emission  missing clumpiness in central region?
Seyfert Light Curves

- 500 micron (triangles): cold, dense disk, optically thin, in quasi-steady state
  - no time evolution
- at shorter wavelengths, the curves for the inclination angles split up
- the strongest evolution visible for 0.1 micron (max of opacity): scattering plus primary
  - ER01: constant (low density lifted dust)
  - ER10: rising trend, decreasing optical depth in cone (no steady state)
  - ER20: episode of strong and dense outflows
Summary

• X-ray heating plus radiation pressure on dust able to maintain geometrical thickness by invoking a “fountain” process (Wada 2012)
• dust continuum radiative transfer calculations to connect to available and future observations
• best agreement with observations is found for models which show a three-component obscuring structure: a dense disk and a puffed-up structure in combination with a tenuous outflow component
• strong morphological differences between MIR and FIR images
• might be testable with ALMA observations (work in progress)