Hypercat - Hypercube of AGN tori

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Clumpy torus model

- Single cloud optical depth $\tau_v$
- Clouds/ray in equatorial plane $N_0$
- Angular torus width $\sigma$
- Torus thickness $Y = \frac{R_o}{R_d}$
- Radial cloud distribution $r^{-q}$
- Observer viewing angle $i$

Observer viewing distance $R_{\text{out}} = Y R_d$
Most *du jour* torus models; Nenkova+2002, 2008a&b; 1100 citations

Model SEDs brought to you since 2008

www.clumpy.org
**Clumpy torus model**

The diagram illustrates the geometry of a clumpy torus model with an observer viewing from the side. The vector of parameters is given as:

$$\vec{\theta} = (\sigma, i, Y, N_0, q, \tau_V, \lambda)$$

- **Single cloud optical depth** $\tau_V$
- **Clouds/ray in equatorial plane** $N_0$
- **Angular torus width** $\sigma$
- **Torus thickness** $Y = R_o/R_d$
- **Radial cloud distribution** $r^{-q}$
- **Observer viewing angle** $i$
Torus now resolvable, VLTI, ALMA, and TMT, GMT, ELT

Imanishi+2018
(see also Garcia-Burillo+2016, Gallimore+2016)
Resolved dust emission in the Mid-IR (VLTI)

NGC1068
Jaffe+2004,
2 uv points

NGC1068
Raban+2009,
16 uv points

Circinus
Tristram+2014
polar dust emission?

» More AGN with polar elongation MIR emission observed
   (see e.g. Hoenig+2013, Lopez-Gonzaga+2016, Leftley+2018)

» Non-physical, direct modeling of the brightness distribution seen by the interferometer
Some proposed solutions

Re-arrange the clouds...

Hoenig & Kishimoto 2017

Tilt the illuminating disk, use hollow cone...

Stalevski+2017 (see also M. Kishimoto talk yesterday)

Disk+wind

Vollmer+2017
Hypercat in nutshell

Hypercat is...

- Very large **hypercube** of AGN torus images
  (here the CLUMPY model, but you can plug in your own)

- A suite of Python **tools** to easily interact with the hypercube
  (slicing, loading, n-dim interpolation)

- Tools to **simulate** observations (to 1st order, 2nd maybe...)
  (single-dish giant telescopes and interferometers)

- Methods to **analyze** image morphology
  (“traditional” techniques, image moments, wavelets, ...)

- **Hypercat** also has the 2-d **projected cloud maps**
  (compare dust and light morphologies)

... all while hiding the complexity of the problem from the user.
Clumpy SEDs, 1.2e6 param. combos, $N_\lambda = 119 \rightarrow 0.5$ GB

Image hypercube w/ same parameter sampling would be 15-50 TB!!

Limit sampling (336k) & $N_\lambda = 25 \rightarrow 0.9$ TB (271 GB compressed)

Get the hypercubes today!

FTP: ftp://noao.edu/pub/nikutta/hypercat/

Straight from your local dealer [ ask me for my external HDD ;-) ]

$\rightarrow$ 3.2 CPU-years to compute images (once...)

(245 billion voxels in 9-dim space, plus dust maps)
ngc1068 = Source(cube, luminosity='1.6e45 erg/s',
    distance='14.4 Mpc', pa='42 deg')
vec = (43, 75, 18, 4, 0.08, 70, 10)  # sig, i, Y, N0, q, tv, wave
sky = ngc1068(vec, total_flux_density='2700 mJy')

- IR radiative transfer is self-similar; $L$ set scale: $R_{\text{dust}} \propto \sqrt{L}$
- Interpolates image on n-dim hypercube for the vector of parameters
NGC1068 best-fit parameters from SED fitting (Lopez-Rodriguez+2018)

\[ \sigma = 43, \ i = 75, \ Y = 18, \ N_0 = 4, \ q = 0.08, \ \tau_V = 70 \]
Hypercat GUI (very basic for now)
Simulate observations - PSFs from pupils

PSFs from pupil images (*thank you, telescope consortia!*
Pretty big pupils...
Last week...

One of the GMT mirrors (8.4m) being polished in Tucson
Realistic observation simulations

NGC1068 best-fit parameters from SED fitting (Lopez-Rodriguez+2018)

$\sigma = 43, \ i = 75, \ Y = 18, \ N_0 = 4, \ q = 0.08, \ \tau_V = 70$

PSF convolution + detector pixelization + noise
Realistic observation simulations

Model  | JWST | Keck | GMT  | TMT  | ELT  |
-------|------|------|------|------|------|
4.75 μm | 148.5 mas | 111.3 mas | 36.7 mas | 30.6 mas | 23.3 mas |
8.8 μm  | 275.1 mas | 206.2 mas | 68.1 mas | 56.8 mas | 43.1 mas |
9.6 μm  | 300.2 mas | 225.0 mas | 74.3 mas | 61.9 mas | 47.0 mas |
10\,\mu m silicate feature strength $S_{10} = \ln \frac{F(10\,\mu m)}{F(\text{cont})}$

Moderate absorption at the center, mild emission in polar region
Interferometric observations

Extract visibilities from model images, compare to data (VLTI, ALMA)

Best fit (@12 µm):

- $\sigma = 21$ deg
- $i = 73$ deg
- $Y = 20$
- $N_0 = 7$
- $q = 0.1$
- $\tau_V = 75$
- $D = 13.1$ Mpc
- $L = 4.4e44$ erg/s
- axis $PA = 42$ deg
Best-fit parameters from interferometry fitting

\[ \sigma = 21, \ i = 73, \ Y = 20, \ N_0 = 7, \ q = 0.08, \ \tau_V = 75 \]
Multi-wavelength view

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\[ \sigma = 43, \quad i = 75, \quad Y = 18, \quad N_0 = 4, \quad q = 0.08, \quad \tau_V = 70 \]
Quantifying morphology - Example: measure size

▶ Half-light radius

\[
\frac{1}{F_{\text{tot}}} \int_0^{R_{1/2}} \frac{dr}{2\pi r} \int_0^{R_1/2} \frac{dr}{2\pi r} = \frac{1}{2}
\]

▶ Gini coefficient

\[
G = \frac{\sum_i (2i - n - 1) \cdot l_i}{n \sum_i l_i}
\]

▶ Radii of gyration

\[
R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}}
\]
Quantifying morphology

Image moments

\[ \mu_{pq} = \sum_x \sum_y I(x, y) (x - \bar{x})^p (y - \bar{y})^q \]

where \( \bar{x}, \bar{y} \) are the image centroid coordinates, and \( p, q \) are integers \( \geq 0 \).

Some beneficial features of moments:

- independent of magnitude
- translation-invariant
- moment definitions exist that are scale- or rotation-invariant
- very easy to measure offsets, sizes, elongations, rotations, asymmetry (skew), peakedness (kurtosis)
Morphology size: Gini coefficient

All pixels same value: $G = 0$
A single pixel non-zero: $G = 1$
Uniform random: $G = 1/3$

$\sigma, N_0, \tau_V, \lambda = 15 \text{ deg}, 1, 10, 2 \mu m$

smallest morphology, $G = 0.97$

$\sigma, N_0, \tau_V, \lambda = 75 \text{ deg}, 12, 160, 18 \mu m$

largest morphology, $G = 0.40$
Radii of gyration

\[ R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}} \]

(b) Stretch

\[ \sigma_y \text{ of Gaussian (pix)} \]

\[ R_{g}^x \quad R_{g}^y \quad \text{elongation} \]
Half-right radius & radii of gyration

\[ Y = 18, \; q = 0.08, \; \tau_V = 70, \; \lambda = 10 \; \mu m \]

\[
\begin{align*}
\sigma &= 15 \; (\text{deg}) & \sigma &= 30 \; (\text{deg}) & \sigma &= 45 \; (\text{deg}) & \sigma &= 60 \; (\text{deg}) & \sigma &= 75 \; (\text{deg}) \\
N_0 &= 1 & N_0 &= 4 & N_0 &= 7 & N_0 &= 10
\end{align*}
\]
Morphology elongation

\[ e = \frac{R_y^g}{R_x^g} \]

Measured elongations in N-band (Burtscher+2013)

- NGC 1068: 1.3
- NGC 424: 1.3
- NGC 3783: 1.5
- Circinus: 2

Clumpy models (@10 \( \mu \text{m} \))

- Can produce \( e \approx 1.5 \)
- \( e > 2 \) possible closer to edge-on views

\( (i = 75 \text{ deg}, Y=18, q=0.08 \text{ fixed here}) \)
Elongation as function of wavelength

\[ \sigma = 43 \, \text{deg}, \, \gamma = 18, \, N_0 = 4, \, q = 0.08, \, \tau_V = 70 \]
Summary

- Must model 3-d dust distros to produce physical 2-d brightness maps
- Hypercat empowers you to study resolved AGN imagery, pain-free
- Simple Clumpy torus models can produce significant polar elongations (torus inner wall)
- NGC1068: the same model can give perpendicular orientations in N band and ALMA frequencies
- Models can fit SEDs well, and visibilities too; now must fit both simultaneously

Near future

- Submit paper 1 (January?)
- Assess detectability and resolvability of all nearby AGN, with all instruments (lead: Kohei Ichikawa)
- Compare models and all current + future resolved observations (lead: Enrique Lopez-Rodriguez)
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Thank you! Gracias!

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www.clumpy.org

ftp://noao.edu/pub/nikutta/hypercat/