Hypercub - 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 $Y = R_o/R_d$
radial cloud distribution $r^{-q}$
oobserver viewing angle $i$

Vector of parameters
\[ \vec{\theta} = (\sigma, i, Y, N_0, q, \tau_V, \lambda) \]
Clumpy so far: SEDs

Nenkova+2002, 2008a&b; 1160 citations so far

Model SEDs brought to you since 2008

www.clumpy.org
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

Raban+2009,
16 uv points

Circinus

Tristram+2014
polar dust emission?

▶ More AGN with polar elongation MIR emission observed
(e.g. Hoenig+2013, Lopez-Gonzaga+2016, Leftley+2018,
Asmus 2019)

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

Re-arrange the clouds...

Tilt the illuminating disk, use hollow cone...

Hoenig & Kishimoto 2017

Stalevski+2017

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 \text{ GB} 

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

- Limit sampling (336k) & \( N_{\lambda} = 25 \rightarrow 0.9 \text{ TB} \) (271 GB compressed)

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**Get the hypercubes today**

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

- Or straight from your local source [ *ask me for my external HDD ;-) *]

\[ \rightarrow 3.2 \text{ CPU-years} \text{ to compute images (once...)} \]
\[ (245 \text{ billion voxels in 9-dim space, plus dust maps}) \]
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, NO, q, tv, wave
sky = ngc1068(vec, total_flux_density='2700 mJy')

- IR radiative transfer is self-similar; $L$ sets scale: $R_{dust} \propto \sqrt{L}$
- Interpolates image on n-dim hypercube for the vector of parameters
Multi-wavelength view

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 (basic for now)
Simulate observations - PSFs from pupils

PSFs from pupil images *(thank you, telescope consortia!)*

Images of pupils come with Hypercat.
Pretty big pupils...
Recently in Arizona...

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
IFU-like observations

$10\mu m$ 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
- $L = 4.4\times10^{44}$ erg/s
- axis $PA = 42$ deg
Multi-wavelength view

Best-fit parameters from interferometry fitting

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

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

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

- **Half-light radius**

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

- **Gini coefficient**

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

- **Radii of gyration**

\[
R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}}
\]
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, $G = 0.40$
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)
Radii of gyration

\[ R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}} \]
Elongation $e = \frac{R_g^y}{R_g^x}$

Measured elongations in N-band (Burtscher+2013)

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

Clumpy models (@10 µm)

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

(i = 75 deg, Y=18, q=0.08 fixed here)
Light morphology vs dust distribution

\[ \sigma = 43, \ Y = 18, \ q = 0.08, \ \tau_V = 70, \ N_0 = 4 \]
Summary & Future

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) on multi-pc scales
▶ Very long scale (> several 10 pc) elongations are unlikely the “torus”
▶ NGC1068: the same model can give perpendicular orientations in N band and ALMA frequencies; dust distro ≠ light morpho in general
▶ Models can fit SEDs well, and visibilities too; now must fit both simultaneously
Thank you!

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www.clumpy.org

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