The 10-micron silicate feature in AGN

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AGN unification



Urry & Padovani 1995

Spitzer solved problems

10-micron silicate emission in type 1 sources (long expected)



- ▶ 10-micron silicate emission in type 2 sources
- ► Feature shape and peak shifts
- Lack of deep absorption features

 \Rightarrow Address all puzzles with a clumpy dust torus.

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Directly illuminated clouds



Nenkova+2008b

- Hot bright and cool dark faces
- High and low T at same position and same distance
- We use cold (interstellar) OHM silicates in most cases + graphites from Draine



Jaffe+2004

CLUMPY torus model



Nenkova+2008b

radial cloud distribution r^{-q}

clouds/ray in equatorial plane N_0

angular torus width

 σ

torus thickness $Y = R_o/R_d$

single cloud optical depth $\tau_{\rm v}$

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observer viewing angle *i*

CLUMPY torus model



Cloud number per radial ray

$$N(i) = N_0 e^{-\left(\frac{90-i}{\sigma}\right)^2}$$

Escape probability

$$P_{esc} = e^{-N(i)}$$

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For each (x,y) in sky plane, integrate along path z

$$I_{\lambda}^{C}(z) = \int^{z} P_{esc}(z', z) S_{C,\lambda}(z') N_{C}(z') dz'$$

Brightness Maps and Spectral Energy Distributions



$$Y = 20$$
, $\sigma = 25^{\circ}$, $i = 60^{\circ}$, $\lambda = 10 \ \mu m$

0.1 0.01 3. F3. / FAGN 0.001 inclination angle i= 20.9 i = 30.9 i= 40 9 0.0001 1 = 50.5 1= 60.5 i = 70.º i= 80 9 COPYRIGHT BY THE CLUMPY GROUP AT UNIVERSITY OF KENTUCKY 0.01 0.1 100 λfum

CLUMPY fluxes $f = \frac{\lambda F_{\lambda}}{F_{AGN}}$

ISM-OHM/p0.5-RJ1mioTORUSG/SED/Y030/SED-AA00-TORUSG-stg30-Y030-N07-g2.0-tv030.0.txt

Model database

Database of model SEDs

http://www.pa.uky.edu/clumpy/

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- Large parameter space covered
- $\blacktriangleright~\sim$ 1.3 million models
- ► freely accessible
- can run own models

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Puzzle 1: 10-micron emission in type 2 sources (Direct evidence for clumpiness)

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10-micron silicate emission in type 2 sources



► fit Spitzer SED of a type 2 QSO with CLUMPY model SEDs • more

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- find best-fit model among all
- derive model parameters (statistics, Bayesian analysis)

CLUMPY model fluxes:

$$f = rac{\lambda F_\lambda}{F_{AGN}} o F_{AGN}$$
 sets scale

Best fit model

Type-2 quasar SST1721+6012, z = 0.325



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Well-constrained CLUMPY parameters



Bayesian analysis - marginalized posteriors

likelihood $\propto { m e}^{-\chi^2/2}$



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Puzzle 2: Feature shape and peak shifts (Dust composition or radiative transfer effect?)

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Feature shape and peak shifts

Astronomical silicate dust peaks around \sim 9.8 μ m

Modeled silicate dusts peak at

Draine et al. 2000 \sim 9.48 μ m Ossenkopf, Henning, & Mathis 1992 \sim 10.0 μ m

Yet...



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Subtraction of continuum

More examples...



Hao et al. 2005

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Fitting with more exotic dusts



Sturm et al. 2005

Fitting with CLUMPY and standard dust



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Defining a continuum



Best-fit model for PG1211+143

$$q = 0$$

$$V_0 = 5$$

 τ

$$r_v = 20$$

$$\sigma = 20$$

 $\sigma = 25$

Flat, shifted peaks with...

- standard dust
- clumpy rad. transfer

defining a continuum: see Sirocky+2008

Origin of $10\mu m$ emission





Puzzle 3: Distribution of feature strengths (Lack of deep absorption features)

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Lack of deep absorption features



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Observed distributions of S_{10}



Feature strength

$$S_{10} = \ln rac{F(\lambda)}{F_{cont}(\lambda)}$$

From Hao et al. 2007 sample...

- Remove ULIRGs
- ► Measure S₁₀
- Remove outliers

Yields 59 type 1 and 39 type 2 sources

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► Type is just a probability Assign... Type 1 when $P_{esc} > 1/2$ Type 2 when $P_{esc} < 1/2$

Real parameter sampling is unknown Chose physically reasonable parameters (Nenkova+2008a,b):

$$q = 0 - 3$$
 $N_0 = 1 - 15$ $\tau_v = 30 - 100$ $\sigma = 15 - 50$ $Y = 10 - 100$ $i = 0 - 90$

Uniform sampling

Yields 340k type 1 and 500k type 2 models

Compare observed and synthetic distributions of S_{10}



A clumpy dust torus explains all of these:

- ► Silicate features in **emission** from type 2 sources
- ► Broad emission features with shifted peaks and standard dust
- ▶ No deep absorption features and observed distribution of S_{10}

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Problem: hot BB



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Problem: hot BB



= 990

Thank you for your attention!

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http://www.pa.uky.edu/clumpy/

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Additional slides

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For each (x,y) in sky plane, integrate along path z

$$J_{\lambda}^{\mathcal{C}}(z) = \int^{z} P_{esc}(z',z) S_{\mathcal{C},\lambda}(z') N_{\mathcal{C}}(z') dz'$$



 $S_{C,\lambda}(z')$ cloud source function at z'

more

- N_C local cloud number per unit length
- $P_{esc}(z', z)$ probability for photons generated at z' to escape through rest of path z

- Heated by isotropic radiation bath
- Thermalized (one temperature)
- Diffuse SFN depends on distance only



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Local cloud source function



Diffuse cloud source function

 $S^{diff}_{C,\lambda}(r)$

Local cloud source function

$$S_{C,\lambda}(z') = p(r,\beta) \underbrace{S_{C,\lambda}^{dir}(r,\alpha)}_{direct SFN} + [1 - p(r,\beta)] \underbrace{S_{C,\lambda}^{diff}(r)}_{diffuse SFN}$$

Fitting

Goal: minimize fitting error

$$\chi^{2} = \sum_{j=1}^{N} \left(\frac{F_{AGN} \cdot f_{j}^{m} - \lambda_{j} F_{j}^{o}}{\sigma_{j}} \right)^{2}$$
$$\chi^{2}_{r} = \chi^{2} / N_{dof}$$

- f_i^m model flux at wavelength j
- $\lambda_j F_i^o$ observed flux at j
- σ_j observations errors at j

CLUMPY model fluxes: $f^m = \frac{\lambda F_\lambda}{F_{AGN}} \rightarrow \text{find } F_{AGN} \text{ (the scaling)}$ (back

Dust absorption coefficients



Feature-feature diagram: OHMc silicates



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Feature-feature diagram: OHMw silicates



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Feature-feature diagram: Draine silicates



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