Observational Constraints on Interstellar Dust Properties

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This talk limited to:

- Dust in diffuse ISM (not dark clouds, not protostars)
- "Normal star-forming galaxies" – like the MW.
  (*not* low-metallicity, early-type, extreme starburst, etc.)

Most observational constraints are on **electromagnetic properties**:

- Extinction vs. λ
- Polarized extinction (polarization of starlight)
- Scattering: from X-rays to IR
- Emission: IR to microwave
- Polarization of emission (IR, FIR, submm, microwave)

Other constraints (not discussed here):

- depletions (including variations in depletions)
- photoelectric heating
- catalysis of H_2 (and other species?)
- grain-assisted recombination of ions

Reverse-Engineering Interstellar Dust

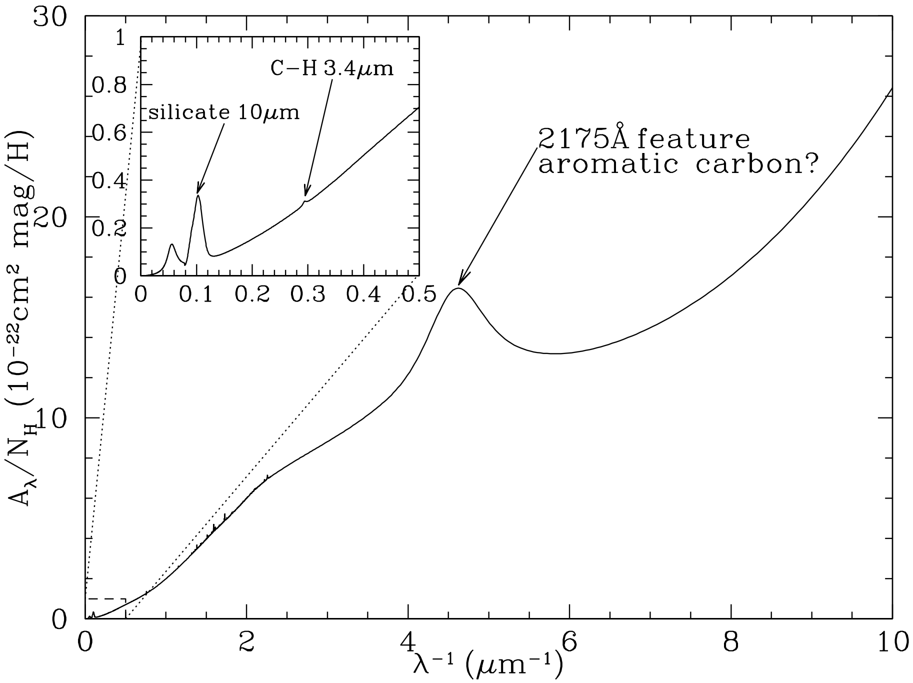
collaboration with
Brandon Hensley (JPL):

see Poster XXX

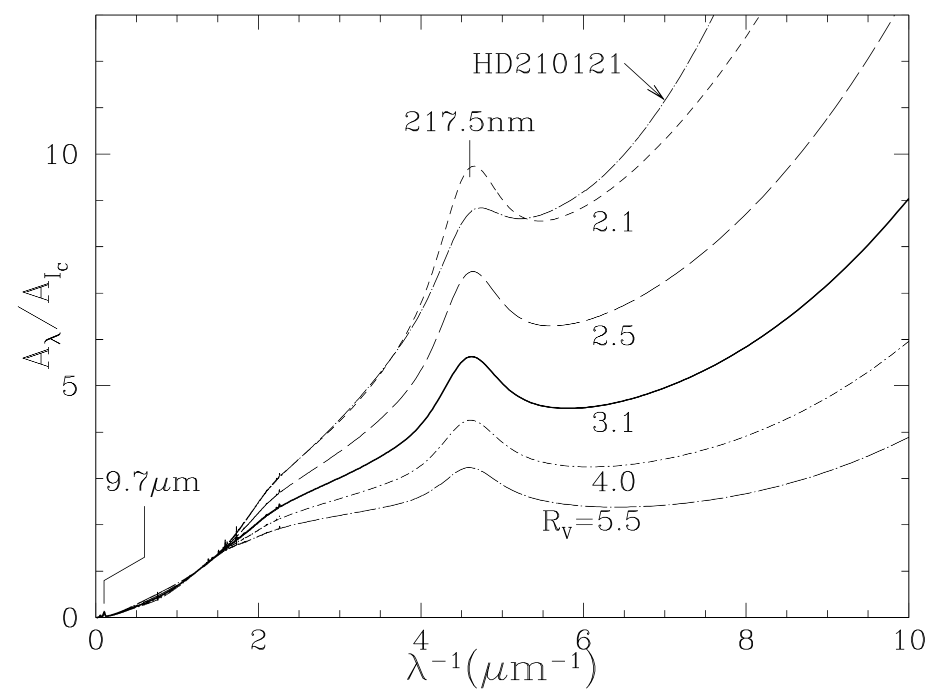
Reverse-Engineering Interstellar Dust

- Propose a model: materials and size distributions
- Must be consistent with abundance constraints
  (i.e., atoms that are missing from the gas phase: *interstellar depletion*)
- Calculate optical properties
  (use theoretical methods to calculate scattering, absorption, and emission for model grains).
- Because we don't know what materials form in ISM, some freedom to "invent" materials (e.g., "astrosilicate")
  - *informed by lab studies of candidate materials*
  - *require consistency with laws of physics*
- Compare with observations (extinction, polarization, IR-submm emission)
- Adjust as needed...
- Insufficient constraints: *model will not be unique...*

IR-Optical-UV Extinction



typical diffuse ISM

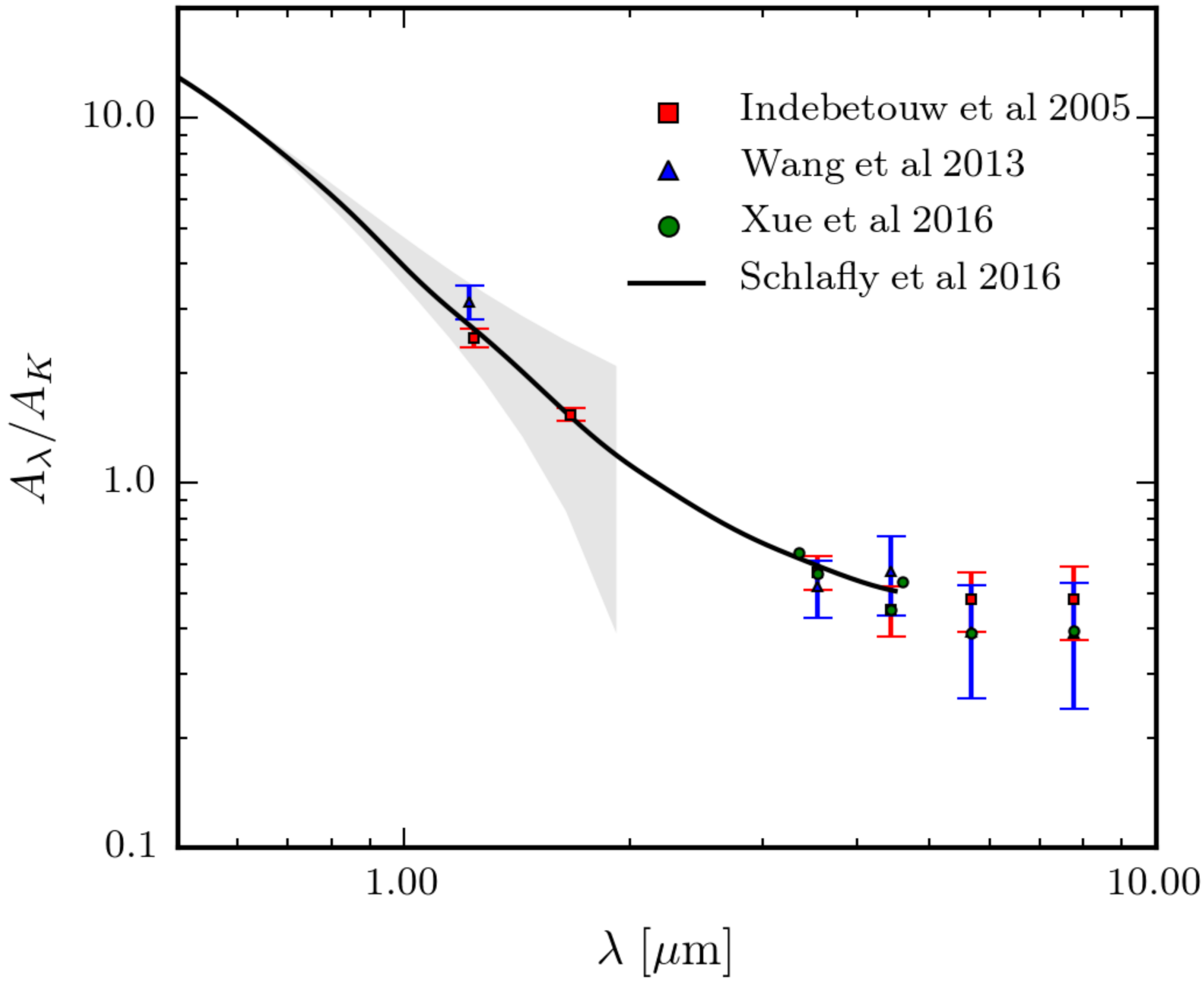


sightline-to-sightline variations

- *Lessons from modeling:*
  - Optical extinction and scattering: **Most of the grain mass at** $a \gtrsim 0.1\mu\mathrm{m}$.
  - Rising extinction down to $\lambda = 0.1\mu\mathrm{m}$:
    substantial number of grains with sizes down to at least $0.01\mu\mathrm{m}$
  - IR features at $9.7\mu\mathrm{m}$ (Si-O stretch) and $18\mu\mathrm{m}$ (O-Si-O bend):
    substantial fraction of grain mass must be silicate material
- Weak feature at $3.4\mu\mathrm{m}$: C-H stretch. **Hydrocarbon material** present.
- Strong 2175 Å feature: Probably $\pi \rightarrow \pi^*$ excitation in sp^2-bonded C (example: graphite).
- Dust properties vary from one sightline to another: **dust evolution in ISM**

IR-Optical Extinction

- Progress based on stellar photometry by
  - 2MASS
  - Spitzer Space Telescope
  - WISE
  - SDSS
  - Pan-STARRS
  - APOGEE
- **5–8μm extinction in diffuse ISM is significantly larger than had been thought pre-2005**



Symbols: Indebetouw et al. (2005), Wang et al. (2013), Xue et al. (2016), Schlafly et al. (2016). Shaded area: Fitzpatrick & Massa (2007).

from Hensley & Draine (2018) – see Poster xxx

Scattering

- Reflection nebulae
  illuminator: nearby star(s)

- Diffuse Galactic light
  diffuse ISM = reflection nebula
  illuminator: diffuse starlight

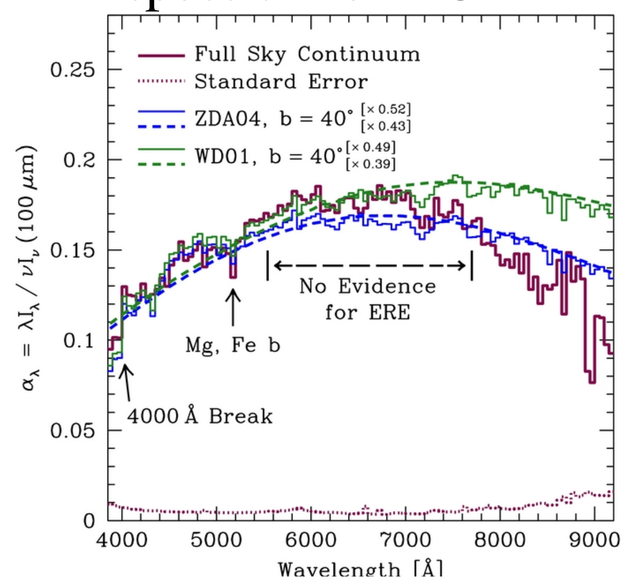
- “Cloudshine”
  externally-illuminated translucent cloud
  illuminator: diffuse starlight

- “Coreshine”
  externally-illuminated dark cloud
  illuminator: diffuse starlight

Tests of size distribution and composition

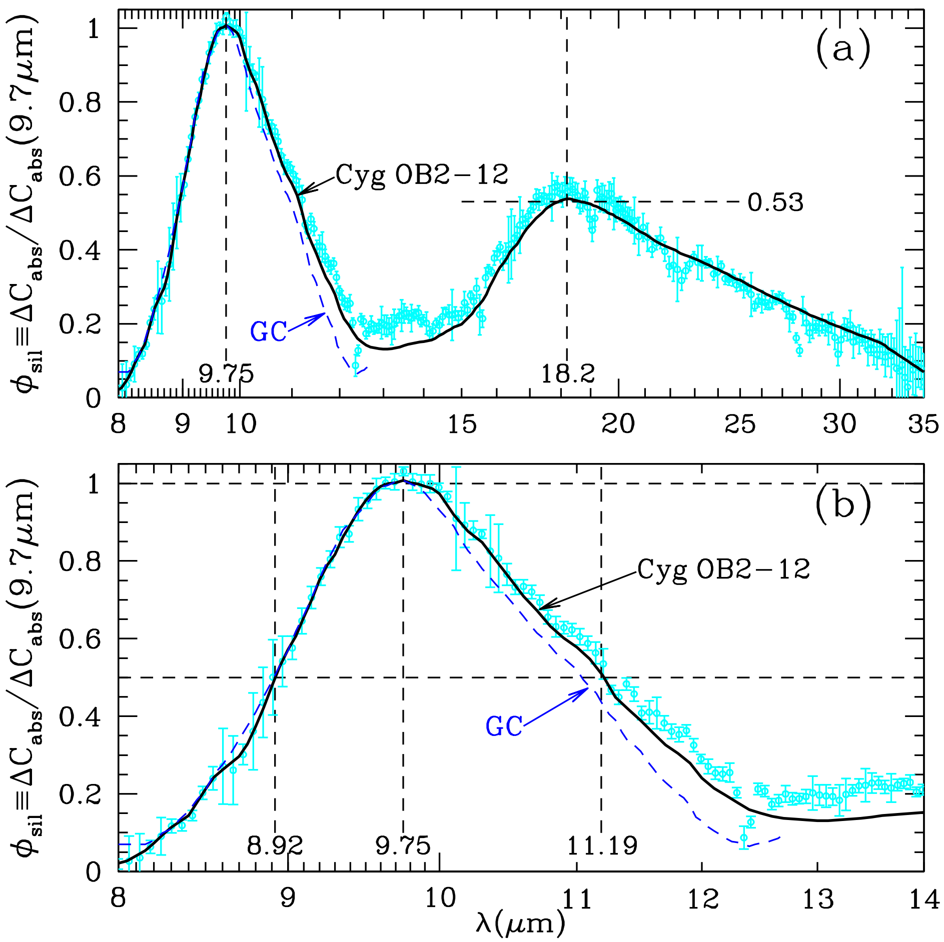
NGC 7023 (credit: Claustonberry Observatory)

spectrum of DGL



from Brandt & Draine (2012)

Silicate Composition



Solid: Cyg OB2-12 (Poteet, private communication)

Cyan: Cyg OB2-12 (Fogerty et al. 2016)

Dashed: Galactic Center (Kemper et al. 2004)

- $9.7\mu m$ and $18\mu m$ features: **silicates**
- Crystalline fraction $< 2\%$ (Kemper et al. 2004)
- Essentially all Si, Mg is in silicate grains
- Silicates: ∼2/3 dust mass in diffuse ISM
- Composition based on lab spectra of amorphous silicates:
  Mg-rich olivine/pyroxene, e.g.,:

  $Mg_{1.32}Fe_{0.10}SiO_{3.45}$ (Min et al. 2007)

  $Mg_{1.48}Fe_{0.32}SiO_{3.79}$ (Poteet et al. 2015)

  $Mg_{1.37}Fe_{0.18}Ca_{0.002}SiO_{3.55}$ (Fogerty et al. 2016)

  (Mg:Fe ratio somewhat uncertain)

Carbon in Diffuse ISM

C/H

$\sim$ 324 ppm total
$\sim$ 177 ppm gas (ζ Oph)
$\sim$ 147 ppm dust (ζ Oph)

$$\frac{\textbf{carbon dust mass}}{\textbf{total dust mass}} \approx 19\%$$

$$\frac{\textbf{carbon dust volume}}{\textbf{total dust volume}} \approx 30\%$$

IR emission features: (3.3, 6.2, 7.7, 8.6, 11.3, 12.7μm)
PAHs with $< 10^3$ C atoms: $\sim$35 ppm [$q_{\rm PAH} = 0.047$]

larger carbon grains: $\sim$110 ppm

2175Å feature:
$\pi \rightarrow \pi^*$ transition in sp^2-bonded C
(PAHs, or very small graphitic grains)

need $\sim$60ppm C/H to account for 2175Å feature (PAHs)?

Composition of larger carbonaceous grains uncertain:

- polycrystalline graphite?
- amorphous carbon?
- hydrocarbons?

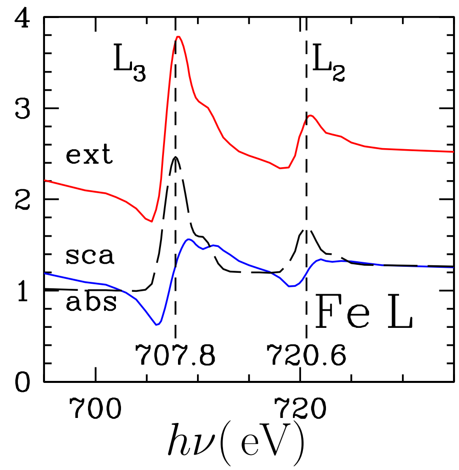
3.4μm feature: C-H bond in aliphatic carbon
but not known how much C-H
Abundance of diamond-like (sp^3-bonded) carbon uncertain

- nanodiamonds found in meteorites
- 3.47μm absorption feature

Composition Puzzles

Where is the Fe?

- Mg-rich silicates appear to consume only $\sim 20\%$ of the Fe.
- Where is the rest of the Fe?
  - Metallic Fe ?
    (easy to hide – no features)
  - γ-Fe_2O_3 maghemite? (15μm feature)
  - Fe_3O_4 (features at 14, 23μm)
  - FeO (wustite)? (feature at 22μm)
- No identifications to date
- In principle can diagnose with Fe L-band absorption spectrum at $\sim 705 - 725\,$eV



from Draine (2003)

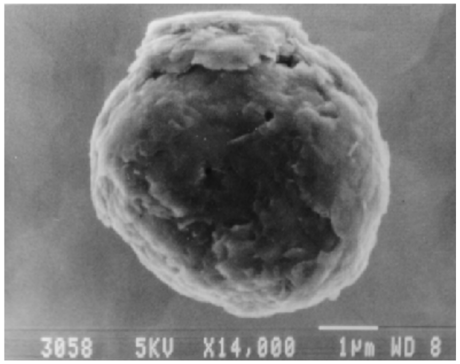
Where is the O?

- Jenkins (2009): O depletion greater than expected for silicates and metal oxides
- Not in H_2O ice on normal-sized grains – 3.1μm absorption not seen
- *Perhaps* very large ($a \gtrsim 1\mu$m) H_2O ice grains (Poteet et al. 2015)?

Grain Geometry

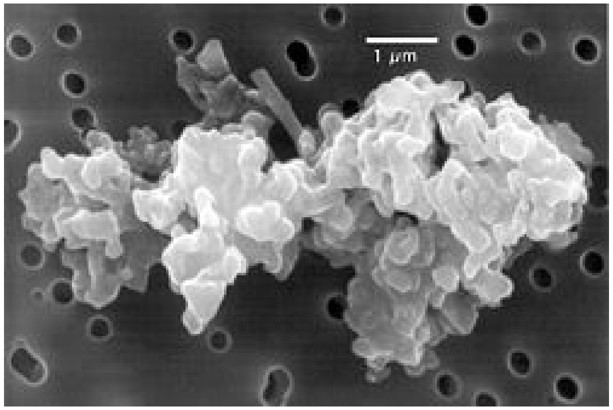
- Observed polarization of starlight (and polarized FIR emission): interstellar grains are *not* spherical. What is the geometry of interstellar dust? Two extremes:

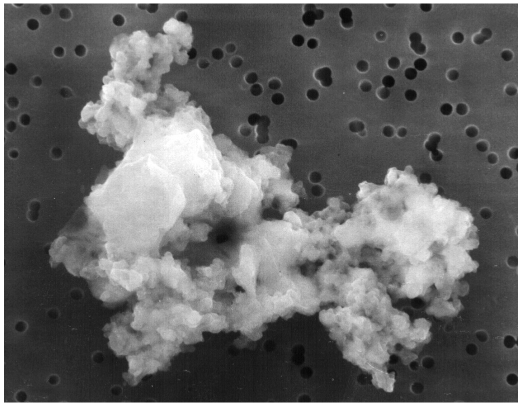
◇ Are interstellar grains fairly smooth and compact?



Presolar onion-like graphite grain (diameter $\sim 5\mu\mathrm{m}$). Photo from S. Amari.

◇ Or are they typically loose aggregates of smaller particles, with a large "porosity"?



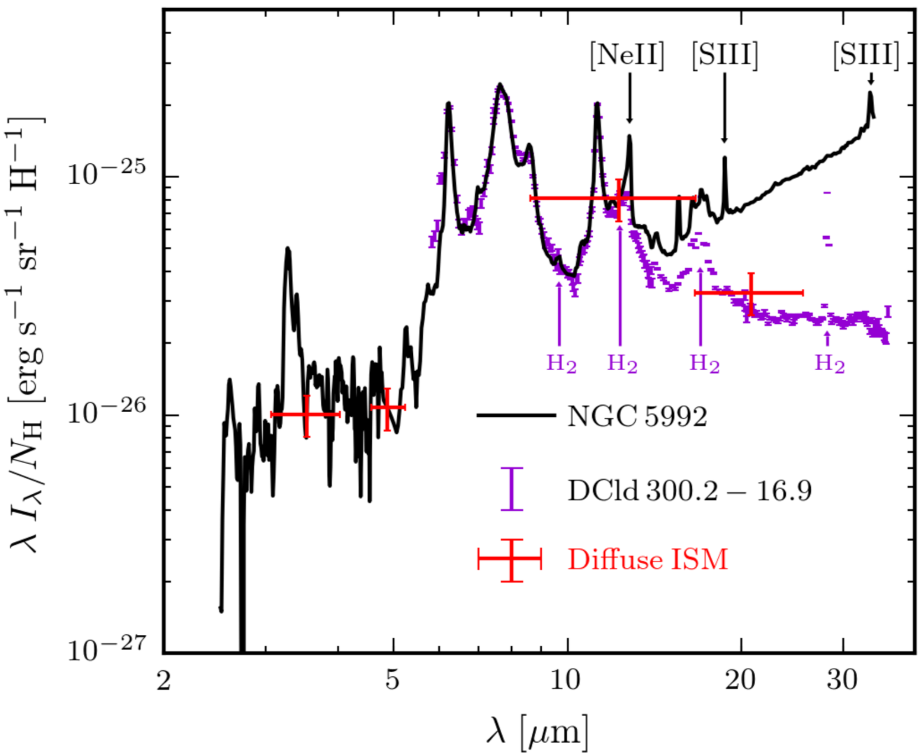


Two interplanetary dust particles collected from stratosphere (diameter $\sim 10\mu\mathrm{m}$).

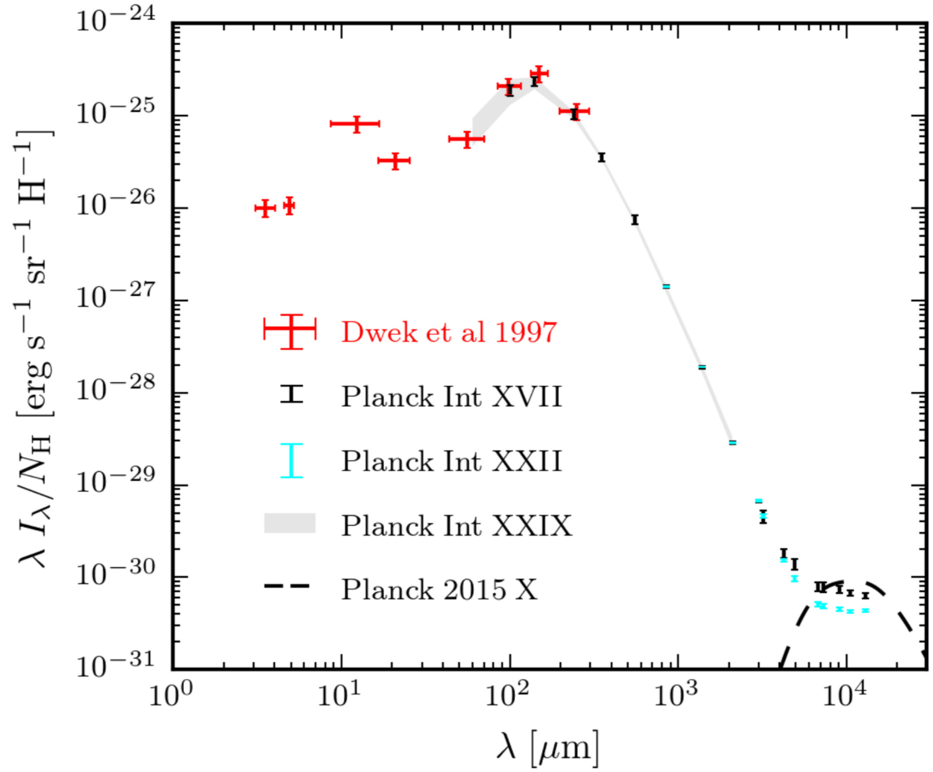
Elemental compositions similar to primitive meteorites: silicates + carbonaceous material.

Images courtesy E.K. Jessberger and Don Brownlee.

Infrared and Submm Emission



from Hensley & Draine (2018)

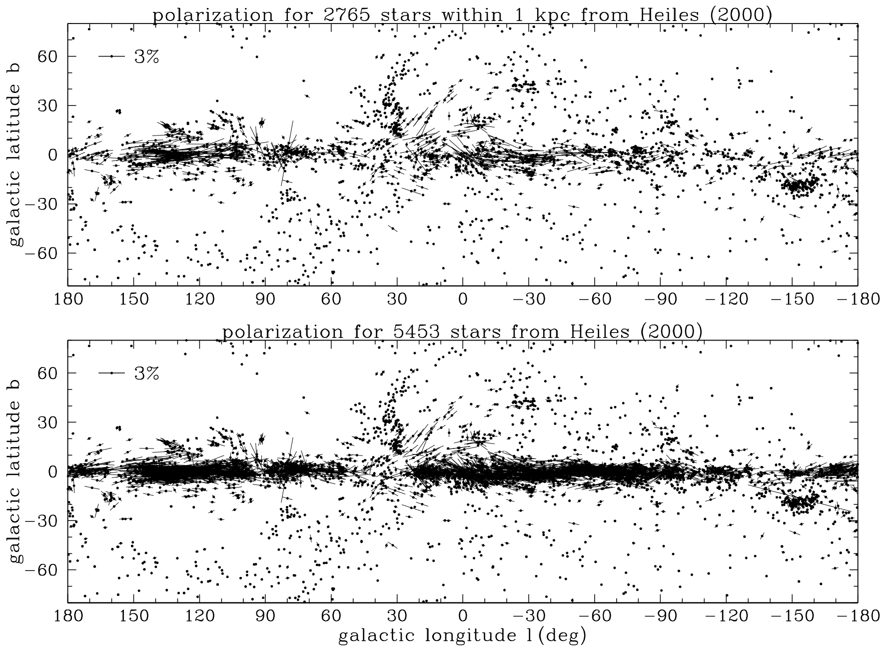


from Hensley & Draine (2018)

SED of diffuse ISM

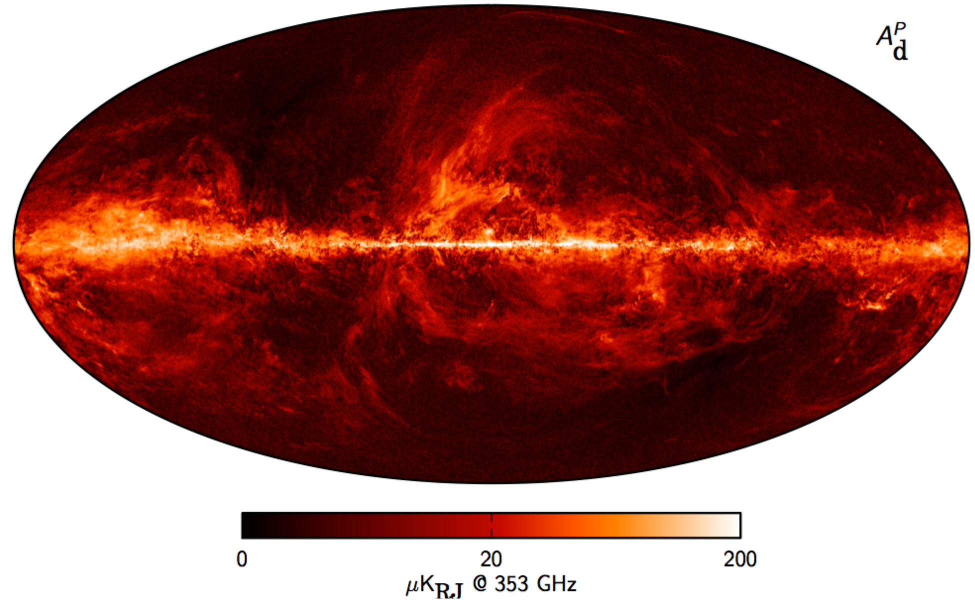
- PAH emission features at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7μm
- local translucent cloud DCld 300.2 -16.9 taken as representative of emission from diffuse ISM
- Very similar to NGC 5992 at $\lambda < 12\mu$m

Polarization of Starlight and Submm Emission

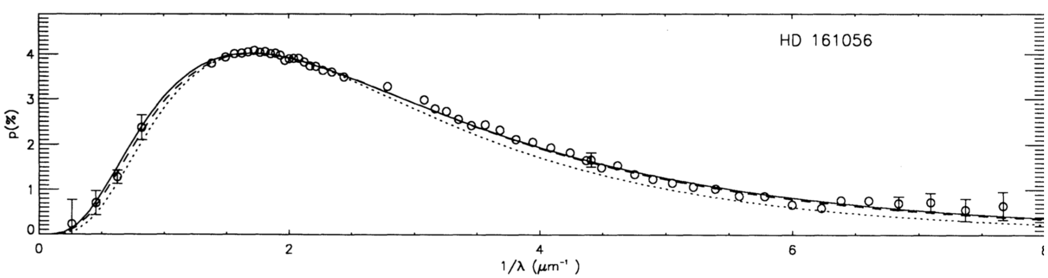


Polarization of starlight (from Draine 2011)

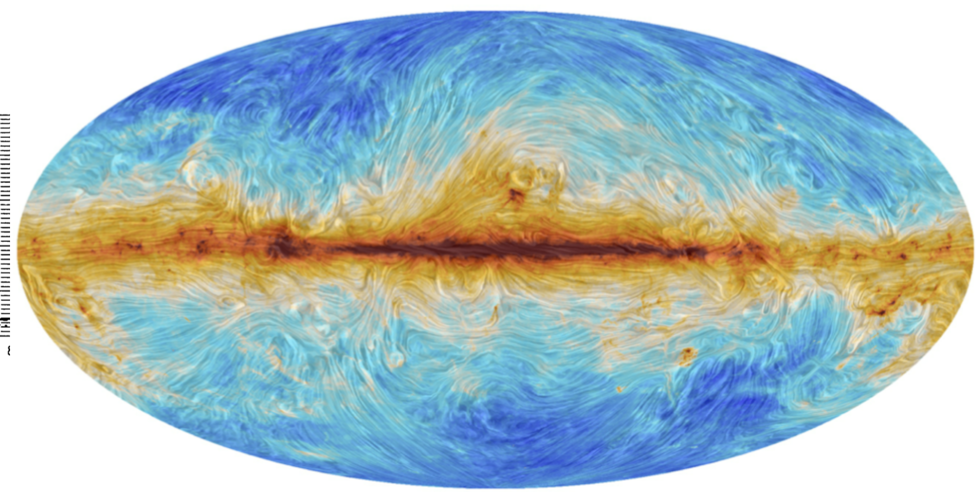
Polarized emission at 850μm



Direction of $\vec{B}_{gal}$ $[\vec{E}(850\mu\mathrm{m})$ rotated by 90°]



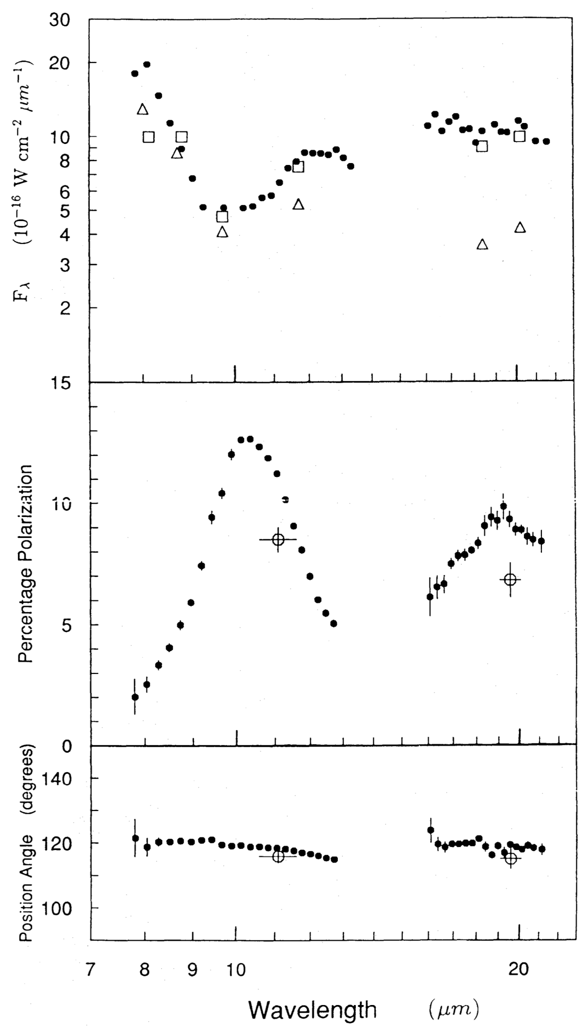
λ-dependence for HD 161056 (Clayton et al. 1995)
2175Å feature *not* polarized



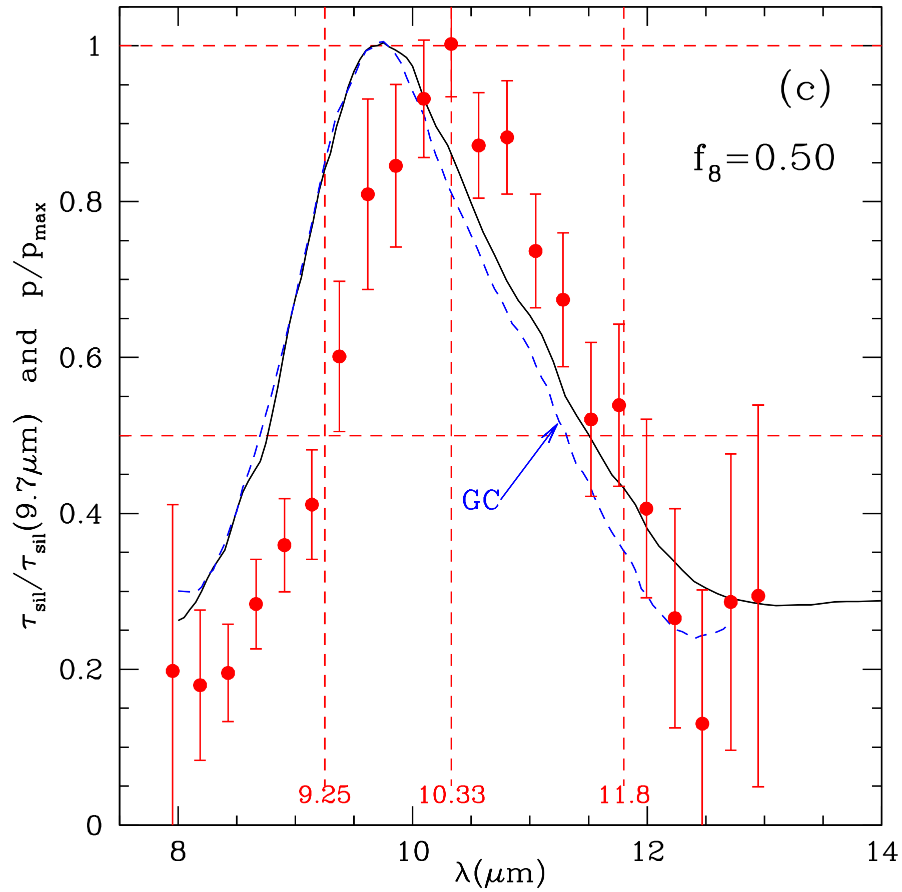
from Planck Collaboration et al. (2016)

Polarization in Spectral Features

- 2175Å feature (carbonaceous): **not** polarized
- 3.4μm C-H stretch feature: no evidence of polarization (Chiar et al. 2006)
- 10μm silicate Si-O stretch: **strong polarization**



BN Object (Aitken et al. 1989)



Extinction and polarization profiles in diffuse ISM
polarization data from Wright et al. (2002)

Constraints on Grain Shape and Porosity

- Need to reproduce starlight polarization, up to

$$\frac{p_{\rm max}}{E(B-V)} \approx 0.09$$

- Grains that produce starlight polarization must also produce polarized submm emission
- UV polarization/extinction very small: smallest grains are *not* aligned.
  Alignment fraction appears to be almost a step function:
  $a \lesssim 0.05\mu\text{m}$: negligibly aligned
  $a \gtrsim 0.10\mu\text{m}$: substantially aligned
- Many models assume
  partially aligned silicate grains
  randomly-oriented (or minimally-aligned)
  carbonaceous grains, e.g.,
  - Draine & Fraisse (2009)
  - Siebenmorgen et al. (2014)
  - Siebenmorgen et al. (2017)
  - Guillet et al. (2018) *see Poster...*
  - Hensley & Draine (2018) *see Poster...*
- (submm polarization)/(optical polarization) depends on shape and porosity
- At fixed opacity (cm^2/g) porous grains are less effective polarizers,
- Ratio (submm pol.)/(optical pol.) depends on shape and porosity
- Vary grain shape and porosity:
  Hold IR-submm opacity fixed
  [$\epsilon(\lambda)$ depends on shape and porosity].
- Use observed $P_\nu(850\mu\text{m})/p_V$ to find allowed shapes and porosities

Allowed Shape and Porosity for Silicate Grains

Observed:

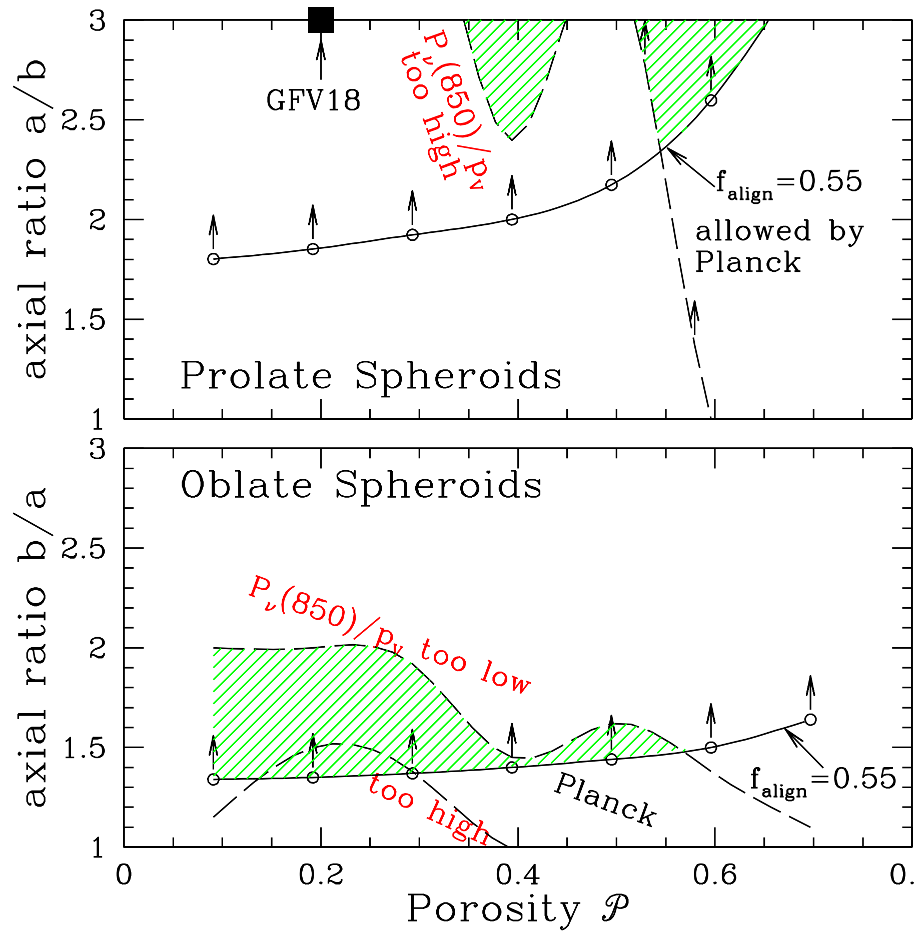
$$\frac{P_\nu(850\mu\mathrm{m}\,)}{p_V} = (5.4 \pm 0.5)\,\mathrm{MJy\,sr}^{-1}$$

(Planck Collaboration et al. 2015):

$P_\nu(850\mu\mathrm{m}\,)$ = polarized intensity
p_V = starlight polarization on sightline

Models with partially-aligned silicates, randomly-oriented carbonaceous grains: Allowed shape and porosity

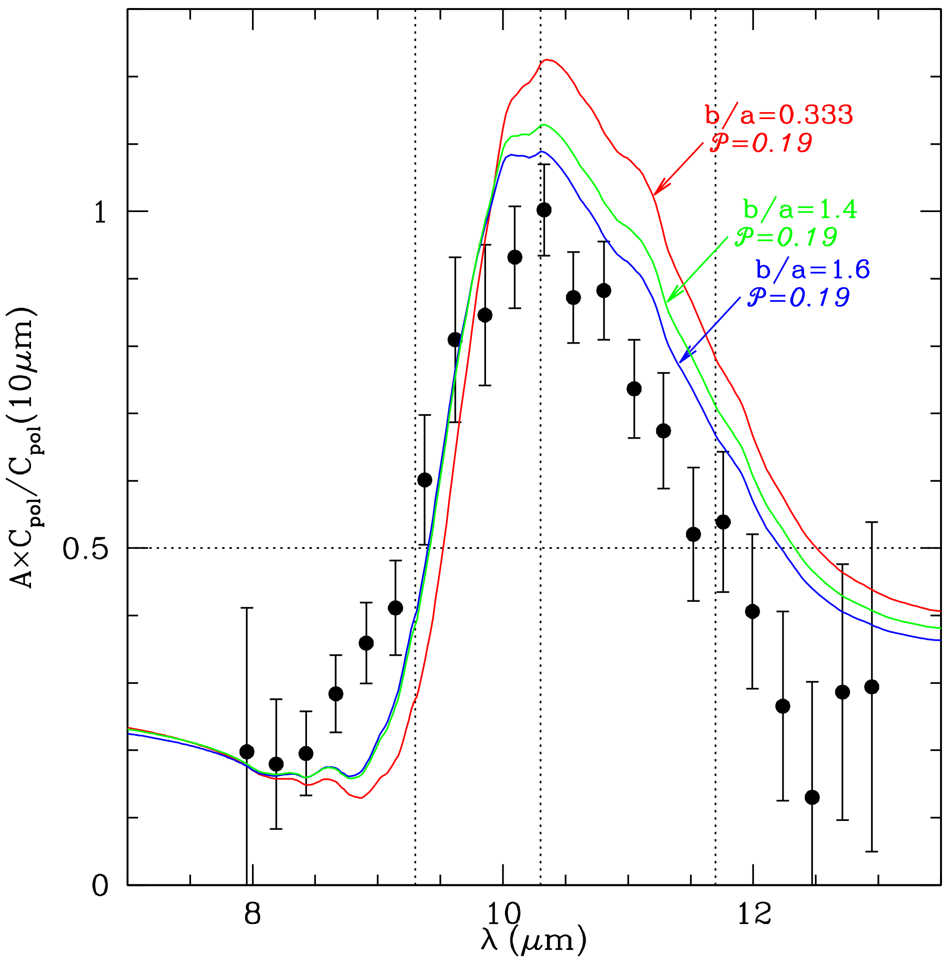
(assuming Draine & Hensley (2018a) dielectric function)



- Guillet et al. (2018) [GVF18] favor **3:1 prolate** spheroids with porosity $\mathcal{P} \approx 0.2$
- Draine & Hensley (2018b) favor **∼1.5:1 oblate** spheroids with porosity $\mathcal{P} \approx 0.2$

Polarization in the 10μm Feature

- For fixed *absorption* profile, polarization profile depends on both shape and porosity
- *Oblate* spheroids appear to fit observed polarization profile better than prolate spheroids: (Draine & Lee 1984; Aitken et al. 1989)
- GFV18 assume 3:1 prolate spheroids for modeling polarization of starlight and submm emission



- above models: identical aborption profile (Cyg OB2-12)
- **Oblate** gives better fit to diffuse ISM polarization profile (Wright et al. 2002)

Anomalous Microwave Emission (AME)

Poster Child

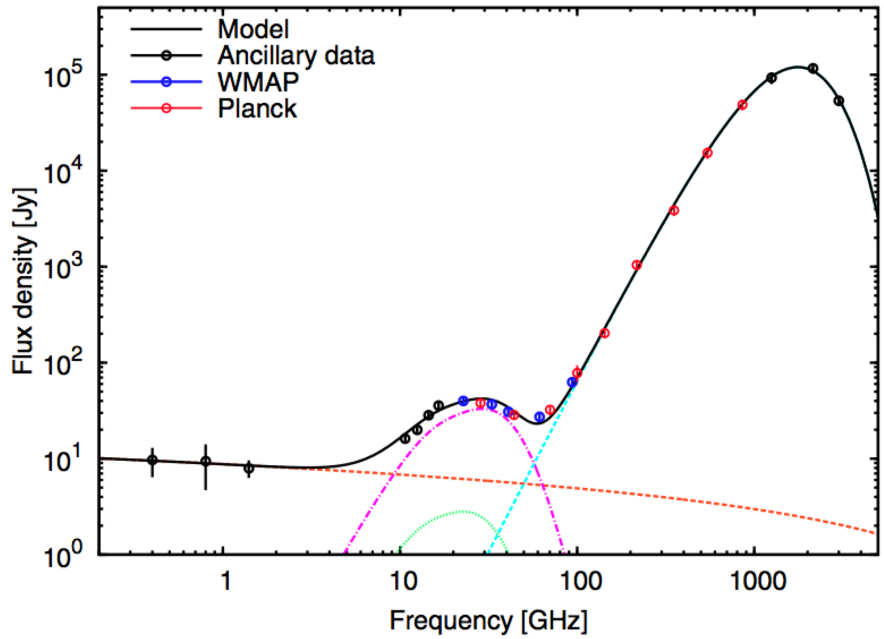


Fig. 4. Spectrum of AME-G160.26−18.62 in the Perseus molecular cloud. The best-fitting model consisting of free-free (orange dashed line), spinning dust, and thermal dust (light blue dashed line) is shown. The two-component spinning dust model consists of high density molecular gas (magenta dot-dashed line) and low density atomic gas (green dotted line).

Planck Collaboration et al. (2011)

More Cases...

Planck Collaboration: A study of AME in Galactic clouds

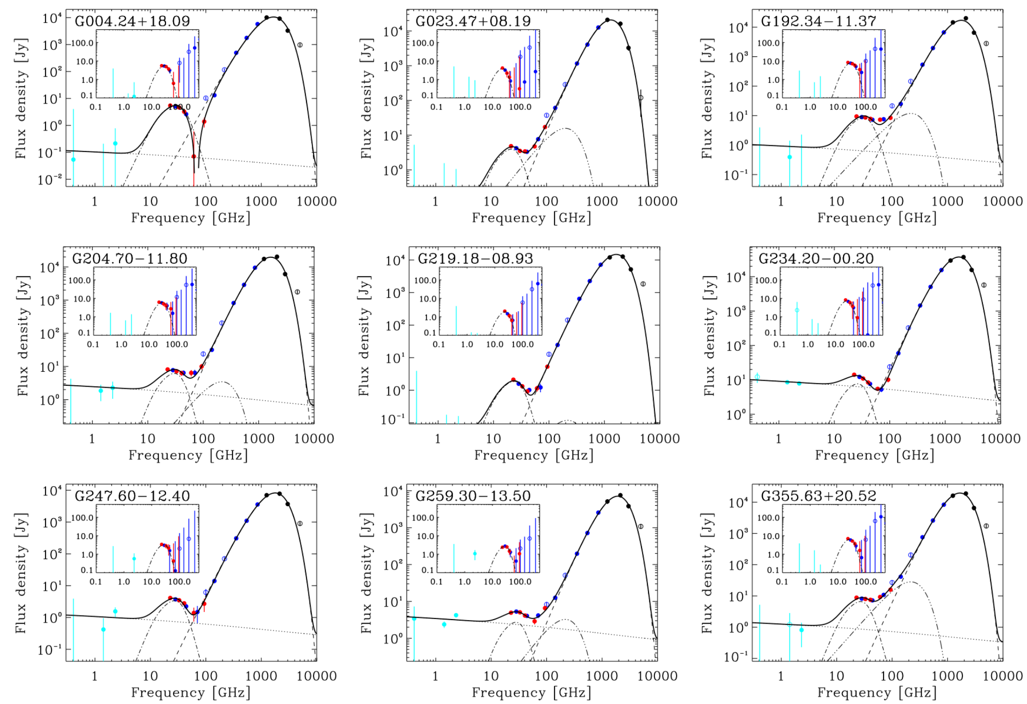


Fig. 8. SEDs for the sources with very significant AME and $f_{max}^{UCH\,II} < 0.25$. Data points are shown as circles with errors and are colour-coded for radio data (light blue), WMAP (red), *Planck* (blue), and DIRBE/ IRAS (black). The best-fitting model of free-free (dotted line), thermal dust (short-dashed line), CMB (triple-dot dashed line), and spinning dust (dot-dashed line) is shown. Data included in the fit are shown as filled circles, while the other data are unfilled. The residual spectrum, after subtraction of free-free, synchrotron, CMB, and thermal dust components, is shown in the *insert*. The best-fitting spinning dust model is also shown.

Planck Collaboration et al. (2014)

spectrum inconsistent with synchrotron or free-free

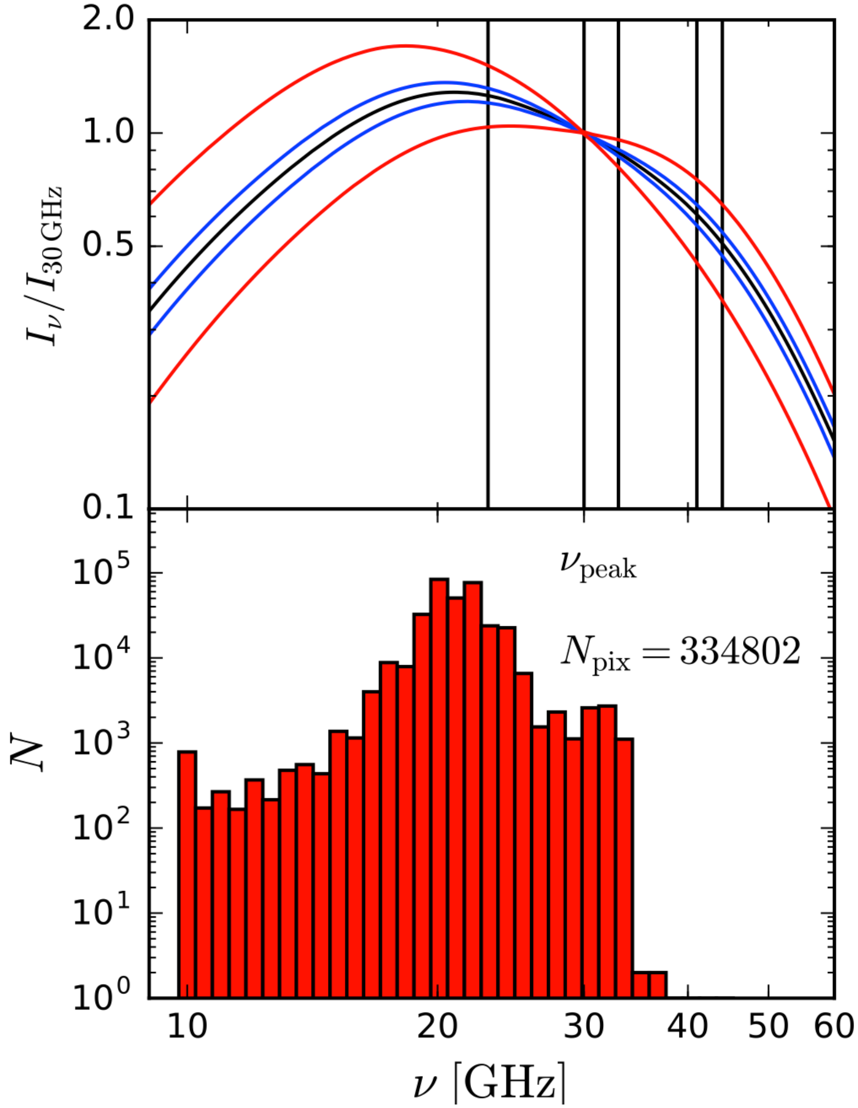
AME peaks near ∼30 GHz

peak frequency appears to vary from region-to-region

AME is ∼30 times stronger than power-law extrapolation of dust opacity to 30 GHz

Spectrum of the AME over the sky

WMAP+Planck ("Commander" analysis):



from Hensley & Draine (2017)

- AME spectrum: only well-determined on bright sources, which may not be typical...
- Full-sky analysis is based on only 5 bands (23-45 GHz):
  typical AME $\nu_{\mathrm{peak}} \approx 20\,\mathrm{GHz}$
- Eagerly await more data:
  C-BASS all-sky map at 5 GHz...
  QUIJOTE (Tenerife): 10-40 GHz

Anomalous Microwave Emission

AME Intensity

- Dust radiates at $10-60\,\mathrm{GHz}$ much more strongly than expected for thermal emission from large grains: "Anomalous Microwave Emission" (AME)
- $\nu_{\rm peak} \approx 20\,\mathrm{GHz}$
- $\nu_{\rm peak}$ varies from region to region
- PAHs, expected to spin at $\sim 10-60\,\mathrm{GHz}$, could account for AME *if* dipole moment is right
- *Surprise:* **NO** evidence of correlated variations in

$$\frac{AME \text{ power}}{\text{total dust power}} \quad \text{with} \quad \frac{PAH \text{ power}}{\text{total dust power}}$$

  (Hensley et al. 2016)
- Perhaps AME is rotational emission from **nanosilicates**
  [or perhaps nanodiamonds? (Greaves et al. 2018)]

AME Polarization

Theory:

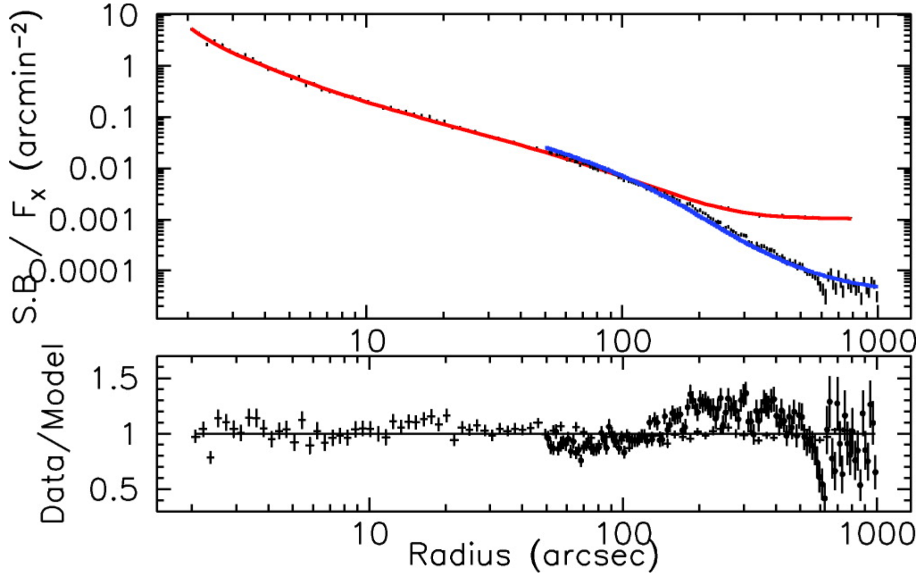
- Nanoparticles small enough to spin at $\sim$20 GHz are expected to be **randomly-oriented** (Lazarian & Draine 2000; Draine & Hensley 2016) [but: see (Hoang et al. 2016)]
- If AME is rotational emission, it should be **unpolarized**

Observations:

- AME is essentially unpolarized
  supports "spinning dust" hypothesis

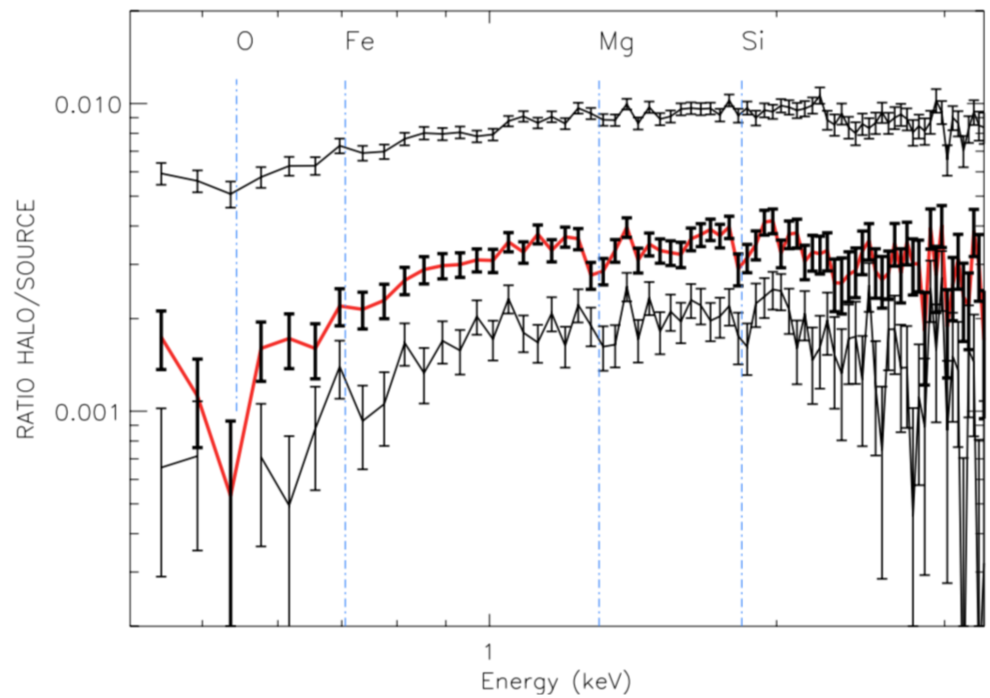
X-Ray Studies: Scattering Halo Intensity and Spectrum

- Small-angle scattering by dust
  $\rightarrow$ X-Ray "halo" around point sources
- For given model, halo can be accurately calculated (even for irregular grains: Hoffman & Draine 2016)
- Comparison of standard graphite-silicate model with observations:



GX5-1 (Smith 2008)

Spectrum of scattering halo:



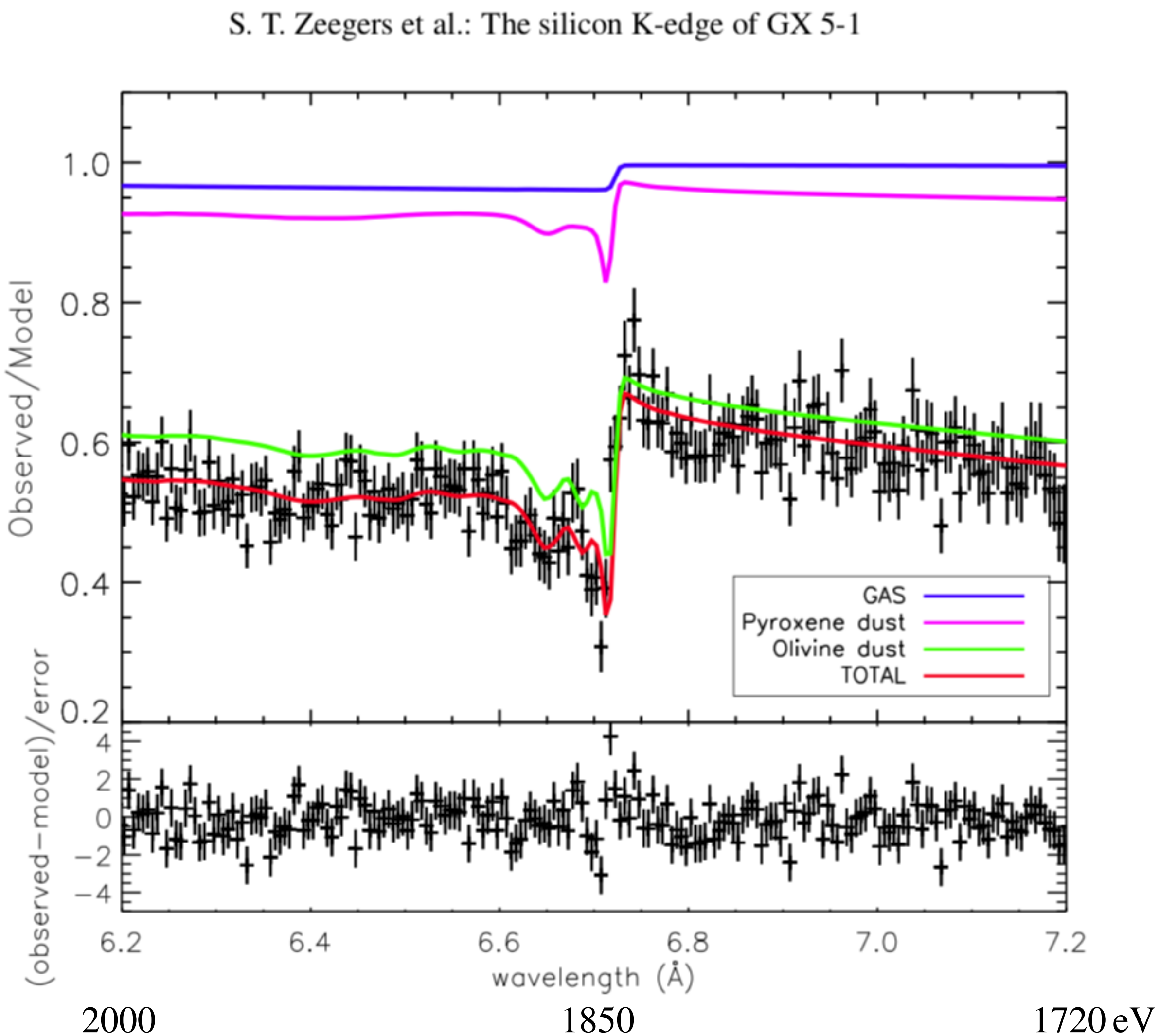
Cyg X-2 (Costantini et al. 2005)
(XMM-*Newton*)
$\sim 230'', 290'', 350''$

- Tests of: Size distribution, porosity, composition

X-Ray Studies: Transmission Spectrum

- Extinction =
  scattering + absorption
- High S/N →
  study details near X-ray absorption edges
- Sensitive to chemical environment of absorbing atom
- Deduce chemical composition of dust
- Chandra resolution marginal – were hoping for *Hitomi*...

e.g., use Si K edge to study silicates



Chandra spectrum of GX5-1 (Zeegers et al. 2017)

Some Conclusions...

- Size distribution extending from molecular sizes ($\sim$4Å, $\sim$30 atoms) to $\gtrsim 0.3\mu\mathrm{m}$
- Most of mass in large grains, most of surface area in small grains
- Small grains: substantial PAH component (may also include significant population of silicate nanoparticles (Hensley & Draine 2017)
- Grain mass: mostly silicate, $\sim$1/3 of volume is carbonaceous
- Silicates:
  - Amorphous silicate strongly confirmed by IR spectroscopy
  - Composition intermediate between olivine (M_2SiO_4) and pyroxene ($MSiO_3$), where M = Mg or Fe
  - Silicates appear to be Mg-rich
  - Most Fe in non-silicate form (metallic Fe? Fe oxides?)
  - Large silicate grains are aligned.
  - Silicate grains may be approximated by $\sim$1.5:1 oblate spheroids, moderate porosity
- Anomalous Microwave Emission (AME)
  - Probably "spinning dust"
  - Nanosilicates may dominate rotational emission
  - Theory: spinning dust emission at $\gtrsim 20\,\mathrm{GHz}$ should be unpolarized

Some Open Questions ...

- What is grain porosity and actual grain geometry?
- Are silicate and carbonaceous materials actually segregated?
  To what extent mixed in single grains?
- Why do carbonaceous grains appear to be non-aligned?
  (lack of polarization in $3.4\mu\mathrm{m}$ C-H stretch)
- How is size distribution maintained in ISM?
- What is the carbonaceous material?
  - polycrystalline (turbostratic) graphite?
  - glassy carbon (metallic)?
  - (hydrogenated) amorphous carbon (semiconductor)?
  - (hydrogenated) diamond (insulator)?
- What form is most of the Fe in?
  Is it ferromagnetic?
- Where is the "missing" oxygen in translucent clouds?


THANK YOU

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