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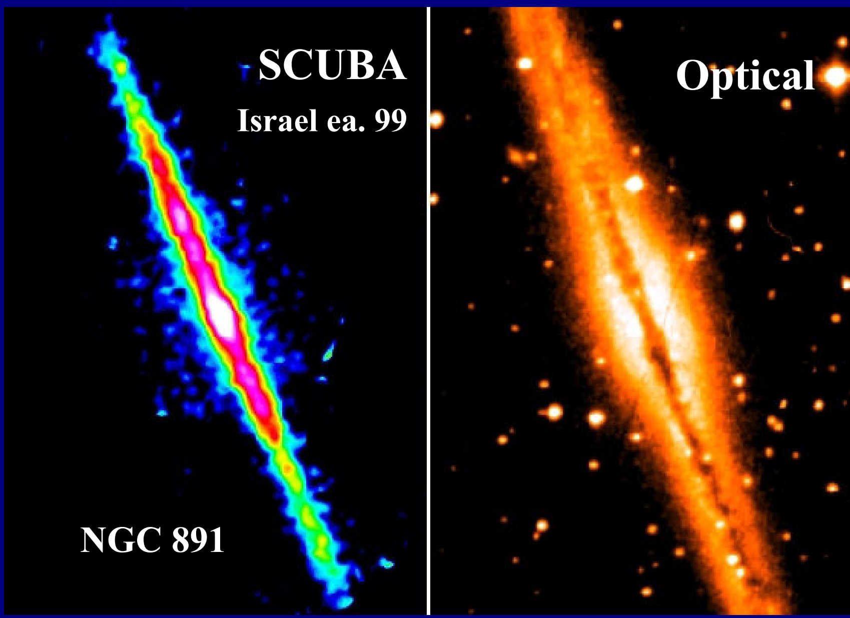
Cosmic Dust in Space



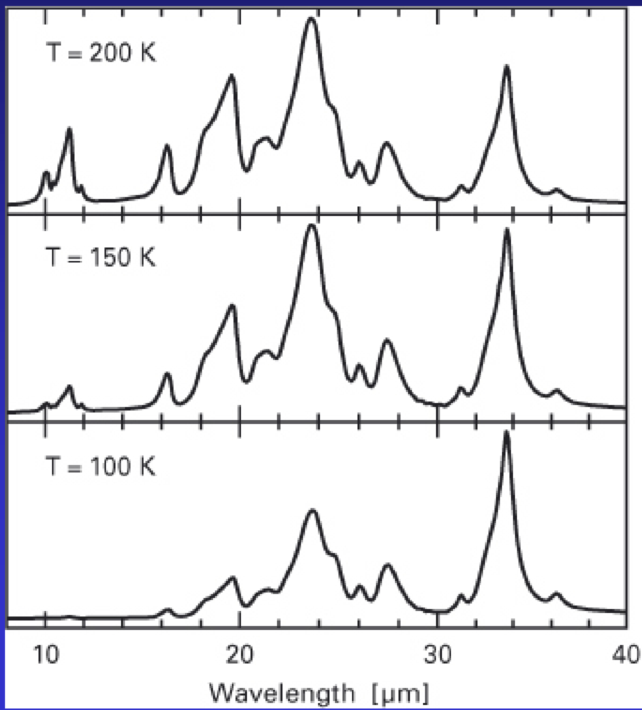
Disks 2006, September 2006, Vidago Palace, Portugal

Motivation
Cosmic Dust Studies

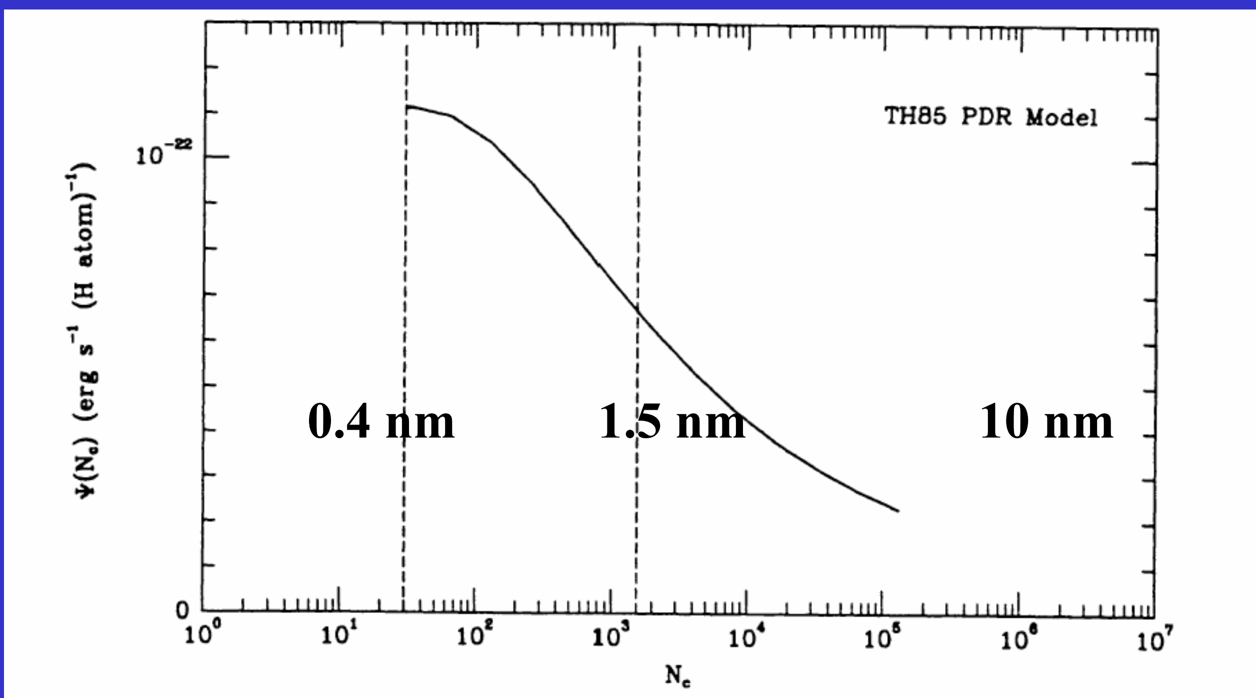
- Dust extinction, polarization, spectroscopy, continuum emission as diagnostic tools (Optical depth, magnetic fields, temperature, chemistry, growth processes, mixing, …)
- Dust: Thermal, dynamical, and chemical structure
- Interesting structural and optical behaviour (Tunneling processes at low temperatures)

Example: Spectrum of forsterite particles at different temperatures

Flux



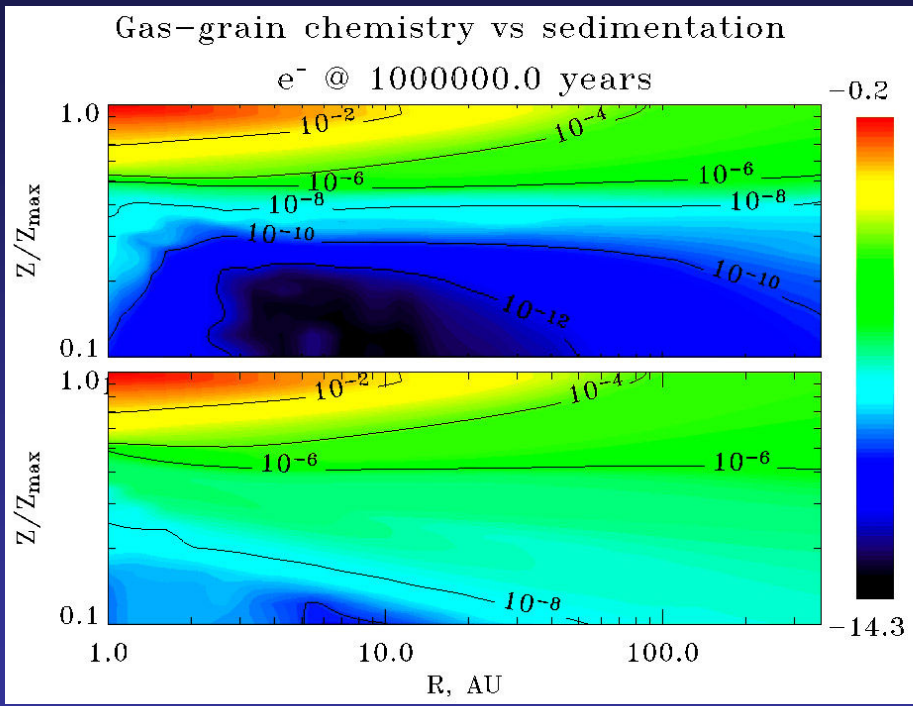
Photoelectric heating



Bakes and Tielens (1994)

Ionization structure of a T Tau disk

(Semenov, Wiebe, Henning, 2004, A&A, 417, 93)

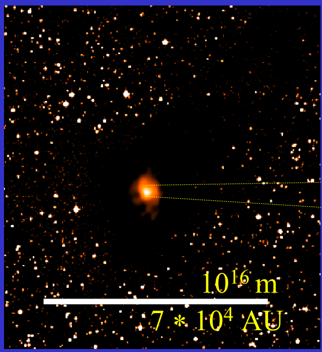


„Layered“ vertical structure

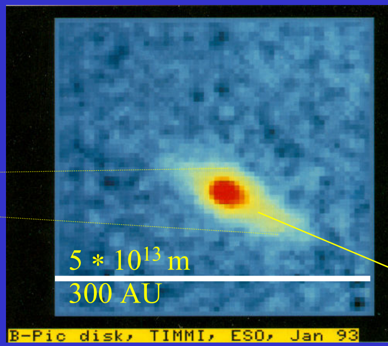
What can you expect?

- Talk # 1: General properties of dust + Optics of dust particles
- Talk # 2: Mineralogy of protoplanetary dust grains
- Talk # 3: Evidence for grain growth (Saturday morning)

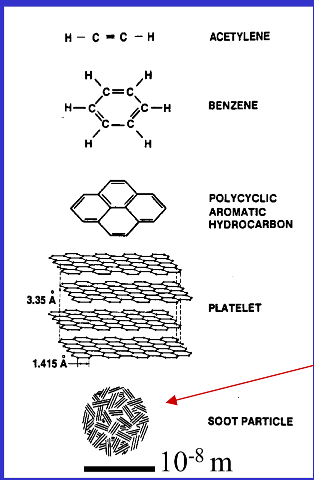
DUSTY DIMENSIONS



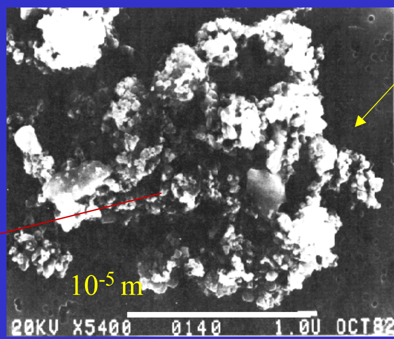
Molecular cloud core



Circumstellar dust disk



Small particle

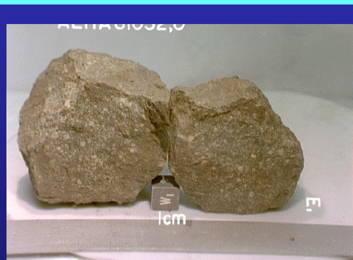


Coagulated dust grain

Learning about Dust in Space

Direct analysis

- Instruments on spacecraft
- Sample return (Stardust)
- Dust collection in upper atmosphere
- Dust in the museum (meteorites)



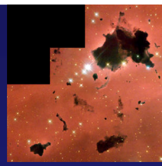
Dust properties ?

- Structure & shape
- Chemical composition, mineralogy
- Size distribution

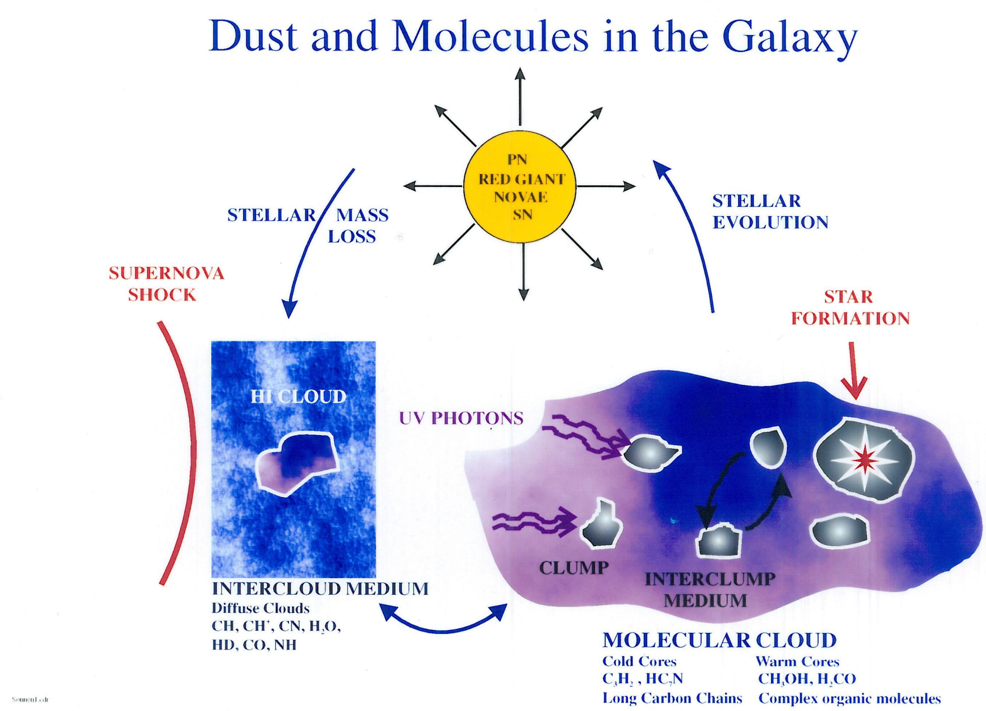
Remote sensing

- Astronomical observations

Nature of Cosmic Dust



- Fractional abundance of elements and abundance pattern (Chemical composition)
- Extinction and polarization curves (UV, VIS, NIR) (Chemical composition, size)
- Scattered stellar light
- Infrared resonances (Chemical composition, size)
- IR/millimetre dust continuum emission (Size)
- Stardust in meteorites
- Analysis of cometary material and IDPs (?)



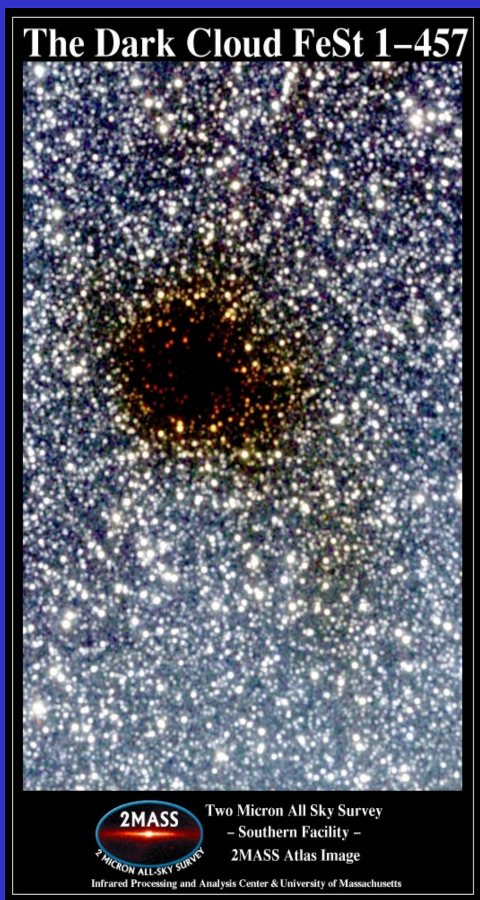
Basic Types of Dust Mixtures

Time ↓

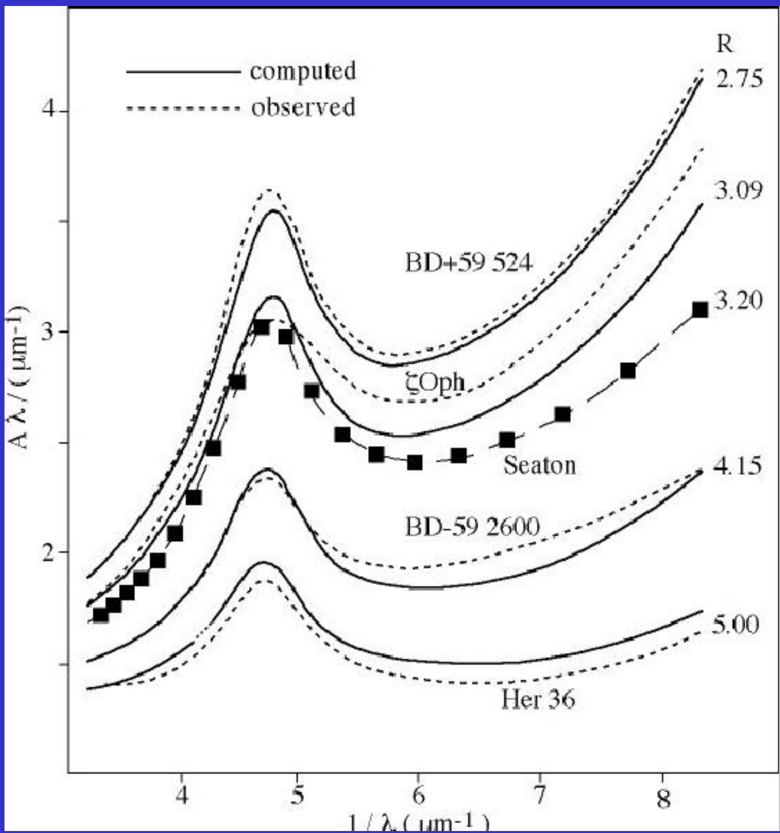
- **Stardust** — Original dust formation
- **Interstellar Dust** — UV/cosmic ray processing; Modification by shocks
- ⇅
- **Molecular Cloud Dust** — Surface chemistry; Ice mantles, Coagulation
- **Protostellar Dust**
- **Interplanetary Dust**

Some facts at the beginning

- Silicates and other oxides (IR features), carbonaceous dust (UV bump, 3.4 µm feature)
- Additional materials (carbides, nanodiamonds)
- Molecular ices in cold clouds
- Broad size distribution (VSGs, PAHs)
- Grain growth in disks

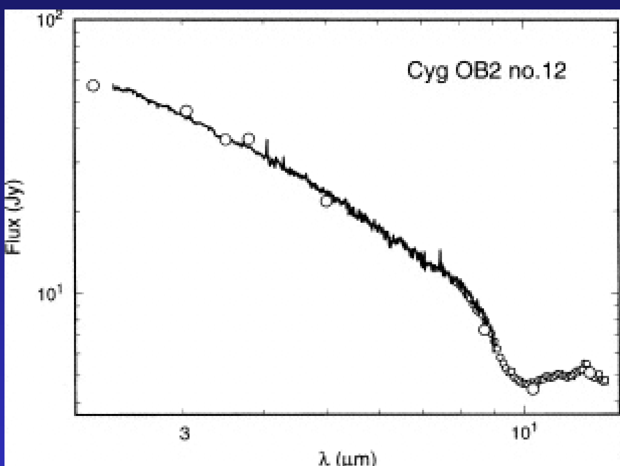


Extinction Curves



h1

Diffuse ISM dust (Whittet et al. 1997)



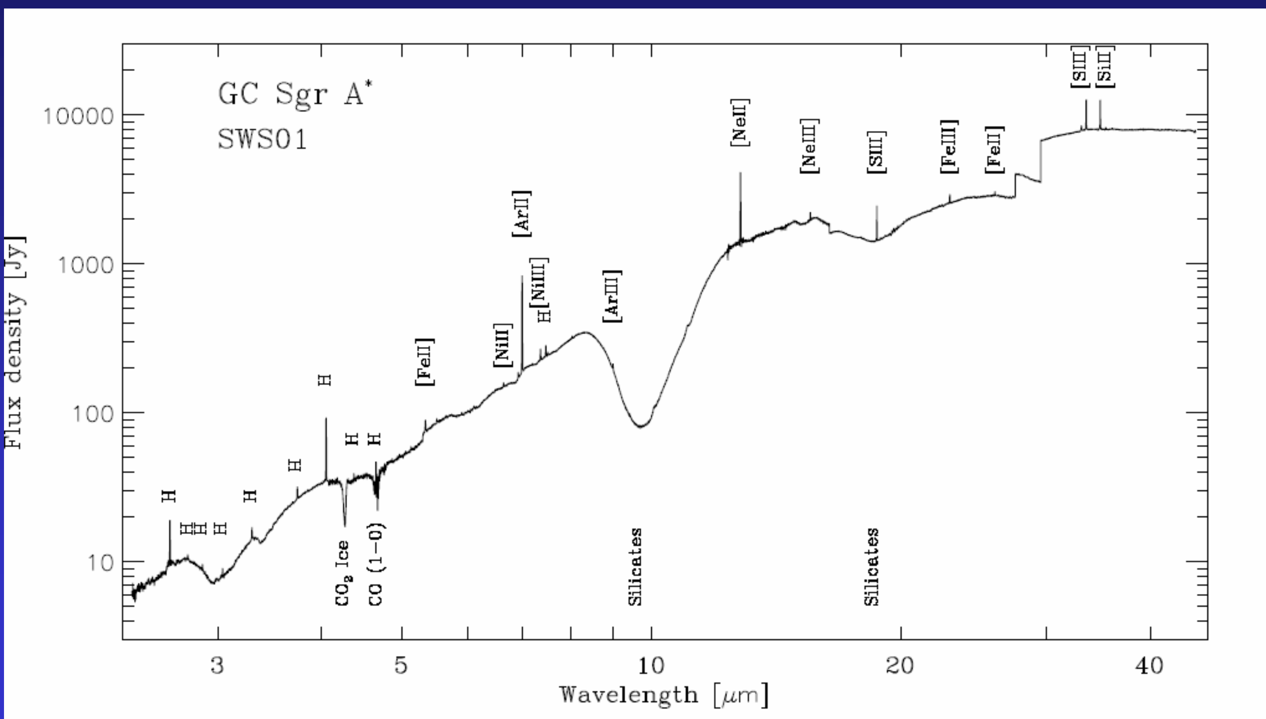
No evidence for crystalline silicates in the diffuse ISM (<2%, Li & Draine 2001, Jäger et al. 2003, Kemper et al. 2004)

Amorphization by cosmic rays/shock processing in ISM/re-condensation of am. silicates in the ISM (Jäger et al. 2003)

h1 Amorphization easier for Fe-rich silicates
henning; 10-08-2005

h5

Diffuse ISM dust (Lutz et al. 1996)



Carbonaceous dust material is poor in oxygen!

h5 Amorphization easier for Fe-rich silicates
henning; 10-08-2005

Dust emission spectrum

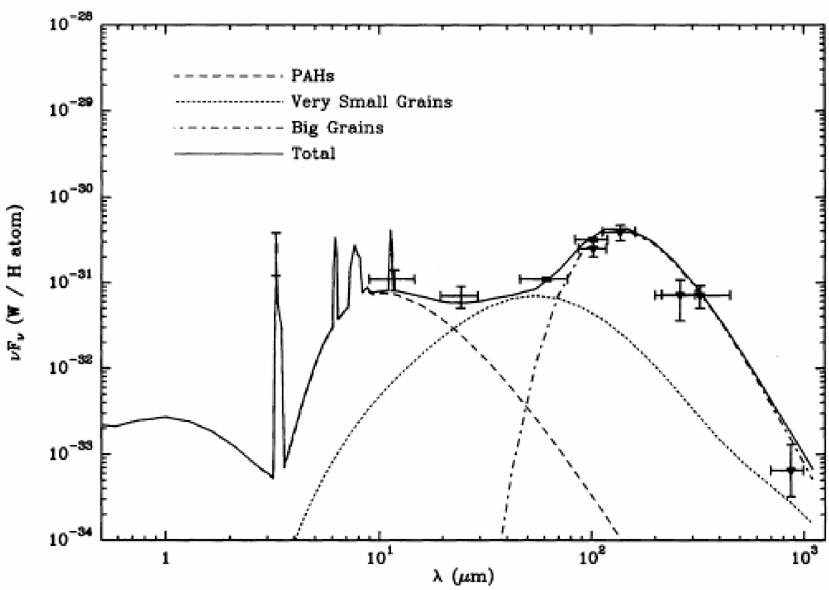
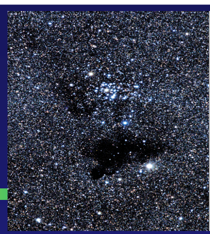
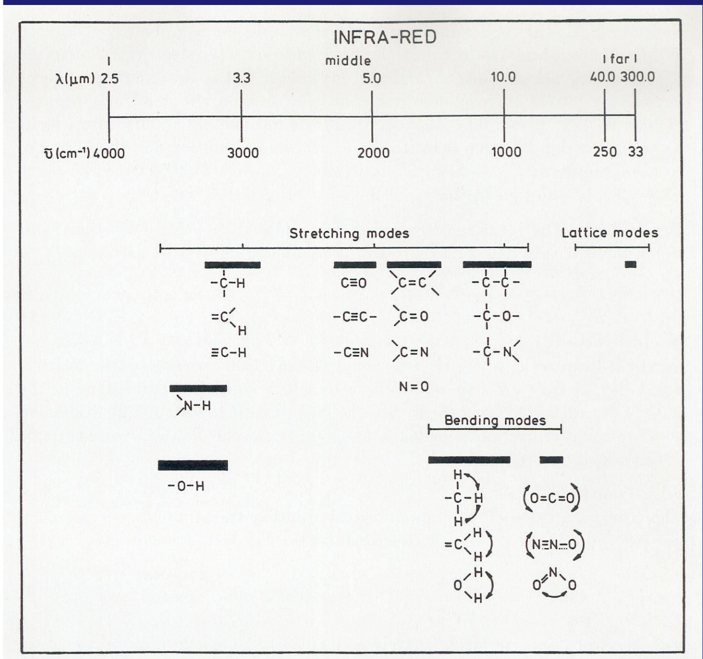


Fig. 4. Dust emission spectrum. Observations (crosses) pertain to the "cirrus" interstellar diffuse medium (see Table 1 and text). The horizontal bars represent the filter width used in the observations (given in Table 1). The model resulting spectrum (continuous line) is the sum of the three components that are PAHs, VSGs, and BGs.

Desert, Boulanger & Puget (1990)

Infrared spectroscopy - The infrared fingerprint region

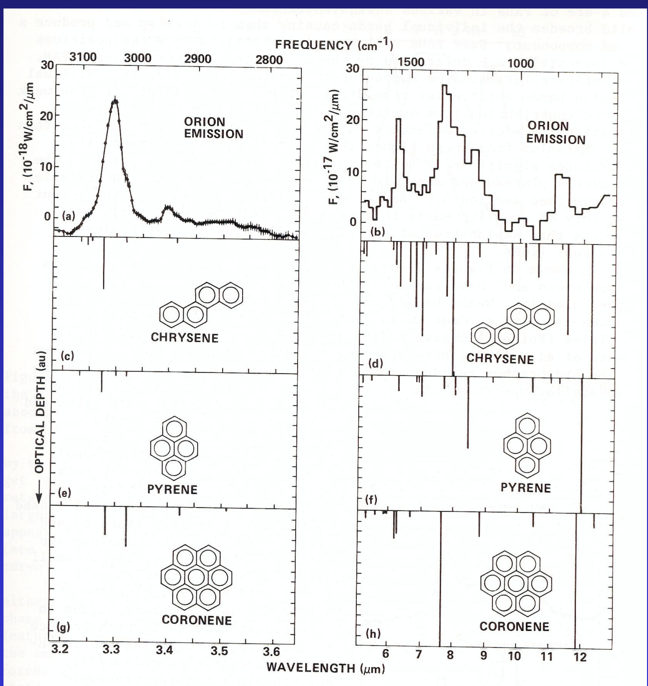




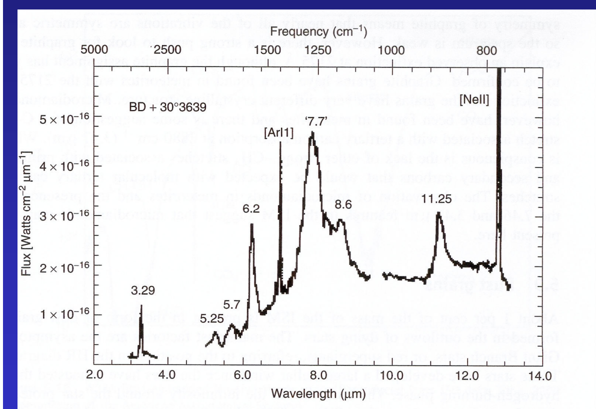
- Silicates: 10 and 18 μm
- Oxides: 12 to 30 μm
- Carbonaceous material: (aliphatic): 3.4 μm
- PAHs (3.28, 6.1, 7.7, 8.6 and 11.3 μm + other bands)
- Molecular Ices (e.g. H_2O: 3.08, 6.0 and 42 μm)

Adapted from Allamondola (1984)

Emission spectrum

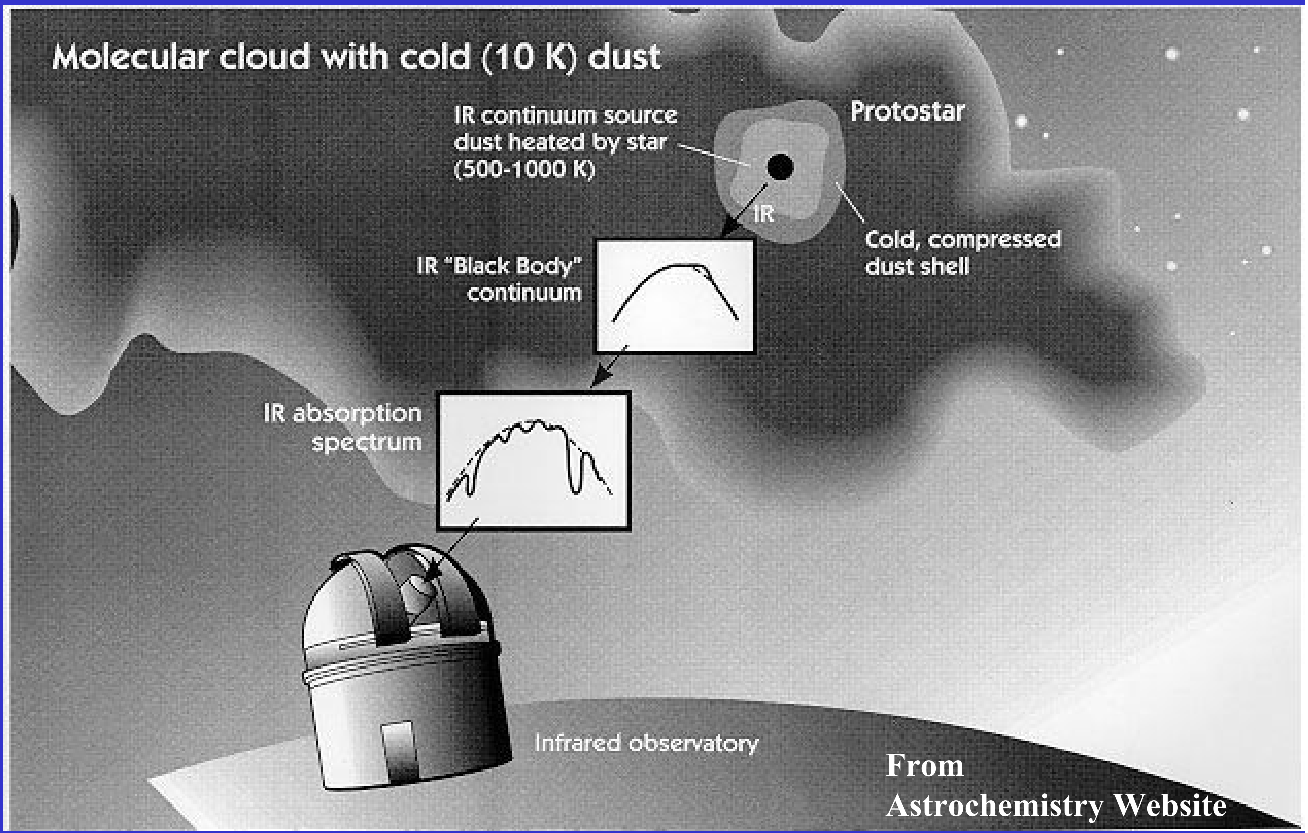


(Allamandola et al. 1987)

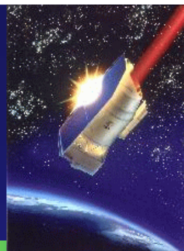


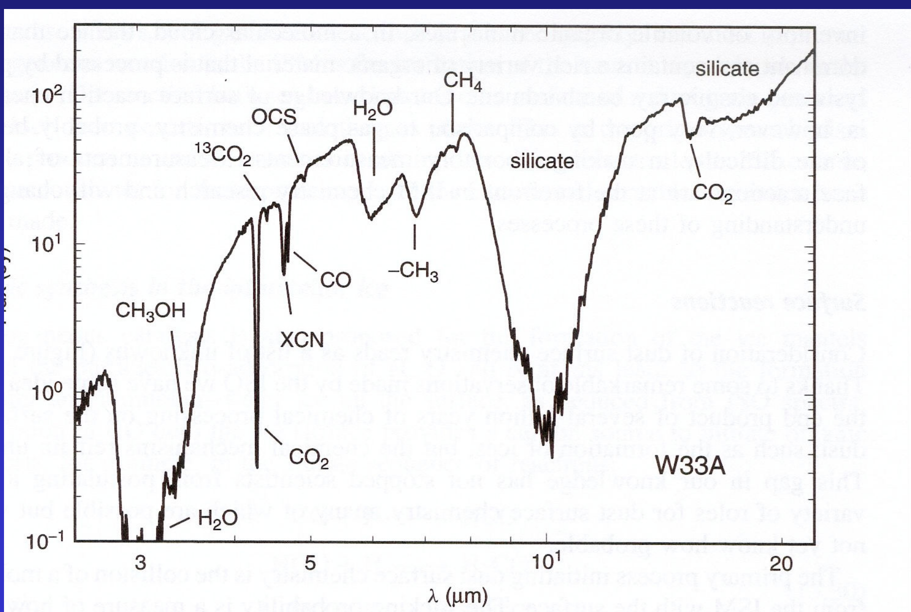
(After S. Sandford)

Infrared absorption spectroscopy



Infrared absorption spectroscopy of molecular ices in cold regions





Data from the Infrared Space Observatory – Gibb (2000)

Grain Model for Molecular Cloud Material

J. M. Greenberg
„Yellow Stuff“

What did we learn so far?

- Main dust components: Silicates (10 and 18 µm features), Carbonaceous dust (217.5 nm feature, 3.4 µm absorption feature)
- Other dust components exist (SiC, oxides, nitrides)
  - Detected in envelopes around AGB stars
- Molecular ices (H_2O, CO, CO_2, HCOOH, CH_3OH, CH4, NH_3)
- Emission features due to PAHs
- Very Small grains vs. „classical grains“

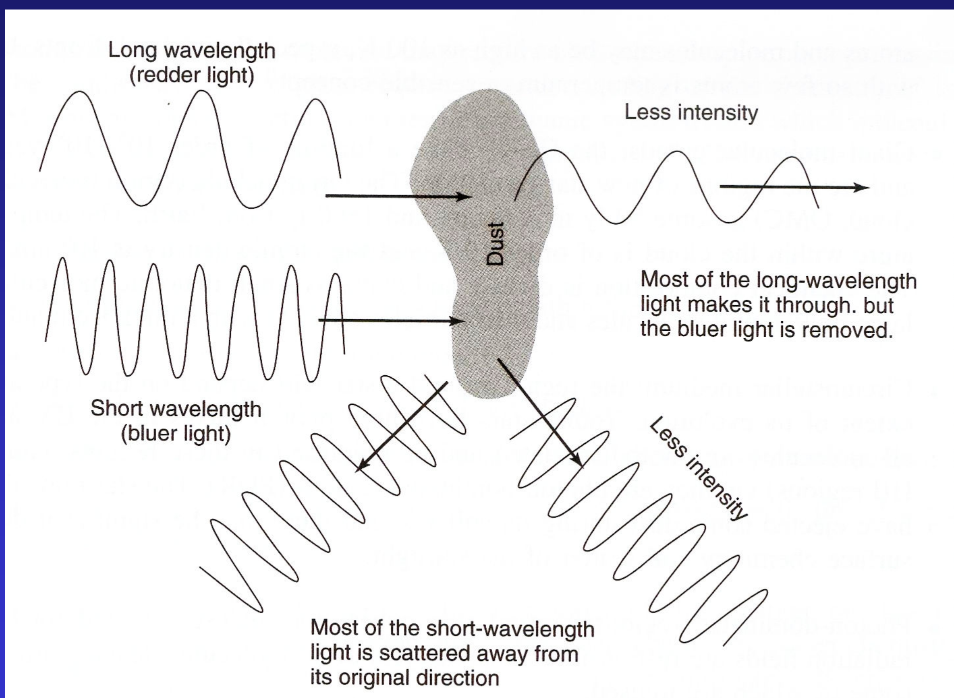
Grain Models for the diffuse ISM

Draine & Lee (1984): Mixture of (bulk) graphite and silicate grains, Power law size distribution after Mathis et al. (1977, MRN): $dN(a)/da \sim a^{-3.5}$ (10 nm to 300 nm)

Hong & Greenberg (1980): Silicate spheres (0.01 µm), graphite spheres (0.018 µm), Core-mantle grains

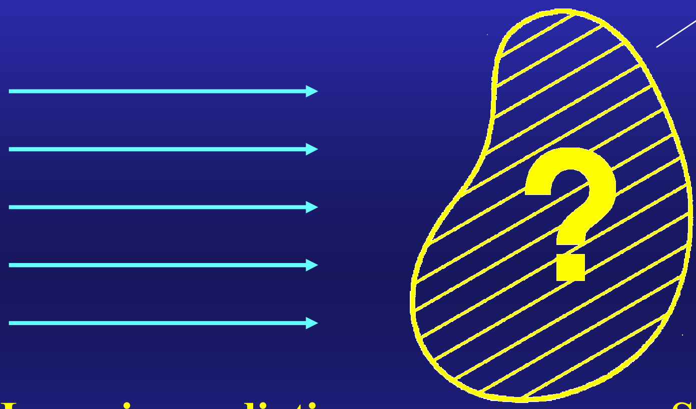
Mathis & Whiffen (1989): Composite grains (fvac=0.8, power law size distribution with exponent 3.7 (30 to 900 nm) Free graphite particles

Interaction of light with small particles



After Fraser et al. (2002), see „Astrochemistry“

Dust and Radiation



Absorption

- Transformation of energy to some other form
- Re-emission at different wavelengths

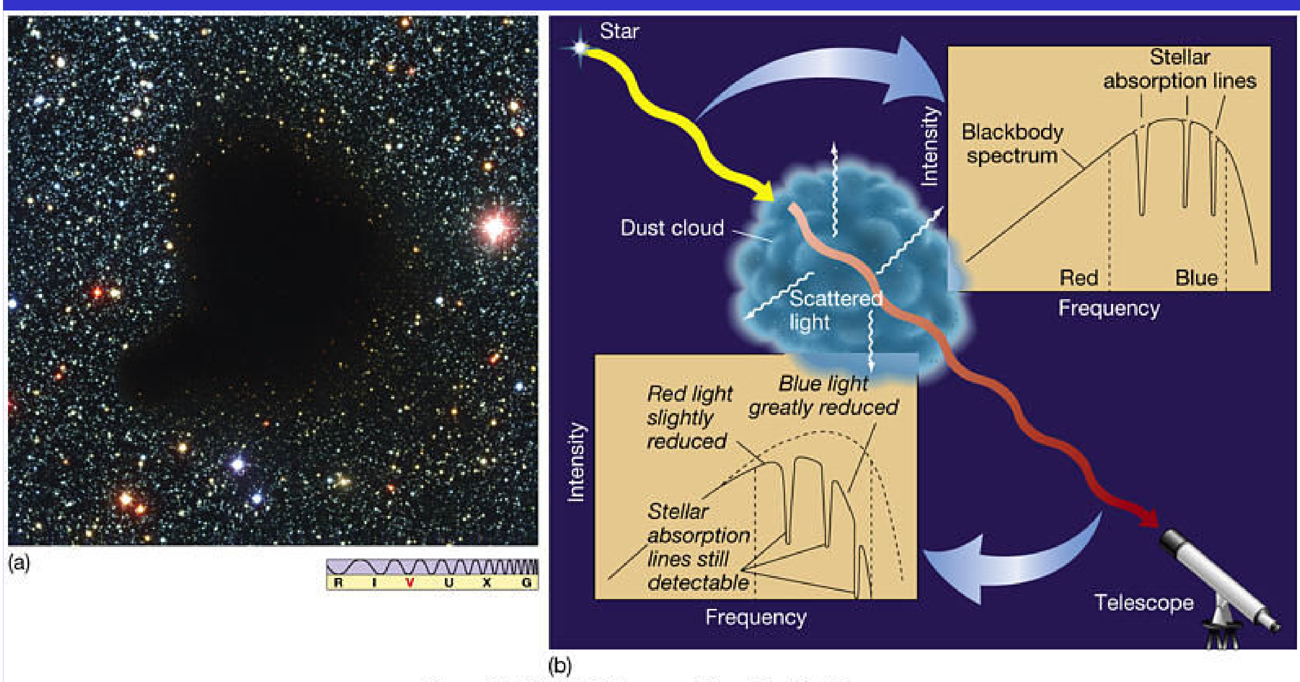
Incoming radiation

- plane waves
- polarised somehow
- some spectrum

Scattering (elastic)

- Change in direction
- Change in polarization
- No change in wavelength

Reddening of stellar light



(a) (b)

Light Scattering by Particles

Important quantity: Poynting vector (all in SI units)

S = **E** x **H**

Energy per unit time and area carried by the EM field;
E and **H** – Electric and magnetic field vectors

Let us chose an area with unit normal vector **n**
(outward normal chosen, see Bohren & Huffman 1983)

Rate W at which EM energy crosses the boundary A is:

$W = \int_A \mathbf{S}\ \mathbf{n}\ dA$ (W>0 net transfer into volume = absorpt.)

Light Scattering by Small Particles

Time-averaged Poynting vector for time-harmonic field is:

$$\langle \vec{S} \rangle = \left\{ \vec{E} \times \vec{H} \right\}$$

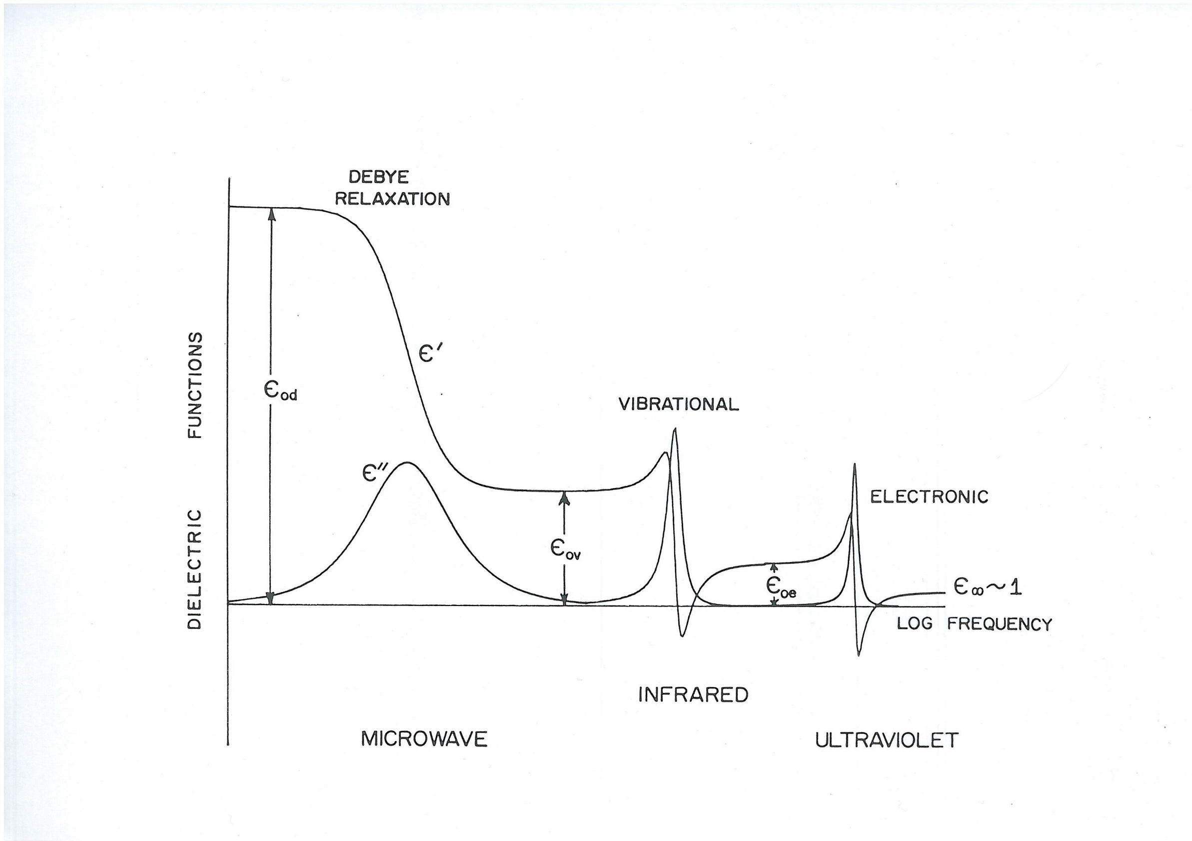
Complex refractive index: $m = n + ik$; $m^2 = \varepsilon$

Plane harmonic wave:

$\mathbf{E}_C = \mathbf{E}_0 \exp(-2\pi k\ z/\lambda) \exp(i\ 2\pi n\ z/\lambda - i\omega t)$

Attenuation (k) Phase velocity (c/n)

Dielectric Function



Light Scattering by Particles

Time-averaged Poynting vector for plane and homogeneous wave:

½ Re(sqrt(ε/μ) E_0^2 exp(-4 π*k* z/λ) **e** which means in

Vacuum:

½ E_0^2 = F (magnitude of Poynting vector, flux)

also called irradiance I (energy per unit area and time)

Light Scattering by Particles

Cross sections for scattering and absorption:

$C_{sca} F_{incident} = W_{sca}$ (Rate at which energy is scattered)

$C_{abs} F_{incident} = W_{abs}$ (Rate at which energy is absorbed)

$C_{ext} = C_{abs} + C_{sca}$ Extinction cross section

$A = C_{sca}/C_{ext}$ Albedo

Angular dependence of scattering expressed by phase function $p(\theta,\Phi)$ with $\int p(\theta,\Phi)\, d\,\Omega = 1$

Light Scattering by Particles

$F(\theta, \Phi) = F_{incident}/r^2\, p(\theta, \Phi)\, C_{sca}$

Asymmetry parameter:

$g = \int p(\theta, \Phi)\, d\Omega$

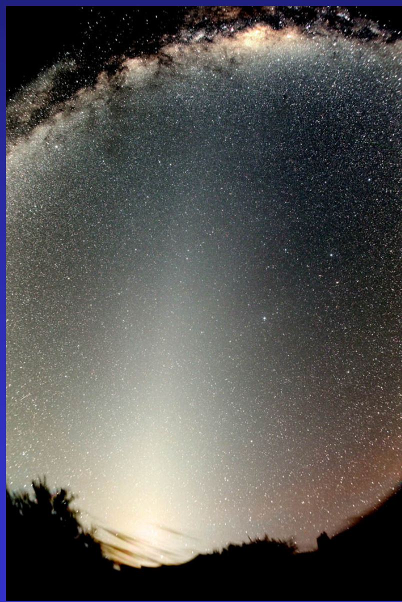
g= 0 (isotropic scattering),
g=1 (pure forward scattering),
g=-1 (pure backscattering)

Radiation pressure cross section:
$C_{pr} = C_{ext} - g\, C_{sca}$: Transmitted momentum $F\, C_{pr}/c$

Light Scattering by Particles

Other quantities: Efficiencies $Q=C/\sigma_{geom}$

Mass absorption coefficient κ_m:
Cross section per unit mass
$C_{abs}/\delta V$ (Sphere – $\frac{3}{4}$ $Q/a\delta$)



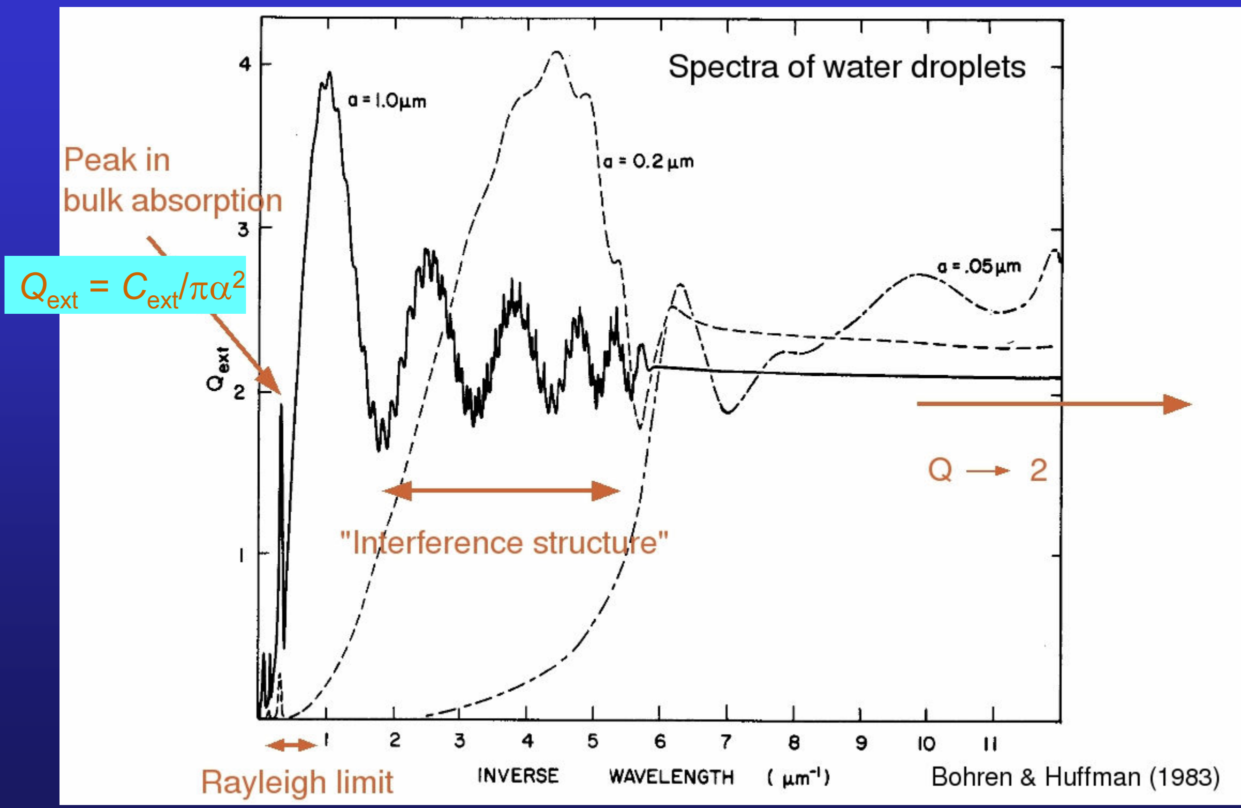
Important cases: Wavelength versus particle size

- **$\lambda \ll a$: Geometrical Optics**
  Propagation of light described by rays
  For absorbing media: Light can penetrate only within the skin depth (scattering is surface effect)
  $C/V \infty 1/a$
  Very large particles: $Q_{ext} = 2$ (Babinet`s theorem)

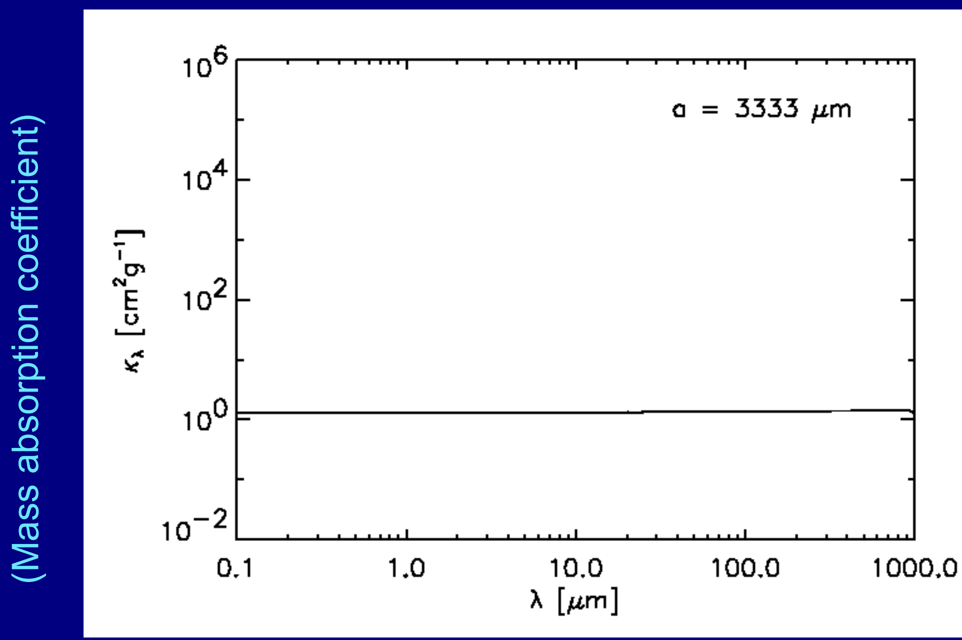
- **$\lambda \sim a$: Wave Optics** (Spherical particles: G. Mie 1908)
  C dominated by interferences and resonances

- **$\lambda \gg a$: Rayleigh limit/Quasistatic limit $|m|x \ll 1$**
  Incident and internal fields can be considered to be static fields; only dipole electric mode needs to be considered

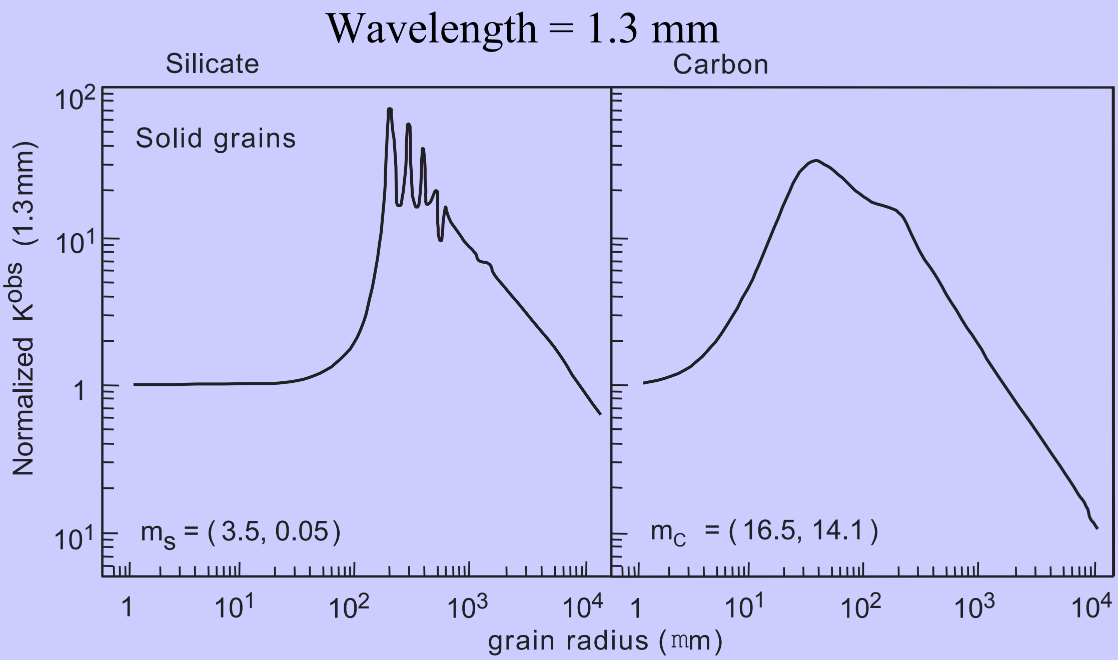
Mie Theory – Results - Spectrum



Grain growth: Change of MAC



Millimetre Opacity – Function of Size



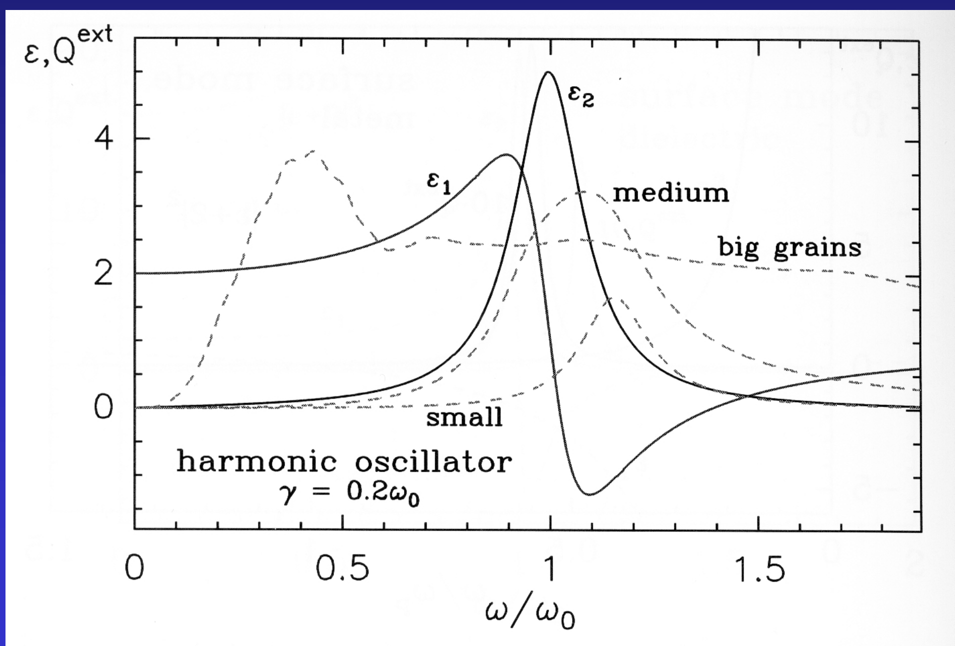
$$\kappa\left(\nu, \mathrm{a}\right) \propto \pi \mathrm{a}^2 \mathrm{Q}\left(\nu, \mathrm{a}\right) / 4\pi / 3\, \rho_d\, \mathrm{a}^3$$

Very small grains: κ(ν, a) independent of a

Very large grains: $\kappa(\nu, a) \propto a^{-1}$

Krügel and Siebenmorgen (1994)

Light scattering



Light Scattering - Spheres

Mie theory (G. Mie 1908)

Scattering problem for spheres (scattered and internal field determined by expanding both fields into an Infinite series of independent solutions to the wave equation):

Very small particles in the Rayleigh limit:
$x=2\pi a/\lambda \ll 1$ and $|m|x \ll 1$

Non-magnetic material:
$Q_{ext} = 4\ x\ \mathrm{Im}\{(m^2-1)/(m^2+2)\}$

$Q_{sca} = 8/3\ x^4\ |(m^2-1)/(m^2+2)|^2$

Light Scattering by Small Particles - Shapes

$C_{abs} = k\ \mathrm{Im}(\alpha)$ with α – polarizability

Ellipsoids (averaged over all orientations)

$C_{abs} = k\ \mathrm{Im}\ (\alpha_1 + \alpha_2 + \alpha_3)$

$C_{sca} = k^4/2\pi\ [|\alpha_1|^2 + |\alpha_2|^2 + |\alpha_3|^3]$

With $\alpha_i = V\ (\varepsilon - \varepsilon_m)/3(\varepsilon_m + L_i\ (\varepsilon - \varepsilon_m))$

Sphere: $L_i = 1/3$ (geometry factors, between 0 and 1)
$C_{abs} = k\ 3\ V\ \mathrm{Im}[(\varepsilon - \varepsilon_m)/(\varepsilon + 2\ \varepsilon_m)$

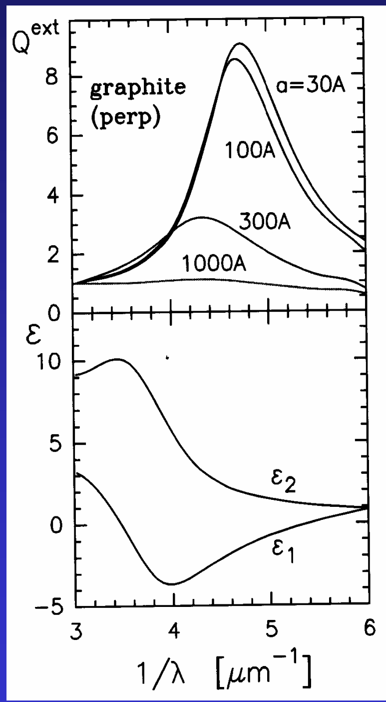
Light Scattering by Small Particles - Shapes

$C_{abs} = k\ \ 3\ V\ \mathrm{Im}[(\varepsilon - \varepsilon_m)/(\varepsilon + 2\ \varepsilon_m)]$

Surface resonances when imaginary part close to 0 and real part $\varepsilon_1 = -\ 2\ \varepsilon_m$

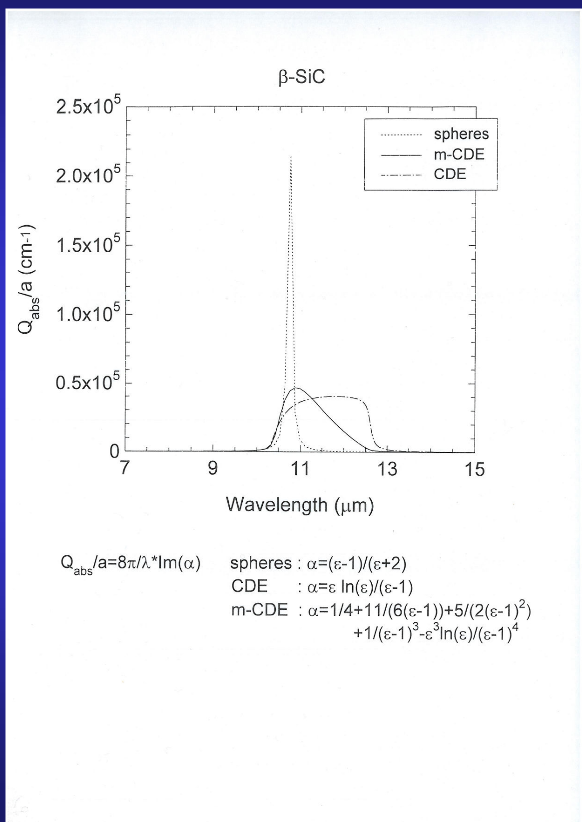
For a continuous distribution of ellipsoids:

$C_{abs} = k\ V\ \mathrm{Im}[2\ \varepsilon/(\varepsilon - 1)\ \ \log\varepsilon]$

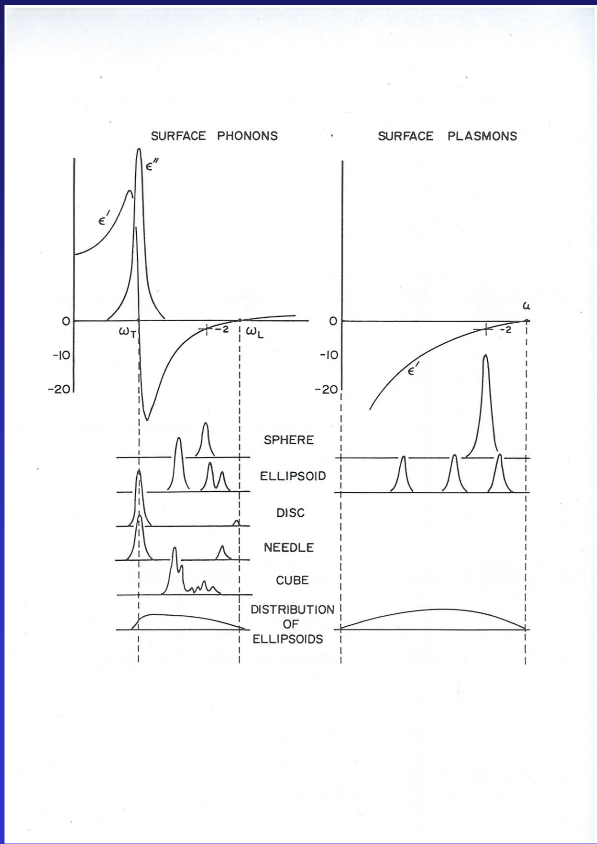


Log z denotes the principal logarithm of a complex number

Surface Modes

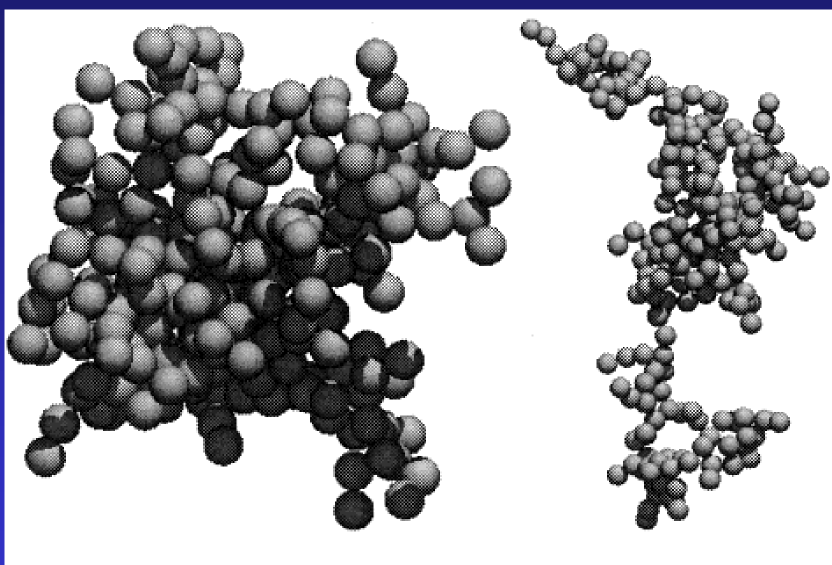


Surface Modes



Bohren & Huffman (1983)

Optical properties of aggregates



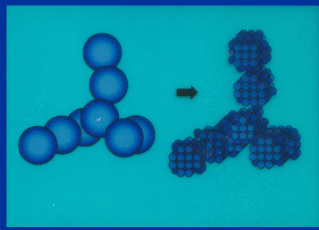
PCA

CCA

Modelling composite and fluffy grains: Average extinction $< C_{ext} >$ of a large number of clusters (ensemble average)

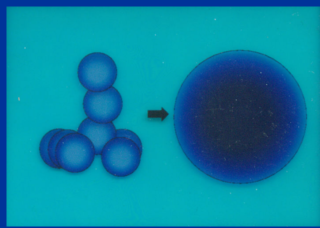
(a) „Deterministic“ approach

DDA, DMM



Calculate the extinction of individual clusters and average results.
Criticism: Very complicated, no sysmmetries, too much information needed.

(b) „Statistical“ approach



Derive equations for the average electric field and calculate average extinction.

Advantages: Method uses only „relevant“ information and exploits symmetries to facilitate calculations.

EMT SPFT

Silicate and carbonaceous aggregates

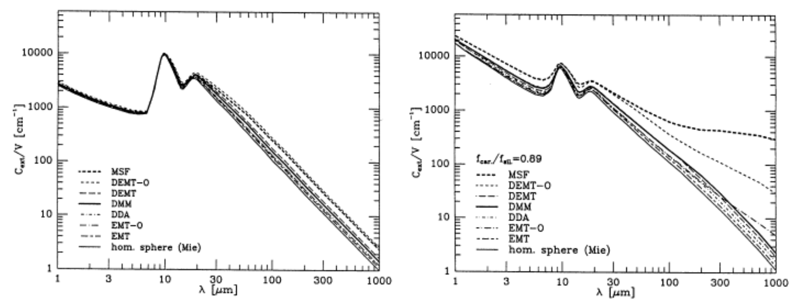


Fig. 5. C_{ext}/V for the silicate PCA clusters. The thick lines denote the lower (DMM, solid line) and the upper (MSF, dashed line) limit for the extinction of the clusters. For comparison C_{ext}/V for a compact sphere (Mie) are plotted

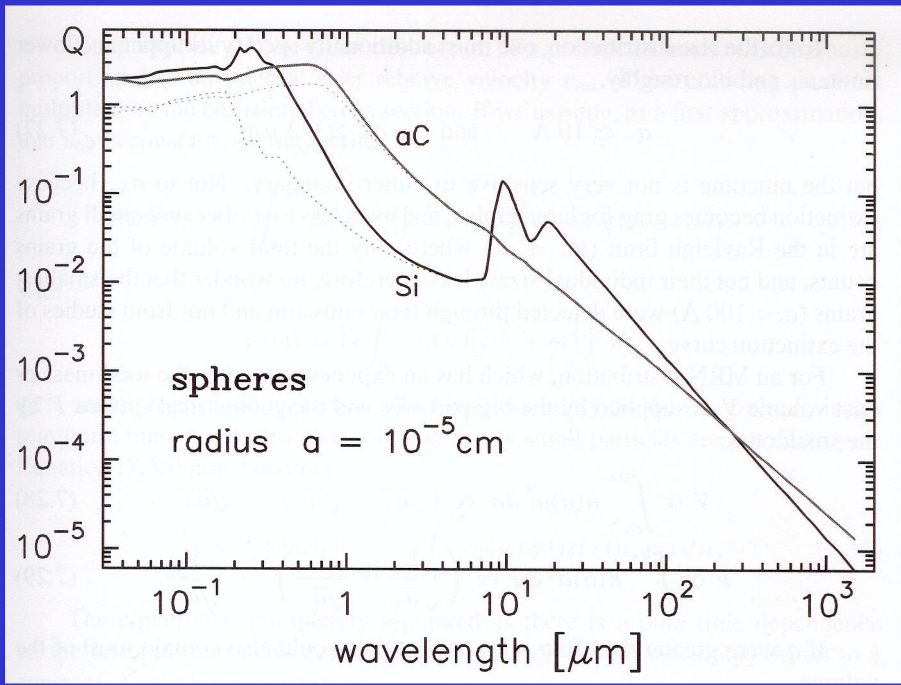
Fig. 7. Same as Fig. 5 except that the mixture of silicate and carbon is the refractory component in the clusters. The Mie curve, the DMM curve and the curve for the upper limit are the volume averages of the silicate and carbon PCA clusters

Fig. 6. Same as Fig. 5 except that amorphous carbon is the refractory component in the clusters

Fig. 8. Same as Fig. 6 but for the CCA clusters

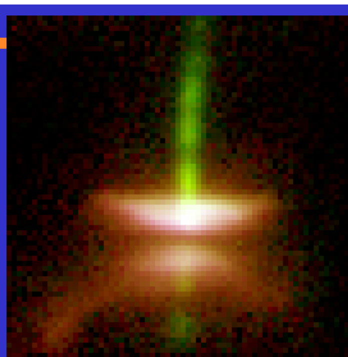
Stognienko, Henning & Ossenkopf (1995)

Optical behaviour of small particles



After Krügel (2003, p.235) – Absorption (dots), extinction (solid line)

Dust models for Accretion Disks



Pollack et al: 1994, ApJ 421, 615

- Olivine ($[Fe, Mg]_2 SiO_4$), orthopyroxene ($[Fe, Mg] SiO_3$), volatile and refractory organics, water ice, troilite (FeS), and metallic iron
- κ (1 mm) = 5 x 10^{-3} cm^2g^{-1} (gas + dust)

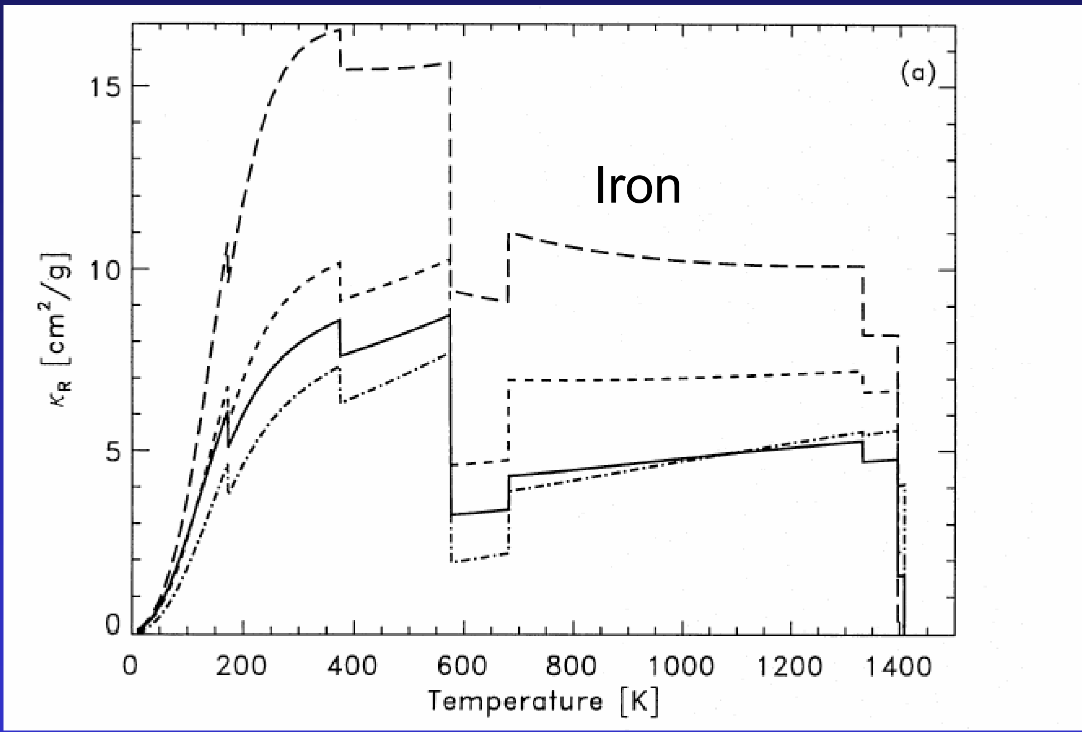
Krügel & Siebenmorgen: 1994, AA 288, 929

- Fluffy grains composed of subparticles of astronomical silicate and amorphous carbon with an admixture of frozen ice
- κ (1.3 mm) = 2 x 10^{-2} cm^2g^{-1} (gas + dust)

Henning & Stognienko: 1996, AA 311, 291 (Semenov et al. 2003)

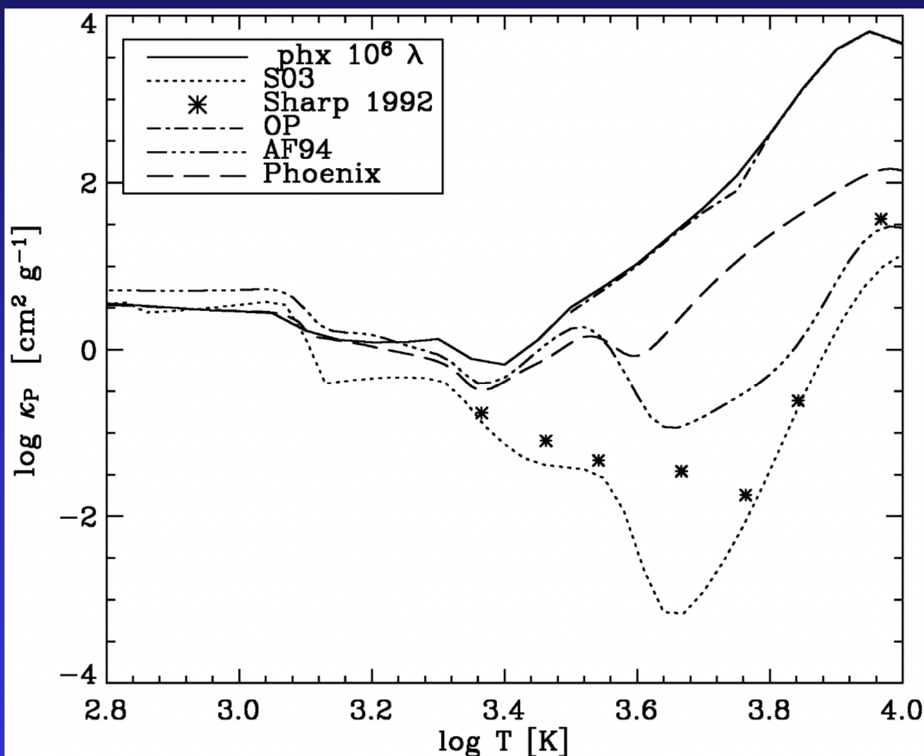
- Improved optical data and agglomeration models, Role of Fe
- κ (1.3 mm) = 10^{-2} cm^2g^{-1} (gas + dust, Fe-rich silicates)

The Role of Iron



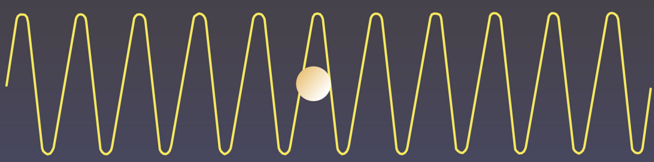
Henning & Stognienko (1996)

Comparison of different Planck means



Ferguson et al. (2005)

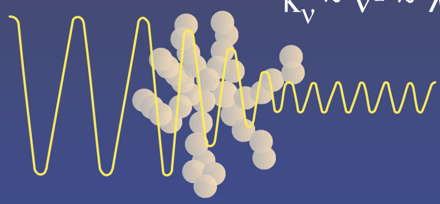
MM-waves interact with all atoms



Particle size << wavelength
⇒ coupling ~ $\lambda^{-\beta}$
1^{st} order: size independent, wave sees every atom

Conductors: "antenna" growth, absorption by free electrons

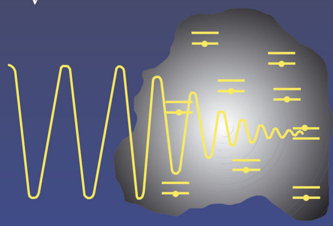
$\kappa_\nu \sim \nu^2 \sim \lambda^{-2}$ plasma skin depth



Fe, graphite

Insulators: absorption by lattice resonances

$\kappa_\nu \sim \nu^2 \sim \lambda^{-2}$ Lorentz "tail"



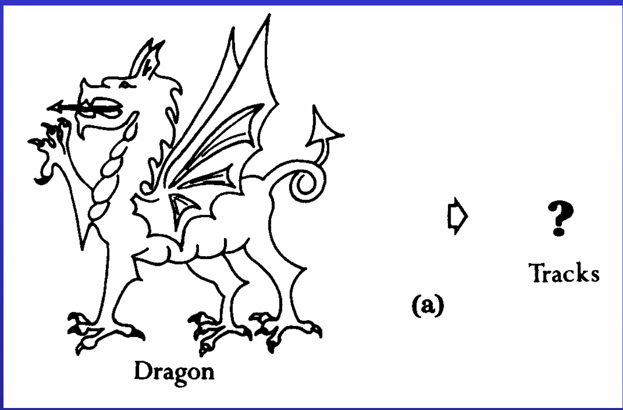
Olivines (silicates): Mg_2SiO_4

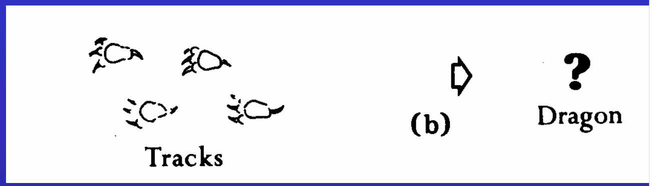
Disks

Construct your dust model …

1. Assume chemical composition, shape, size, internal structure distribution
2. Select the relevant laboratory data for n, k (material structure?, temperature?)
3. Calculate the cross sections (scattering codes)
4. Construct appropriate mean values
5. Apply these data in your radiative transfer calculation

The Inverse Problem





Bohren & Huffman (1983)

- Make some guess about the dragon
- Solve the forward problem
- Check, if the guess was correct
- If not, make a different guess ...

Back to Astrophysics …

Dust and Stars

- Without stars no dust (production of metals)
- Without dust no stars (dust surface – H_2 formation)
- Interaction of dust with radiation field (e.g. massive star formation)

Dust and Gas

- Formation of particles from the gas phase
- „Sink“ for gas phase atoms and molecules
- Formation of molecules
- Heating of the gas (photoelectric effect)
- Ionization degree

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Even more material to read…

Recent review papers:

Dorschner, J., Henning, Th.: Dust Metamorphosis in the Galaxy. Astron. Astrophys. Rev. 6, 271, 1995

Henning, Th. et al.: Laboratory Studies of Carbonaceous Dust. In: *Astrophysics of Dust.* 2004

Ehrenfreund, P., Charnely, S.: Organic Molecules in the ISM. ARAA 38, 427, 2000

Henning, Th., Salama, F.: Carbon in the Universe. Science 282, 2204, 1998

Henning, Th. et al.: Silicates – Space and Laboratory. In: Astrochemistry – Recent Successes and Current Challenges. Proceed. of IAU Symp. 2006

Some Books

Whittet, D.C.B: Dust in the Galactic Environment. IOP Bristol, 1992

Krügel, E: The Physics of Interstellar Dust. IOP. Bristol, 2003

Bohren, C.F., Huffman, D.R.: Absorption and Scattering of Light by Small Particles. Wiley. 1983