Astronomy 537

Lecture 5: Dust in The Milky Way Galaxy

Key concepts:

Dust

Extinction from Dust

PAH and other features

Correlation with neutral hydrogen

Interstellar dust

So far, we have been considering only the gas phase of the ISM. Interstellar dust is an important solid-state component of the ISM.

- Solid, macroscopic particles composed of dielectric and refractory materials.

- Presence of dust inferred by interaction with starlight:

  - Extinction due to absorption and scattering
  - Reflection by dusty clouds close to stars (Reflection Nebulae)
  - Polarization by scattering or passage through region with aligned dust grains
 - Absorption in silicate bands, or ice bands (H_2O, CO_2 ices)

- Presence of dust inferred from emission from dust grains:
  - Mid-IR to far-IR thermal continuum emission from heating by a radiation field
  - Thermal continuum from non-equilibrium heating (*Sellgren grains*) at near-IR to mid-IR (1-25μm)
  - IR emission bands from heated grains (some of which are the 'DIBs')
  - Radio continuum emission from rotating grains

How important is dust?

- Gas to dust ratio in the MW ~ 100:1. ISM is about 10% of the baryonic mass, so dust grains ~ 0.1% of total mass.

- However, they absorb 30-50% of the starlight emitted, and re-radiate in the IR => 0.1% of the baryons are responsible for ~30-40% of the bolometric luminosity of the Galaxy.

- Dust grains are very important for chemistry, as they are the primary sites of molecular formation
  - Responsible for essentially all H_2 in the ISM.
  - Grains *needed* for reactions.

- Dust is also thought to be the starting points for coagulation into larger grains in protostellar disks, leading to planetesimals and eventually to planets
 - Carrying complex organic molecules with them
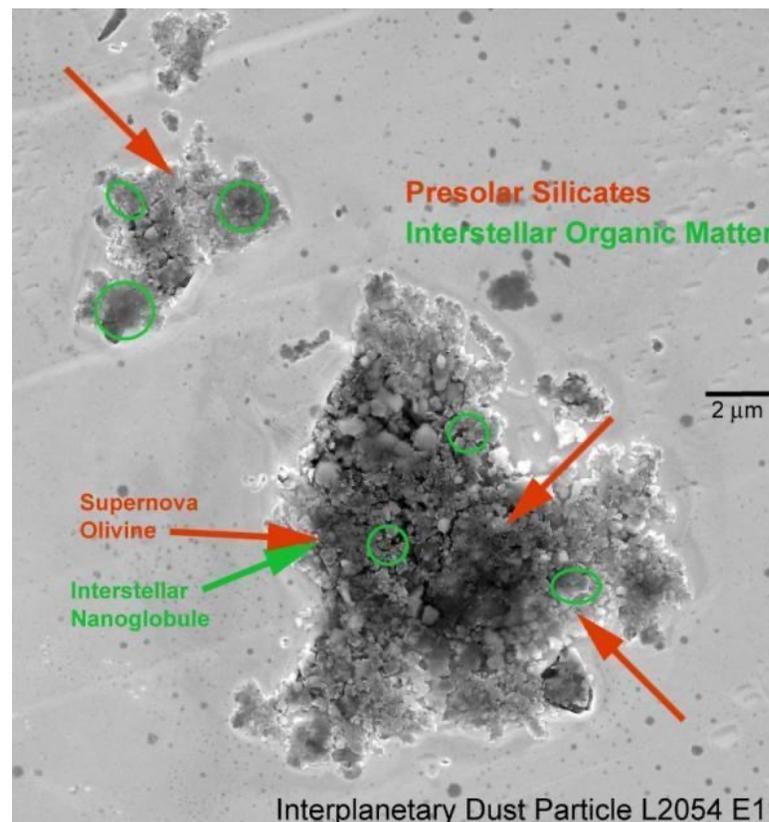
Busemann et al. 2003

Interstellar Extinction

How we usually think about dust grains – Barnard's catalogue of dark clouds in the early 1900s.

- Simply, $I_\lambda = I_{\lambda,0} e^{-\tau_\lambda}$ where $I_{\lambda,0}$ is the original emission of the source and τ_λ is the dust optical depth.

- This assumes all extinction lies between the source and us, and no scattering of additional light into our line of sight (no source function in the radiative transfer equation).

- The optical depth of the dust as a function of wavelength is characterized using 'interstellar extinction curves'.
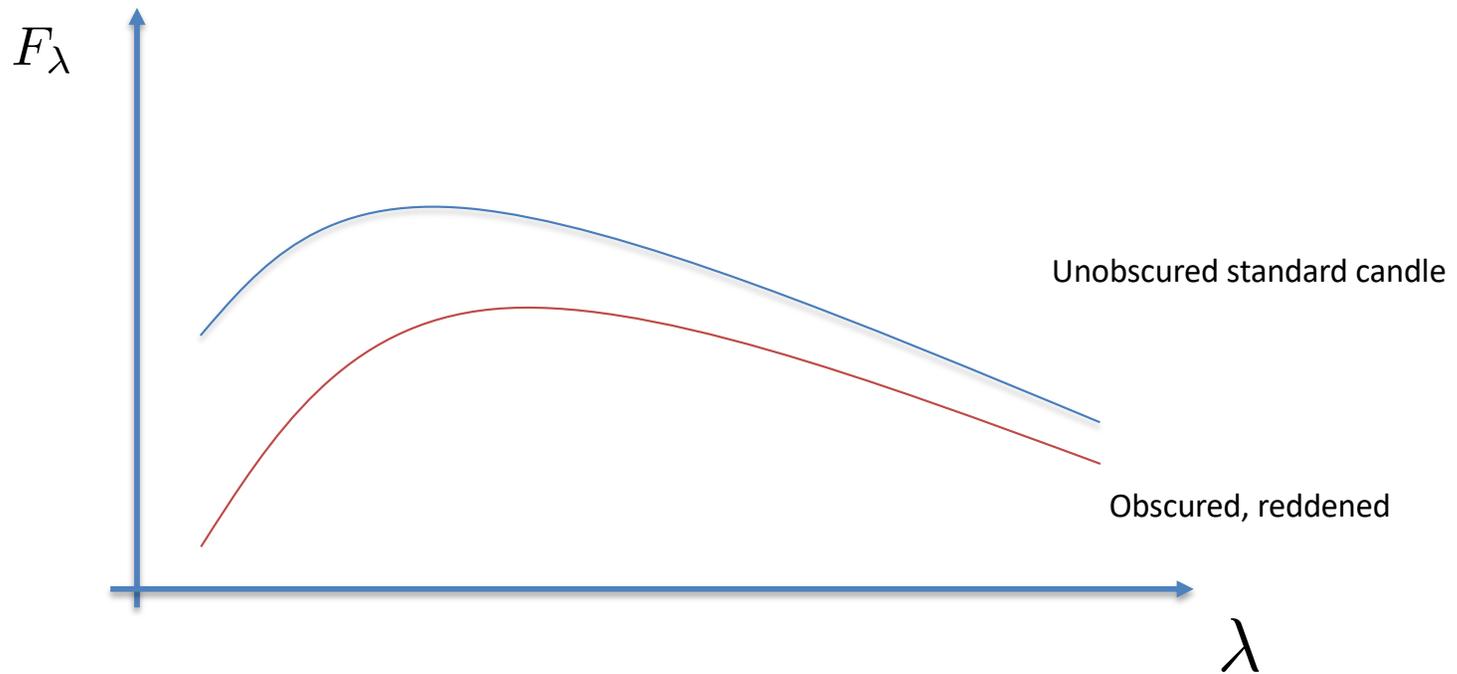
Pair method: Extinction measured by comparing the spectra of stars with identical spectral type (e.g., two G5 stars), one with obscuration and one unobscured ("standard candle").
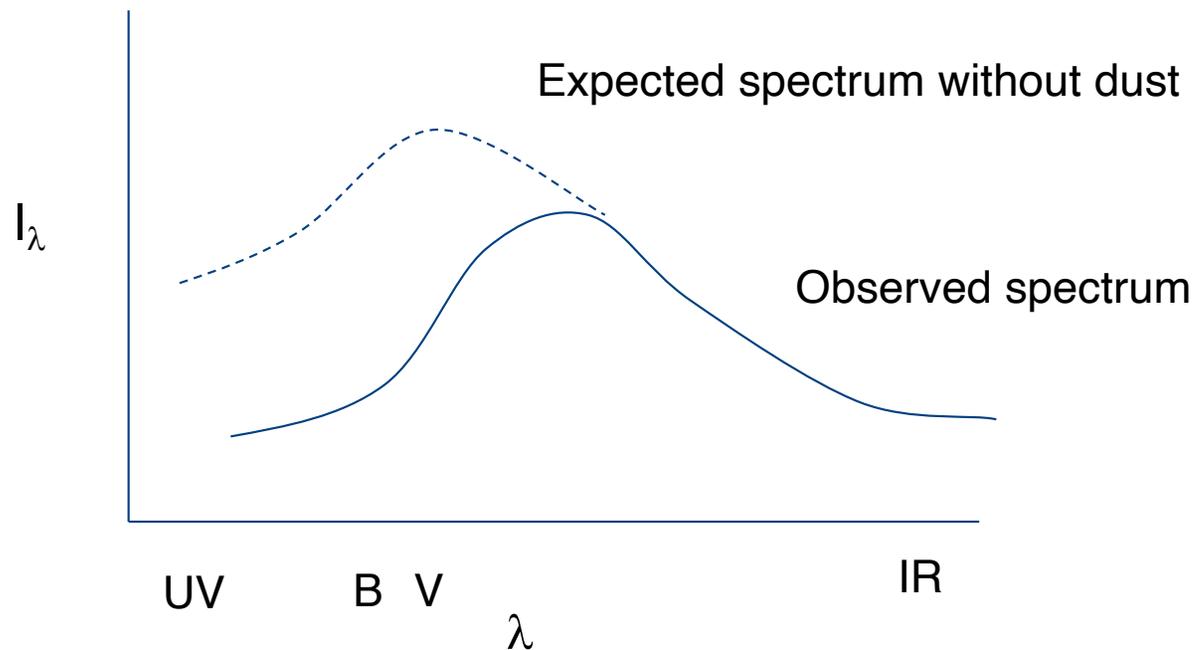
- Gives extinction as a function of wavelength

Extinction versus wavelength

Take the spectrum of a star.

Absorption lines => spectral type => T_{eff} => spectrum shape if no dust.

Difference compared to observed shape => extinction versus λ.

Expected spectrum without dust

I_λ

Observed spectrum

UV   B V   IR

λ

Extinction at a given wavelength, A_λ, is difference between observed magnitude m_λ and unabsorbed magnitude $m_{\lambda,0}$.

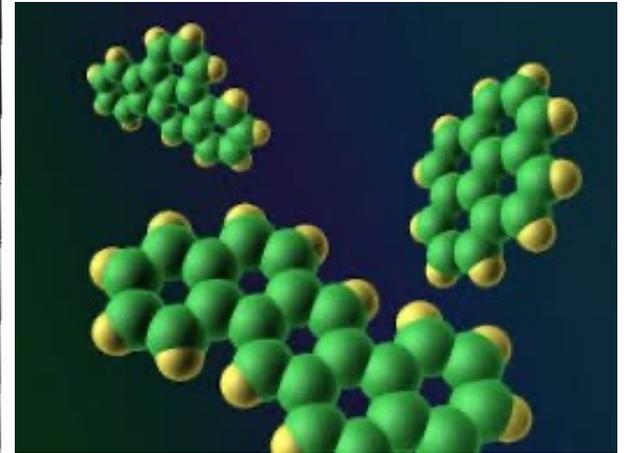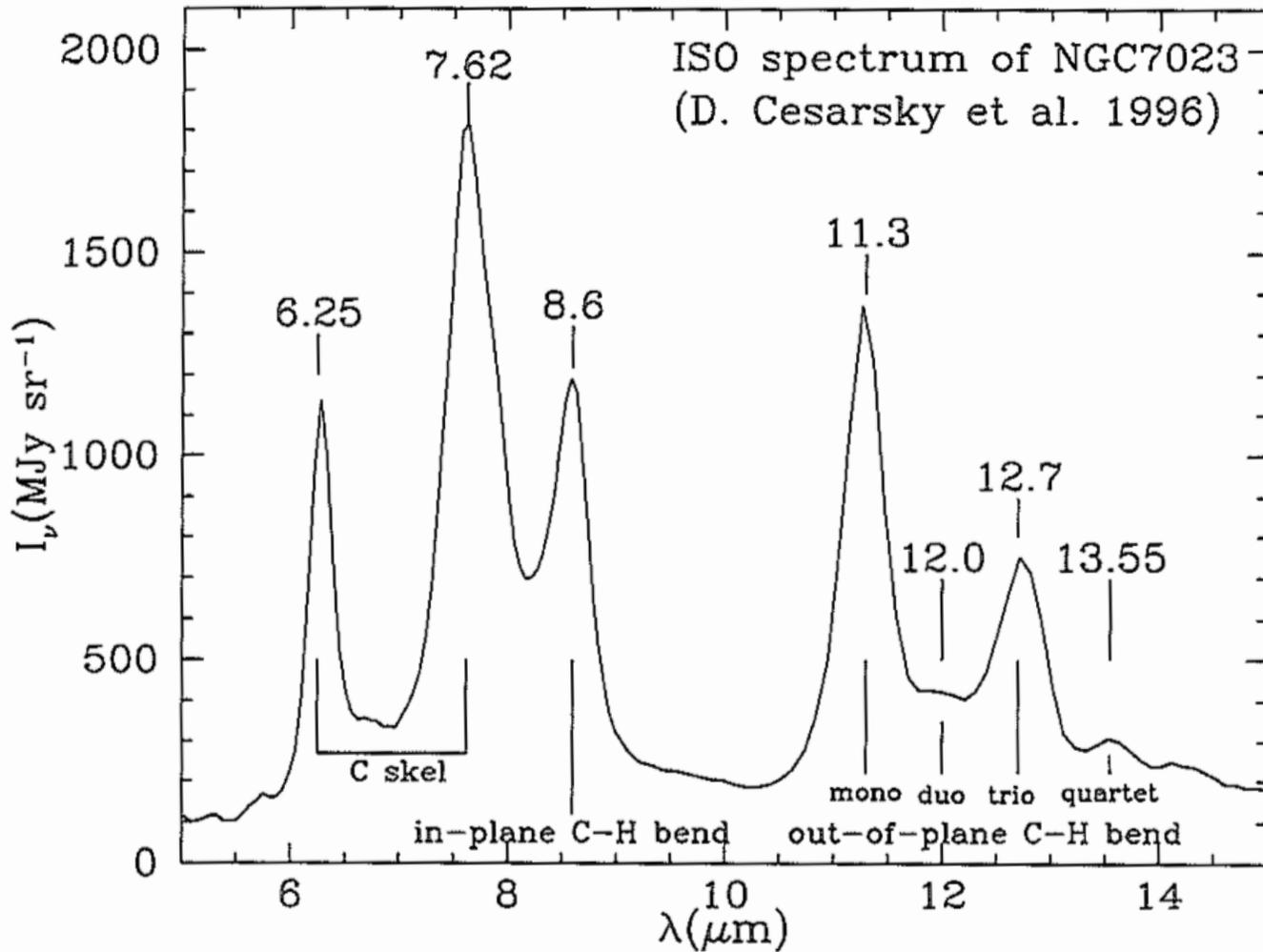$$A_\lambda = m_\lambda - m_{\lambda,0} = -2.5 \log(\frac{F_\lambda}{F_{\lambda,0}})$$

Optical depth converts to extinction using the radiative transfer equation:

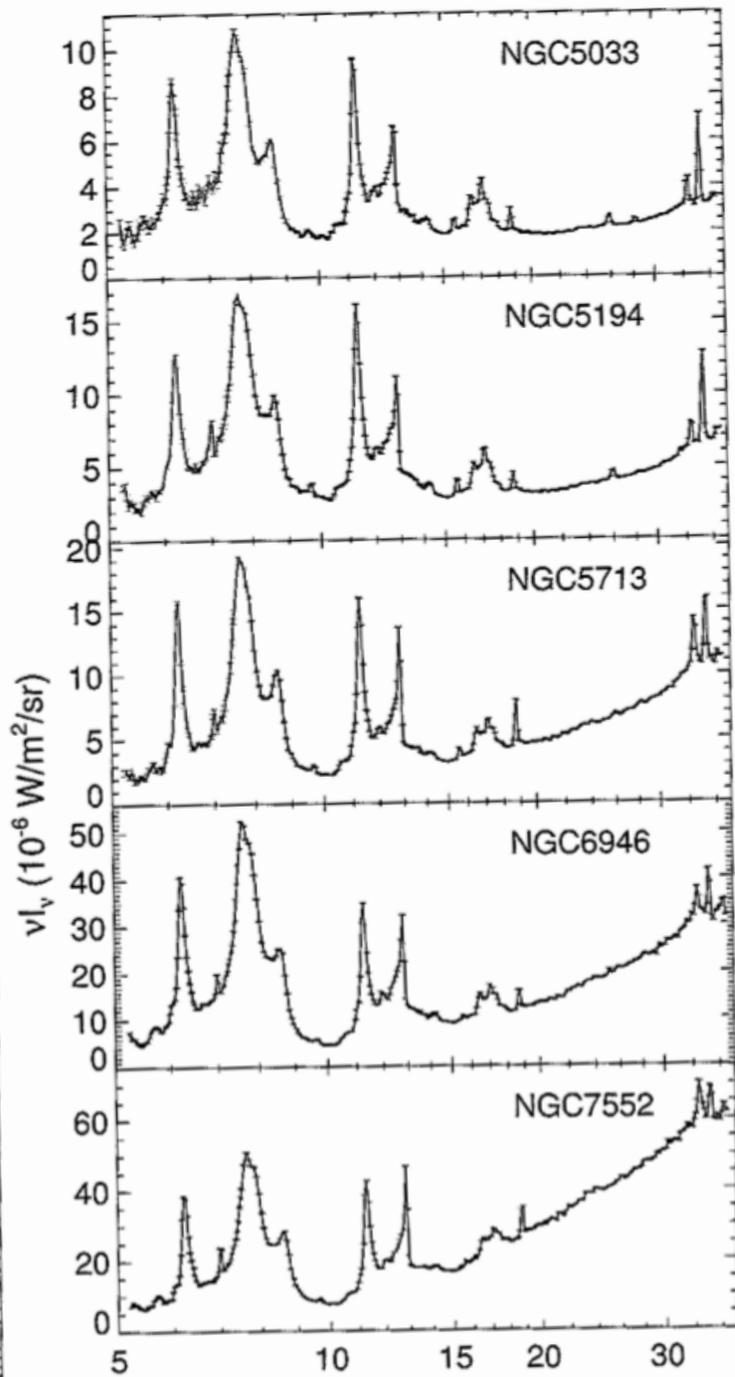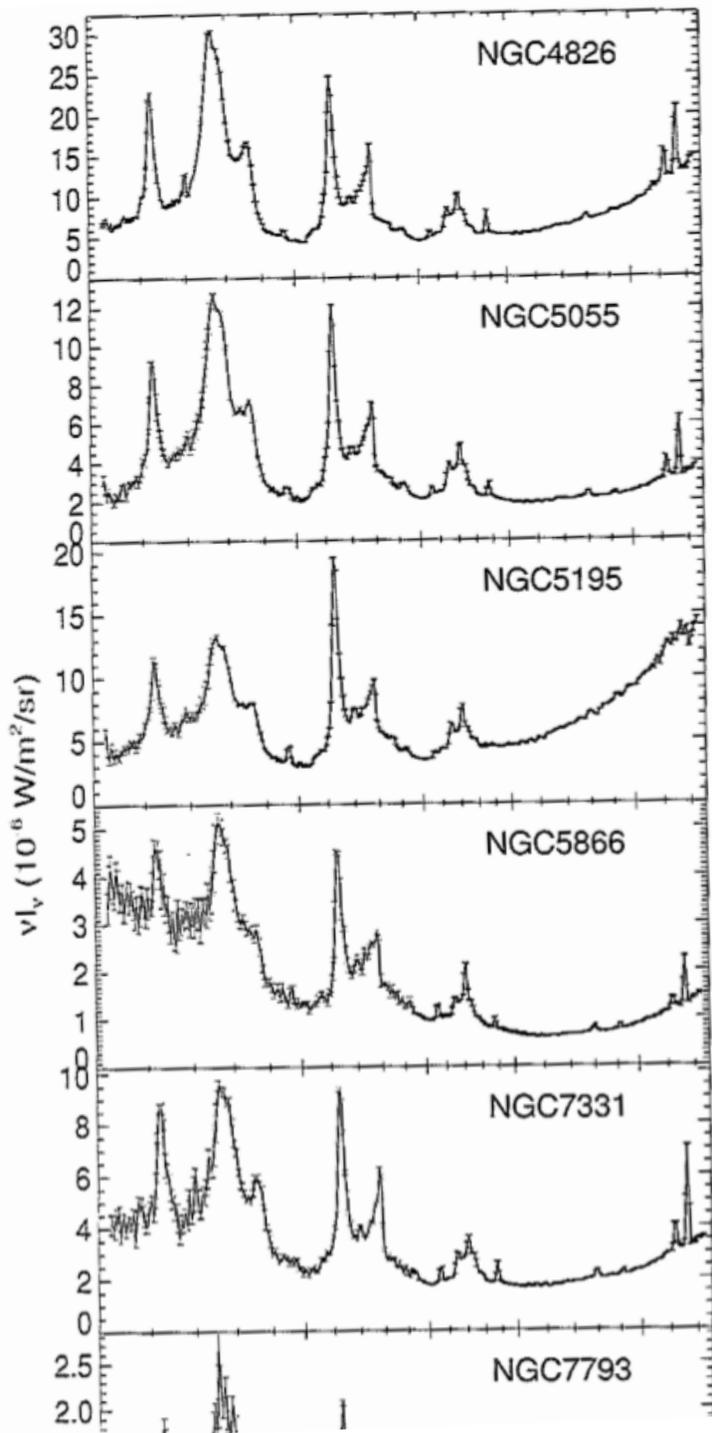$$A_\lambda = 2.5 \log(e) \times \tau_\lambda \approx 1.086 \tau_\lambda$$

$$\tau_\lambda = \int \kappa_{\mathrm{gr}}(\lambda) \sigma_{\mathrm{gr}}(\lambda) ds$$

Polycyclic Aromatic Hydrocarbon (PAH) features
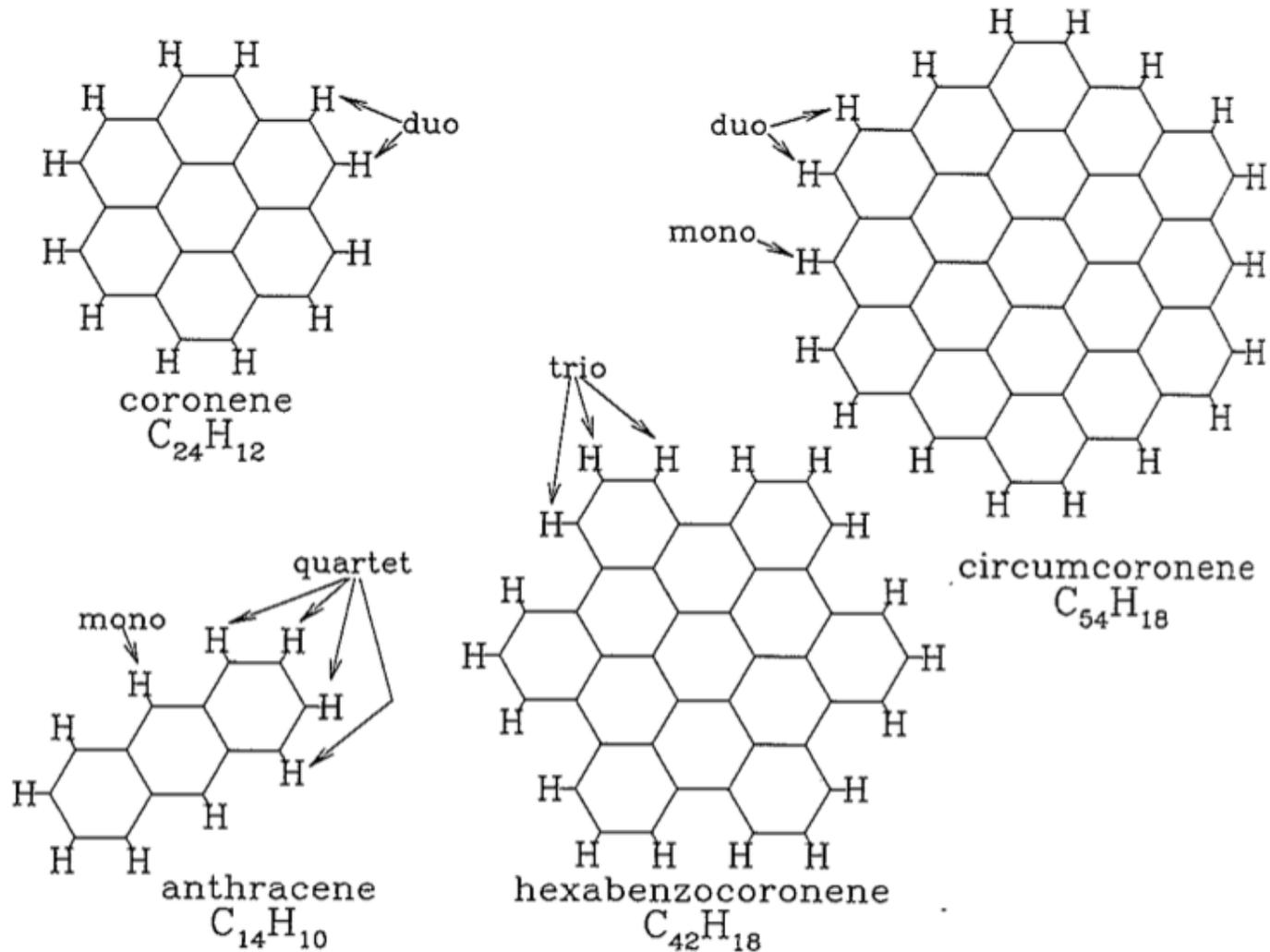
A group of five quite narrow emission bands at 6.25, 7.6, 8.6, 11.3 and 12.7 μm (and at 3.3 not shown here).
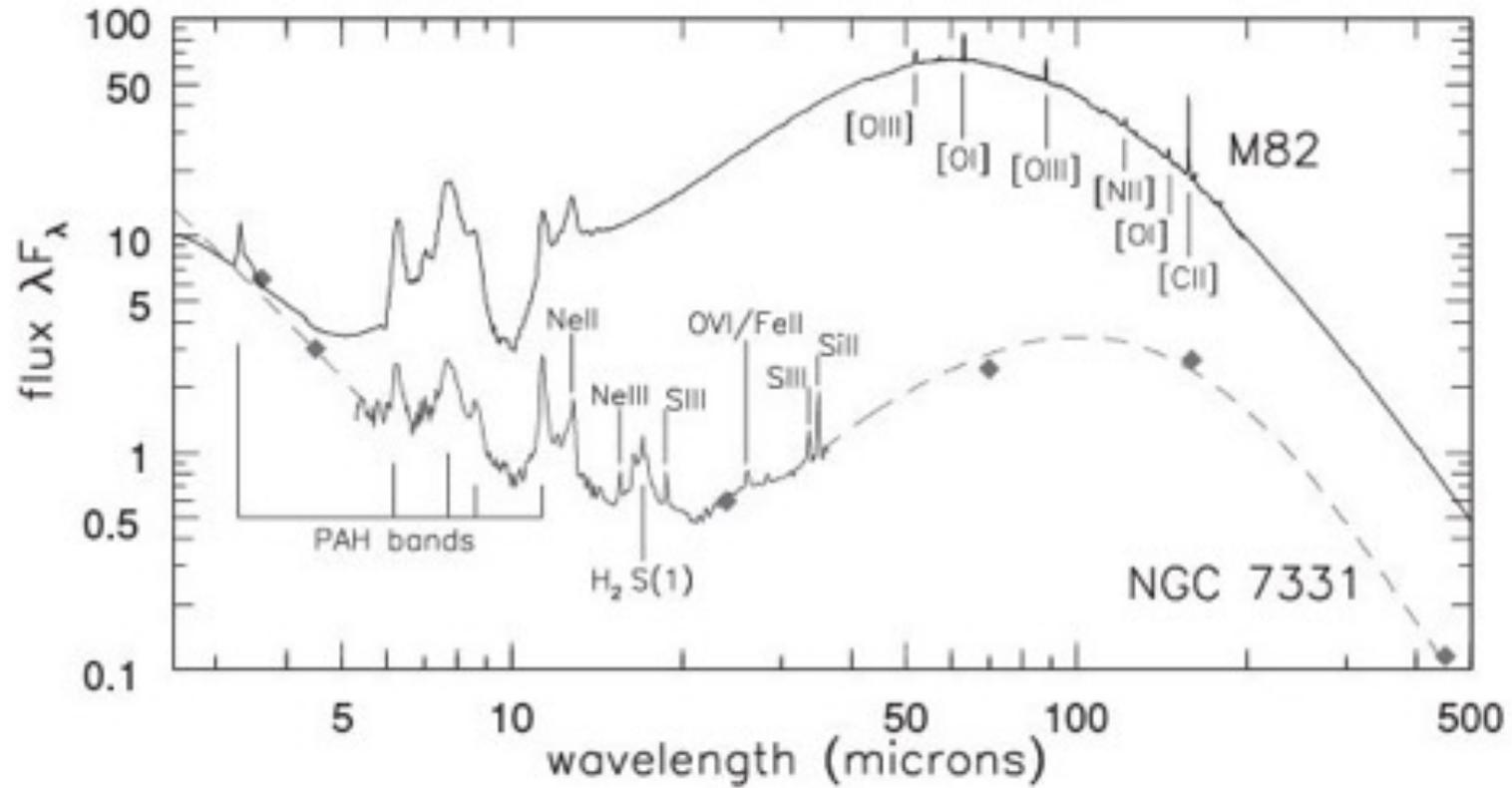
Smith et al 2007

- Attributed to vibrational transitions in polycyclic aromatic hydrocarbon (PAH) molecules.
- Planar structures consisting of carbon atoms organized into hexagonal rings, with hydrogen atoms attached at the boundaries.

coronene
$C_{24}H_{12}$

anthracene
$C_{14}H_{10}$

hexabenzocoronene
$C_{42}H_{18}$

circumcoronene
$C_{54}H_{18}$

Dust in M82 and NGC 7331

What happens to absorbed starlight?

Grains heated to 10-100s of K => IR blackbody emission.

This provides way to estimate extinction. See paper by Schlegel, Finkbeiner and Davis (1998).

Basic idea - if you know the dust temperature from the IR color, then you can derive the dust column density from 100μm all-sky maps.
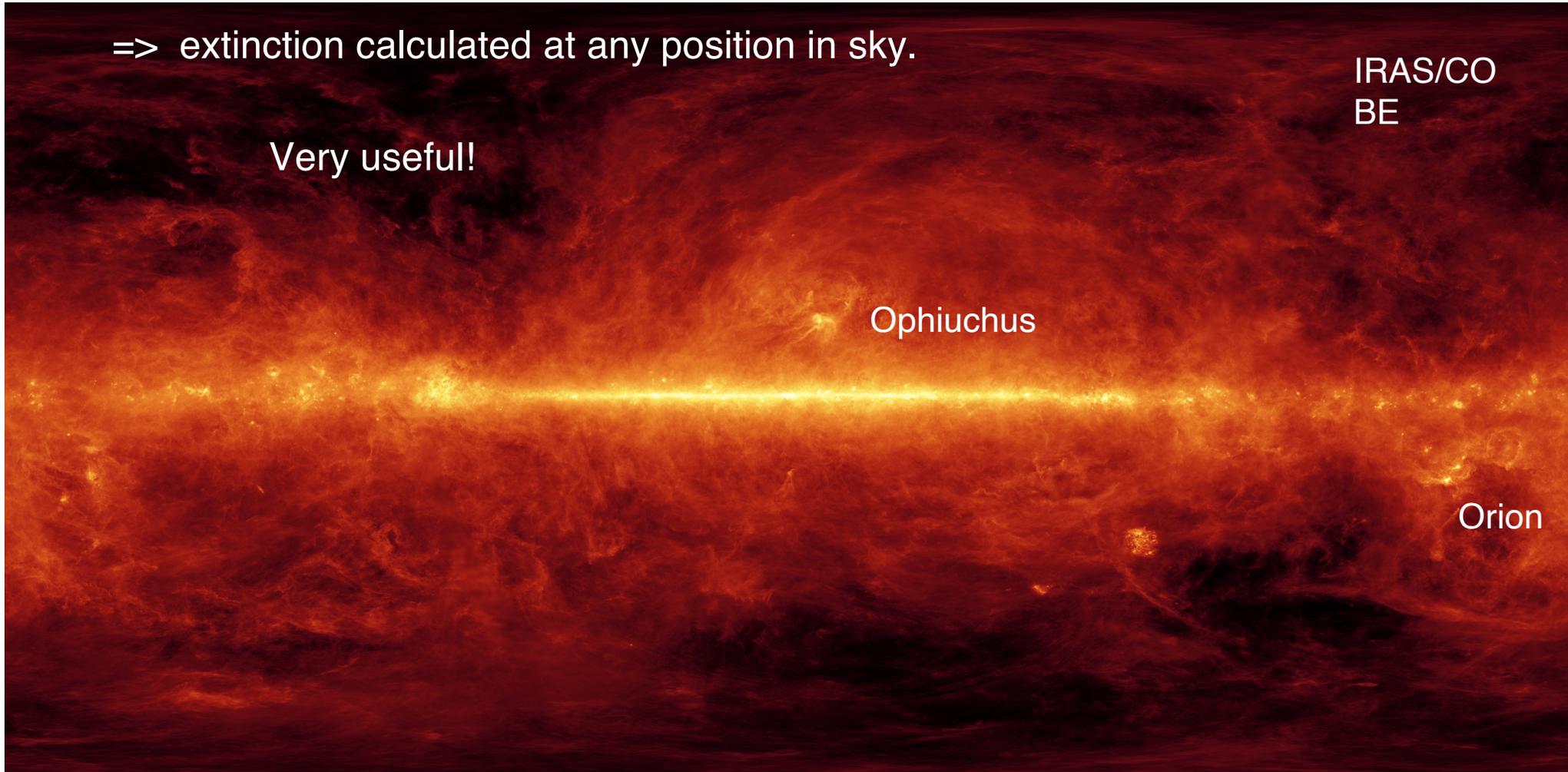

=> extinction calculated at any position in sky.

Very useful!

IRAS/COBE

Ophiuchus

Orion

Worksheet: Assuming blackbody radiation, find the approximate temperature of a dust grain that peaks around 150 microns. Show that a large dust grain 1 pc from an O star with luminosity 10^6 L_{sun} will be heated to roughly this temperature.

Journal Class

- **The Thousand-Pulsar-Array programme – mapping the galactic magnetic field**

Oswald et al. 2025

Discussion leader: **Ella Hort**

Note: To encourage discussion everybody must pose at least one question during the group discussion

Journal Class:

- Everybody reads paper (skip the appendices)
- Leader (for Paper 2 **Ella Hort**)
  - Gives a summary of the important points in the paper (~ 10 min) referring to interesting figures
  - Defines any unusual terminology

- Group discussion
  - Is the paper well motivated?
  - Points out any major assumptions or flaws
  - Are the results plausible? Important?
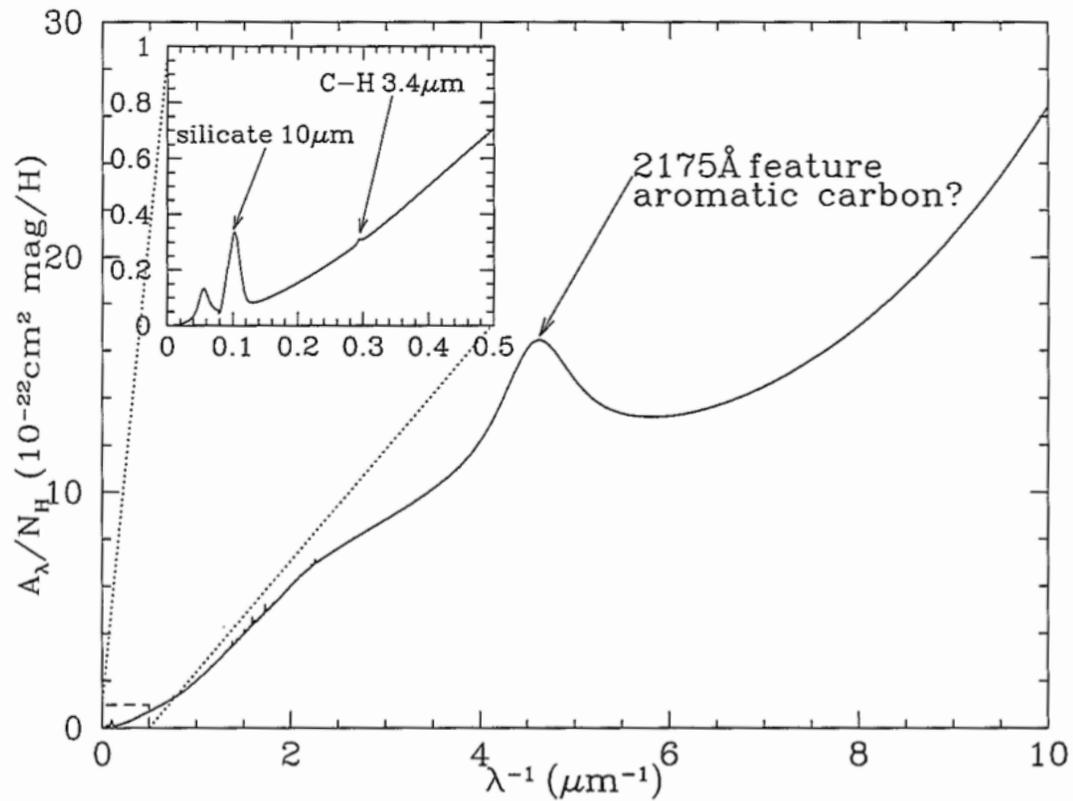
This is a typical shape of the extinction function, where the exact form depends on the grains. You will see this shape no matter where you derive the curve.

Suggests grain properties are similar in most places and, consequently, that grains form in a very similar fashion.

Extinction increases with decreasing wavelength, referred to as reddening. The amount of reddening is measured through the *color excess*:

$$E(B - V) = (B - V) - (B - V)_0 \equiv A_B - A_V$$

Color excess between stars can be compared if normalizing to a common color excess, for instance:

$$\frac{A_\lambda - A_V}{A_B - A_V} = \frac{E(\lambda - V)}{E(B - V)}$$

This measurement is typically straightforward, using a "standard candle".

It is often preferred though to measure how much extinction you have compared to, for example, the extinction in V band:
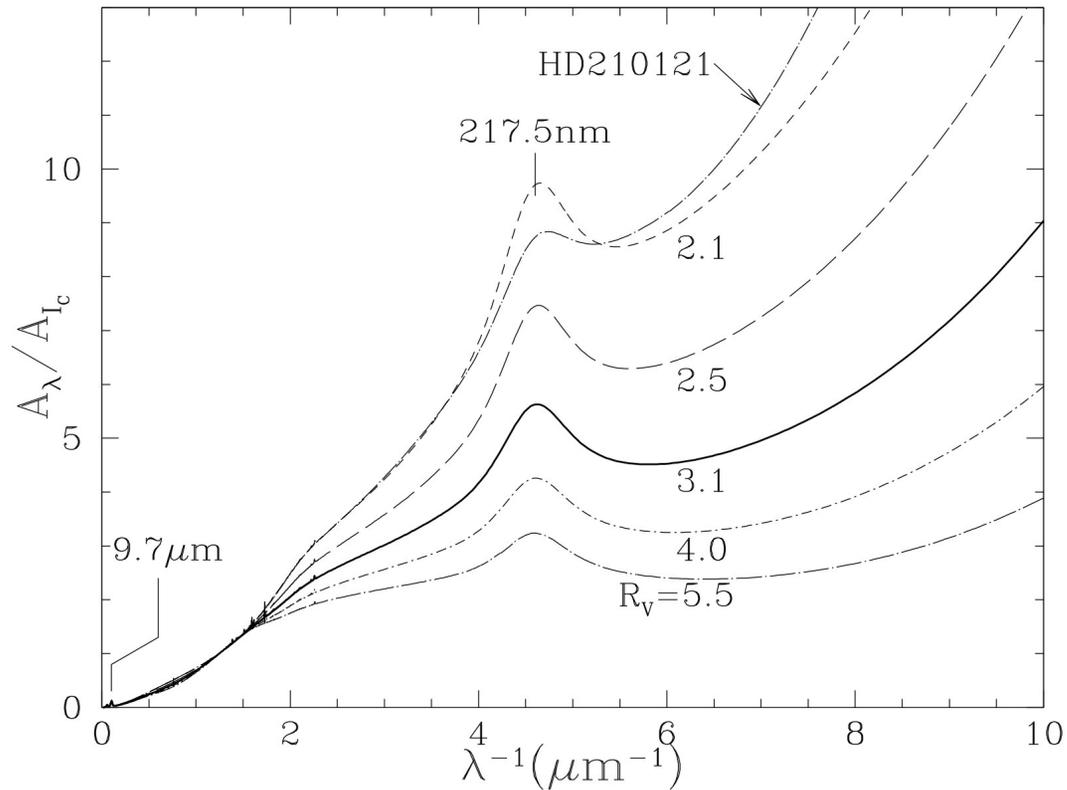
$$\frac{A_\lambda}{A_V}$$

Cardelli (1989) showed that A_λ/A_V can be described by a function, typically a power law in the optical/near-IR.

- We define a "total-to-selective" extinction ratio R_V:

$$R_V = \frac{A_V}{E(B-V)}$$

R_V then connects reddening to extinction, giving a relation between the *E(B-V)* and the total extinction in V band, A_V.
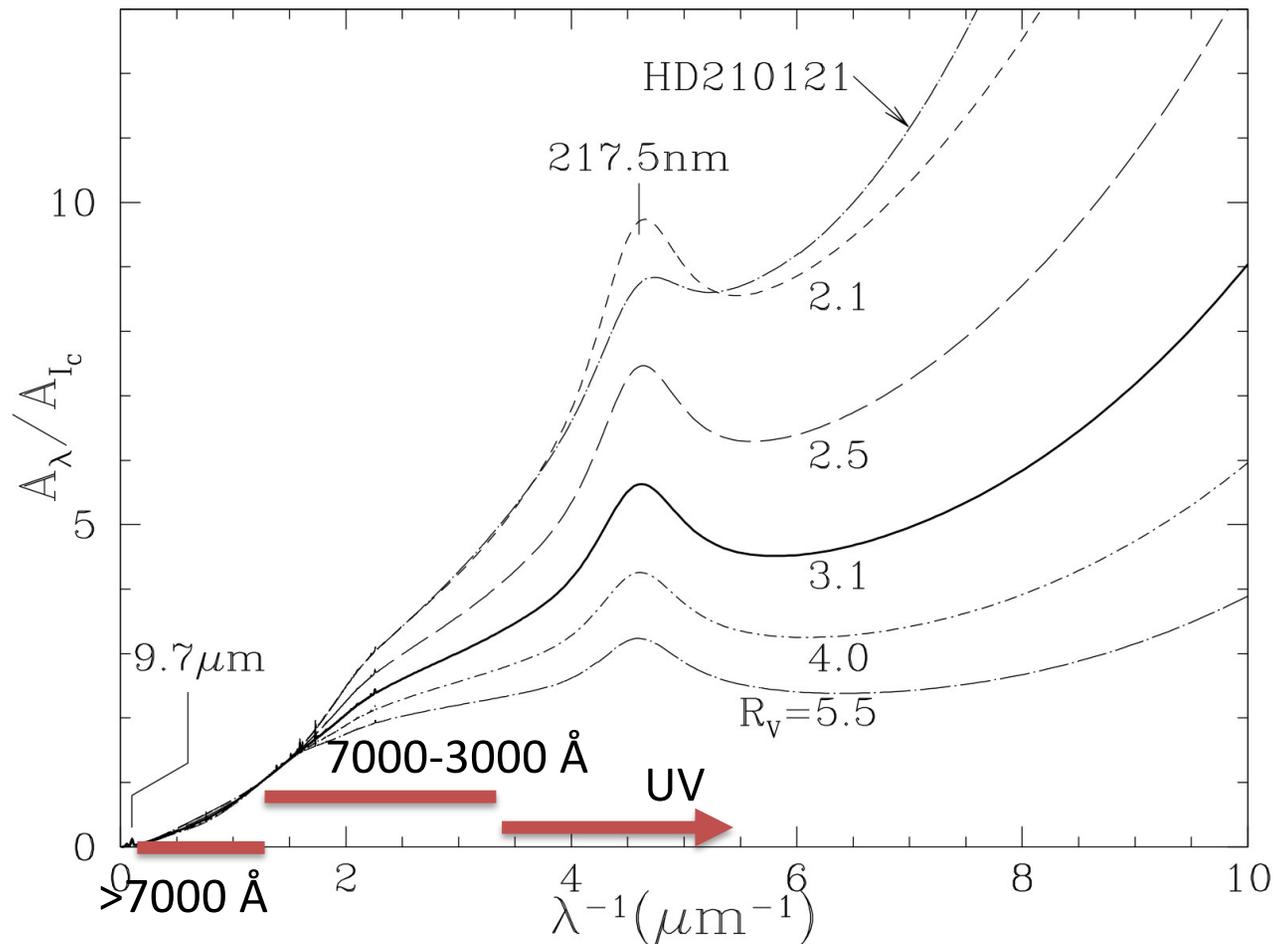
If $R_V \to \infty$, the extinction curve is completely flat => all wavelengths absorbed equally (ideal 'gray' absorber).

Small values of 3-5 => dust is not gray.

Observationally R ranges between 2 and 6, the most typical values are:

- R_V=3.1; for the diffuse ISM

- R_V=5; for dense molecular clouds (for example, towards the Galactic Center)

- This description works well between 3000-7000 Å.
- At 7000 Å – 8µm the extinction law is independent of R_V.
- On the UV side, there is a large variation in the observed extinction, requiring multiple parameters for a decent fit.
  - Primary source of variation is strength, width and peak wavelength of "2175 Å bump".
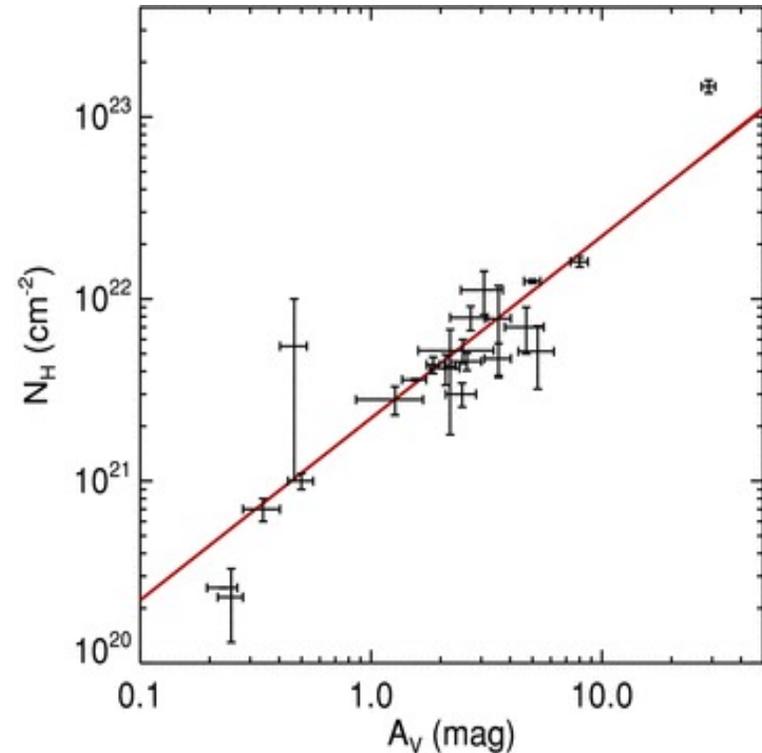
Correlation of extinction with N_H

Total amount of extinction is strongly correlated with the the total hydrogen column density N_H.

$$N_{\rm H} = E(B - V)\, 5.8 \times 10^{21} \ {\rm cm}^{-2} \ {\rm mag}^{-1}$$

This provides conversion relations between total visual extinction A_V and N_H:

$$A_V = \frac{N_{\rm H} R_V}{5.8 \times 10^{21}} \ {\rm mag\, cm}^2$$


Güver & Özel, 2009
SNR environments

Measuring N_H then gives a rough estimate of the amount of extinction.

Interstellar polarization

In addition to absorbing and scattering light passing through the ISM, elongated dust grains that are aligned can polarize light.

Observations of polarized light demonstrates that dust grains can not be spherical, and that they must be globally aligned, presumably by large-scale magnetic fields.

Starlight Polarization (5500 Stars)
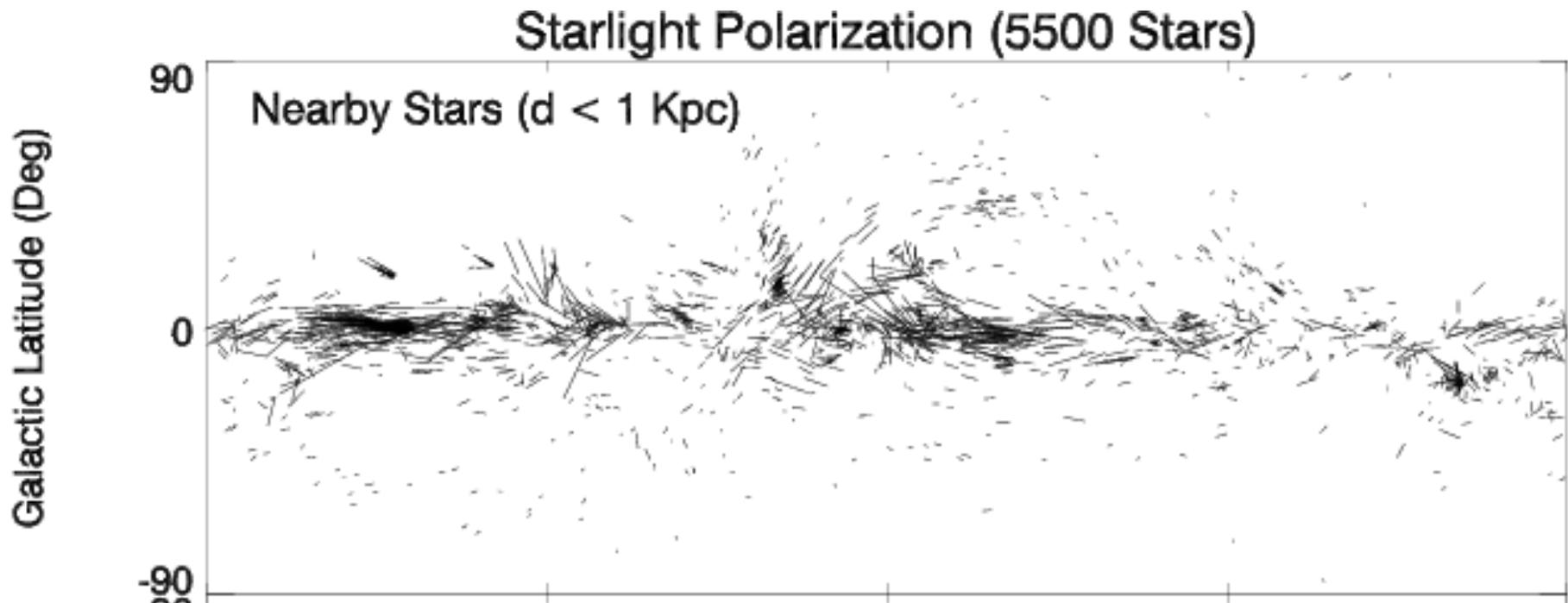
Dust grains: scattering and absorption (ch 22)

Dust has not been re-producible in labs, so much of understanding comes from calculations.

- The physics is interaction between light and solid particles, that have specific dielectric or metallic properties (real or complex index of refraction)

- Involves solving Maxwell's Equations for interactions with solid particles, worked out by Gustav Mie in 1908.

Starting point

Absorption cross section $C_{\mathrm{abs}}(\lambda)$

Scattering cross section $C_{\mathrm{sca}}(\lambda)$

Extinction cross section

$$C_{\mathrm{ext}} = C_{\mathrm{abs}} + C_{\mathrm{sca}}$$

The cross-sections can be related to the grain sizes, and often the work is described using the *efficiency factor*, Q.

$$Q_{\text{sca}} \equiv \frac{C_{\text{sca}}}{\pi a_{\text{eff}}^2} \qquad Q_{\text{abs}} \equiv \frac{C_{\text{abs}}}{\pi a_{\text{eff}}^2}$$

The effective area a_{eff} is the radius of an equal-volume sphere $\quad a_{\text{eff}} = \left(\dfrac{3V}{4\pi}\right)^{1/3}$

For icy particles, $Q_{\text{scat}} \gg Q_{\text{abs}}$ but $Q_{\text{abs}} \neq 0$.

- Thus, strongly scattering grains still absorb some of the incident radiation and heat up.

- Then, they must emit at least some thermal radiation (we'll look at this later).

The sizes of the grains are often parameterized using a dimensionless size parameter, relating grain size to light wavelength:

$$x \equiv \frac{2\pi a}{\lambda}$$

Then, there is an index of refraction *m* (related to the dielectric function) which has both real and imaginary parts:

$$m = m_1 - im_2$$

- If the real part is large (this is our regular index of refraction known from classical optics), the grain is an effective *scatterer*, which is the case for dielectric grains or icy grains.

- If the imaginary part is large, the grain is an effective *absorber*, which is the case for metallic grains.

The wave vector relates to the refractive index, and the electric field is written

$$k = m(\omega)\frac{\omega}{c} \qquad\qquad E \propto e^{ikx - i\omega t}$$

The E-field is then proportional to the exponent of Im(m), and the intensity of the light traveling through the material:

Absorbing part of refractive index

$$E \propto e^{ikx - i\omega t} \propto e^{-\mathrm{Im}(m)\frac{w}{c}x}$$

$$I = |E^2| \propto e^{-2\mathrm{Im}(m)\frac{w}{c}x}$$

Describes an exponential fall off with distance which we recognize as optical depth.

- The absorption coefficient then is $\kappa_\omega = \mathrm{Im}(m)\dfrac{w}{c}$

The theoretical descriptions for the absorption and scattering cross section can be defined:

$$C_{\text{abs}} = 18\pi \frac{\text{Im}(m)}{(\text{Re}(m) + 2)^2 + \text{Im}(m)^2} \frac{V}{\lambda}$$

$$C_{\text{sca}} = 24\pi^3 \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 \frac{V^2}{\lambda^4}$$

Two cases of scattering:

<u>Long wavelengths:</u> small x $(a << \lambda)$

This limit is classical Rayleigh scattering. If we assume dielectric spheres with no absorption (m is real), we have:

$$Q_{\text{ext}} \approx Q_{\text{sca}} = \frac{24\pi^3}{\pi a_{\text{eff}}^2} \left(\frac{m^2 - 1}{m^2 + 2} \right)^2 \frac{V^2}{\lambda^4} \propto \lambda^{-4}$$

Using *Q* since plots have this as y-axis.

Shorter wavelengths: larger *x (a* comparable to *λ)*

This limit is from classical Mie scattering, derived by van der Hulst. Again, with no absorption, in the regime of *m=1-2*:

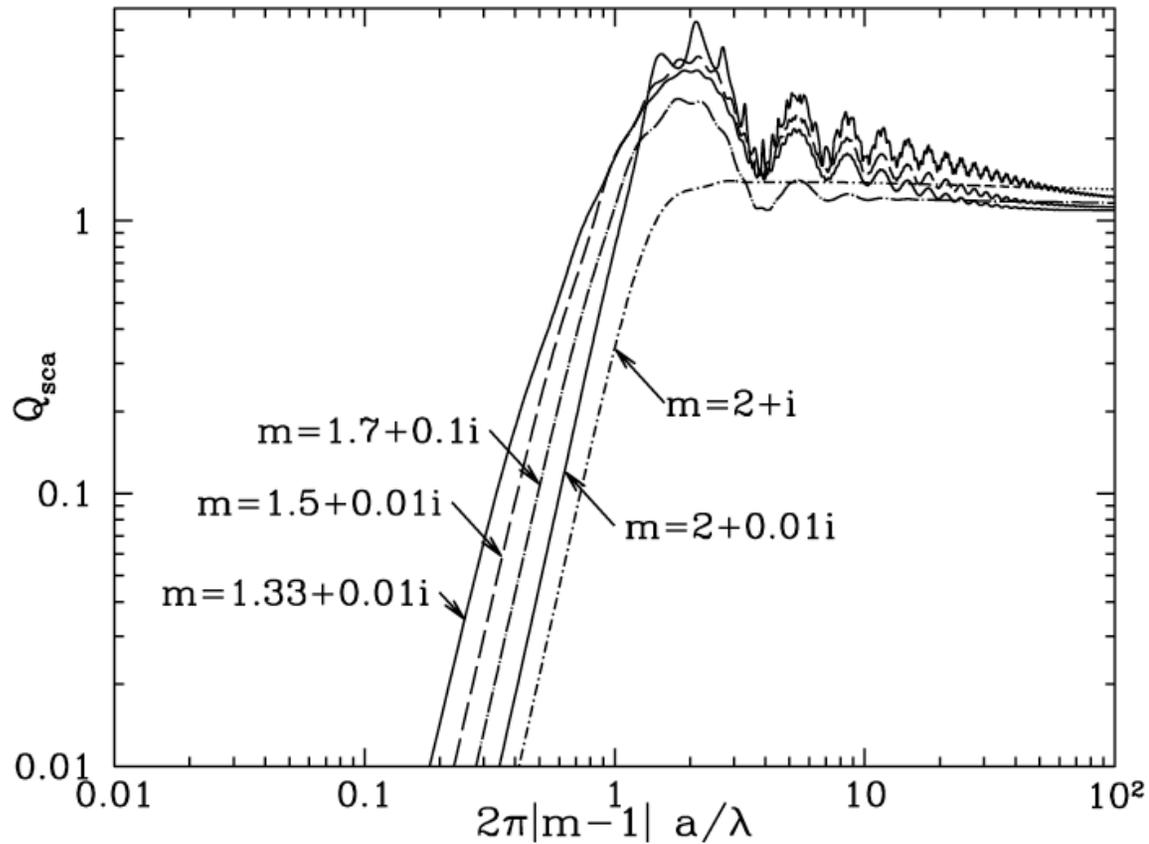$$Q_{\text{ext}} \approx Q_{\text{sca}} = 2 - \frac{4}{\beta}\sin\beta + \frac{4}{\beta^2}(1 - \cos\beta)$$

$$\beta = \frac{4\pi a}{\lambda}(m - 1)$$

In this case the behavior of Q_{ext} is oscillatory around $Q_{\text{ext}}=2$.

Maxima in Q_{ext} occur when the refracted light passing through the particle interferes destructively with the light diffracted around the particle.

Small x, long λ   Large x, short λ

Figure 22.2 Scattering efficiency factors Q_{sca} for spheres with various refractive indices m.

Note the two different regimes where $Q \sim \lambda^{-4}$ for small x, then flattens out.

Recall at short λ though, the extinction curve was more like $\sim \lambda^{-1}$

We can add an absorption term, meaning we add an imaginary part to the index of refraction, we get at long wavelengths:
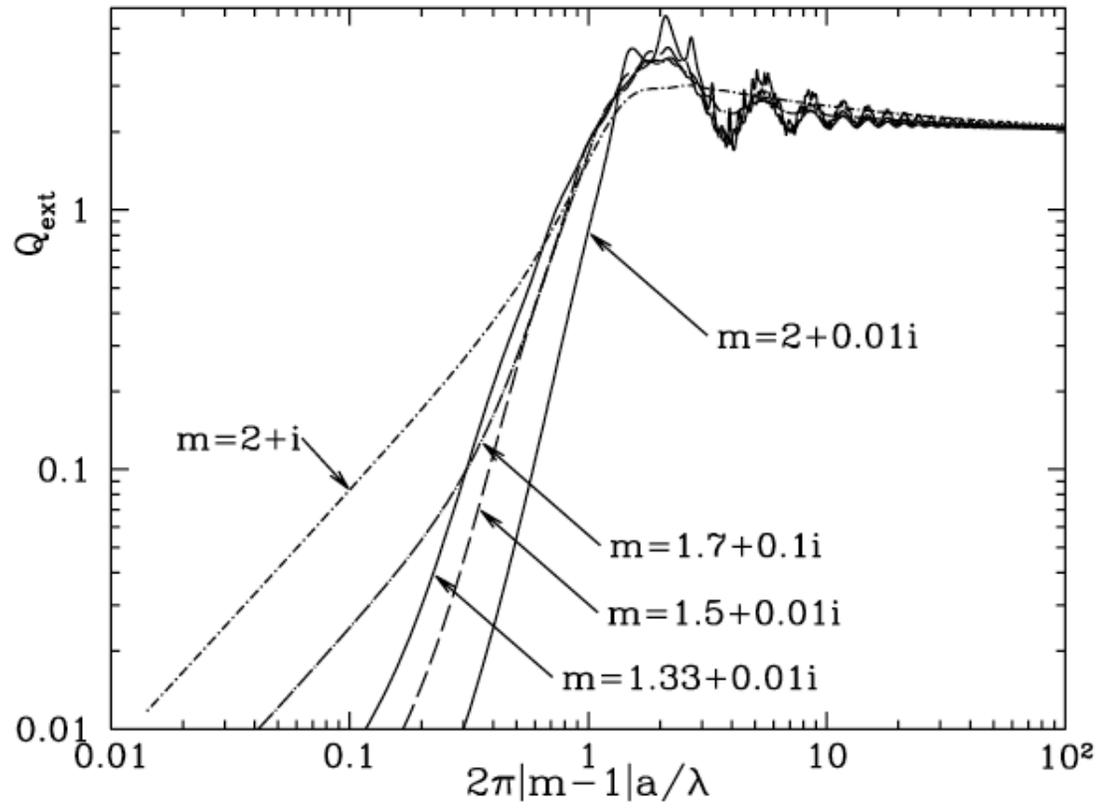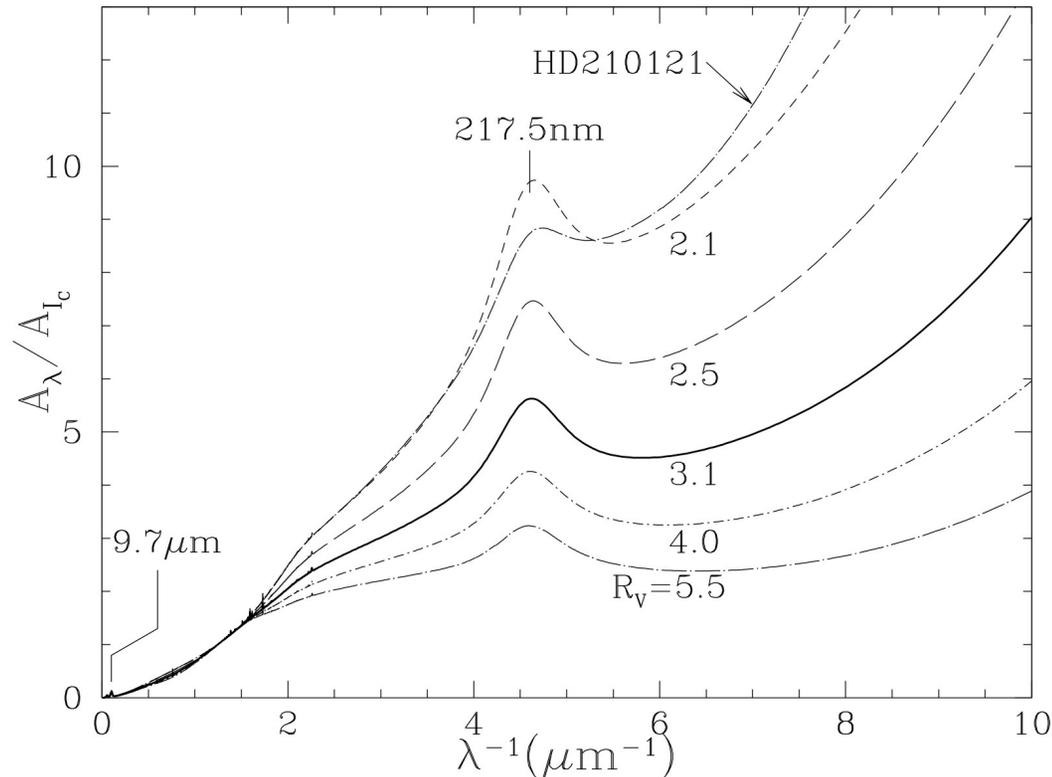
$$Q_{abs} > Q_{scat}$$

And then

$$Q_{abs} \propto \lambda^{-1}$$
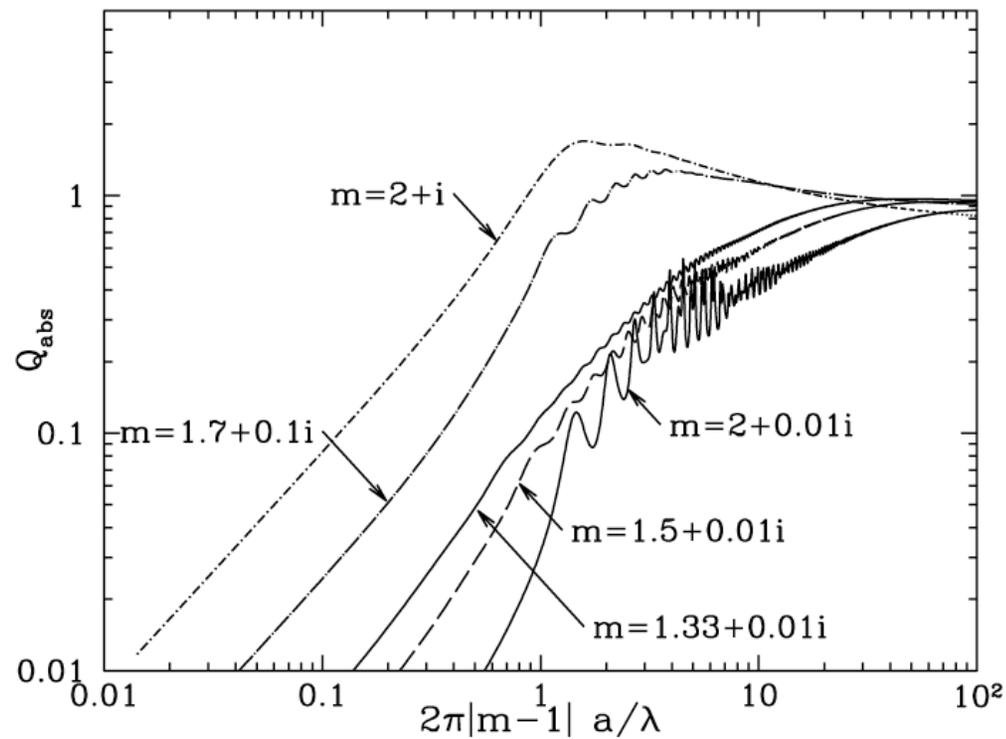
Figure 22.1 Absorption efficiency factors Q_{abs} for spheres with various refractive indices m.

Combining the two we get $Q_{ext} = Q_{abs} + Q_{sca}$

The classical Mie scattering curve for a given grain size shows a sharp rise at long wavelengths (small x) and then flattens out at short wavelengths.

- That the observed interstellar extinction curve is not flattening out according to this tells us that there must be a distribution of particle sizes

- The distribution of relative "flattenings" at short wavelengths suggests that there are more small grains than large grains (doesn't "flatten out" unless $R_V > 5$)

Various shapes and composition forms different Q_{ext} functions. Here amorphous silicate grains.
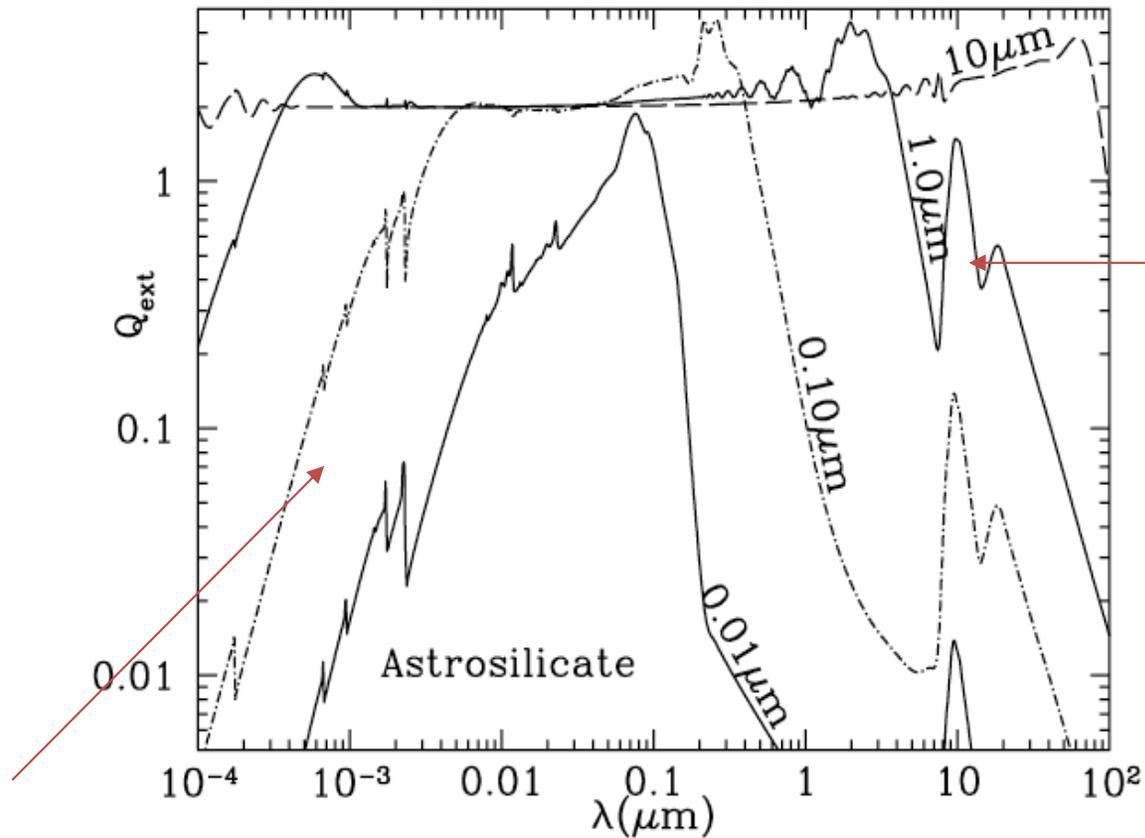
9 and 18μm silicate features.

X-ray absorption edges.

X-ray absorption edges

Dust grains can scatter X-rays.

- The X-ray photon is absorbed primarily in n=1 levels
  - Causes 'edges' in the spectra

- Energies of the edges modified by being in solid materials rather than in the gas phase.

- Photoelectric absorption edges have been seen for C, O, Fe, Mg, and Si with Chandra and XMM.
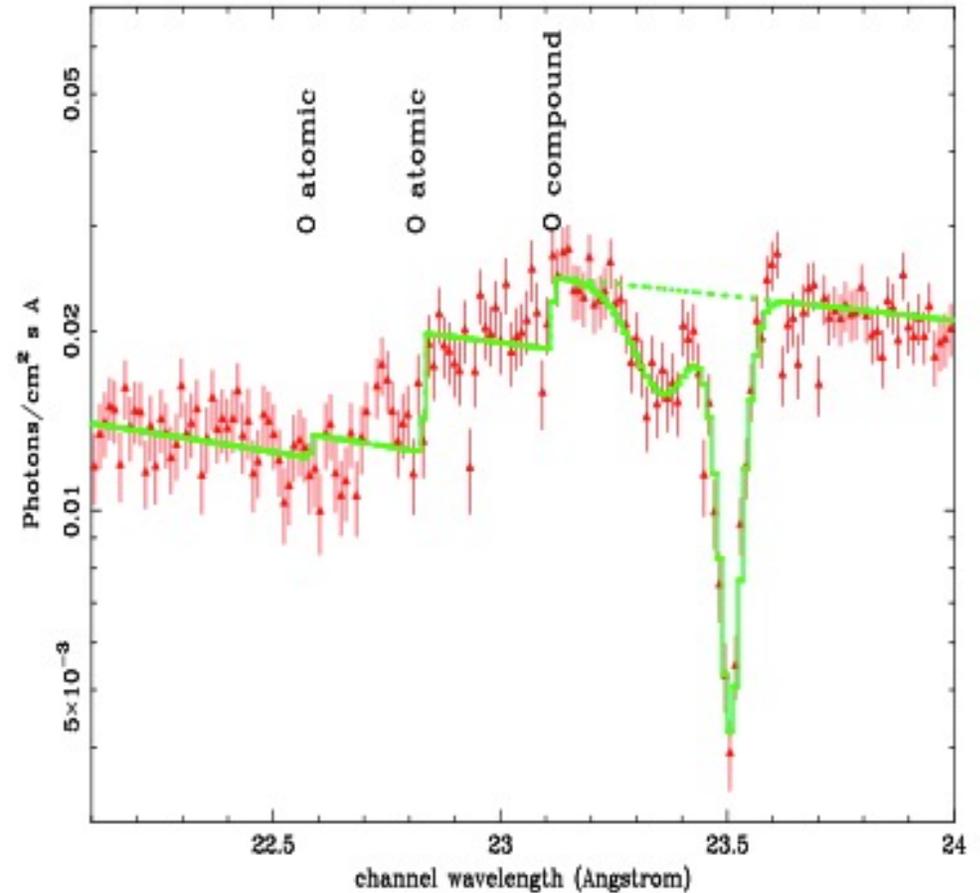
Zoom in in wavelength, to show differences of carbonaceous and silicate grains.
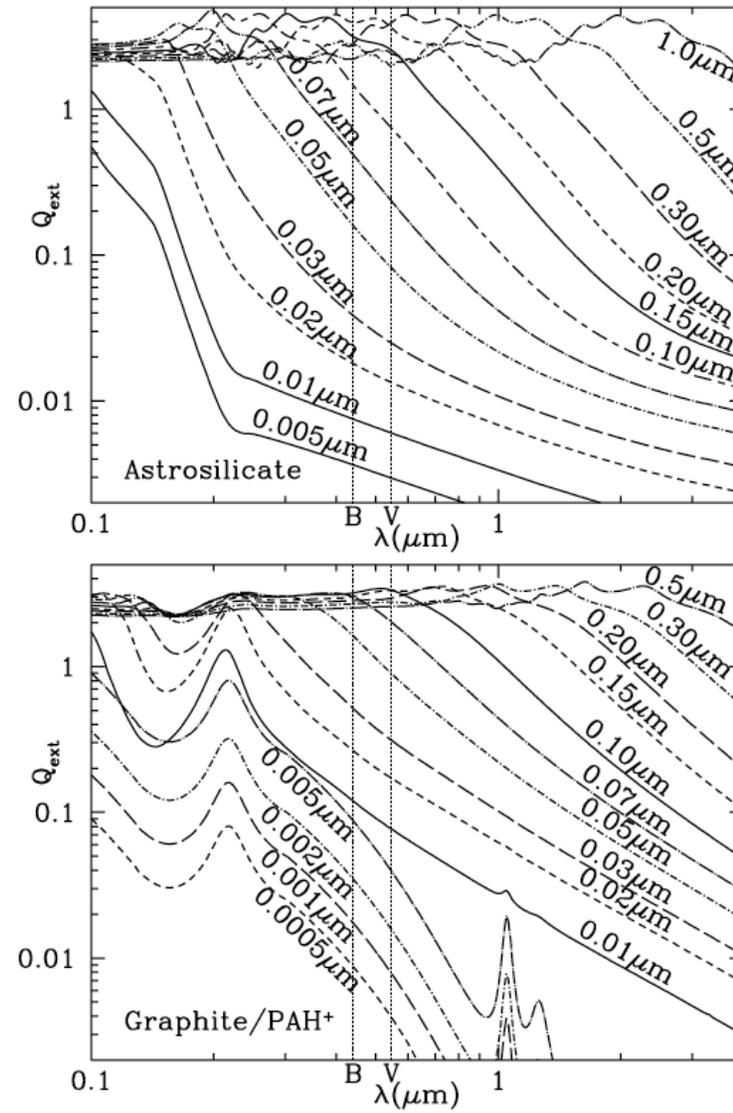
Composition of Interstellar Dust (ch 23)

There is plenty of spectral structure in the extinction curve, both in the form of absorption as well as emission features. Gives us important information of the composition and structure of dust grains.
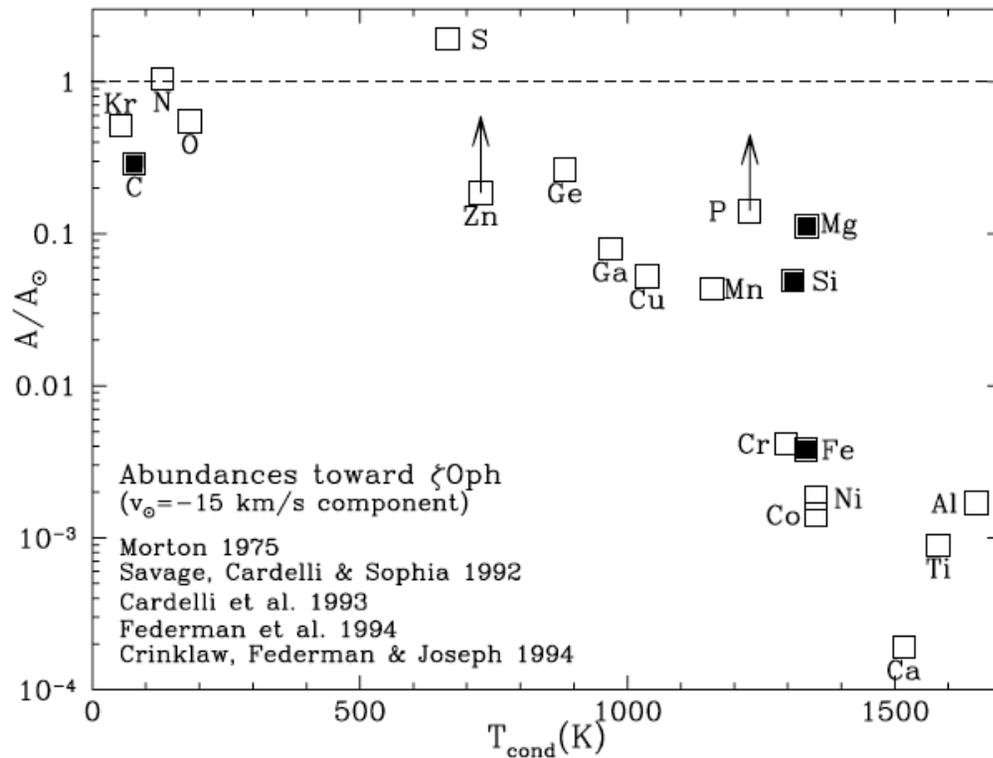
Gas-phase abundances relative to solar towards a diffuse cloud ζ Oph.

Notice depletion of C, Mg, Si, Fe which are major constituents of dust grains.

Studies like these used to determine dust primarily consists of: Silicates, Silicate oxides (SiO_2, MgO, Fe_3O_4), carbon solids, hydrocarbons (PAHs), carbides (SiC), and metallic Fe.

Spectral features

The strongest feature is the "bump" at 2175±50 Å.

- Attributed to carbon-rich particles: graphite, hydrogenated amorphous carbon grains; aromatic forms of carbons

- The feature is a strong function of metallicity, with the bump being a bit weaker in, e.g., the LMC extinction curve, and then more or less absent in the SMC.
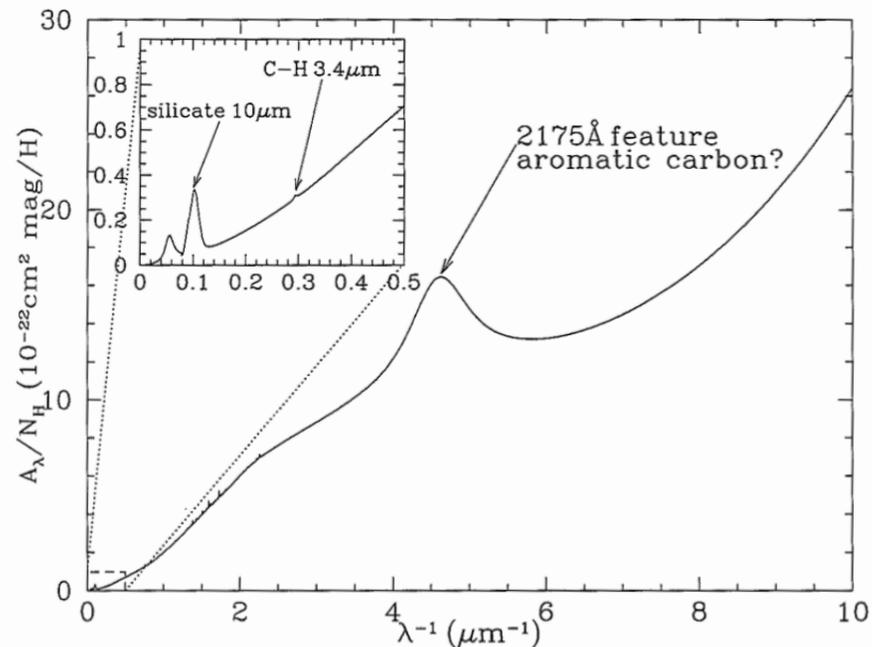
Mid-IR Silicate features

A set of broad bands at 9.7 and 18μm, due to bending and stretching modes in silicate materials.

The identification of these features is fairly certain – seen in O-rich stars.
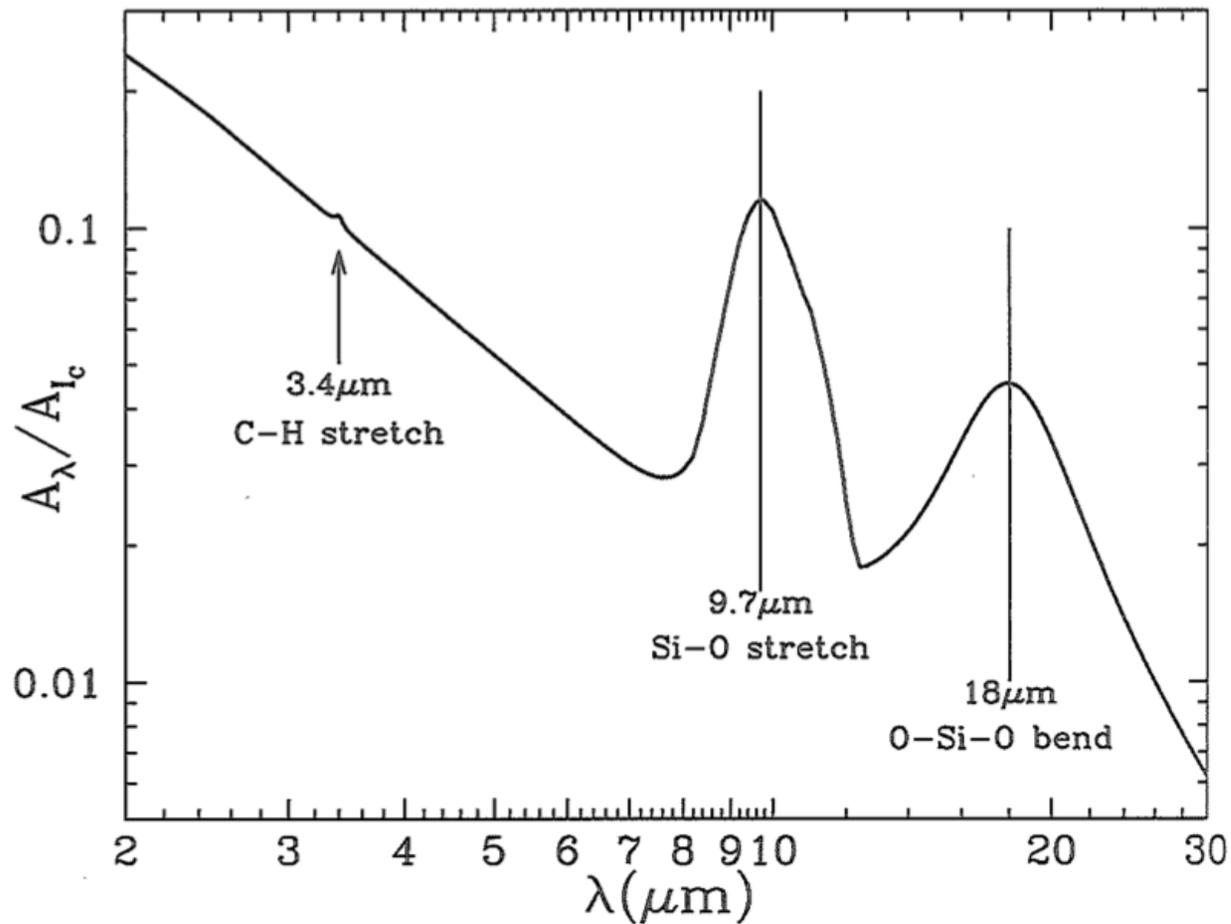
- In the lab, silicate crystals have a lot more transitions around this wavelength, interpreted as the astrophysical silicate is primarily amorphous rather than crystalline in nature.

- The 18μm band is likely due to O-Si-O bending modes in silicates, also relatively securely identified.

- Sometimes a band at 11.3μm is identified with Si-C stretch and bend modes.

Because these compounds/molecules are attached to solid objects, the energy levels are distorted from the pure molecular bands seen in the laboratory.
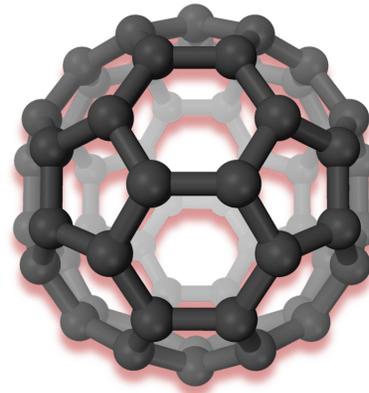
One to one identification is very difficult!

Diffuse Interstellar Bands (DIBs)

Weak, broad features (>100Å) seen at visible and IR wavelengths.
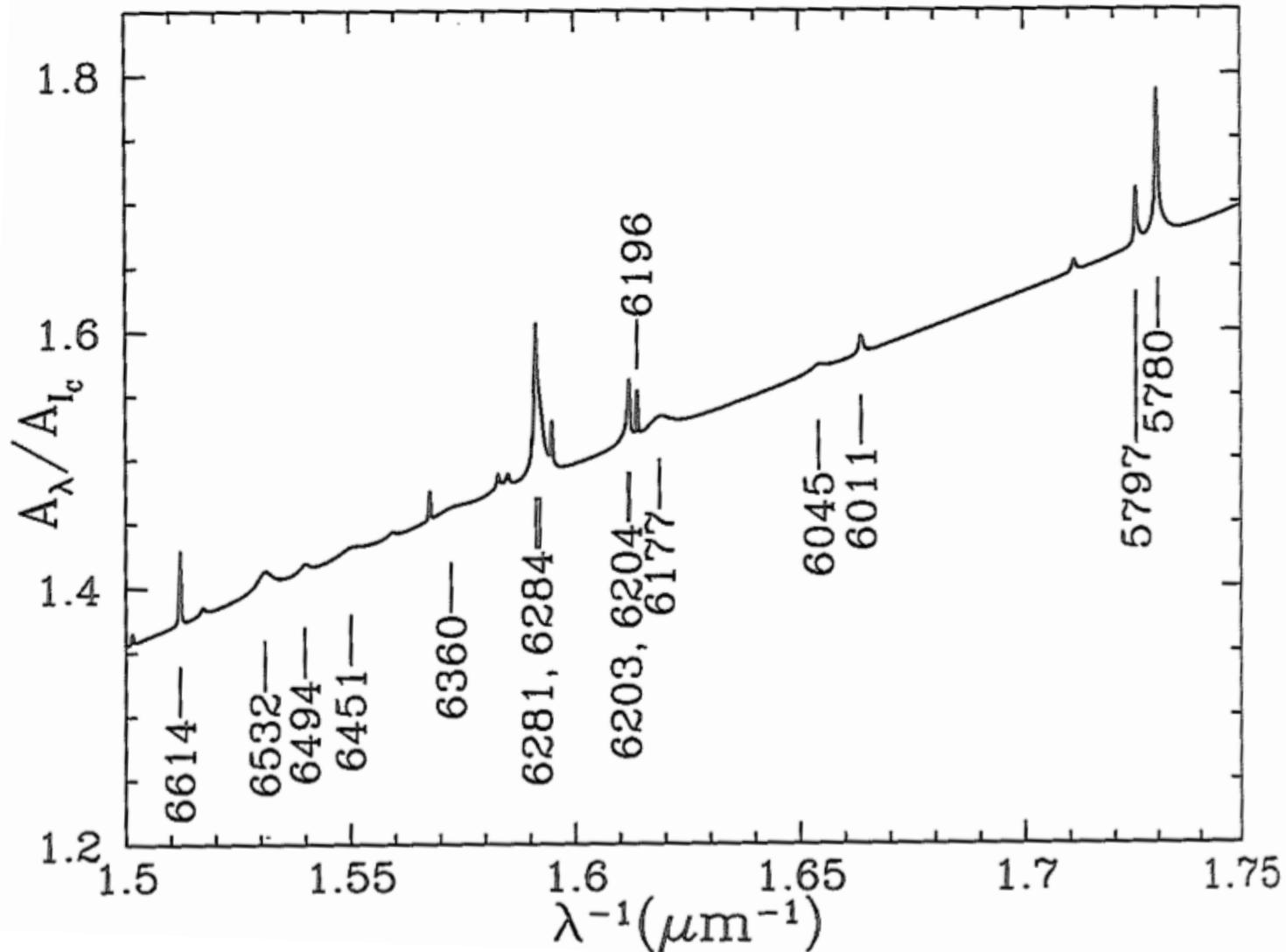
- Strengths of DIBs correlated with dust extinction, but the exact physical connection not clear.

- Only one possible identification of a pair of lines that matches from experiments in lab
  - Buckminsterfullerene C_{60}

- Fine structure lines have been suggested in a couple of features, with the conclusion that at least some DIBs arise in large, free-flying molecules (extremely small dust grains)
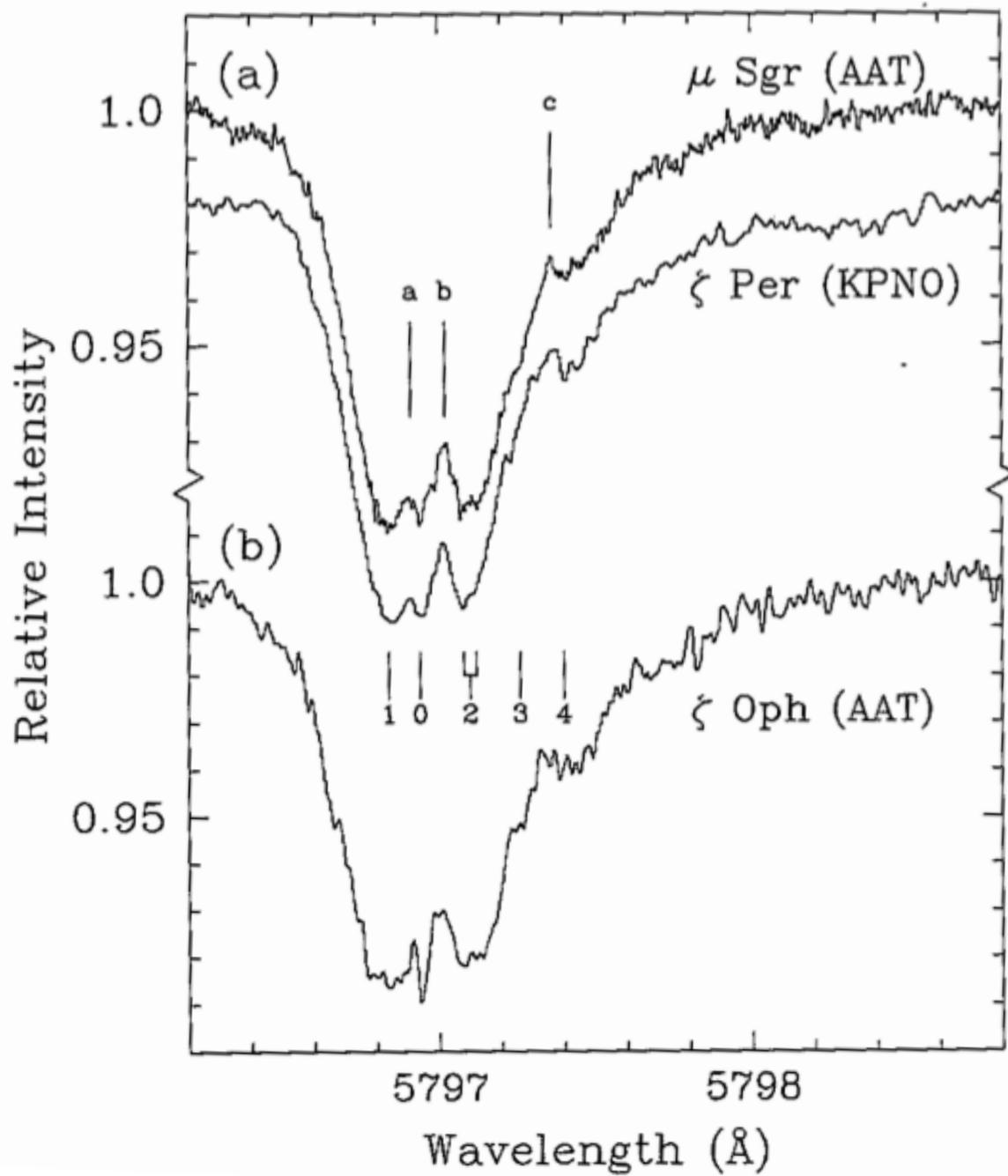
Fine structure lines along 3 different lines of sight.

Seen in the 5797Å DIB line.

Kerr et al. 1998

Interstellar ices

Strongest ice feature is the 3.1μm O-H stretch band in water ice, a H-O-H bend in water at 6.1μm, an unidentified feature at 6.8μm, and a band at 10μm identified with SiO. Other ice bands are CO, CH_4, NH_3, and CH_3OH.

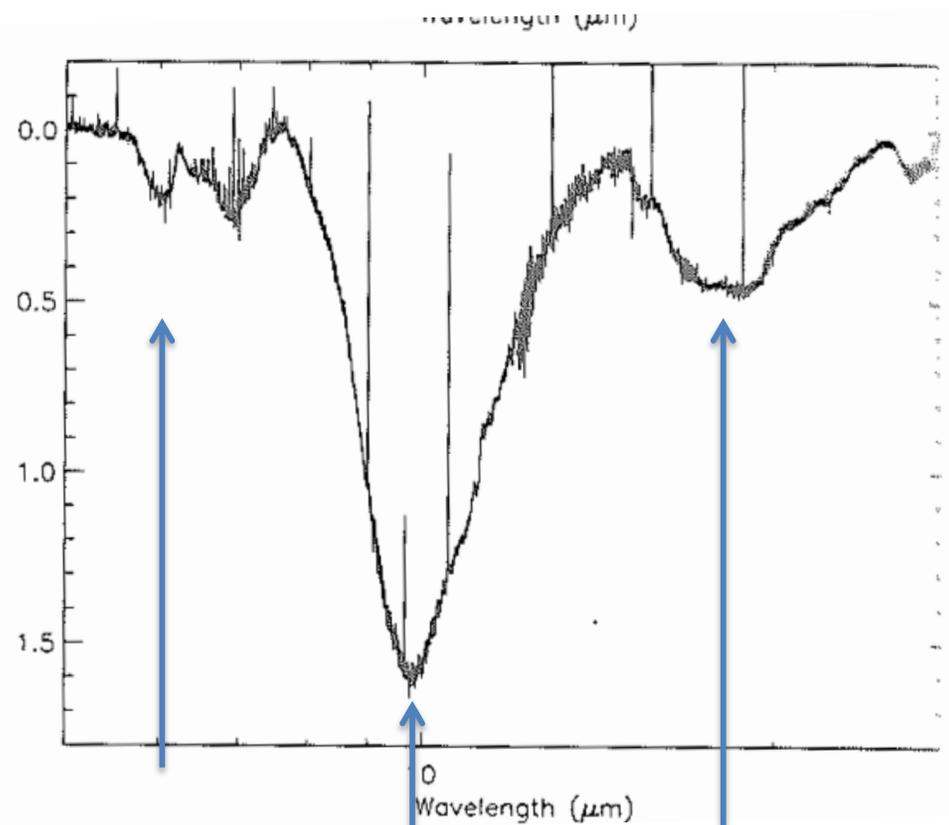- These are thought to arise in icy "mantles" encasing dust grains found in dense molecular clouds.

100 nanometers

ice coating

graphite and silicates
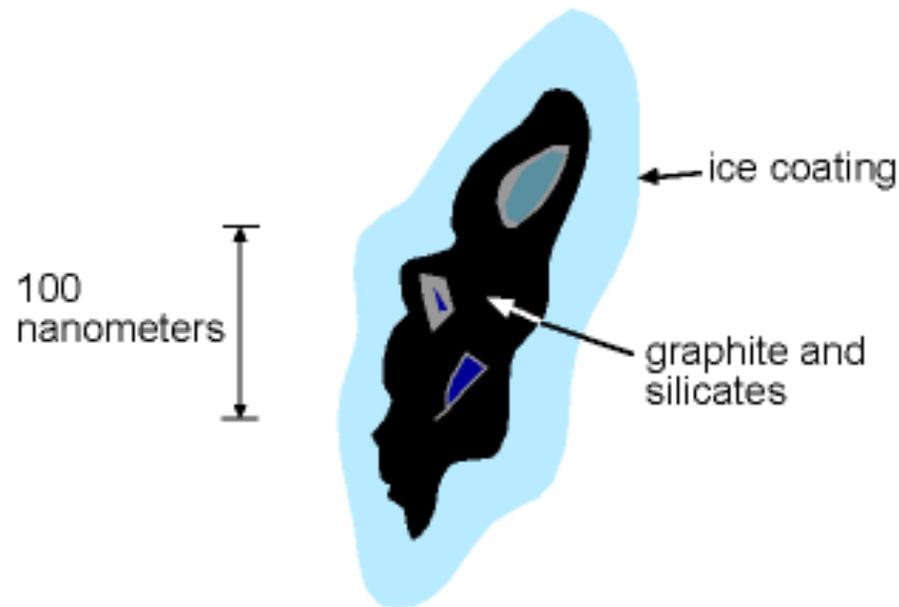
A typical dust grain (note the tiny scale!).
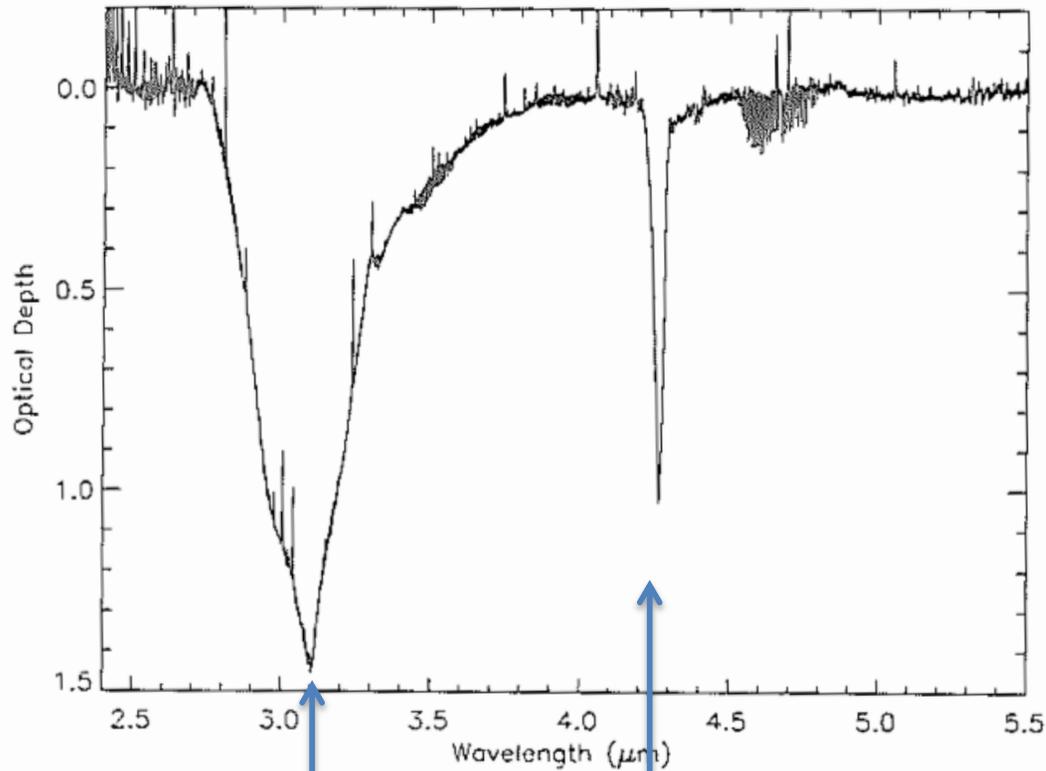
O-H stretch in H_2O

C-O stretch in CO_2

H-O-H bend in H_2O

Si-O stretch in amorphous silicate

O-Si-O bend in amorphous silicate

- Ice mantles not found on grains in the general ISM, since exposure to the general ISRF will sublime the ices.

  - Example: H_2O ice features in Taurus dark cloud only seen when $A_V > 3.3$

- The ice bands are smeared out into broad features because they are in a solid state condensed onto a solid grain.

- CO is most often observed in the gas phase, but can condense as a 'frost' onto dust grains when the temperature <17 K.

  - Such condensation can severely deplete CO out of the gas phase deep inside molecular clouds.
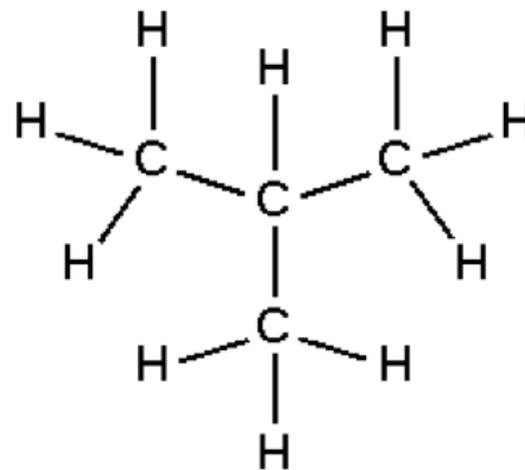
<u>3.3μm aliphatic C-H feature</u>

A broad extinction feature seen along LOS where extinction is particularly high $(A_V > 10)$.

Identified as a C-H stretching mode, in *aliphatic* hydrocarbons, which are organic molecules with carbon atoms joined in straight or branched chains.

Examples are ethane and isobutane:
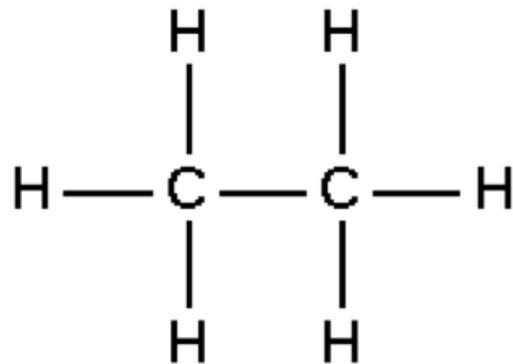
Ethane   Isobutane

- The 3.3μm feature is due to C-H stretching mode in PAHs.

- The 6.2 and 7.7μm feature is vibrational modes of the carbon skeleton.

- The 8.6μm feature is in-plane C-H bending modes,

- Features at 11.3, 12.0, 12.7 and 13.55μm are due to out-of-plane bending C-H mode

- Interstellar PAHs may not be as perfect as indicated in the picture on previous slides
  - May be missing an edge H atom
  - One H may have been replaced by radicals like OH or CN
  - One of the C may have been replaced with N

- A neutral PAH can be photoionized by the lower energy $h\nu < 13.6$ eV starlight in diffuse cloud, creating a PAH^+ ion.
  - Large PAHs can be multiply ionized

- Collisions of a neutral PAH with a free electron can create a PAH^- ion.

- The fundamental vibrational modes (C-H stretching and bending, vibrational modes of the carbon skeleton) remain close to the same frequency
  - Electric dipole moment can be sensitive to the ionization state

  - The 11.3μm C-H out of plane bending mode is much stronger in neutral PAH versus PAH ions

  - Conversely, the 7.7μm vibrational mode of the carbon skeleton has a much stronger electric dipole moment in the PAH ions compared to the neutral PAHs