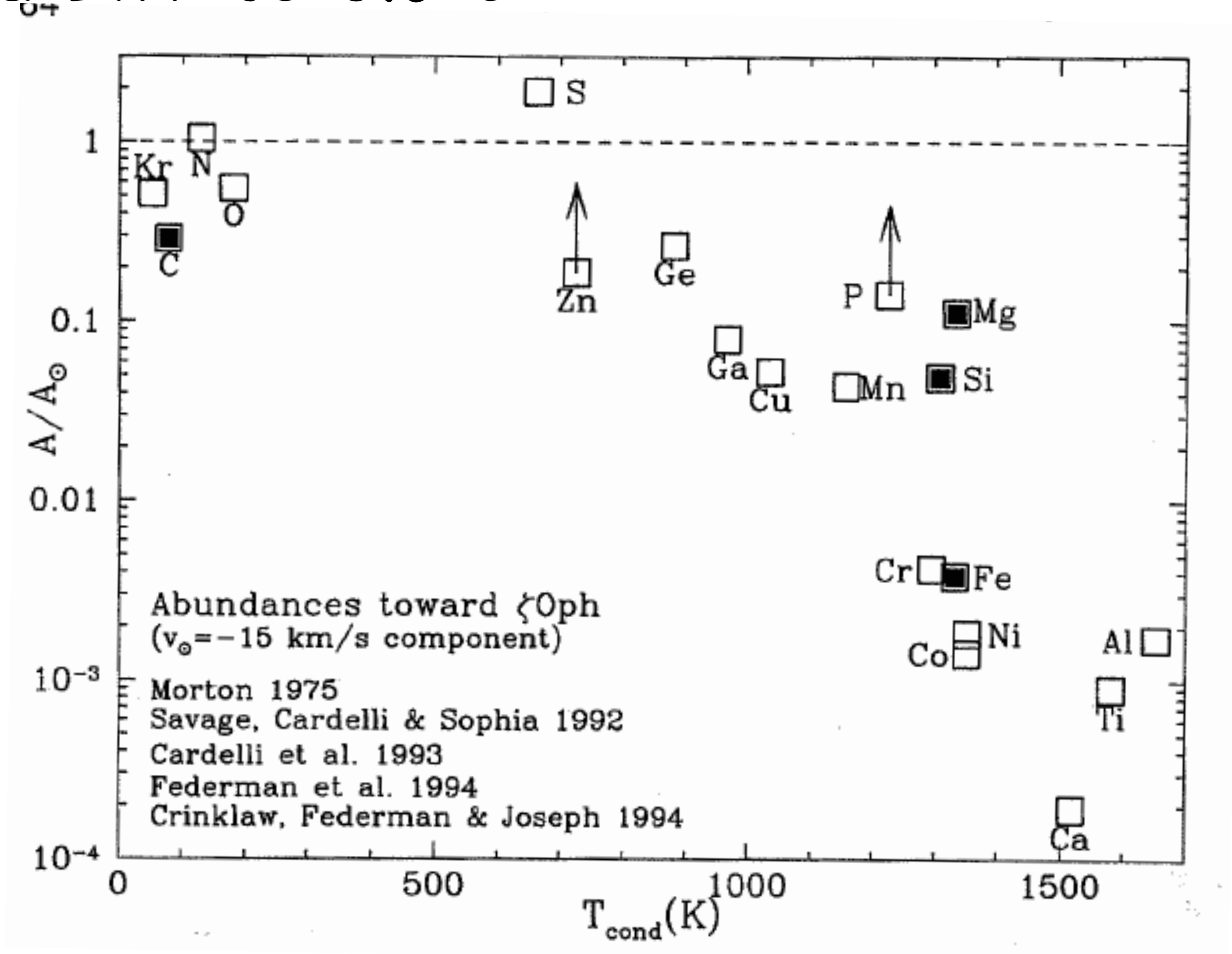
Dust in the Diffuse Universe

- Obscuring Effects
- Chemical Effects
- Thermal Effects
- Dynamical Effects
- Diagnostic Power

Evidence for Grains: Chemical Effects

- Catalyzes molecular hydrogen formation.
- Depletion of elements (gas to solid)
  - The relative elemental abundances in interstellar clouds are quite different from that measured in the Sun.
  - Elements that can form refractory solids are among those which have high depletion.
    - Si and O can form silicates with Mg and Fe
    - Fe may form graphite, silicon carbide, or iron oxides
  - Suggests that as cooling gas moves away from a star, some elements condense into solid particles and are removed from the gas phase

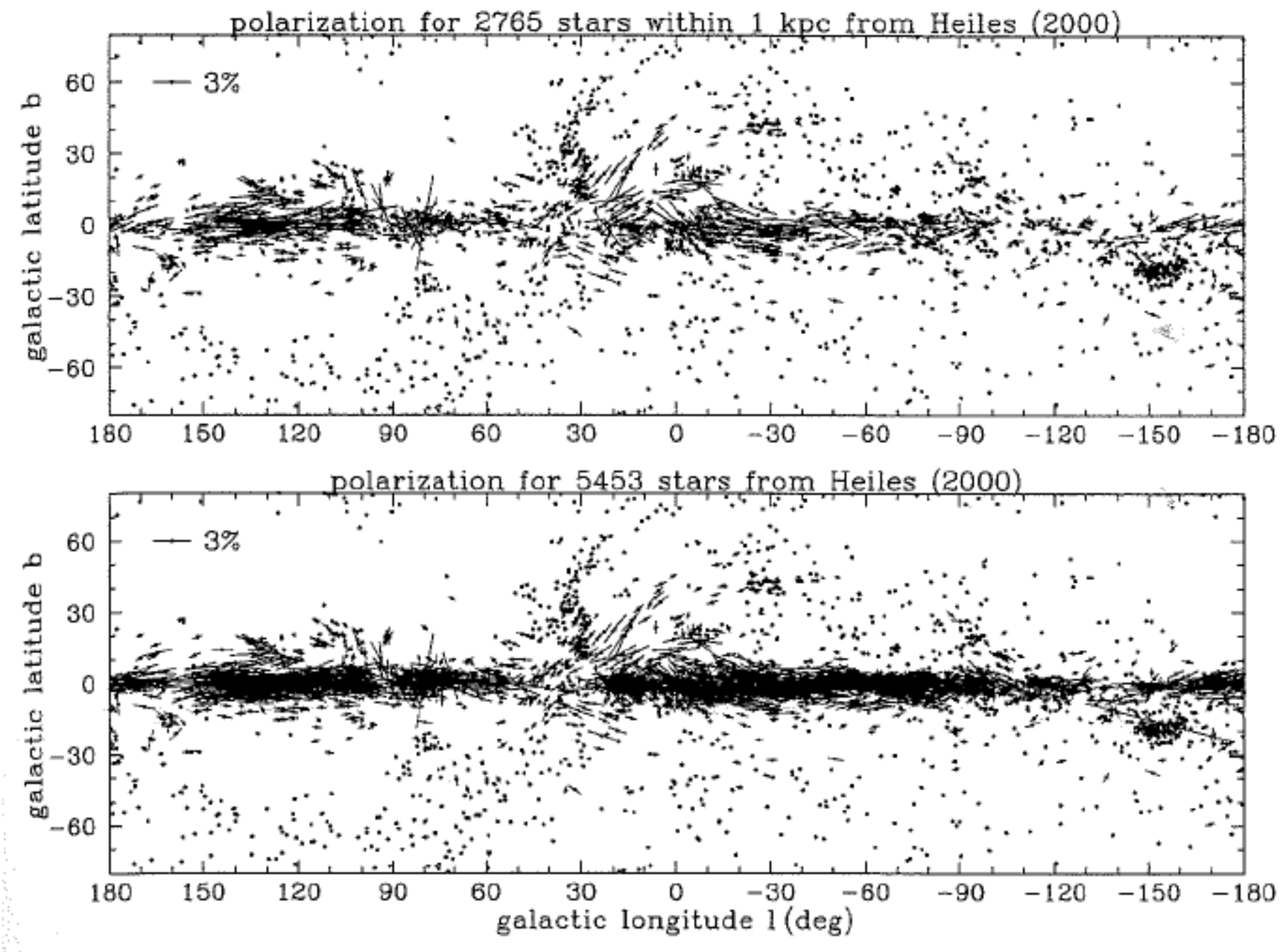
Gas-phase Abundances Relative to Solar in a Diffuse Cloud

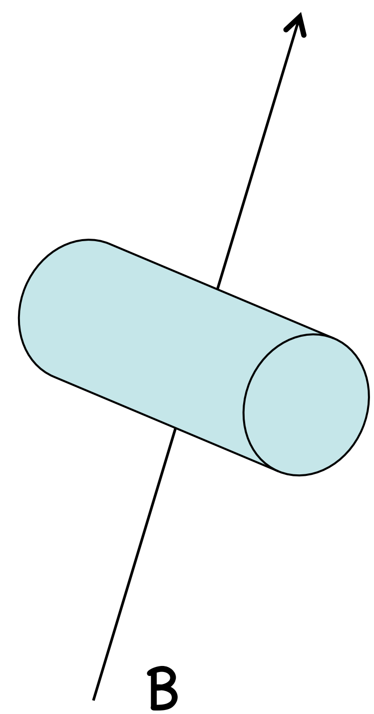


Evidence for Grains: Polarization

- Starlight is linearly polarized by a few percent
- The amount of polarization observed is correlated with the amount of extinction in that direction.
- Grains such as graphite are anisotropic.
- Polarization requires partial alignment of elongated grains.
- Anisotropic grains will normally be rotating due to collisions. Magnetic moment tends to align with the interstellar magnetic field.

Linear Polarization of Starlight





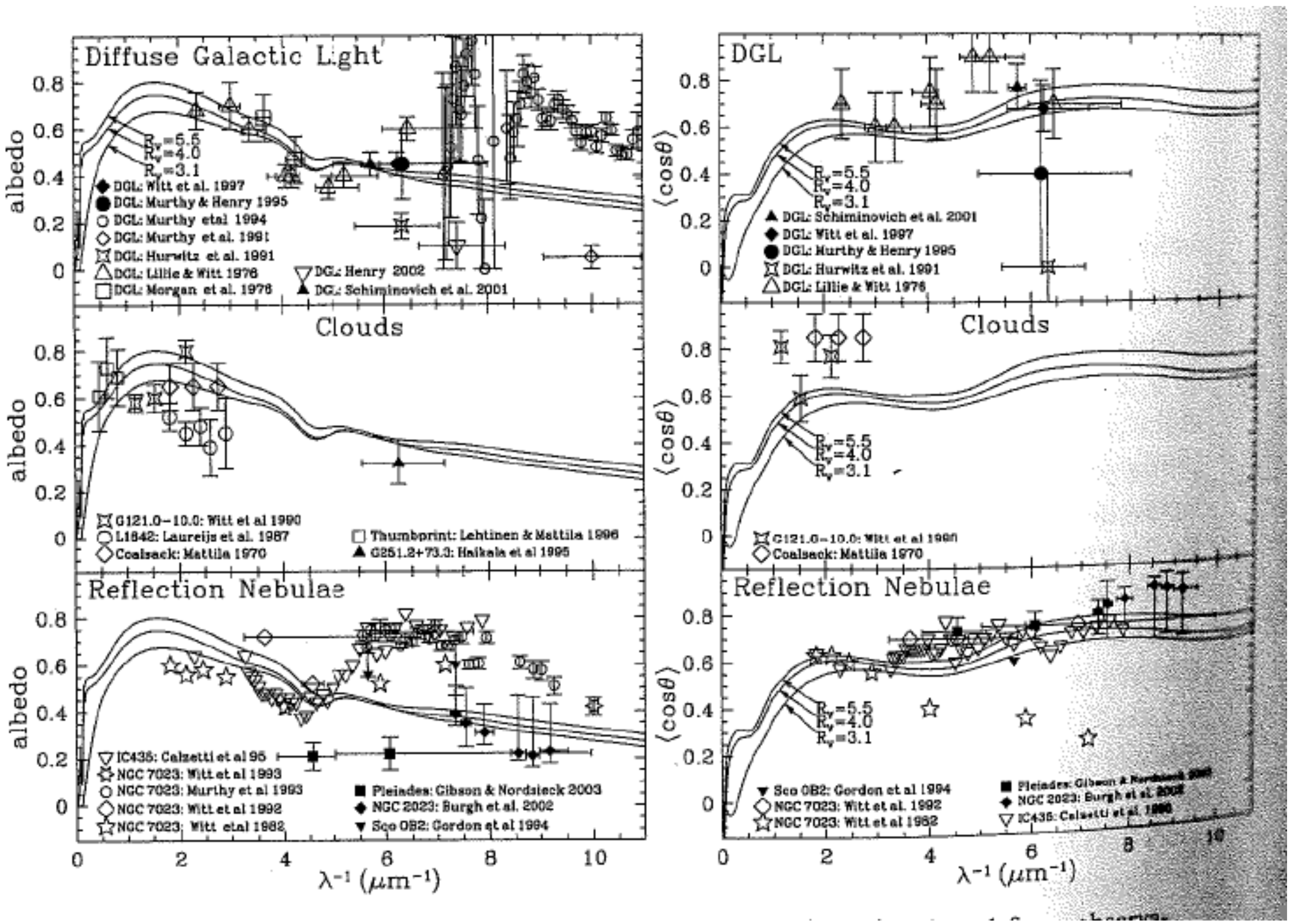
Evidence for Grains: Scattered Light

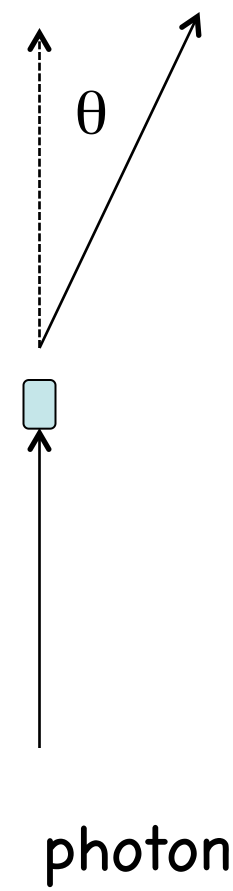
- Cross section for scattering by grains is several orders of magnitude larger than that for Rayleigh scattering by atoms & small molecules
- Albedo = scattering cross section / extinction cross section
- Scattering is about as important as absorption at optical wavelengths (0.5 um)

Zodiacal Light

Reflection Nebulae

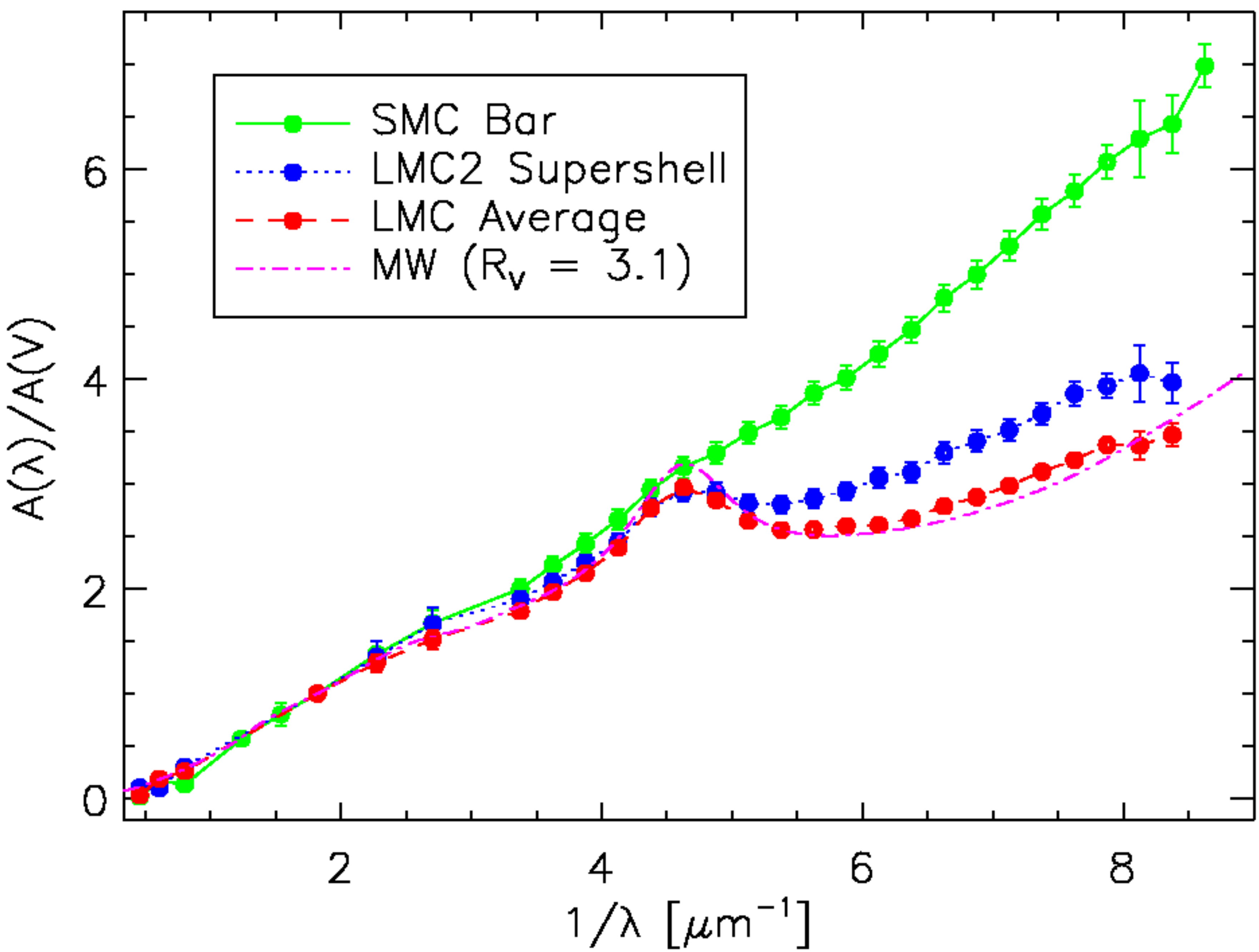
Albedo and Scattering Angle





Obscuring Effect of Grains

- Extinction reduces the observed intensity of starlight
  - Balmer decrement
- Measure brightness of two similar stars, only one of which is behind a gas cloud (correcting for distance differences).
  - Extinction curve
    - Can't measure it below the HI Lyman limit.
    - Hard to measure at very long wavelengths where it's small.
  - Ratio of selective to total extinction is sensitive to grain size.


SMC Bar
LMC2 Supershell
LMC Average
MW (R$_V$ = 3.1)
A(λ)/A(V)
1/λ [μm^{-1}]
0
2
4
6
8

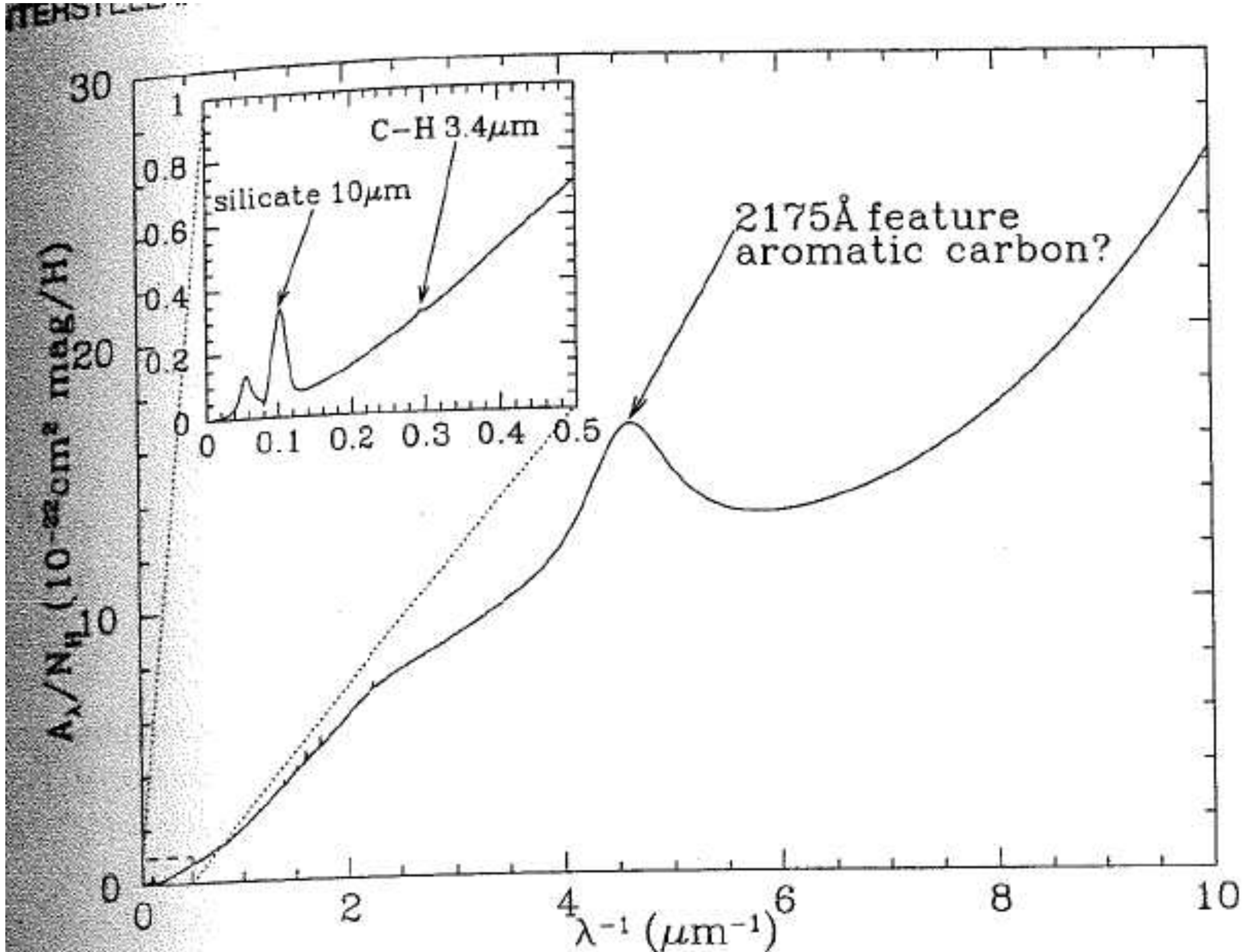
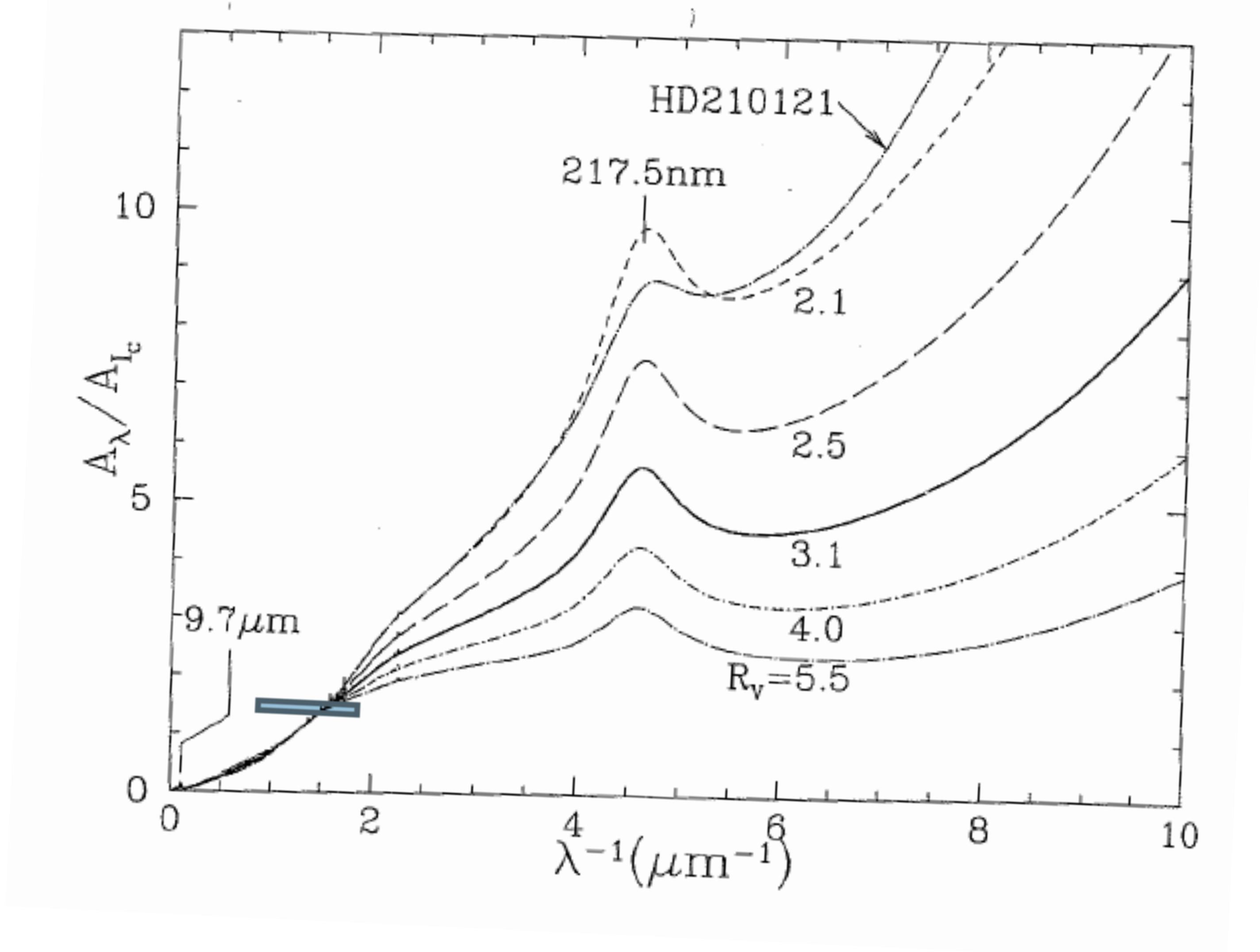


Figure 21.1 Extinction versus inverse wavelength λ^{-1} on a typical sightline in the local diffuse ISM. The inset shows the extinction at $\lambda > 2\,\mu m$.



HD210121
217.5nm
2.1
2.5
3.1
4.0
R_V=5.5
9.7μm
A_λ/A_{I_c}
$\lambda^{-1}(\mu m^{-1})$
0
2
4
6
8
10
0
5
10

Size & Shape of Grains

- Wavelength dependence of extinction (A_λ) in the optical is roughly λ^{-1}, even at 1000 A.
  - Requires very small grains make a substantial contribution to extinction.
  - $2 \pi a \leq \lambda$, so $a \leq 0.015$ um.
- Starlight is significantly polarized at 5500, so the grains with a ~ 0.1 um are non-spherical and substantially aligned with the B field.
- The polarization of starlight decreases towards bluer wavelengths. The grains with $a \leq 0.05$ um which dominate the extinction at $\lambda < 0.3$ um are either spherical or minimally aligned.
- Most of the mass is in the larger grains.
- Most of the surface area is in the samller grains.

Composition of Grains

- Pronounced peak at 2175 A in Milky Way is largely absent in Magellanic Clouds,
  - Attributed to C sheets
  - Drude profile
- 3.4 um feature from C-H stretching
- Silicate features
  - 9.7 um Si-O stretching
  - 18 um Si-O-Si stretching

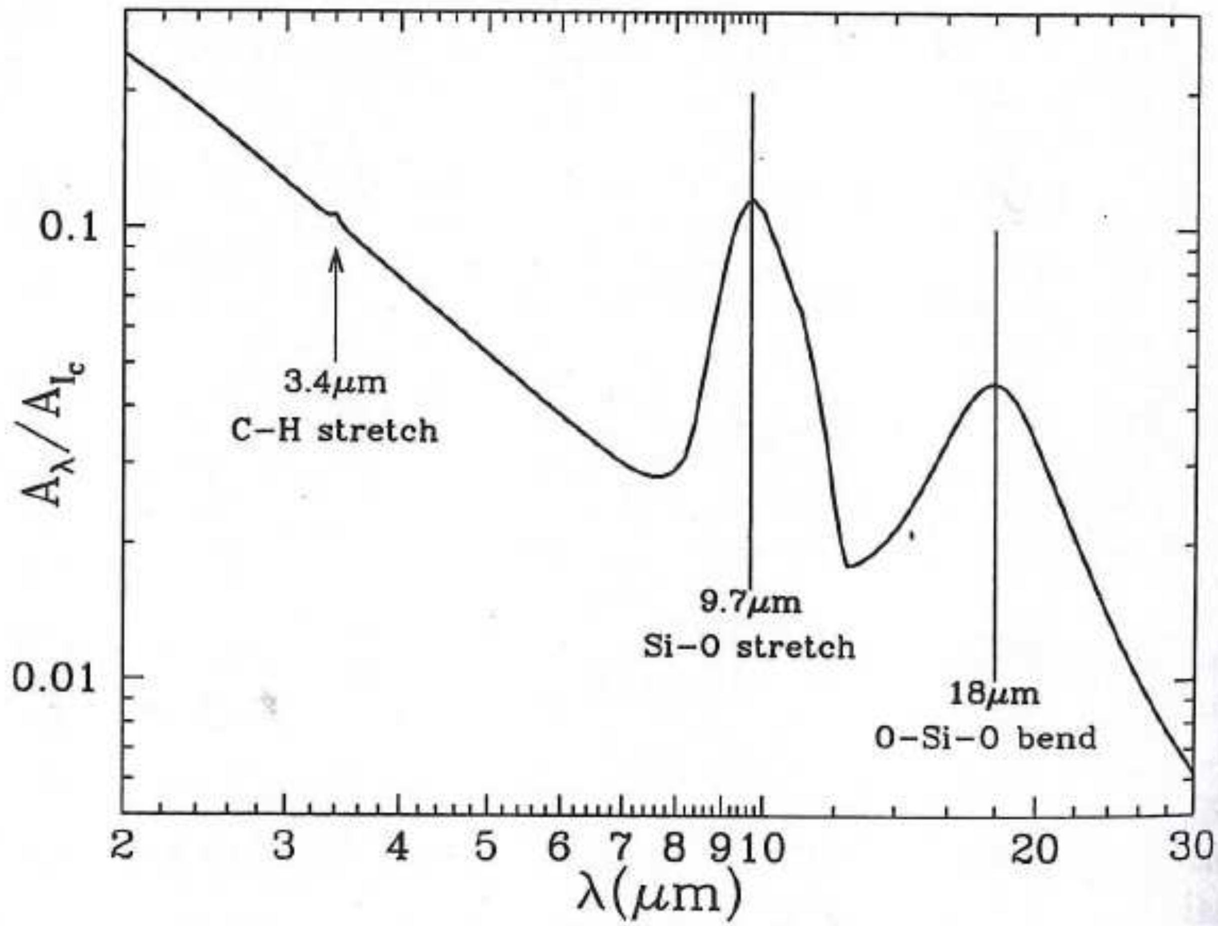


Figure 23.2 Infrared extinction curve. The 8 to 13 μm silicate profile is as observed toward the Galactic Center by Kemper et al. (2004), but with $A_V/\Delta\tau_{9.7\,\mu m} = 18.5$, as appropriate for sightlines through diffuse gas within a few kpc of the Sun (see Table 1 of Draine 2003*a*). The 3.4 μm C–H stretching feature is indicated.

Temperature of Grains

- Heated by starlight
- Grain temperture << Stellar temperature

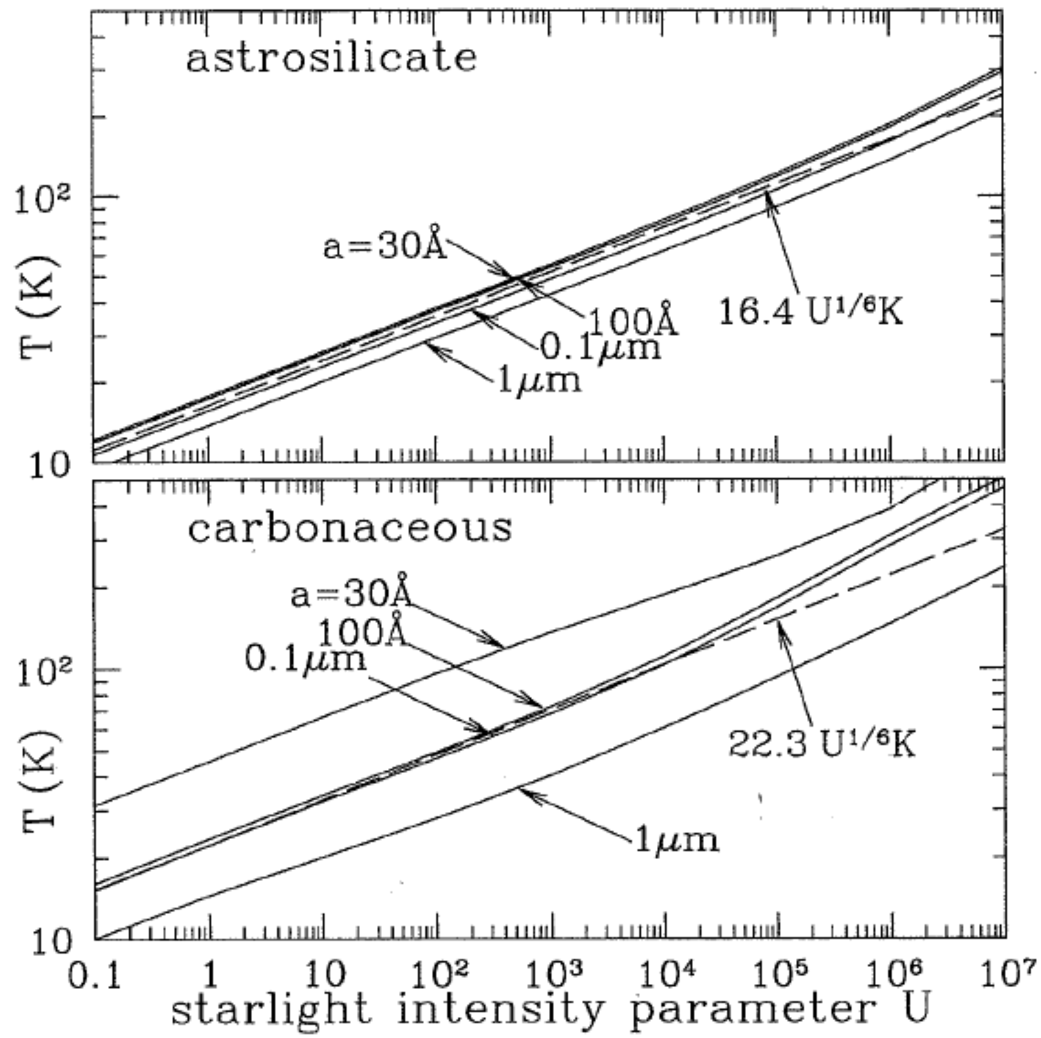
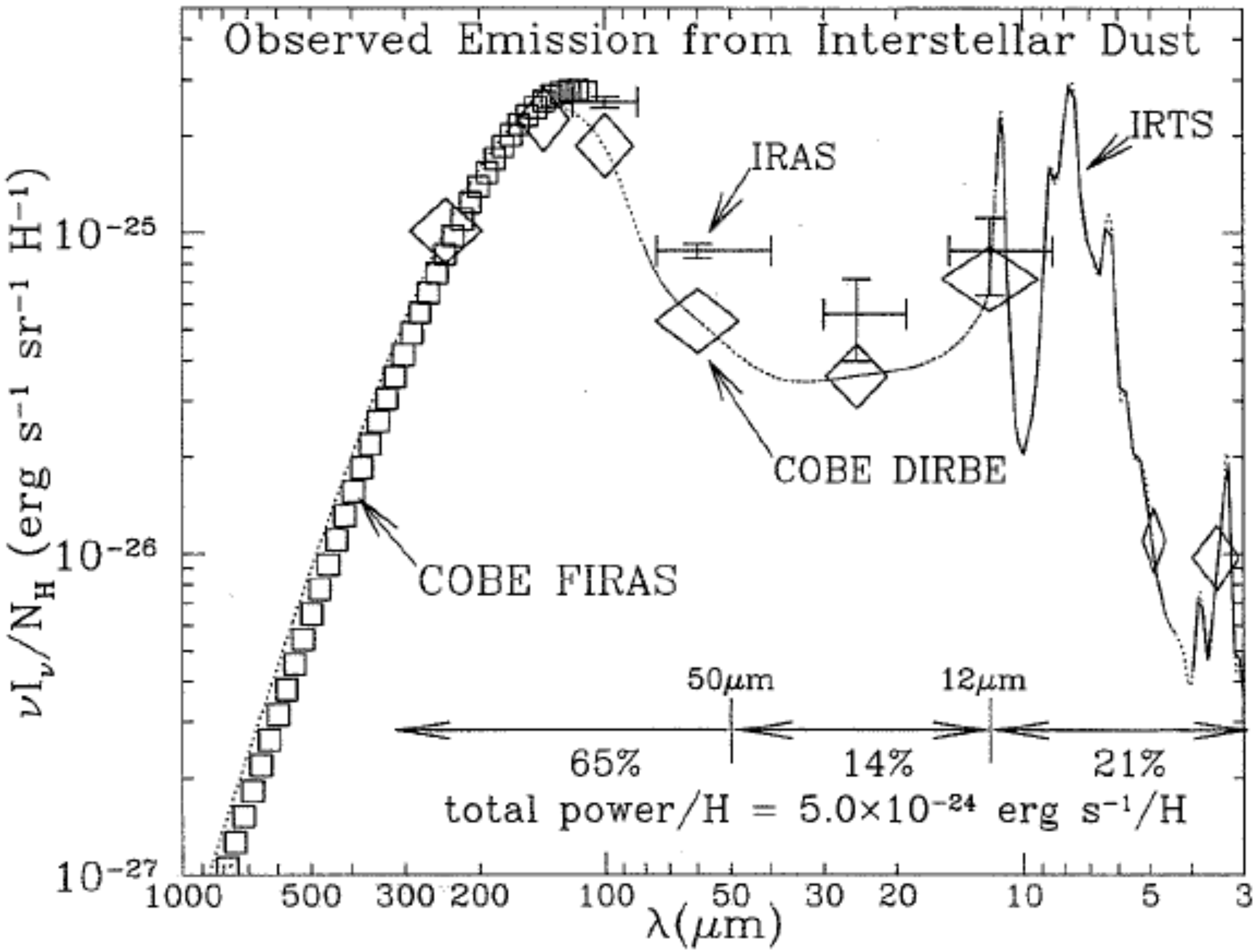


Figure 24.4 Equilibrium temperature for astrosilicate and carbonaceous grains heated by starlight with the spectrum of the local radiation field, and intensity U times the local intensity. Also shown are the power-laws $T = 16.4U^{1/6}$ K and $T = 22.3U^{1/6}$ for $a = 0.1\ \mu$m from Eqs. (24.19 and 24.20).


Observed Emission from Interstellar Dust
IRTS
IRAS
COBE DIRBE
COBE FIRAS
50μm
12μm
65%
14%
21%
total power/H = 5.0×10⁻²⁴ erg s⁻¹/H
νI_ν/N_H (erg s⁻¹ sr⁻¹ H⁻¹)
10⁻²⁵
10⁻²⁶
10⁻²⁷
1000 500 300 200 100 50 30 20 10 5 3
λ(μm)

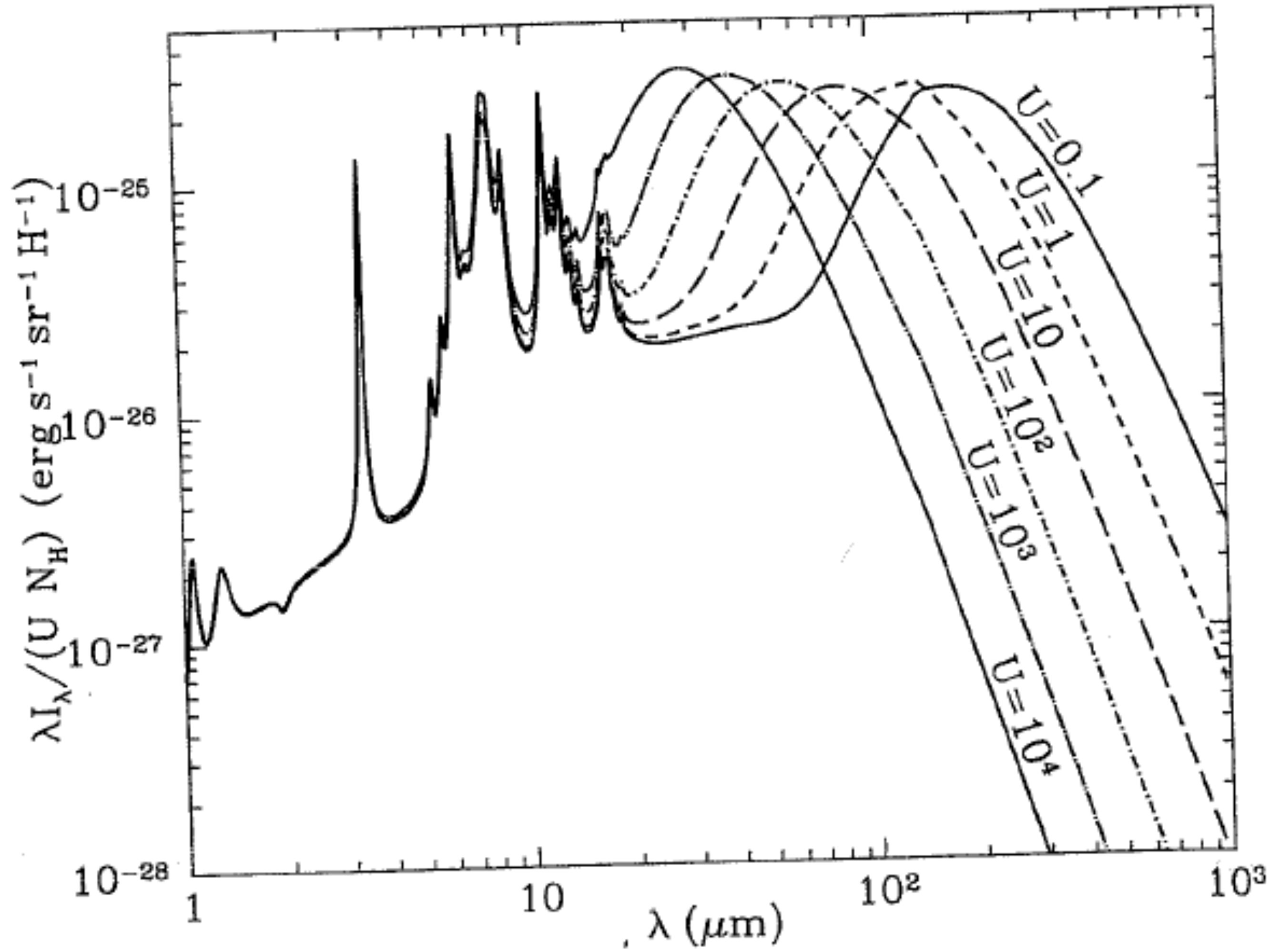
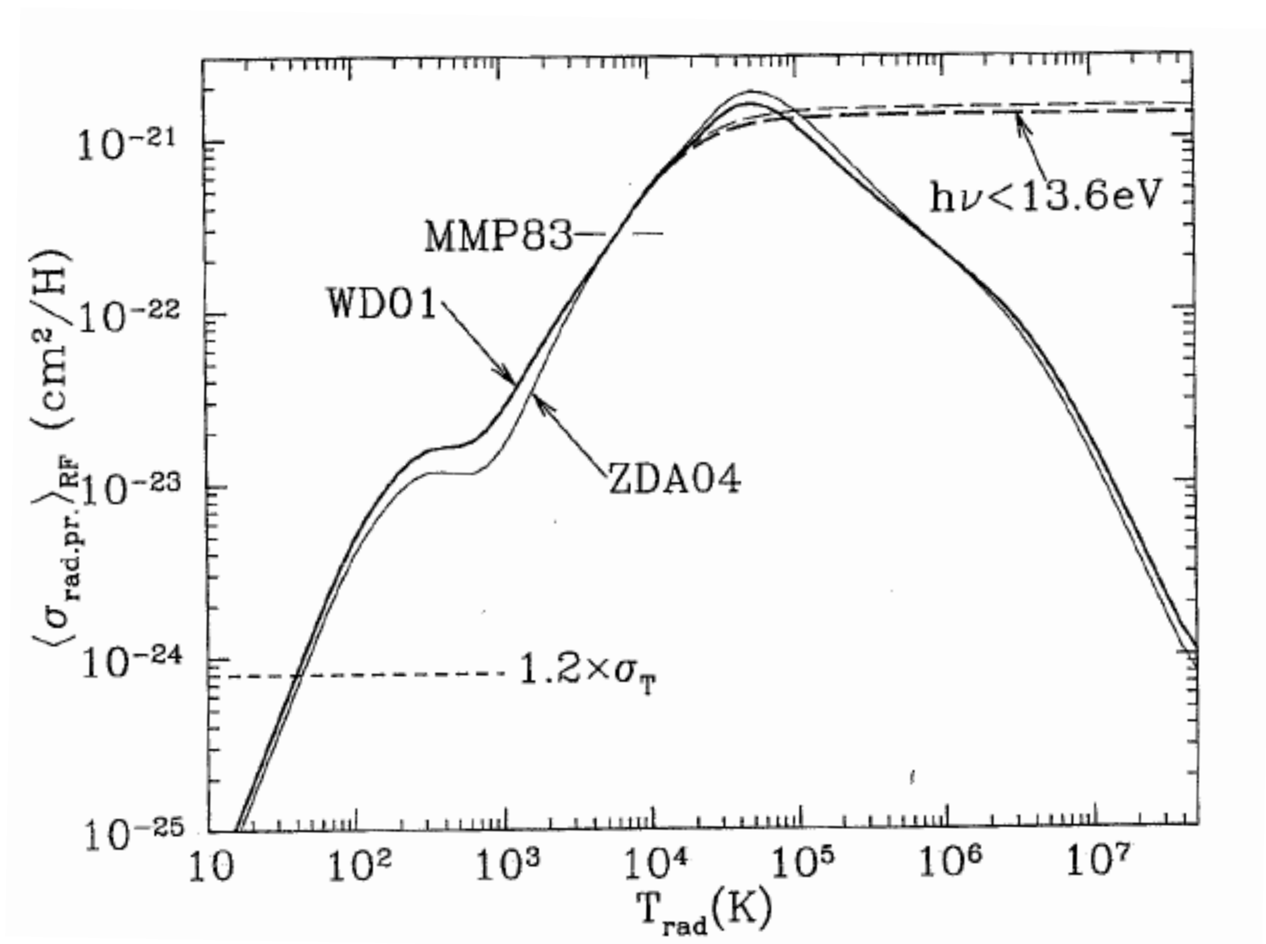


Figure 24.7 Infrared emission spectrum for model with silicate and graphite/PAH grains in ISRF intensity scale factor U from 0.1 to 10^4 ($U = 1$ is the local ISRF). Spectra are scaled to give power per H nucleon per unit U, calculated using the model of Draine & Li (2007).

Radiation Pressure Cross Section per H (averaged over a Planck Spectrum)



Photoelectric Heating of Gas

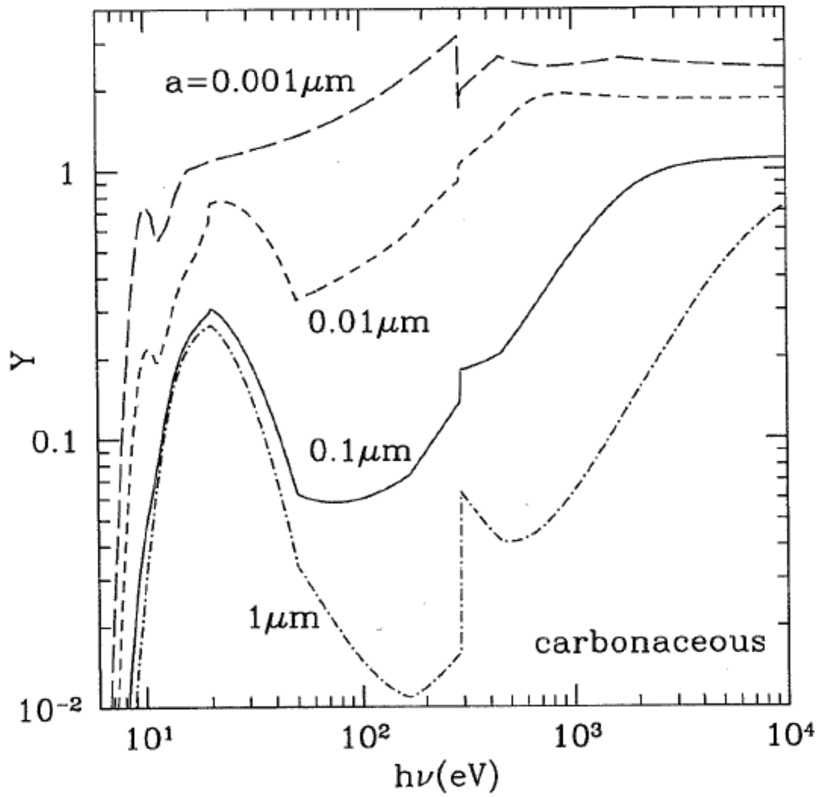
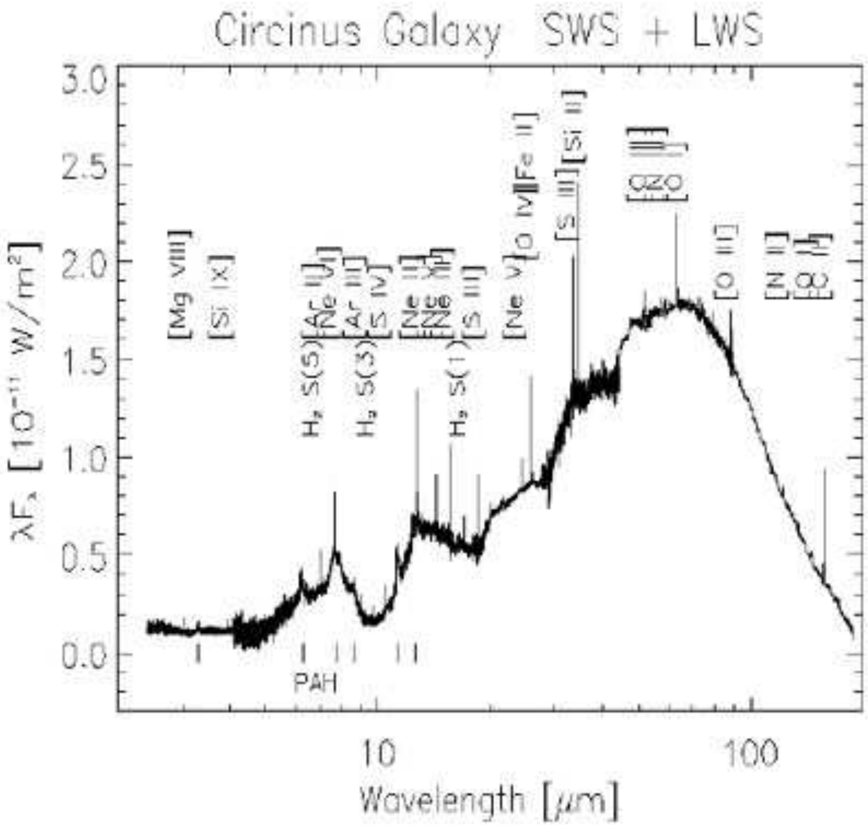


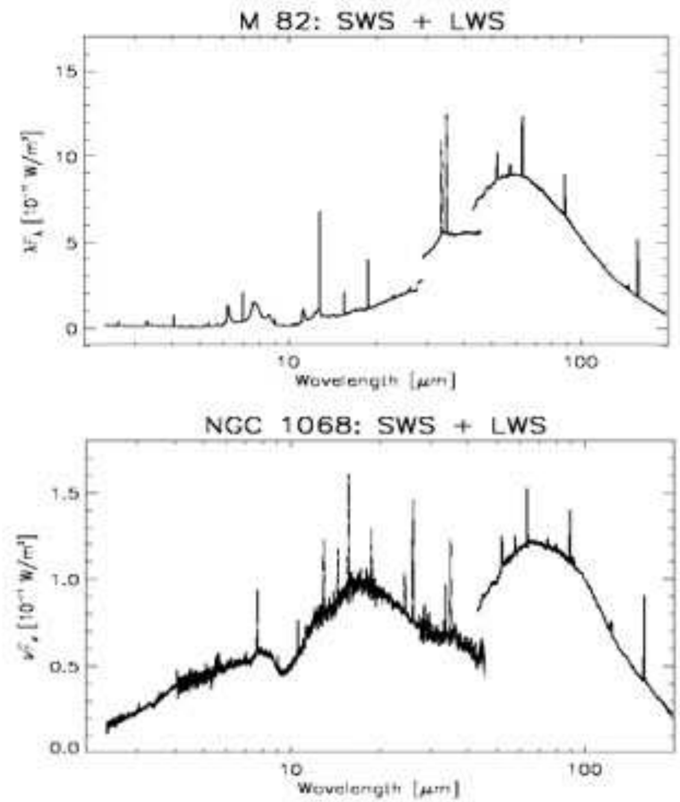
Figure 25.1 Photoelectric yield Y for uncharged carbonaceous grains for selected radii, as a function of photon energy. For sufficiently small grains, Y can exceed unity because of secondary electron emission for $h\nu \gtrsim 14\,\mathrm{eV}$, and Auger electron emission for $h\nu > 291\,\mathrm{eV}$. From Weingartner et al. (2006), reproduced by permission of the AAS.

Diagnostic Power

- Total heating rate often reveals ‘obscured’ star formation.
- Infrared spectroscopy of solids
- Absorption features from particular bonds in solid particles

Solid state spectral lines





Optics of Grains

- How do grains of a given size, shape, and refractive index modify the radiation which falls on them?
- Just apply Maxwell's equations with appropriate boundary conditions on the grain surface.
- Produce extinction curves for solids of various size, shape, and refractive index.
- Juggle these to build the observed extinction curve. For the optical, need
  - Size a=3e-5 cm
  - n_{grains}=1e-12 n_H
  - Refractive index ~ 1.3

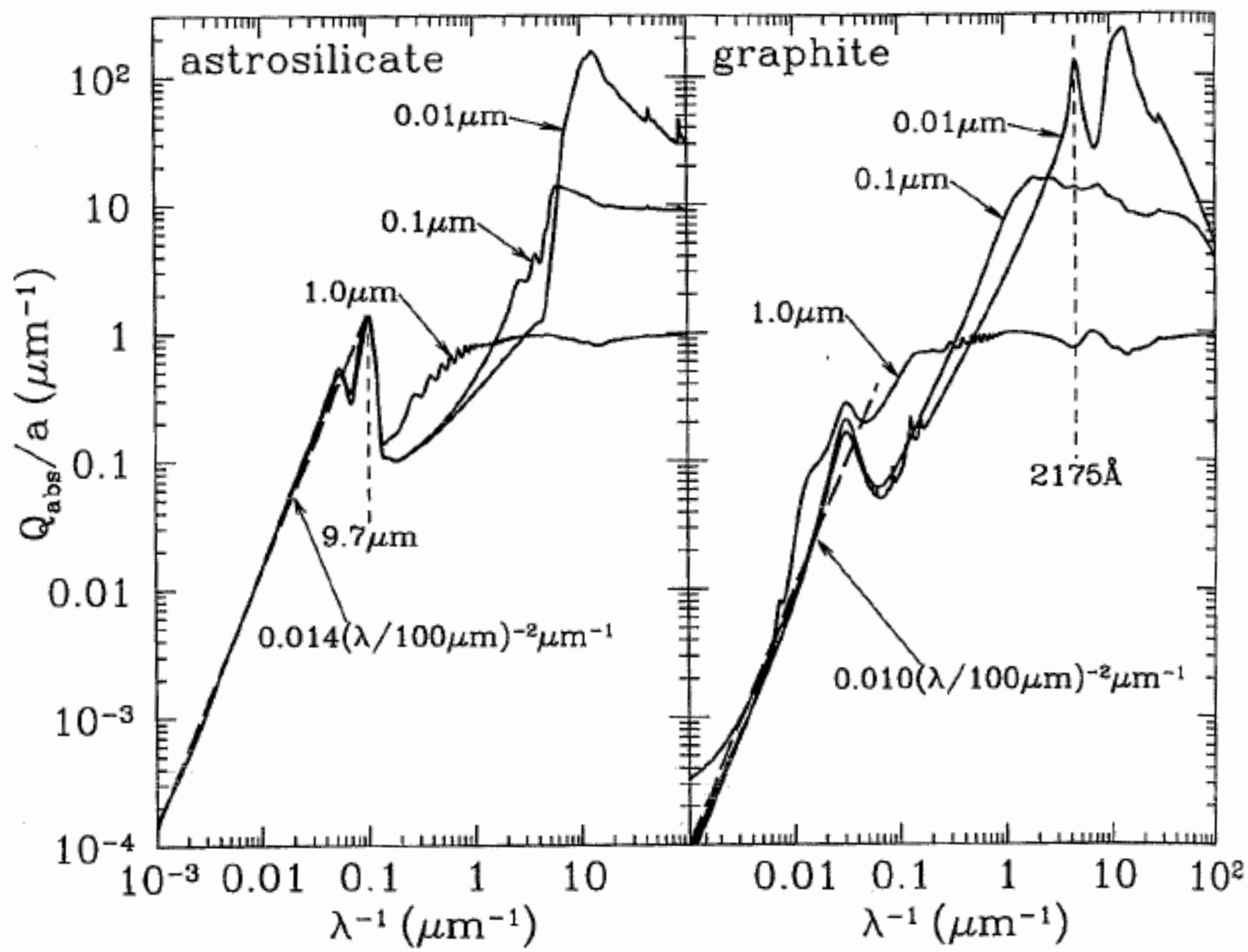


Figure 24.1 Absorption efficiency $Q_{\rm abs}(\lambda)$ divided by grain radius a for spheres of amorphous silicate (left) and graphite (right). Also shown are power-laws that provide a reasonable approximation to the opacity for $\lambda \gtrsim 20\,\mu$m.

Dust in astrophysics

1) obscuring effects
   - need to correct observed intensities for attenuation

2) chemical effects
   - sequesters certain elements
   - catalyzes H_2 formation

3) thermal effects
   - photoelectrons from dust grains can dominate the heating of gas in regions where UV starlight is present.
   - IR emission from dust is an important cooling mechanism in dense regions

4) dynamical effects
   - couples radiation pressure to the gas
   - couples magnetic field to the gas in regions of low fractional ionization

- Optical Properties of Grains

$$I(\lambda) = I_o(\lambda)\, e^{-\tau_{ext}}$$

$$\tau_{ext} = \tau_{abs} + \tau_{scattering}$$

- Describe extinction with
  (1) magnitudes of extinction $A(\lambda)$
  (2) logarithmic reddening constant c

- Magnitudes of extinction

$$m_1 - m_2 = -2.5 \log f_1/f_2$$

$$m' - m = -2.5 \log \frac{I(\lambda)}{I_o(\lambda)}$$

$$A(\lambda) = -2.5 \log e^{-\tau}$$

$$= -2.5 \frac{\ln e^{-\tau}}{\ln 10}$$

$$\boxed{A(\lambda) \doteq 1.086\, \tau(\lambda)}$$

- Define a dimensionless extinction efficiency Q_e that depends on grain composition and size.

$$\tau_{ext} = N_d\, Q_e\, \sigma_d$$

σ_d ← Geometrical cross section of a single grain

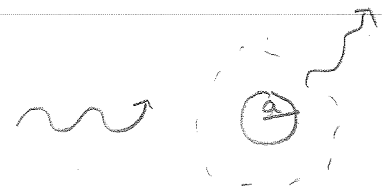
Q_e ← $\frac{\text{extinction cross section}}{\pi a^2}$

N_d ← column density of grains per unit area

$$Q_e = Q_{abs} + Q_{scattering}$$

$$\frac{Q_{scatter}}{Q_e} \equiv \text{albedo} \Rightarrow 1 \text{ for perfect reflection}$$

Scattering is strongest when particles have $a \gtrsim \lambda$.
The process is closely related to optical diffraction.



Q_{scatt} describes the integral of the scattering cross section over all solid angles.

For a given grain size, Q increases to shorter wavelengths with an asymptotic value $Q_{scatt} \simeq 2$ – about twice the geometric area

If the dielectric properties of the grain are such that there's no absorption, then this reduces to $Q_{scatt} \propto \lambda^{-4}$ efficiency of Rayleigh Scattering. Maximum eff. at $\lambda \sim 2\pi a$

Absorption (imaginary m), we have $Q_{abs} \propto \lambda^{-1}$.

Determines the grain temperature

$$\int F(\lambda)\, Q_{abs}(a,\lambda)\, d\lambda = \int Q_{abs}(a,\lambda)\, B_\lambda(\lambda, T_g)\, d\lambda$$

Heating cooling

$j = \kappa I_\nu$

Measure the extinction curve

- Trick is to measure magnitudes of two stars of same spectral at 2 different wavelengths.
    - Distance affects the flux at λ_1 and λ_2 the same
    - Dust absorption is stronger at bluer wavelengths

- Color excess

$$E(\lambda_1) - E(\lambda_2) = \Delta A(\lambda_1) - \Delta A(\lambda_2)$$

- 2175 Å feature
  small carbon grains $r \sim 200$ Å
  Drude resonance profile - surface charge resonance on small C grains

- 2175 Å feature becomes weaker and UV extinction law steepens as we go to regions of lower density and metallicity

$$F(\lambda) = F_0(\lambda)\, 10^{-c f(\lambda)}$$

$$\frac{N_H}{E_{B-V}} \sim$$

5.9×10^{21} cm^{-2} mag^{-1}	Gal
2.4×10^{22}	LMC
0.7-4×10^{22}	SMC