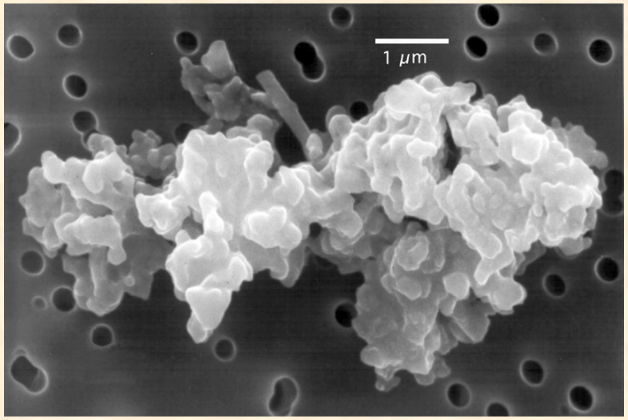
Dust

- Observational signatures
- Dust absorption
  - Reddening curves
  - The dust/gas ratio
  - Scattering and absorption theory
- Dust emission
- Lifestyles of dust grains



What are the observational signatures of dust?

- Absorption/Scattering:
  - Extinction/reddening (scattering and absorption)
  - Reflection (e.g., reflection nebula)
  - Broad absorption features (e.g., 2200 Å, 9.7μm, 18μm)
  - Diffuse Interstellar Bands (DIBs) in optical: weak, relatively broad absorption
  - Polarization (elongated and aligned dust grains)
- Emission in the IR:
  - Thermal continuum (modified blackbody)
  - Very Small Grain (VSG) continuum
  - Polycyclic Aromatic Hydrocarbon (PAH) features in 3 -11μm region

Absorption: Extinction and Magnitudes

Magnitudes: $m_1 - m_2 = -2.5 \log\left(\frac{F_1}{F_2}\right)$

Extinction: $A_\lambda = m_\lambda - m_0 = -2.5\log\left(\frac{F_\lambda}{F_0}\right)$ where F_λ =observed flux

F_0 = flux if no dust

Why do we use magnitudes to measure extinction?

$$A_\lambda = -2.5\log\left(\frac{F_\lambda}{F_0}\right) = (2.5)(0.434)\ \ln\left(\frac{F_0}{F_\lambda}\right)$$

$$\boxed{A_\lambda = 1.086\tau_\lambda}$$

So A_λ is proportional to τ_λ and the dust column

Extinction and Reddening

Separate into two terms: $A_\lambda = R_\lambda E(B-V)$

$$R_\lambda = \frac{A_\lambda}{E(B-V)} \quad \text{(reddening curve)}$$

$$E(B-V) \equiv A_B - A_V \quad \text{(measures amount of reddening)}$$

$$A_B = -2.5 \log\left(\frac{F_B}{F_{B0}}\right) \qquad A_V = -2.5 \log\left(\frac{F_V}{F_{V0}}\right)$$

E(B –V) is known as the color excess or “the reddening”

B magnitude is at ~ 4400Å

V magnitude is at ~ 5500Å

How do we determine a reddening curve?

- find an identical object with no reddening
- get the fluxes at each wavelength (i.e., spectra)

$$\text{Let } X = \frac{F_{\lambda 0}}{F_\lambda} = \frac{\text{observed flux of unreddened object}}{\text{observed flux of reddened object}}$$

$$\boxed{E(B-V) = 2.5\,(\log X_B \ - \ \log X_V)}$$

To get reddening at any wavelength, relative to $E(B-V)$:

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

So to get the extinction curve observationally:

$$\boxed{R_\lambda = \frac{A_\lambda}{E(B-V)} = \frac{E(\lambda - V)}{E(B-V)} + R_V} \quad \text{where } R_V = \frac{A_V}{E(B-V)}$$

How do we determine A_V?

- Need to know the reddened star's intrinsic (unreddened) flux (F_{V0})
- Assume the reddened (0) and unreddened (1) stars have identical luminosities (e.g., same exact spectral type)

$$L_V = 4\pi D_1^2 F_{V1} = 4\pi D_0^2 F_{V0} \quad (\text{D} = \text{distance})$$

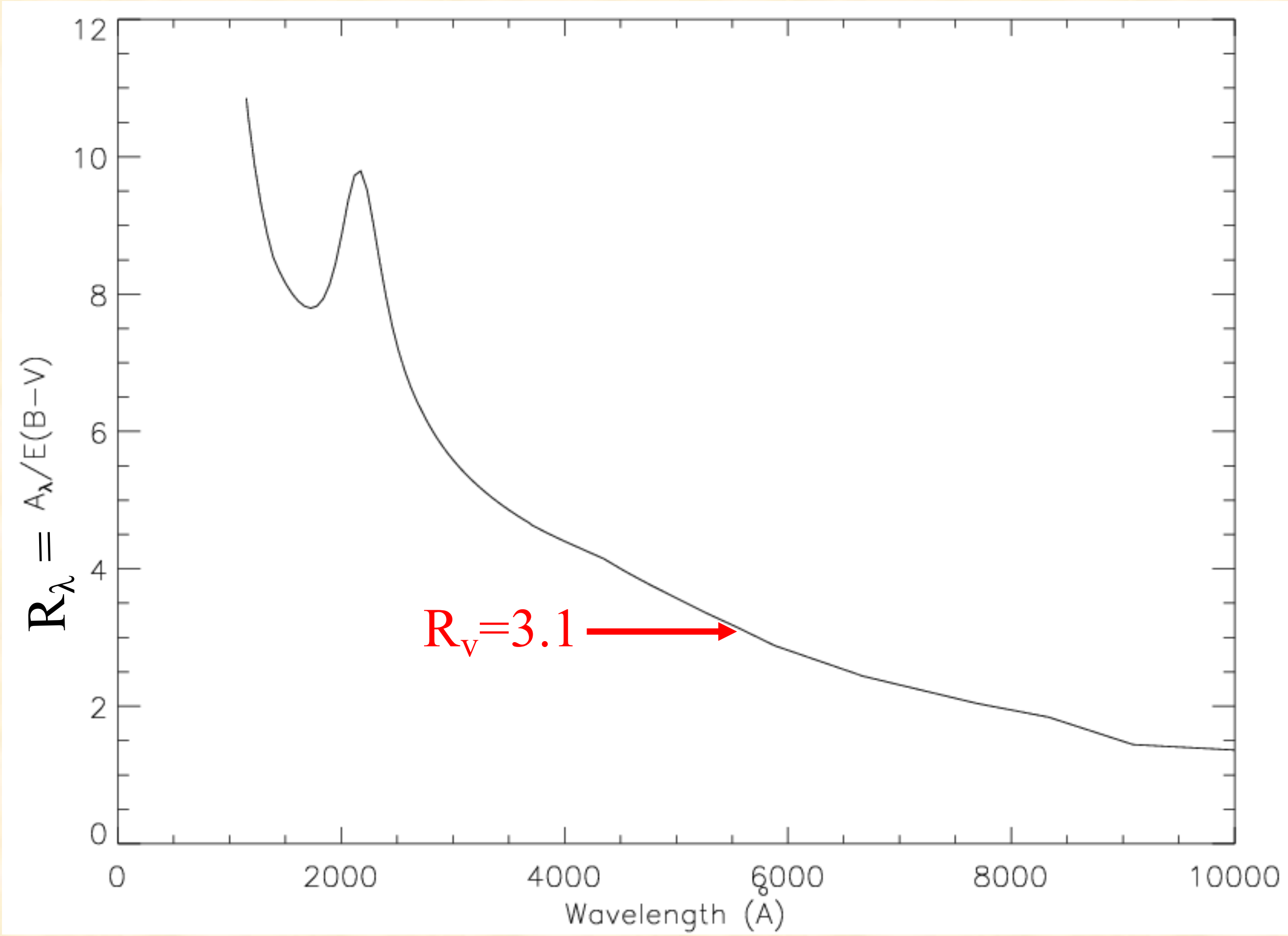
$$\text{So } F_{V0} = \frac{D_1^2}{D_0^2} F_{V1}$$

$$A_V = 2.5 \log\left(\frac{F_{v0}}{F_V}\right) \qquad \left(\frac{\text{intrinsic (unreddened) flux}}{\text{observed flux}}\right)$$

From determinations of A_V for local stars in Galaxy:

$$R_V = \frac{A_V}{E(B\text{-}V)} = 3.1$$

Standard Galactic Extinction Curve
(Savage & Mathis, 1979, ARAA, 17, 731)

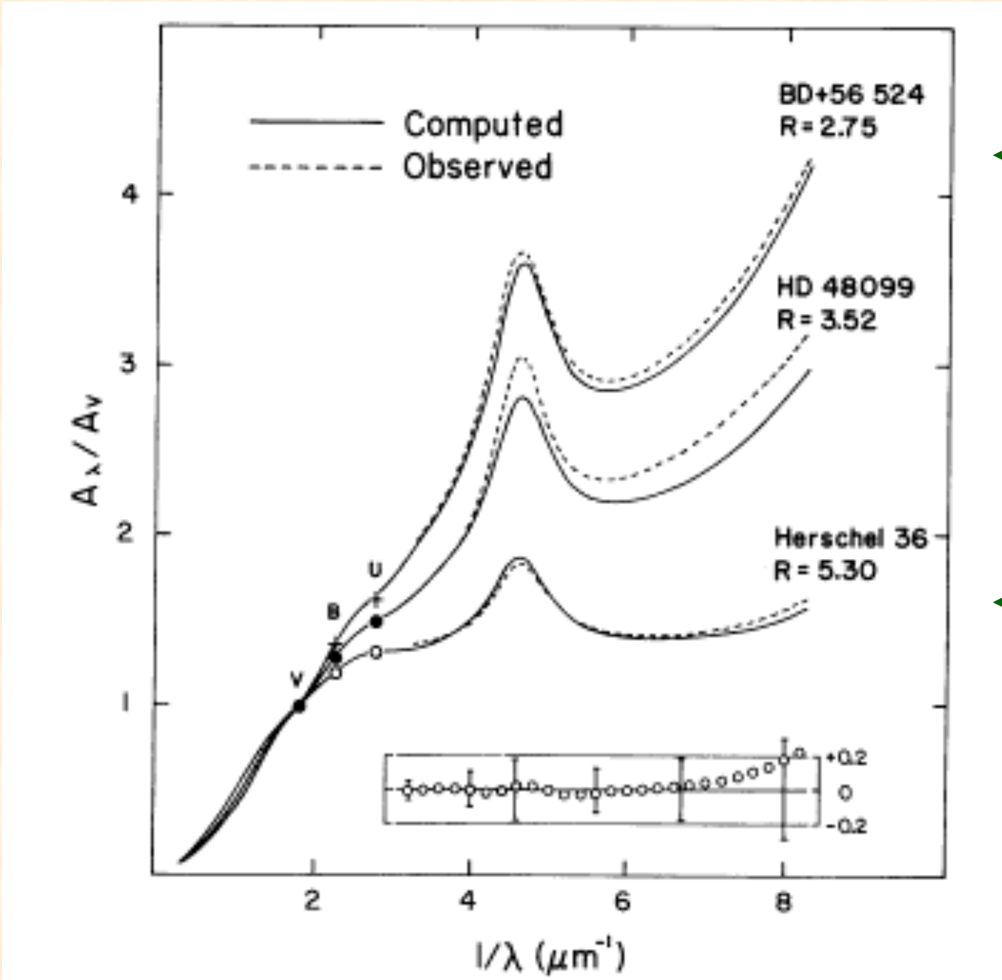


- Sharp rise to UV: due to small dust grains
- 2200 Å bump: due to carbon (graphite? PAHs?)

To correct for extinction: $F_0 = F_\lambda 10^{0.4A_\lambda} = F_\lambda 10^{0.4R_\lambda E(B-V)}$

All Galactic reddening curves are not the same!

(Cardelli, Clayton, & Mathis, 1989, ApJ, 345, 245 [CCM])



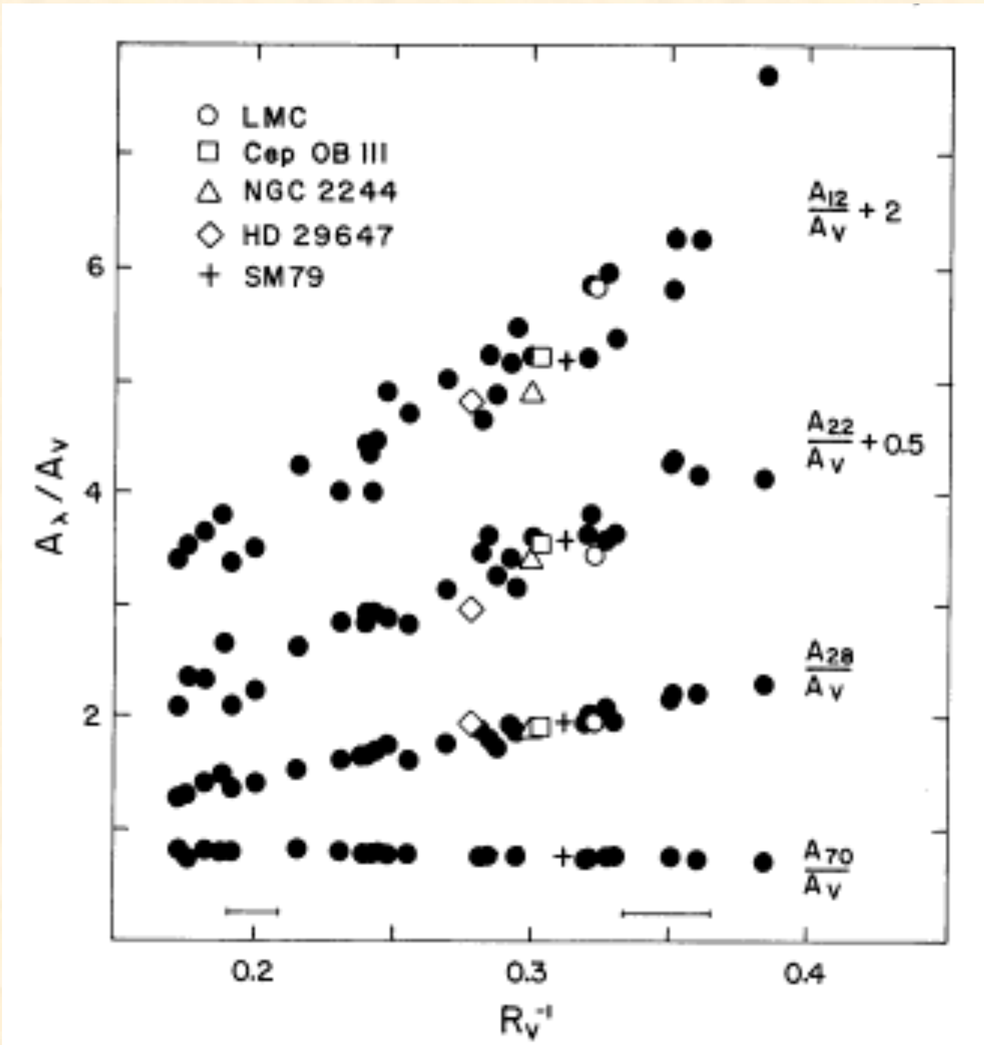
diffuse ISM

outer part of molecular cloud
→R_V depends on environment!

(see also: Mathis, 1990, ARAA, 28, 27)

- reddening curves are similar at λ > 7000 Å, diverge in UV
- the UV extinction can be parameterized by R_v^{-1}

Relative Extinction vs. R_V^{-1} (CCM)



1200 Å

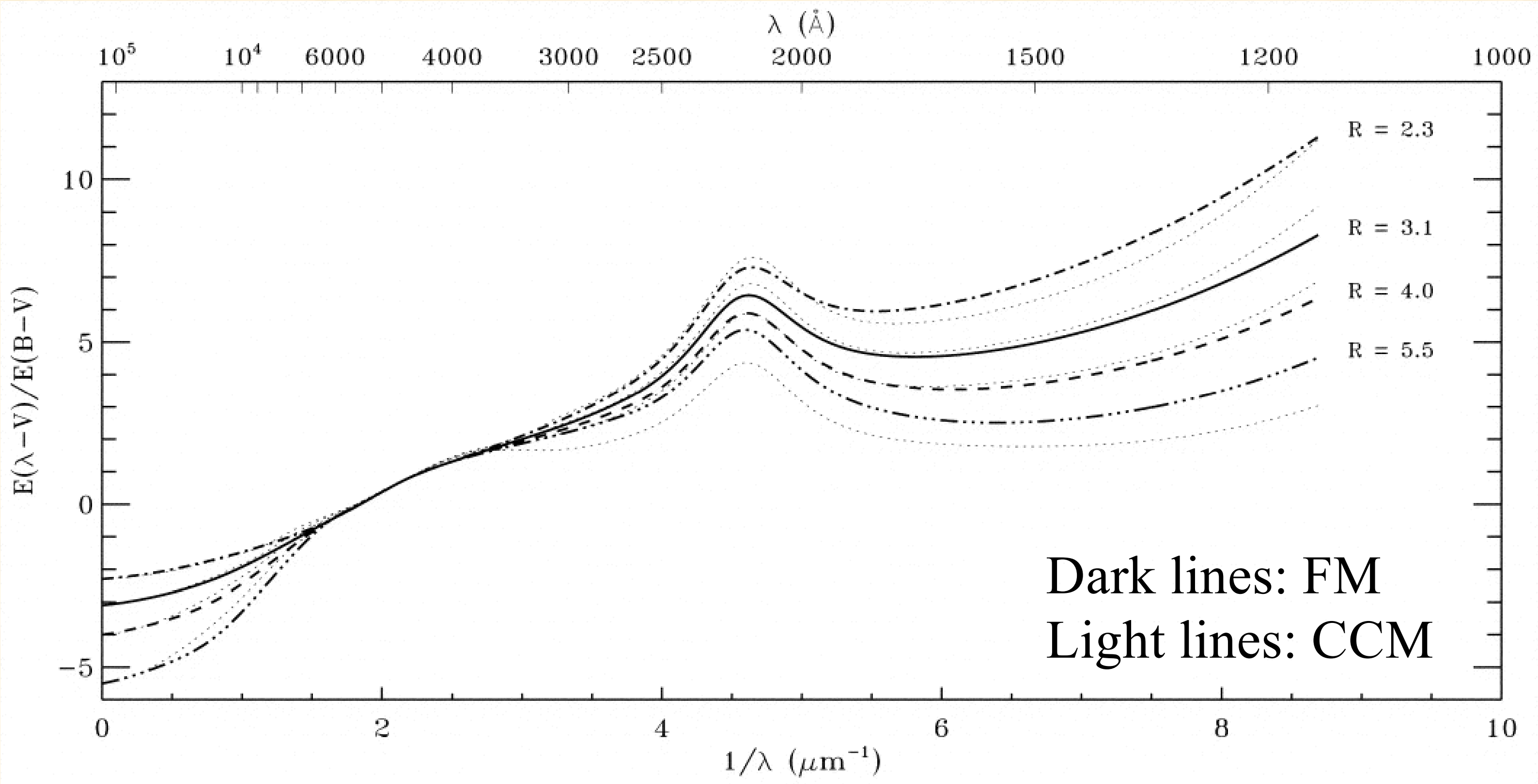
7000 Å

- extinction at a particular wavelength only depends on one parameter (increases linearly with R_V^{-1})

→ only one set of reddening curves for the Galaxy

Current Galactic Reddening Curves

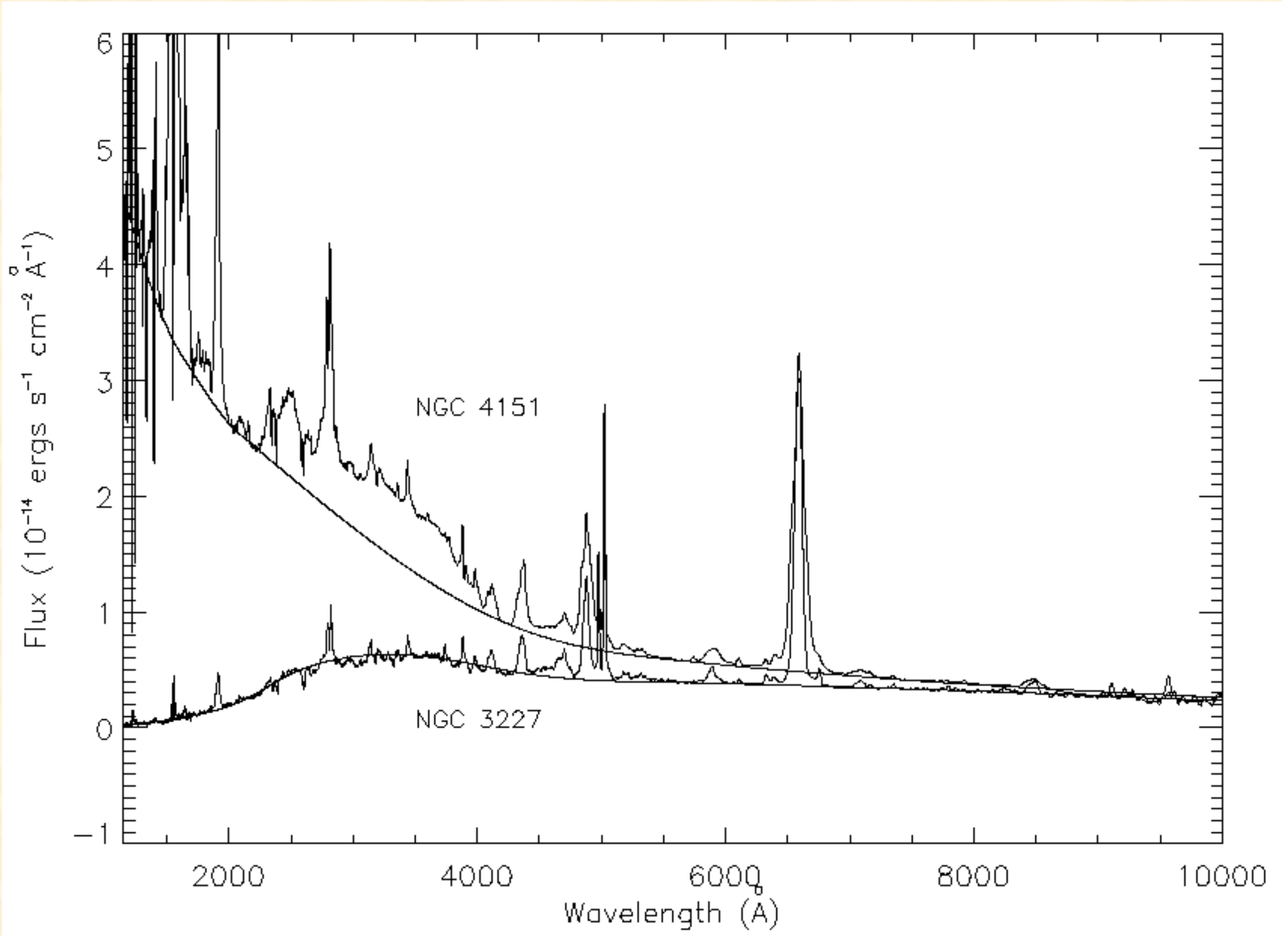
(Fitzpatrick, 1999, PASP, 111, 63 [FM])



- Fitzpatrick (1999) gives a prescription for reddening correction. (available as IDL procedure FM_UNRED; good from 912 Å to 3.5 μm)
- Which curve do I use? Depends on the information you have:
  1) Derive from the star (or one nearby), best
  2) Measure or assume R_V from environment. OK
  3) Assume $R_V = 3.1$ (average curve). not so great

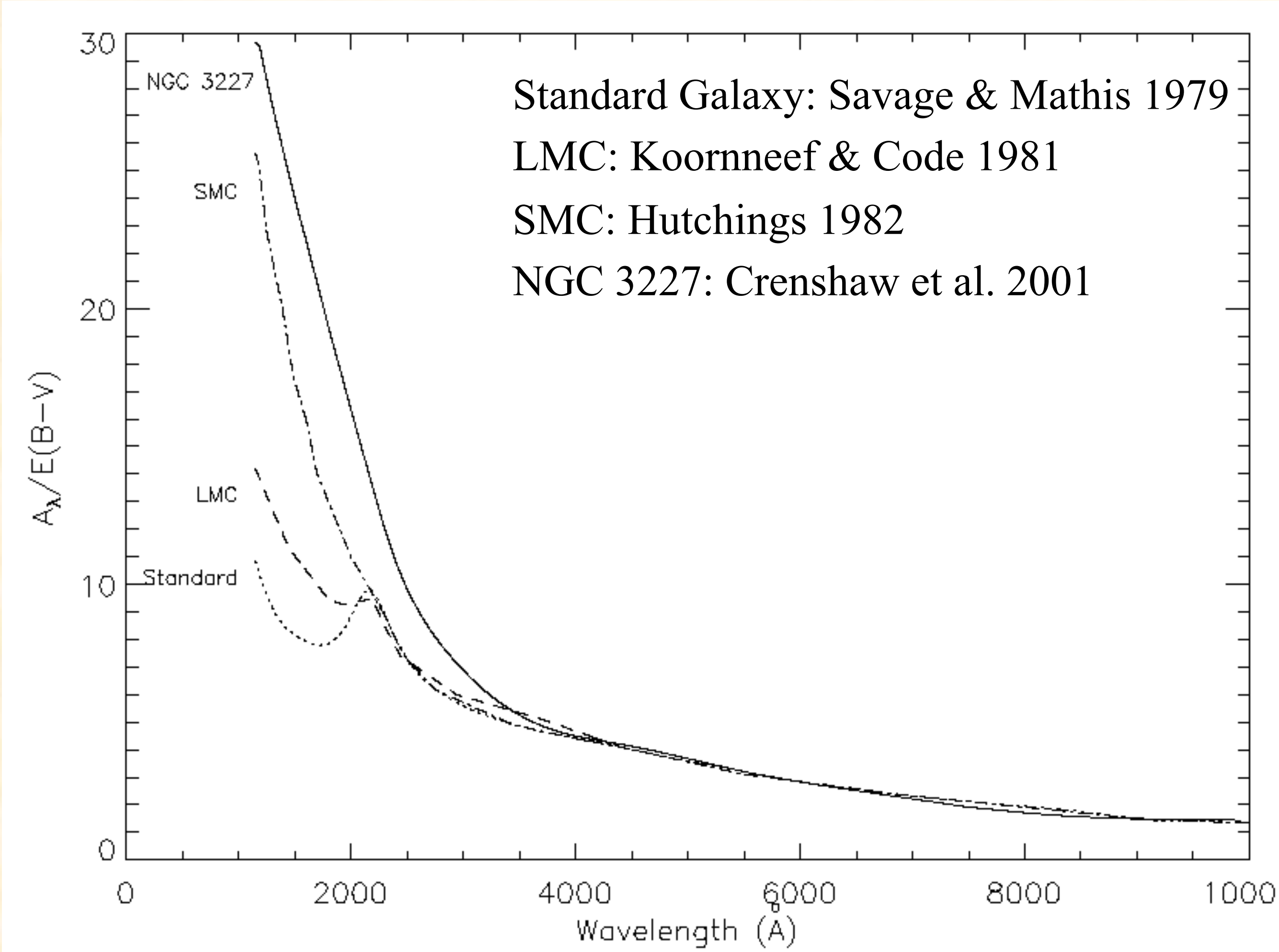
Extragalactic Reddening Curves

Ex) STIS Spectra of Seyfert 1 Galaxy NGC 3227



- X=ratio of continuum fits: NGC 4151/NGC3227
- E(B-V) = 0.18, E(λ-V)/E(B-V) from X
- Don't know intrinsic flux: get R_V from adding constant to match other extinction curves in IR (Galaxy, LMC, SMC): R_V = 3.2

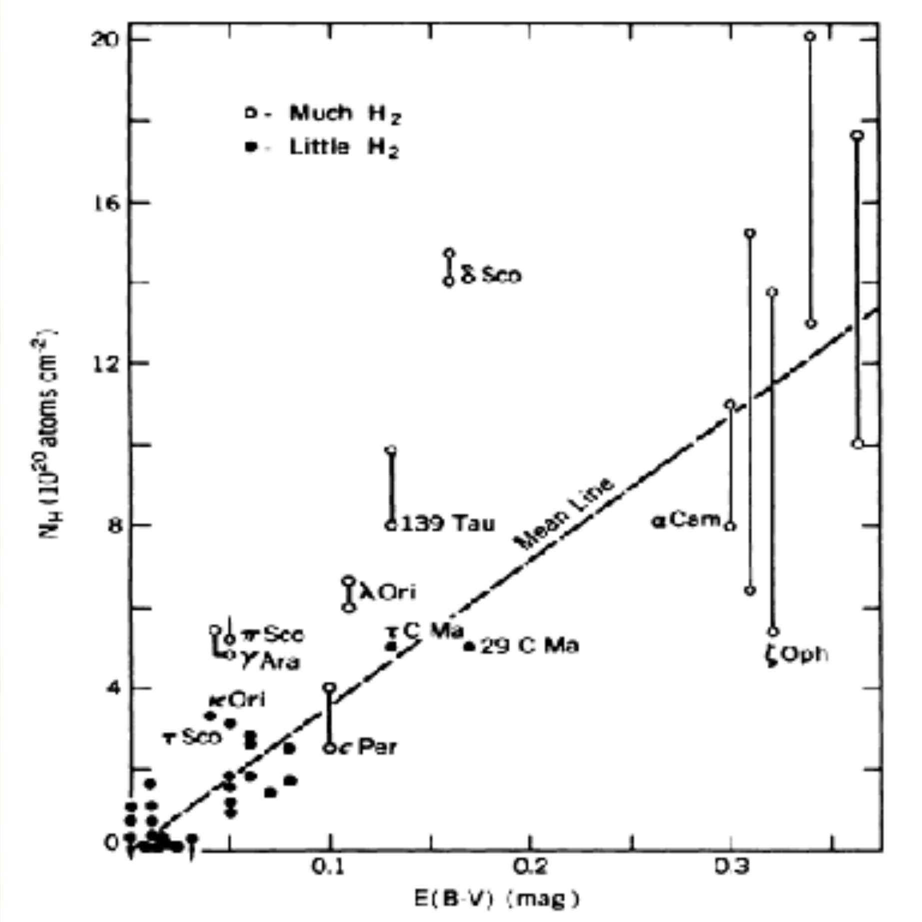
Extragalactic Reddening Curves



- Sharp rise to UV in SMC and NGC 3227
→Larger number of small dust grains

- 2200 Å feature decreases from Galaxy to LMC to SMC
→Decreases with metallicity

Gas Column vs. Dust Reddening



(Bohlin, 1975, ApJ, 200, 402)

- There is a fairly uniform gas/dust ratio in the local ISM.

$$\boxed{\text{Standard relation: } N(H) = 5.2 \times 10^{21}\, E(B-V) \quad (\mathrm{cm}^{-2})}$$

(Shull & Van Steenburg, 1985, ApJ, 294, 599)

So what is the dust/gas ratio (locally)?

- Depletions: about 1/3 of the CNO is depleted
- Cosmic abundances: the mass fraction of CNO is 0.011
- The heavier elements are mostly depleted; their mass fraction is 0.0027
- So the mass fraction of CNO in dust is: ~0.0037
- The mass fraction of heavier elements is: ~0.0027

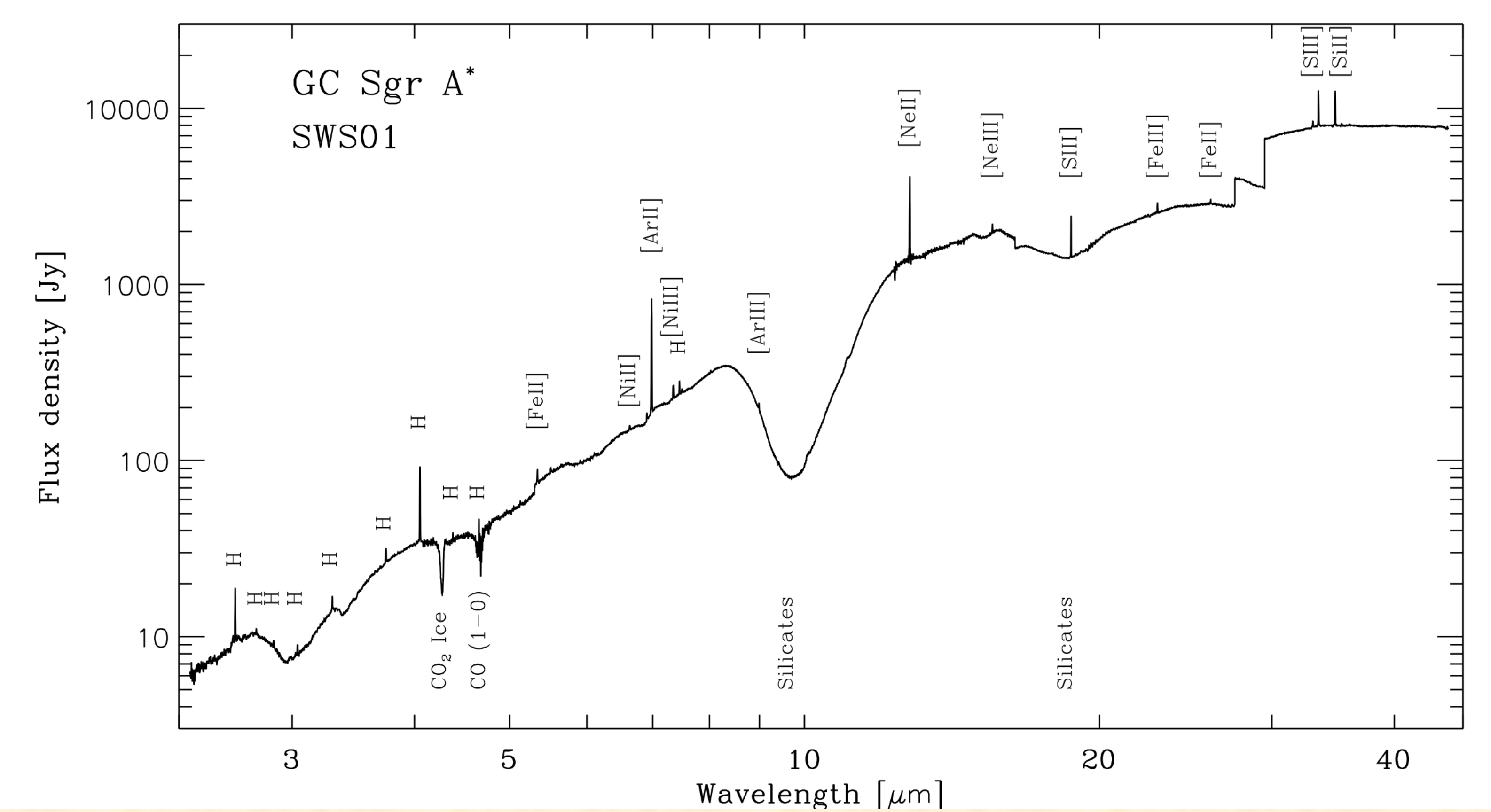
$$\boxed{\text{So } \frac{\rho_{dust}}{\rho_{gas}} \approx 0.006}$$

If $n_H \approx 1 \text{ cm}^{-3}$, $\rho_{gas} \approx 1.6 \times 10^{-24} \text{ g cm}^{-3}$

Then $\rho_{dust} \approx 1 \times 10^{-26} \text{ g cm}^{-3}$

- Dust mass is only ~1% of the gas mass, but the dust is much more effective in reprocessing starlight than the gas!

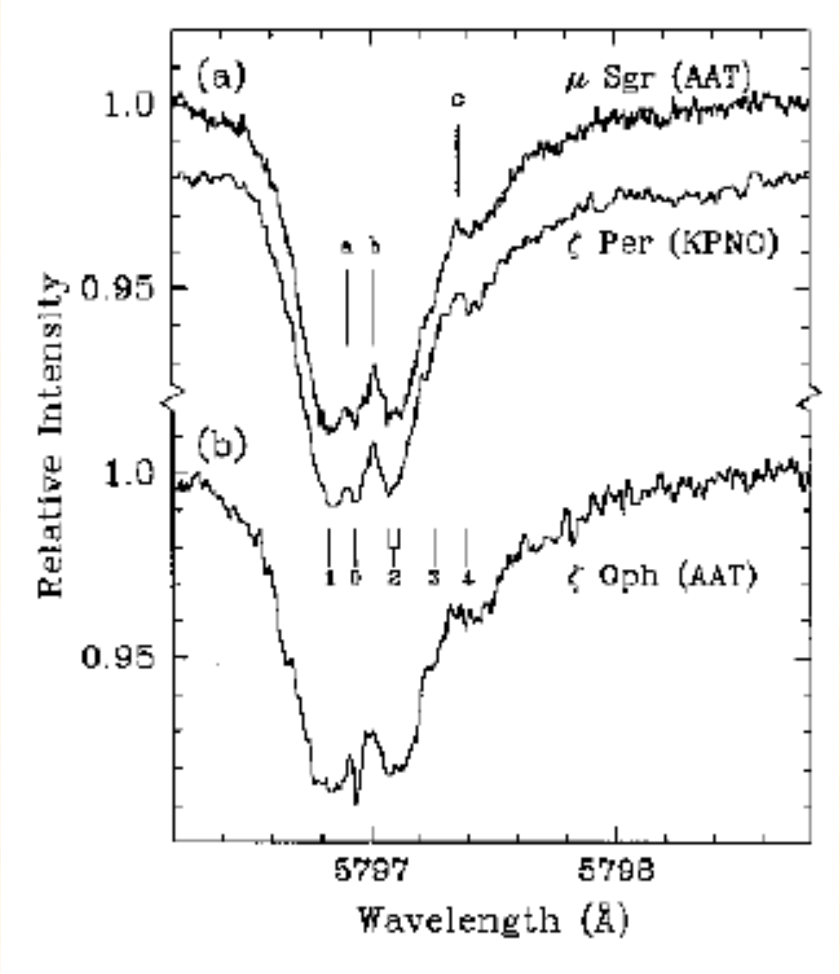
Dust Absorption in the Mid-IR



ISO Spectrum of Galactic Center (Lutz, et al. 1996, A&A, 315, L269)

- 9.7 and 18 μm absorption due to silicates (9.7 μm: Si-O bending and stretching, 18 μm: O-Si-O bending modes) – may appear in emission in hot dust.
- 3 μm absorption due to O-H bond in H_2O ice
  - evidence for ice mantles around dust grains in molecular clouds

Diffuse Interstellar Bands



(Kerr, et al. 1998, ApJ, 495, 941)

- High resolution spectrum of one band: weak (low constrast)
- Correlates with ISM column density and dust extinction, but origin still unknown (PAHs?).

Polarization

- Many stars show linear polarizations of up to a few percent.
- The polarization is due to dust, so:

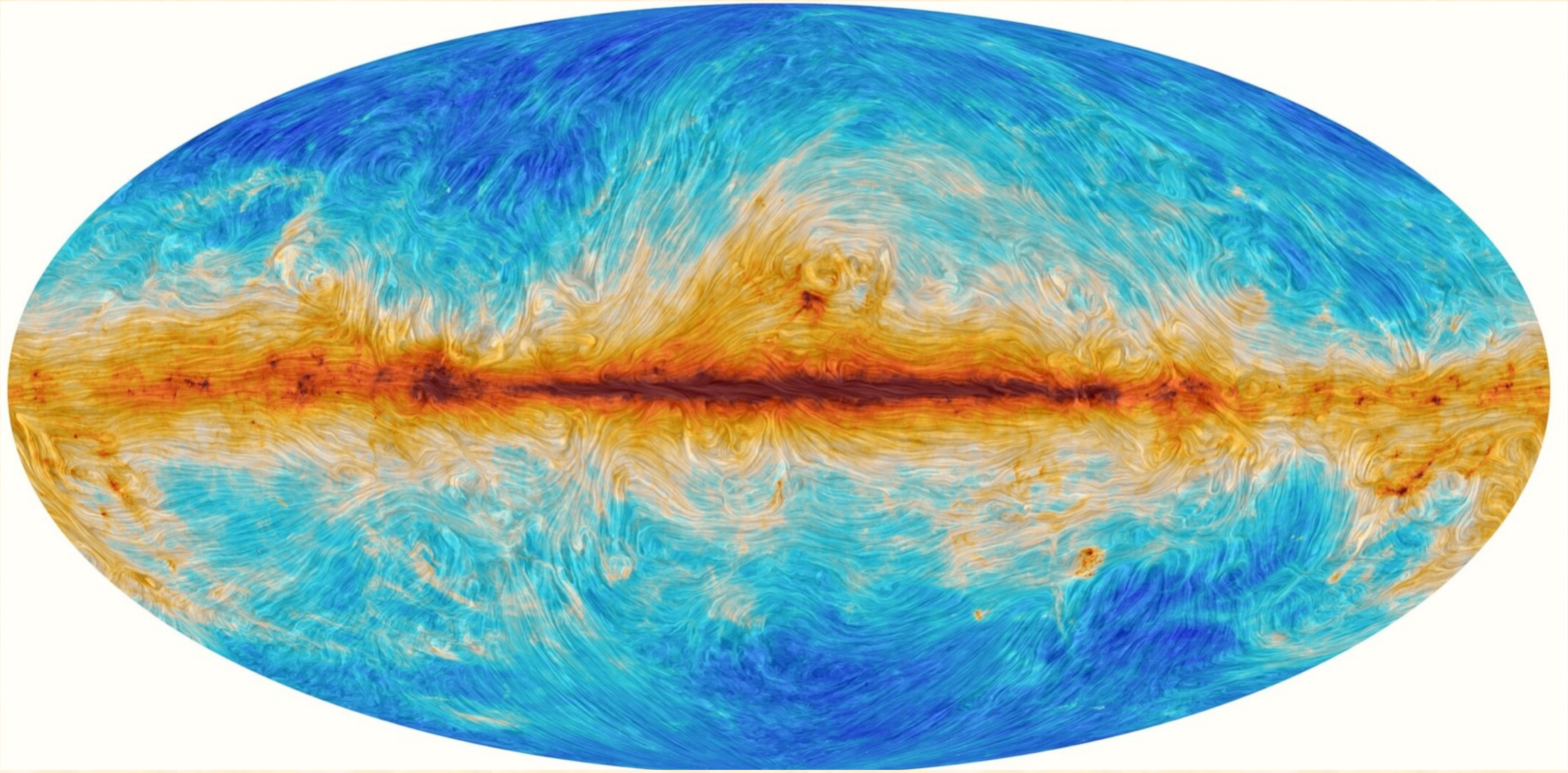
  1) The dust grains are elongated, to preferentially absorb the E or B vector.

  2) They are preferentially aligned, so that the polarization caused by individual grains do not cancel out

  - they are aligned by the Galactic B field, which induces a magnetic moment in each grain

  - Polarization as a function of Galactic latitude and longitude have been used to map the Galactic B field (1 - 10 μGauss),

Galactic Magnetic Field



Credit: ESA and the Planck Collaboration

- Polarized dust emission from the Planck mission.

What is the dust like? Theoretical Extinction Curves:

The decrease in flux due to dust extinction is:

$F = F_0 \ \exp(-\tau_D)$ where $\tau_D = n_D \pi a^2 s Q_E$ (assuming spheres)

(n_D = dust particles per cm^{-3}, a = grain radius, s = path length)

$$Q_E = \text{extinction efficiency} = \frac{\text{optical cross section}}{\text{geometric cross section}}$$

$Q_E = Q_S + Q_A$ (Q_S =scattering efficiency, Q_A =absorption efficiency)

Q_S, Q_A are functions of:

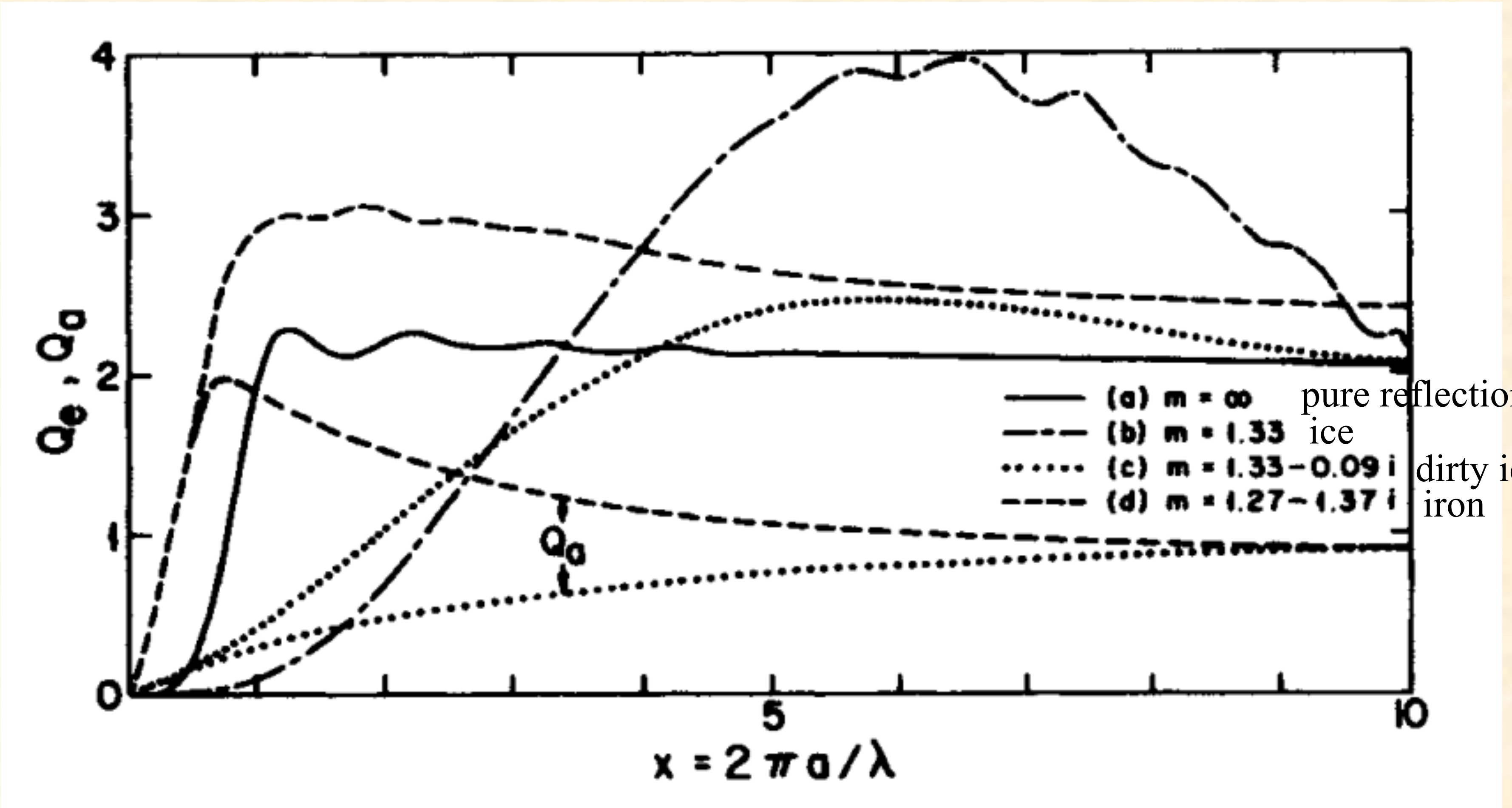
1) a, λ $\rightarrow$ parameterized by x = $2\pi a/\lambda$

2) m = complex index of refraction for material

(real: scattering, imaginary: absorption)

and can be determined from the Mie theory of scattering (solution of Maxwell's equations for spherical particles)

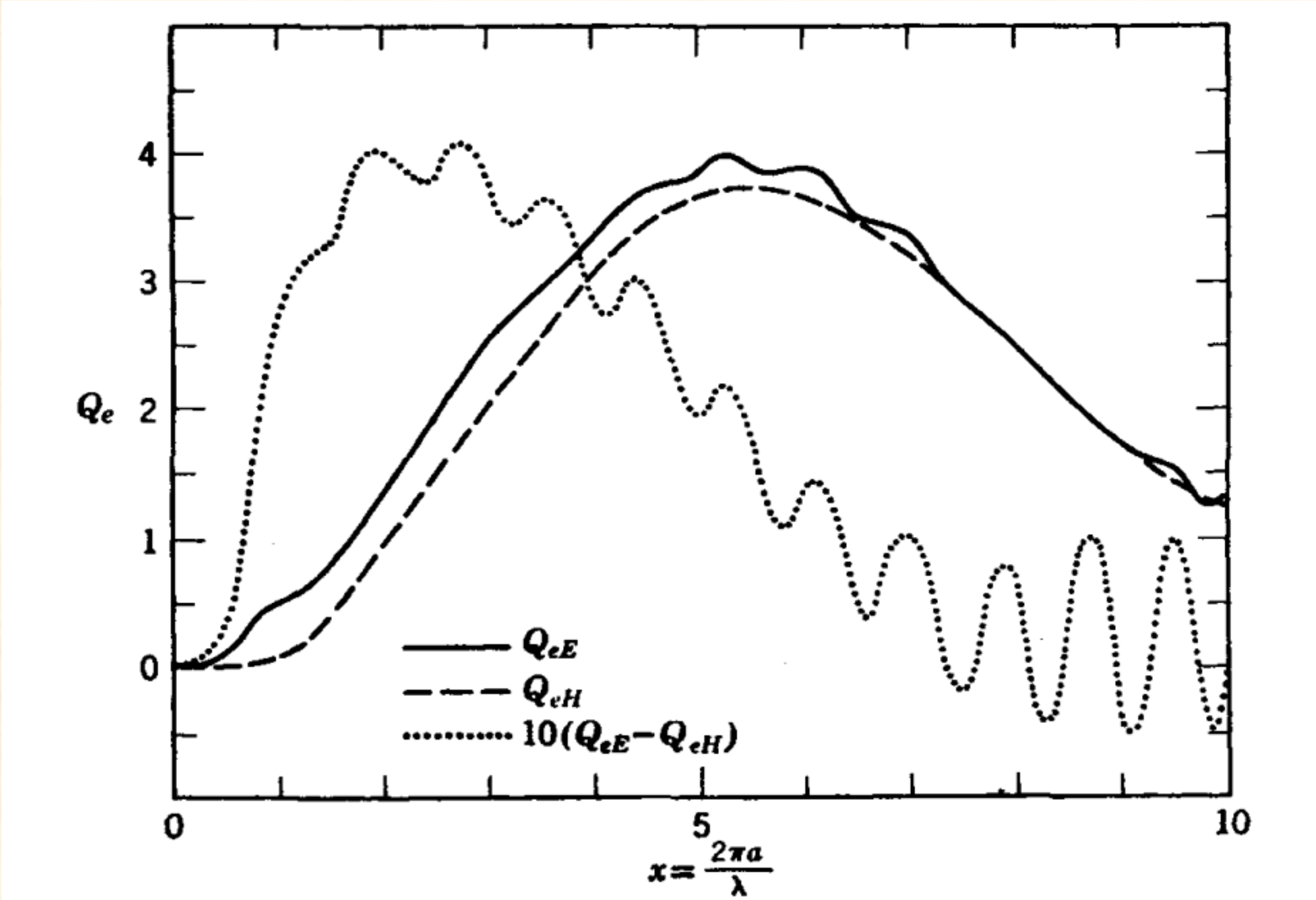
Theoretical Efficiency Factors (Spheres)



(Spitzer, page 152)

- no absorption for pure reflections and ice spheres
- sharp increase near λ~ 2πa (classic diffraction case)

Theoretical Efficiency Factors for Cylinders (m=1.33)



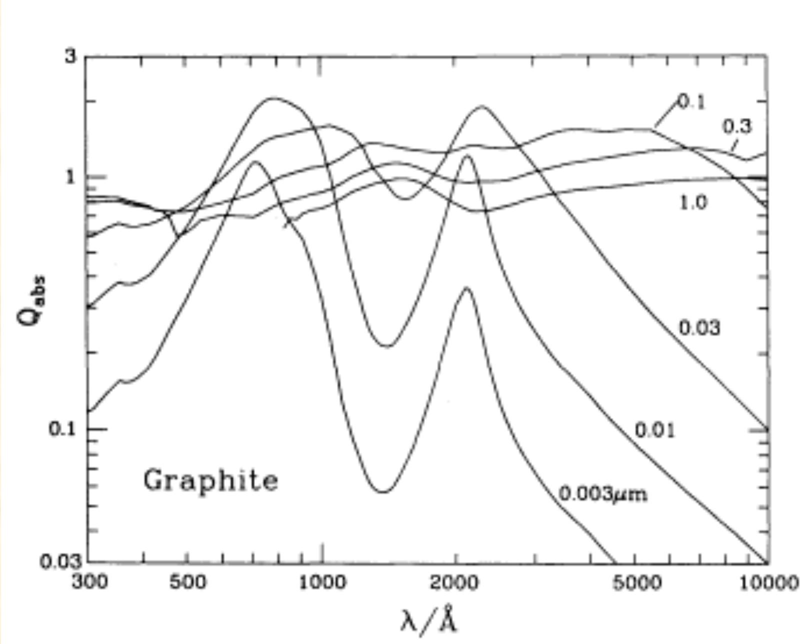
(Spitzer, page 173)

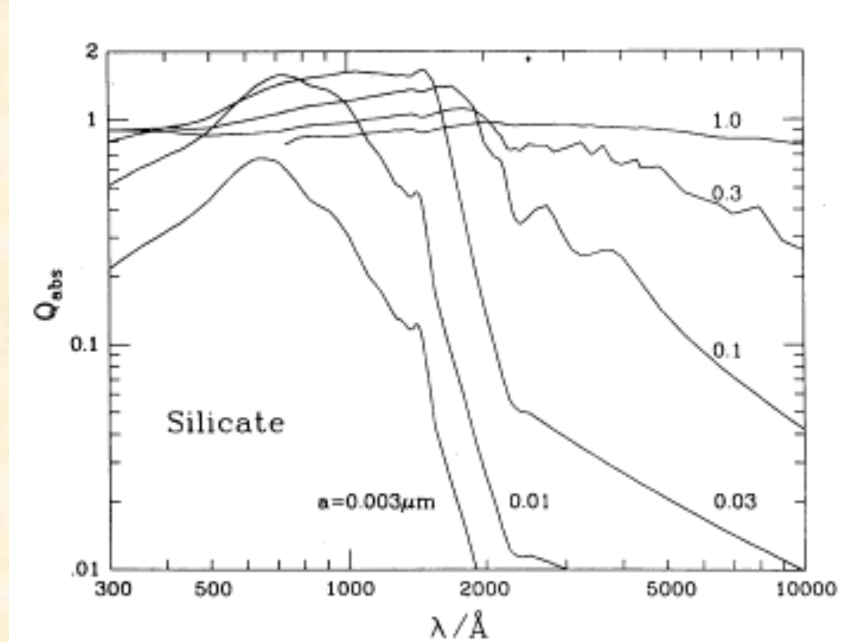
a = cylinder radius, length = 2a

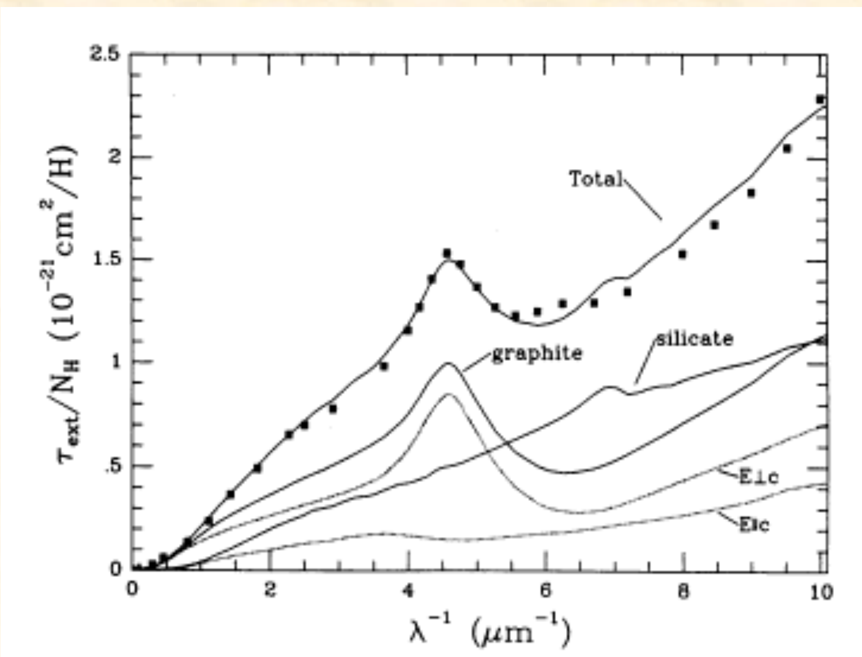
- Extinction declines more sharply with decreasing λ
- Difference between E and H vectors give polarization (wiggles average out for a distribution of particles)

Detailed Calculations

(Draine & Lee, 1984, ApJ, 285, 89)







A distribution of grain sizes can match the observations (Mathis, Rumpl, & Nordsieck (1977, ApJ, 217, 425) :

$$n_D \propto a^{-3.5} \ (n_D = dust\ density)$$

$$a = 0.005 \mu m \ to \ 0.25 \mu m$$

Problems (or Challenges)

- Large number of extinction curves to understand!
- Many combinations of
  1) a C-based grain (e.g., graphite, PAHs, amorphous) and
  2) a silicate grain (e.g., pyroxenes, olivenes, amorphous)
  can provide a general match to curves and absorption features
- Need to match specific models against high-accuracy extinction curves and spectral features
- But note: m affected by damage to grain by UV photons or cosmic rays, or by ion contamination

Thermal Continuum Emission

- In the diffuse ISM, the dust temperature (T_D) is due to ambient starlight (otherwise it would be 3K).
- At a distance r from a star with luminosity L, the flux balance for a dust sphere with radius a is:

$$\int \frac{L_\lambda}{4\pi r^2}\, \pi a^2 Q_A(a,\lambda)\, d\lambda = \int 4\pi a^2 Q_{Em}(a,\lambda)\, \pi B(\lambda, T_D)\, d\lambda$$

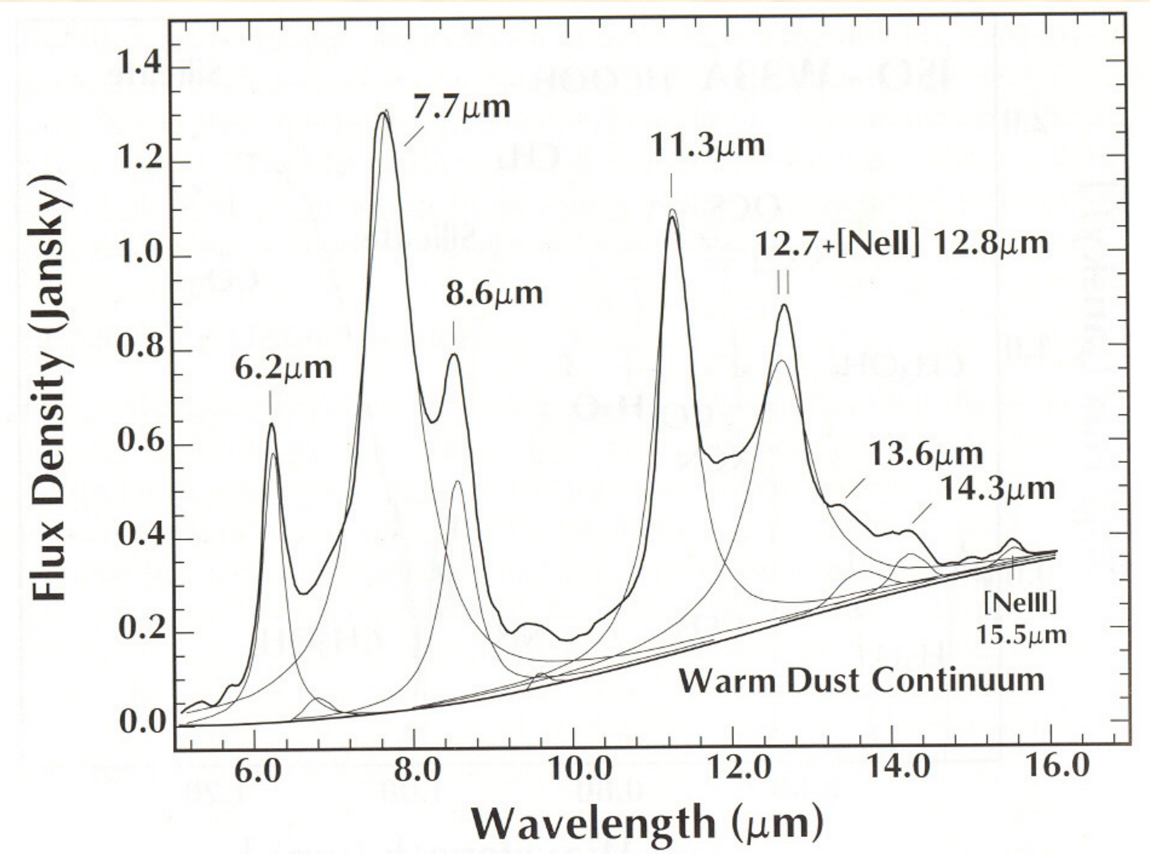
$$\text{where } B = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k T_D) - 1} \quad \text{(Planck fct.)}$$

- Given Q_A and Q_{Em} (absorption in the UV, emission in the IR), the above can be solved for T_D
- Typically $Q_{Em} \sim \lambda^{-1}$ (dust grains radiate inefficiently at long λ) →shifted slightly toward shorter λ ("hotter" than a BB would be).
- For the IR "cirrus": $T_D \approx 20$ K →peaks at ~150 μm, (far-IR)
- Star formation regions: $T_D \approx 100$ K →peaks at ~30 μm (mid-IR)

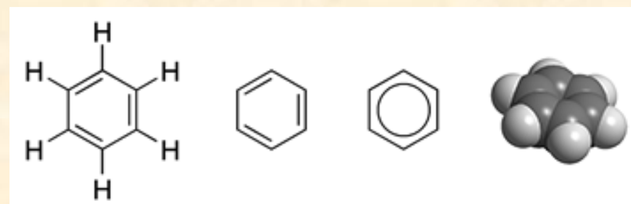
Very Small Grain (VSG) Continuum

- VSGs (< 100 Å in size) are *not* in thermal equilibrium with the radiation field.
- A VSG is heated by a single photon and releases energy quickly (temperature of a single grain is highly time-dependent)
- Results in emission at shorter λ, in near- to mid-IR (1 - 30 μm).
- About 1/3 of the diffuse ISM dust emission can be attributed to VSGs (Draine, 2003, ARAA, 41, 241).

PAH Emission Features



ISO spectrum of starburst region in M82



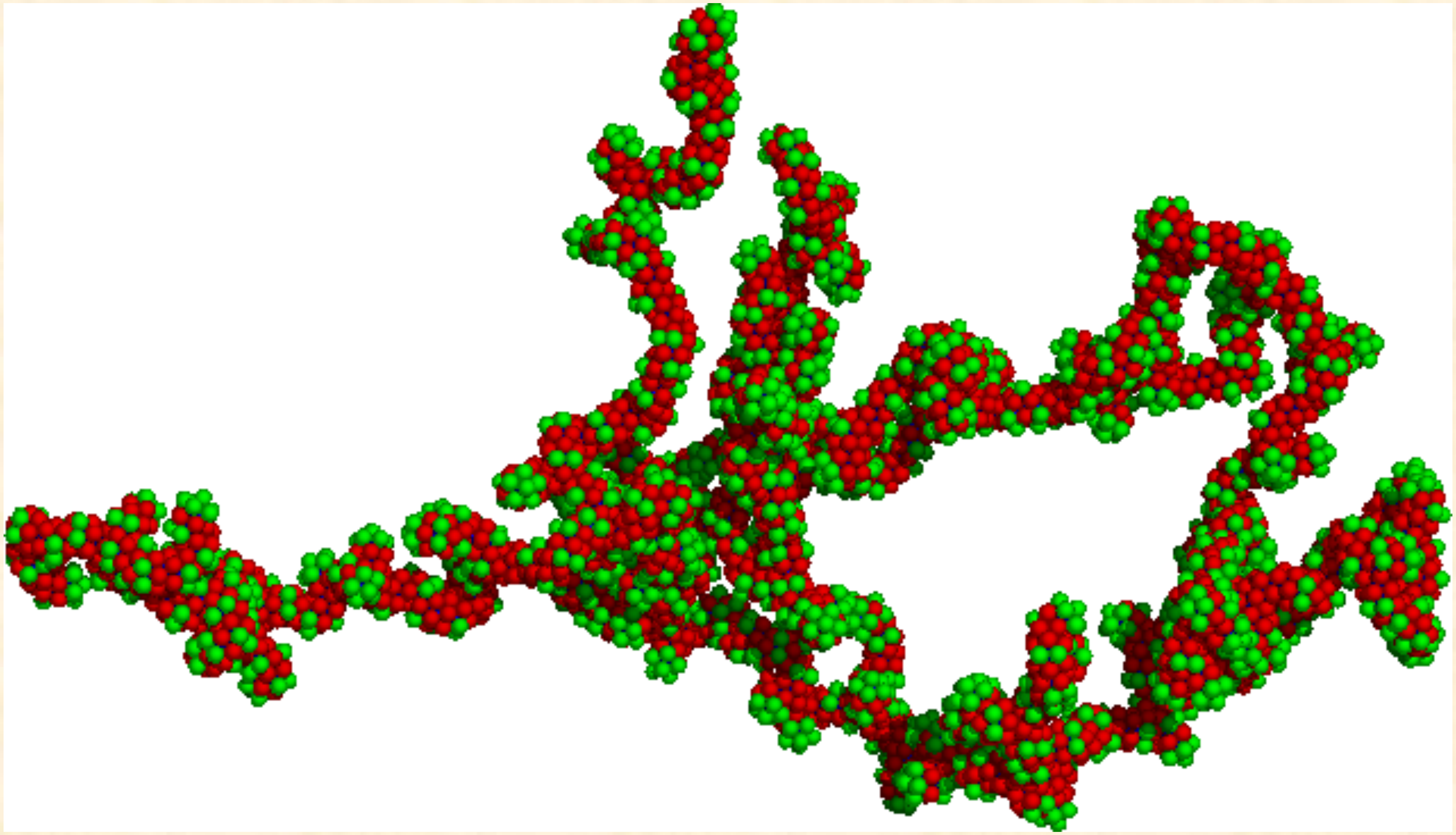
- Polycyclic Aromatic Hydrocarbons (PAHs): linked benzene (C_6H_6) rings: naphthalene ($C_{10}H_8$) … ovalene ($C_{32}H_{14}$) …
- Seen in emission in photodissociation regions (PDRs) - responsible for 2200 Å absorption feature?

Lifestyles of Galactic Dust Grains

- Created in dense, cooling gas flows
  - primarily red giant winds and ejection of planetary nebulae; also novae, supernovae, and supermassive stars (η Car).
  - molecules with refractive elements condense to solid phase first
  - clusters of molecules clump together to form dust grains
  - high temperatures (300 – 1500 K) and densities ($n_H \approx 10^9$ cm^{-3}) provide the pressure for molecules to stick together
- Grains cycle through molecular clouds ~10 times before being incorporated in a new star (Mathis, 1990, ARAA, 28, 37)
  - grains grow massive by coagulation of smaller grains and condensation of molecules onto grains
  - ice mantles form (or ice fills the voids in fluffy dust grains?)
- Grains can be destroyed or reduced in size by:
  - cosmic-ray sputtering (atoms knocked out by + ions)
  - shocks from SNRs, UV photoejection of electrons
  - sublimation: graphites and silicates sublimate at ~ 1500 K, ice mantles sublimate at 20 - 100K

What are the dust particles like?

- shapes, masses, and exact compositions still uncertain



- one possibility: fractal dust grains (Wright,1987, ApJ, 320, 818)

JWST PAH Image of NGC 628

Credit: Gabriel Brammer / Janice Lee et al. and the PHANGS-JWST collaboration