8. Interstellar Dust

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Interstellar Dust: Direct Observed Properties

- Wavelength-dependent attenuation ("extinction") of starlight by absorption and scattering, now observable at wavelengths as long as 20 μm ("mid-infrared"),and as short as 0.1 μm ("vacuum ultraviolet").
- Polarization-dependent attenuation of starlight, resulting in wavelength-dependent polarization of light reaching us from reddened stars.
- Scattered light in reflection nebulae.
- Thermal emission from dust, at wavelengths ranging from the sub-mm to2 μm.
- Small-angle scattering of X-rays, resulting in "scattered halos" around X-ray point sources.
- Microwave emission from dust, probably from rapidly spinning ultrasmall grains.

Interstellar Dust: Indirect Observed Properties

- Presolar grains preserved in meteorites, the dust samples from solar nebula in ancient time.
- "Depletion" of certain elements from the interstellar gas, with the missing atoms presumed to be contained in dust grains.
- The observed abundance of H_2 in the ISM, which can only be understood if catalysis on dust grains is the dominant formation avenue.
- The temperature of interstellar diffuse H I and H_2, in part a result of heating by photoelectrons ejected from interstellar grains.

Extinction

- The extinction A, measured in “mag” is defined by

$$\frac{A_\lambda}{\mathrm{mag}} = 2.5\log_{10}\left[F^0_\lambda / F_\lambda\right]$$

- The relationship between extinction and optical depth is therefore very simple!

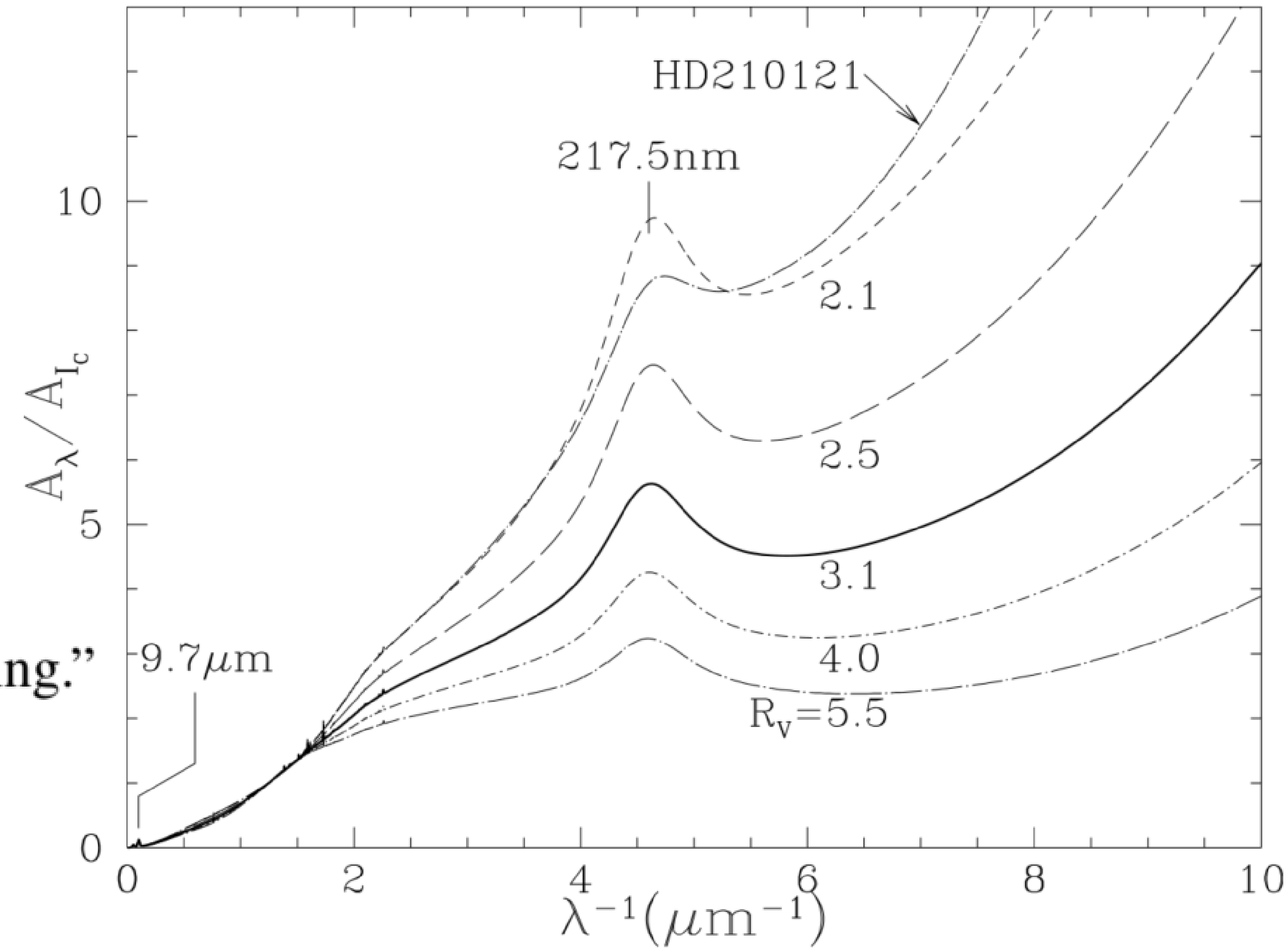
$$\frac{A_\lambda}{\mathrm{mag}} = 2.5\log_{10}\left[\mathrm{e}^{\tau_\lambda}\right] = 1.086\,\tau_\lambda$$

Extinction Curve in the Local ISM

- The slope of the extinction curve at visible wavelength is characterized as:

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

$E(B-V) \equiv A_B - A_V$ is the "reddening."



Dust-gas coupling

$$\tau_\lambda = \int_0^s n_d(s')\sigma_\lambda ds' \sim \sigma_\lambda \int_0^s n_d(s')ds' = \sigma_\lambda N_d$$

- Dust extinction appears to be relatively well-mixed with gas.
- Dust column density should also be related to gas column density.

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

- For sightlines with Rv=3.1,

$$\frac{A_V}{N_{\rm H}} = \frac{3.1}{5.8 \times 10^{21}\,{\rm H\,cm^{-2}mag^{-1}}} = 5.3 \times 10^{-22}\,{\rm mag\,cm^2H^{-1}}$$

- So if you have a map of hydrogen column density, you can convert it to dust map.

Implications of Dust Properties by Extinction Law

- "Mie scattering" theory
  - Assuming dust particles are spherical with radius a. The geometric cross-section of dust is πa^2. We define dimensionless efficiency factor $Q_\lambda = \sigma_\lambda / \pi a^2$.
  - When the wavelength $\lambda \gg a, Q_\lambda \sim 0$; when the wavelength $\lambda \ll a, Q_\lambda \sim 1$.
  - When $\lambda \sim a, Q_\lambda \sim \frac{a}{\lambda}, \sigma_\lambda \sim a^3/\lambda$!
- Ff the dust grains were large compared to the wavelength, we would be in the "geometric optics" limit, and the extinction cross section would be independent of wavelength ,with Rv>>1.
- Grains smaller than the wavelength must be making an appreciable contribution to the extinction at all observed wavelengths, down to λ = 0.1 μm.

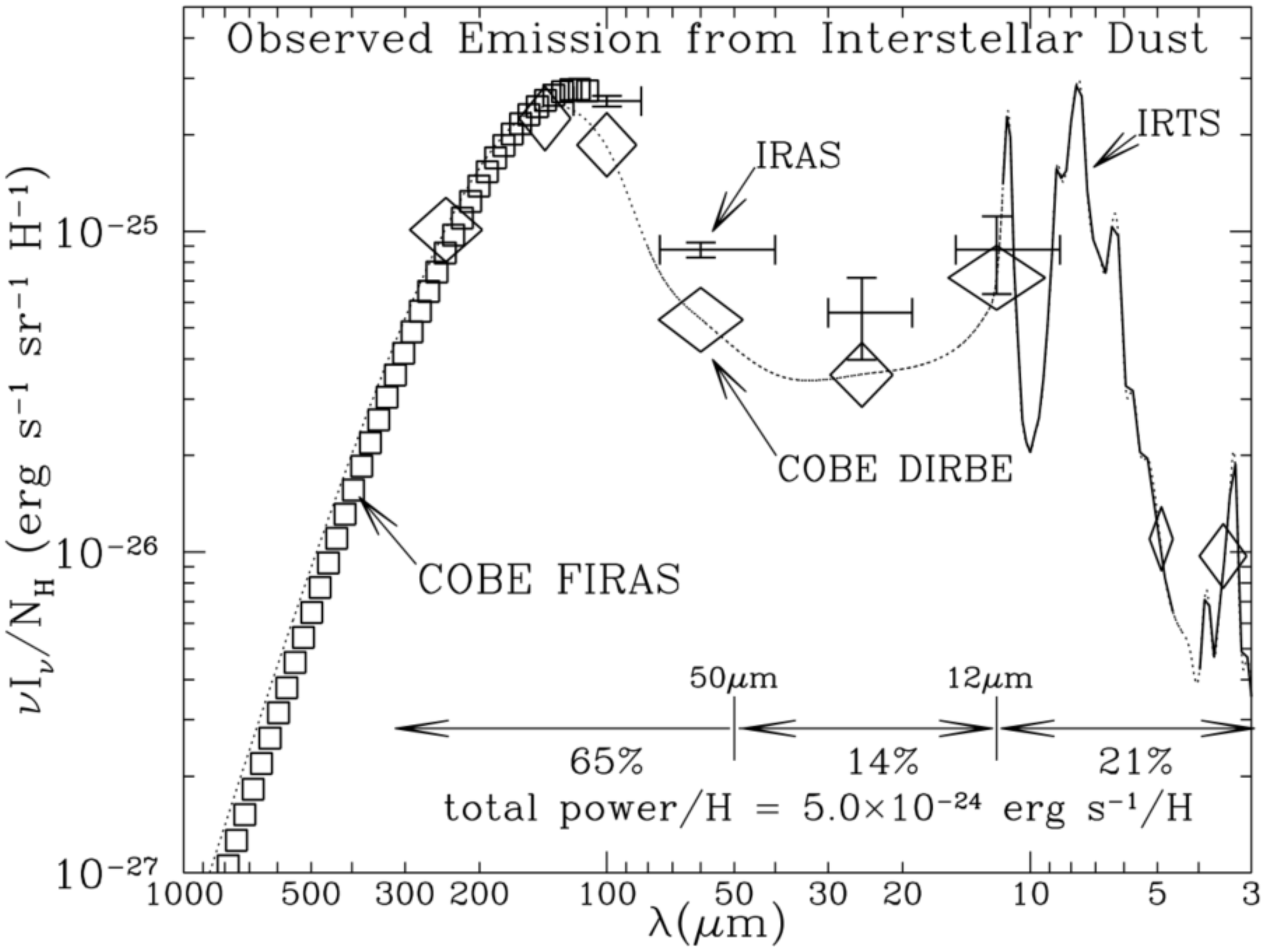
Scattering of Starlight by Dust

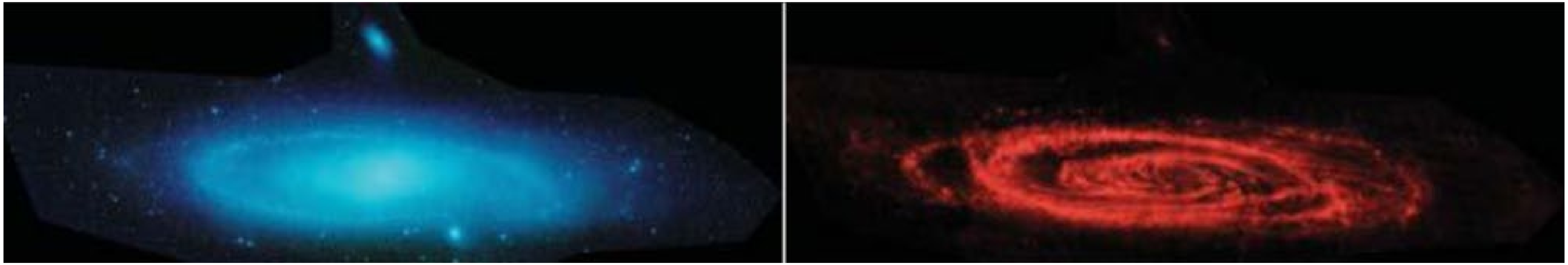
- Bluer lights are preferentially bright in the reflective regions.
- Stellar absorption lines appears in the spectra of the reflective nebulae.
- Correlated spatially with the IR emission.
- Dust particles dominating the scattering at $\lambda \approx 0.6$ μm have a >~ $\lambda/2\pi \approx 0.1$ μm.

Trifid Nebula (M20)

Infrared Emission

- The IR emission provides strong constraints on the nature of dust grains.
- Dust must include a component that can account for the fact that 1/3 of the radiated power is shortward of 50 micro.
- Strong emission features at 3, 6-8, and 12 micro.





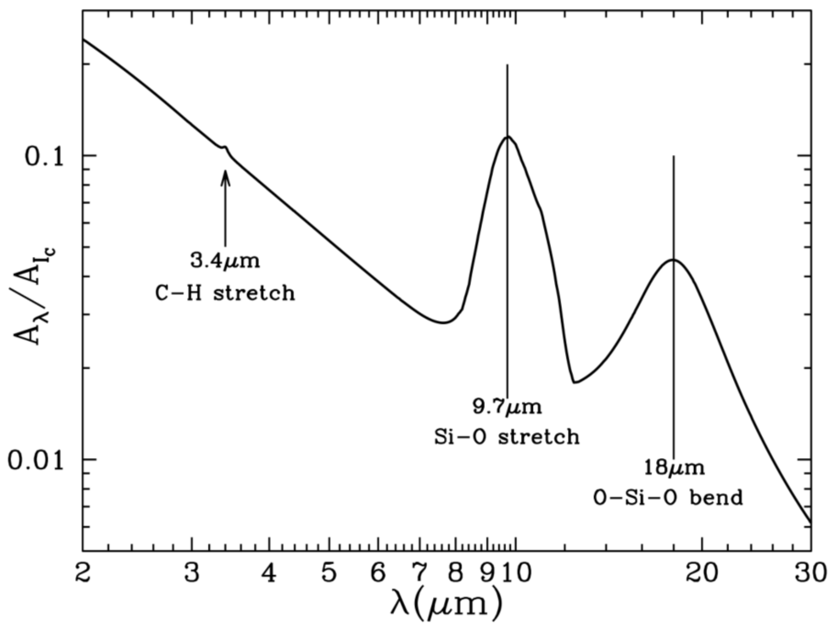
M31-M32 star distribution and IR emission map

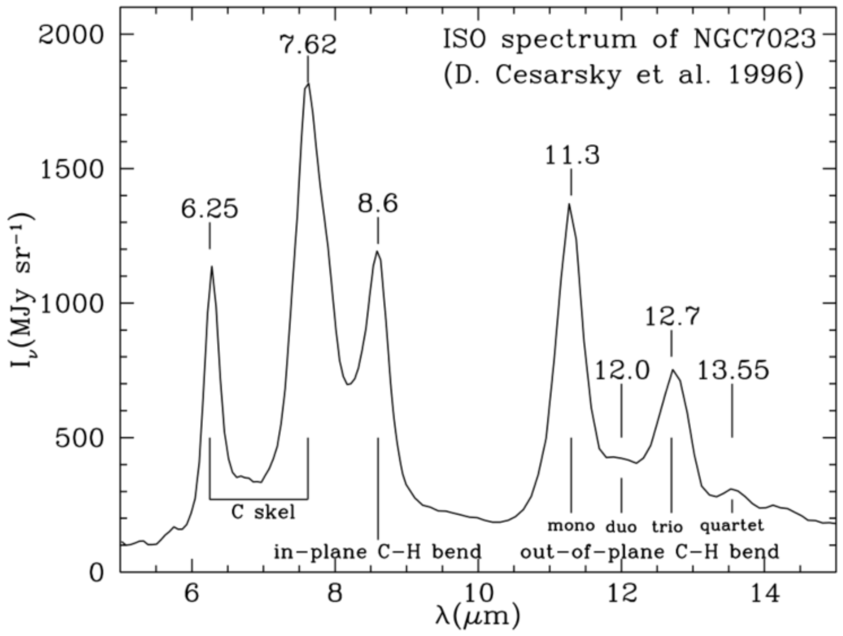
Possible Materials for Dust Grains

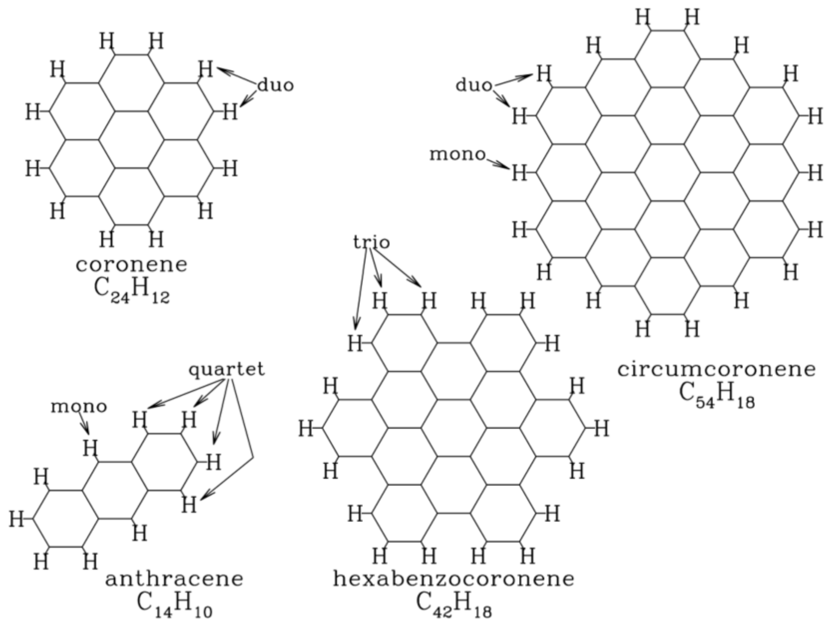
- Silicates, e.g., **pyroxene** composition $Mg_xFe_{1-x}SiO_3$, or **olivine** composition $Mg_2xFe_{2-2x}SiO_4$ $(0 \leq x \leq 1)$
- Oxides of silicon, magnesium, and iron (e.g., SiO_2, MgO, Fe_3O_4)
- Carbon solids (graphite, amorphous carbon, and diamond)
- Hydrocarbons (e.g., polycyclic aromatic hydrocarbons)
- Carbides, particularly silicon carbide (SiC)
- Metallic Fe

Spectral Features of Dust

- The 2175A feature in the extinction curves is thought to be caused by some form of sp2-bonded carbon material in the dust grains.
- The 3.4, 9.7 and 18 micro IR absorption features are believed to be caused by Silicates.
- Vibrational transitions in PAH are responsible for the IR emission features.





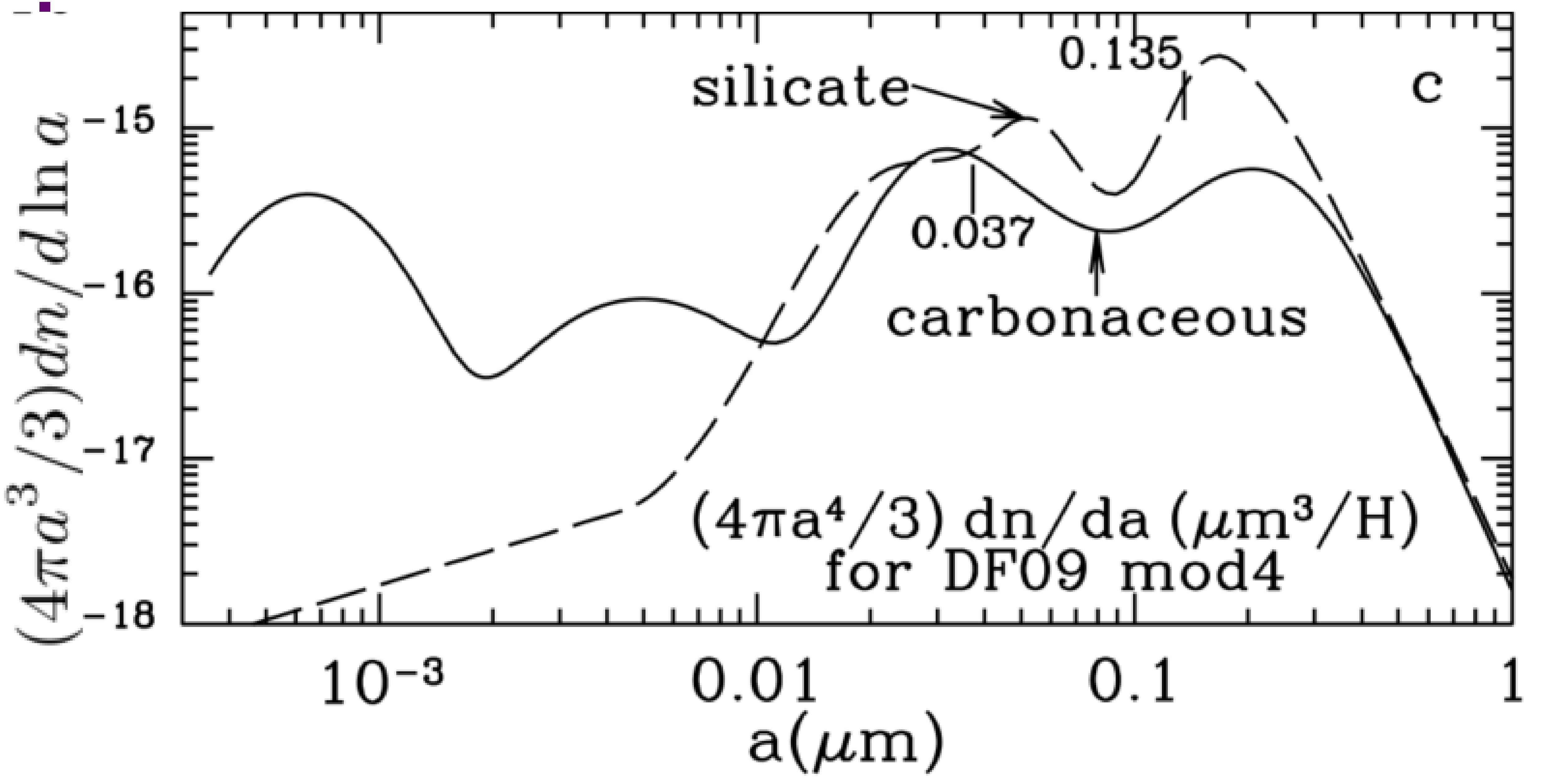


Models for Dust: Composition and Geometry of Dust.

- A class of models that has met with some success assumes the dust to consist of two materials: (1) amorphous silicate (~3.7 g/cm3), and (2) carbonaceous material (~2.2 g/cm3).
- The famous Mathis-Rumpl-Nordsieck 1977 (MRN) size distribution could reproduce the observed extinction from near IR to UV.

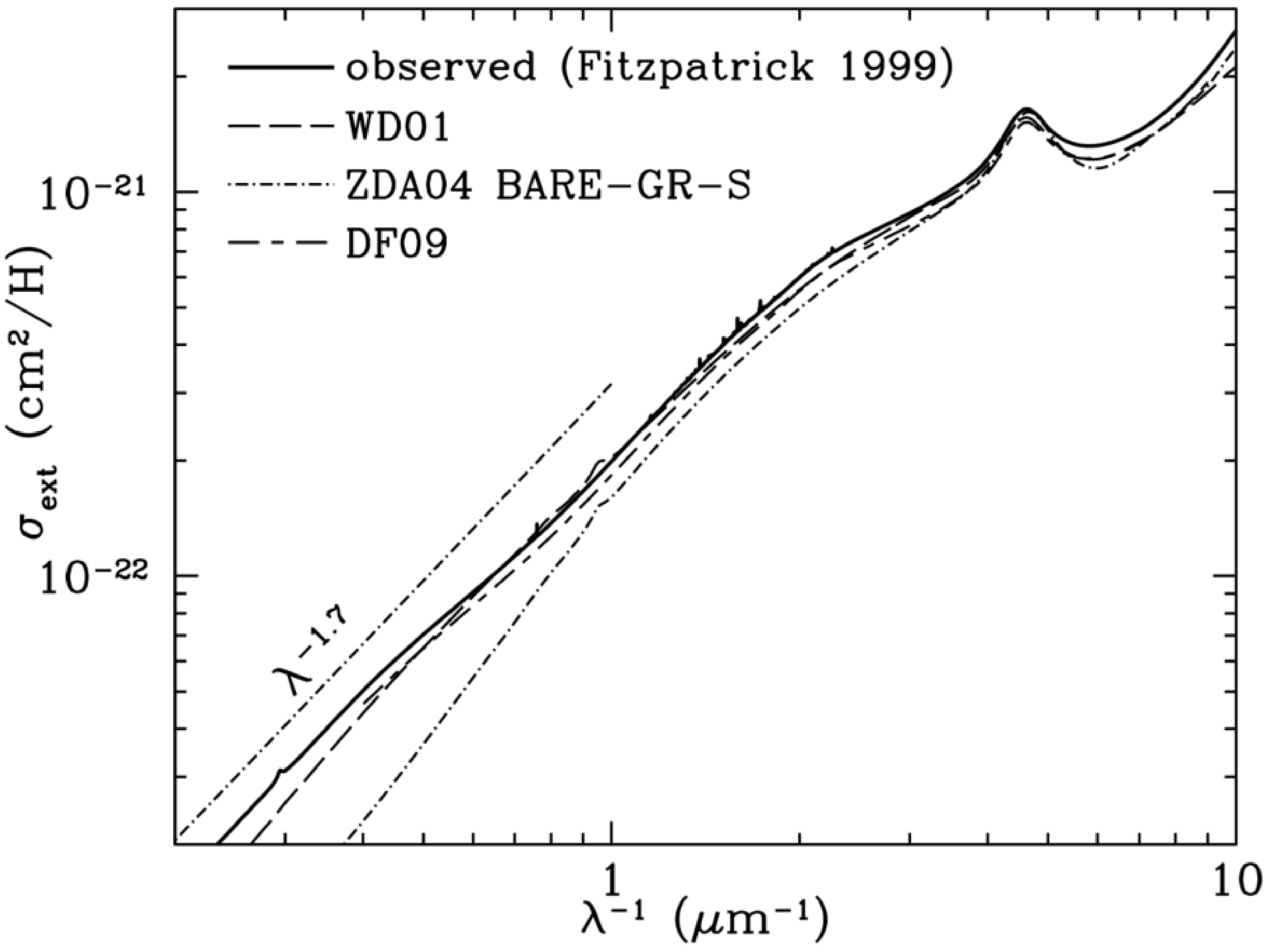
$$dn/da \propto a^{-3.5}$$

- This size distribution has most of the mass in the larger grains, and most of the surface area in the smaller grains.
- More sophisticated dust models includes Weingartner & Draine 2001, Zubko+2004, Draine & Li 2007, Draine & Fraisse 2009; Das+2010.

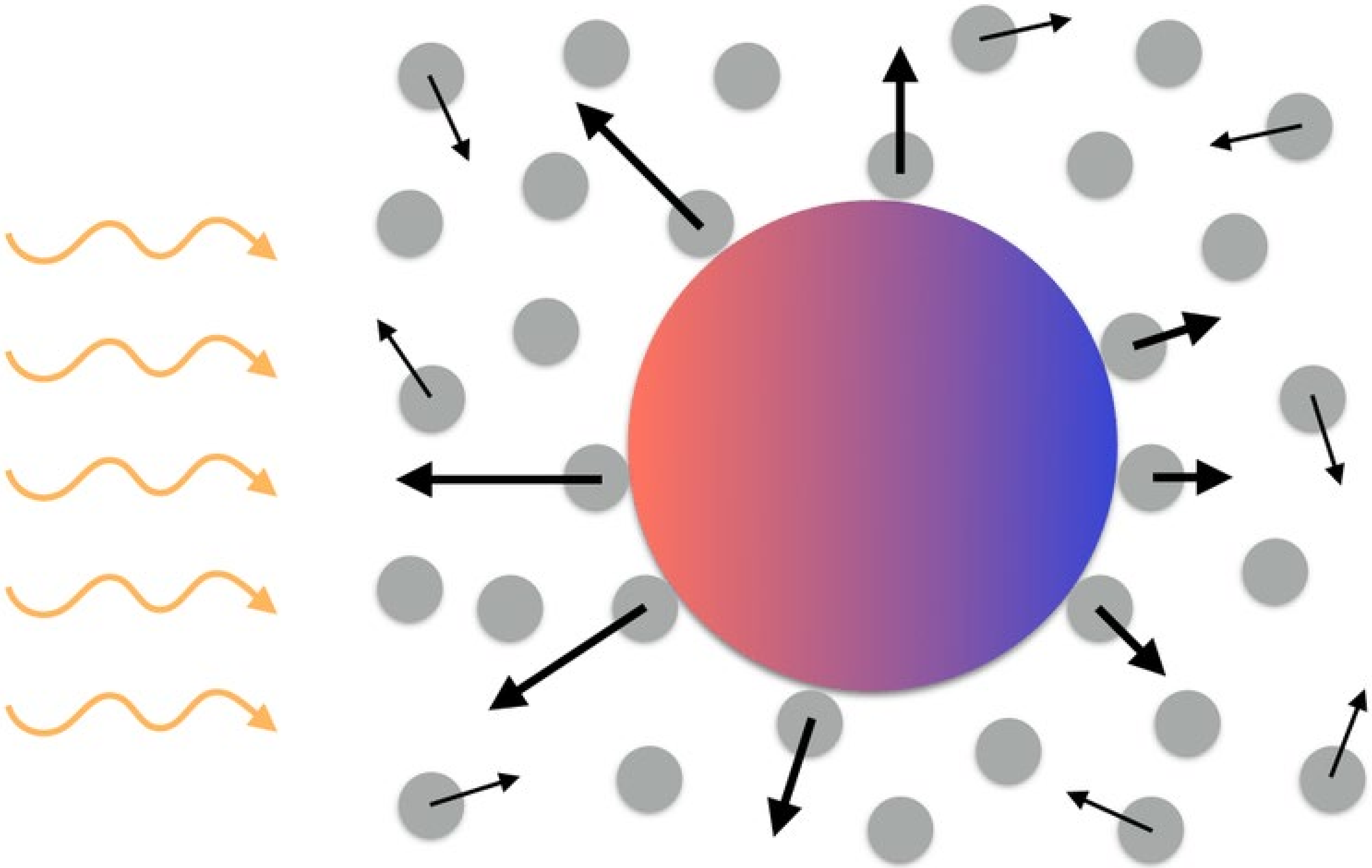


0.135
silicate
c
0.037
carbonaceous
$(4\pi a^4/3)\,dn/da\,(\mu m^3/H)$
for DF09 mod4
−15
−16
−17
−18
10^{-3}
0.01
0.1
1
$a(\mu m)$
$(4\pi a^3/3)dn/d\ln a$

Reproduce Observed Extinction for Rv~3.1



Physics of Dust Grains: Interaction with Radiation and Gas.



Dust Temperature: Heating

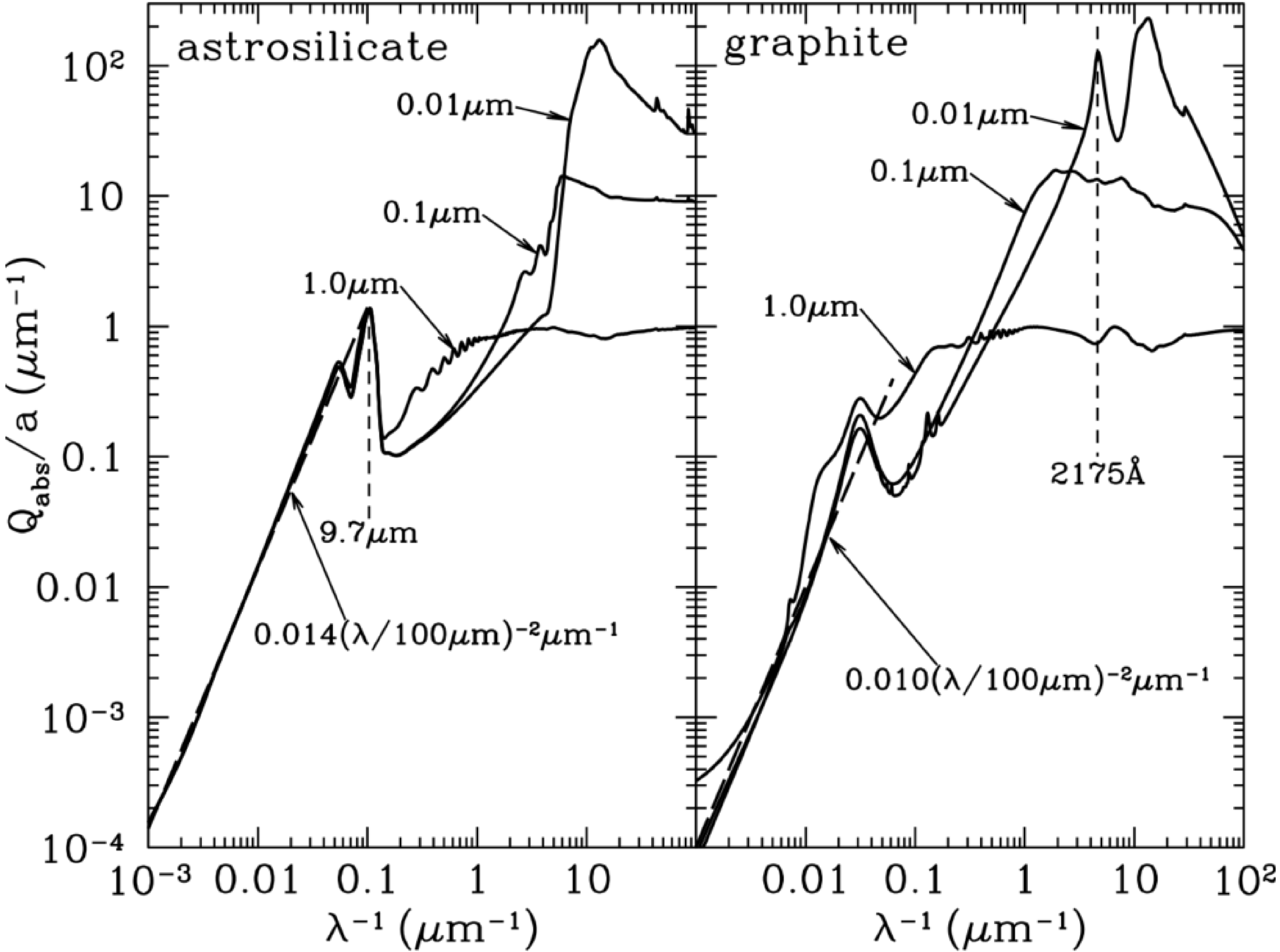
- When an optical or ultraviolet photon is absorbed by a grain, an electron is raised into an excited electronic state.
- If the electron is sufficiently energetic, it may be able to escape from the solid as a "photoelectron." The PE with free energy will heat the ambient gas and becomes the dominated heating mechanism around UV radiation fields.
- In most solids or large molecules, the electronically excited state will deexcite nonradiatively, with the energy going into many vibrational modes – i.e., heat of dust particles.

$$\left(\frac{dE}{dt}\right)_{\rm abs} = \int \frac{u_\nu d\nu}{h\nu} \times c \times h\nu \times Q_{\rm abs}(\nu)\pi a^2$$

$$= \langle Q_{\rm abs}\rangle_\star \pi a^2 u_\star c$$

Spectrum-averaged absorption cross-section

$$\langle Q_{\rm abs}\rangle_\star \equiv \frac{\int d\nu \; u_{\star\nu} Q_{\rm abs}(\nu)}{u_\star}$$



astrosilicate
graphite
0.01μm
0.1μm
1.0μm
9.7μm
0.014(λ/100μm)⁻²μm⁻¹
0.010(λ/100μm)⁻²μm⁻¹
2175Å
Q_abs/a (μm⁻¹)
λ⁻¹ (μm⁻¹)
10²
10
1
0.1
0.01
10⁻³
10⁻⁴
10⁻³
0.01
0.1
1
10
10²

Dust Temperature: Cooling

Planck-averaged emission efficiency

$$\langle Q_{\rm abs} \rangle_T \equiv \frac{\int d\nu B_\nu(T) Q_{\rm abs}(\nu)}{\int d\nu B_\nu(T)}$$

- Grains lose energy by infrared emission, at a rate

$$\left(\frac{dE}{dt}\right)_{\rm emiss.} = \int d\nu \, 4\pi B_\nu(T_d) C_{\rm abs}(\nu) = 4\pi a^2 \langle Q_{\rm abs} \rangle_{T_d} \sigma T_d^4$$

- If Q can be approximated as a power-law in frequency $Q_{\rm abs}(\nu) = Q_0 \left(\nu/\nu_0\right)^\beta = Q_0 \left(\lambda/\lambda_0\right)^{-\beta}$

$$\langle Q_{\rm abs} \rangle_T \approx 1.3 \times 10^{-6} (a/0.1\,\mu{\rm m})(T/\,{\rm K})^2 \quad ({\rm silicate})$$

$$\approx 8 \times 10^{-7} (a/0.1\,\mu{\rm m})(T/\,{\rm K})^2 \quad ({\rm graphite}).$$

Dust Temperature: Steady-State Grain Temperature

- Cooling and heating balance leads to a steady state dust temperature Tss.

$$4\pi a^2 \langle Q_{\rm abs}\rangle_{T_{\rm ss}} \sigma T_{\rm ss}^4 = \pi a^2 \langle Q_{\rm abs}\rangle_\star u_\star \, c$$

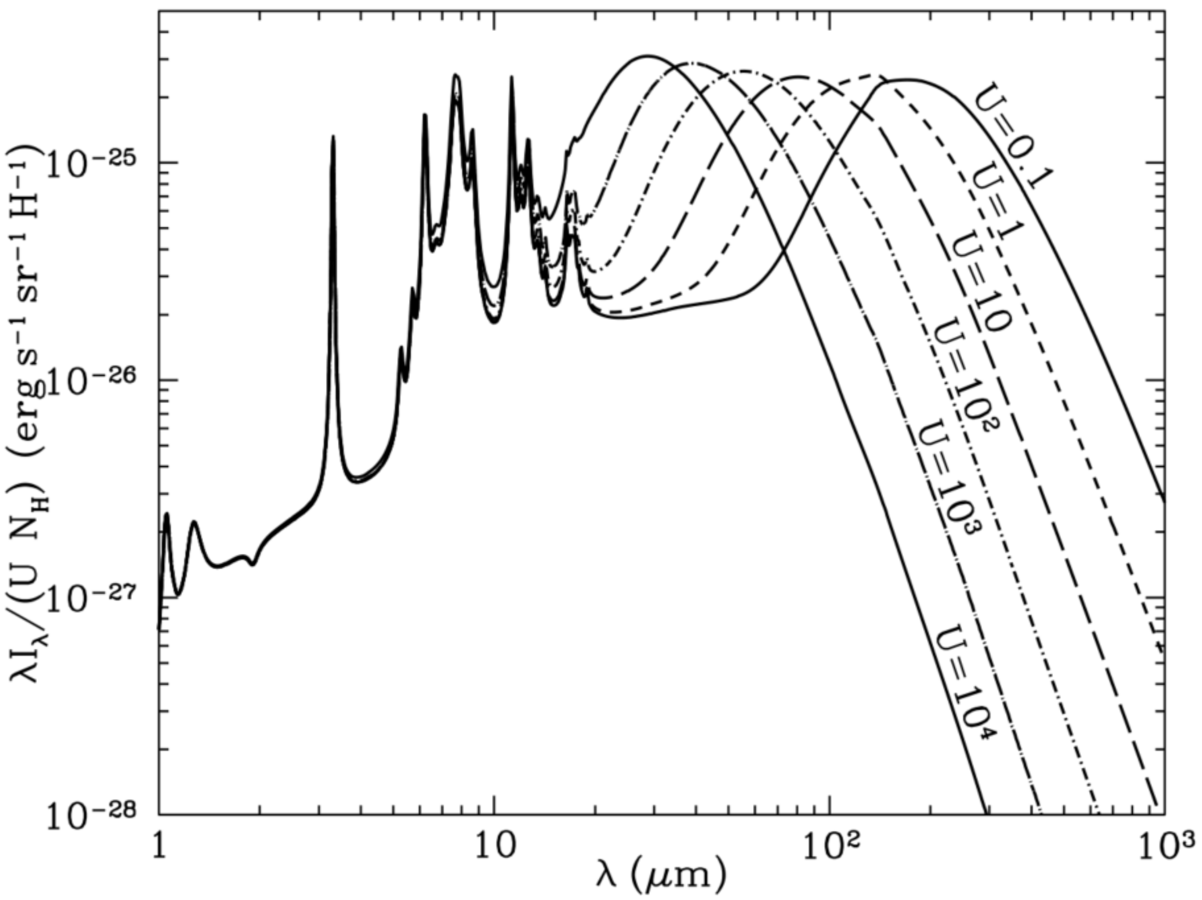
$$T_{\rm ss} = \left(\frac{h\nu_0}{k}\right)^{\beta/(4+\beta)} \left[\frac{\pi^4 \langle Q_{\rm abs}\rangle_\star \, c}{60\Gamma(4+\beta)\zeta(4+\beta) Q_0 \sigma}\right]^{1/(4+\beta)} u_\star^{1/(4+\beta)}$$

$$\approx 16.4\,(a/0.1\,\mu{\rm m})^{-1/15}\, U^{1/6}\,{\rm K} \quad , \quad {\rm silicate}, 0.01 \lesssim a \lesssim 1\,\mu{\rm m}$$

$$\approx 22.3\,(a/0.1\,\mu{\rm m})^{-1/40}\, U^{1/6}\,{\rm K} \quad , \quad {\rm graphite}, 0.005 \lesssim a \lesssim 0.15\,\mu{\rm m}$$

The IR emission from Dust

- Calculation IR emissivity from dust requires a grain model to provide the size distributions dni_/da for each composition i, the absorption cross sections Cabs, and the temperature distribution functions of dust (dP/dT).
- The Draine & Li 2007 model reproduced many interesting features of the IR radiation of dust.
- The thermal emission peak shifts toward shorter wavelength as U is increased because grains become warmer.
- The PAH emission features account for ~25% of the total power but do not change as the radiation intensity is changed.



$$j_\nu = \sum_i \int da \frac{dn_i}{da} \int dT \left(\frac{dP}{dT}\right)_{i,a} C_{\rm abs}(\nu; i, a) B_\nu(T)$$

Collisional Heating and Cooling of Dust

- Consider a neutral, spherical grain of radius a, at rest in a gas with temperature Tgas. The net rate of collisional heating by the gas can be written as

$$\left(\frac{dE}{dt}\right)_{\rm gas} = \sum_i n_i \left(\frac{8kT_{\rm gas}}{\pi m_i}\right)^{1/2} \pi a^2 \times \alpha_i \times 2k(T_{\rm gas} - T_{\rm dust})$$

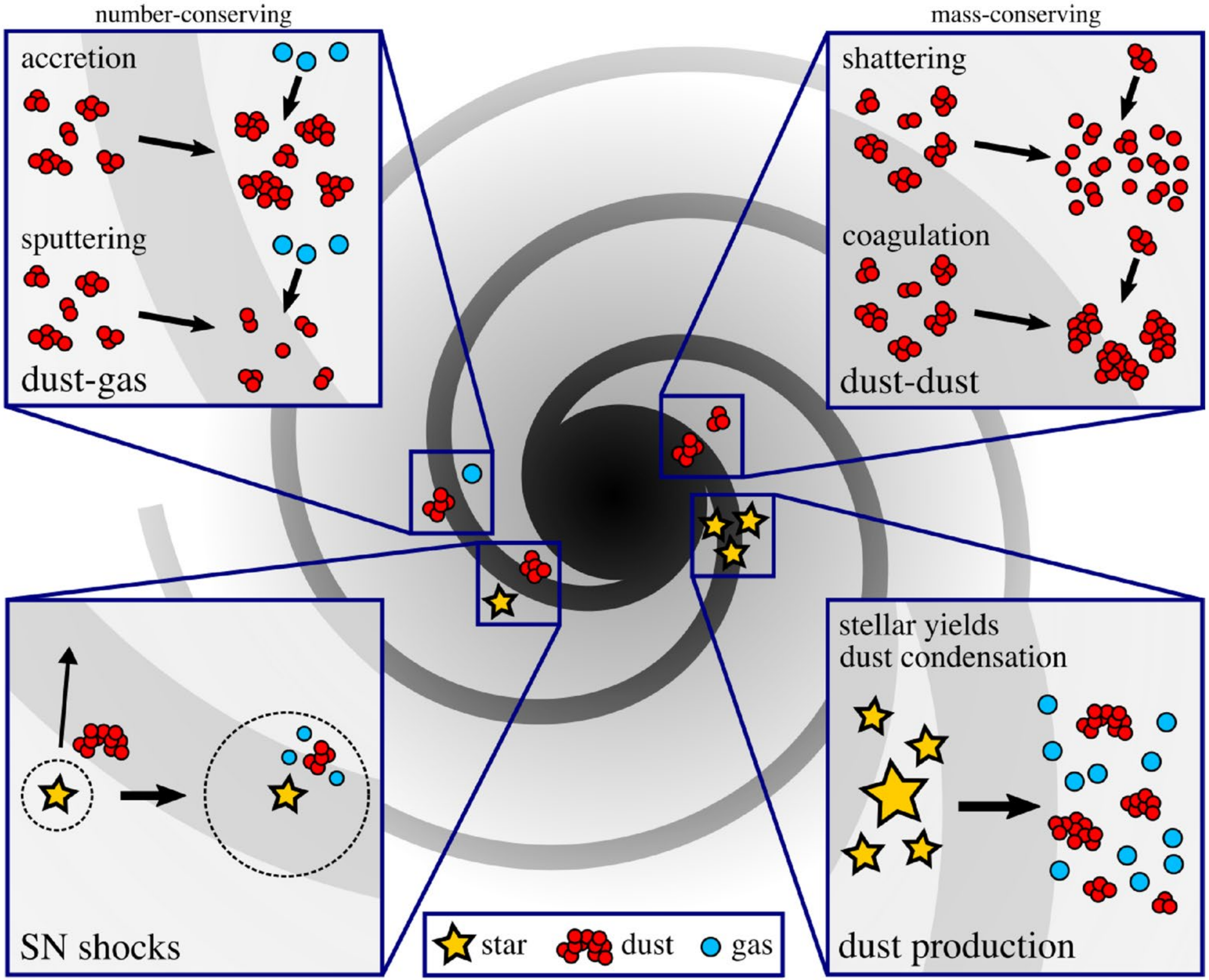
- In atomic H, the ratio of collisional heating to radiative heating is

$$\frac{(dE/dt)_{\rm gas}}{(dE/dt)_{\rm abs}} = \frac{n_{\rm H}(8kT/\pi m_{\rm H})^{1/2} 2\alpha_{\rm H} kT}{\langle Q_{\rm abs}\rangle_\star u_\star c} \times 1.05$$

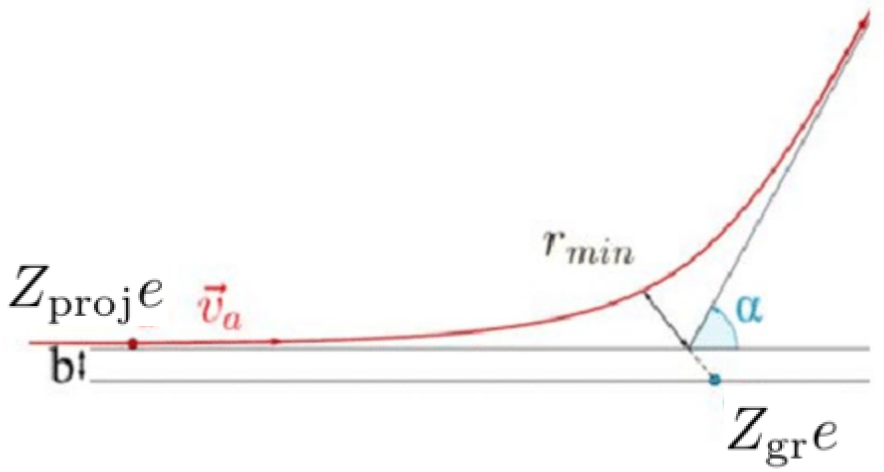
$$= \frac{3.8 \times 10^{-6}}{U} \frac{\alpha_{\rm H}}{\langle Q_{\rm abs}\rangle_\star} \left(\frac{n_{\rm H}}{30\,{\rm cm}^{-3}}\right) \left(\frac{T_{\rm gas}}{10^2\,{\rm K}}\right)^{3/2}$$

- IR emission between days 6000 and 8000 of SN 1987A was dominated by ~ 180 K silicate dust, heated by a plasma with n_e ≈ 3e4 cm−3 and T ≈ 5e6 K.

Grain Physics: Production / Destruction



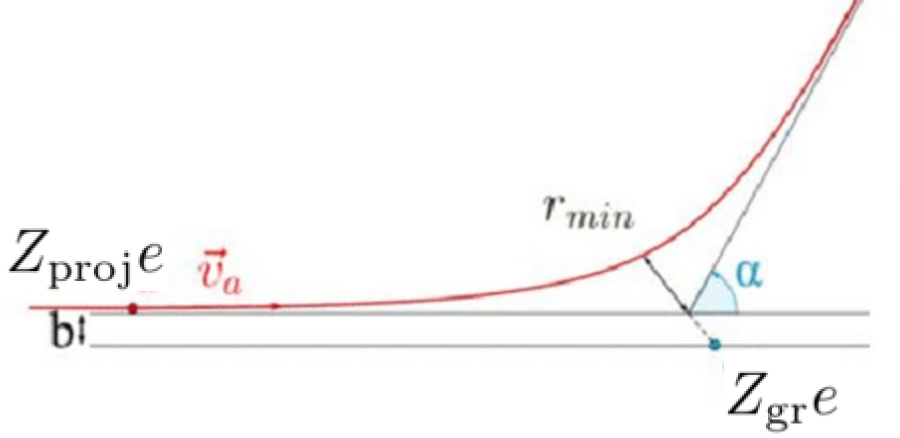
Grain Physics: Charges



- Interaction between charged grain and approaching projectile!
- Angular momentum conservation leads to the speed of the projectile at closest is $(2E/m_{\rm proj})^{1/2}b/r_{\rm min}$
- Energy conservation leads to $E = \left(\frac{b}{r_{\rm min}}\right)^2 E + \frac{Z_{\rm gr}Z_{\rm proj}e^2}{r_{\rm min}}$
- By settling r_min=a, the maximum impact parameter b_max can be solved!

$$\sigma(E) = \pi b_{\rm max}^2(E) = \pi a^2 \left[1 - \frac{Z_{\rm gr}Z_{\rm proj}e^2}{aE}\right]$$

Grain Physics: Charges



- The collision rate between grain and thermal gas is

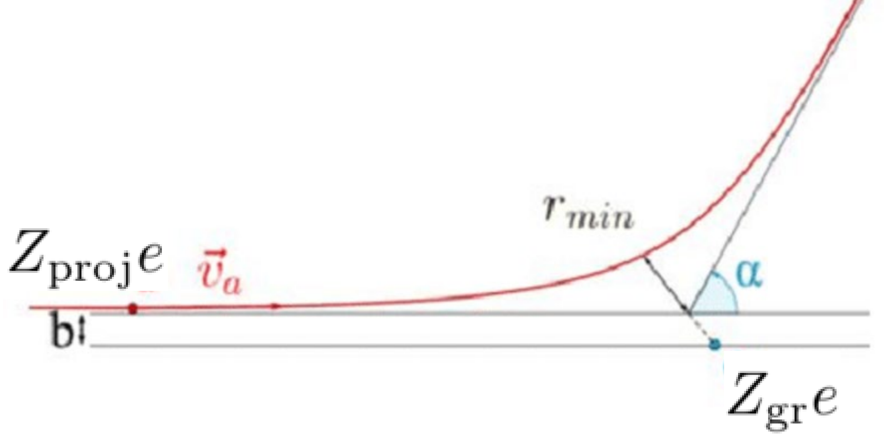
$$\left(\frac{dN}{dt}\right)_{\rm proj} = n_{\rm proj}\int_{E_{\rm min}}^{\infty} \sigma(E)\, v f_E\, dE$$

$$= \pi a^2 n_{\rm proj}\left(\frac{8kT}{\pi m_{\rm proj}}\right)^{1/2} F(Z_{\rm proj}\phi) \quad ,$$

$$\phi \equiv \frac{Z_{\rm gr}e^2}{akT} \quad , \qquad F(x) \equiv \begin{cases} (1-x) & \text{if } x < 0 \\ {\rm e}^{-x} & \text{if } x > 0 \end{cases}$$

- The function F is the amount by which Coulomb focusing changes the collision rate relative to the rate for an uncharged grain.

Grain Physics: Charges



- The rate of collision with ions balances the rate of collisions with electrons:

$$Z_i n_i s_i m_i^{-1/2}(1 - Z_i\phi) = n_e s_e m_e^{-1/2} \mathrm{e}^{\phi}$$

- For pure hydrogen plasma: $$(1-\phi)\mathrm{e}^{-\phi} = \sqrt{1836.1}$$

- The final stead-state grain charge is

$$Z_{\mathrm{gr}} = \frac{Ua}{e} = -2.504\frac{akT}{e^2} = -150\left(\frac{a}{0.1\ \mu\mathrm{m}}\right)T_4$$

Grain Physics: Dynamics in the ISM

- The motion and rotation of dust grains is determined by the forces and torques that act upon them.
- Drag force of dust by gas similar to aerodynamical drag (F~v2).

$$\frac{\mathrm{d}\boldsymbol{v}_{\mathrm{d}}}{\mathrm{d}t} = -\frac{K_{\mathrm{s}}(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})}{m_{\mathrm{d}}} \qquad \frac{\mathrm{d}\boldsymbol{v}_{\mathrm{g}}}{\mathrm{d}t} = -\frac{\nabla P}{\rho_{\mathrm{g}}} + \frac{\rho_{\mathrm{d}} K_{\mathrm{s}}(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})}{\rho_{\mathrm{g}} m_{\mathrm{d}}}$$

- In terms of relative velocity

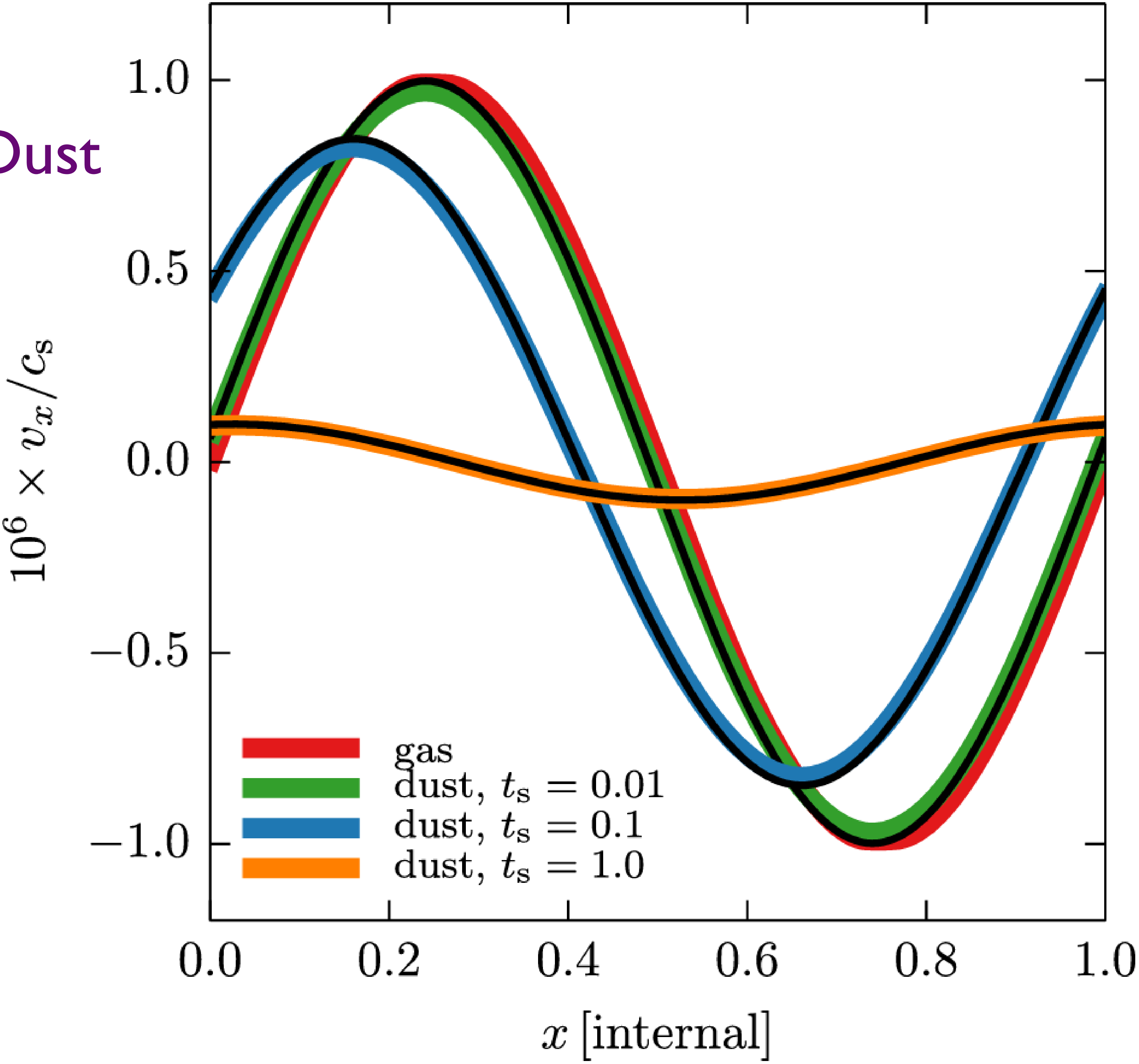
$$\frac{\mathrm{d}(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})}{\mathrm{d}t} = -\frac{\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}}}{t_{\mathrm{s}}}$$

Stopping timescale:

$$t_{\mathrm{s}} = \frac{m_{\mathrm{d}}\rho_{\mathrm{g}}}{K_{\mathrm{s}}(\rho_{\mathrm{g}} + \rho_{\mathrm{d}})} = \frac{\sqrt{\pi\gamma}\, a \rho_{\mathrm{gr}}}{2\sqrt{2}\rho_{\mathrm{g}} c_{\mathrm{s}}} \left(1 + \frac{9\pi}{128}\left|\frac{\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}}}{c_{\mathrm{s}}}\right|^2\right)^{-1/2}$$

Decoupling of Gas and Dust

- Dust most closely follows the gas when the stopping time-scale is short, corresponding to high drag.
- When stopping time is long, which is the case for large grains, gas and dust start to decouple between each other.



Grain Physics: Other Forces

- Lorentz Force for charged dust grains in magnetic fields.
- Radiation pressure onto dust and recoil forces.
- Thermal and suprathermal rotation of large grains.
- Alignment of dust grains (angular momentum and magnetic fields)