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Section 7.6 - End of Section 7

7.6 Grain Opacities

Key Point:
- theoretically explains how dust grains absorb and scatter light
- how these processes are connected to the observed extinction curve.

1. How is dust extinction calculated theoretically?
- previous sections: extinction curves were discussed based on observational data.
- it is also important to reproduce these curves through theoretical models.

Steps in the theoretical calculation:

- **Index of refraction:**
  Laboratory measurements are conducted for the refractive indices of materials
- **Assumption of grain shape:**
  For simplicity, dust grains are usually assumed to be spherical.
- **Application of scattering theory:**
  The scattering and absorption properties of grains are calculated using electromagnetic scattering theory
- **Grain size distribution:**
  - A distribution function $n(a)$, representing the number of grains as a function of their radius a
  - Assumed to compute the overall effect.
- **Derivation of extinction curve:**
  - By combining the above elements, a theoretical extinction curve is obtained
  - compared with observations to test its validity.

2. Extinction Efficiency $Q_x(a)$ and Cross Section σ_x

extinction efficiency $Q_x(a)$: depends on the grain size a the wavelength λ of the incoming light.

$$\kappa_\lambda(a) = n_D C_\lambda = Q_\lambda(a)\,\pi a^2 n_D$$

$K_\lambda(a)$: extinction coefficient
n_D: number density of dust grains
C_λ : extinction cross section of a single grain
$Q_\lambda(a)$: dimensionless extinction efficiency (includes both absorption and scattering)
πa^2: projected area of the grain

Behavior of $Q_\lambda(a)$

- If $a \gg \lambda$:

$$Q_x(a) \sim 1$$

→ optically large grains (efficient interaction)

- If $a \ll \lambda$:

$$Q_x(a) \propto \lambda^{-\beta}, \quad \text{where } \beta \approx 1 \sim 2$$ depending on the composition of the grain

→ small grains become more efficient at absorbing/scattering shorter wavelengths

➔ explains why **extinction is stronger in the ultraviolet**: small grains are very effective at interacting with UV photons.

7.6 Grain Opacities

3. Absorption vs. Scattering

• **Absorption**: the photon's energy is absorbed by the dust and converted into thermal energy

• **Scattering**: the photon is redirected without energy loss.

➔ Observed extinction is the sum of absorption and scattering.

4. Figure 7.9

(1) Upper panel – Absorption cross section

•Y-axis: effective absorption cross section per hydrogen nucleon:

$$<Q_\lambda \pi a^2 n_D> \text{ : total extinction at a wavelength } \lambda$$

•Absorption is strong in the ultraviolet, especially at:

- 2200 Å: graphite bump
- 10–20 μm: silicate absorption feature

•In the UV, dust absorbs ionizing photons more effectively than neutral hydrogen.

- When the neutral hydrogen fraction $n(H^0)/n(H) < 3\times10^{-4}$, dust dominates ionizing photon absorption.

(2) Lower panel – Scattering cross section

•Forward scattering (which barely changes a photon's path) is excluded using the factor:

$$(1-g)\cdot Q_{scattering}$$

•g: asymmetry factor (degree of forward scattering).

•At long wavelengths, the albedo is low, -> dust is strongly absorbing.

•In the UV to optical, albedo ≈ 0.5

•In the ionizing regime, absorption again dominates over scattering.

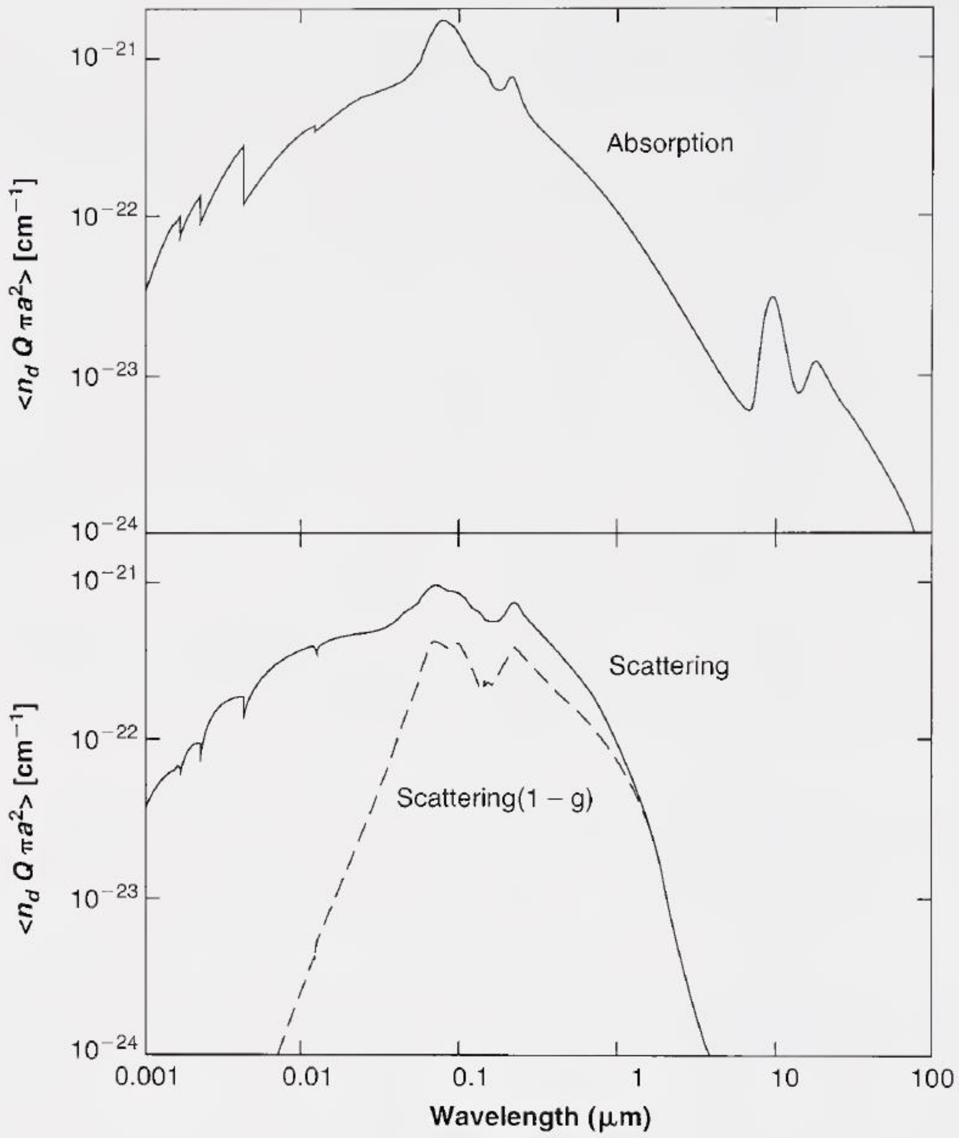

Figure 7.9

Theoretical mean absorption and scattering cross sections. These are the results of calculations which reproduce ISM extinction with two materials, graphite and an astronomical silicate, and a distribution of grain sizes. The plotted quantity is the effective cross section per unit hydrogen nucleon. The dust optical depth is this quantity multiplied by the column density of hydrogen.

7.7 Effects of Grains on Surrounding Gas

Key point: The theoretical study of the effects of interstellar dust (grains) on the surrounding gas, particularly the charge state and temperature of dust within a nebula, and the resulting heating effects.

1. Dust Is Not Just an Obstacle: It Plays a Key Physical Role

- it significantly affects both the ionization and temperature structures of a nebula.
- dust is considered to be about as important as helium.
- Dust can absorb ultraviolet radiation and heat the surrounding gas.

2. Electric Charge on Dust Grains

Dust grains are usually charged. Why?
Their charge is determined by the competition among three processes:
1. PhotoEjection (pe): Absorption of ultraviolet photons → electron emission (photoejection) → makes dust positively charged (+)
2. Capture electron (ce): Capture of positive ions → Makes dust more positively charged (+)
3. Capture proton (cp): Electron capture (electrons from gas) → makes dust negatively charged (-)

Charge on a particle (dust):

$$\frac{dZ}{dt} = \left(\frac{dZ}{dt}\right)_{pe} + \left(\frac{dZ}{dt}\right)_{ce} + \left(\frac{dZ}{dt}\right)_{cp} = 0, \qquad (7.20)$$

Equilibrium Charge

- As the grain's charge changes, the probabilities for electron escape or capture also change
- The grain's charge Ze is determined by the balance:

  Electron emission rate + electron capture rate + cation (positive ion) capture rate = 0

➔ **The equilibrium charge Ze is related to the particle's radius a, radiation field, electron temperature, electron density, etc.**

7.7 Effects of Grains on Surrounding Gas

$$\frac{dZ}{dt} = \left(\frac{dZ}{dt}\right)_{pe} + \left(\frac{dZ}{dt}\right)_{ce} + \left(\frac{dZ}{dt}\right)_{cp} = 0, \qquad (7.20)$$

1. The rate of increase of the charge Ze due to photoejection of electrons:

$$\left(\frac{dZ}{dt}\right)_{pe} = \pi a^2 \int_{\boxed{\nu_K}}^{\infty} \frac{4\pi J_\nu}{h\nu} Q_{abs}\phi_\nu \, d\nu, \qquad (7.14)$$

ϕ_v : photodetachment probability ($0 \leq \phi_v \leq 1$)

$$\boxed{\nu_K} = \left\{ \begin{array}{ll} \nu_c + \dfrac{Ze^2}{ah} & Z > 0 \\ \nu_c & Z \leq 0 \end{array} \right\} \text{[Hz]}, \qquad (7.15)$$

dust particle is electrically neutral or has a negative charge: effective threshold $v_K = v_C$,
dust particle is positively charged: the lowest energy photoelectrons cannot escape

Ze^2/a : potential energy of an electron at the surface of the particle
h: Planck's constant.

2. The rate of increase of the charge due to capture of electrons

$$\left(\frac{dZ}{dt}\right)_{ce} = -\pi a^2 n_e \sqrt{\frac{8kT}{\pi m}} \xi_e Y_e,$$

$$Y_e = \left\{ \begin{array}{ll} 1 + \dfrac{Ze^2}{akT} & Z > 0 \\ \exp\left(Ze^2/akT\right) & Z \leq 0 \end{array} \right\}. \qquad (7.17)$$

ξ_e is the electron-sticking probability ($0 < \xi_e < 1$),

3. The rate of increase of the charge caused by capture of protons

$$\left(\frac{dZ}{dt}\right)_{cp} = \pi a^2 n_p \sqrt{\frac{8kT}{\pi m_h}} \xi_p Y_p,$$

$$Y_p = \left\{ \begin{array}{ll} e^{-Ze^2/akT} & Z > 0 \\ 1 - \dfrac{Ze^2}{akT} & Z \leq 0 \end{array} \right\} \qquad (7.19)$$

3. Variation of Charge: Inner vs. Outer Regions

- In **inner region of the nebula (closer to the star)**: UV is strong → photoejection dominates → grains are positively charged
- In **outer region (far from the star)**: UV is weak, electron thermal speed is higher → electron capture dominates → grains become negatively charged

➔ Thus, the charge state of a dust grain varies depending on its position in the nebula and also depends on its radius a.

4. Grain Temperature T_d

In thermal equilibrium, the grain both gains and loses energy:

Heating:

- Main source: absorption of UV radiation
- Part of the photon energy is carried away by photoelectrons; the rest heats the grain

Cooling:

Dominated by infrared emission, governed by Kirchhoff's law: $j_\nu(T) = \kappa_\nu B_\nu(T)$

The total cooling due to a spherical grain of radius a is:

$$4\pi J = n_D \pi a^2 \int_0^\infty Q_{abs} 4\pi B_\nu (T_d)\, d\nu. \qquad (7.21)$$

a representative particle with a = 3.0×10^{-5} cm, T_D ~ 100 K at r = 3 pc from the star.

Result:

Smaller grains are hotter, because:

Their absorption efficiency Qabs is smaller at long wavelengths

➔ they cool less efficiently, leading to higher equilibrium temperatures

5. Figure 7.10: Grain Potential and Temperature Inside an H II Region

Left Panel (grain potential : Ze^2/a) :

- **Inner region:** grains are positively charged (photoionization dominates)
- **Outer region:** grains are negatively charged (electron capture dominates)
- Smaller grains have larger potentials due to smaller a

Right Panel (Grain Temperature):

- Smaller grains are hotter (less efficient cooling)
- Graphite grains are hotter than silicates (higher cross section at higher energies)

Potential and temperature of ISM grains within the simple H II region model

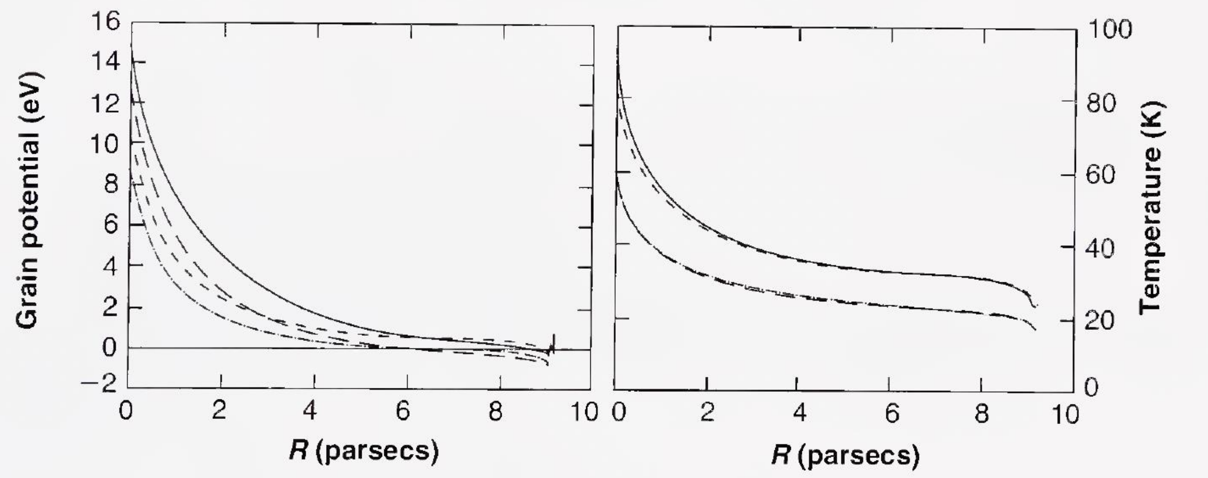

Figure 7.10

The computed grain potential and temperature across the model H II region shown in Figure 2.3. ISM grains and photoionization by a 40,000 K black body are assumed. Two grain types, graphite and silicate, and two sizes, 3×10^{-6} cm and 2×10^{-5} cm, are shown. The types of grains are solid line, small graphite; long dashed, large graphite; short dashed, small silicate; and dash dot, large silicate. Smaller grains tend to be hotter and have a larger potential.

➔ Smaller grains tend to be hotter and have a larger potential.

6. Dust's Effect on Nebular Structure

- Dust absorbs UV in the Lyman continuum → causes the H-ionization front to appear closer to the star than it would in a dust-free case.
- -> dust reduces the overall size of the ionized region.
- Dust photoionization can also contribute up to ~30% of the total heating in certain regions of the nebula.

7.7 Effects of Grains on Surrounding Gas

7. Dust Sublimation
When ***dust becomes hot*** enough, it sublimates (transitions directly from solid to gas).
Approximate sublimation temperatures by species:

- CH_4: 20 K
- NH_3: 60 K
- H_2O: 100 K
- Graphite, Silicates, SiC: ~1000 K → stable even inside H II regions

8. Dust Grains Are Not Perfect Spheres (Polarization and Alignment)
Observations show that starlight passing through interstellar dust is polarized. This implies that:

- Dust grains are non-spherical
- Grains are aligned with the galactic magnetic field

Alignment mechanism:

- Grains are made of paramagnetic materials
- Grain rotation couples with the magnetic field
- interaction causes grains to align with the field

Such polarization observations allow astronomers to infer the structure and strength of the galactic magnetic field.

7.8 Dynamical Effects of Dust in Nebulae

Key point: Although radiation pressure does not directly move dust, it transmits the force of radiation pressure through the dust to the gas as a whole, influencing the evolution of the nebulae.

1. Radiation Pressure on Dust

Light from the central star exerts radiation pressure on dust grains.

Dust experiences pressure proportional to

$$Q = Q_{absorption} + Q_{scattering}(1-g)$$

→ This includes both absorption and scattering (excluding strong forward scattering).

In most cases,

$$Q \approx 1$$

→ Radiation pressure is very strong.

2. Why Dust Doesn't Move Freely: Strong Coupling with Gas

- Dust grains are tightly coupled to the gas via physical interactions.
- Dust doesn’t move independently; instead, it transmits the radiation force to the gas.
- It's like pushing on dust causes the surrounding air to move as well.

3. How Is Dust Velocity Determined?

Two competing forces on a dust grain:

Force Type	Description	Direction
Radiation Pressure	Pushes the grain outward from the central star	outward
Drag Force	Resistance from the gas when the grain moves	inward

When these forces balance, the grain reaches a terminal velocity (w_t).

[For Neutral Grains]

Drag is due to simple grain–gas collisions → Use Equation (7.24):

$$F_{coll} = \frac{4}{3} n_p \pi a^2 \left(\frac{8kTm_H}{\pi} \right)^{1/2} w, \tag{7.24}$$

w is the dust's velocity relative to the gas

a is the grain radius

Typical result:

$w_t \approx 10$ km/s, time to move 1 pc$\sim 10^5$ y

[For Charged Grains]

Coulomb (electromagnetic) force enhances drag → much stronger resistance

If |Z|>50, Coulomb drag dominates.

→ Grain motion becomes even slower, nearly stationary relative to the gas.

→ In most nebular environments, dust is effectively frozen into the gas.

7.8 Dynamical Effects of Dust in Nebulae

4. The entire gas is subject to radiation pressure

•Since the dust is completely attached to the gas, the radiation pressure exerted on the dust pushes the entire gas.

• -> a radiation pressure term is added to the equation of motion of the entire nebula.

• $n_D \cdot F_{rad}$ is the force transmitted to the gas by the radiation pressure exerted on the dust.

$$\rho \frac{Du}{Dt} = -\nabla P - \rho \nabla \phi + n_D \boxed{\frac{a^2 L}{4r^2 c}\mathbf{e}_r} \quad (7.27)$$

$$F_{rad} = \pi a^2 \int_0^\infty \frac{\pi F_\nu}{c} Q_\nu \, d\nu$$
$$= \pi a^2 \int_0^\infty \frac{L_\nu}{4\pi r^2 c} Q_\nu \, d\nu \approx \boxed{\frac{a^2 L}{4r^2 c}} \quad (7.23)$$

5. Result of This Effect: A Central "Hole" Forms

- As radiation pressure pushes dust outward, and the dust in turn pushes gas, the central region of the nebula gets cleared of gas over time.
- -> the formation of a central cavity or "hole".
- Observational example:
  NGC 2244 (Rosette Nebula), which shows a hollowed-out central region.

Figure 7.11
NGC 2237, the Rosette Nebula, an H II region in Monoceros, taken in the light of Hα and [N II]. The central hole may have been swept clear of gas by radiation pressure on the dust from the central star cluster. (Photo © UC Regents/Lick Observatory)

- Structure with an empty center of the nebula
- The radiation pressure of the central cluster pushes out the dust, and the dust pushes out the gas, forming a hole in the center.

6. Dust Also Matters in the Early Stages of Stellar Evolution

In the early stages of planetary nebula formation from red giants,
→ Radiation pressure on dust can shape the initial gas distribution.

7. Limitations: Physical Properties of Dust Are Still Uncertain

While the existence of dust is confirmed observationally, many properties remain uncertain, including:

- Exact refractive index
- Shape, impurities, and thermal response

→ These factors are not yet fully constrained by experiments.