Astrofisica Generale II — 3

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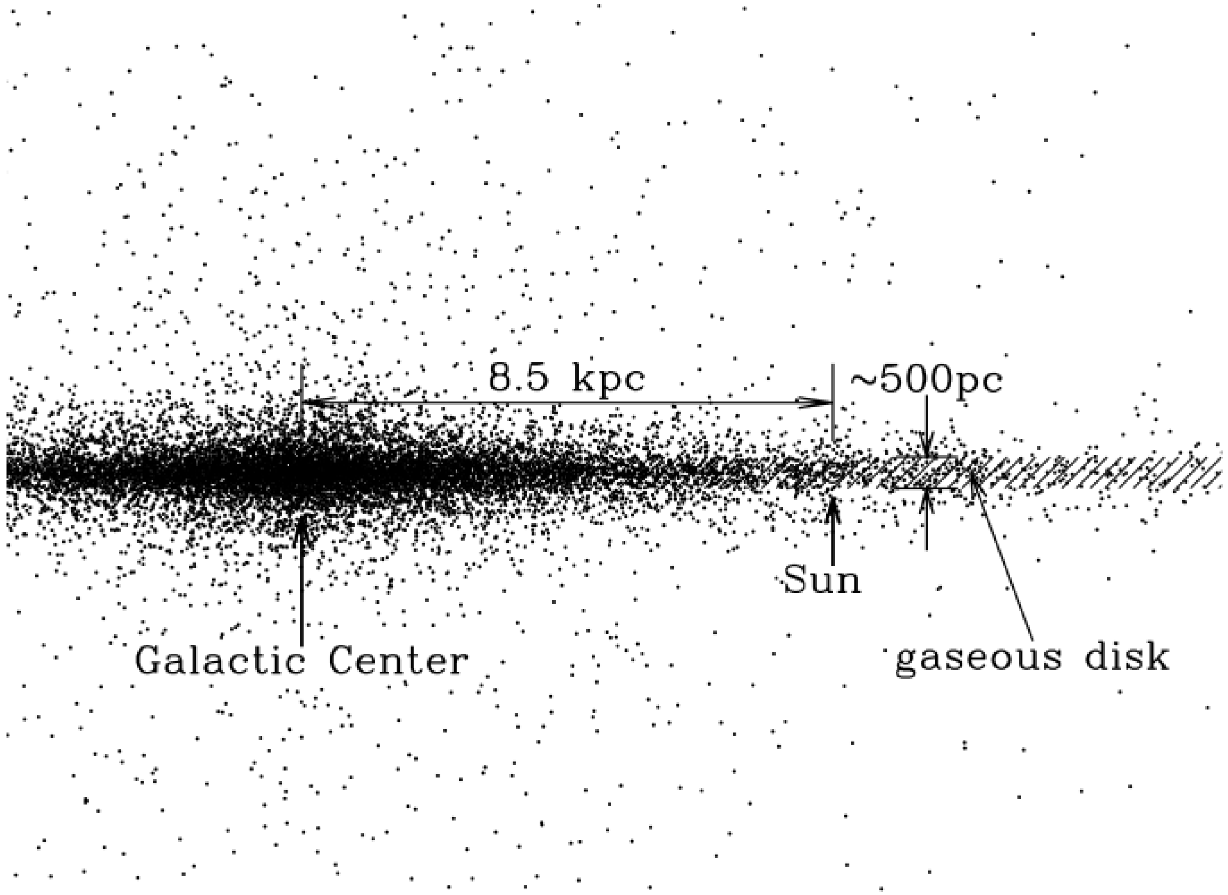
The Interstellar Medium (ISM)

The Galactic Plane

Evidence of the interstellar medium (ISM) is given by the presence of opaque regions on the galactic plane, with a thickness of $\sim 100 \div 500$ pc.

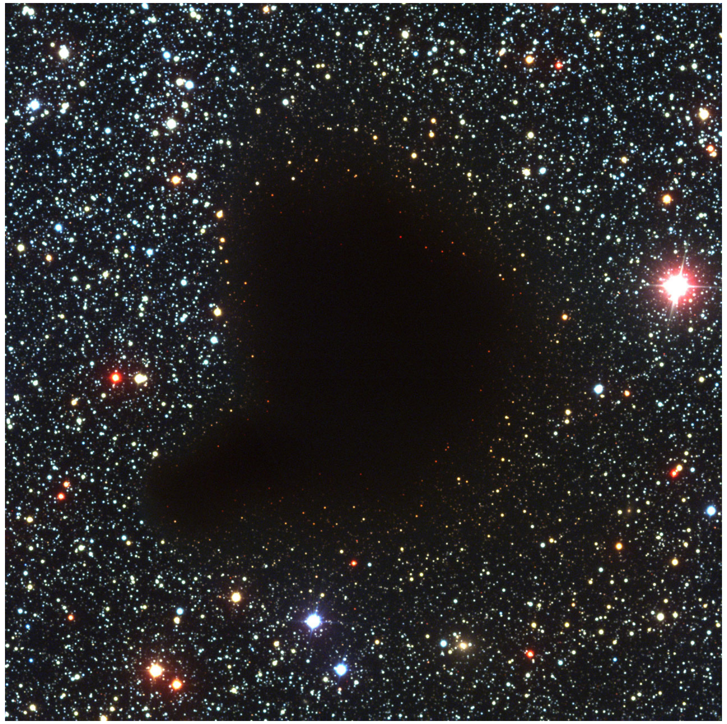
The Gaseous Disk



Adapted from B. Draine, *Physics of the interstellar and galactic medium*, Princeton University Press (2011).

Globules and nebulae

The ISM shows globules whose size is of the order of ~ 1 pc, called “globules” and “nebulae”.



Barnard 68 («Black cloud»)

The Interstellar Medium

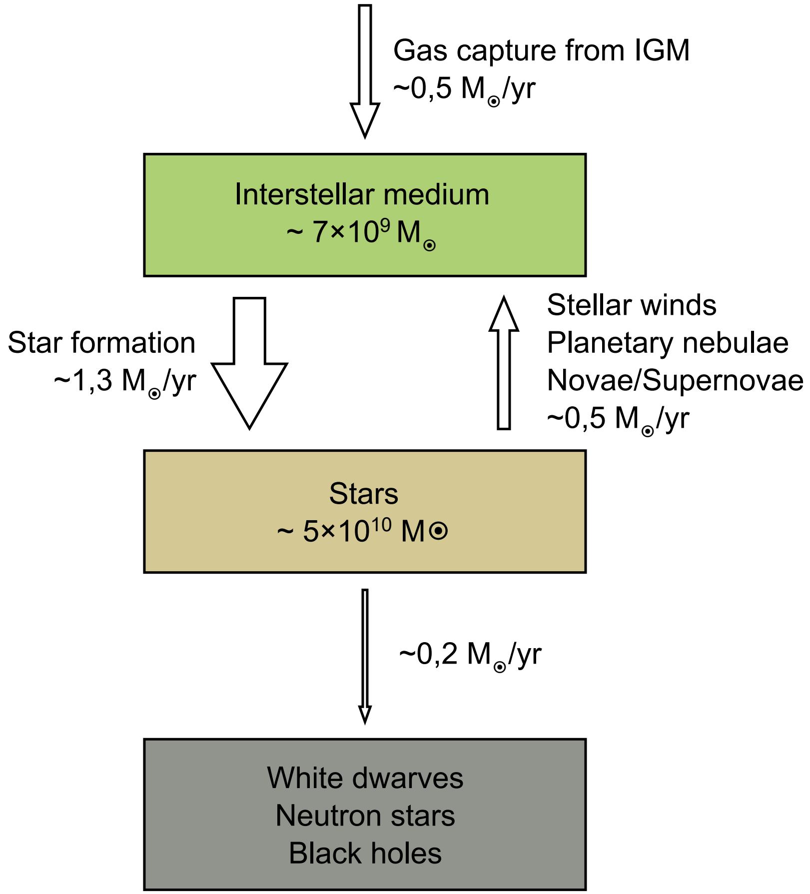
There are two reasons why the ISM is interesting:

1. It contains a significant portion of the Galaxy's mass ($10^{10}\ M_\odot$);
2. It is a site of star formation:

$$
\begin{aligned}
t_{\text{O-star}} &< 1\,\mathrm{Gyr}, \\
t_{\text{Milky Way}} \sim \max t_{\mathrm{gc}} &\gtrsim 10\,\mathrm{Gyr}.
\end{aligned}
$$

Therefore, the fact that we observe "O" stars in the Milky Way today implies that star formation is still ongoing.

Baryons in the Mikly Way



Adapted from B. Draine, *Physics of the interstellar and galactic medium*, Princeton University Press (2011).

Components of the ISM

ISM includes everything in the Galaxy that lies between stars. It is made of:

1. **Gas**;
2. **Dust**;
3. Cosmic rays;
4. E.m. radiation (starlight, CMB, …);
5. Interstellar magnetic field;
6. Gravitational field;
7. Dark matter.

Today we will only deal with **gas** and **dust**.

The interstellar medium

Observation methods:

- Dust:
  1. Obscuration (in V band);
  2. Direct emission (UV, IR, mm).
- Gas: emission/absorption of lines.

Flux Extinction

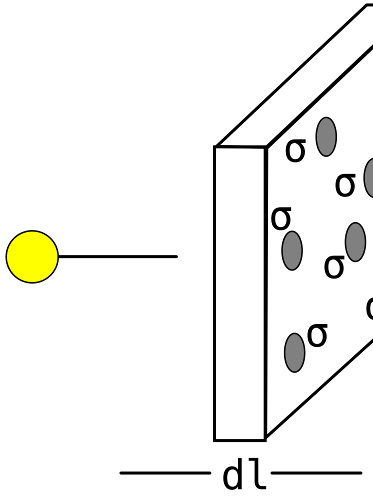
- The flux of bright objects is reduced by the ISM through **scattering** and **absorption**:

  1. Scattering changes the direction of propagation of the radiation;

  2. Absorption increases the temperature of the interstellar medium.

  The two phenomena are collectively referred to as **extinction**.

- The density of the ISM can vary from 10^{-4} to 10^{+6} cm^{-3}, but these are still very low values! (Air has a density of 10^{19} cm^{-3})



- A photon traversing a thickness $\mathrm{d}l$ of ISM has a certain probability p of interacting with its particles, being extinguished (scattered/absorbed).
- If there are $N = n(l) \times A \times \mathrm{d}l$ particles in the thickness, then

$$p = \frac{N\sigma_\lambda}{A} = \frac{n(l) A \,\mathrm{d}l\, \sigma_\lambda}{A} = n(l)\sigma_\lambda \mathrm{d}l.$$

(assuming that $\mathrm{d}l$ is so small that the particles do not eclipse each other).

Extinction Equation

- Given the probability p of extinction, at a certain λ the spectral radiance I_λ ($[I_\lambda] = \mathrm{W}/\mathrm{m}^2/\mathrm{Hz}/\mathrm{sr}$) will be reduced due to extinction:

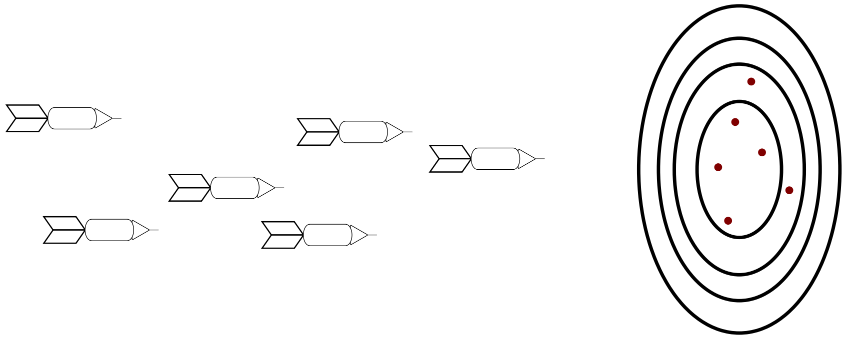
$$\mathrm{d}I_\lambda = -p \times I_\lambda = -n(l)\,\sigma_\lambda\,I_\lambda\,\mathrm{d}l.$$

- Solving the differential equation, we get

$$I_\lambda(l) = I_0 \exp\left(-\sigma_\lambda \int n(l')\,\mathrm{d}l'\right) = I_0 \exp\bigl(-\tau\,\lambda(l)\bigr),$$

and therefore the spectral radiance depends on the distance if there is extinction!

Column Density



We define **column density** the quantity

$$N_{\rm col} = \int_0^l n(l')\,\mathrm{d}l',$$

from which $[N_{\rm col}] = \mathrm{cm}^{-2}$. If $n(l)$ is constant, $N_{\rm col} = n \times l$.

Extinction Coefficient

- The value $\tau_\lambda(L) = N_\text{col}\,\sigma_\lambda$ is called the **extinction coefficient**, and it is a dimensionless number.
- Extinction is the combined effect of absorption and scattering. Their relative importance depends on the physical properties of the grains and on λ.
- The *albedo* $a_{\lambda,\text{diff}}$ is defined as the fraction of extinction due to scattering:

$$
I_\lambda(l) = I_0 e^{-\tau_\lambda} = I_0 e^{-\tau_\lambda\left(a_{\lambda,\text{diff}} + a_{\lambda,\text{abs}}\right)},
$$

with $a_{\lambda,\text{diff}} + a_{\lambda,\text{abs}} = 1$.

Extinction and Magnitude

- Switching from I to flux b ($[b] = \mathrm{W}/\mathrm{m}^2$), if the measured flux is lower due to extinction, it means that the magnitude **increases**:

$$A_\lambda \equiv m'_\lambda - m_\lambda = 2.5\log_{10}\frac{b_0}{b_\lambda(l)} = 2.5\log_{10}e^{\tau_\lambda(l)} = 1.0857\,\tau_\lambda(l)$$

(A is sometimes called *total absorption*).

- Therefore, we can use the approximation

$$A_\lambda \approx \tau_\lambda(l).$$

ISM and Distance Measurement

- In the presence of extinction A, in general we have

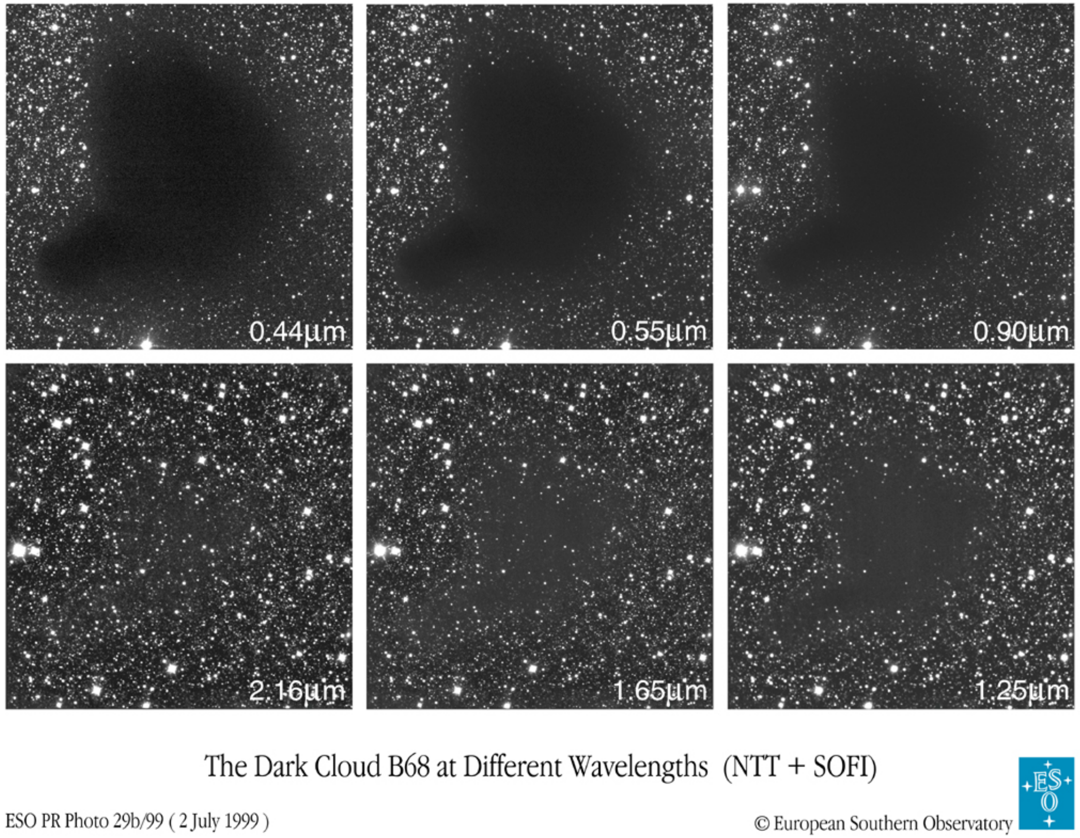
$$
\begin{aligned}
m'_\lambda &= m_\lambda + A_\lambda \\
&= M_\lambda + 5\log_{10}\frac{d}{10\,\mathrm{pc}} + A_\lambda
\end{aligned}
$$

  (the presence of A_λ makes the star appear fainter).

- Therefore, in the presence of extinction, knowing M_λ is no longer sufficient to derive d!

Extinction as a function of λ

The notation A_λ suggests that extinction depends on wavelength.



Extinction as a function of λ

- Around the visible spectrum, extinction is more intense if λ is small (blue light).
- This implies that the number of observed stars increases in the IR.
- Furthermore, stars appear redder (*stellar reddening*). Let's see how to quantify the impact of reddening on the observation of the flux.

Color Excess

- We measure the color index of a star in two filters, e.g., B and V:

$$m_V = M_V + 5\log_{10}\frac{d}{10\,\mathrm{pc}} + A_V\,,$$
$$m_B = M_B + 5\log_{10}\frac{d}{10\,\mathrm{pc}} + A_B\,.$$

- From the difference between the two equations, we get

$$m_B - m_V = (M_B - M_V) + (A_B - A_V).$$

Color Excess

$$m_B - m_V = (M_B - M_V) + (A_B - A_V).$$

- The value $m_B - m_V$ is measured directly.
- The value $M_B - M_V$ is estimated from the spectral type.
- The value $A_B - A_V$ can then be easily derived and is called **color excess**, or **reddening** (see Draine, *Physics of the interstellar and galactic medium*, p. 238).
- Usually, $E(B - V)$ is written instead of $A_B - A_V$ (E stands for *Excess*).

Physics of Extinction

Physics of Extinction

- Recall the definition of A_λ:

$$A_\lambda = 2.5 \log_{10} e^{\tau_\lambda} \approx \tau_\lambda.$$

- The *extinction coefficient* τ_λ is linked to the microscopic physics of the ISM:

$$\tau_\lambda = \sigma_\lambda N_{\mathrm{col}},$$

where N_{col} is the column density of the ISM between us and the observed object, l is the thickness, and σ_λ is the total cross section (absorption and scattering) at wavelength λ.

Physics of Extinction

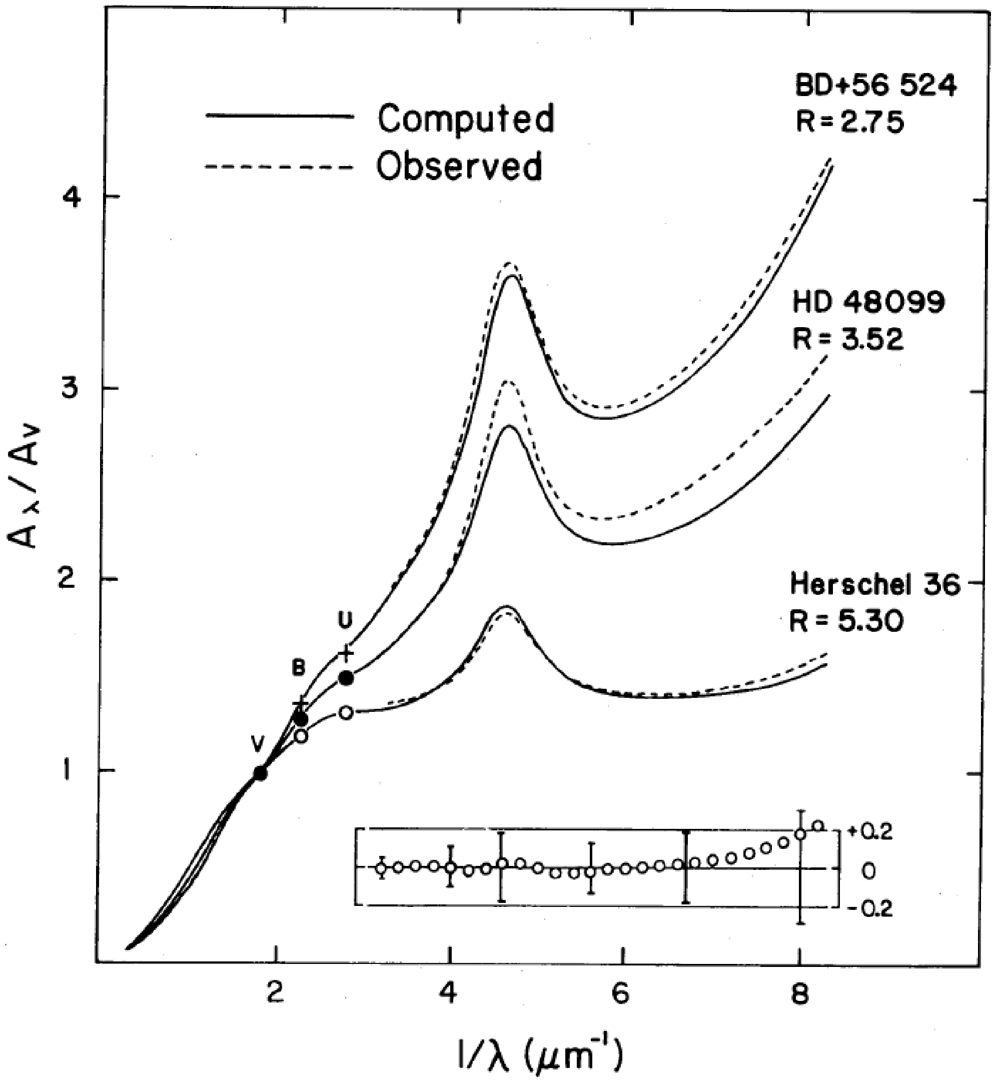
- If $A \propto N_{\text{col}}$, this means that observing dust clouds of different sizes/densities leads to different values of A, even if σ is the same.
- If we want to study the dependence of extinction on λ, we use the (dimensionless) quantity

$$f(\lambda) \equiv \frac{A_\lambda}{A_V} = \frac{\tau_\lambda}{\tau_V} = \frac{N_{\text{col}}\,\sigma_\lambda}{N_{\text{col}}\,\sigma_V} = \frac{\sigma_\lambda}{\sigma_V},$$

and in this way the dependence on the column density disappears!

Physics of Extinction

- The study of $f(\lambda)$ reveals a few interesting features:
  1. In the visible/IR, $f(\lambda) \propto 1/\lambda \propto \nu$ (blue light is easier to absorb);
  2. There is a peak in the UV;
  3. Structures are seen in the IR spectrum.
- The shape of $f(\lambda)$ however also depends on the direction of observation (there are many types of dust!), especially in the UV.



Note that the x axis shows $1/\lambda$ instead of λ.

Dust in the Interstellar Medium

Dust in the ISM

What is the typical size r_g of dust grains?

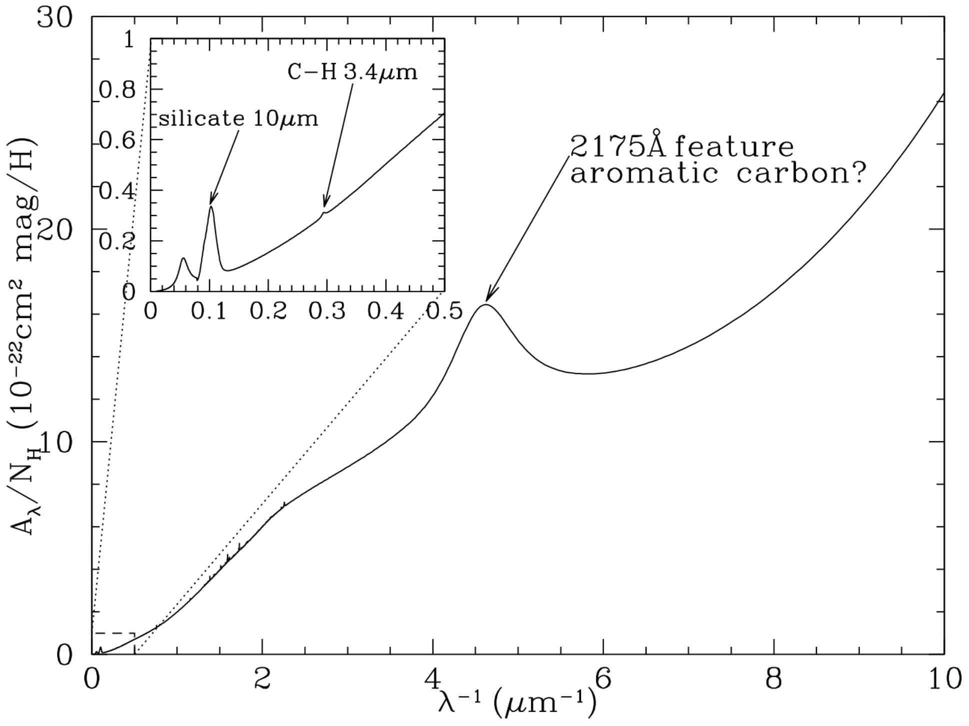
- If $r_g \gg \lambda$, geometric optics applies, and $A(\lambda)$ is constant;
- If $r_g \ll \lambda$, then $\sigma \sim 0$ and therefore $A(\lambda)$ is small and constant;
- If $r_g \sim \lambda$, then diffraction is important, and $A(\lambda)$ depends strongly on λ.

Grain Size

Experimental evidence indicates that there are two types of dust grains:

1. **Large grains** (μm–mm) generate an IR spectrum. Spectral structures are observed at ~1÷10 μm, indicative of silicates (SiO, SiO_2) and ice (H_2O);
2. **Small grains** (1–10 nm) generate extinction in the UV, and are aggregates of ~100 atoms (hydrocarbons, carbon, graphite).

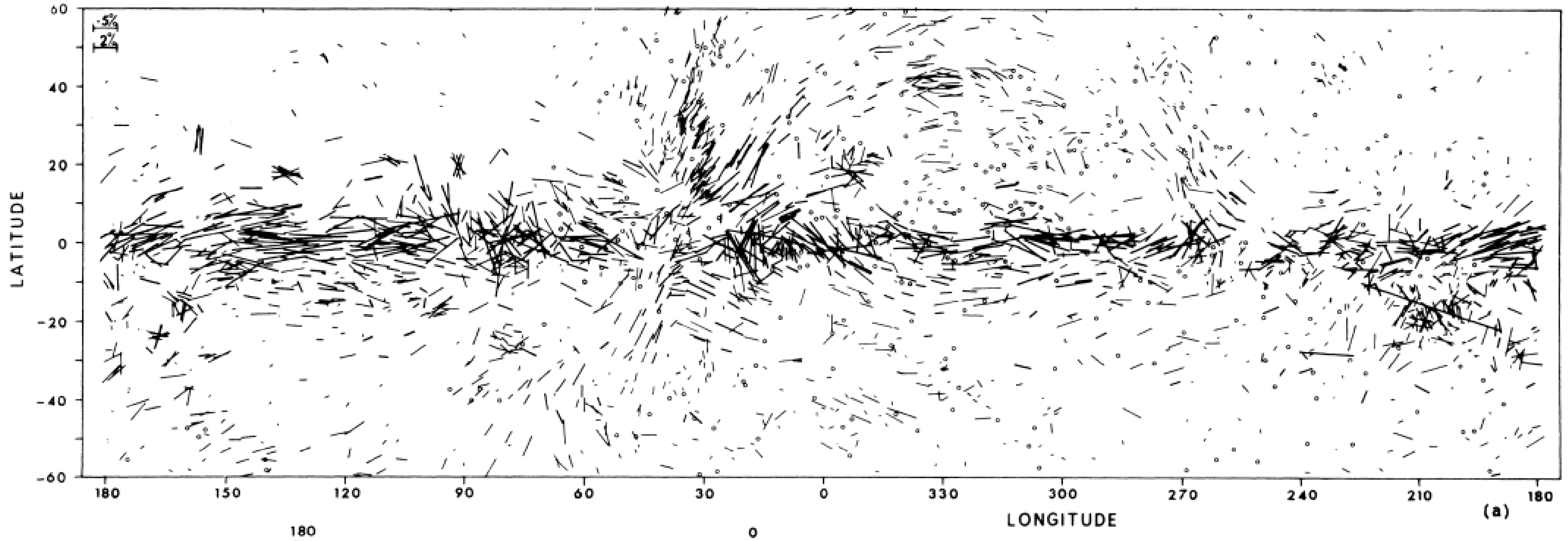
Dust in the ISM: Composition



B. Draine, *Physics of the interstellar and galactic medium*, Princeton University Press (2011).

Shape of Dust Grains

- Hints on the shape of the grains come from **polarization** measurements.
- The light from stars passing through the ISM is polarized. This is assumed to depend on the shape of the grains in the ISM, because HI, HII and He have spherical symmetry and cannot induce polarization.
- The polarization of starlight on the galactic plane is greater if dust is present between us and the star.



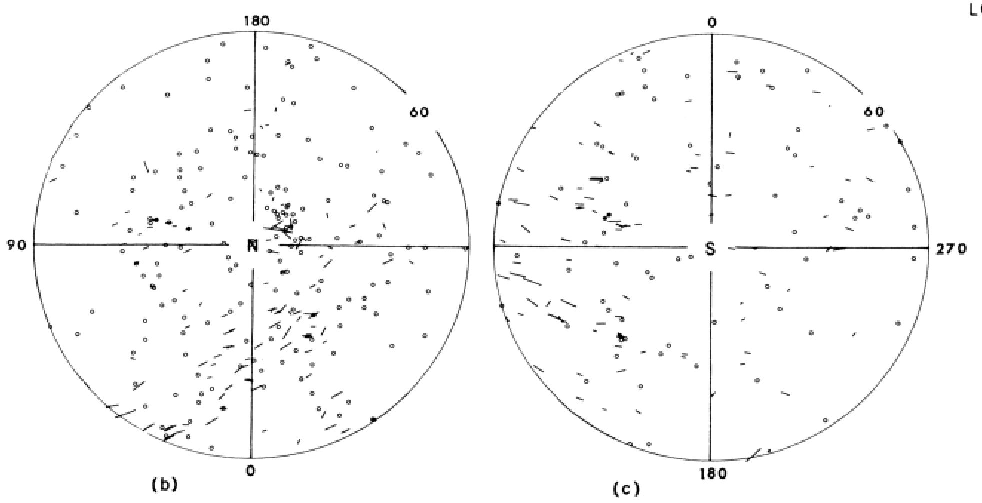


Fig. 9.13. Polarization of starlight. Panel (a) presents data at low Galactic latitudes, while (b) and (c) present high latitude data. The stars measured are at the center of each line whose length is proportional to the percentage polarization P. The angle drawn is the direction of the electric field vector $\mathbf{E}$. Small circles indicate $P < 0.08\%$. Thin lines are used for $P < 0.6\%$ and thick lines for $P > 0.6\%$ (see scale at top left) (after Mathewson and Ford (Ma70)). With the permission of the Officers and Council of the Royal Astronomical Society.

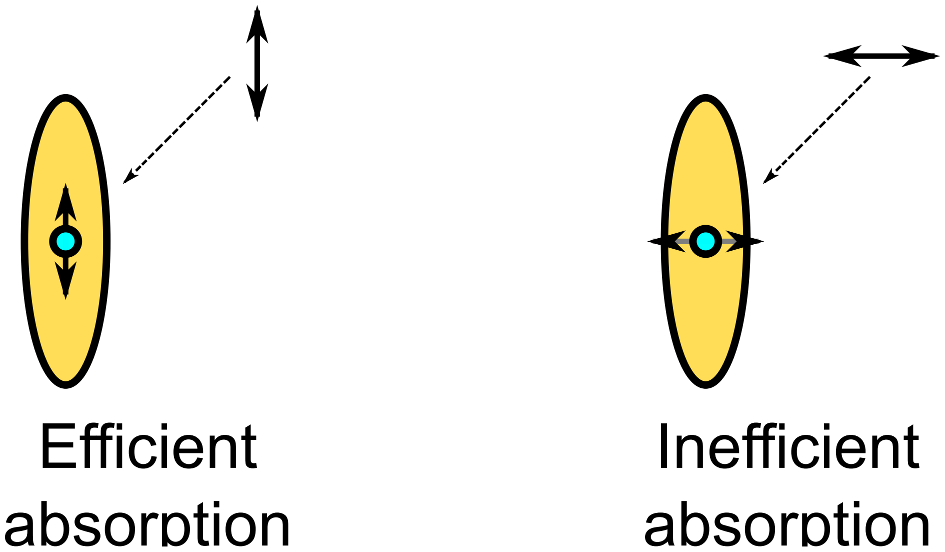
Harwit, *Astrophysical concepts* (4th edition), pag. 426, Springer (2006)

Dust Grain Shape

- Starlight in the galactic disk is preferentially polarized **parallel** to the plane
- But stars in the vicinity of the Sun do not emit light as polarized as that observed → it is the ISM that causes the polarization
- Thus, dust grains must absorb photons more or less easily depending on their polarization angle

Dust Grain Shape

The most likely shape of the grains is an ellipsoid: in this way the electrons are free to respond to the external field $\vec{E}$ more in some directions than in others.



Polarization is observed mainly in the visible, while it is absent in the UV (geometric optics!)

Observations on Polarization

- Average polarization level: $1\,\% \div 2\,\%$;
- Weak dependence on λ;
- Dependence on A_V:
  - If A_V is small, the polarization is always low;
  - If A_V is large, the polarization can be anything.

(Therefore, the presence of dust is **necessary but not sufficient** for polarization).