

Interactions of photons:

Interactions of photons with matter are important for their production in high energy phenomena, as well as for determining their spectra and also their detection. Here we briefly discuss different interactions of photons with matter. We consider two separate energy regimes: low energy photons whose energy is $E \ll m_e c^2$ ($\approx 0.5 \text{ MeV}$), and high energy photons with an energy $E \gtrsim m_e c^2$.

(1) Low energy photons. First let us discuss the interactions of low energy photons (say UV and longward).

— Molecular absorptions. This has to do with excitation of vibrational and rotational degrees of freedom associated with multiple atoms in a molecule. It is straightforward

(2)

to show that $E_{\text{vib}} \gg E_{\text{rot}}$.

- Atomic absorption. The two main types are bound-bound and bound-free transition. In the bound-bound transition an electron goes from one atomic bound state to another one. Hence bound-bound absorption is peaked strongly around the energy difference between the two bound states.

In the bound-free transition the photon energy is high enough to kick the electron out of an atom and ionize the atom. It can be shown that the cross section for bound free absorption decreases with frequency like ν^{-3} .

- Free-free absorption. A photon can be absorbed by a free electron in the presence of another charged particle (for example, a proton). This process is sometime called the "bremsstrahlung absorption". The cross section for the

free-free absorption decreases with the frequency like ν^{-3} .

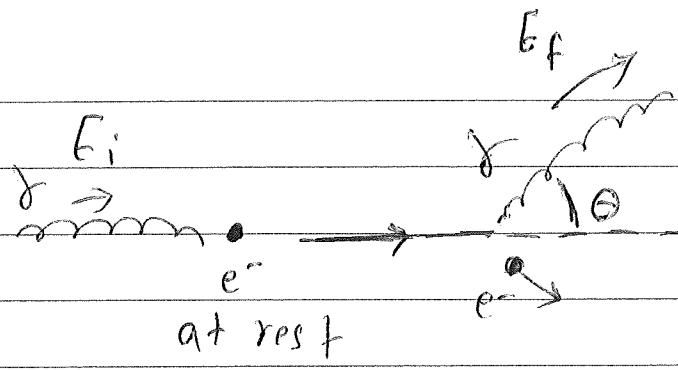
- Scattering of free electrons. In the low-energy regime ($E \ll m_e c^2$) the scattering is elastic, and is called Thomson scattering. The cross section for Thomson scattering is useful to remember; $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$.

(2) High-energy photons. There are other things that can happen when the photon energy is comparable to or higher than $m_e c^2$.

- Compton scattering. For high energy photons the energy of the scattered photon is not the same as that of the incident photons (i.e., the scattering is inelastic). The process is called Compton scattering and its cross section is given by the Klein-Nishina formula. The energy of the scattered photon E_f is related to that of the incident photon

according to:

$$E_f = \frac{E_i m_e c^2}{m_e c^2 + E_i (1 - \cos \theta)}$$



Note that for forward scattering ($\theta=0$) we have $E_f = E_i$.

For all other scattering angles $E_f < E_i$. In the low energy limit ($E_i \ll m_e c^2$) we have $E_f \approx E_i$, which is the limit for Thomson scattering.

Pair-production. At energies above $2m_e c^2$, and in the presence of other charged particles, a photon can split into an electron-positron pair. In the presence of a strong magnetic field, a photon can also split into two photons.

Atmospheric Absorption:

Our eyes have developed the greatest sensitivity to photons with a wavelength $\lambda \sim 300-700$ nm range, the

"visible" part of the spectrum. This waveband encompasses most of the Sun's spectral output (roughly a black body peaking at $\lambda \sim 600$ nm). Also, it represents one of the few regions in the spectrum where atmospheric absorption is essentially nonexistent.

Let us briefly discuss the atmospheric absorption and its main sources in different wavebands.

- Radio waveband ($3 \text{ MHz} \leq \nu \leq 30 \text{ GHz}$). At the low frequency end of this range, 1-10 MHz, observations of extraterrestrial sources becomes very difficult because of the reflection of radio waves by the ionospheric plasma. Even if the telescope is located above the ionosphere, observations at frequencies lower than about 1 MHz are difficult to make because of the same plasma

⑥

reflection effects occurring in the interplanetary and interstellar plasma.

- Millimeter/Sub-millimeter waveband ($30 \text{ GHz} \leq \nu \leq 3000 \text{ GHz}$)

A distinct astronomical feature of this waveband is the presence of a wealth of molecular absorption lines in Gal sources. At frequencies above $\sim 300 \text{ GHz}$, there are very strong absorption bands due to water vapor, carbon dioxide and other molecules in the atmosphere. To have a reasonable chance of making observations at these frequencies, it is essential to observe from a high, dry site (such as Mauna Kea in Hawaii).

- Infrared waveband ($3 \times 10^{12} \text{ Hz} \leq \nu \leq 3 \times 10^{14} \text{ Hz}$). There is a distinction between those parts of this waveband that can be observed from high ground-based sites and

those that can only be successfully observed from above the atmosphere. There are a few windows within this wave band that are accessible from high, dry sites. While observations outside these windows have to be done from balloons, high flying aircrafts or satellites.

- Ultra violet wave band ($10^{15} \text{ Hz} \leq \nu \leq 3 \times 10^{16} \text{ Hz}$). The atmosphere ^{here} is opaque to photons in this wave band because of ozone and molecular absorption. Therefore astronomy within this wave band has to be carried out from above the atmosphere.

- X-ray wave band ($3 \times 10^{16} \text{ Hz} \leq \nu \leq 3 \times 10^{19} \text{ Hz}$). The atmosphere ^{here} is opaque to X-ray photons because of the bound-free absorption by the atoms that make up the molecular gases of the atmosphere.

γ -ray wave band ($\nu \gtrsim 3 \times 10^{19}$ Hz). At frequencies between 3×10^{17} Hz and 3×10^{20} Hz (corresponding to energies between 100 keV and 1 MeV) the bound-free absorption is the dominant mechanism. At energies above 10 MeV, photons passing through the atmosphere begin to produce electron-positron pairs. Between these two energies, $1 \text{ MeV} \leq E \leq 10 \text{ MeV}$, the dominant interaction is the Compton scattering. As a result, observations of γ -rays must be carried out by satellites in orbits. However, at very high energies, $E \gtrsim 100 \text{ GeV}$, γ -ray photons are so energetic that they initiate electromagnetic cascade in the upper atmosphere. Cerenkov radiation of the electrons and positrons in the showers can be detected at the ground level. Hence, the very high energy

(9)

γ -rays can be detected from the ground, although indirectly, by using the atmosphere as the detector. This is the principle behind the Cerenkov telescopes like H.E.S.S. (High Energy Stereoscopic System) and HAWC (High Altitude Water Cerenkov Gamma Ray Observatory).

The attenuation suffered by a ray of photons traveling in a material with intensity I is described by:

$$\frac{dI}{ds} = -k_s I$$

Here k is the opacity, which is defined as $k \equiv \frac{n\sigma_{\text{total}}}{\rho}$ where σ is the absorption cross section, n is the number density of the particles in the material, ρ is the mass density of the material, and s is the path length. If k_s is almost constant, we find;

$$I(d) = I_0 \exp(-kSd)$$

Here d is the distance traveled in the material.

For photon energies $E \gtrsim 0.5 \text{ MeV}$, we have $k \lesssim 0.1 \text{ cm}^2 \text{ g}^{-1}$.

This implies that astronomical measurements at these energies must be carried out at column densities

$Sd \lesssim 10 \text{ g cm}^{-2}$ to avoid strong attenuation. On the Earth,

this column density corresponds to a height of 30 km.

Therefore, high energy astrophysics is primarily a high altitude and space-based discipline.

This exercise can be extended to the entire spectrum,

from radio to γ rays. The figure on the next page

shows the penetration length of extraterrestrial photons

descending to a level above the ground where the

attenuation factor e^{-kSd} drops below $\frac{1}{e}$.

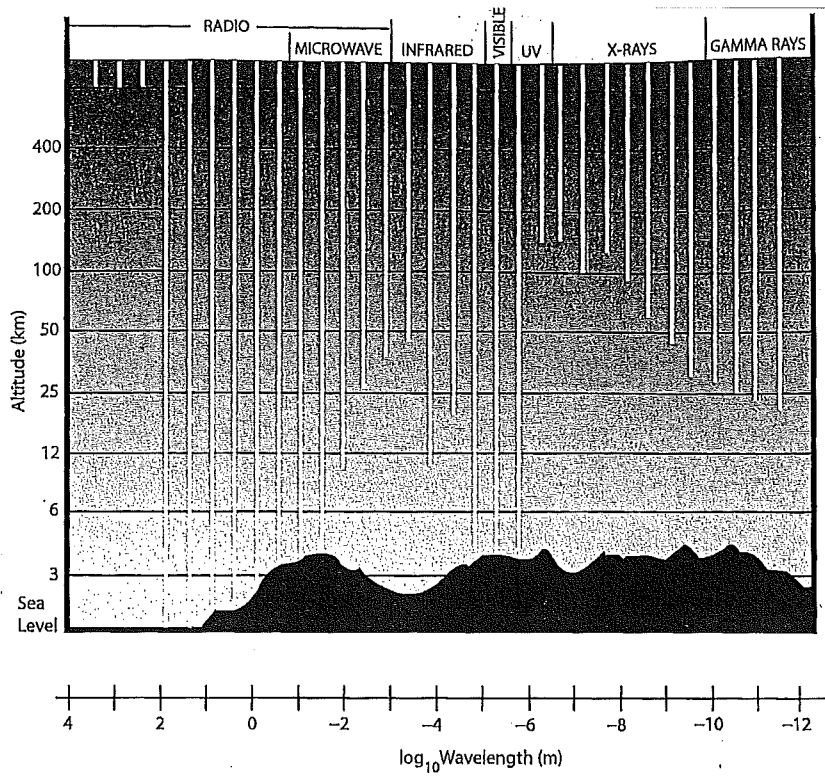


Figure 1.4 Transparency of Earth's atmosphere as a function of wavelength, showing the depth (in km) to which photons of a given energy will penetrate before being absorbed or scattered. The surface of the Earth is completely shielded from that portion of the spectrum (beyond the UV) of particular relevance to high-energy astrophysics. (Image courtesy of Jerry Woodfill and NASA)

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