PHYC 581: High Energy Astrophysics
Fall 2018

Lecture 2: 08/22/2018

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 $E \ll m_e c^2$ (~ 0.5 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 absorption. This has to do with excitation of vibrational and rotational degrees of freedom associated with multiple atoms in a molecule. It is straightforward to show that $E_{vib} \gg E_{rot}$.

- 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 lik ν^{-3}.

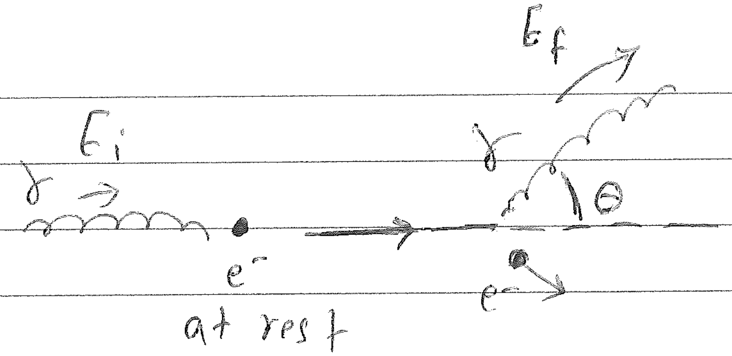
- Free-free absorption. A photon can be absorbed by a free electron in the presence of another charged particle (for example, a proton). This process is sometime called the "bremsstrahlung absorption". The cross section for the free-free absorption decreases with the frequency lik ν^3.

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

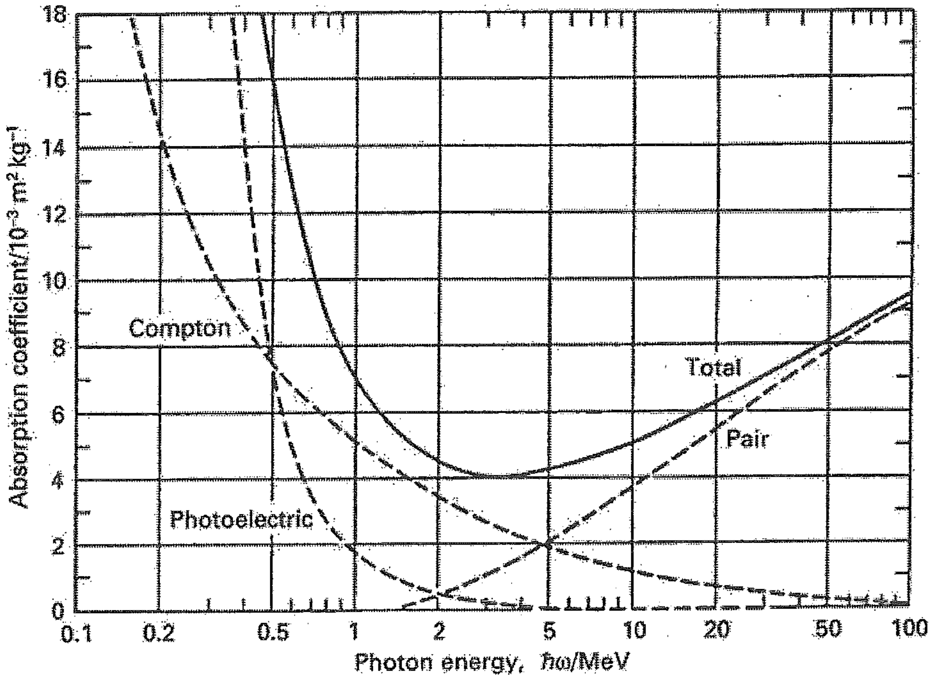
$$E_f = \frac{E_i \, m_e c^2}{m_e c^2 + E_i (1 - \cos\theta)}$$



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 $2 m_e c^2$, 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.

The figure on the next page shows the absorption coefficient for the photoelectric, Compton, and pair-production processes as a function of frequency for X-ray and γ-ray photons.



The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron–positron pair production (Enge, 1966).

From "High Energy Astrophysics" (Page 272)
by Malcolm S. Longair
Cambridge University Press
Third Edition 2011

Atmospheric Absorption:

Our eyes have developed the greatest sensitivity to photons with a wavelength $\lambda \sim 300$-700 nm range, i.e., the "visible" part of the spectrum. This waveband encompasses most of the Sun's spectral output (roughly a blackbody peaking at $\lambda \sim 600$ nm). Also, it represents one of the few regions in the spectrum where atmosphere absorption is essentially nonexistent. Let us briefly discuss the atmospheric absorption and its main sources in different wavebands.

- Radio waveband ($3\,\text{MHz} \lesssim \nu \lesssim 30\,\text{GHz}$). At the low frequency end of this range, 1-10 MHz, observation 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 atmosphere, observations at frequencies lower than about 1 MHz are difficult to make. The reason for this is that exactly the same plasma reflection effects occuring 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 Cool sources. At frequencies above ~ 300 GHz, there are very strong absorption bands due to water vapor, carbon dioxide and other molecules in the atmosphere. To have a reasnoble 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 ($3\times10^{12}\ \text{Hz} \leq \nu < 3\times10^{14}\ \text{Hz}$). There is a distinction between those parts of this waveband that can be observed from high ground-based sites an 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.

- Ultraviolet waveband (10^{15} Hz $< \nu < 3\times10^{16}$ Hz). The atmosphere is opaque to photons in this waveband because of Ozone and molecular absorption. Therefore astronomy within this waveband has to be carried out from above the atmosphere.

- X-ray waveband (3×10^{16} Hz $< \nu < 3\times10^{19}$ Hz). The atmosphere 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 waveband ($\nu \geqslant 3\times10^{19}$ Hz). At frequencies between 3×10^{19} 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, $E \geqslant 100$ GeV, γ-ray photons are so energetic that they initiate electromagnetic cascades 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

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

(HAWC (High Altitude Water Cerenkov Gamma Ray Observatory) is a water Cerenkov telescope).

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

$$\frac{dI}{ds} = -k\rho I$$

Here k is the opacity, which is defined as $k \equiv \frac{n\sigma}{\rho}$ where σ is the total 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 $k\rho$ is almost constant, we find:

$I(d) = I_0 \exp(-\kappa \rho d)$

Here d is the distance traveled in the material. For photon energies $E \gtrsim 0.5$ MeV, we have $\kappa \lesssim 0.1\ \mathrm{cm}^2\,\mathrm{g}^{-1}$. This implies that astronomical measurements at these energies must be carried out at column densities $\rho d \lesssim 10\ \mathrm{g\,cm}^{-3}$ 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 hows the penetration length of extraterrestrial photons descending to a level above the ground where the attenuation factor $e^{-\kappa \rho d}$ drops below $\frac{1}{e}$.

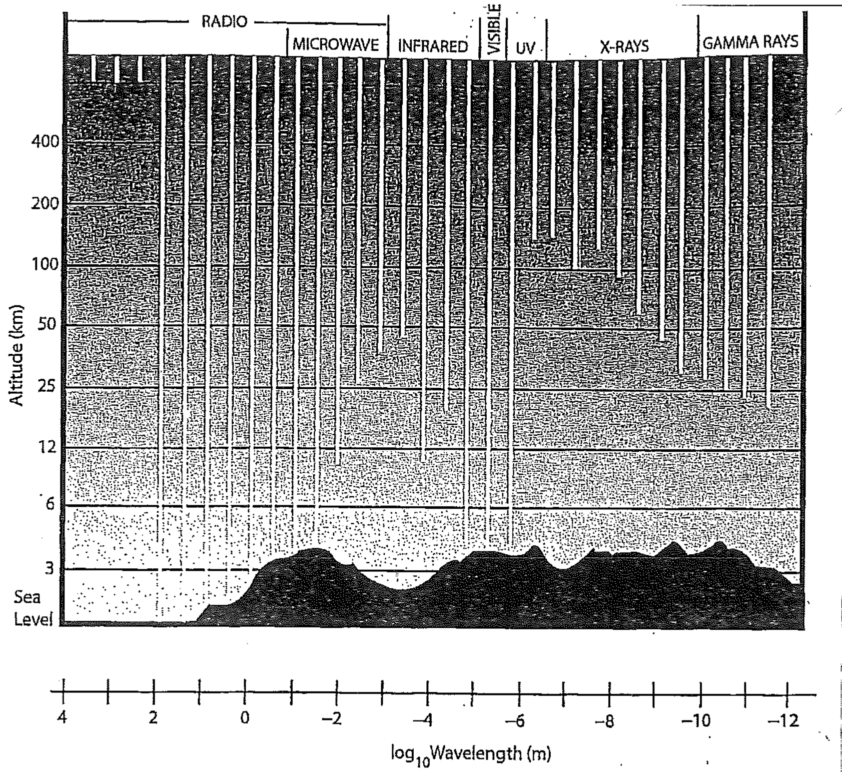


Figure 1.4 Transparency of Earth's atmosphere as a function of wavelength, showing the depth (in km) to which photons of a given energy will penetrate before being absorbed or scattered. The surface of the Earth is completely shielded from that portion of the spectrum (beyond the UV) of particular relevance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

From "High-Energy Astrophysics" (Page 14)
by Fulvio Melia
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