Appendix G

A Primer on Absorption and Scattering Opacity

One of the two fundamental properties of light-matter interaction is *absorption*, wherein light energy disappears, and a like amount of energy is converted to heat. The other property is *scattering*, in which the path of the light ray is merely deflected by the matter. We might think that specular reflection from a polished surface is a third type, but this phenomenon can be shown to be a consequence of scattering. Thus two (and only two fates) await a photon when it suffers an encounter with matter. This is true regardless of the form the matter takes: whether in a solid (land surfaces), in condensed form (the ocean) or whether it is composed of gaseous molecules or suspended particles (atmospheres). This book concerns itself with the dual influences of absorption and scattering on radiation fields in planetary media.

Consider first the property of absorption, and imagine a medium in which only absorption is important for the light field. Although it is inherently easier to understand than scattering, it is difficult to find many commonplace examples in which *only* absorption is present. Carbon soot is perhaps the best example. An object covered with soot approaches the ideal *blackbody* behavior, described in elementary thermodynamic textbooks. However, since we are interested in atmospheres and oceans in this book, let us first consider a medium consisting of finely-dispersed soot particles.

Imagine sunlight to fall on such a medium, and consider the attenuation of the light as it passes through this soot cloud. The ability of the medium to attenuate the light will depend upon three quantities: (1) the number per unit volume n of the soot particles; (2) the particle sizes, r; and (3) the distance along the light ray, s. For simplicity we assume the particles are all the same size, and the cloud has uniform spatial density. The relevant attenuation quantity depends upon the *projected cross-sectional area* of the soot cloud in the direction of the light ray, $n\pi r^2 s$. This quantity is a pure number, and is the absorption *opacity*, or *optical depth*, τ_a. (Here we have assumed that the particles act as simple geometric light obstacles, which applies for sizes much larger than the sensing wavelength.) Another way to think of τ_a is the projected shadow area, per unit area, of all the particles along a ray path. If we ignore mutual shadowing effects (and this is usually permissible) a moments thought reveals that the actual distribution of particles along the light ray is unimportant, only the product ns. Thus the relevant quantity is the total *column number* per unit area $\mathcal{N}$, and $\tau = \pi r^2 \mathcal{N}$. A high opacity at a particular visible-light frequency ν means that sunlight will be absorbed high up in the atmosphere, and a small opacity means that it will penetrate deeply. If $\tau(\nu) << 1$, the atmosphere is said to be *optically-thin*, or *transparent* at that frequency, and if $\tau(\nu) >> 1$, it is said to be opaque.

It remains to determine the degree to which the light is transmitted, and this involves a function of τ. It is shown in Chapter 2 that for sufficiently small frequency intervals $\Delta\nu$, this function is the exponential function $\exp[-\tau(\nu)]$. This familiar relationship is known popularly as *Beer's Law*, but for our own reasons, we call it the *Extinction Law.* Since absorption and transmission are opposite sides of the coin, the absorption varies as $1 - \exp[-\tau(\nu)]$. The absorption process leads to a heating of the particles, in contrast to the scattering process.

Atmospheres also emit their own radiation, as do all bodies whose temperatures are above absolute zero. The solar atmosphere, due to its high temperature, emits copiously in the visible spectrum, whereas the cooler atmospheres of the earth and planets emit most of their energy in the thermal infrared. The opacity also plays a key role in the ability of media to emit radiation. This is one of many examples of the principle of detailed balance which are considered in this book, and is more familiar as *Kirchoff's Law*, which says in brief, that *an efficient absorber is an efficient emitter.* To be more precise, the ability of an atmosphere to emit depends upon its opacity per unit length, or per unit volume, and depends upon the local absorptive properties of the medium.

Scattering processes add complexity to the above situation, in redirecting and modifying the radiation field without destroying it. Even soot particles are not "mini-black holes", but scatter a small amount of light. Otherwise we would not be able to distinguish soot particle texture or color. If the particles were non-scattering, the soot cloud would be invisible, except when viewing the light beam directly — it would behave like a neutral density filter which progressively dims the light as we move farther away from the light source.

Now consider the opposite extreme of finely-dispersed water droplets (fog), which are efficient scatterers of visible radiation. "Reflection" from a cloud of these particles causes an incident light beam to be attenuated in a very similar way to the soot cloud, according to the scattering opacity τ_s. However, the light is not destroyed (or at least only a small fraction) but only deflected from its original path. For example around a fog-enshrouded lampost we witness this process as a host of twinkling starlike points of light. In the original direction of the light, the effect is the same as absorption, that is, a dimming of the light in proportion to the number of scattering particles along the path. The opacity is calculated in exactly the same way, except that the physical process is not a heating of the particles, as in absorption†. In fact a measurement of the attenuation with an ideal detector of small acceptance angle in the two cases of an absorbing soot cloud and a totally-scattering water fog would be exactly the same. This assumes that they have the same opacity. Furthermore if we were to measure the radiation in directions away from the light source, the scattering fog would be a source of secondary 'emission'. The same measurement for the soot cloud would register zero radiation. This secondary light source is due to scattering of the light into our line of vision, and is the reason why we can "see" the cloud itself – for that matter, it explains why we are able to view the world around us. A major complexity in a quantitative description of the scattered light is the fact that every particle "sees" not only the original light source, but also the light scattered from its neighbors. This gives rise to higher orders of scattering, referred to as *multiple scattering*, and this "diffusion" of the light tends to produce a more uniform spatial distribution of brightness. Multiple scattering is one of the important subjects of this book.

Consider some implications of the scattering and absorption/emission processes on the earth's atmosphere and ocean. First,

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† Actually, the process of scattering *does* alter the velocity of the particles through a momentum exchange with the incident photons, and strictly speaking, this could cause a heating of the gas. However, these radiation pressure effects are negligible for radiation energies of concern in this book.

because of the atmosphere's high transparency in the visible spectrum $(0.4 - 0.7 \mu m)$, the earth's land and ocean surfaces are subjected to mostly direct solar heating on cloud-free days. On cloudy, overcast days the light field consists of diffuse (multiply-scattered) photons. In general, both effects provide the so-called *short-wave radiative forcing* of the climate system. At the same time, the land and ocean radiate infrared radiation to the atmosphere, and to space (depending upon the infrared opacity as a function of wavelength). This gives rise to radiative cooling, i.e. *long-wave radiative forcing.* The combined radiative effects, when averaged over the diurnal cycle, lead to a *net radiative forcing*, which is variable over the earth's surface. Spatial and temporal variations in this forcing give rise to weather and climate, which themselves alter the radiative forcing, in a highly non-linear interactive system (called feedback). Long-term changes in the long-wave forcing, such as carbon dioxide increases, will alter the atmosphere and ocean in ways which we do not yet fully understand.

In conclusion, absorption and scattering give rise to attenuation according to the same basic formula, $\exp(-\tau)$. If both processes are present, and this is always the case in the real world, the net opacity is found to be the *sum* of the absorption and scattering opacities, $\tau = \tau_a + \tau_s$. Absorption tends to destroy the radiation field, and heat the absorbing particles. Because of their finite temperature, the particles also radiate light into all directions, in proportion to their absorptive properties as a function of frequency. Scattering redirects an original beam of light into generally all 4π sterradians. Multiple scattering causes the radiation field to become more uniform (diffuse). These two processes give rise to short-wave and long-wave radiative forcing of climate, as well as many other atmospheric phenomena. In this book, we will deal with the "up-front" radiative processes, essential to understanding climate and climate change.