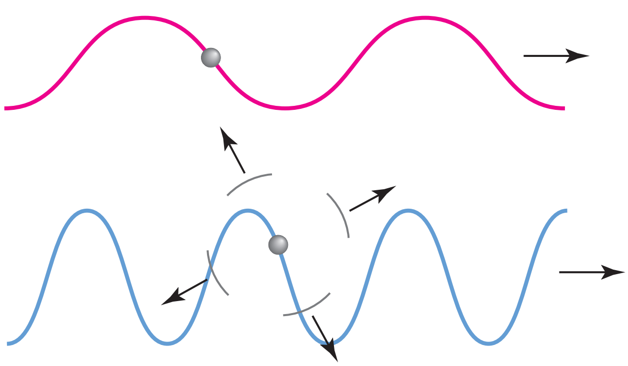
Scattering of Starlight

Starlight, like all other kinds of electromagnetic (EM) radiation, is absorbed and scattered by the gas molecules and dust in the interstellar medium (ISM). These processes depend on the atomic and molecular composition of the ISM. In addition, the second process depends on the size of the dust particles. Absorption occurs as white light from a distant star travels through clouds in the ISM and particular frequencies excite electrons in the atoms and molecules of the gases to various excited states. The excited states quickly re-emit photons of the absorbed frequencies but do so essentially into 4π solid angle rather than just in the direction of the incident starlight. Thus, an observer viewing the star through a cloud in the ISM will see wavelengths corresponding to the absorbed frequencies absent or nearly so from the star's originally continuous spectrum. It is the resulting absorption spectrum that enables astronomers to determine the composition of the gas clouds.

Starlight is also scattered by the molecules and dust, and this process, too, is wavelength dependent. As long-wavelength EM radiation, for example, radio waves, passes through a cloud in the ISM, the electric field of the radiation forces the electrons into vibration even though the photons lack the energy necessary to elevate the electrons to excited states. This action removes some energy from the light, reducing its intensity and increasing the temperature of the cloud as the now more energetic atoms transfer some of their energy to other atoms and molecules via collisions. Shorter-wavelength EM radiation (= higher-frequency, higher-energy photons) causes increased vibrations of the electrons, which act as miniature antennae, radiating the absorbed energy as radiation of similar wavelength into space, once again into essentially 4π solid angle. In fact, the shorter the wavelength of the incident radiation, the more efficient is the process of absorption and re-emission into space (see Figure SS-1). Thus, for the visible EM spectrum, blue light is more effectively scattered than green light, green more effectively than yellow, and so on, with red light scattered the least effectively of all. As a result, starlight reaching Earth has been reddened by passing through the ISM.



SS-1 Electrons in the molecules oscillate slowly in response to the low-frequency, less energetic red light. They oscillate more rapidly and with more energy in response to the electric field of the blue light and act as miniature antennae radiating at the frequency of the blue light.

Dust particles in the clouds in the ISM range in size from about 0.3 nm to about 300 nm. While none have yet been studied directly, many astronomers think that the dust particles are made mostly of carbon or silicates sheathed in a layer of methane, water, or ammonia ice (see Figure SS-2*a*). In 1908 Gustov Mie assumed for simplicity that the dust particles were spheres with an average radius *a* and geometrical cross section $\sigma = \pi a^2$. This permits the definition of a factor Q_λ that describes the amount of intensity reduction or extinction of starlight of wavelength λ as

$$Q_\lambda = \frac{\sigma_\lambda}{\sigma} \qquad \textbf{SS-1}$$

where σ_λ is the cross section for the wavelength λ. Mei also showed that for light whose wavelength is comparable to the dimensions of the dust particles, $Q_\lambda \sim a/\lambda$, which in turn implies that

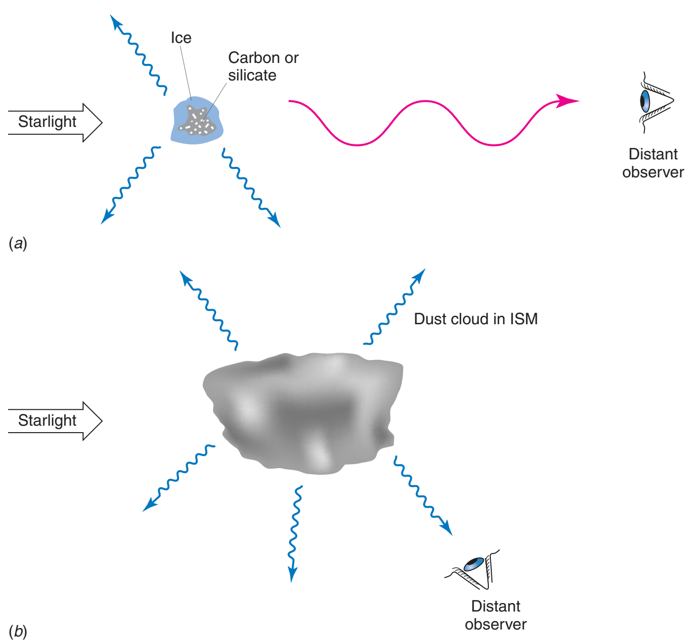
$$\sigma_\lambda \propto \frac{a^3}{\lambda} \qquad \text{for } \lambda \approx a \qquad \textbf{SS-2}$$

Note that if $\lambda \gg a$, then $Q_\lambda \to 0$; that is, very long wavelengths (e.g., radio wavelengths) are unaffected by the dust particles. This is analogous to a small cork floating in the ocean: the passing ocean waves are unaffected by the cork's presence. Mei also showed that for $\lambda \ll a$, $Q_\lambda \to$ constant, which means that

$$\sigma_\lambda \propto a^2 \quad \text{for } \lambda \ll a \qquad \textbf{SS-3}$$

This situation is analogous to ocean waves encountering an island. Those waves that strike the island are stopped and those that miss the island just pass on by; it is the island's dimensions that are important, independent of the length of the waves. As Equation SS-2 indicates, the effect of dust particles in the ISM also leads to reddening of the light from distant stars and galaxies.

So we see that the scattering of starlight by both molecules and dust in the clouds in the ISM leads to *interstellar reddening*, which causes stars to appear more red than their effective temperatures would imply. Fortunately, this problem can be mitigated by careful analysis of the absorption and emission line spectra. Notice that a cloud viewed off the line of the incident starlight appears to have a faint bluish glow from the blue light scattered by the molecules and dust (see Figure SS-2*b*).



SS-2 (*a*) The small dust particles scatter blue light more effectively than light with longer wavelengths. (*b*) Viewed off the line of the incident starlight, observers see the ISM dust clouds with a faint bluish glow.