Light Scattering in Interstellar Clouds

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Introduction

The scattering of light by interstellar media is one of the major mechanisms affecting the radiative transfer of light in the universe. The goal of this paper is to explore the effect of scattering on the transmission of light through interstellar clouds. Scattering is caused by the interaction of photons with the particles (elementary particles, atoms, molecules, or dust) that make up clouds. Each particle has a radius within which it will cause a photon to scatter. Along a photon's path through a cloud, the scattering radius of each particle defines a cross sectional scattering area. If the photon passes within that area, it will be scattered at an angle that depends on the physics of the interaction. For simplicity, in this paper, it is assumed that the scattering interaction results in the photon being redirected in a random direction. Therefore, the scattering process can be modeled as that of absorption followed by isotropic emission of each photon.

The scattering properties of an individual cloud can be modeled in a statistical way by considering the average scattering properties of the particles that make it up. The scattering optical depth of a cloud, τ_{sc}, can be described as a function of the average scattering cross section σ and the spatial density η of each of the cloud's constituent particles. Using these parameters, the probability of scattering per unit length of propagation can be defined using a scattering coefficient:

$$\alpha_{sc} = \eta_1\sigma_1 + \eta_2\sigma_2 + ... = \sum_i \eta_i\sigma_i \tag{1}$$

which leads to a definition of the optical depth of a cloud as light propagates through it:

$$d\tau_{sc} = \alpha_{sc} ds \tag{2}$$

where ds is an infinitesimal path length in the direction of propagation. For light propagating through the cloud toward a distant observer, the change in specific intensity due to scattering with respect to optical depth is:

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + \int_\Omega \frac{I_\nu(\Omega')}{4\pi} d\Omega' \tag{3}$$

Where the first term describes the light in the direction of propagation that is scattered away from the observer, and the second term describes the light traveling in every direction which is scattered toward the observer. Because the integral in equation 3 requires a full description of the direction and position of all light propagating through the cloud at each moment, it does not yield easily to an analytical solution. Instead, in this paper, a take a statistical approach is taken using Monte Carlo techniques[1] to make a computational model the system.

Methods

In this paper, a simplified system is simulated that describes photons originating from a point source star traveling through a purely scattering medium toward an observer (see figure 1). For simplicity, it is assumed that scattering is isotropic and frequency independent, and that the cloud is spherical, with radius R and scattering coefficient α_{sc}.

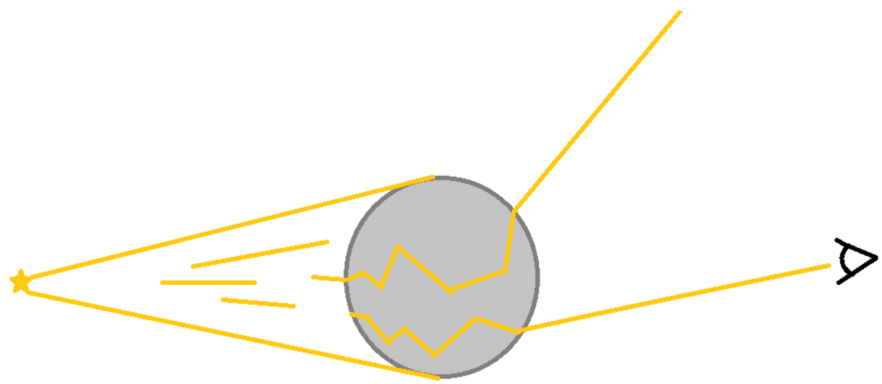


Figure 1. Diagram of modeled system. Light from a point source star propagates through a spherical scattering cloud toward a distant observer.

With these assumptions, propagation of a photon through the cloud can be modeled as a random walk (fig 2): A photon enters the cloud and travels some distance before it is scattered, after which it travels another distance before it is scattered again, and so on until it escapes the cloud in N total steps. The distance L the photon travels before each scattering interaction will vary greatly depending on the local optical depth. For each step, a local optical depth $d\tau$ can be sampled as:

$$d\tau = -log(\xi) \tag{4}$$

where ξ is chosen from a random uniform distribution in the interval (0,1]. The step length L is then defined using $d\tau$, the maximum step length (within cloud) $L_{max} = 2R$, and the maximum optical depth $\tau_{max} = L_{max}\alpha_{sc}$ as follows.

$$L = \frac{d\tau L_{max}}{\tau_{max}} = \frac{-log(\xi)}{\alpha_{sc}} \tag{5}$$

Giving the mean free path length of a photon in the cloud:

$$\overline{L} = \frac{2R}{\tau_{max}} \approx \frac{1}{\alpha_{sc}} \tag{6}$$

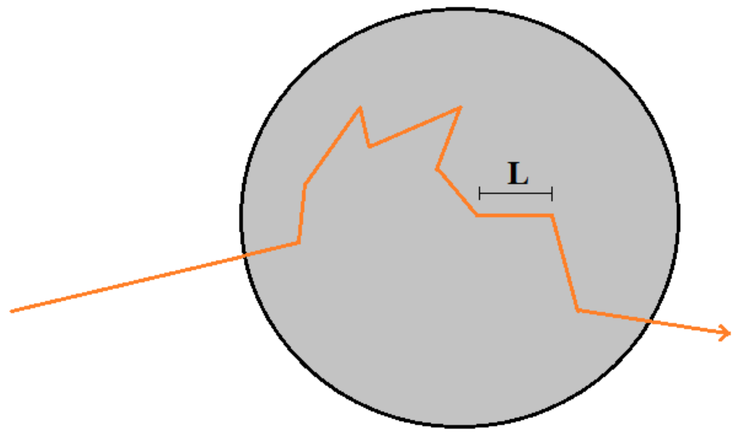


Figure 2. Diagram of the random walk of a photon in a spherical scattering cloud. Each scattering step has a different length, L. The total number of scattering steps N=10 in this diagram.

Under this formulation, it is expected that the average number of steps for a photon to escape the cloud to be:

$$\overline{N} = \frac{2R}{\overline{L}} \approx \tau_{max} \tag{7}$$

After each scattering interaction, a new direction of travel is chosen randomly from uniform distributions: $0 \leq \phi < \pi$ and $0 \leq \theta < 2\pi$ in spherical coordinates. This procedure is followed for each photon from entrance into the cloud until it escapes. Once it has escaped the cloud, a determination is made whether the photon will be seen by the observer.

Results

The simulation described above was run for a system with an isotropic point radiation source entering a spherical cloud at a maximum angle of one degree. A photon leaving the cloud considered to be seen by a distant observer if it passes within half of an arcminute of the observer (fig. 3). The simulation was run for varying values of the cloud optical depth τ_{sc} ranging from 10^{-3} to 10^{2}. One million photons were simulated for each value of τ_{sc}.

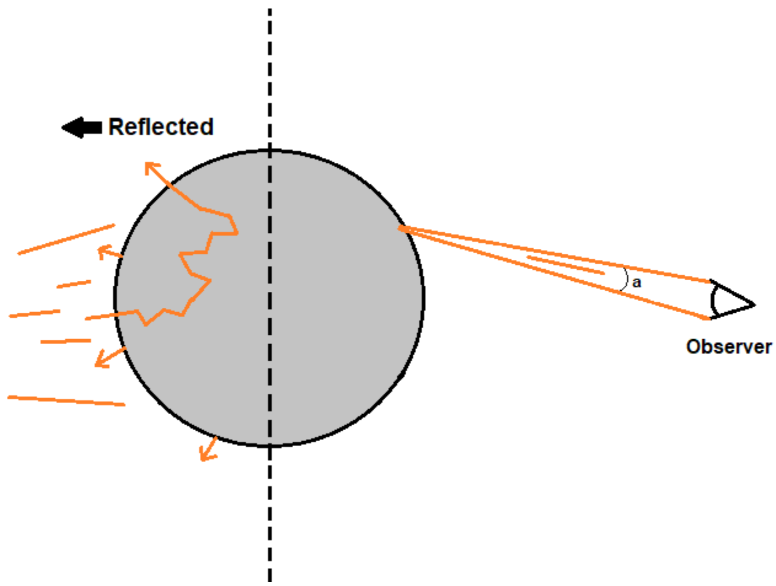


Figure 3. Diagram of incident light from from a star (left) entering spherical scattering cloud. The light that leaves the cloud on the same side as it enters is considered to be "reflected. The light that leaves the cloud within solid angle, a, is considered to be seen by the observer.

In figure 4, the percentage of photons seen by the observer is shown as a function of the optical depth. For clouds with $\tau_{sc} < 0.1$, the percentage of photons entering the cloud that are transmitted to the observer is constant (about 7%). For clouds with high optical depth ($\tau_{sc} > 1$), there is a very sharp decrease in the percent seen. This behavior is further highlighted in figure 5. The mean number of scattering steps that photons take before leaving (fig. 5a) the cloud is constant for $\tau_{sc} < 0.1$, and linear for $\tau_{sc} > 1$. This is expected for the value of $\overline{N}$ from equation 7 above. Figure 5b shows the percentage of photons "reflected", which is defined as leaving the cloud on the same side as they entered. The percentage of reflected photons is linearly proportional to τ_{sc} for optically thin clouds ($\tau_{sc} < 0.1$), and levels off near 98% for optically thick clouds ($\tau_{sc} > 10$).

From this data, some general characteristics of scattering clouds can be outlined with respect to their optical depth. The greater the optical depth, the more scattering interactions are to be expected for a photon traveling through the cloud. This is because the mean free path is inversely proportional to the optical depth (equation 6). With regard to reflection, consider that for the photon to reach the opposite side of the cloud it must make on average more steps to get across to the other side of the cloud. Therefore, $\overline{N}_{same} < \overline{N} < \overline{N}_{opposite}$. There are many more paths that lead a photon to escape on the same side of the cloud as it entered, so a much higher percentage of photons is expected to leave on that side as optical depth increases.

The percentage of photons seen by the observer are at a maximum for optically thin clouds, and at a minimum for optically thick clouds. This is because as the number of scattering interactions increase, photons have a higher likelihood of being deflected away.

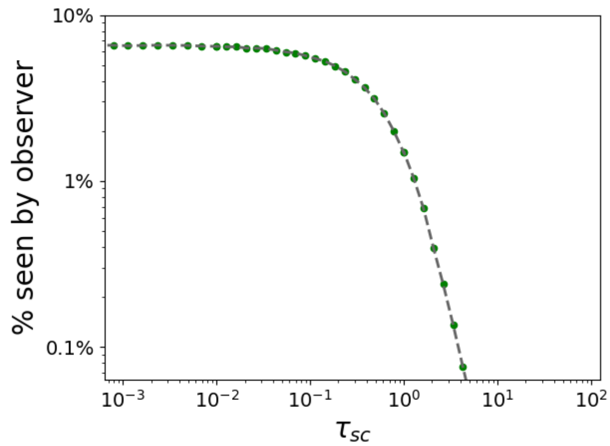
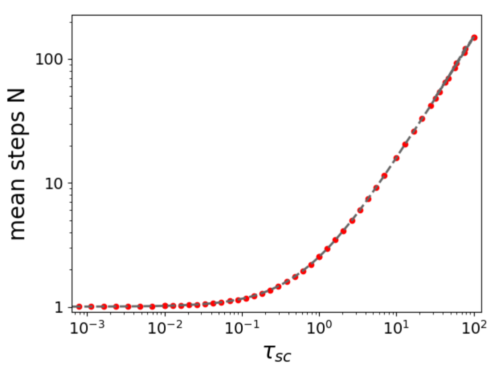
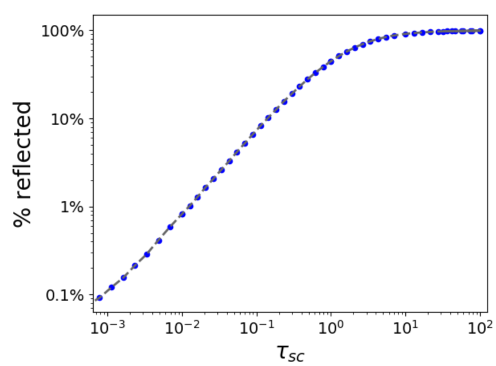


Figure 4. Plot of the percentage of photons seen by the observer with respect to cloud optical depth τ_{sc}. Each data point was the percentage from a population of one million simulated photons.



(a) $\overline{N}$ steps.



(b) Reflected Photons.

Figure 5. (a) Plot of the mean number scattering interactions, $\overline{N}$, of photons traveling through scattering cloud. (b) Plot of the percentage of photons that escape the cloud on the same side as they entered (See fig. 3). For both plots, each data point was the percentage from a population of one million simulated photons.

Conclusion

In this paper, the behavior of a purely scattering cloud over a varying range of optical depths is explored. The Monte Carlo simulation of photons entering a spherical cloud was used to explore the characteristic behaviors of clouds under varying conditions. Our results showed that the percentage of photons entering a cloud that are transmitted to an observer is highly dependent on optical depth. Optically thin clouds ($\tau_{sc} < 0.1$) scatter the least amount of light, and therefore transmit the most. Conversely, optically thick clouds scatter away most of the light ($\tau_{sc} > 1$).

A number of assumptions were made in the simulated model that effect the generality of these findings. Most significant are the assumptions of isotropic and frequency independent scattering. Observations of interstellar scattering prove real scattering to be both anisotropic and highly frequency dependent[2]. Despite these simplifications in our model, our results still support the very broad conclusions discussed about optical depth and light transmission. To further this research, a more complex model would need to be constructed to explore the intricacies of scattering in real interstellar clouds.

References

1. Wood, K., Whitney, B., Bjorkman, J. & Wol, M. Introduction to Monte Carlo Radiation Transfer. 20.

2. Draine, B. T. *Physics of the Interstellar and Intergalactic Medium* (2011).