Scattering of Directional Light

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Abstract

Backlight scattering in a single event explains the nearly uniform full images of all planets and their moons. The uniformity of the full-moon image has been discussed in the literature in terms of multi-event scattering. Similar images of other bodies have not been discussed yet. Multi-event scattering must follow Lambert's Cosine scattering law; however, no object images comply with this law. Single-event scattering is automatically coherent because a single electromagnetic source wave stimulates all the scattering dipoles. Therefore, coherence provides an account for the "Opposition Effect", the enhancement of 180° backscattering, by constructive interference. Opposition enhancement has been considered so far to be a separate effect from image uniformity.

The coherence of single-event scattering may enable separation from noncoherent scattering noise by applying interferometric methods, so that objects like asteroids can be observed with better resolution or at a higher distance. The removal of incoherent noise may also result in a deeper observation within a scattering medium, such as biological tissues.

Keywords

Light, scattering, Lambert, diffuse, coherent, interference

Introduction

Back scattering of directional light was first studied by Lambert, who postulated the Cosine scattering law [1, 2] This law states that the intensity of back scattered light is proportional to the Cosine of the angle θ between a light ray striking the surface and a line perpendicular to that surface, Fig-1. Thus, the back scattering intensity is maximal when the surface is perpendicular to the ray at $\theta = 0$ ° and fades by the Cosine function to zero when the ray grazes the surface at $\theta = 90$ °.

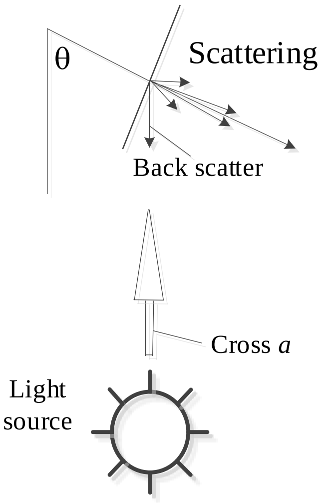

Fig-1: Back scattering. Lambert’s scattering law states that the intensity of back scattered light is proportional to Cosine of the angle of the coming light and the perpendicular to the scattering surface.

In the case of back scattering from a sphere the scattering is maximal at the center of the sphere and decreases to zero according to the Cosine law when moving toward the sphere periphery [3, 4]. This law seems nearly self-evident when looking at the surface through a unit area "*a*" in the direction of the incoming ray. The observed surface area through it is proportional to 1/Cos(θ); therefore, the radiation density on the surface is proportional to Cos(θ). The light scattered backwards is also proportional to Cos(θ) because the scattering maximum is perpendicular to the surface. Fig-2 shows a “rendered”, simulated, image of back scattered light from a sphere according to Lambert’s law [3,4].

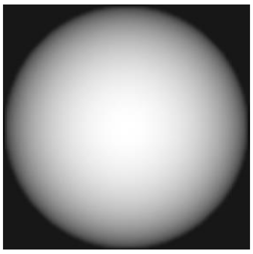

Fig-2: A rendered, simulated, sphere, following Lambert cosine Law [3, 4].

The Full moon image, Fig-3 [5], is best observed during moonrise. The image corresponds to the backscattering of sunlight, and it is somewhat surprising, therefore, that the full moon image is uniform from the image center toward its periphery, except for details of rocks and dry seas. The Moon image does not follow the Lambert’s Cosine law.

Fig-3: Nasa photo of the full moon [5]

Fig-4: Nasa photo of the full-earth [6]

In recent decades, images of the full Earth, Fig-4, have been taken from space, and uniformity has been observed in them [6]. Similar uniformity or near uniformity is observed in the backward configuration of sunlight scattering for images of all planets and their moons, Fig-5 [7].

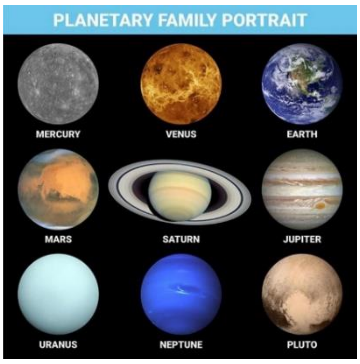

Fig-5: Nasa full images of the planets [7].

No similar images obey Lambert's Cosine law, including terrestrial images. The only images that do obey the law are “rendered”, that is, images that are at least partly simulated.

The "opposition effect", the enhanced light scattering when the light approaches the backward direction, is observed in celestial and terrestrial bodies as well. Fig-6 shows it in Saturn rings [8].

Fig-6: Saturn rings glow during opposition [8].

This effect has been discussed as an independent effect of uniformity, and is attributed to shading and coherent light scattering [9]- [13]. However, the reason for the coherence has not been mentioned by authors.

Results and Discussion

Moon uniformity has been discussed in the literature in terms of surface properties such as roughness, shading, and retro-reflection [14, 15]. There have been no discussions on all other planet images. However, all planet and moon surfaces differ significantly in type, structure, and morphology; never the less, all their images are nearly uniform. Thus, it is unlikely that uniformity is an outcome of some specific surface properties but rather an outcome of a more general and fundamental principle. In particular, the Earth's full image, the "blue marble" [6], contains vast areas of gas phase, clouds, liquid phase, oceans, and solid phase, land, each of which is nearly uniform separately.

On earth, Fig-7 shows a smooth glass cup filled with milk, Fig-8 shows an egg with fine rough surface, and Fig-9 shows a tennis ball with a coarse rough surface. More photos are in [16]. The photos were taken with a flash in a dark room with a dark background. The photos look similar and they do not depend on the roughness level of the surface. Again, there are no images, neither celestial, nor terrestrial, that obey Lambert's cosine law. The only images that do obey the law, Fig-2, are rendered, images that are at least partly simulated.

Fig-7: A glass cup with milk

Fig-8: An egg

Fig-9: A tennis ball

In all the discussions of back scattering, without exception, it is assumed that the scattering process is diffusive, that is, the light passes many scattering events before it returns to an observer. However, in a diffusive process the events are independent and there is no way for the scattering to be coherent. In such a case, the Lambert's Cosine scattering law becomes very strong and the scattering process must obey it, which is never the case.

To gain some insight into these light scattering processes, it may be useful to consider an electromagnetic light wave travelling within matter. The wave stimulates dipole oscillations, and each such a dipole becomes a source of a wave itself which adds to the overall light radiation. If the material is uniform, the radiation waves coming from all the dipoles will interfere with and cancel each other, and there will be no light scattering except in the forward direction where the effect is refraction. Light scattering is the outcome of material non-uniformity; where the interference of light from the dipole sources is not fully destructive [17].

A volume of non-uniform material can be divided into sub-volumes of uniform domains. The domain size determines the scattering properties of a material. In a single micron size, or less, there is wide-angle Rayleigh Scattering that tends to be uniform in space. This scattering is typical of gases, liquids and solutions, and is the source of the sky's blue color. For domain sizes of a few tens of microns, there is narrow-angle Mie Scattering typical of solids. In both cases, the scattering intensity is proportional to the intensity of the stimulating light. The icy rings of Saturn glow in the opposition configuration, while the glow from the gaseous surface of the star is far weaker [8].

A fundamental difference exists between single- and multiple-event scattering. In single event the light is scattered once before it reaches the observer. Since these dipoles are stimulated by the single source wave, they will oscillate coherently in a single plane perpendicular to the source wave direction. The light scattered by each dipole is maximal in the direction perpendicular to this plane [17], that is, back to the light source. Therefore, the light backscattered by all of them is also maximal in the direction back to the light source.

In multiple event scattering, light is scattered many times before it reaches the observer. Therefore, any dipole oscillates in a random plane in space, and there is no correlation or coherence between the radiations of different dipoles. The equivalent radiation is perpendicular to the surface plane of the scattering material. In this case, Lambert's Cosine law of light scattering must be satisfied.

Consider a line between a light source and a point on the surface of a scattering sphere defined by the angle θ. A unit cross section area "a" is perpendicular to this line (Fig-10). The area on the sphere surface observed through the "a" will be a / Cos(θ), thus, it is equal to a at the sphere center, and it increases toward the periphery. Similarly, the light density on the sphere is proportional to a * Cos(θ), and it dwindles to zero at the periphery.

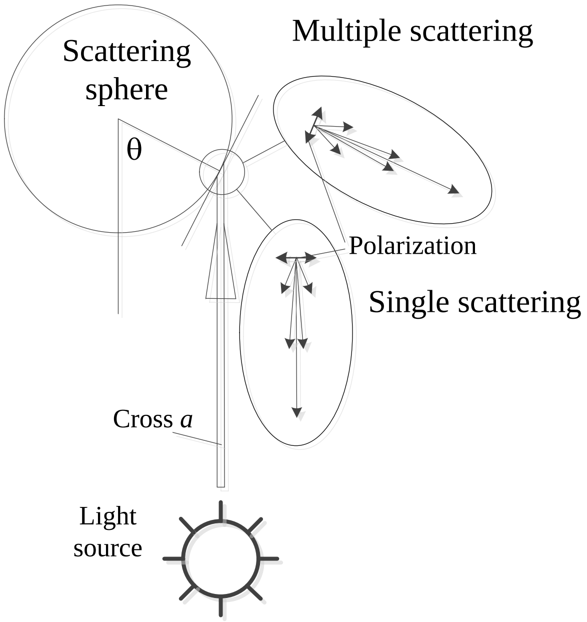

Fig-10: Back scattering in multiple events and a single event. The equivalent scattered light in multiple events is perpendicular to the surface. The maximum scattered light in a single event is directed back to the source.

In a single event, the scattering intensity back to the light source, $I_{\max}^{s}$, is equal to the maximum scattering intensity *a*:

$$I_{\max}^{s} = a * \text{Cos}\,(\theta) * 1 / \text{Cos}(\theta) \qquad (1)$$

Thus, in the backscattering of a single event, the intensity is independent of the surface angle to the source, and a sphere will appear uniform, as for example, the moon.

In multiple-event scattering, the maximal scattering intensity, $I_{\max}^{m}$, is perpendicular to the scattering surface, and its component back to the light source is proportional to Cos(θ):

$$I_{\max}^{m} = a * \text{Cos}(\theta) * \text{Cos}(\theta) * 1 / \text{Cos}(\theta) \qquad (2)$$

Thus, in multiple-event scattering, the intensity follows Lambert's Cosine scattering law, and the maximum intensity at the sphere center dwindles by the Cosine function to zero at its periphery.

In a mixture of single and multiple event scattering there will be a sum of constant, $I_{\max}^{s}$, and variable, $I_{\max}^{m}$,parts.

Why does single-event scattering seem to be dominant? In opaque substances, the mean free path within the material is too short for many scattering events before the light is absorbed. In transparent materials, the probability of light returning to the source decreases with the increasing number of scattering events. A single scattering event appears to have the highest probability.

Summary and conclusions

Backlight scattering by a single event provides an account of nearly uniform full images of all planets and their moons. There are no objects that comply with Lambert's Cosine scattering law. Single-event scattering is automatically coherent because a single electromagnetic source wave stimulates all these scattering dipoles. Thus, coherence provides an account for the "Opposition Effect,” enhancement of 180° back scattering, by constructive light interference. Opposition enhancement has been considered in the literature as a separate effect of the image uniformity.

The coherence of single-event scattering may enable separation from noncoherent scattering noise by applying interferometric methods, such that objects like asteroids can be observed with better resolution or at a higher distance. The removal of incoherent noise may also enable deeper image observation within a scattering medium, such as biological tissues.

Most of the surrounding imagery consists of single-event scattering. Including it in illumination models may improve illumination engineering.

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Elephant

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