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Photometry of dark atmosphereless planetary bodies: an efficient numerical model

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ABSTRACT

We present a scattering model for regolith-covered Solar System bodies. It can be used to compute the intensity of light scattered by a surface consisting of packed, mutually shadowing particles. Our intention is to provide a model in which other researchers can apply in studies of Solar System photometry.

Our model is a Lommel–Seeliger type model, representing a medium composed of individual scatterers with small single-scattering albedo. This means that it is suitable for dark regolith surfaces such as the Moon and many classes of asteroids. Our model adds an additional term which takes into account the mutual shadowing between the scatterers. The scatterers can have an arbitrary phase function. We use a numerical ray-tracing simulation to compute the shadowing contribution.

We present the model in a form which makes implementing it in existing software straightforward and fast. The model in practice is implemented as files containing pre-computed values of the surface reflection coefficient, which can be loaded into a user's program and used to compute the scattering in the desired viewing geometries. As the usage requires only a little simple arithmetic and a table look-up, it is as fast to use as common analytical models.

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1. Introduction

The surfaces of most atmosphereless Solar System bodies are covered by a layer of *regolith*, loose material consisting of packed mineral grains. Examples include the Moon and the asteroids. The properties, such as the particle size distribution and composition, of the regolith vary between different bodies.

Photometry is an important tool to study especially the small bodies; of most asteroids we know very little aside from some number of photometric brightness measurements at different points in time. Still, photometric time series (lightcurves) can provide information on the shape and rotational state of the asteroid, as well as their size, when combined with other methods. For reviews on the applications of asteroid disk-integrated photometry, see Kaasalainen et al. (2002) and a chapter in the upcoming Asteroids IV book.

The scattering of light by regolith surfaces has been studied for a long time. The best known phenomena in the field include the brightness of the lunar disk and its variations with lunar phase (e.g. Hapke and van Horn, 1963; Lumme and Irvine, 1982). It has long been known that at low phase angles (close to full moon), the brightness of the surface grows significantly higher. The same is also true for asteroids (Muinonen et al., 2002). A truly rigorous study of the scattering by a large particulate surface with irregular grains and a wide size distribution is still beyond our computational capabilities. Various approximations must be employed in every model. An up-to-date review on the subject is expected in the upcoming *Asteroids IV* book.

In this paper, we present a numerical implementation of a model for scattering by a regolith surface, which takes into account the mutual interactions between the particles in a loosely packed regolith. Our aim is to provide a tool for other researchers, which can be easily implemented and used.

In Section 2, we cover the theoretical background of our scattering model. In Section 3, we describe the numerical methods used to compute the model values. In Section 4, we describe the resulting scattering models. In Section 6, we present our conclusions, with an application example in Section 5.

2. Theory

The scattering of a surface element is generally a function of the directions of the incident and emergent light, the *viewing geometry*. We assume the surface is isotropic and only the relative directions matter. In our usage the viewing geometry is given as

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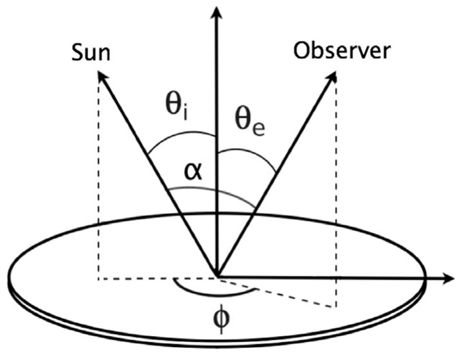

Fig. 1. The definition of the viewing geometry of a surface. θ_i is the angle between the incident light and the surface normal, θ_e between the observer's direction and the normal.

four angles, shown in Fig. 1. θ_i is the *angle of incidence* and θ_e the *angle of emergence*. α is the *solar phase angle* and ϕ is the *azimuth angle*.

Only three of the four angles are needed to fully describe the geometry. Parts of the model are easier to describe in terms of ϕ and other parts in terms of α, so these two angles are both used. The cosines of θ_i and θ_e are used often and called μ_0 and μ.

In general, the relationship between the observed intensity of the light scattered by the surface for incident flux density πF_0 can be written

$$I(\mu_0, \mu, \phi) = \mu_0 R(\mu_0, \mu, \phi) F_0, \tag{1}$$

where R is the *bidirectional reflection coefficient*, which depends on the properties of the surface. R can be separated into two parts, the *phase function* and the *disk function*, where the first depends only on the phase angle and the second is a function of the full viewing geometry. This is due to the background in lunar photometry, where the phase function is a constant at any given time and depends on the lunar phase, while the disk function is a function on the location on the visible lunar disk.

There are many possible choices for R. For many applications, Lommel–Seeliger scattering is chosen. The Lommel–Seeliger model is a single-scattering solution of radiative transfer for semi-infinite planar medium. It is valid for materials with low single-scattering albedo, where the effects of multiple scattering are negligible. In Lommel–Seeliger scattering, $R \propto 1/(\mu_0 + \mu)$.

We model the scattering by a thick layer of spherical particles. We use the concept of a *volume element*, which is a small part of the surface which can be thought of as the single scatterer in a Lommel–Seeliger type scattering model. Our model has the form

$$R(\mu_0, \mu, \phi) = \frac{\hat{\omega}_V}{4} P_V(\alpha) S(\mu_0, \mu, \phi) \frac{1}{\mu + \mu_0}, \tag{2}$$

where $\hat{\omega}_V$ and P_V are the volume-element albedo and phase function, respectively, α is the phase angle, and S is the *shadowing correction*, which takes into account the interaction between volume elements.

The shadowing correction is not a "shadowing function" in the usual ray-tracing sense, meaning the fraction of illuminated surface points. Instead it is defined as the ratio between a particulate surface and a homogeneous Lommel–Seeliger surface. In the Lommel–Seeliger model, rays are attenuated exponentially everywhere inside the surface material. In a particulate surface rays whose returning path is similar to their incident path will be attenuated less. Because of this the shadowing correction is generally greater than 1. In the limit of a very loosely packed material, this S function depends only on the roughness of the surface. We compute the values of the shadowing correction numerically. See Section 3.1 for details.

3. Numerical methods

3.1. Deriving the shadowing correction through ray-tracing

We compute the shadowing correction S from Eq. (2) numerically for surfaces with different porosity and roughness properties (see Section 3.2) and discretize it over the hemisphere of all illumination geometries (see Section 3.3).

We use a surface composed of spheres with Lommel–Seeliger scattering surfaces as a tool to compute S. We use a ray-tracing simulation to compute the intensity scattered by such a surface, $\hat{I}_{RT}$. An isotropic phase function ($P(\alpha) = 1$) is used in the simulation. We ignore the effects of multiple scattering, only using the first scattering order. Since multiple scattering will only reduce the effects of shadowing, this means that our shadowing correction is in general larger than for a surface with significant multiple scattering.

In the limit of a very sparse medium, the ray-tracing is equivalent to a semi-infinite Lommel–Seeliger scattering surface with the disk-integrated brightness of a Lommel–Seeliger sphere as the single-scattering phase function. The shadowing correction S is defined as the ratio between the ray-tracing result and such a Lommel–Seeliger surface.

The surface brightness $\hat{I}_{RT}$ is computed with a so-called backwards ray-tracing algorithm; we trace a ray first from the "camera" towards the surface, find the first intersection point with a particle of the medium, and then trace a ray from the surface point to the light source. At the intersection point, the viewing geometry is computed relative to the local surface normal, and the brightness of the scattered ray is computed using the Lommel–Seeliger scattering model.

The ray-tracing is averaged over four realizations of the random macroscale surface roughness (see Section 3.2). In total, 80 000 rays are traced for each discrete viewing geometry.

For the theoretical Lommel–Seeliger surface, the brightness is

$$I_{LS} = \frac{\hat{\omega}_V}{4} P_{LS}(\alpha) \frac{\mu_0}{\mu_0 + \mu}, \tag{3}$$

where because our volume element is a Lommel–Seeliger scattering sphere, our volume-element albedo is the Bond albedo of such a sphere, $\hat{\omega}_V = \frac{2}{3}(1 - \ln 2)\omega_0$, where ω_0 is the single-scattering albedo used in the simulation. P_{LS} is the disk-integrated brightness of a Lommel–Seeliger scattering sphere, as a function of the phase angle,

$$P_{LS}(\alpha) = \frac{3}{4}(1 - \ln 2)^{-1}\left(1 - \sin\frac{\alpha}{2}\tan\frac{\alpha}{2}\ln\left(\cot\frac{\alpha}{4}\right)\right), \tag{4}$$

normalized so that

$$\int_{4\pi} \frac{P_{LS}}{4\pi} \, d\Omega = 1. \tag{5}$$

The shadowing correction S can now be computed as the ratio between the ray-tracing result and the theoretical value,

$$S = \frac{\hat{I}_{RT}}{I_{LS}} = \frac{1}{4} \frac{\mu_0 + \mu}{\mu_0} \frac{\hat{I}_{RT}}{\hat{\omega}_V P_{LS}(\alpha)}. \tag{6}$$

The S computed this way is approximately independent of the scattering model chosen for the individual spheres (in our case Lommel–Seeliger). This approximation of S becomes worse as the packing density of the surface increases.

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