EPSC Abstracts
Vol. 12, EPSC2018-762, 2018
European Planetary Science Congress 2018

Wavelength-dependent multiple scattering modeling for planetary regoliths

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Abstract

We present a computational approach for modeling light scattering and absorption in planetary regoliths composed of densely packed particles. The approach is based on the rigorous electromagnetic theory hence it allows for a quantitative analysis of photometric and polarimetric observations of airless planetary bodies. We will model and compare the photometric and polarimetric phase functions of typical asteroids and the surface of comet 67P/Churyumov-Gerasimenko.

1. Introduction

Interpretation of remote light scattering observations of small bodies in the Solar System relies on numerical modeling. Surfaces of small bodies such as asteroids and comets are covered by small dust particles, that is, planetary regolith. Solving light scattering characteristics of such surfaces is not an easy task. First, particle sizes are of the order of the wavelength of incident light, meaning that one has to consider the wave nature of light described by Maxwell's equations. Second, the particles are not spherical, and third, the entire body is large compared to the wavelength which renders the exact electromagnetic solvers inapplicable.

Large numbers of different approximate models exist that are loosely based on the radiative transfer equation, e.g., the Hapke model. The model parameters, however, are not directly linked to the physical properties of the target [1]. Further, the standard radiative transfer approach does not work for media composed of densely packed particles. For the quantitative interpretation of light scattering observations of planetary regoliths, rigorous and efficient numerical methods are needed.

Recently, we have developed a numerical method based on the rigorous multiple scattering theory, called as radiative transfer with reciprocal transactions (R^2T^2) [2, 3], which allows us to close the gap between the exact solutions for microscopic particles and the approximate solutions for macroscopic objects. Thus, we can build a chain of numerical solvers that provide a realistic model for light scattering and absorption in planetary regoliths. In this work, we demonstrate that these methods can be used to interpret spectropolarimetric and photometric observations of planetary regoliths.

2. Numerical methods

Modeling electromagnetic scattering by planetary regoliths is a multiscale scattering problem involving microscopic and macroscopic details. Thus, not a single numerical method can solve such a problem alone, but we need to combine different methods in a hierarchical manner. Figure 1 illustrates different numerical solvers and the particle size range in which each method is applicable at visible wavelengths.

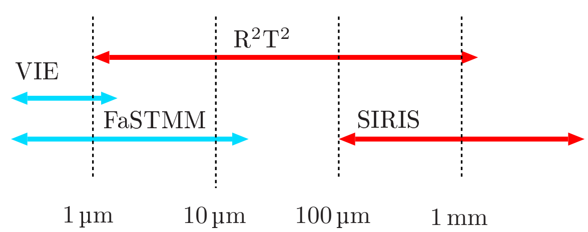

Figure 1: The range of applicability for different numerical methods is shown. The blue lines denote the exact numerical methods and the red lines denote the approximate methods. In order to solve scattering by planetary regoliths, the methods are used in a hierarchical manner.

2.1 Exact methods

Exact numerical methods such as the volume integral equation (VIE) method and the fast superposition T-matrix method (FaSTMM) solve Maxwell's equations exactly without any physical approximation [4]. The drawback is that they are computationally expensive, and in practice, they cannot be applied for large objects. Here we use the exact method to compute input data to the R^2T^2 method.

2.2 Approximate methods

The R^2T^2 method is based on the order-of-scattering (OOS) representation of the electric field. We formulate the OOS solution for the clusters of particles (volume elements) rather than the single particles allowing us to find the solution for a scattering problem involving densely packed particle systems. To solve the OOS equation, we apply a Monte Carlo algorithm in which each scattering sequence is computed exactly with the FaSTMM. Thus, we can treat large media consisting of arbitrarily shaped and inhomogeneous particles. The method, however, cannot treat macroscopic surface roughness, hence as a final step, we use the output of the R^2T^2 as input for the SIRIS solver [5]. The SIRIS solver is a Monte Carlo radiative transfer solver coupled with geometric optics that can take macroscopic surface roughness into account.

3. Numerical example

We consider scattering by 1-cm sized porous particle (porosity = 0.75) consisting of iron-rich silicate grains ($m = 1.7 + \mathrm{i}0.03$) of size 0.4 ± 0.1 microns at $\lambda = 649$nm. Such material compositition is typical for S-type asteroids. Figure 2 shows the Mueller matrix element S11 normalized to the geometric albedo and the degree of linear polarization -S_{12}/S_{11} for two different types of small grains, irregular and spherical.

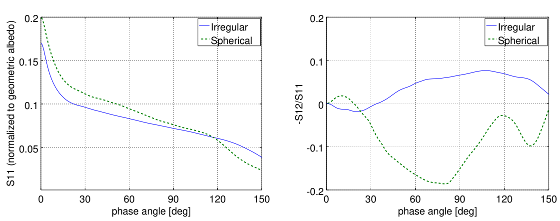

Figure 2: Computed intensity and the degree of linear polarization for the 1-cm sized iron-rich silicate particle consisting of densely packed irregular or spherical grains.

The polarization phase curve demonstrates the importance of using non-spherical particles as constituent grains of the medium. Resonances associated with the spherical shapes are clearly visible. With irregular grains the resonances vanish and the polarization curve is more consistent with observations, i.e., showing a bell-shaped polarization curve with a negative branch at low phase angles and the maximum positive polarization near 90 degrees.

4. Conclusions

We have presented a novel numerical method for modeling light scattering and absoption in planetary regoliths. The method allows for a quantitative interpretation of photometric and polarimetric observations of airless planetary bodies such as asteroids, moons, and comets.

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