Light scattering by porous volcanic ash particles

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Single-scattering properties of volcanic ash particles are evaluated theoretically using a novel shape model for porous particles with cratery surfaces. Preliminary discrete-dipole approximation computations reveal that light scattering by the model particles produces large-scale features comparable to the measured properties of real volcanic ash particles. The effect of internal porosity is also investigated, and it turns out that internal porosity generally promotes positive polarization and decreases the depolarization ratio.

INTRODUCTION

After a volcanic eruption, the smallest ash particles can remain in the atmosphere for days to months [1], affecting the radiation balance on Earth. Airborne volcanic ash particles also pose a major threat to aviation and would therefore be essential to distinguish and identify by remote sensing and radar techniques.

Quantitative assessment of the radiative impact of volcanic ash clouds requires accurate knowledge of the optical behavior of single ash particles, in size comparable to or larger than the wavelength. Inspired by SEM images (Scanning Electron Microscope) and the light-scattering measurements of such particles [2], we have developed a sophisticated shape model for porous particles with vesicular surfaces. Using this model and the discrete-dipole approximation (DDA) [3], we are able to compute the single-scattering properties of small volcanic ash particles and study the effects of porosity on their scattering. Because the sizes of the measured volcanic ash particles range from submicron to a few millimeters [2], DDA cannot cover the entire range of size parameters at visible wavelengths. Nevertheless, the measurements act as a valuable qualitative reference to which we can compare whether our shape model seems plausible for volcanic ash in terms of scattering.

VOLCANIC ASH PARTICLES

SEM images of volcanic ash (an example in Fig. 1a) present a variety of irregular shapes which can be roughly categorized as vesicular (hereafter porous ash particles) or non-vesicular, depending on their composition and the way they were formed [4]. Vesicles are empty cavities formed by gas bubbles that escape when the volcanic melt is cooled to glass. In this work we focus on the modeling of porous ash particles.

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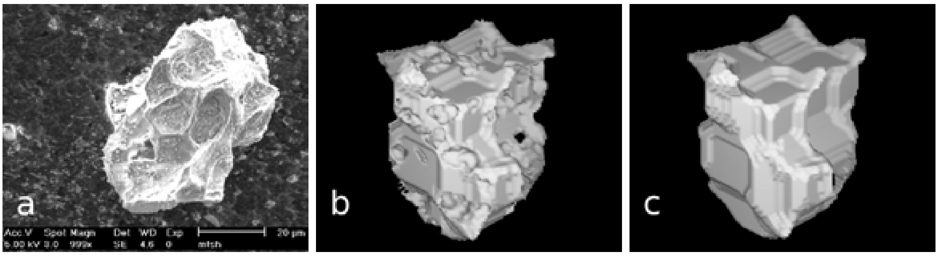

Figure 1. a) SEM image of a volcanic dust particle. b) Porous model shape. c) Compact shape.

Shape model

A shape model for porous volcanic ash particles (Fig. 1b) is constructed using the following five steps illustrated in Fig. 2: a) creating a cluster of spheres, b) calculating the concave hull for the cluster, c) replacing the spheres with Gaussian random spheres, d) finding the volume constrained between the Gaussian particles and the concave hull, and finally, e) peeling extra dipoles away from the surface.

The first phase utilizes a generic ballistic clustering algorithm. The radii of the spheres r follow a power-law distribution

$$n(r) = \frac{2r_1 r_2}{r_2^2 - r_1^2} r^{-3}, \tag{1}$$

where r_1 and r_2 are the minimum and maximum radii, respectively. Our sample shape in Fig. 1b is made using 200 spheres and $r_2 = 2r_1$. In the second phase, a generating sphere of radius r_g is rolled around the particle: the inner surface formed by the sphere defines the concave hull, as explained in more detail by [5]. Here we have set $r_g = r_2$. After this, the spheres of the ballistic cluster are replaced with Gaussian random spheres, which are statistically deformed spheres fully defined by two parameters: the standard deviation of radial distance σ and the power-law index ν [6], in these studies set to $\sigma = 0.2$ and $\nu = 4.0$. The porous particle itself is then composed of the volume in between the Gaussian random spheres and the concave hull. A compact version of the particle can be created by filling the cavities occupied by air. Finally, unnatural overhangs are reduced by flaying and smoothing the particle several times. In the case of porous particles, this procedure also exposes the internal structure and results in random-sized and shaped craters on the surface, as depicted in Fig. 1b. Next to it, Fig. 1c shows the compact version of the shape. The packing density of the porous shape is 0.77 when compared to the compact particle.

PRELIMINARY RESULTS

Light scattering by small volcanic ash particles is computed using DDA. While assessing the impact of porosity on scattering, the dimensions of the particle are kept constant. For the compact shape, the equal-volume-sphere size parameters are in these preliminary studies set to $x_\mathrm{eq} = 4$ and 8. Since the measured refractive indices of different volcanic ash samples

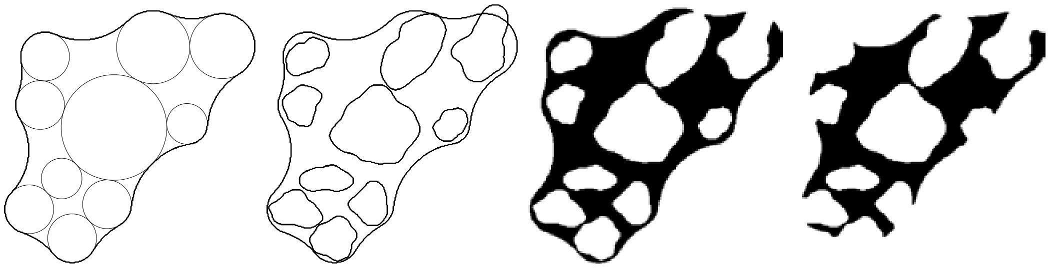

Figure 2. A two-dimensional sketch on the shape model for porous volcanic ash particles. The phases are explained in the text.

vary, as reviewed in [2], we use $m = 1.6 + 0.001\mathrm{i}$ that has real and imaginary parts somewhat higher than plain silicates to roughly account for possible absorbing constituents in the samples. The DDA computations are averaged over 242 orientations to mimic randomly oriented particles.

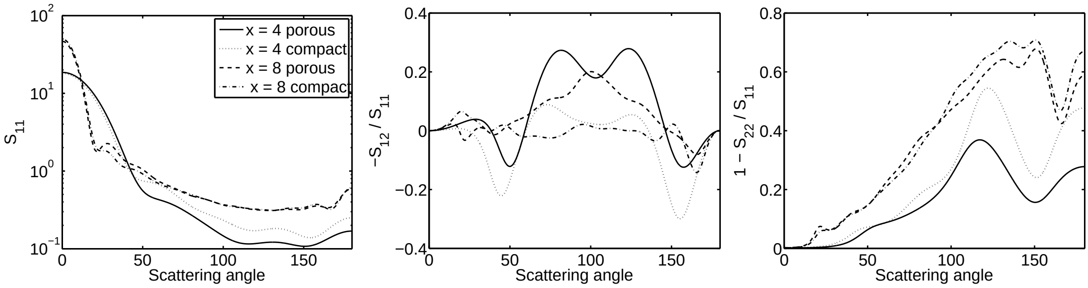

Figure 3. Light scattering results for porous and compact particles with $x = 4$ and 8. The porous shape acts as a model for small volcanic ash particles.

The first results presented in Fig. 3 show that porosity does affect light scattering, for example by promoting positive degree of linear polarization on intermediate scattering angles and decreasing depolarization ratio from 100 degrees scattering angle to backscattering. The effects of porosity on scattering are dependent on whether the outer dimensions or the volume of the particle are kept constant during the study. This makes it challenging to unambiguously distinguish the origin of the discrepancies in scattering. We will look into this by analysing the size dependency of scattering for both particle types and by comparing the size-integrated results. Also, particles with another type of porosity will be taken into account by simulating a shape with fewer but larger holes in the material.

Considering the modeling of the measured optical properties of volcanic ash presented in [2], the results of the porous particles are qualitatively encouraging: the large-scale characteristics of the measurements, including featureless sidescattering in intensity and generally positive polarization, are seen especially in the case of the larger porous particles. Although the results presented here for intensity, degree of linear polarization, and depolarization ratio show smaller-scale variations that are not seen in the measurements, it is expected that these deviations will disappear when calculating the scattering properties of an ensemble of model particles. Next, the study will be continued further by averaging the scattering results obtained for several sizes and different sample shapes.

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