Journal of Quantitative Spectroscopy & Radiative Transfer 131 (2013) 175–187

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Light scattering by feldspar particles: Comparison of model agglomerate debris particles with laboratory samples

Evgenij Zubko [a,b,*], Karri Muinonen [a,c], Olga Muñoz [d], Timo Nousiainen [e], Yuriy Shkuratov [b], Wenbo Sun [f], Gorden Videen [g,h]

[a] Department of Physics, P.O. Box 64, FI-00014, University of Helsinki, Finland
[b] Astronomical Institute of V.N. Karazin Kharkov National University, 35 Sumskaya St., Kharkov 61022, Ukraine
[c] Finnish Geodetic Institute, P.O. Box 15, FI-02431 Masala, Finland
[d] Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain
[e] Department of Physics, P.O. Box 48, FI-00014, University of Helsinki, Finland
[f] Science Systems and Applications, Inc., Hampton, VA 23666, USA
[g] Army Research Laboratory AMSRL-CI-EM, 2800 Powder Mill Road, Adelphi, MD 20783, USA
[h] Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA

A R T I C L E I N F O

Article history:
Received 19 December 2012
Received in revised form
17 January 2013
Accepted 20 January 2013
Available online 31 January 2013

Keywords:
Light scattering
Irregular particles
Agglomerated debris
Dust
Feldspar

A B S T R A C T

We present comparisons of the non-zero light-scattering Mueller-matrix elements of agglomerated debris particles with those of well-characterized experimentally measured feldspar samples at blue and red wavelengths. The only completely free parameter in our comparisons is the small-size cut-off of the sample, which was not known. The significance is that both the light scattering and the measured properties of model and real particles agree very well. While some tweaking of the particle parameters could achieve some improvement, the fits are remarkably good, with significant deviations ($\sim$5%) occurring in portions of the polarization elements, e.g. S_{34}. We suggest that the reason for the good fits is not that the model particles exactly represent those of the sample particles, but rather that both sets of particles belong to a class of highly irregular particles, whose high degree of irregularity dominates the resulting scattering behavior, suppressing the effect of any characteristic morphological features.

1. Introduction

Modeling of light scattering by single dust particles is a challenging problem that is required for various atmospheric and cosmic remote-sensing applications. A principal difficulty that accompanies such modeling is non-uniqueness of the light-scattering properties of different particle groups. Indeed, it often turns out that the measured light-scattering response can be equally well modeled with a few, dramatically different scattering systems [e.g., 1,2]. Moreover, it is quite possible that the resulting model particles bear little resemblance to those of the measured sample. For instance, as was shown in [3,4], a mixture of highly prolate (aspect ratio $\varepsilon > 1.44$) and oblate ($\varepsilon < 0.7$) spheroids can provide a reasonably good fit to laboratory measurements of light scattering by various mineral dust particles [5]. However, as one can see from the scanning-electron-microscope (SEM) images of the samples presented in [5], the micron-sized dust particles are irregularly shaped and nearly equidimensional in appearance, bearing little morphological resemblance with the spheroids used in the simulation [1,3].

It is reasonable to suggest that the hazard of non-unique modeling results can be substantially reduced

* Corresponding author at: Department of Physics, P.O. Box 64, FI-00014, University of Helsinki, Finland. Tel.: +358 50 415 5476.
E-mail addresses: evgenij.zubko@helsinki.fi, ezubko@rambler.ru (E. Zubko).

0022-4073/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jqsrt.2013.01.017

through increasing the number of light-scattering characteristics being considered simultaneously. Indeed, as was found in [3], a mixture of spheroids can reproduce reasonably well the angular profiles of intensity I and degree of linear polarization P measured in a feldspar sample separately at wavelength $\lambda=0.442\ \mu m$ and $0.633\ \mu m$; whereas, simultaneous modeling at different wavelengths fails to reproduce the experimental data. In other words, the best fits obtained at different wavelengths correspond to spheroids with considerably different distributions over aspect ratio and size distribution. It is interesting to note that similar inconsistency appears in modeling of multi-wavelength photo-polarimetry of Comet C/1995 O1 (Hale–Bopp) with the so-called *Ballistic Cluster–Cluster Aggregates* (BCCAs) and *Ballistic Particle–Cluster Aggregates* (BPCAs) [e.g., 6]. Merikallio et al. also noticed this inconsistency for mineral dust samples when modeling using spheroids [4]. In addition, Leinonen et al. compared aggregate particles and spheroidal particles with snowflake measurements made at microwave frequencies. They compared the results against measurements at three frequencies and noted that the spheroid model could not reproduce both dual-frequency ratios simultaneously; whereas, the aggregates could be made to fit the measurements [7].

This inconsistency that may appear in modeling of multi-wavelength measurements of light scattering from dust particles should be interpreted in a positive way, as it provides a means of obtaining additional morphological information about the particles under consideration. In this manuscript we present an alternative modeling of multi-wavelength light scattering by feldspar particles that were measured in [5]. We use the so-called *agglomerated debris particles* (see, e.g., [8]), which are irregularly shaped and equi-dimensional. The use of such model particles made it possible to resolve some modeling challenges in cometary physics (e.g., [9–11]). We stress that we do not consider such agglomerated debris particles as a perfect model for feldspar particles. We rather consider both such particles to be in a class we designate as highly irregular particles, whose light scattering does not change significantly even though their specific morphological properties are different. In our simulations, we have modeled many highly irregular particles having, in some cases, vastly different morphological characteristics. One observation in these studies is that the light-scattering properties of these different types of particles may not change drastically between these particle types [12]. This observation is not limited to modeling studies. One striking feature of the Amsterdam–Granada Light-Scattering Database is not actually how rich and varied the light-scattering data appear between the different samples, but rather how *similar* the light-scattering characteristics are between samples having different morphological properties [3,21]. We consider especially in this paper the measured feldspar particles [3] that have received previous modeling attention.

This paper is organized as follows. In the next section, we give a short introduction into physical properties of the feldspar sample and its light-scattering response in blue ($\lambda=0.442\ \mu m$) and red ($\lambda=0.633\ \mu m$) light, which were obtained in [5]. We also discuss some previous attempts to model these measurements. In Section 3, we describe the morphology of agglomerated debris particles and circumstances of computation of light scattering by these particles; whereas, in Section 4, modeling results are presented and discussed. Finally, in Section 5, we summarize the principal findings of these modeling efforts.

2. Laboratory measurement of light scattering by feldspar particles and its modeling

Feldspar is a prevalent constituent of the terrestrial desert dust and, as consequence, can be abundant in the Earth atmosphere [13]. However, feldspar also occurs on other bodies in the Solar system. For instance, feldspar is a dominant mineral on the lunar highlands [14]; it is also detected on planet Mercury [15] and asteroid (21) Lutetia [16]. The sample of feldspar measured in [5] was collected in Finland and, later, processed to fine-grained powder. The main constituents of this sample are detected as follows: K-feldspar, plagioclase, and quartz. The complex refractive index m is estimated to be in the range $\mathrm{Re}(m)=1.5$–1.6 and $\mathrm{Im}(m)=0.001$–0.00001. When deposited on a surface, the feldspar sample is described to be *light pink to white* in appearance. The reflectance of the deposited feldspar sample accurately measured near backscattering at scattering angle $\theta=178^\circ$ was found to be about 88% in red light and 67% in blue light as compared to a Halon photometric standard [17]. Such high albedo implies that the upper limit in the assumed range of imaginary part of refractive index $\mathrm{Im}(m)$ is significantly overestimated; whereas, at least, in the red band, $\mathrm{Im}(m)$ should be less than 0.001. Indeed, as was found in [18], the reflectance of random discrete media to be about 90% implies that the single-scattering albedo ω of the constituent particles should be approximately 99.9%. Note that the single-scattering albedo ω is defined as follows $\omega=C_{sca}/C_{ext}$, where C_{sca} and C_{ext} are the scattering cross section and the extinction cross section, respectively (see, e.g., [19]). However, even $\mathrm{Im}(m)=0.0005$, that is half the lower upper limit in [5], produces insufficiently high albedo $\omega=98.5$–99.8% [20].

In Fig. 1, we reproduce one of the SEM images (top) and size distribution (bottom) of the feldspar sample; these data are adapted from the publically available Amsterdam–Granada Light-Scattering Database [e.g., 21]. The solid bar shown in the SEM image corresponds to a size of $10\ \mu m$. As one can see, the micron-sized grains reveal highly irregular morphologies. The vast majority of such grains are not highly elongated in appearance but look more equi-dimensional.

The projected-surface-area distribution of the feldspar sample was measured using a *Fritsch particle sizer* [5,22] based on diffraction. In Fig. 1, bottom panel, we show the corresponding normalized number size distribution as a function of the equivalent-sphere radius retrieved. The diffraction technique utilizes measurements of the forward-scattering peak covering a range of scattering angles from a fraction of a degree to more than 60° [23]. Once measured, Fraunhofer theory is used to retrieve the