DOI: 10.1478/C1V89S1P028

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 89, Suppl. No. 1, C1V89S1P028 (2011)

A STUDY OF LIGHT SCATTERING BY WAVELENGTH-SIZED PARTICLES COVERED BY MUCH SMALLER GRAINS USING THE SUPERPOSITION T-MATRIX METHOD

JANNA M. DLUGACH,[a*] MICHAEL I. MISHCHENKO,[b]
DANIEL W. MACKOWSKI,[c] AND IGOR A. ZINCHENKO [a]

ABSTRACT. By using the results of a direct, numerically exact solution of the Maxwell equations we analyze the behavior of the light scattering characteristics for polydisperse spherical particles covered with a large number of smaller grains. We show that the effect of the presence of microscopic dust on the surfaces of wavelength-sized particles depends on the particle absorption and the relative size of irregularities. In our computations, a new parallel superposition T-matrix code developed for use on parallel computer clusters is applied.

1. Introduction

It is well known that many natural and artificial particles exhibit both overall nonsphericity of shape and small-scale surface irregularities. The latter can manifest themselves in the form of microscopic grains dusting the surfaces of the larger host particles [1, 2]. The effects of overall nonsphericity of wavelength-sized particles on the optical cross sections and the elements of the Stokes scattering matrix have been studied extensively and have been demonstrated to be quite significant (e.g., [3] and references therein). At the same time, the effects of microscopic surface irregularities are much less investigated. By using the geometric optics technique there have been attempts to analyze the effects of surface imperfections on light-scattering characteristics of particles with sizes substantially greater than the incident wavelength [4, 5]. In our work [6], the numerically exact superposition T-matrix method was used to compute the scattering cross sections and the Stokes scattering matrix for polydisperse weakly absorbing spherical particles covered with a large number of much smaller weakly absorbing grains. We have shown the optical effect of the presence of microscopic dust on the surfaces of wavelength-sized, weakly absorbing particles to be much less significant than that of a major overall asphericity of the particle shape. In this work, we study the effect of particle absorption and size parameter scale of irregularities on light scattering properties of such particles. Furthermore, on the basis of numerous computations, our objective is to test a new parallel Fortran-90 code developed for use on parallel computer clusters, described in [7] and publicly available on-line [8].

2. Methodology and computational results

In order to analyze the possible optical effects of the presence of microscopic grains covering the surface of the wavelength-sized particles, similarly to [6] we adopt a scattering model in the form of a sphere with the size parameter X_1 dusted by $N_g = 49$ much smaller grains with the size parameter X_2. Employing a random-number generator, we generate such scattering target composed of *N* particles $(N = 1 + N_g)$ where the small non-overlapping grains are placed on the surface of the larger host particle. The angular distribution and polarization state of the light scattered by a particle group in random orientation in the far-field zone is fully described by the so-called normalized Stokes scattering matrix

$$F(\theta) = \begin{pmatrix} a_1(\theta) & b_1(\theta) & 0 & 0 \\ b_1(\theta) & a_2(\theta) & 0 & 0 \\ 0 & 0 & a_3(\theta) & b_2(\theta) \\ 0 & 0 & -b_2(\theta) & a_4(\theta) \end{pmatrix}, \quad (1)$$

where θ is the scattering angle, and the Stokes parameters are defined with respect to the scattering plane. The zeros denote scattering matrix elements negligibly small (in the absolute sense) relative to the other elements at the same scattering angle. The (1,1) element $a_1(\theta)$ is the phase function normalized according to

$$\frac{1}{2}\int_0^\pi \sin\theta a_1(\theta) d\theta = 1 \quad (2)$$

To compute the light scattering characteristics expressed in terms of the elements of the scattering matrix, we use the efficient superposition *T*-matrix method developed for multi-sphere groups [7, 8, 9]. To eliminate oscillations typical for monodisperse particles, the scattering characteristics are averaged over a standard power-law distribution [3] with an effective size parameter $X_{1,eff} = 10$, effective variance $\nu_{eff} = 0.05$, and host size parameters in the range $X_1 \in [6.61; 14.39]$. The numerical integration over sizes is based on a Gaussian integration formula with 100 quadrature points. Recall that in [6] the refractive index of the host particle and small grains was adopted to be $m = m_R + im_I = 1.55 + i0.0003$, and the ratio of their size parameters $X_{1,eff}/X_{2,eff}$ was constant and equal to 10. In this work, we consider such two cases:
i) in order to analyze the effect of particle absorption, we perform computations of the scattering characteristics for $m_R = 1.55, m_I = 0.3$ and $X_{1,eff}/X_{2,eff} = 10$;
ii) to investigate the influence of the size of microscopic irregularities on the surface of the host particle, the refractive index is adopted to be the same as in [6] ($m = 1.55 + i0.0003$) but the ratio of the size parameters $X_{1,eff}/X_{2,eff} = 5$.

Some of the results of our computations are given in Table 1. For comparison, we also present the data for uncontaminated polydisperse host (i.e. when the number of grains $N_g = 0$) computed from the Lorenz Mie theory as well as the numerical data obtained early in [6]. The values of the extinction, C_{ext}, and scattering, C_{sca} cross sections correspond to a wavelength of 0.628 μm. It is seen that the increasing size parameter scale of irregularities influences the values of C_{ext}, C_{sca}, single scattering albedo ω, and asymmetry parameter g. At the same time the presence of strong absorption does not result in appreciable effect of irregularities on the values of C_{ext}, C_{sca}, g and ω.

Table 1.

m	X_1/X_2	N	C_{ext},(μm^2)	C_{sca},(μm^2)	ω	g
$1.55 + i0/0003$	-	1	6.314	6.265	0.9923	0.668
$1.55 + i0.0003$	10	50	6.607	6.558	0.9926	0.661
$1.55 + i0.0003$	5	50	10.670	10.606	0.9940	0.609
$1.55 + i0.3$	-	1	6.464	3.183	0.492	0.912
$1.55 + i0.3$	10	50	6.845	3.265	0.477	0.920

In Fig. 1 we depict the results of computations of all non-zero elements of the Stokes scattering matrix both for "uncontaminated" and contaminated hosts with m_I = 0.0003, 0.3, and $X_{1,eff}/X_{2,eff}$ = 5 and 10. Let us discuss these data briefly. It is seen that

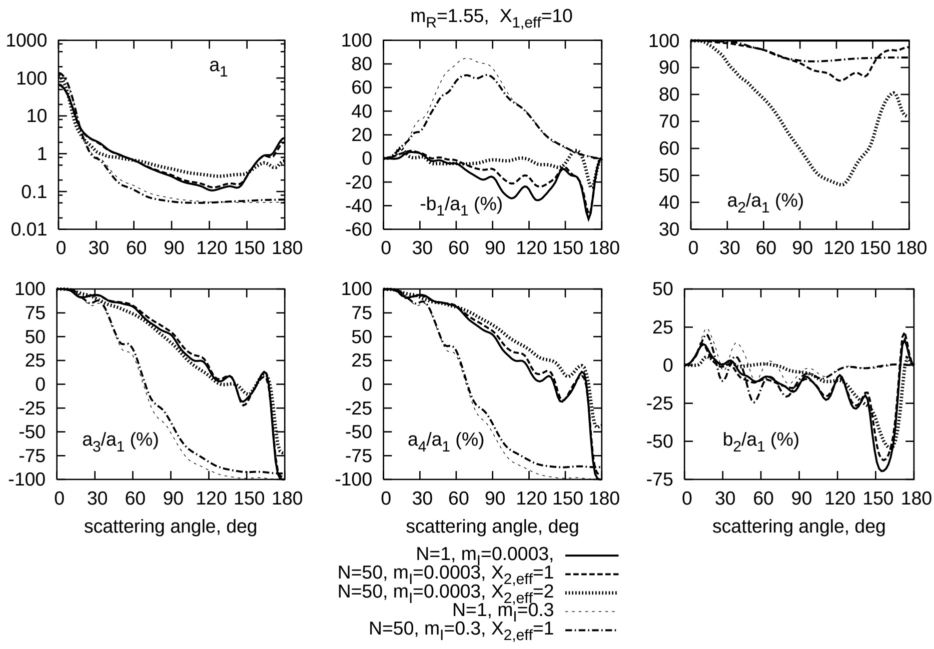

Figure 1. Elements of the normalized Stokes scattering matrix for polydisperse hosts and polydisperse hosts "dusted" with 49 small grains.

the optical effects of surface contamination become stronger with increasing the value of particle absorption and the size parameter scale of irregularities, and the effect of the size of irregularities is larger as compared with absorption which is least pronounced for the phase function $a_1(\theta)$. It is interesting to note that increasing the relative size of irregularities results in virtually neutral behavior of linear polarization $-b_1(\theta)/a_1(\theta)$ in the range $\theta <$ 150. The most noticeable indicator of nonsphericity is the deviation of $a_2(\theta)/a_1(\theta)$ from

100%, which increases with increasing the size of grains and decreases with increasing absorption; this is also characteristic, e.g., of randomly oriented spheroids.

We must note that all our computations have been performed using a new Fortran-90 superposition T-matrix parallel code developed for use on parallel computer clusters. A detailed description of this code is given in [7, 8]. We have used a computer cluster consisted of eight nodes with the total number of cores in the cluster = 64 (2.5GHz) and the total amount of RAM = 64 GB. Here because of the space shortage, we can only note that if a parallel cluster is characterized by N_1 number of nodes and N_2 number of cores in each node, then the computing time decreases proportionally to $N = N_1 N_2$, and the available storage increases proportionally to N. In conclusion, we can state that our numerous computations show both high accuracy and high efficiency of applying this code.

Acknowledgments

We thank an anonymous reviewer for useful comments on the original manuscript. We acknowledge the special support by the Ukrainian National Academy of Sciences under the Main Astronomical Observatory GRAPE/GPU/GRID computing cluster project. This research was sponsored by the NASA Radiation Science Program managed by Hal Maring.

References

[1] H. Volten, O. Muñoz, E. Rol, J. de Haan, W. Vassen, J. Hovenier, K. Muinonen, and T. Nousiainen, ”Scattering matrices of mineral aerosol particles at 441.6 nm and 632.8 nm”, *J. Geophys. Res.*, **106**, 1735 (2001).

[2] T. Nousiainen, ”Optical modeling of mineral dust particles. A review”, *J. Quant. Spectrosc. Radiat. Transfer*, **110**, 1261 (2009).

[3] M. I. Mishchenko, L. D. Travis, and A. A. Lacis, *Scattering, Absorption, and Emission of Light by Small Particles* (Cambridge University, 2002).

[4] K. Muinonen, T. Nousiainen, H. Lindqvist, O. Muñz, and G. Videen ”Light scattering by Gaussian particles with internal inclusions and roughened surfaces using ray optics”, *J. Quant. Spectrosc. Radiat. Transfer*, **110**, 1628 (2009).

[5] T. Nousiainen, O. Muñoz, H. Lindqvist, P. Mauno, and G. Videen, ”Scattering of light by mineral-dust particles much larger than the wavelength”, in *Conference Proceedings of Electromagnetic and Light Scattering XII*; University of Helsinki, 2010; K Muinonen, A. Penttila, etc. Eds. (University of Helsinki, Finland, 2010); p.p. 206 - 209.

[6] M. I. Mishchenko, J. M. Dlugach, and D. W. Mackowski, ”Light scattering by wavelength-sized particles ”dusted” with subwavelength-sized grains”, *Optics Letters*, **36**, 337 (2011).

[7] D. W. Mackowski, M. I. Mishchenko, ”A multiple sphere T-matrix code for use on parallel computer clusters”, *J. Quant. Spectrosc. Radiat. Transfer*, doi: 10.1016 /j.jqsrt.2011.02.019 (2011).

[8] Available at http://www.eng.auburn.edu/users/dmckwski/scatcodes/.

[9] D. W. Mackowski, M. I. Mishchenko, ”Calculation of the T-matrix and the scattering matrix for ensembles of spheres”, *J. Opt. Soc. Am. A*, **13**, 2266 (1996).

[a] Main Astronomical observatory of the National Academy of Sciences of Ukraine
Department of Physics of the Solar System Bodies
Zabolotny Str., 27
03680 Kyiv, Ukraine

[b] NASA Goddard Institute for Space Studies
NY 10025, New York, USA

[c] Department of Mechanical Engineering
Auburn University, AL 36849, USA

* To whom correspondence should be addressed | Email: dl@mao.kiev.ua

Paper presented at the ELS XIII Conference (Taormina, Italy, 2011), held under the APP patronage; published online 15 September 2011.