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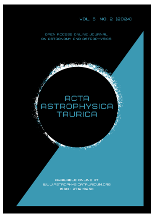

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Impact of the internal structure on the scattering properties of inhomogeneous particles

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ABSTRACT

Inhomogeneous particles are widespread in nature. When interpreting observational data on remote sensing of celestial bodies, the relative abundances of various elements are often determined. This paper aims to study the impact of the mutual arrangement of inhomogeneities on the scattering properties of layered particles. Silicate-carbon (silicate covered with a layer of carbon) and carbon-silicate (carbon covered with a layer of silicate) particles were considered. Computer simulation of the scattering properties of layered particles using the shape matrix method showed that the mutual arrangement of layers at the same carbon and silicate abundances noticeably affects both the integral scattering characteristics (scattering factor, absorption factor, single scattering albedo) and the linear polarization degree. A comparison of the simulation results with the results of polarimetric observations of the F-type asteroid (3200) Phaethon showed that the asteroids of this type are highly likely characterized by silicate-carbon particles, which have both a higher degree of linear polarization at the corresponding phase angle and a lower albedo.

Key words: light scattering, polarization, layered particles, shape matrix method

1 Introduction

Various scattering objects occurred in nature often have a heterogeneous internal structure, and the problem of light scattering by inhomogeneous particles is of great interest in various sciences, such as astrophysics, atmospheric and oceanic optics, biophysics, etc. For instance, plant and animal cells, algae and bacteria, aerosols in the atmosphere, and regolith on the surface of atmosphereless celestial bodies are examples of objects with heterogeneous (often layered) structure. Besides, particles formed in natural or technological processes often have an inhomogeneous composition. Studying the scattering properties of inhomogeneous particles is widely applied in many fields, such as pharmaceutical industry, nanotechnology, chemistry, astrophysics, biology, and medical sciences (Gumerov, Duraiswami, 2005). In some cases, inhomogeneous scatterers can be represented by multilayered particles.

Particular interest in studying particles with layered structure is related to the study of objects in the Solar system. In the laboratory analysis of particles, brought to Earth by spacecrafts, such as samples from the asteroid (162173) Ryugu, particles were covered with a thin layer of carbon to prevent them from dispersing under the influence of scanning radiation (Kimura et al., 2022). When preparing the Rosetta mission, the instrument for studying cosmic dust GIADA (Grain Impact Analyzer and Dust Accumulator) was calibrated by studying layered particles consisting of silicate covered with a layer of amorphous carbon (Ferrari et al., 2014). This approach was substantiated in Greenberg, Hage (1990) who proved that particles with layered structure can be formed during evolutionary processes in the interstellar medium. The dust of a protoplanetary nebula, which forms comets observed in the Solar system, represents an advanced stage in the diffuse cloud of interstellar dust. The diffuse cloud of interstellar dust is believed to consist of heterogeneous particles with a silicate core and a layer of dark organic material covering it (Greenberg, 1985). Photometric and polarimetric studies of asteroid surfaces demonstrate, with some exceptions, the absence of significant changes in the scattering properties of different areas of asteroid surfaces, i.e., a high degree of optical homogeneity of their surfaces. One possible mechanism that can contribute to the optical homogeneity of the surface is the deposition of a carbon layer on particles in the upper layer of the asteroid regolith (Belskaya et al., 2005). Deposits can be formed as a result of the pyrolysis of carbon-containing (organic) material subjected to the process of space weathering (Pronin, Nikolaeva, 1982; Shkuratov et al., 1986; Starukhina, Shkuratov, 1995). On the other hand, Shiraiwa et al. (2010) showed that carbon particles can interact with surrounding non-absorbing particles forming a layer on the surface of a carbon particle. Thus, on the surface of layered silicate-carbon particles, there may be both a carbon layer and a silicate layer. The mutual arrangement of the carbon and silicate layers has a significant influence, for example, on the processes of asteroid formation (Kudo et al., 2002). This study is dedicated to exploring the impact of the mutual arrangement of the carbon and layered layers on the scattering properties of a layered particle.

2 Layered particle model

For the simulation of light scattering processes by layered particles, the model of layered spheres is often used due to the simplicity of the calculation algorithm (Wu, Wang, 1991; Johnson, 1996). However, spherical particles are quite rare in nature. Moreover, it is commonly believed that the spherical shape of a scattering particle has a significant impact on its scattering properties, outshining the influence of the layered structure. Therefore, there is interest in non-spherical layered particles such as spheroids and ellipsoids (Voshchinnikov et al., 2006; Posselt et al., 2002; Gurwich et al., 2000; Farafonov et al., 2003). The particles that are distant from the Sun do not have even such symmetry elements as a rotation axis or a plane of symmetry; thus, it is suggested that many dust particles in the early Solar system had irregular shape rather than spherical (Flynn et al., 2013). A more general method for calculating the scattering properties of arbitrarily shaped layered particles was later developed by Petrov et al. (2007), which is a variation of the shape matrix method (Petrov et al., 2006, 2012). This method allows for the computation of the scattering properties of particles having irregular shape and layered structure. In our study, this method was used for the computer simulation of light scattering processes.

The conjugate random Gaussian particles with both large-scale and small-scale roughness were used as the irregularly shaped particle model (Petrov, Kiselev, 2019). The shape of such a particle $R(\theta, \phi)$ in the spherical coordinate system is described by the equation

$$R(\theta, \phi) = p \cdot R_{\Gamma_1}(\theta, \phi) + (1 - p) \cdot R_{\Gamma_2}(\theta, \phi), \qquad (1)$$

where $R_{\Gamma_1}(\theta, \phi)$ and $R_{\Gamma_2}(\theta, \phi)$ are random Gaussian particles with correlation angles Γ_1 and Γ_2, as described in Muinonen (1996, 1998). In this study, particles with parameters $\Gamma_1 = 7°$, $\Gamma_2 = 50°$, and p = 0.5 were used.

Initially, silicate-carbon (SC) particles were generated, with a particle consisting of silicate $R_{\rm sil}$ being covered with a relatively thin layer of amorphous carbon $R_{\rm carb}$. The relative thickness of the layer ζ was determined by the formula

$$\zeta = \frac{R_{\rm carb} - R_{\rm sil}}{R_{\rm sil}} \times 100\,\%. \qquad (2)$$

Two relative thicknesses were used in this study, $\zeta = 5\%$ and $\zeta = 10\%$. Then carbon-silicate (CS) particles were generated, with a particle consisting of carbon being covered with a layer of silicate. The thicknesses of the CS particle layers were chosen so that the volumes of the silicate component in SC and CS particles were equal, and the volumes of the carbon component were also equal. Examples of such particles are shown in Fig. 1.

The key parameters determining the scattering properties of a particle are its size R and the complex refractive index $m = n + i \cdot k$. In this case, the size refers to the radius of a sphere with the same volume as the silicate material. The refractive index of silicate for the wavelength $\lambda = 0.5317\mu$m, corresponding to the V filter, was taken in Scott, Duley (1996) and is equal to $m = 1.6820 + i \cdot 0.0031$. The refractive index of carbon for the same wavelength, taken in Li, Greenberg (1997), is $m = 1.9470 + i \cdot 0.2940$.

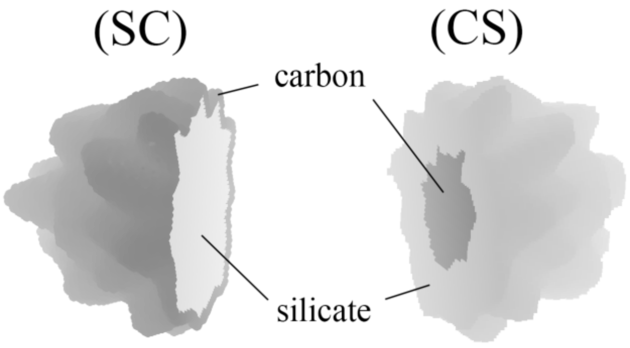

Fig. 1. Example of the silicate-carbon (SC) and carbon-silicate (CS) particles.

3 Results and discussion

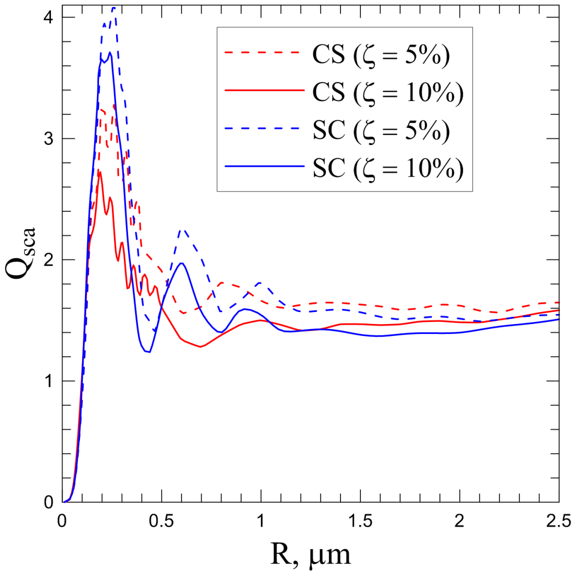

Fig. 2. Dependence of the scattering factor $Q_{\rm sca}$ on the size of scattering particles. Blue lines correspond to SC particles, and red lines correspond to CS particles. Dashed lines denote a carbon layer thickness of $\zeta = 5\%$, and solid lines denote $\zeta = 10\%$.

Firstly, the integral characteristics of scattered radiation were investigated, independent of the illumination and observation geometry: scattering factor $Q_{\rm sca}$, absorption factor $Q_{\rm abs}$, and single scattering albedo ω. The scattering factor determines how effectively an area unit of the scattering object re-scatters light (Petrov et al., 2020), while the absorption factor indicates how effectively an area unit of the scattering object absorbs light. Taking into account the scattering factor and the absorption factor, it is possible to calculate the single scattering albedo ω, which determines the probability that an individual photon will be scattered rather than absorbed by a particle (Mishchenko et al., 2002):

$$\omega = \frac{Q_{\text{sca}}}{Q_{\text{sca}} + Q_{\text{abs}}}. \tag{3}$$

Figure 2 shows the dependence of the scattering factor Q_{sca} on the size of scattering layered particles of various types. Dashed lines correspond to a small thickness of the carbon layer $\zeta = 5\%$, and solid lines correspond to a thickness of the carbon layer $\zeta = 10\%$. Red lines denote CS particles, and blue lines denote SC particles. As can be seen from the figure, for large sizes of scattering particles (several times larger than the wavelength), CS particles scatter light more effectively due to the presence of a bright silicate on their surface, unlike SC particles with a surface layer of dark carbon. However, for sufficiently small particle sizes ranging from 0.2 to 0.4 μm, dark SC particles scatter light much more effectively. This can be explained as follows. In the case of CS particles, the refractive index of the upper layer is significantly smaller than that of the lower layer (this is true for both the real and imaginary parts of the refractive index). For small sizes of scattering particles, an effect similar to the so-called optical brightening occurs. Optical brightening involves the coating, on the refracting surface adjacent to the air, of a thin layer with a refractive index lower than that of the refracting surface, leading to a significant decrease in reflection from the refracting surface, and consequently, to an increase in the light sensitivity of the optical system (Brehovsky, 1973).

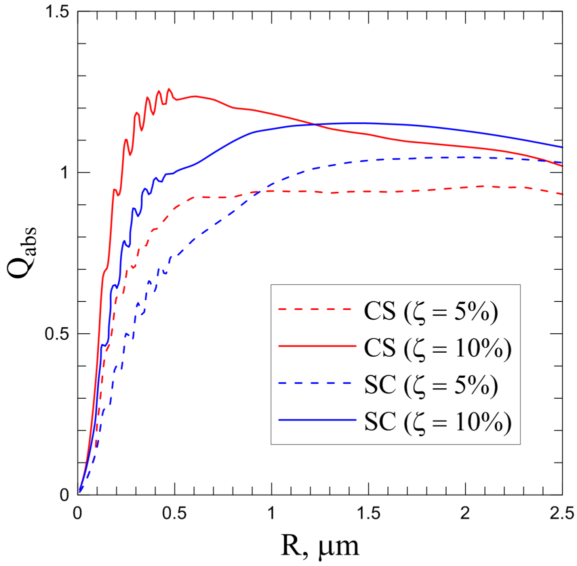

Fig. 3. The same as in Fig. 2 but for the absorption factor Q_{abs}.

Figure 3 shows the dependence of the absorption factor Q_{abs} on the size of scattering layered particles. Particles with $\zeta = 10\%$ have significantly higher absorption capacity due to a higher carbon abundance. For particle sizes up to ≈ 1 μm, CS particles absorb light more effectively, while for larger sizes, SC particles absorb it more, which is presumably related to the mentioned effect similar to the optical brightening effect.

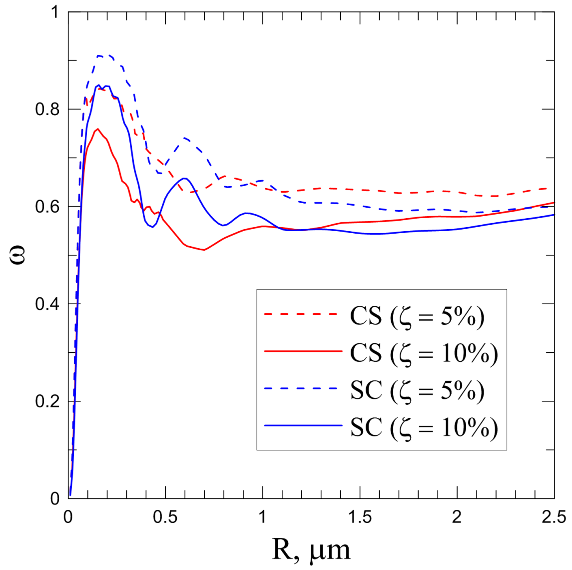

Fig. 4. The same as in Fig. 2 but for the single scattering albedo ω.

Figure 4 shows the dependence of the single scattering albedo on the particle size. As can be seen from the figure, the albedo of particles with $\zeta = 10\%$ is noticeably lower than that of particles with $\zeta = 5\%$ due to a great amount of absorbing carbon. The difference between SC and CS particles is determined by absorption: for sizes <1 μm, the albedo is higher for SC particles, while for larger sizes, it is higher for CS particles.

Of special interest is the impact of the mutual arrangement of layers on the phase dependence of the linear polarization degree, which is widely used in remote sensing of celestial bodies. Linear polarization degree maps were constructed for particles of four types (Fig. 5). Red color indicates positive linear polarization degree; blue, negative one; and white, near-zero. The main difference between various types of particles is evident from the figure: SC particles exhibit a much higher maximum of the linear polarization degree than do CS particles. This is crucial for interpreting observations of the Solar system objects, such as F-type asteroids, which have a relatively high maximum of positive polarization. As established in Kiselev et al. (2022), asteroid (3200) Phaethon has the polarization maximum $P_{\max} = 45\% \pm 1\%$ at the phase angle $\alpha = 124° \pm 0.4°$. This is the only F-type asteroid for which the position and the maximum value of linear polarization could be accurately determined. How well can SC and CS particles reproduce the polarization maximum of this asteroid? To investigate this, the dependence of the linear polarization degree on size at the phase angle $\alpha = 124°$ was constructed (Fig. 6). The horizontal line corresponds to the maximum of the linear polarization degree for asteroid (3200) Phaethon. As can be seen, CS particles are unable to reproduce this maximum, as they exhibit a significantly lower linear polarization degree in almost the entire range of scattering particle sizes. Meanwhile, SC particles with sizes above 1 μm show the same or even greater degree of linear polarization, with a lower single scattering albedo (Fig. 4).

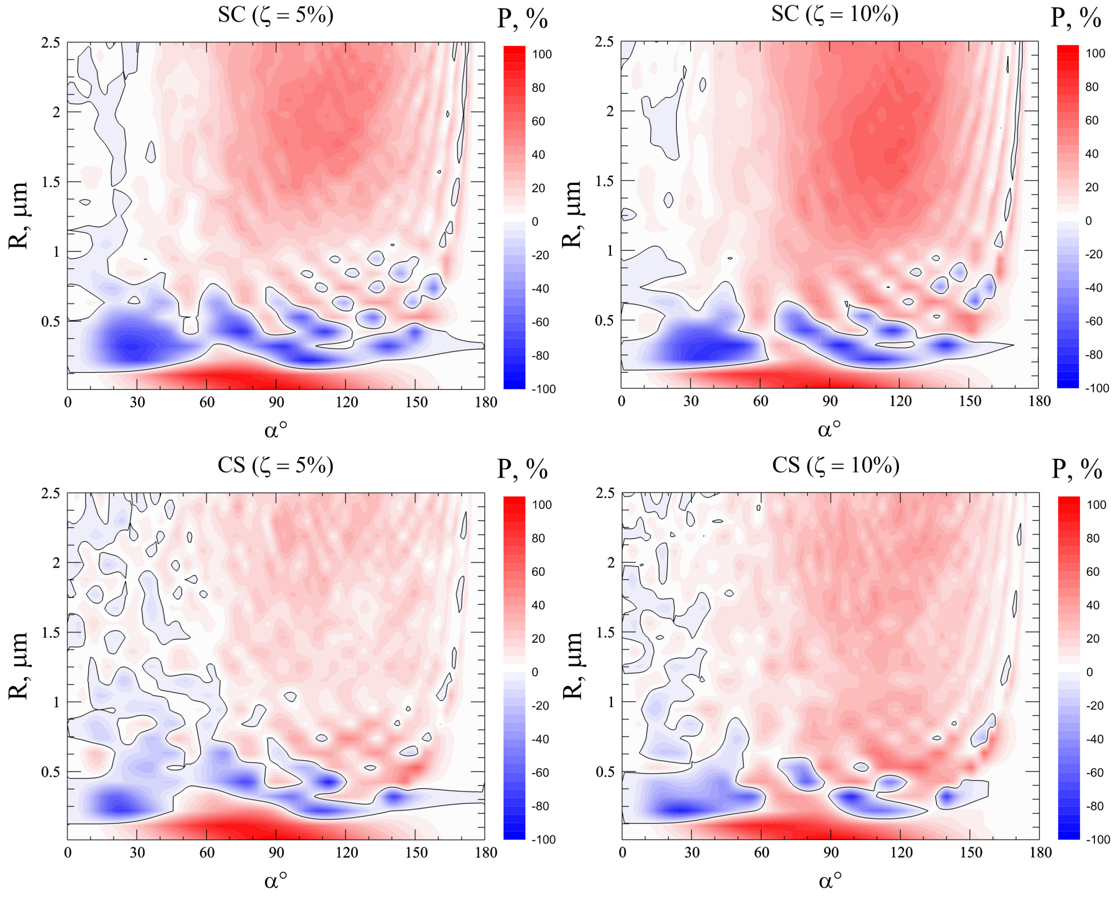

Fig. 5. Map of the degree of linear polarization of scattered light depending on the phase angle (horizontal axis) and the size of ice scattering particles (vertical axis) for four types of particles.

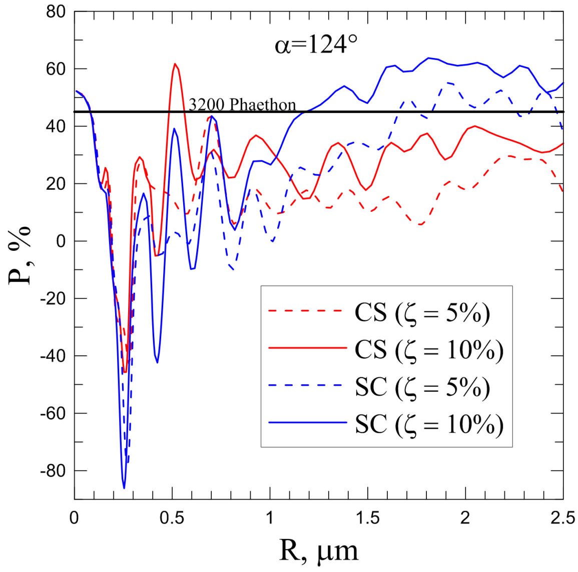

Fig. 6. Dependence of the linear polarization degree on size at the phase angle $\alpha = 124°$ for four types of particles. The solid horizontal line denotes the maximum of the linear polarization degree of asteroid (3200) Phaethon.

Consequently, asteroids of dark spectral types, such as asteroid (3200) Phaethon, are more likely to have SC particles, i.e., heterogeneous particles in which a layer of silicate is covered by a layer of carbon.

4 Conclusions

The main conclusion of this study is that the mutual arrangement of layers in heterogeneous particles composed of carbon and silicate significantly influences the scattering properties of these particles even with the same percentage abundance of carbon and silicate. Calculations using the shape matrix method for irregularly shaped layered particles show that the mutual arrangement of layers affects both integral characteristics, such as scattering factor, absorption factor, and single scattering albedo, as well as the phase dependence of the linear polarization degree. It is established that carbon particles covered with a layer of silicate generally scatter light more effectively than silicate particles covered with a layer of carbon. An exception is observed in the size range from 0.2 to 0.4 μm, where scattering by silicate-carbon particles dominates. An explanation for this effect is provided in the study, similar to the optical brightening effect, which is achieved by coating a thin layer, with a relatively low refractive index, on the refractive surface. It is shown that the mutual arrangement of layers significantly affects the phase dependence of the linear polarization degree. In the case of SC particles, the maximum value of polarization is noticeably higher compared to CS particles. A comparison of simulation results with observations for asteroid (3200) Phaethon revealed that CS particles in most size ranges cannot reproduce such high values of linear polarization, whereas SC particles with sizes larger than 1 μm can achieve such high values of polarization. Therefore, for dark F-type asteroids, regolith particles consisting of silicate covered with a layer of carbon are more characteristic.

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References

Belskaya I.N., Shkuratov Y.G., Efimov Y.S., et al., 2005. Icarus, vol. 178, no. 1, pp. 213–221.

Brehovsky L.M., 1973. Waves in layered media, 2nd ed. M.: Nauka. (In Russ.)

Farafonov V., Il'in V., Prokopjeva M., 2003. Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 79–80, pp. 599–626.

Ferrari M., Della Corte V., Rotundi A., Rietmeijer F.J.M., 2014. Planetary and Space Science, vol. 101, pp. 53–64.

Flynn G.J., Wirick S., Keller L.P., 2013. Earth Planets Space, vol. 65, no. 10, p. 13.

Greenberg J.M., 1985. Physica Scripta, vol. T11, pp. 14–26.

Greenberg J.M., Hage J.I., 1990. Astrophys. J., vol. 361, pp. 260–274.

Gumerov N.A., Duraiswami R., 2005. Acoustical Society of America Journal, vol. 117, no. 4, pp. 1744–1761.

Gurwich I., Kleiman M., Shiloah N., Cohen F., 2000. Applied Optics, vol. 39, no. 3, pp. 470–477.

Johnson B.R., 1996. Applied Optics, vol. 35, pp. 3286–3296.

Kimura Y., Kato T., Anada S., et al., 2022. 53rd Lunar and Planetary Science Conference, vol. 2678.

Kiselev N.N., Rosenbush V.K., Petrov D., et al., 2022. Mon. Not. Roy. Astron. Soc., vol. 514, no. 4, pp. 4861–4875.

Kudo T., Kouchi A., Arakawa M., Nakano H., 2002. Meteoritic and Planetary Science, vol. 37, pp. 1975–1983.

Li A., Greenberg J.M., 1997. Astron. Astrophys., vol. 323, pp. 566–584.

Mishchenko M.I., Travis L.D., Lacis A.A., 2002. Scattering, Absorption, and Emission of Light by Small Particles, Cambridge: Cambridge University Press, UK.

Muinonen K., 1996. Earth Moon Planets, vol. 72, pp. 339–342.

Muinonen K., 1998. Astron. Astrophys., vol. 332, pp. 1087–1098.

Petrov D., Synelnyk E., Shkuratov Y., Videen G., 2006. J. Quant. Spectrosc. Rad. Trans., vol. 102, no. 1, pp. 85–110.

Petrov D., Shkuratov Y., Zubko E., Videen G., 2007. J. Quant. Spectrosc. Rad. Trans., vol. 106, no. 1–3, pp. 437–454.

Petrov D., Shkuratov Y., Videen G., 2012. J. Quant. Spectrosc. Rad. Trans., vol. 113, no. 18, pp. 2406–2418.

Petrov D.V., Kiselev N.N., 2019. Solar System Research, vol. 53, no. 4. pp. 294–305. (In Russ.)

Petrov D.V., Zhuzhulina E.A., Savushkin A.A., 2020. Izv. Krymsk. Astrofiz. Observ., vol. 116, no. 2, pp. 41–48. (In Russ.)

Pronin A.A., Nikolaeva O.V., 1982. Doklady Akademiia Nauk SSSR, vol. 265, pp. 429–432. (In Russ.)

Posselt B., Farafonov V.G., Il'in V.B., Prokopjeva M.S., 2002. Measurement Science and Technology, vol. 13, no. 3, pp. 256–262.

Scott A., Duley W.W., 1996. Astrophys. J. Suppl. Ser., vol. 105, p. 401.

Shiraiwa M., Kondo Y., Iwamoto T., and Kita K., 2010. Aerosol Science Technology, vol. 44, no. 1, pp. 46–54.

Shkuratov Y.G., Stadnikova N.P., Yarmolenko S.N., 1986. Astron. Zhurn., vol. 63, pp. 1183–1188. (In Russ.)

Starukhina L.V., Shkuratov Yu.G., 1995. Icarus, vol. 113, pp. 442–449.

Voshchinnikov N.V., Farafonov V.G., Videen G., Ivlev L.S., 2006. Abstracts of the 9th International Conference on Electromagnetic and Light Scattering by Nonspherical Particles, p. 271–4.

Wu Z.P., Wang Y.P., 1991. Radio Science, vol. 26, no. 6, p. 1393.