COHERENT AND INCOHERENT LIGHT SCATTERING NEAR THE BACKWARD DIRECTION FOR AN IRREGULAR SHAPE PARTICLES OF CIRRUS CLOUDS

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ABSTACT

The problem of light scattering by particles of irregular shape is of great importance [1] since measurements of light scattering by particulate media can be used for retrieving some microphysical characteristics of the particles. The particles of irregular shapes are ubiquitous in nature. For example, the aerosol and dust particles in the atmosphere have irregular shapes. In cirrus clouds consisting of ice crystals the irregular shapes like aggregates are often predominant [2]. In astrophysics, surfaces of the Moon and other planets are covered by regolith particles of irregular shapes, and so on.

When size of the particles x is less or comparable with light wavelengths, the problem of light scattering by such irregular particles can be solved using the “exact” numerical methods like the T-matrix method, discrete dipole approximation, finite difference time domain method, and so on. However, in the case of large particles, these exact methods are not successful because of great demands to computer resources. Here the geometric-optics approximation (GOA) looks reasonable. However, geometric optics ignores wave phenomena that become essential at some scattering angles, especially in the forward and backward directions. It is worthwhile to note that the backscattering direction is of special interest since only this direction is used in active remote sensing instruments like lidars and radars.

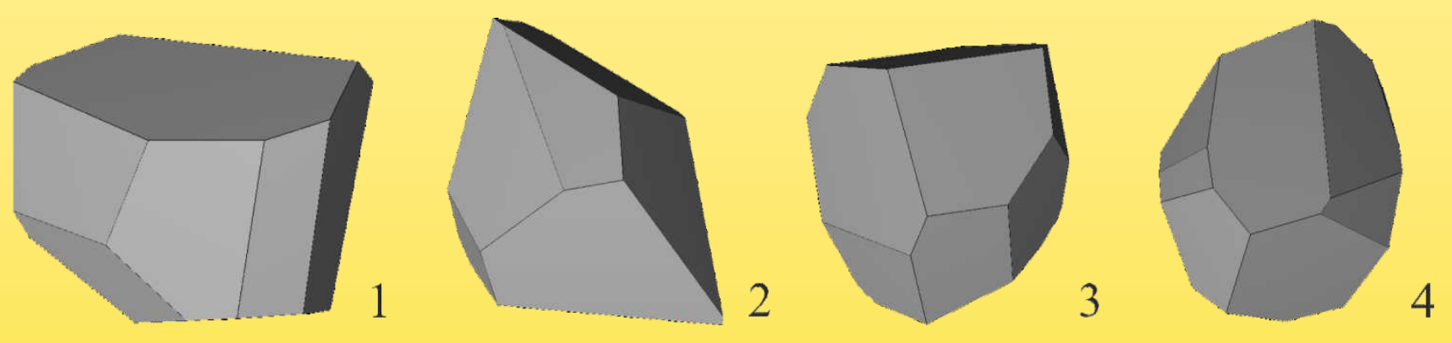


Figure 1. Samples of irregular particle shapes

In this work, we calculate the light scattered by a randomly oriented large faceted particle of irregular shape at $60 < x < 240$. The convex irregular shapes like those shown in Fig. 1 were randomly generated by a computer code. The scattered light is calculated using the physical-optics approximation (PhOA) developed by the authors [3].

Though the PhOA is not an exact method, it is a quite reasonable approximation, at least, for large particles where facet sizes are larger than incident wavelength. In comparison with the exact methods, the PhOA has two advantages. First, the PhOA does not demand extremely large computer resources. Second, the numerical results obtained are obviously interpreted from the physical point of view using the concept of plane-parallel beams created inside a faceted particle.

In this work we have calculated the Mueller (scattering) matrices for large randomly oriented particles of irregular shapes using both geometric-optics and physical-optics approximations [3]. In the case of the irregular shapes shown in Fig. 1, dihedral angles of 90° don't exist and there is a question whether the backscattering peak appears for such particle shapes. We show that light backscatter by a large irregular particle at averaging over random particle orientations is split into the coherent and incoherent part similarly to the phenomena well known for multiple scattering media. The incoherent part has no peak in the exact backward direction and its magnitude is close to the geometric-optics counterpart. The coherent part appears as a narrow backscattering peak whose angular width is approximately equal to the ratio of (wavelength/particle size).

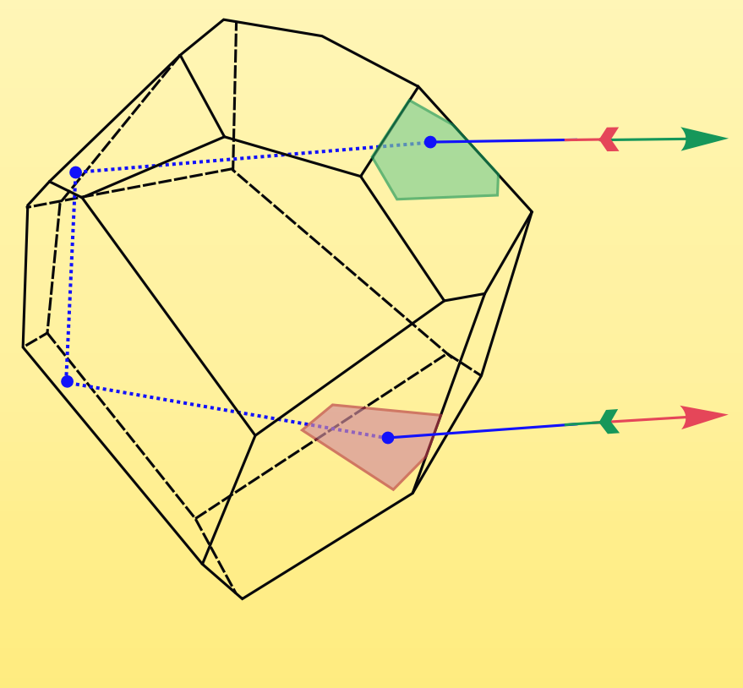


Figure 2. Typical backscattring beams

[1] Mishchenko, M. I., Hovenier, J. W., and Travis, L. D., 2000: *Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications.* Academic Press, New York, USA.

[2] Ding, J., Yang, P., Holz, R. E., *et al.*, 2016: Ice cloud backscatter study and comparison with CALIPSO and MODIS satellite data. *Opt. Express* **24**, 620–636.

[3] Konoshonkin, A. V., Borovoi, A. G., Kustova, N. V., *et al.*, 2016: Light scattering by ice crystals of cirrus clouds: from exact numerical methods to physical-optics approximation. *J. Quant. Spectrosc. Radiat. Transf.* **195**, 132–140.

PHASE FUNCTIONS IN THE GEOMETRIC-OPTICS APPROXIMATION

Figure 3. Phase functions in the GOA for four particle shapes shown in Fig. 1

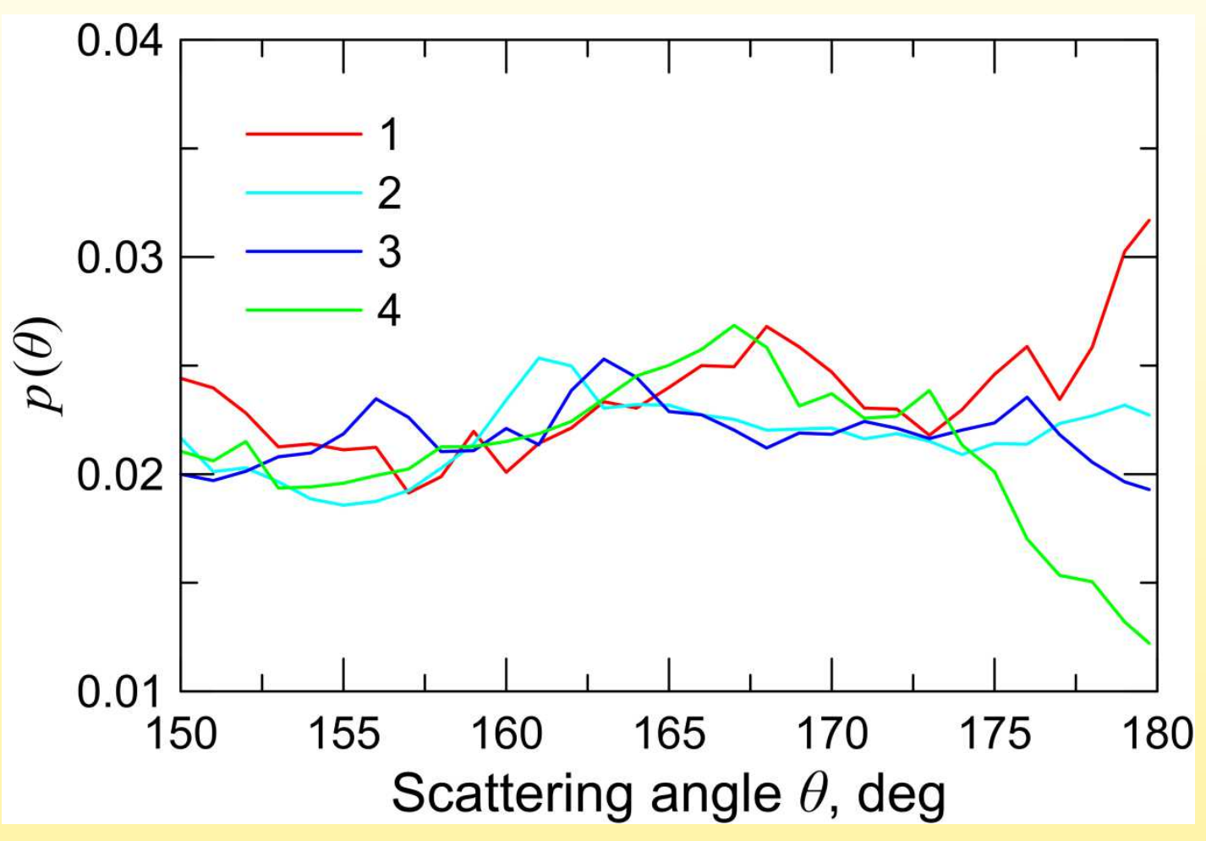
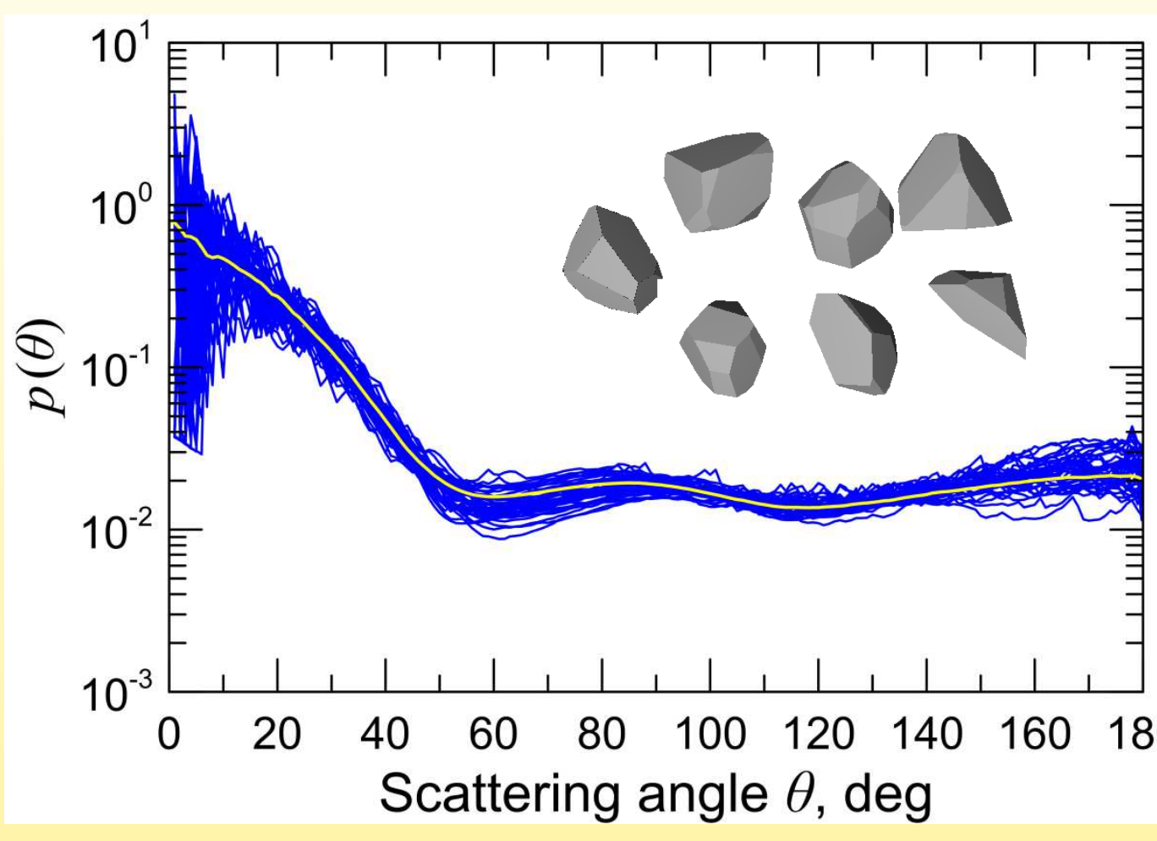


Figure 4. Same as in Fig. 3 for 300 particle shapes for all scattering angles, the yellow line is the average



Unlike the case of pristine crystals, every curve in Figs. 3 and 4 in the cone of [170°, 180°] is a sum of contributions from thousands beams. This fact is illustrated in Fig. 5. Here the solid colored curves correspond to several beams with predominant magnitudes of their contributions. We see that the beam contributions within the GOA are some spiky functions with different location and width of the spikes. The dotted lines in Fig. 5 are the sums for the various numbers N of the additive beams. We obtain that the sum of the spiky functions is smoothed at large N and the number N should be up to 1000. Also we were convinced that all the beams had the similar trajectories like those depicted in Fig. 2.

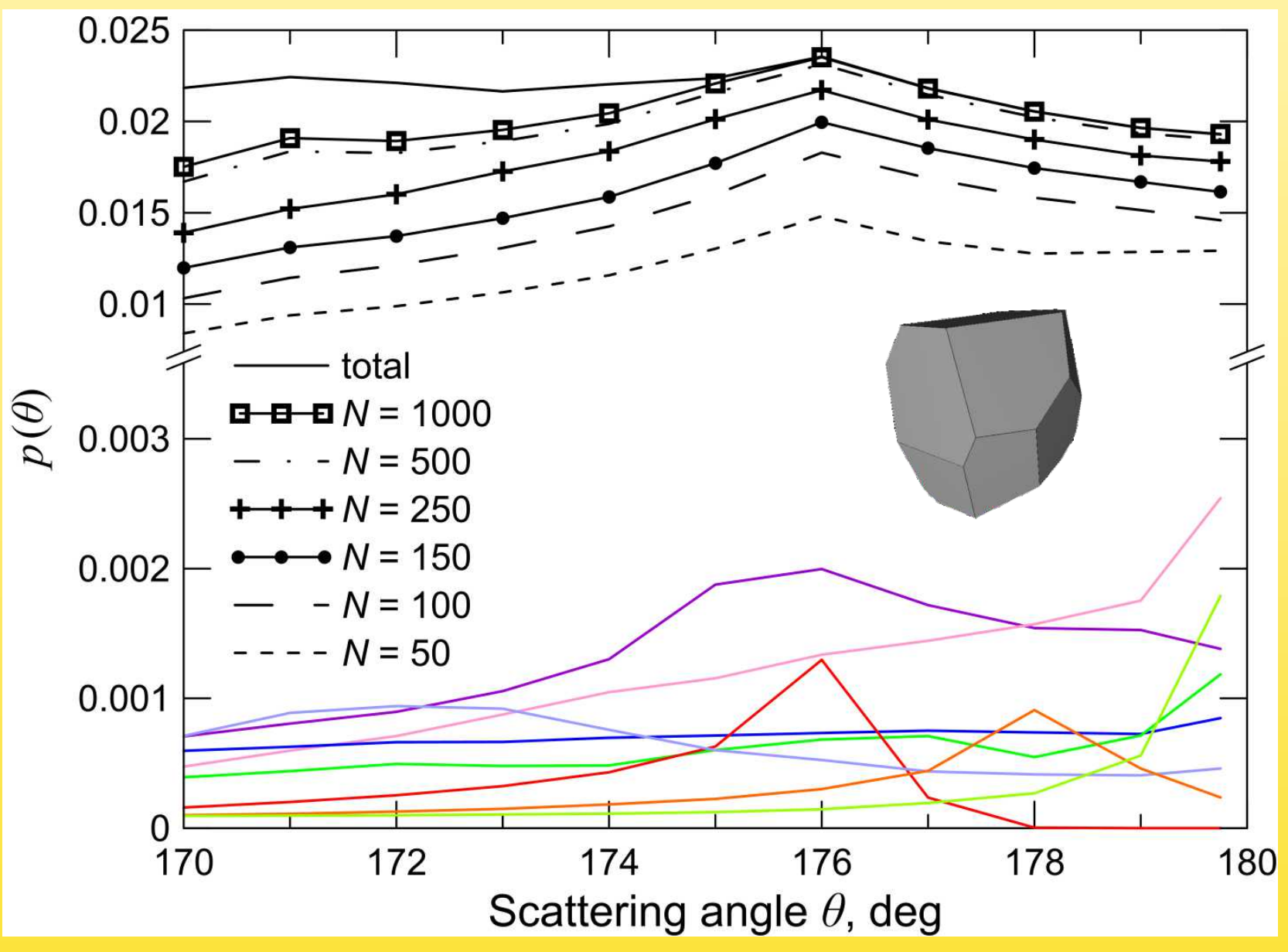


Figure 5. Contributions to the phase function for particle shape 3 of Fig. 1 at different numbers of the beams added

PHASE FUNCTIONS IN THE PHYSICAL-OPTICS APPROXIMATION

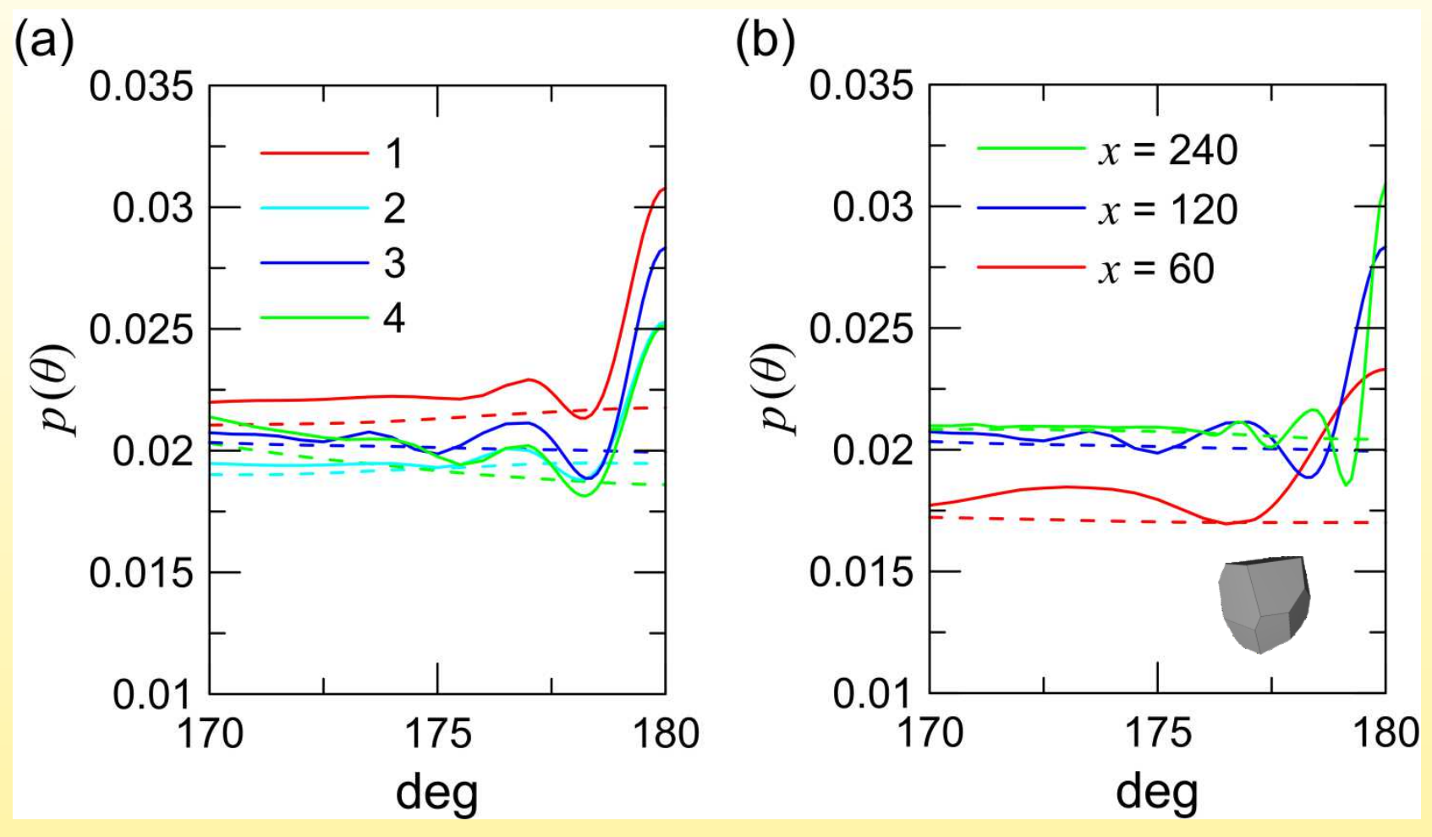


Figure 6. Total phase functions (solid lines) and their incoherent parts (dashed lines) calculated with PhOA: a) for particle shapes 1, 2, 3, and 4 of Fig. 1 with the same size parameter x = 120; b) for particle shape 3 at different size parameters (x = 60, 120, and 240)

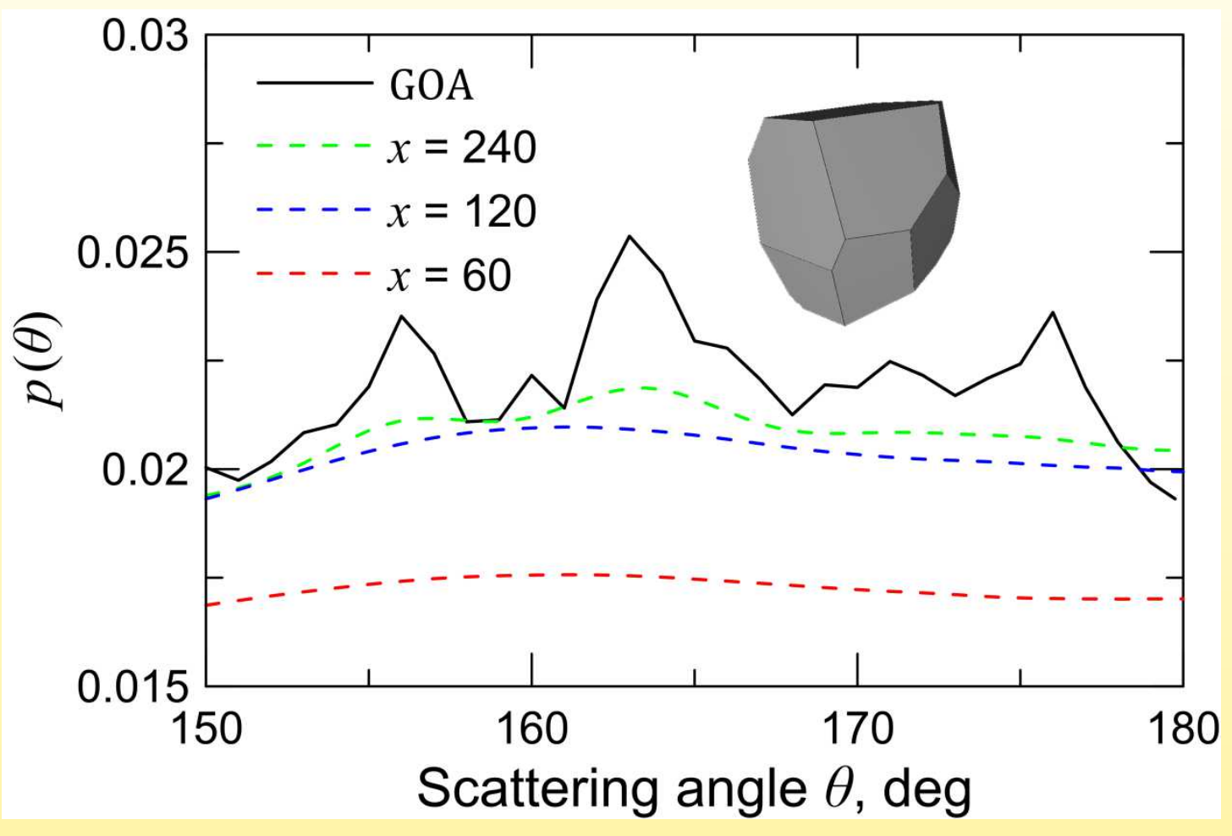


Figure 7. Incoherent phase functions for the shape 3 at different size parameters

We obtained that the small peaks and gaps in Fig. 3 calculated within the GAO at $\theta \to 180°$ have been smoothed by diffraction in the PhOA. As a result, the incoherent phase functions in the PhOA become factually some constants at $\theta \to 180°$ (Figs. 6, 7). Then, on the background of these constants, we obtain the backscattering peak associated with the coherent phase function. Examples of such particles creating both the coherent and incoherent backscattering peaks are the conventional hexagonal ice columns (Fig. 8). Here the dihedral angle of 90° between crystal faces produces the incoherent backscattering peak due to the corner-reflection effect.

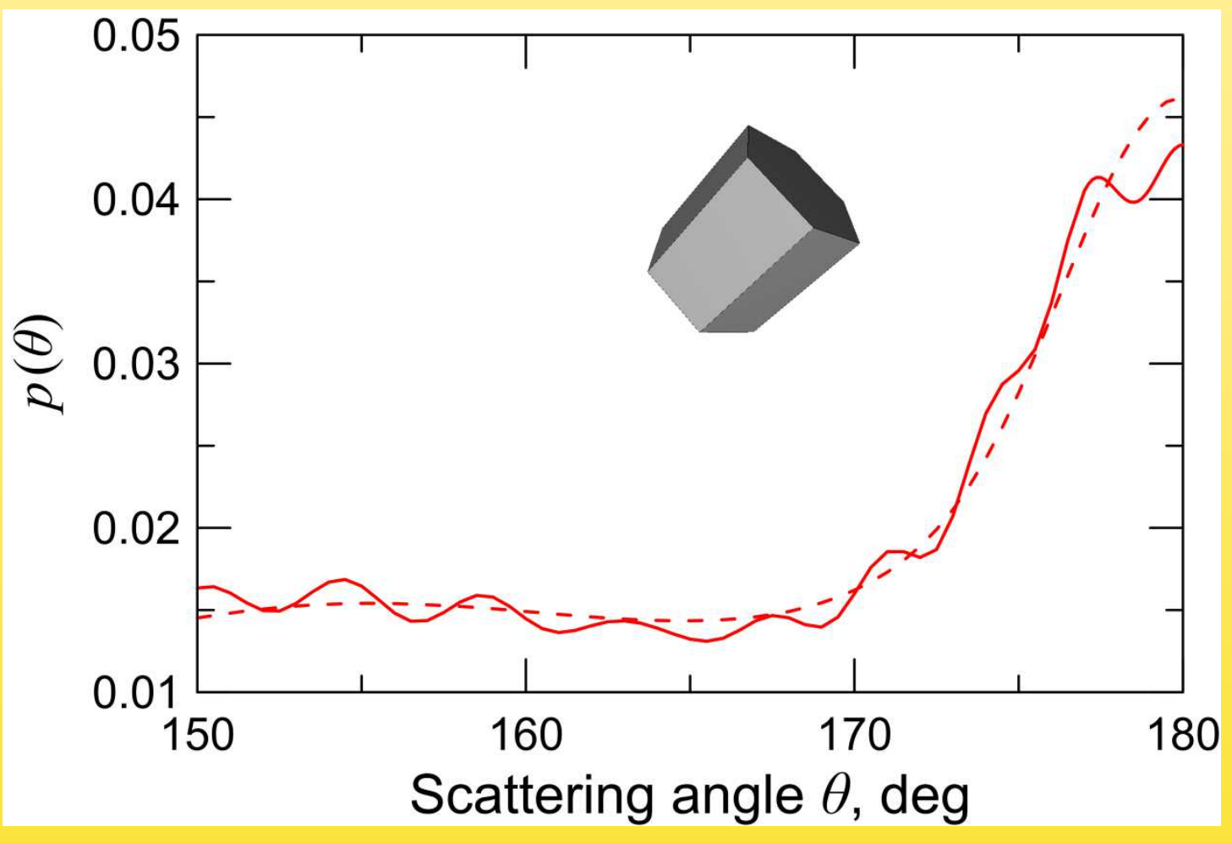
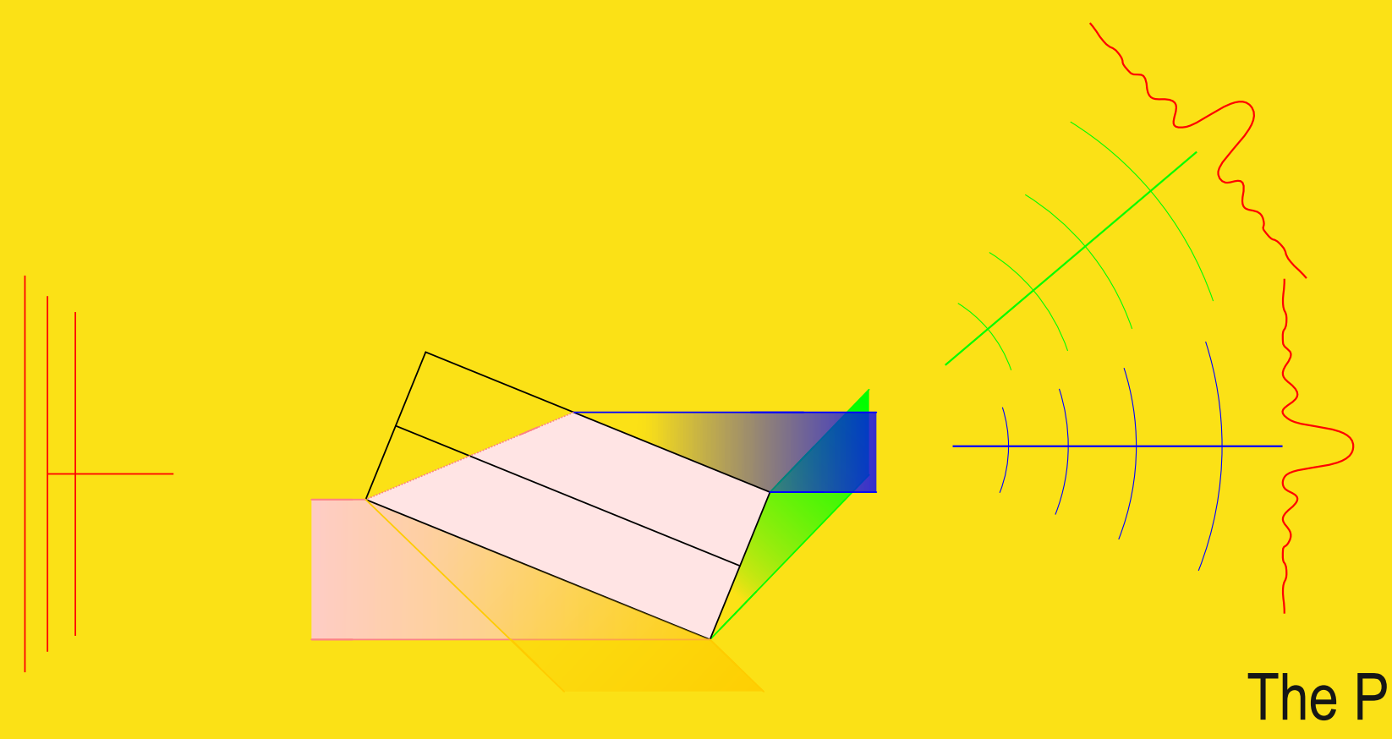


Figure 8. Total (solid) and incoherent (dashed) phase functions for the hexagonal ice column

LIGHT SCATTERING OVER ALL SCATTERING DIRECTIONS



The PhOA limits

$$l\,\mathrm{min} > 7\lambda$$

Diffractinon fringe size

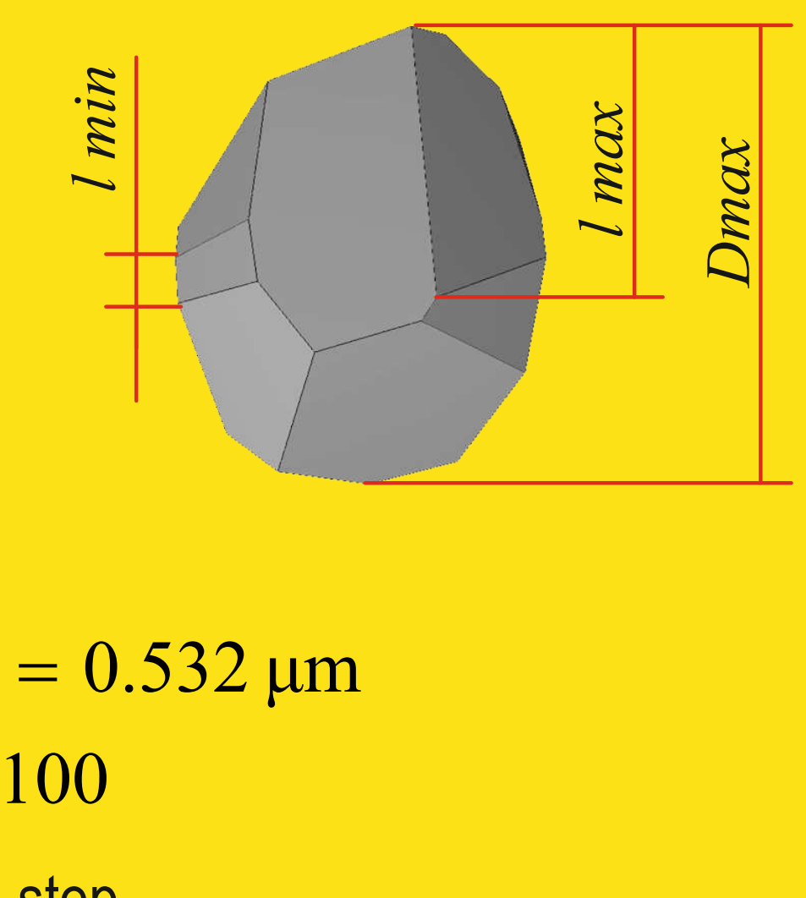
$$\xi = 0.69\frac{\lambda}{l\,max}$$

Scattering angle step

$$\Delta\varphi, \Delta\theta < \xi$$

Orientation angle step

$$\Delta\beta, \Delta\gamma < \frac{\xi}{2}$$



For hexagonal crystal: $D = 17\mu\mathrm{m},\ \lambda = 0.532\ \mu\mathrm{m}$

$$x = \pi D/\lambda \approx 100$$

Scattering angle step

$$\Delta\varphi, \Delta\theta \approx 1.2°$$

Orientation angle step

$$\Delta\beta, \Delta\gamma \approx 0.6°$$

$$N_{total} = 300\cdot 600 = 180\,000$$

Figure 9. PhOA solution for the randomly oriented hexagonal ice column. The convergence of the first element of the Mueller matrix for different number of particle orientations

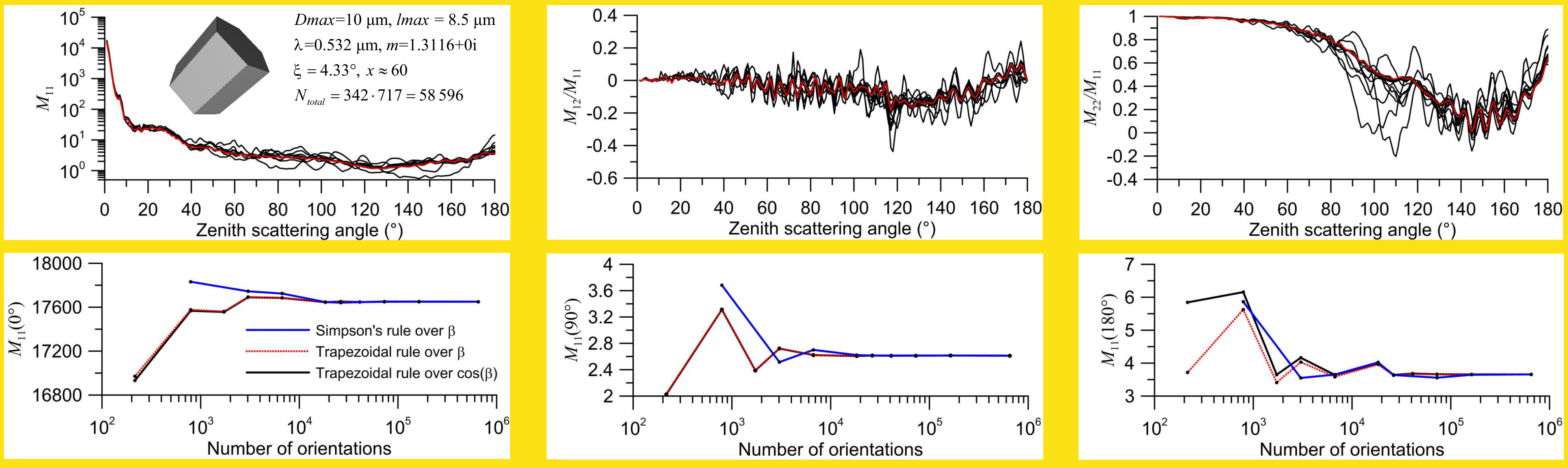


Figure 10. PhOA solution for the randomly oriented irregular ice particle. The convergence of the first element of the Mueller matrix for different number of particle orientations