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# Scattering properties of singular and aggregate atmospheric hexagonal ice particles

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## ABSTRACT

This paper presents the results of calculating and analyzing the light scattering matrix of aggregates of atmospheric hexagonal ice particles located in cirrus clouds. Two types of basic particle shapes for aggregates are considered: a hexagonal column and a hexagonal plate. For both forms, two types of particle arrangement in aggregates were chosen: compact and non-compact. As a result, 4 sets of aggregates were built: compact hexagonal columns, non-compact hexagonal columns, compact hexagonal plates, and non-compact hexagonal plates. Each set consists of 9 aggregates differing in the number of particles in them, and the particles in each individual aggregate have the same shape and size, but different spatial orientation. The light scattering matrices for all aggregates were calculated for the case of arbitrary orientation in the geometric optics approximation. Dependences of the first element of the matrix on the number of particles in aggregate, with different types of particle arrangement, and for two types of shapes are given.

**Keywords:** atmospheric crystals, cirrus clouds, light scattering matrix, geometrical optics, ice aggregates

## INTRODUCTION

Cirrus cloud particles are an important component in atmospheric research tasks (such as laser sensing and radiation transfer). They are formed at altitudes of 7-10 km in the form of ice crystals of predominantly hexagonal shape and sizes from several microns to several millimeters. The concentration of particles in cirrus clouds is usually small relative to other types of clouds, however, due to the peculiarities of the geometry of particles, they have complex scattering characteristics[1]. The optical and microphysical properties of the upper tier clouds are being actively studied in the various national and international projects. For this purpose, all available means and methods are used: measurements from aircraft, satellite research, remote sensing by lidars and radars, etc. A huge amount of work has been done to study the characteristics of the clouds, at the same time, many aspects of the problem of the interaction of radiation with crystal particles are still poorly understood[2-8].

There are direct and remote methods for studying cirrus clouds. Direct measurements include contact measurements from aircraft[9], remote measurements - monitoring of the atmosphere by networks of lidars and photometers. Since direct methods are limited in time and financial resources, in practice, remote methods are more promising. To interpret the lidar data, it is necessary to solve the inverse problem of light scattering for monochromatic laser radiation. However, in order to determine the microphysical characteristics of particles, an information base is needed that compares the microphysical characteristics of particles and the signal reflected from cirrus clouds, which is received by lidars (in the form of a matrix of backscattering of light)[10-14].

Cirrus particles can be divided by microphysical structure in two classes: singular particles (hexagonal columns, plates, bullet etc.) and aggregates consisted of several singular particles. According to the data of in-situ investigations of atmospheric ice crystals aggregates are take a significant part of particles in crystal clouds, however, the detailed information about their scattering properties are absent in existed data bases[5]. Based on the fact that in general crystals in the cloud are arbitrarily oriented, it is expected that aggregates of crystals scatter light according to the same distribution as singular crystals of the same particle shape. In this case, it is possible to reduce the area of study of aggregates using dependence of their properties on number of particles in aggregates.

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Thus, it is necessary to solve the direct problem of light scattering for cirrus cloud particles. For this, there are exact[15,16] and approximate numerical methods. Exact methods require large computational resources due to the large number of calculations required to study particles of complex shapes and sizes much larger than the wavelength, therefore, approximate methods are more suitable for this task. In this work, the Physical optics approximate method was used, which was used to calculate the light scattering matrices of particles characteristic of cirrus clouds[17,18].

The purpose of this work is a study of scattering properties of atmospheric aggregated crystals and its dependences of microphysical structure.

# APPROACH

According to the data of contact studies[19] of cirrus clouds, ice particles in them can be divided into two classes: individual particles: columns, plates, etc., and their aggregates, consisting of several particles (example in Fig. 1). A hexagonal column and a plate were used as basic particle models for aggregates (Fig. 1). Column dimensions: height 100 µm, base diameter 69.6 µm; plates: height 15.97 µm, base diameter 100 µm, according to the crystal growth model[20]. The main goal of the study is to study how the elements of the light scattering matrix depend on the number of particles in the aggregates and on their location.

Since the aggregates of cirrus cloud particles are poorly studied, the purpose of this work is to estimate their contribution to the direction of scattering strictly backward for laser sensing problems. For an adequate assessment of the optical and microphysical characteristics of such particles, it is necessary to study many variants of the structure of the aggregate, changing the number of particles in it, of which it consists, and their arrangement. For such a problem, within the framework of the Physical optics approximation, a program was developed that generates many forms of aggregates with a random arrangement of particles in it according to specified parameters (shape, number of particles, etc.). The arrangement of the composite particles in the aggregate occurs according to the following principle: in the center of the coordinate system, a given number of individual particles is created, each of which is rotated by a random angle; then each particle (except the first) moves away from the center in a randomly chosen direction until it ceases to intersect with all other particles. The final aggregate consists of many particles touching each other, but not intersecting with each other, which corresponds to the case of "sticking together" of particles in a cloud.

Based on this assumption, two types of arrangement of particles in the aggregate were chosen: compact and non-compact. To determine the difference between these locations, you must enter a compacity index:

$$C = \frac{L_{avg}}{D_{\min}}; \qquad L_{avg} = \frac{\sum_{i=1}^{n} \sum_{j=i+1}^{n} L_{ij}}{n},$$

where $C$ is compacity index, $L_{avg}$ is the average length between centers of particles in the aggregate, $D_{min}$ is the minimal dimension of the particle (long diameter for column, height for plate), $n$ is the number of particles in the aggregate. According to this variable the compact and the non-compact sets of aggregates with number of particles ($N$) from 2 to 9 for every base particle were built. Geometry models of 9-particle aggregates for every type are shown in Fig. 2. The average length between centers of particles in the aggregate and the compaction index depending on the number of consistent particles are shown in Fig. 3.

For the created aggregates the light scattering matrices were calculated for all scattering angles within the geometrical optics approximation with refractive index of particles 1.3116 (ice water) for the case of arbitrary spatial orientation of particles in a cloud. Since the original version of the Beam-splitting algorithm[17] was not intended to work with aggregates, a modified version of the algorithm for the case of non-convex particles was used for the calculations[21].

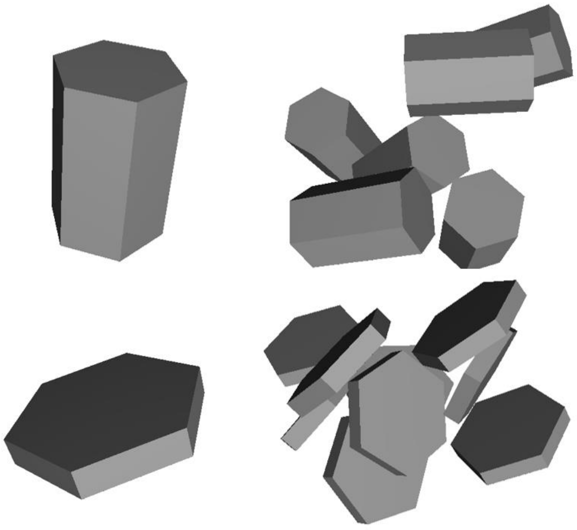

Figure 2. Geometry models of the particles and the 9-particle aggregates: columns (top left), non-compact columns (top right), plates (bottom left), non-compact plates (bottom right)

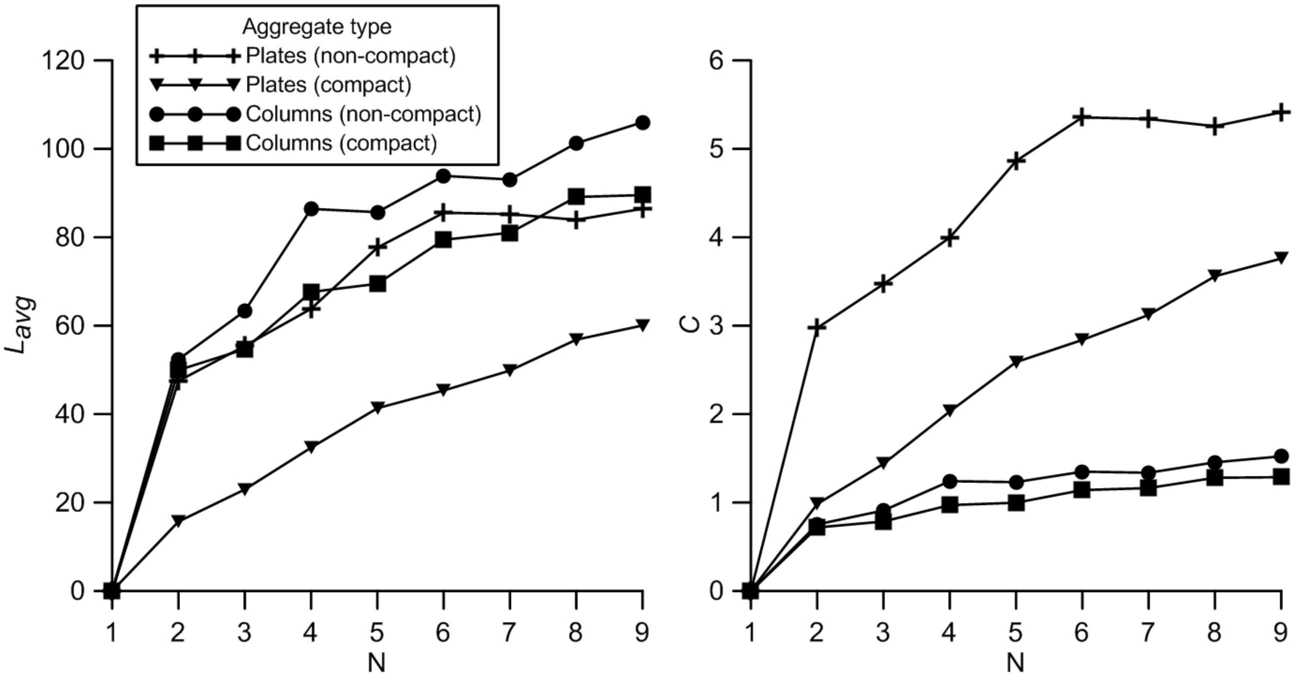

Figure 3. Geometry models of 9-particle aggregates: compact columns (top left), non-compact columns (top right), compact plates (bottom left), non-compact plates (bottom right)

## CALCULATION RESULTS

For the calculated matrices, the dependences of their $M_{11}$, $M_{12}$, $M_{13}$, and $M_{14}$ element on the scattering angle for each aggregate and a single particle are shown in Fig. 3-6. The Fig. 1 shows a similar behavior of the dependences in the entire range for plate aggregates and entire range except region 0-20 degrees for column aggregates.

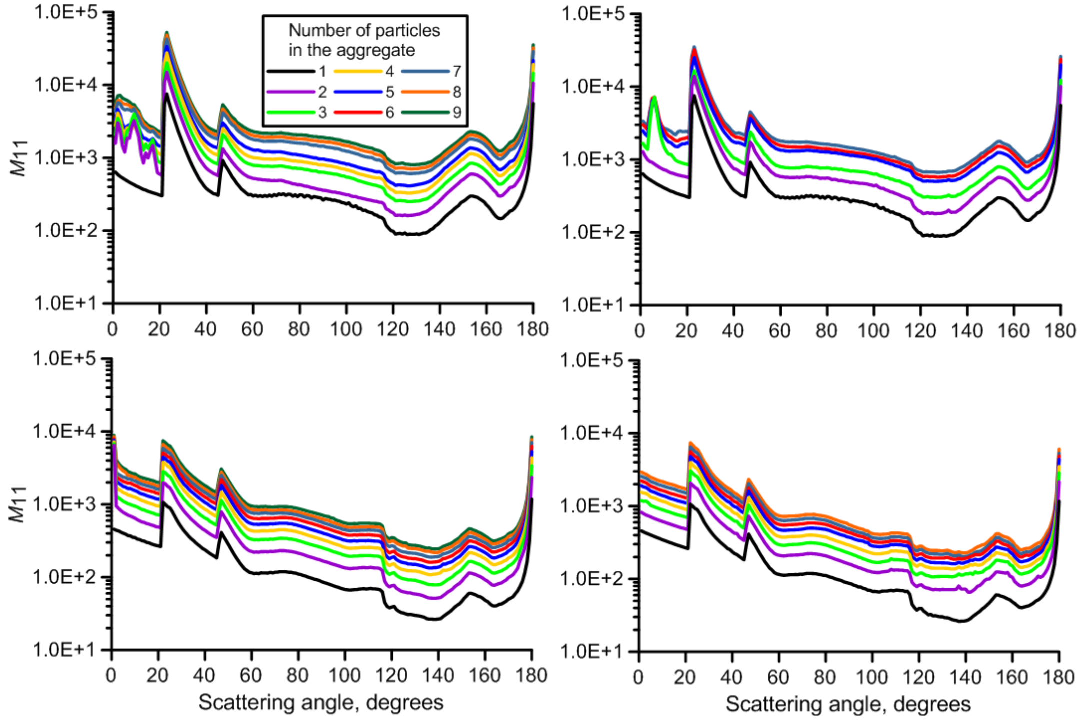

Figure 4. Dependences of their $M_{11}$ element of the light scattering matrix on the scattering angle for the following aggregates: non-compact columns (top left), compact columns (top right), non-compact plates (bottom left), compact plates (bottom right)

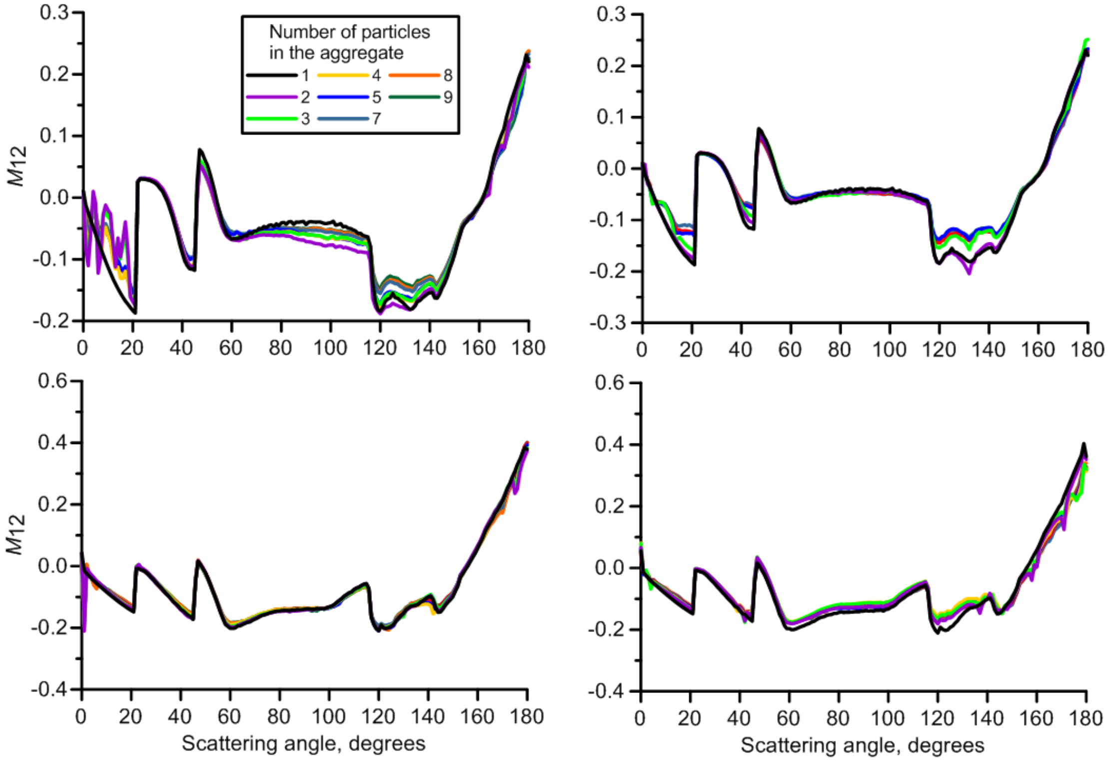

Figure 5. Dependences of their $M_{12}$ element of the light scattering matrix on the scattering angle. Aggregates are the same.

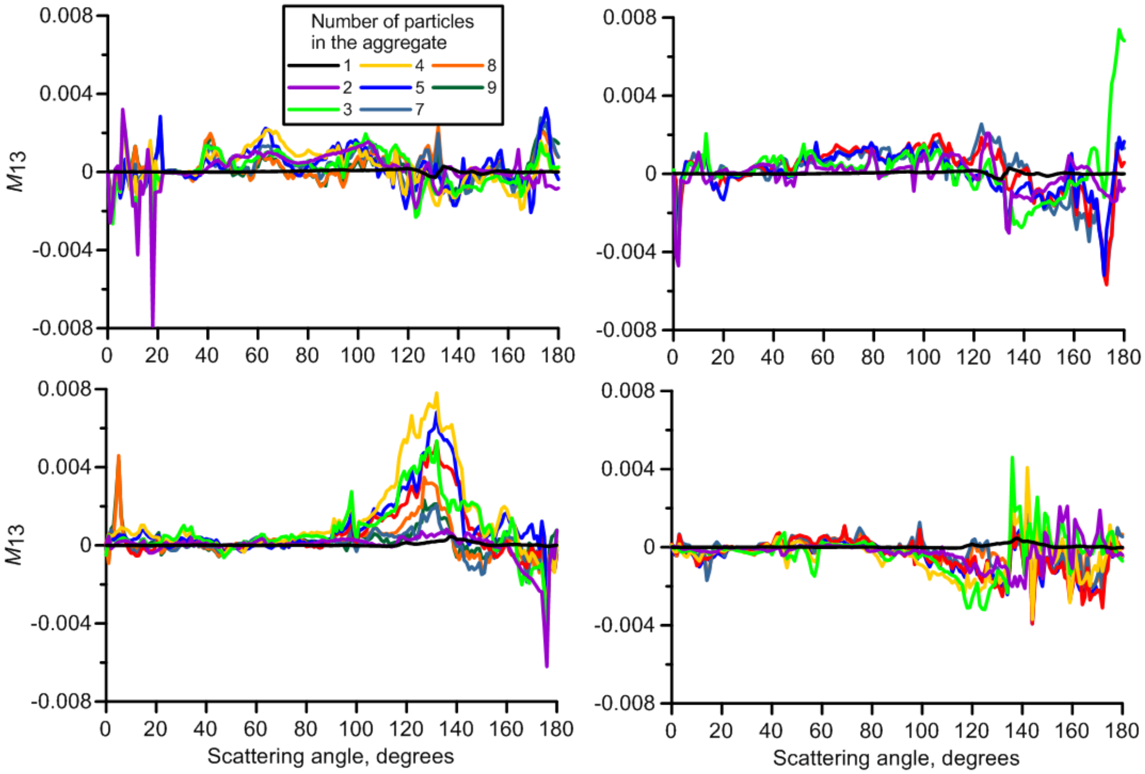

Figure 6. Dependences of their $M_{13}$ element of the light scattering matrix on the scattering angle. Aggregates are the same.

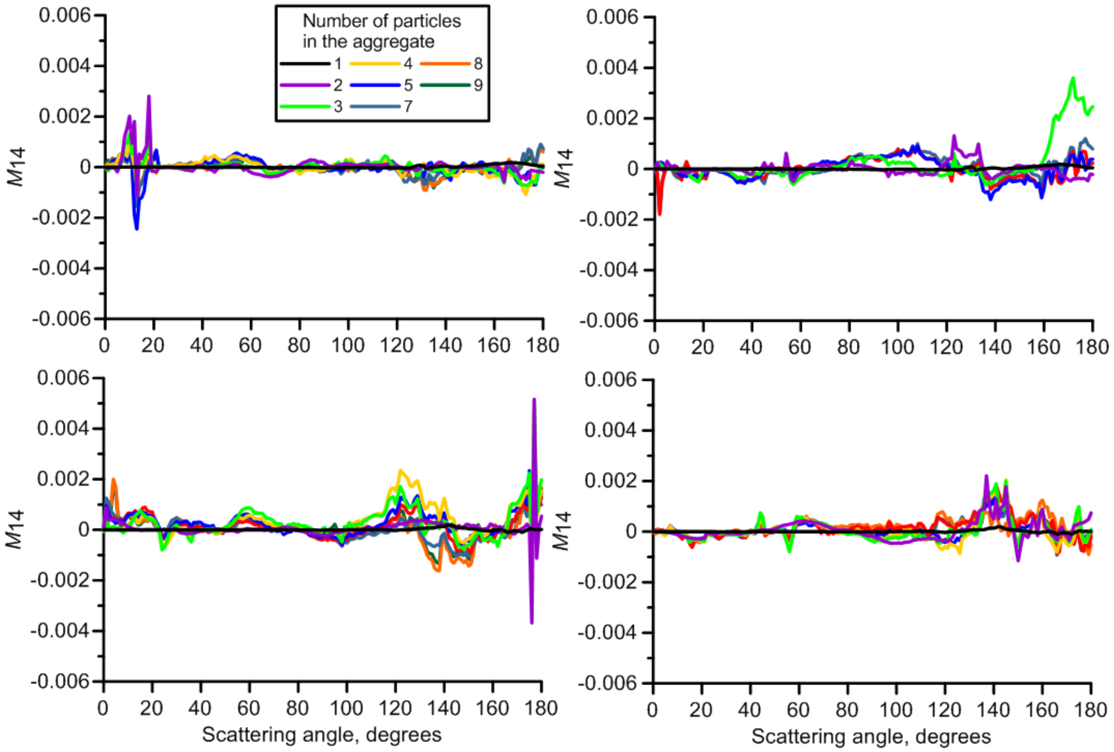

Figure 7. Dependences of their $M_{14}$ element of the light scattering matrix on the scattering angle. Aggregates are the same.

## CONCLUSIONS

Light scattering matrices calculations within the geometric optics approximation for aggregates consisting of hexagonal columns and plates with different arrangement show quasilinear dependences of the first element of the light scattering matrix at individual angles of the phase function of scattering in the angular range from 20 to 180 degrees. This fact can be used to reduce the number of calculations of light scattering matrices for aggregates and to predict their scattering properties based on the solution for one hexagonal particle.

The $M_{11}$ at the angles 0-20 degrees for column aggregates shows not predictable distribution. This fact can be explained by decreasing of energy at the angle of 22 degrees (halo) and redistribution of it to different directions. This energy pike is caused by optical beams that created by side facets of hexagonal particles in the case of singular particle, but it can be disturbed if that beams are redirected by incidence with another particle. For plate aggregates the energy distribution at this angle region is usual because the halo effect occurs not often in hexagonal plates due to its geometry.

It is important to note that the calculation was carried out for two cases of individual arrangement of particles in the aggregate, and the results cannot predict the exact values of the elements of the light scattering matrix for different aggregates. For example, the distribution of M11 in the angular range of 0-20 degrees for a columnar aggregate with a different location may be different. However, the main dependencies are consistent with the initial assumptions. Further studies should consider more examples of aggregates to obtain satisfactory statistics. It is also necessary to calculate the backscattering matrices in the physical optics approximation with the absorption coefficient.

## ACKNOWLEDGMENTS

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