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The Influence of Aspect Ratio and Orientation to Scattering Properties of Ellipsoid Ice Particles

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Abstract

The influence of aspect ratio and orientation to scattering properties of ellipsoid ice particles at 94GHz is studied by Discrete-Dipole Approximation (DDA) method. Absorption efficiency, scattering efficiency, asymmetry factor and backscattering efficiency are computed with aspect ratios vary from 0.2 to 1.0, whose size parameter range are selected from 0 to 5. It is found that the values of scattering properties are increasing if the particle size increases, but if the size is larger than the limit value, oscillation occur, and the oscillation phenomenon will be smoothed by random orientation compared with that of horizontal orientation because scattering properties computed by random orientation method have more average frequency than that of horizontal orientation. In non-oscillating region, the scattering efficiency is larger than the absorption efficiency due to small imaginary part of the complex refractive of ice at 94 GHz, and scattering properties increase if the aspect ratio increases with the same size parameter but this feature is apparent only in the case of horizontal orientation. The asymmetric degree of forward scattering and backscattering increases when particle size increases when size parameter of particle is not exceeding 1.5.

Keywords: *aspect ratio, orientation, DDA, ellipsoid particle, scattering properties, 94 GHz*

1. Introduction

Cirrus cloud, which regularly covers about 20%~30% of the globe, plays an important role in the energy balance of the earth-atmosphere system because it reflects or scatters short wave radiation of the sun, but absorbing the long wave radiation of the atmosphere and the earth's surface [1, 2], studying the radiation characteristics of cirrus and building the database of scattering properties are important [3].

Scattering and absorption characteristics of ice particles in cirrus clouds related to its shape, dimension, orientation, complex refractive index, incident wavelength etc. Orientation of particles, as one of the most important factors to scattering computation, has been discussed [4-7].

Ping Yang [3] studied the optical properties of hexagonal ice crystals with different aspect ratios at random orientation. Lei Chengxin [4] studied the influence of aspect ratio on the scattering properties of small size hexagonal ice crystals in cirrus clouds at 1.06um. Gong Chunwen [5] studied the influence of aspect ratio on the light-scattering properties of small size cylinder ice particles in cirrus cloud by T-matrix method. However, these literatures mainly focus on visible and infrared lights; little literature studies the influence of aspect ratio and orientation on scattering properties of ice particles at 94 GHz, which has unique advantage when detecting dynamic and structural characteristics of cirrus [6].

Because there are ellipsoid particle in cirrus cloud, and some researchers thought it is feasible to calculate the scattering properties of ice particles at millimeter wavelength if we use ellipsoid particle to replace ice crystals with habits of plate, column, and needle [8]. Thus, this paper uses DDA method to study the influence of aspect ratio and orientation on scattering properties of ellipsoid ice particle at 94 GHz, the result can provide a reference for retrieval of ice particles in cirrus cloud.

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2. Introduce of DDA Method

The discrete dipole approximation (DDA) is a general method used to compute scattering and absorption of electromagnetic waves by particles of arbitrary geometry and composition [9, 10]. Initially DDA was proposed by Purcell and Penny packer [9], who replaced the scatter by a set of point dipoles. Draine and Flatau [11] developed the DDA model and provided relevant codes. The principle advantage of DDA is that it is flexible with regard to the geometry of the target. In order to obtain the desired accuracy the inter-dipole space must be sufficiently small when compared to the wavelength, this requires both large computer memory and long computation time when calculate the larger particles [12].

The basic principle of DDA is as follows [6]:

Assuming the polarizability is α_j and the dipole moment is $\overrightarrow{P_j}$ for the jth dipole, the DDA model is attempted to find the solution for a self-consistent set of dipole moments, which can be described with the following formula:

$$\overrightarrow{P_j} = \alpha_j \overrightarrow{E}_{ext,j} = \alpha_j \left(\overrightarrow{E}_{inc,j} - \sum_{k \neq j} A_{jk} \overrightarrow{P_k} \right) \tag{1}$$

Where $\overrightarrow{E}_{inc,j}$ is the electric field at the position j due to the incident plane wave, and $-A_{jk}\overrightarrow{P_k}$ is the contribution to the electric field at the position j due to the dipole at position k. A_{jk} can be expressed by a function of angular wave number K and the relative position of the dipoles j and k. The mathematical expression of A_{jk} can be found in relevant literature [10][11]. Defining $A_{jj} = \alpha_j^{-1}$ reduces the scattering problem to find the dipole moments $\overrightarrow{P_j}$ that satisfy a system of 3N complex linear equations:

$$\sum_{k=1}^{N} A_{jk} \overrightarrow{P_k} = \overrightarrow{E}_{inc,j} \tag{2}$$

Where N is the total number of dipoles. Once (2) has been solved for the unknown polarizations $\overrightarrow{P_j}$, the single scattering parameters including the scattering and absorption efficiencies, the asymmetry parameter and the phase matrix of scattering may be evaluated.

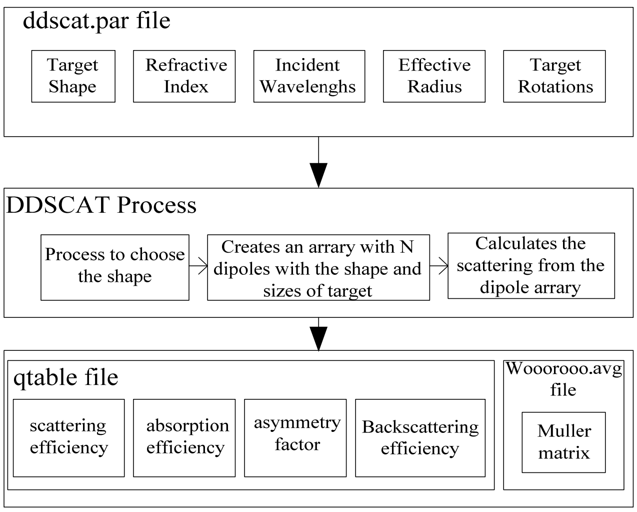

Figure 1. General Process of Computing Scattering Scattering Efficiency, Absorption Efficiency, Asymmetry Factor, Backscattering Cross Section and Phase Function of Target

Figure 1 shows general process of computing the single-scattering properties of studied target. Once the codes of ddscat.par file are correctly set according to actual demand, the single-scattering properties of target can be get after clicking ddscat.exe.

3. The Influence of Aspect Ratio and Orientation on Scattering Properties of Ellipsoid Ice Particles

Definition of aspect ratio of ellipsoid ice particle is as follows:

$$\alpha = b/a \tag{3}$$

Where b is semi- minor axis of ellipsoid, a is the semi-major axis of ellipsoid, which can be expressed as Figure 2.

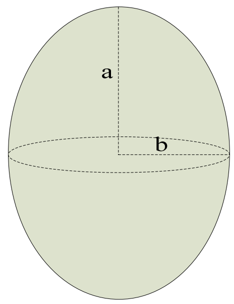

Figure 2. Ellipsoid Particle

The complex refractive index of ellipsoid ice particle is defined as $m = 1.782 + 0.00270i$ in this paper [13], the effective radius of computed ellipsoid ice particle is defined as follows:

$$r_{eff} = (3V / 4\pi)^{1/3} \tag{4}$$

The size parameter of ellipsoid ice particle is:

$$x = kr_{eff} = \frac{2\pi r_{eff}}{\lambda} \tag{5}$$

The ellipsoid ice particle can be horizontal or random orientation. If the ellipsoid is horizontal orientation, the propagation direction of incident electromagnetic wave is parallel to the semi-major axis of the ellipsoid and the ellipsoid ice particle can rotate about horizontal plane, in order to model horizontal orientation in space, we average the scattering properties over about 100 orientations. If the ellipsoid is random orientation, the ellipsoid ice particle can rotate about any direction; we average the scattering properties over 1000 orientations. The scattering properties of absorption efficiency, scattering efficiency, asymmetry factor and backscattering efficiency with the aspect ratio varies from 0.2 to 1.0 can be shown in Figure 3, 4, 5, 6 respectively.

If we multiply the absorption efficiency, the scattering efficiency and the backward scattering efficiency with the geometric cross-section, the absorption cross-section, the scattering cross-section and the backward scattering cross-section can be obtained, which are frequently used in the field of meteorology. The vertical coordinates of Figures (2), (3), (4), (5) use the logarithm of 10 in a base and is multiplied by 10 ($10 * \log(Q_{abs}$ or Q_{sca} or $Q_{bk}))$, the solid line (left part) shows the scattering characteristic of the particle of horizontal orientation and the dotted line (right part) represents the scattering characteristic of the particle of random orientation.

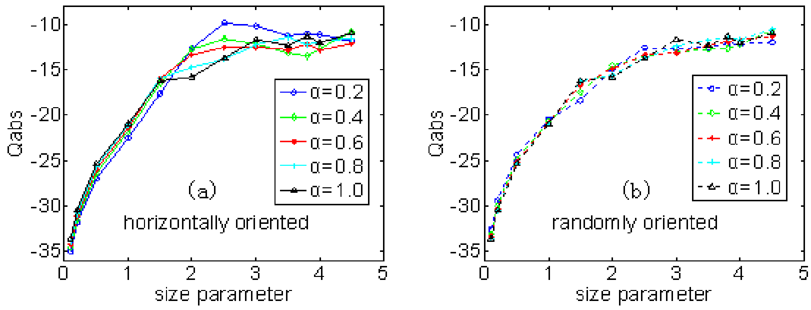

Figure 3. Absorption Efficiency of Ellipsoid Particle with Different Size and Aspect Ratios

Figure 3(a), (b) show the variable trend of absorption efficiency of the ellipsoid particles at the horizontal orientation and the random orientation respectively.

Figure 3(a) shows that: (1) when the size parameter is less than 1.5, the absorption efficiency of the particle increases with the increasing of size parameter, and with the same size parameter or same volume, the absorption efficiency increases if the aspect ratio increases; (2) when the size parameter is larger than 1.5, the oscillating phenomenon happens.

Figure 3(b) shows the variable trend of random orientation, the phenomenon of the absorption efficiency of the particle increases with the increasing of aspect ratio will not happen and the oscillating phenomenon also being weakened compared with Figure 3(a), which can be explained by the effect of average.

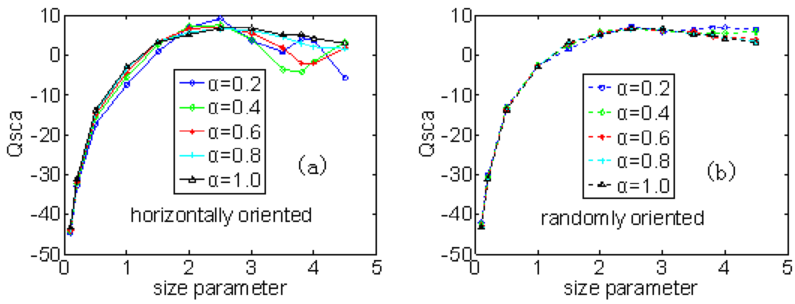

Figure 4. Scattering Efficiency of Ellipsoid Particle with Different Size and Aspect Ratios

Figure 4(a), (b) show the variable trend of scattering efficiency of the ellipsoid particles at the horizontal orientation or the random orientation respectively.

Figure 4(a) shows that: (1) when the size parameter is less than 1.5, the scattering efficiency of the particle increases with the increasing of size parameter, and with the same size parameter or same volume, the scattering efficiency increases if the aspect ratio increases; (2) when the size parameter is larger than 1.5, the oscillating phenomenon happens which means that the relationship between scattering efficiency and size parameter or orientation is not obvious.

Figure 4(b) shows the variable trend of random orientation, the phenomenon of the scattering efficiency of the particle increases with the increasing of aspect ratio will not happen and the oscillating phenomenon also being weakened compared with Figure 4(a) due to the effect of average.

Besides that, compared to Figure 3, the scattering efficiency of the ellipsoidal ice particles is much larger than the absorption efficiency because imaginary part of complex refractive index of ice is small at 94GHz frequency.

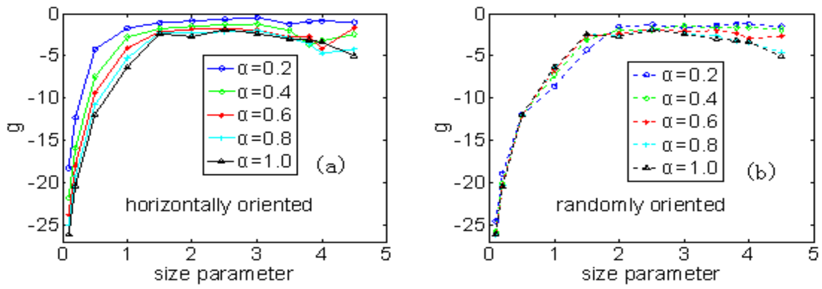

Figure 5. Asymmetry Parameter of Ellipsoid Particle with Different Size and Aspect Ratios

Figure 5(a), (b) show the change trend of asymmetry factor of the ellipsoid particles at the horizontal orientation or the random orientation respectively.

Figure 5(a) shows that: (1) when the size parameter is less than 1.5, the asymmetry factor of the particle increases with the increase of size parameter, and with the same size parameter or same volume, asymmetry factor g increases if the aspect ratio increases; (2) when the size parameter is larger than 1.5, the oscillating phenomenon happens.

Figure 5(b) shows the variable trend of random orientation, the phenomenon of the asymmetry factor of the particle increases with the increasing of aspect ratio will not happen and the oscillating phenomenon also being weakened compared with Figure 5(a).

According to Figure 5, the scatter can be regarded as Rayleigh scattering when particle is smaller than incident wavelength which means asymmetry is small. As the particle's size becomes larger, the energy of incident electromagnetic wave is absorbed when it is refracted into the interior of the particle, the main energy source of scattering characteristic comes from diffraction, which leads to forward scattering is larger than backward scattering and the degree of asymmetry becomes larger.

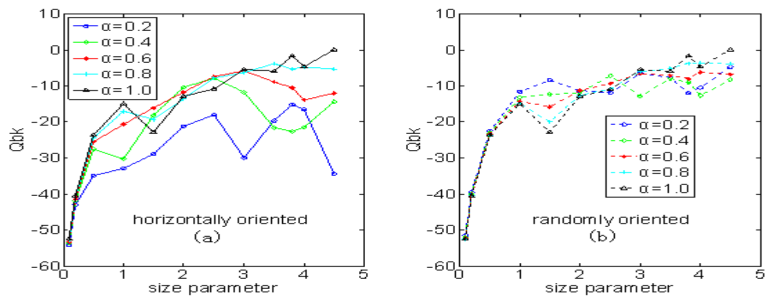

Figure 6. Backscattering Efficiency of Ellipsoid Particle with Different Size and Aspect Ratios

Figure 6(a), (b) show the variable trend of the differential backscattering efficiency (backscattering efficiency is the differential backscattering efficiency multiplied by 4π) of the ellipsoidal particles at the horizontal orientation or the random orientation respectively.

Figure 6(a) shows that: (1) When the size parameter is less than about 1.5, backscattering efficiency increases with the increase of size parameter, and with the same size parameter or same volume, Backscattering efficiency increases if the aspect ratio increases; (2) When the size parameter is lager than about 1.5, the oscillation occurs.

Figure 6(b) shows the variable trend of random orientation, the phenomenon of the backscattering efficiency of the particle increases with the increasing of aspect ratio will not happen and the oscillating phenomenon also being weakened compared with Figure 6(a).

4. Conclusion

The paper analyses the influence of the particle size parameter, aspect ratio and orientation on scattering properties using the discrete dipole Approximation (DDA) method at 94GHz frequency. The result shows that: when the size parameter of ice particle is less than a limit value (typical value 1.5) in this paper, the scattering properties of the ellipsoid ice particles increase with the increasing of the size parameter whether at horizontal orientation or at the random orientation, and with the same size parameter or same volume, the values of scattering properties increase if the aspect ratio increases except asymmetry factor. When size parameter exceeds a limit value (1.5), oscillation phenomenon occurs. The scattering efficiency is much larger than the absorption efficiency; the reason is that the imaginary part of complex refractive index of ice is small ($\varepsilon_i \approx 0.0027$) at 94GHz frequency. Ellipsoid ice particle's forward and backward scattering asymmetry increases with the increasing of size parameter until it reaches the limit value. This paper established a database between the scattering characteristic and the ellipsoid particles and providing a reference for millimeter-wave radar to detect the ellipsoid ice particles.

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