The polarization characteristics of randomly oriented nonspherical ice particles in mm and sub-mm frequency range: Implications to the remote sensing of cirrus clouds using satellite microwave radiometry

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Abstract – The depolarization effects of randomly oriented nonspherical ice particles are studied for frequencies ranging from 90 to ∼900 GHz. It is found that, given the particle shape and the working frequency, the brightness temperature difference between the vertical and the horizontal polarization measured by a space-borne radiometer is only sensitive to ice particles of sizes within a certain range. The center of this range moves from >1000 μm to ∼120 μm for nearly spherical particles when the frequency changes from 90 to 874 GHz. The particle size given here is the median mass equivalent sphere diameter. This range also changes with the particle shape. Generally, particles with a greater aspect ratio show a stronger depolarization effect by larger sizes. These features suggest that radiometric measurements from satellite on the polarization difference may be useful in determining ice particle size and shape in the cirrus clouds.

1 Introduction

Recent studies show that multi-channel radiometric measurements from satellites in the mm and sub-mm frequency range are very useful in quantitatively determining the integrated ice content and the characteristic particle size of cirrus clouds [1]. A mm and sub-mm radiometer has been thus proposed recently for a future cloud monitoring satellite [2]. Although the use of two orthogonal polarizations has been discussed in [1] and is provisionally proposed in [2] for the mm and sub-mm radiometer, it is still not very clear how helpful the information on polarization difference will be in determining the microphysical parameters like characteristic size, shape, and orientation of the ice particles in cirrus clouds.

To solve this problem, fully polarized radiative transfer simulations in the mm and sub-mm frequency range for clouds composed of ice particles having realistic size, shape, and orientation are needed. As a first step of this effort, simulations were carried out for ice clouds consisting of randomly oriented non-spherical particles and by considering only the single scattering effect. Some interesting results are obtained and reported in the next sections.

2 The Depolarization Effect of Rondomly Oriented Nonspherical Ice Particles

At first we look the depolarization effect of a single ice particle with random orientation. To follow the definition of [3], the degree of linear polarization for single scattering of unpolarized light, LP, is given by

$$LP(\theta) = -F_{12}(\theta)/F_{11}(\theta)\,, \tag{1}$$

where $F_{12}(\theta)$ and $F_{11}(\theta)$ are the elements (1,2) and (1,1) of the scattering matrix $\mathbf{F}$ [4]. The particle shapes considered here include three types: the nearly spherical, the cylindrical and the plate-form particles. The single scattering properties of the nearly spherical particle is represented by the average of those calculated for spheroid and cylinder with aspect ratio less than 1.5. The aspect ratio denotes the ratio of the maximum to the minimum dimension of the particle. For cylindrical (plate-form) particles we use the circular cylinder (plate) as a representative, because we find that for random orientation the difference between a circular and a hexagonal cylinder (plate) is rather small. To calculate the scattering matrix, the software packages provided by [5] for the T-matrix method and by [6] for the DDA method are used.

We found that, for nearly spherical particles, the integral photometric characteristics (scattering and absorption cross section, single scattering albedo, etc.) are very close to those of an equivalent sphere. However, the scattering matrices for sphere and nearly spherical particle are rather different, especially in the element F_{12}, which is directly related to the depolarization effect of the particle. In the Rayleigh region where a prominent feature of scattering is the nearly full depolarization ($LP = 1$) in the direction with the scattering angle of 90°, the difference between spheres and nearly spherical particles is small. But as the particle becomes larger and the scattering is beyond the Rayleigh region, the difference becomes rather prominent. Spheres show a very strong oscillation in LP with the change of particle size (see Figure 1); whereas nearly spherical particles show a much weak oscillation (not shown). For cylindrical and plate-form particles, we found that their polarization characteristics depart significantly from that of a sphere. With the increase of the aspect ratio, the Rayleigh region for both cylinders and plates expands to larger sizes, although in different rates. This expansion is especially significant for cylinder. For example, at 463 GHz, a particle with a maximum size of 2 mm will be far beyond the Rayleigh scattering region if it is a sphere. But, when it is a cylinder with an aspect ratio of 9, it still shows Rayleigh scattering feature. Figure 1 shows the comparison between sphere and cylinders.

3 The Polarization Difference Measured by a Space-borne Radiometer

To relate the polarization difference measured by a space-borne radiometer with the microphysical parameters of cirrus clouds, radiative transfer simulations were done for the case of US standard atmosphere. The cirrus cloud is assumed to be a single-scattering medium and located at the height of 10 km. Ice particles within the cloud are assumed to be randomly ori-

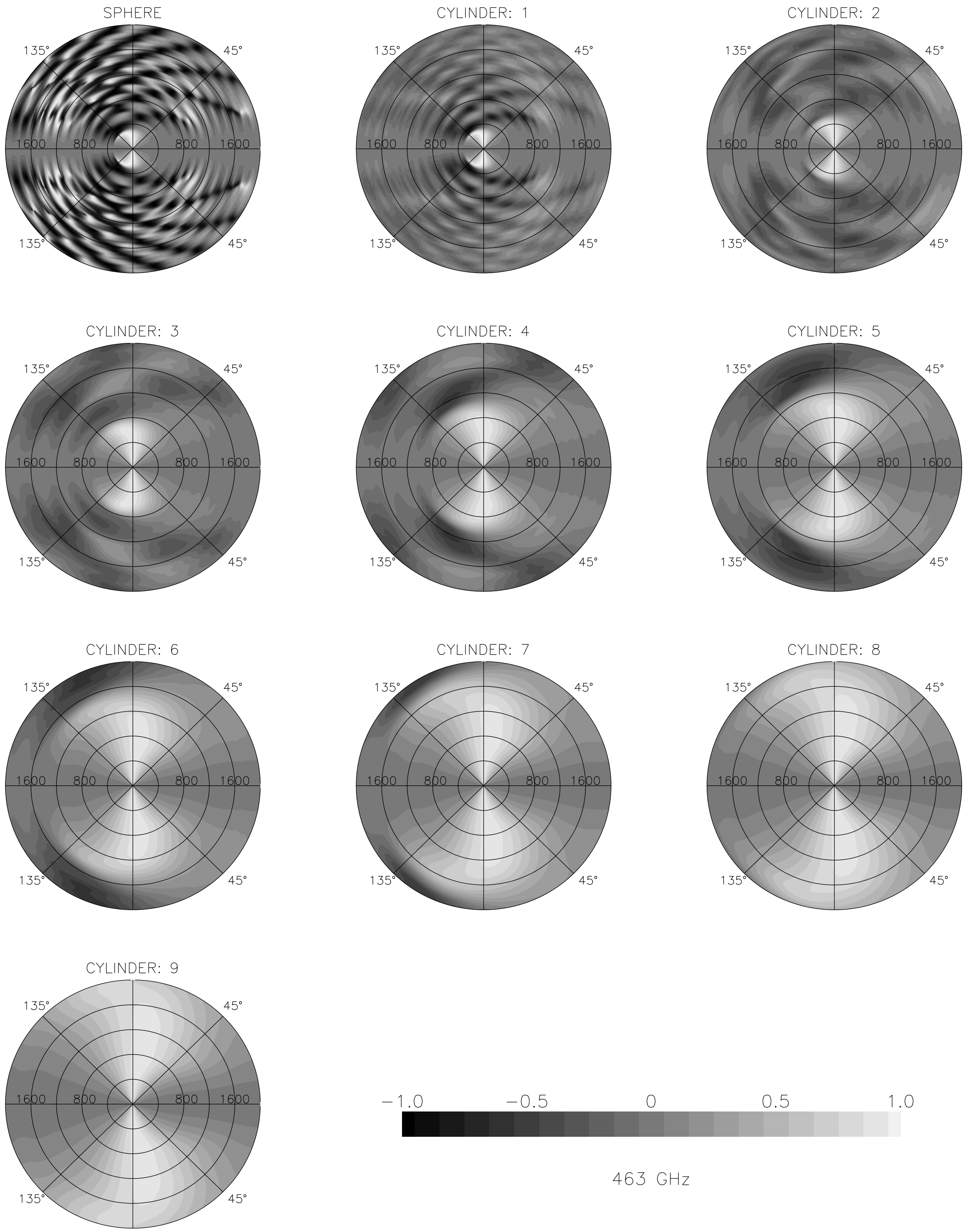

Figure 1: The LP of a sphere and some cylinders with aspect ratios from 1 to 9. Unpolarized light is coming from the left side. The scattering angle is indicated at the edge; the maximum dimension of the particle size (in units of μm) is shown on the radial axis.

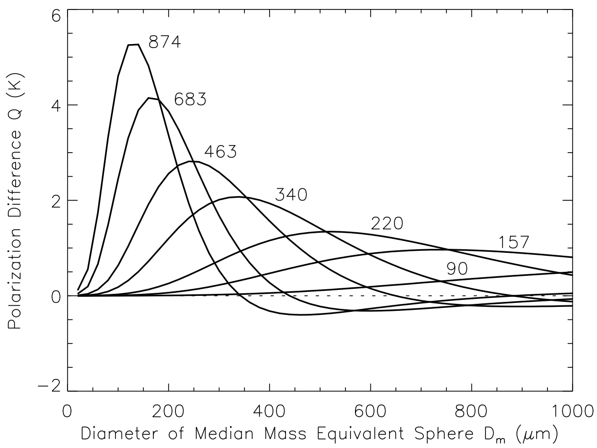

Figure 2: The polarization difference Q measured by a space-borne radiometer at a satellite zenith angle of $54°$. The ice cloud consists of nearly spherical particles with a modified gamma size distribution ($\alpha = 1$); the integrated ice content along the line of sight is $100\,\mathrm{g\,m^{-2}}$.

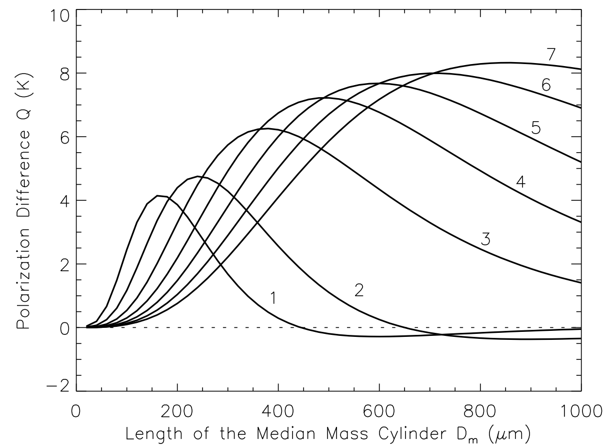

Figure 3: Same as Figure 2 but for a single frequency of 683 GHz and for clouds composed of randomly oriented ice cylinders with aspect ratios ranging from 1 to 7.

ented and to be distributed in the particle maximum dimension according to the modified gamma function [7] as

$$N(D) = aD^{\alpha} \exp(-\frac{\alpha + 3.67}{D_m} D)\,, \qquad (2)$$

where a is a constant and α is the width parameter usually ranging from 0 to 2. Parameter D_m is the median of the distribution of the dimension D to the third power if D extends to infinity. But usually this function is truncated, for example, here at 2 mm. The simulated polarization difference Q (in units of kelvins), observed by a space-borne radiometer with two orthogonal polarization channels, is found to show its maximum sensitivity in satellite zenith angles around $60°$. At a fixed satellite zenith angle (e.g., $54°$), the polarization difference Q shows its maximum response at a size which is inversely proportional to the observing frequency; below and beyond this size Q is approaching zero. At frequencies of 90, 157, 220, 340, 463, 683, and 874 GHz, the corresponding sizes with maximum Q for nearly spherical particles, when expressed in diameter of the median mass equivalent sphere, are >1000, ~ 800, ~ 550, ~ 350, ~ 250, ~ 170, $\sim 120\,\mu$m, respectively (see Figure 2 for details). For clouds composed of ice particles like cylinders or plates, the position of the maximum polarization difference observed from satellite will shift to larger particle sizes, as the the aspect ratio of the particle increases. This is a result of the expansion of the Rayleigh region as discussed in the preceding section. More details are shown in Figure 3.

4 Concluding Remarks

The depolarization effect of randomly oriented ice particles is studied at the mm and sub-mm freuqency range. Preliminary results show that the polarization difference measured from satellite has a unique relationship with the ice particle size and shape, which shows the potential of polarization difference measurements in precisely determining the particle size and shape of cirrus clouds. Future studies will consider the effects of shape mixture of particles and of the multiple scattering.

5 Acknowledgment

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