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# Effects of ice particle shape and orientation on polarized microwave radiation for off-nadir problems

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**Abstract.** The effect of ice crystal shape and orientation from high altitude clouds (9 to 10 km height) on the angular distribution and state of polarization of microwave radiation emerging from the earth's atmosphere is investigated. The potential effects of nonspherical shapes are studied at 200 GHz and for two different shapes: Oblate and prolate spheroids with a preferred orientation of the axis of symmetry and an aspect ratio of 5.0 and 0.2, respectively. The results show strong effects of shape and orientation on both the total intensity and polarization state. Propagation directions close to the horizontal are of special interest to troposphere/lower stratosphere microwave limb-sounding investigations. Although the presented calculations do not consider realistic ice clouds with hexagonal particles and the limb sounding geometry is not explicitly taken into account, the results obtained for large off-nadir angles lead to the conclusion that particle shapes, especially in case of particles with preferred axis of orientation, have a significant effect on intensity (up to 15 K) and polarization difference (up to 30 K).

## Introduction

Remote sensing of the atmosphere with microwave frequencies requires precise radiative transfer models which include the effect of multiple scattering. At high microwave frequencies, e.g. 200 GHz, even small particles (cloud droplets) become comparable to wavelength. Ice particles in cirrus clouds are often hexagonal cylinders of different aspect ratios, forming needles or plates[*Heymsfield and Platt*, 1984]. Due to the limitation of the analytic Lorenz-Mie theory to spherical scatterers one has to use numerical models for the treatment of scattering by such nonspherical ice crystals. For solar radiation the scattering process can be calculated with the geometric optics approximation[*Macke*, 1993]. For the microwave spectral region the amplitude scattering function (ASF), which is based on the solution of Maxwell's equations, must be calculated first. From the ASF the interaction parameters can be derived[*Tsang et al.*, 1995].

Recent studies on nonspherical hydrometeors were limited to orientational averages of particles[*Haferman et al.*, 1997] resulting in a simpler formulation of the scattering problem. The effect on microwave radiation due to scattering by cirrus particles with preferred orientation was adressed by Evans and Stephens [*Evans and Stephens*, 1995a, b] using the discrete dipole approximation (DDA): Different shapes (mainly columns and plates) were randomly orientated in the horizontal plane in order to study the sensitivity of brightness temperature depression ($\Delta T_b$) at the top of the atmosphere at two zenith angles (0° and 49° as a function of the ice water path (IWP). They found sensitivities ($\Delta T_b$/IWP) of about 0.1 $K\,g^{-1}m^2$ for 220 GHz, depending on size distribution and particle shape. The different sensitivity of vertical and horizontal polarization for different shapes at 49° zenith angle was explained as an effect of particle shape (mainly the aspect ratio).

This study will report that the polarization induced by nonspherical particles as well as the brightness temperature depression show a strong variation along the viewing angle. The investigation was carried out with numerical calculations which cover the full range of zenith angles from nadir to 180° throughout the whole atmosphere. Although the results are based on a simplified particle shape the results of Evans and Stephens could be reproduced within the expected ranges (taking into account the different size distributions used). Calculations at 200 and 340 GHz lead to nadir sensitivities of 0.17 and 0.65 $K\,g^{-1}m^2$, respectively. The effect of polarization at 49° could be confirmed, too: e.g. at 200 GHz higher sensitivities for horizontal polarization (0.13 $K\,g^{-1}m^2$) than for vertical polarization (0.06 $K\,g^{-1}m^2$) were obtained, leading to a positive polarization difference (PD, defined as $I_v - I_h$).

This paper gives special consideration to the radiation in off-nadir directions close to the horizontal, where very large variations of both the brightness temperature and PD are observed. The origin of polarization can not be understood as an effect of particle shape only, but as combined effect of shape and orientation of the ice crystal together with the directional variation of radiation in the vicinity of the scattering particle. The distribution of radiation within the atmosphere is thus a main target of this investigation.

Recent studies have shown the importance of the knowledge of particle shape on one hand and the consideration of anisotropic radiation (directional variation) on the other hand[*Liu and Simmer*, 1996; *Czekala et al.*, 1998]. The effects of nonspherical shape strongly depend on the direction of observation and becomes especially interesting when approaching horizontal direction.

The comparison of results obtained with Lorenz-Mie theory and results depending on full nonspherical scattering theory is difficult. One has to define the equivalent ensemble of spheres that is compared with the ensemble of nonspherical particles. There are different approaches to this task and each of them has its own limitations. Defining an effective diameter using an equivalent projected area of a particle neglects the effect of the particle's volume, which is important in the single scattering calculation. The following calculations use an effective radius defined by equal volumes of spherical and nonspherical particles. For all methods the

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size parameter in the case of large aspect ratios of the scattering particle is underestimated: Because spheres have a minimum radius per unit volume a needle- or plate-like crystal will lead to an equivalent drop size that is much smaller than the largest dimension of the nonspherical crystal.

## Radiative Transfer Model

The calculations presented in this report were carried out with the microwave radiative transfer model MWMOD developed by Simmer[*Simmer*, 1994] and recently extended to nonspherical scattering by Czekala[*Czekala et al.*, 1998]. The model uses plane parallel layers and an arbitrary set of discrete zenith angles to describe the atmosphere and the radiation field within. The radiative transfer equation is solved with the successive order of scattering method. Absorption of gases is calculated using Liebe's MPM code[*Liebe et al.*, 1993]. Interaction parameters for extinction, emission and scattering at spheres are calculated according to Lorenz-Mie. For single scattering parameters of nonspherical particles the T-Matrix code from Mishchenko[*Mishchenko et al.*, 1996] is used to calculate the ASF. From the ASF the absorption vector, extinction matrix and scattering phase matrix are computed[*Tsang et al.*, 1995]. Due to the current implementation of the single scattering model in the radiative transfer model the calculations are restricted to spheroids which have a fixed orientation with their rotational axis aligned to the vertical. Profiles of temperature and water vapor are taken from a modified US-standard profile which has a temperature of 225 Kelvin at the tropopause.

Investigations on the sensitivity to particle shape are carried out under very simplified conditions: An ice cloud is positioned between 9 and 10 kilometers height. The particle size distribution is exponential with a maximum radius of 200 $\mu$m. The ice water content is fixed to $0.05\,\mathrm{kg/m^2}$. For nonspherical calculations the volume of the spheres is converted to spheroids with a fixed aspect ratio of 5. This shape is used as an approximation of ice disks that are supposed to be found in cirrus clouds. The second shape is a spheroid with an aspect ratio of 0.2, having similarities with needle-like crystals with their longest axis orientated along the vertical. The latter configuration is not meant as a realistic scenario, but helps interpreting the results obtained with the oblate particles. The choice of 200 GHz was motivated by investigations related to the MASTER instrument (Millimetre-wave Acquisitions for Stratosphere — Troposphere Exchange Research), which is designed with frequency bands between 200 and 500 GHz.

## Application to off-nadir Directions

The radiative transfer code produces reliable results for plane parallel atmospheres and angles between nadir and 85° zenith angle. Closer to the horizontal the results become less accurate due to resolution effects: In each hemisphere the angle which is closest to the horizontal represents the intervall up to 90° and therefore produces poor results, but for all other angles the results are reliable. A set of 16 angles per hemisphere is choosen with the last seven angles close to the horizontal: 79°, 83°, 85°, 86°, 87°, 88°, and 89°. This angle selection scheme results in a increased resolution along the tangent direction, reducing the stepwise transition between upwelling and downwelling radiation in transparent atmospheres.

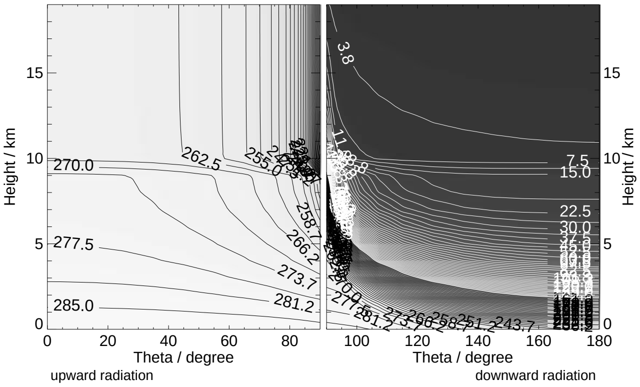

**Figure 1.** Brightness temperature with respect to vertical position and direction of propagation: Zero angle means nadir upward direction, 90 degree is the horizontal and 180 degree is directed downward. This plot is calculated for 200 GHz and a cloud consisting of oblate spheroids with an IWC of $0.05\,\mathrm{kg/m^2}$.

This vector radiative transfer model is not able to produce correct results for limb-viewing geometry, which requires spherical geometry. Tangent directions in a horizontal infinite model will lead to infinite optical path lengths, resulting in infinite total optical thickness. But the sensitivity of intensity and polarization at angles close to the horizontal can be studied in order to get an impression of the effects to be expected for limb-sounding.

This assumption is based on the fact that along the limb path between the tangent point and the sensor all radiation is emerging in upward directions from the atmospheric plane parallel layers. So the effects observed close to the horizontal, but in upward directions, give a good indication about the relevant processes.

## Results

### Influence of Shape on Intensity

The resulting distribution of radiation with angle and height for a cloud consisting of oblate spheroids is shown in Fig.1. Above the cloud the intensity depends almost only on viewing angle, below the cloud the intensity is also depen-

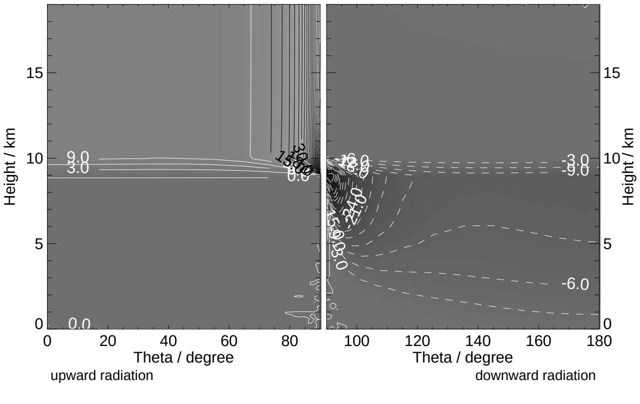

**Figure 2.** Brightness temperature depression (clear minus cloud) for oblate spheroids (all other parameters as in Fig.1).

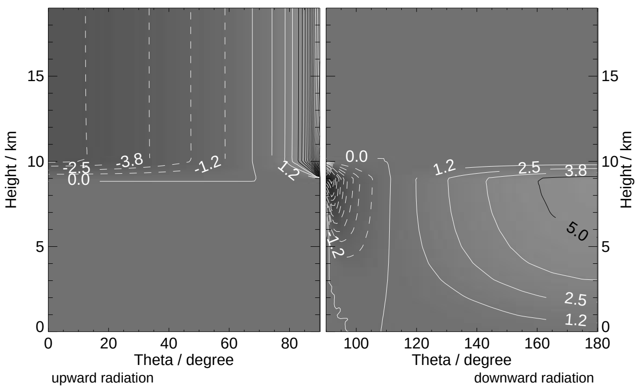

**Figure 3.** Brightness temperature difference between oblate spheroids and spheres (all other parameters as in Fig.1).

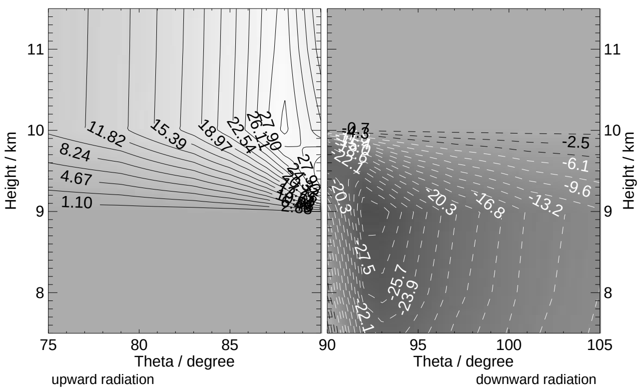

**Figure 5.** Subset of polarization difference for oblate spheroids (all other parameters as in Fig.1).

dent on the height. Within the cloud the radiation decreases with height (close to nadir) and also with the off-nadir angle.

The brightness temperature depression ($\Delta T_b$) caused by the ice cloud compared to a cloud free atmosphere is shown in Fig.2. A small variation of $\Delta T_b$ around the nadir direction is followed by large variations closer to the horizontal. Comparison of spherical and nonspherical calculations (Fig.3) show some remarkable results: Oblate ice crystals lead to an increased depression of brightness temperature in nadir directions and a less effective depression at higher zenith angles. The reason for this behaviour is the scattering efficiency of the oblate spheroids, which has a maximum in nadir directions and drops below the scattering efficiency of spheres when approaching 90°.

As a general rule of thumb, this effect changes its sign when switching either to downward directions or to prolate crystal shapes (Fig.4). The differences between spherical and nonspherical results reach values of up to 10 K for both shapes, depending on direction.

This observation suggests that the large differences in total intensity and their angular variation can be explained by polarization effects: Nonspherical particles lead, in general, to a higher polarization ratio. But the extinction depends very strongly on direction and polarization. So the combination of polarizing the thermal emission from the atmosphere below and then adapting to the effect of polarization dependent extinction and absorption coefficients lead to results that can not be obtained with radiative transfer calculations restricted to total intensity.

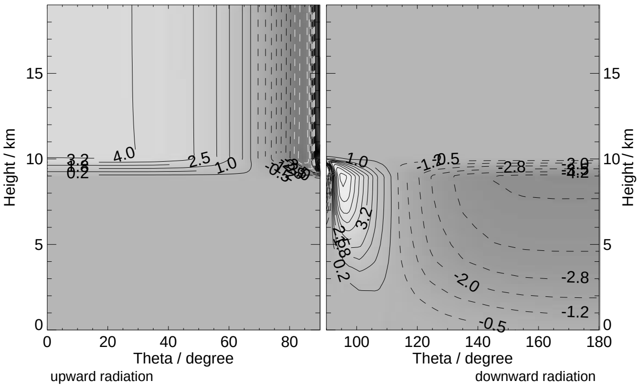

**Figure 4.** Brightness temperature difference between prolate spheroids and spheres (all other parameters as in Fig.1).

### Influence of Shape on Polarization

As pointed out above the effect of nonspherical ice clouds on polarization is remarkable. The variable of interest is the PD, which is defined as $(I_v - I_h)$. An ice cloud with oblate particles leads to postive PDs at upward directions, whereas negative PDs occur at downward directions and zero PD close to nadir in both cases. This behaviour is reversed when switching from oblate to prolate spheroids and will not be discussed here in detail.

Investigations on the distribution of intensity with the direction of propagation as well as vertical position clearly show that all polarization is produced by the combination of particle shape (and the scattering function that originates from that shape) and the non-isotropic radiation in the vicinity of the particle. Close to the horizontal the variation of intensity within the cloud is strongest, producing a PD above 20 K near 85° zenith angle. Figure5 shows the PD in more detail for a smaller angle range close to the horizontal.

Previous investigations[*Czekala et al.*, 1998] with lower frequencies, but larger particles, have shown that the polarization difference tends to be much lower when radiation is similar in all directions of propagation. In order to prove this statement the results of an artificial test case are investigated: The same cloud is positioned between 4 and 5 kilometers, leading to higher opacities and therefore to a more isotropic radiation. The resulting PDs are reduced by a factor of ≈ 5 within the cloud, before further damping of the PD above the cloud.

But in the earth's atmosphere the total optical thickness (in a particular direction) and therefore the radiation intensity shows a very strong variation around the horizontal. This makes the limb-sounding geometry highly sensitive to all kinds of polarization effects.

## Conclusions

Although the geometry of the designed model is not able to calculate real limb-sounding geometry this paper shows that large errors can be be expected when radiative transfer is computed applying Lorenz-Mie theory to cirrus clouds. The effect of particle shape on both, intensity and polarization, is large and complicated. Furthermore it is essential to state again[*Hansen*, 1971] that polarization should not be neglected, even if only the total intensity is of interest.

The nonspherical shapes used in this study are extreme examples with respect to particle orientation and therefore produce stronger effects than expected in reality. These simplifications enable us to study the basic processes in nonspherical microwave scattering, but there are more realistic particle shapes to be investigated as well as realistic orientations. A particle of interest is the polycrystal introduced by Macke[*Macke et al.*, 1996], which is a good approximation to a irregular shaped cirrus particle in the visible region.

Polarization effects, originating from nonspherical ice crystals, show a strong dependance on orientation of the particle and viewing geometry. In order to understand the polarization of radiation, which may be used for remote sensing of clouds, the knowledge of the directional radiation distribution within the cloud is essential.

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