Single Scattering of Partly Oriented Aspherical Cloud Ice Crystals at Sub-millimeter Wavelengths

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Abstract— **The recently suggested sub-millimeter sensors for the global observation of cirrus clouds all bear several channels widely separated from each other and spanning the range from 180 to 880 GHz. While the potential of retrieving the integrated ice water content and the mean effective particle size of ice clouds has been investigated, the quantitative retrieval of particle shape and orientation information is still an active research area. Here we investigate the influence of the parameters of a Gaussian distribution of the horizontal particle orientation on The single scattering cross section. It is only slightly affected, but the polarization signal is reduced to 90% of the completely horizontally oriented case if the standard deviation σ_β of the horizontal distribution is 15° and reduced to 50% if $\sigma_\beta = 30^\circ$.**

I. Introduction

Although cirrus cloud play a crucial role in the atmospheric radiation budget, our present knowledge of cirrus cloud distribution, properties and how to handle cirrus clouds in GCMs and in numerical weather forecast models is still insufficient. In order to obtain daily global cirrus information, space borne passive millimeter and sub-millimeter sensors have been suggested [1], [2], [3]. As a common feature, they all bear several channels widely separated from each other spanning the range from 180 to 880 GHz. While the potential of retrieving the integrated water content and the mean effective particle size (D_{me}) of ice clouds from sub-millimeter sensors has been demonstrated, [2], the quantitative retrieval of the particle shape and orientation is still an active research area. It has been shown that information about the shape can be obtained from the polarization signal, generated by the scattering of the aspherical ice particles, preferentially oriented horizontally [4]. This paper contributes to the single scattering properties of frequently met pristine particle shapes, namely prolate (columns) and oblate (plates) ellipsoids and circular cylinders by investigating the influence of partly horizontally oriented ice crystals on the total extinction and scattering cross sections.

The degree of horizontal orientation is important to know because it influences the ice cloud albedo and hence the Earth radiation budget [5], but we only have poor information on it: On the one hand, based on laboratory studies, lidar observations and theoretical modeling, a preferred horizontal orientation of the crystals 'within few degrees' has been reported [4]. On the other hand, using the specular reflection globally observed with the POLDER instrument aboard ADEOS as a signature of the horizontal orientation, only in about 40% of the pixels with suitable observing conditions specular reflection is really observed [5]. Therfore it is worthwhile to check the potential of passive sub-millimeter observations to determine the degree of horizontal orientation. Here we investigate as a first step the influence of a partly horizontal orientation on the single scattering properties of ice crystals.

II. Ice Crystal Models

A. Shape and composition

Four pristine ice crystal shapes are considered: Each prolate (columns) and oblate (plates) ellipsoids and circular cylinders with aspect ratios varying from 1 to 5 (plates) in steps of 1 and from 1 to 0.2 in steps of 0.2 (columns). While the ellipsoids comprise spherical particles as reference case with circular symmetry, the cylinders are a good approximation of the hexagonal plates and columns frequently occurring in ice clouds. The length of the particles is varied in steps of 0.1 up to 5 mm. The refractive index is set to the one of pure ice at 183 GHz and -20°C: $n = 1.786 + 0.0049i$ [6]. The influence of the variation of the refractive index with temperature in the range from -5°C to -60°C is neglible.

B. Orientation

The orientation of the crystals is described by the three Eulerian angles: α and β are the azimuthal and polar angles, respectively, of the rotational axis in the laboratory coordinate system with the z-axis aligned in the vertical direction, and the rotation angle γ of the crystal around its symmetry axis. In order to investigate the influence of the degree of orientation on the signal of a sub-millimeter sensor, the polar angle β is assumed to have a truncated Gaussian distribution ($N(m_\beta, \sigma_\beta)$) [7]

$$p(\beta) = \frac{1}{C_0} \exp\left(-\frac{(\beta - m_\beta)^2}{2\sigma_\beta^2}\right) \sin\beta \qquad 0 \le \beta \le \pi/2$$

$$C_0 = \int_0^{\pi/2} \exp - \frac{(\beta - m_\beta)^2}{2\sigma_\beta^2} \sin\beta \, d\beta$$

with m_β the mean and σ_β the standard deviation. For plates, we have $m_\beta = 0$, for columns $m_\beta = \pi/2$.

III. Computations

We have calculated the total scattering cross section

$$C_{sca} = \frac{1}{I^{inc}} \int_{4\pi} I^{sca}(\mathbf{n}^{sca})\, d\mathbf{n}^{sca}$$

with the scattered intensity

$$I^{sca} = Z_{11} I^{inc} + Z_{12} Q^{inc}$$

and the total extinction cross section

$$C_{ext} = \frac{1}{I^{inc}} [K_{11} I^{inc} + K_{12} Q^{inc}]$$

with K_{ij} elements of the extinction matrix $\mathbf{K}$ and Z_{ij} elements of the phase matrix $\mathbf{Z}$ [8], both determined from the amplitude matrix $\mathbf{S}$, the latter determined with a public T-matrix code [9] in double precision arithmetic and assuming an observation angle of 56° with zenith.

For the incident radiation of frequency 183 GHz (wavelength 1.639 mm), the three polarization states unpolarized, vertically and horizontally polarized have been considered, corresponding to $(I^{inc}, Q^{inc}) = (1, 0)$, $(1, 1)$ and $(1, -1)$ respectively. The integration over the incident beam was done in steps of 5°. The polar orientation angle β was also varied in steps of 5°, at each step averaging over the azimuthal angle α from 0 to 170° in steps of 10°.

IV. Results

The figure shows the results for oblate (left column) and prolate cylinders (right column), the results for ellipsoids (not shown here) are similar. The total extinction and scattering cross sections (top row) are normalized to the volume of the particles so that all curves are of similar height. For all particles we observe a stretching of the cross sections as the aspect ratio ϵ departs from 1 (yellow) towards smaller (oblate, down to 0.2 (violet)) or larger (prolate, up to 5 (violet)) values, that is, equal-volume particles with high aspect ratio behave similar as nearly spherical, but larger ones. This 'asphericy stretching' of the length scale is much more pronounced for prolate than for oblate particles. A distribution of β around the horizontal orientation with $\sigma_\beta = 20°$ (row 2) influences the result only slighly.

The polarization signal $(C_{ext,v} - C_{ext,h})/(C_{ext,v} + C_{ext,h})$ (row three) increases with the asphericy as expected. It decreases as we loosen the horizontal orientation of the particles. This is shown in row 4 assuming a Gaussian distribution $\mathrm{N}(m_\beta, \sigma_\beta)$ with $m_\beta = 0$ for oblate and $m_\beta = 90°$ for prolate crystals. In order to describe this relation quantitatively, the polarization signal was averaged over all particle sizes from 0.1 to 2 mm and plotted as a function of the standard deviation σ_β of the assumed normal distribution (bottom row). The weighting for the highest values $\sigma_\beta = 90°$ is nearly uniform, the lowest weight being 60% of the highest one. If the horizontal orientation is varied only slightly ($\sigma_\beta < 15°$), the reduction of the polarization signal is below 10%, and it decreases to 50% of the value at complete horizontal orientation at $\sigma_\beta = 30°$.

The calculations have been performed for the frequency 183 GHz. They can linearly be scaled to other frequencies of the sub-millimeter sensors because we can account for this dependency by determining the extinction at the particle size of the same size parameter $2\pi r_{eq}/\lambda$. The secondary dependency of the results on the refractive index is neglible: The real part changes in the frequency range from 183 to 880 GHz by less than 0.003 (relatively: less than 0.002), the imaginary part (attenuation) is low for all considered values. The influence of the refractive index is in the order of the line thickness in the figure (not shown here). When scaling the figure to the frequencies of the recently proposed sensor CIWSIR [3], namely 183, 325, 448, 682 and 874 GHz, the abscissa will reach from 0 to to 5, 2.8, 2.0, 1.34, and 1.0 mm, respectively. These ranges cover the sizes of most cloud ice crystal because the maximum of the particle length distribution is typically around 0.2 mm.

V. Conclusions

The single scattering investigations presented here are easy to program, fast in calculation and suitable to investigate the basic scattering features of the ice crystals present in cirrus cloud. While the intensity is only slightly affected by the deviation of the particle orientation from the frequently assumed horizontal one, the polarization signal is influenced by both particle orientation and shape. The possibility to retrieve both quantities from multi-frequency observations remains to be investigated. Further insight into the potential of the polarization signal for quantitative retrieval can be expected from coincident observations with orientation sensitive sensors such as multi-angle instruments or lidar.

References

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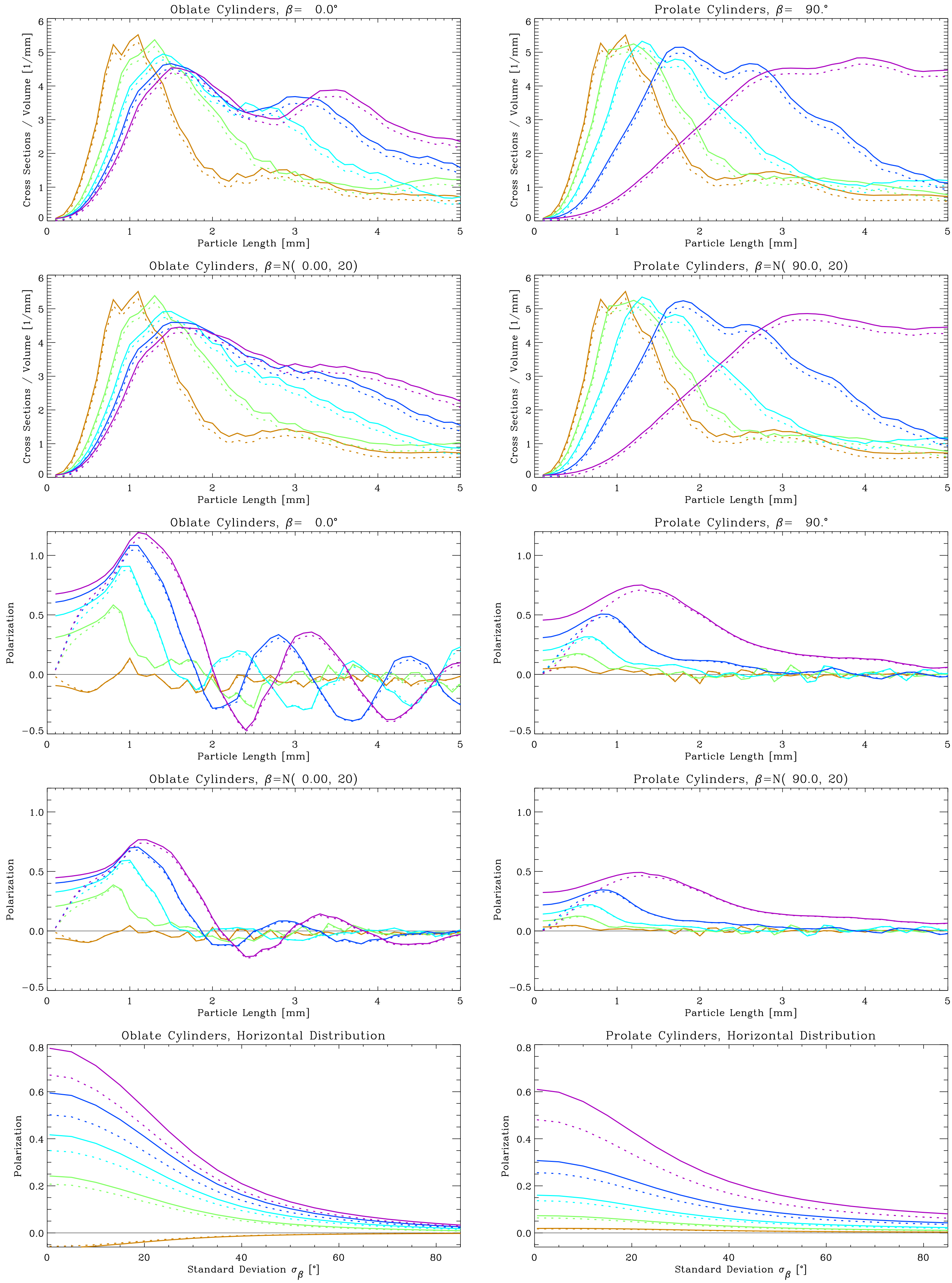

Fig. 1. Total extinction (solid) and scattering (dotted) cross sections and polarizations of oblate (left) and prolate (right) cylinders, observed at 183 GHz. Aspect ratios: yellow, green, light blue, blue, violet=1, 2, 3, 4, 5 (left column) and 1, 0.8, 0.6, 0.4, 0.2 (right column).