Irregularly shaped ice aggregates in optical modeling of convective ice clouds

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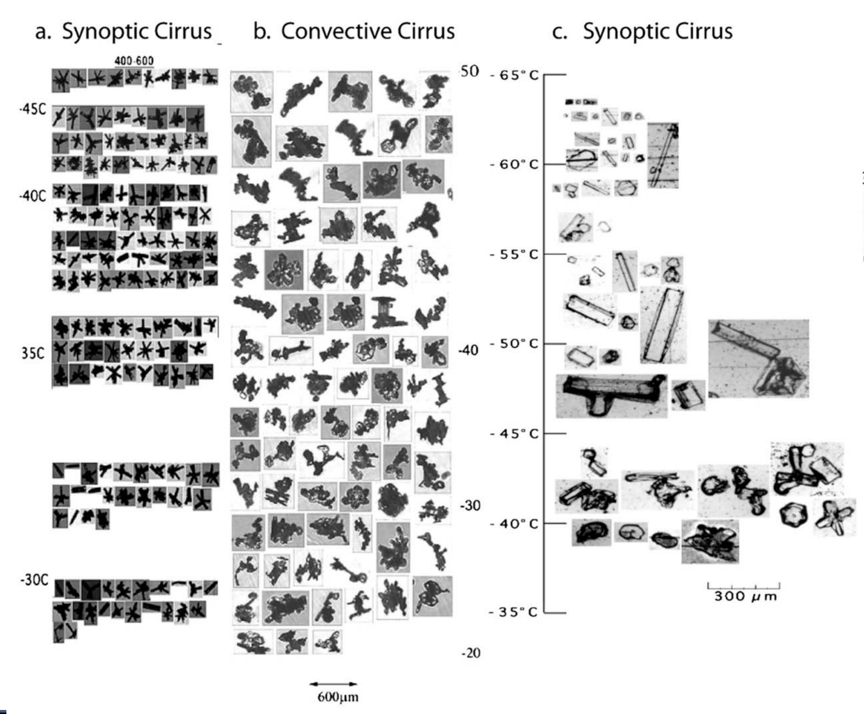
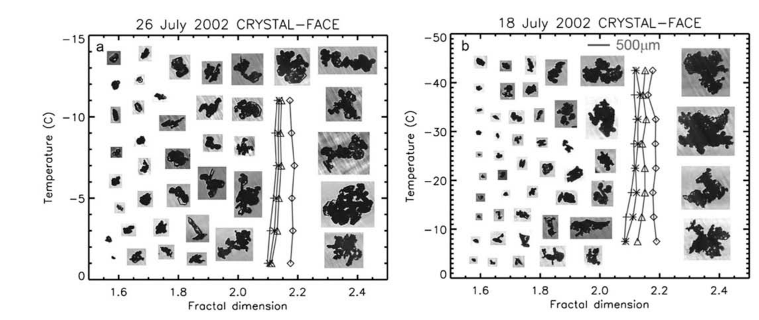
ABSTRACT

We propose a model of irregular shaped ice particles for satellite and ground-based cloud remote sensing applications. Microphysical observations have shown that ice particles in convective clouds tend to have highly irregular structures as a result of aggregation process. To simulate such complex structures, we used spatial Poisson-Voronoi tessellations. Furthermore, we adopted fractal-like shapes that were consistent with the proposed mass-dimension and area ratio-dimension relationships of measured cirrus particles. Single-scattering properties of the modeled "Voronoi aggregates" at visible wavelengths with size parameters up to 2250 were estimated from numerical calculations using the finite-difference time-domain method and the geometrical-optics integral-equation method. The phase functions for randomly oriented Voronoi aggregates showed features with no halos in the forward-scattering direction and a flat angular dependence in the side-to-backscattering directions. These characteristics and resultant asymmetry factors agreed with those of measured ice particles. Moreover, we confirmed the weak size and shape dependences of these scattering properties for the Voronoi aggregates, as well as high backscattering depolarization ratios.

Ice particle images (Baum et al. 2011)



fractal relationship between size and mass (Heymsfield et al. 2010)



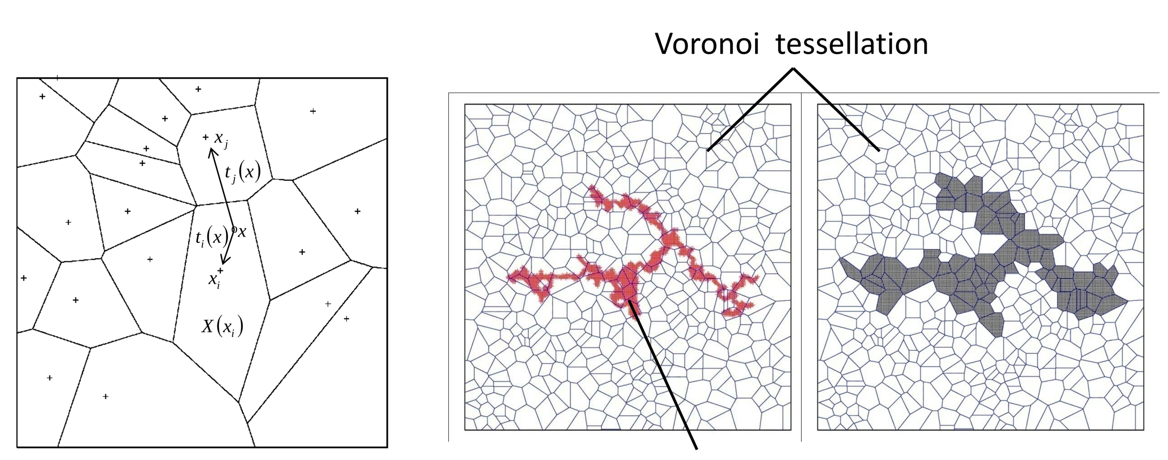
$m = 0.00528D^{2.1}$ (cgs)

area ratio to size relationship (Schmitt and Heymsfield 2010)

$A_r = 0.20D^{-0.29}$ $A_r \equiv \frac{4A}{\pi D^2}$

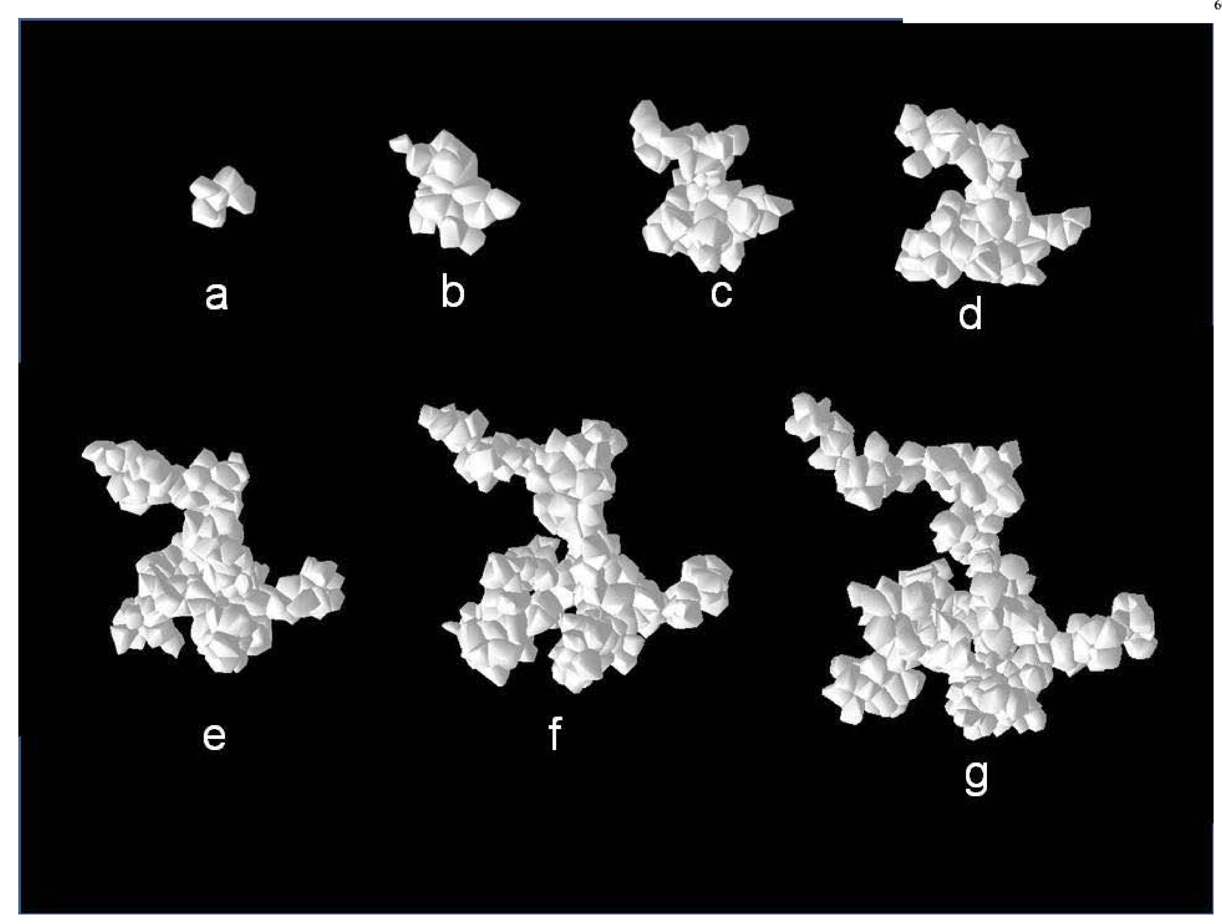
Shape model of ice aggregates

- Prepare spatial Poisson-Voronoi tessellation
- Apply a 3-D pattern that define the frame structure of the particle model
- Cells which include the frame points are extracted as the elements of the aggregate model
- Different-sized aggregates are created by changing the size of the frame pattern

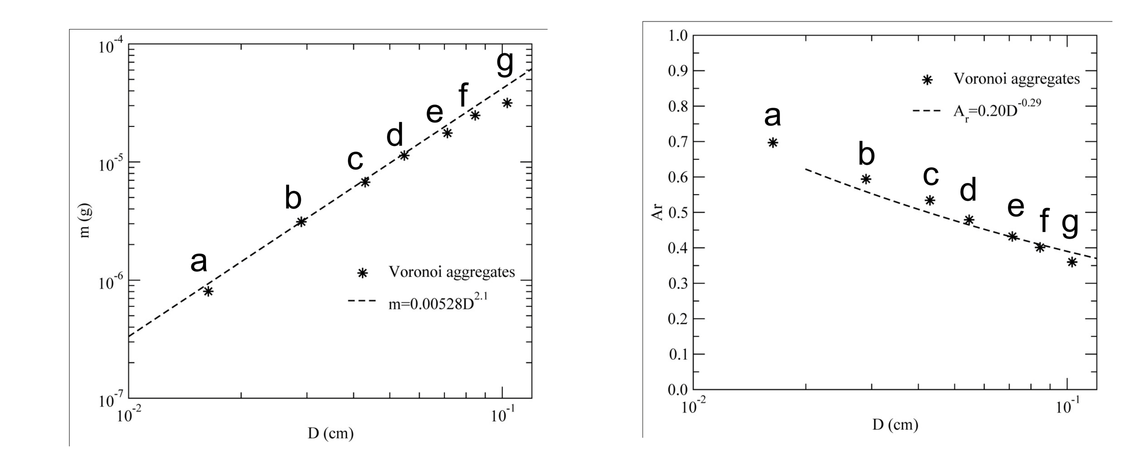


$X(\mathbf{x}_i) = \{\mathbf{x} \in \mathbb{R}^d : t_i(\mathbf{x}) < t_j(\mathbf{x}) \text{ for all } j \neq i\},\ t_i(\mathbf{x}) := \|\mathbf{x} - \mathbf{x}_i\|$

Voronoi Aggregates

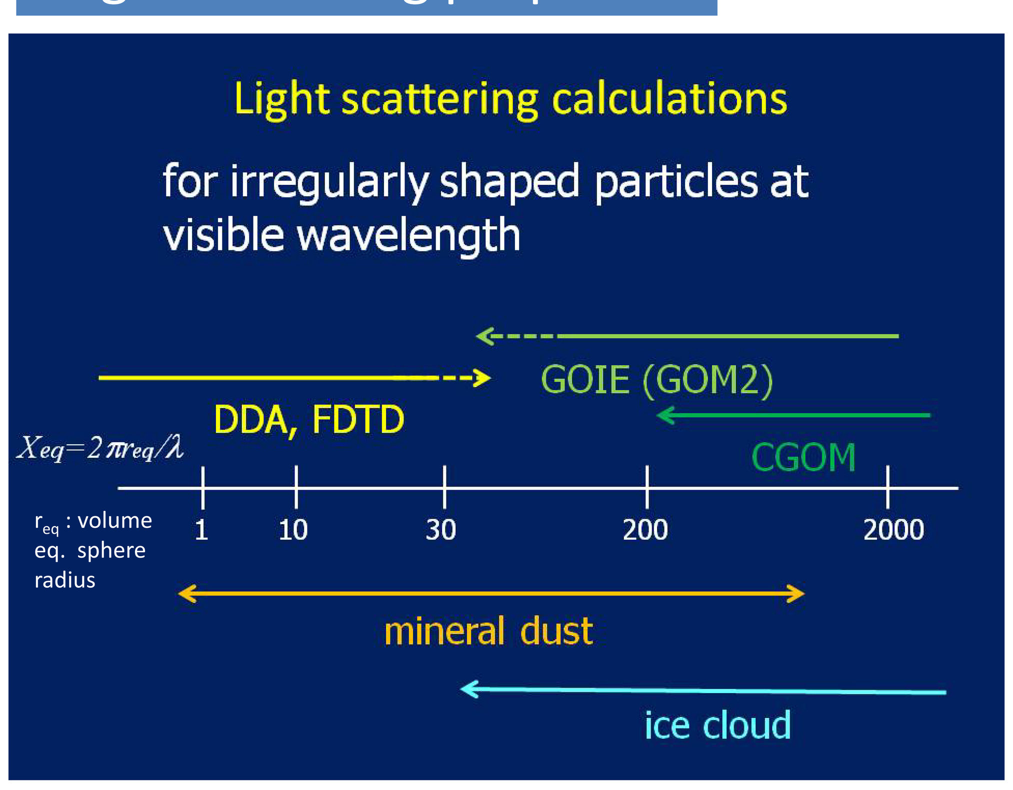


Orientation averaged geometries for Voronoi aggregates assuming an average cell size of 70μm.



The models of irregularly shaped particles have fractal-like shapes, which is consistent with the measured m-D and Ar-D relationships. Moreover, the modeled particles have irregular structure not only in their overall shapes, but also in each cell of the particle elements.

Single scattering properties



Wavelength : $\lambda = 0.565\mu m$

Refractive index : $n = 1.31 + 3.14\times10^{-9} i$

Numerical method : Finite-Difference Time Domain (FDTD)
Geometric Optics Integral Equation (GOIE)

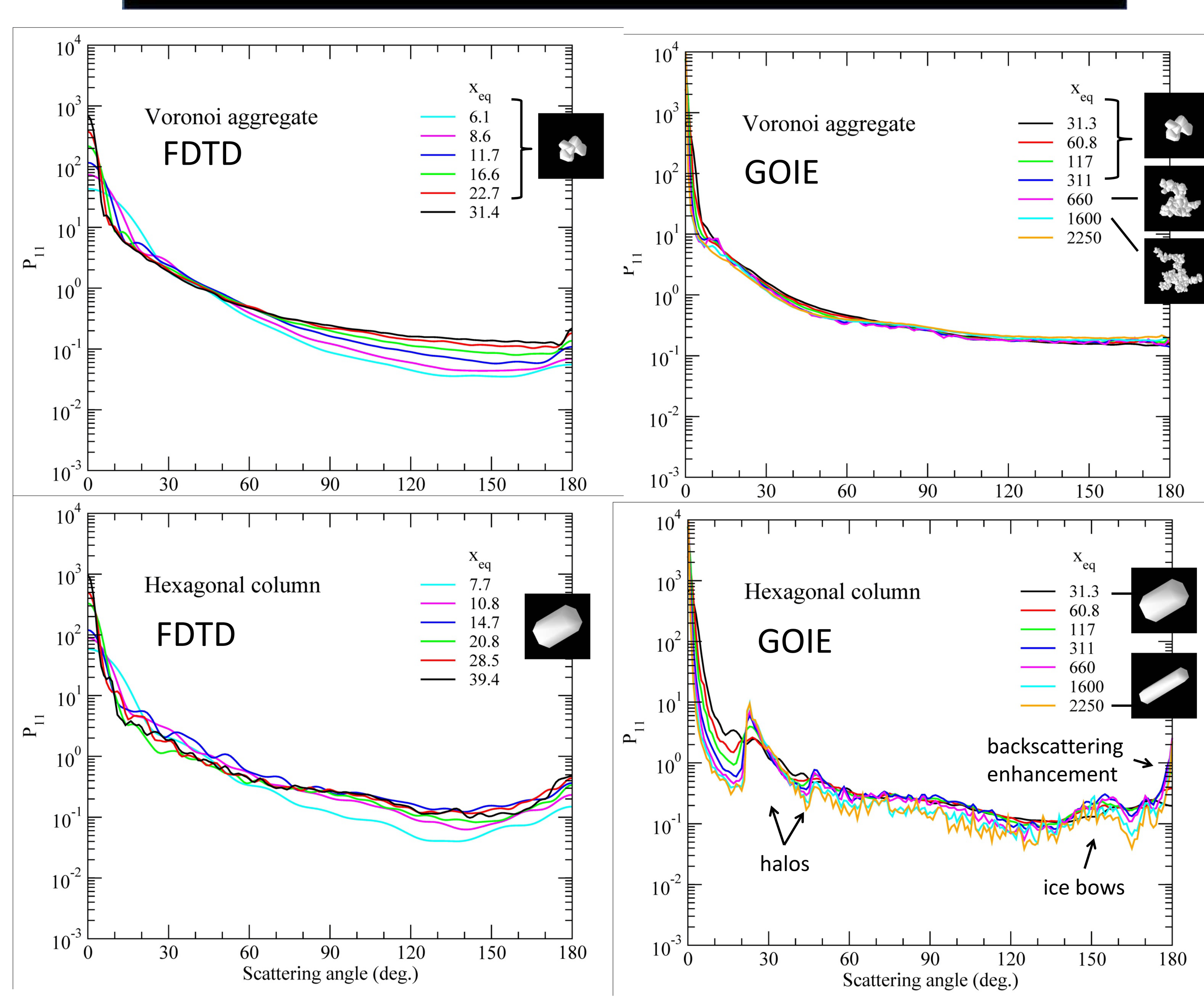
Voronoi aggregates

$x_{eq} < 660$: shape(a)

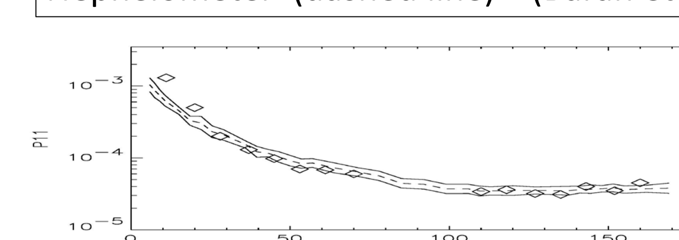
$660 \le x_{eq} \le 2250$: shape(a)-(g)

Hexagonal columns (Yang et al. 2000)

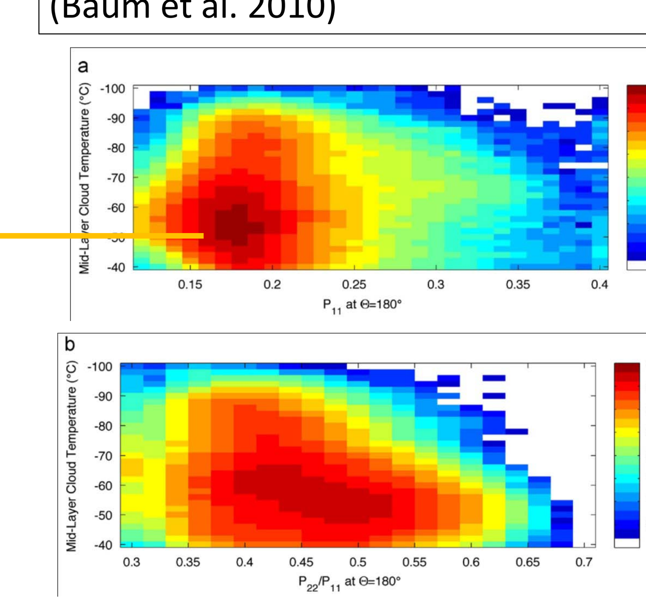
Six-branched bullet rosette (Yang et al. 2000)



ensemble-averaged phase function for ice particles in the Antarctic measured by Polar Nephelometer (dashed line) (Baran et al. 2005)



global CALIOP data for $P_{11}(\pi)$ and $P_{22}(\pi)/P_{11}(\pi)$ (Baum et al. 2010)

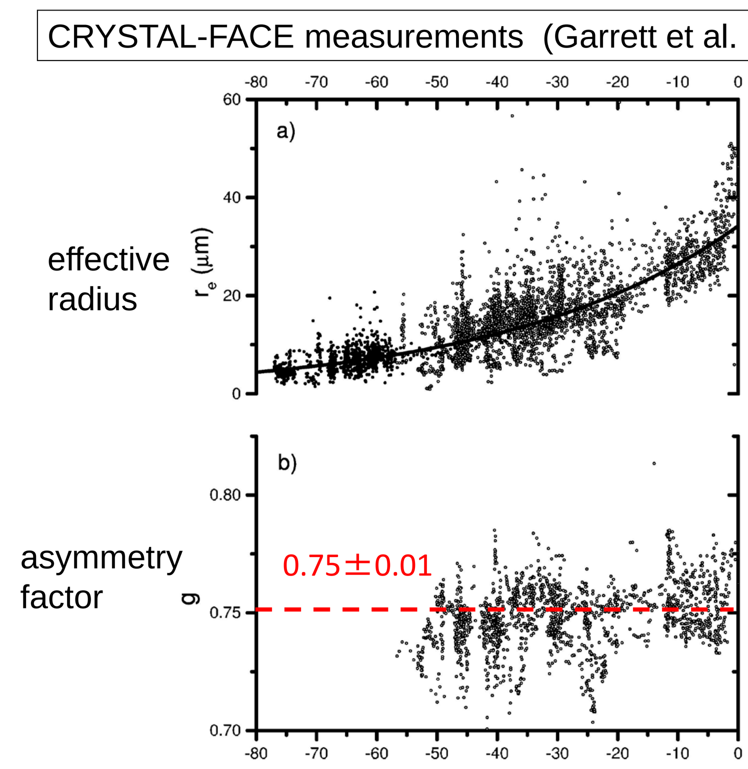


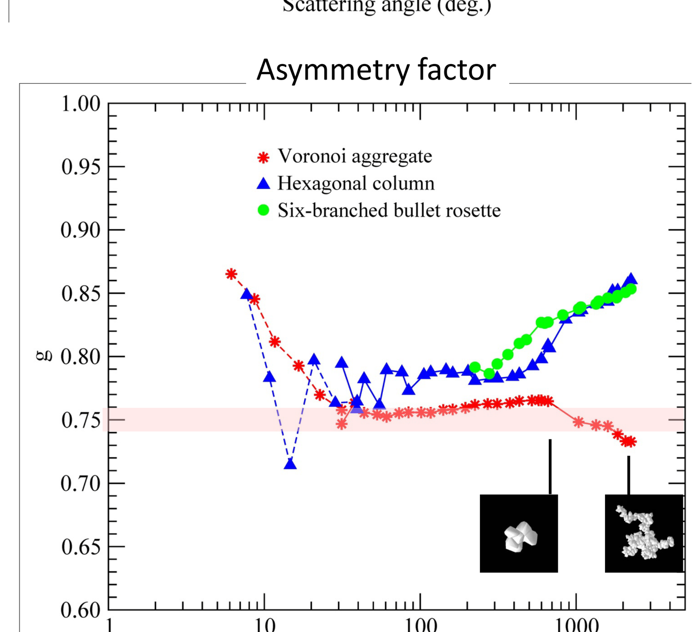
$0.15 \le P_{11}(\pi) \le 0.20$

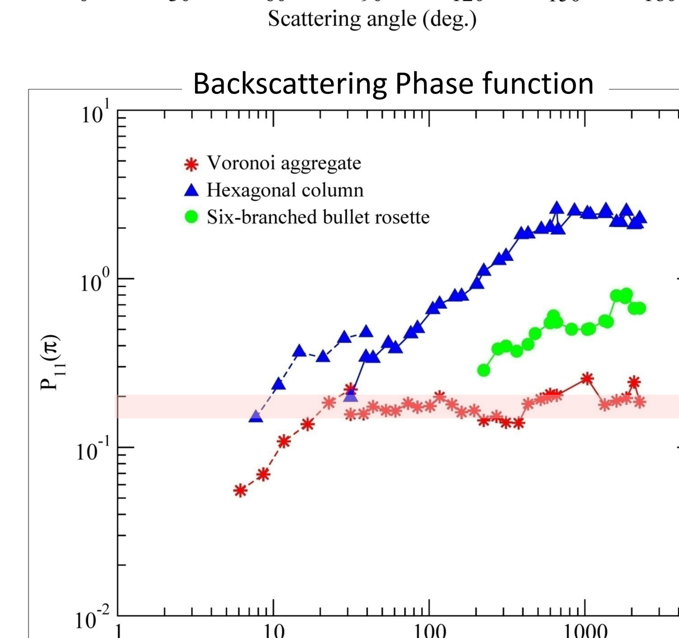
$0.35 \le P_{22}/P_{11} \le 0.6$

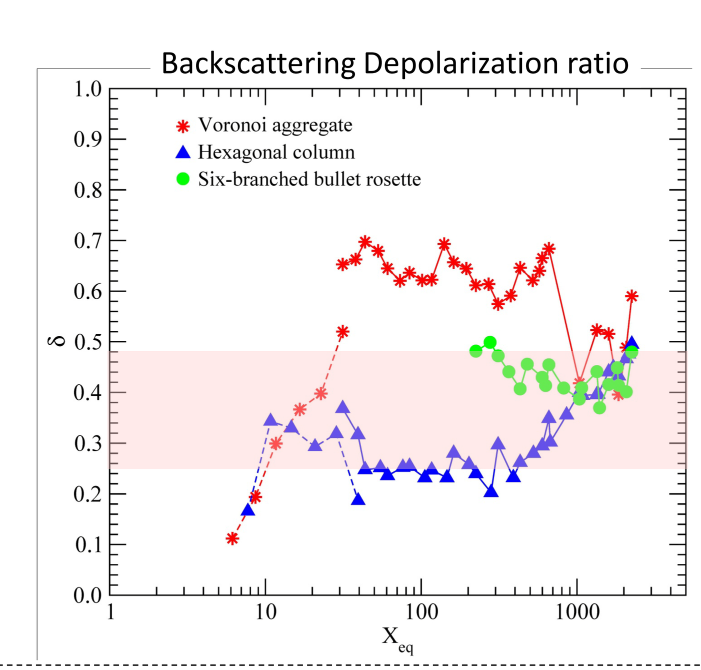
$0.25 \le \delta \le 0.48$

CRYSTAL-FACE measurements (Garrett et al. 2003)









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The key properties of the modeled irregular ice particles

◎ No halos in the forward-scattering direction and a flat angular dependence from side-to-backscattering directions of the phase function.

◎Asymmetry factors 0.73-0.77, and values of 0.14-0.25 for backscattering phase function.

▲Higher values for depolarization ratios than those of hexagonal columns and bullet rosettes in the range $30 < x_{eq} < 1000$.

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