Optical and Radiative Properties of Ice Clouds

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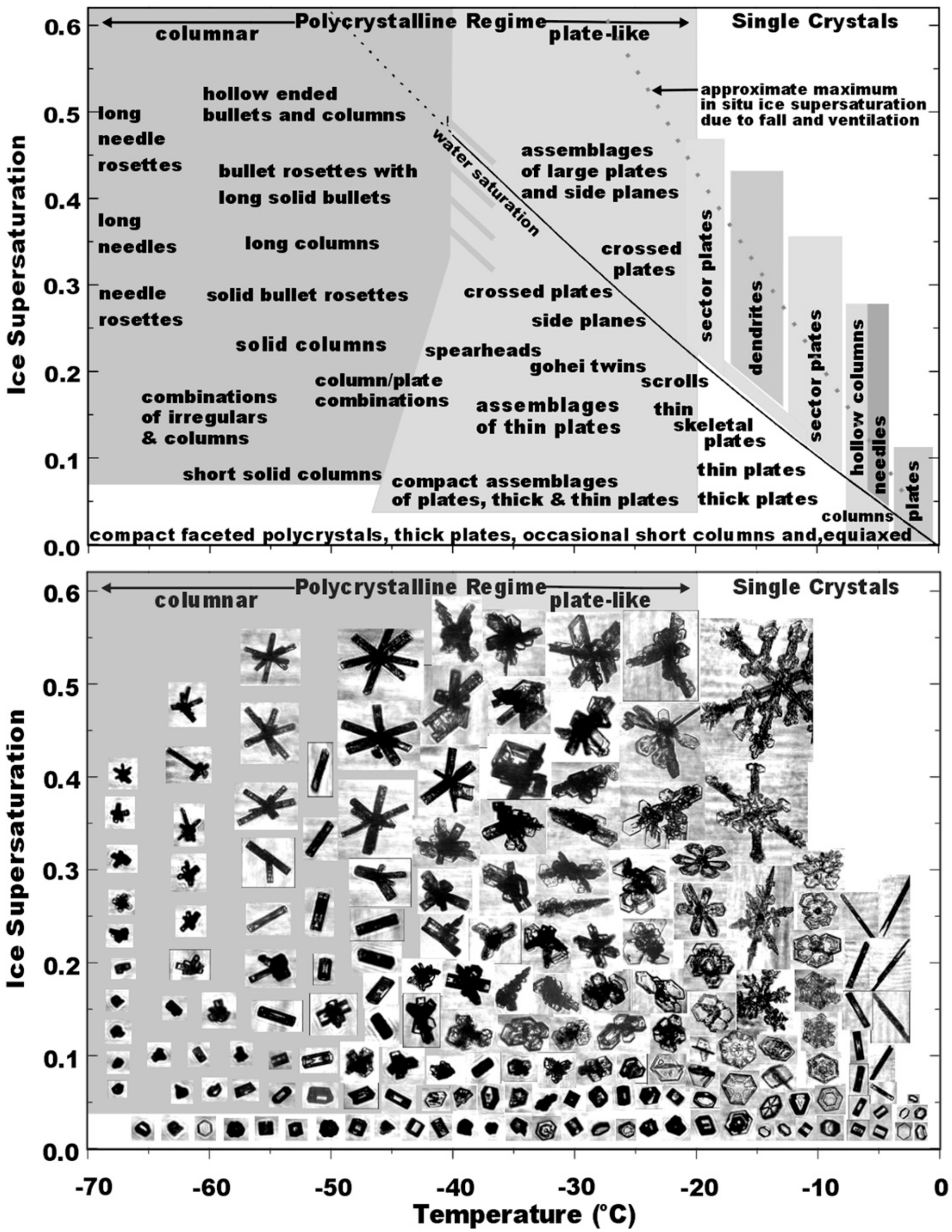
Outline

- Ice Clouds & Science Background
- Development of Data Library
  - Select representative ice crystal habits
  - Most updated refractive index
  - State-of-the-art computational methods
- Perspectives & Summary



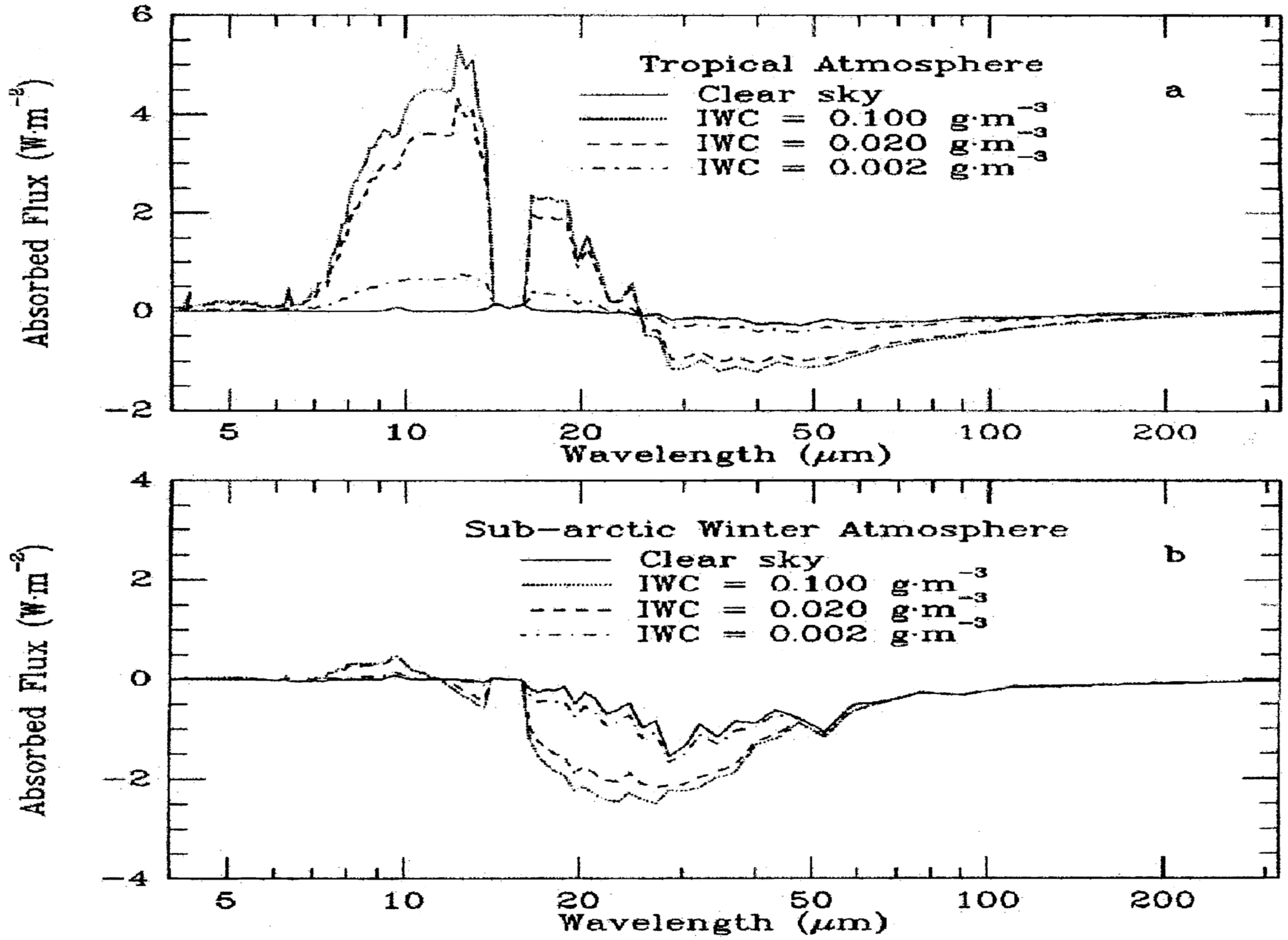
Comprehensive Ice Crystal Habits

Exclusively nonspherical

Endless ice habits

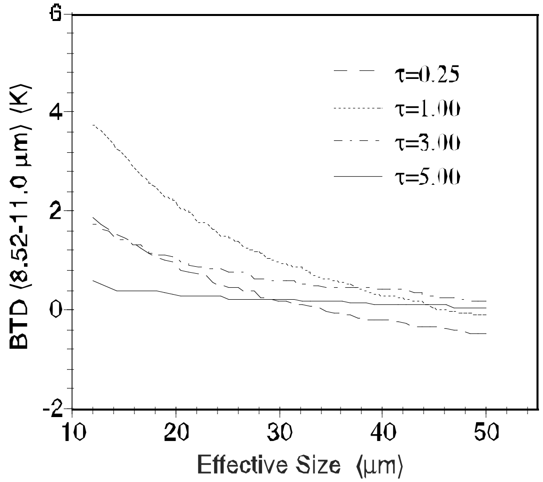
Bailey and Hallett, 2008

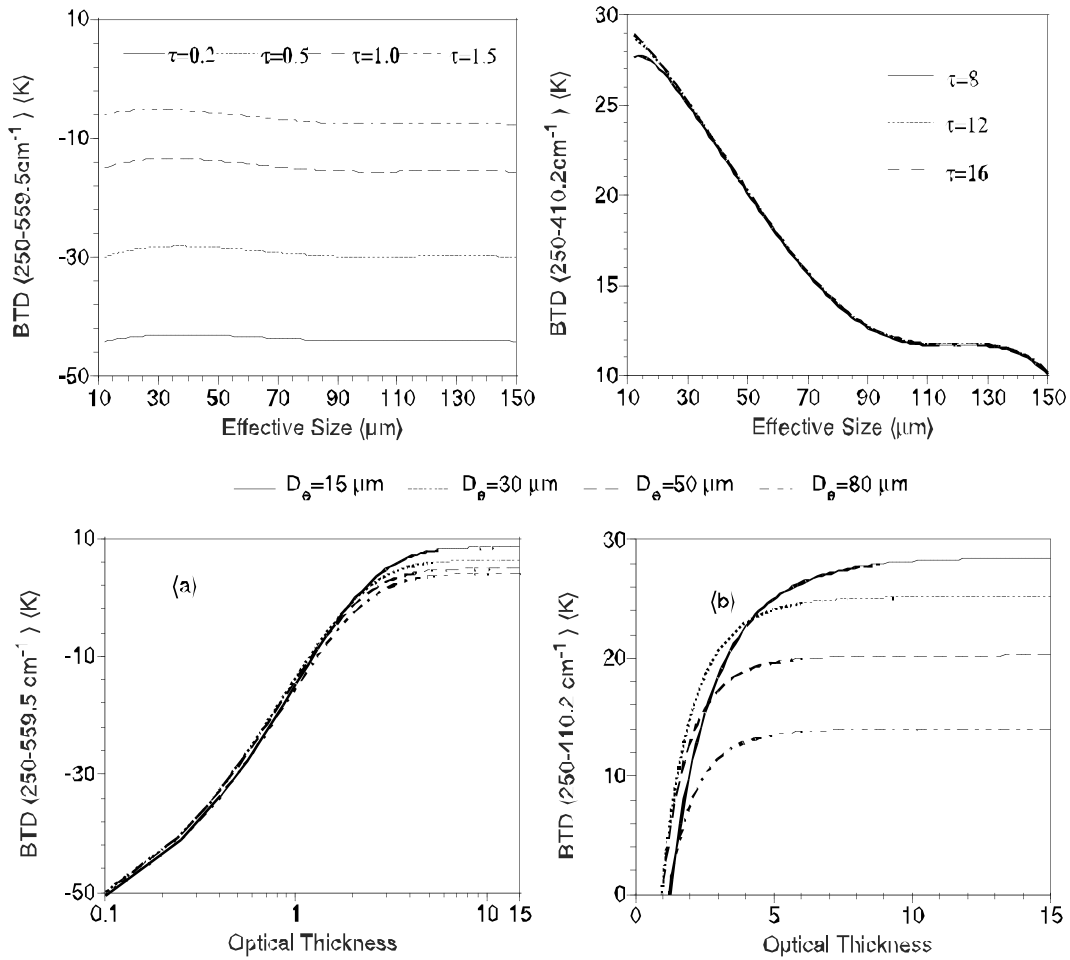
Cirrus clouds modulate outgoing far-infrared radiation



Stackhouse and Stephens, 1991

Spectral Signature: Sensitivity





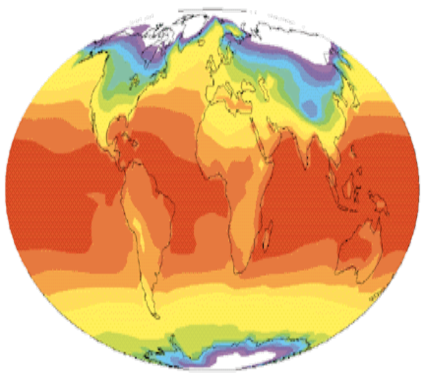
Yang et al (2003)

Ice Cloud Model

Ice Cloud Scattering Model

GCMs

Remote Sensing



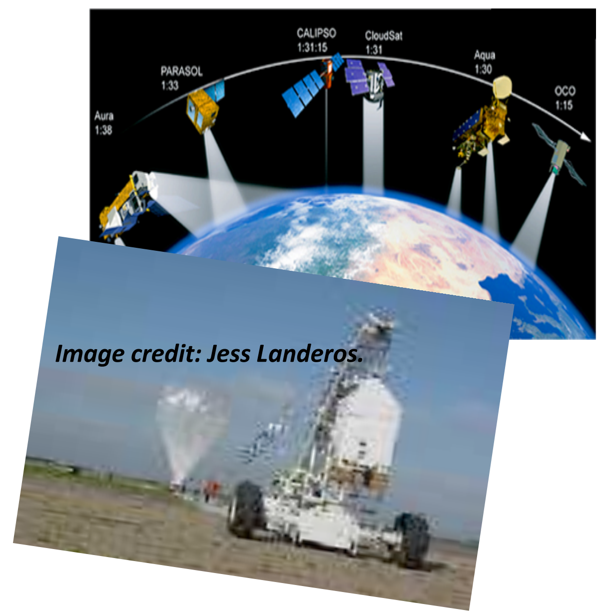
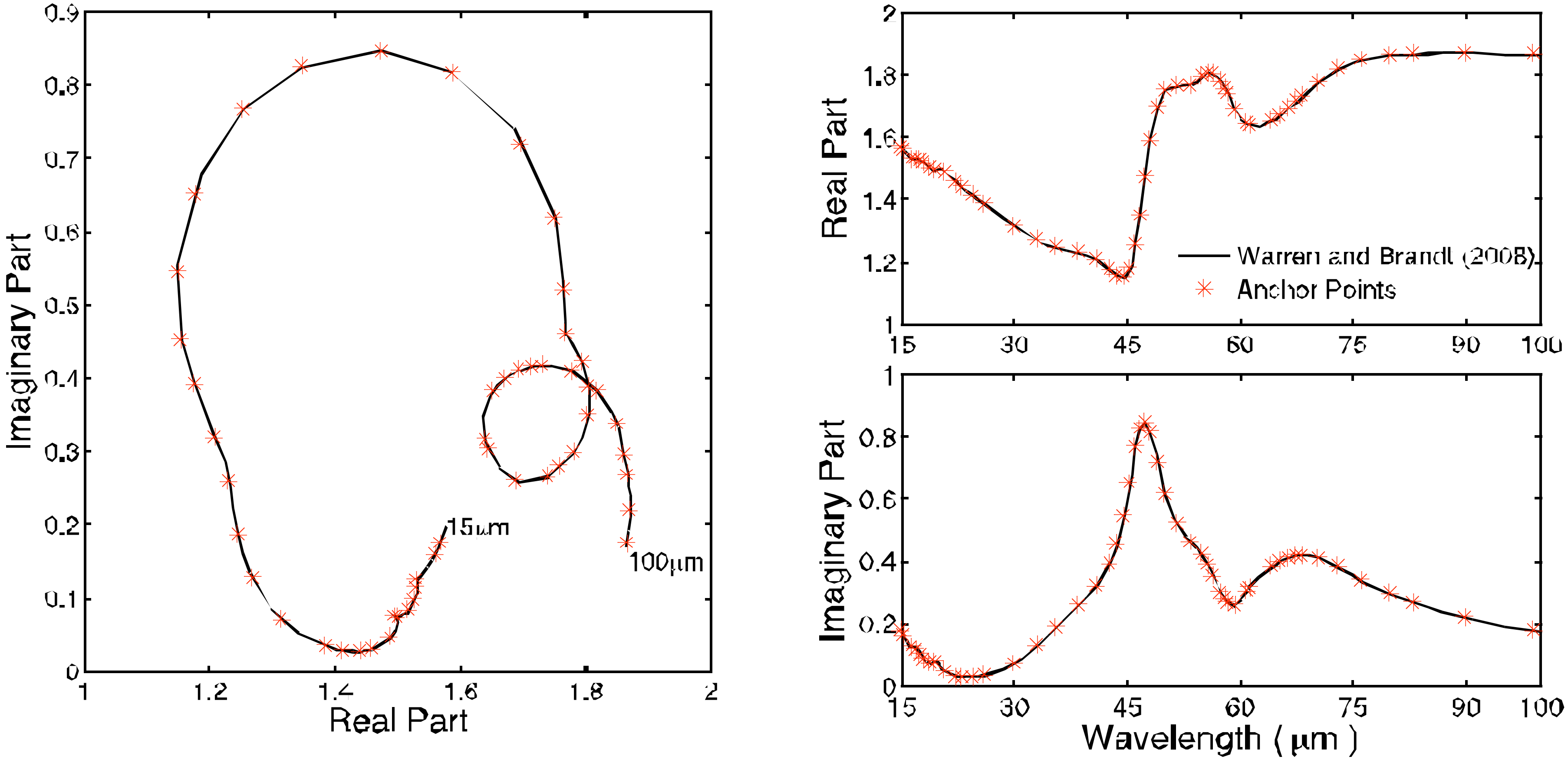


Image credit: Jess Landeros.

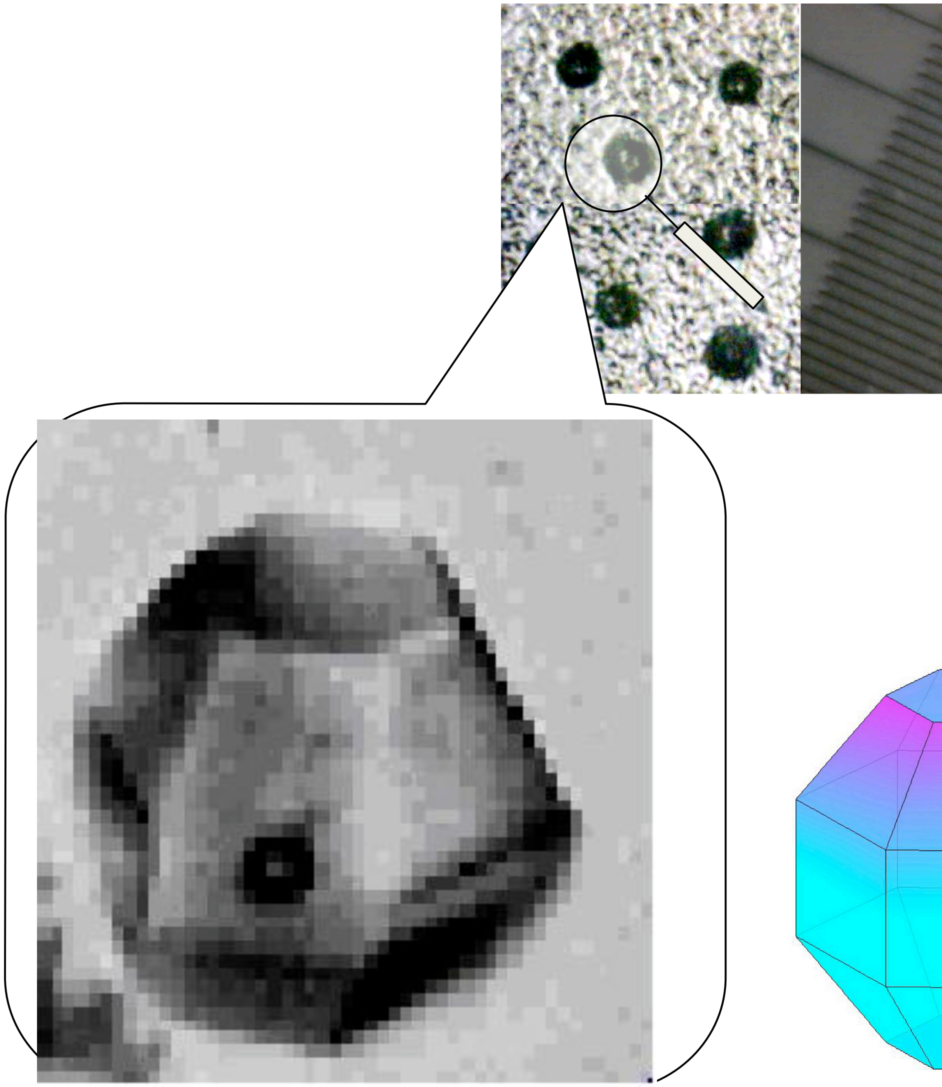
My research effort is to develop new techniques and enhance the current modeling capabilities to improve, refine and extend current ice scattering model..

Refractive Index: 15-100 µm



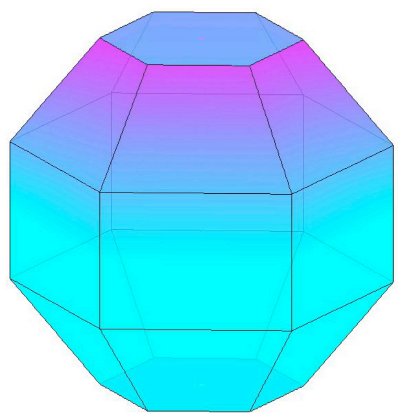
Warren & Brandt (2008)

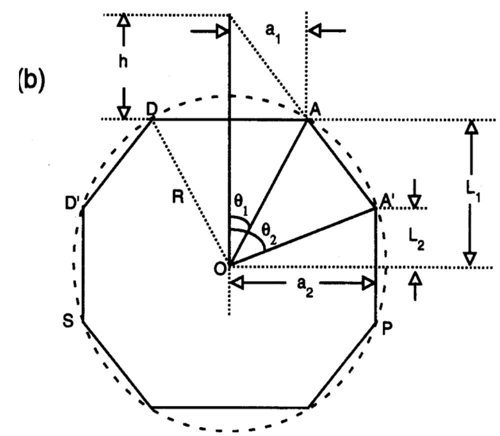
Ice Crystal Habit: Droxtal



Source : Andy Heymsfield

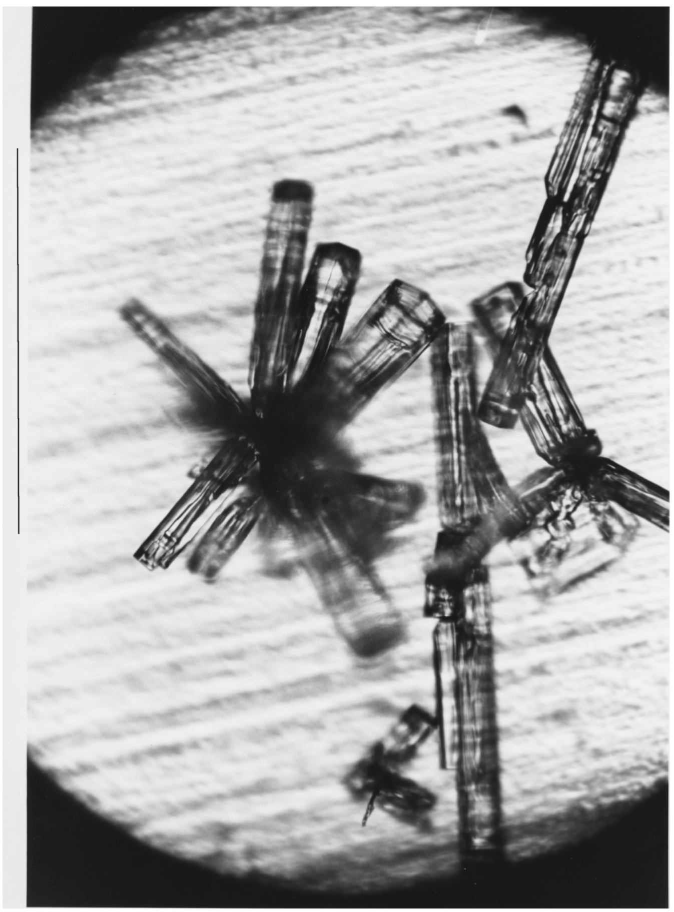
- Dominant in the uppermost portions of cirrus clouds
- 20-Faced Polyhedron
  - 12 isosceles trapezoid
  - 6 rectangular
  - 2 hexagonal



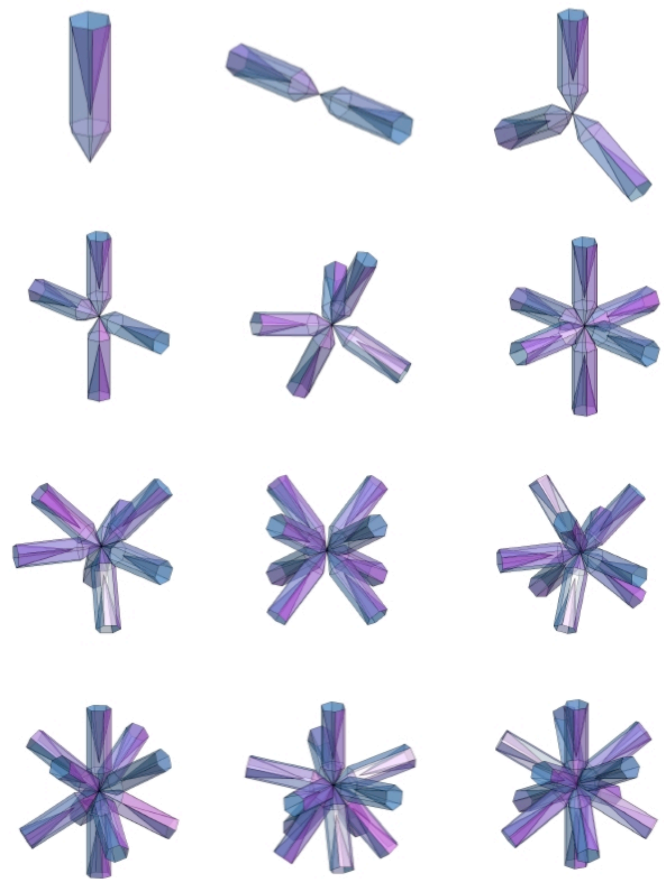


Ice Crystal Habit: Hollow Bullet Rosettes

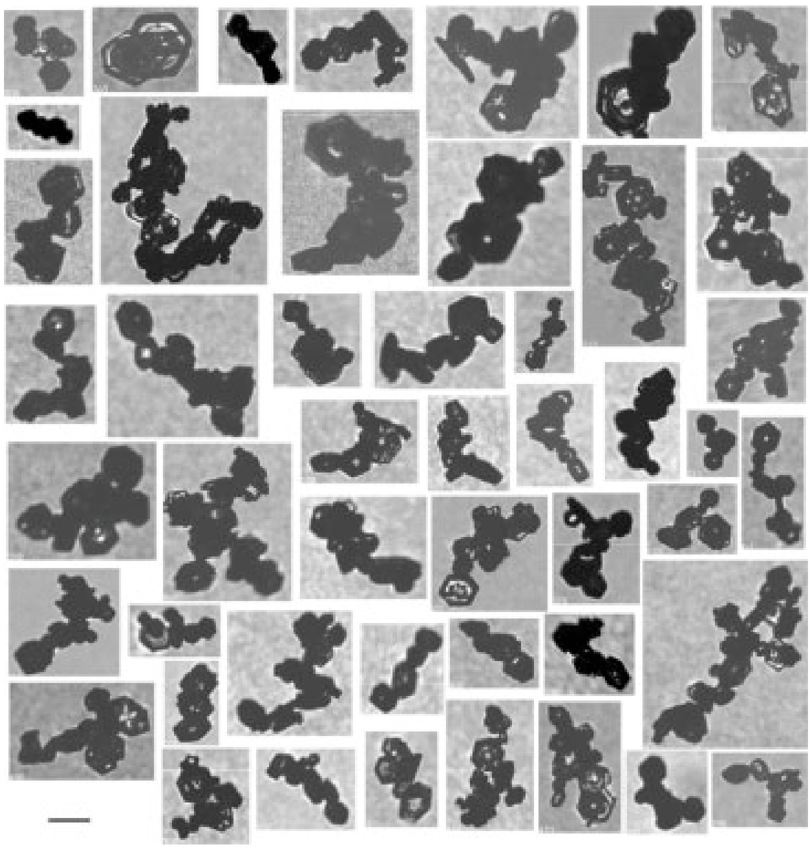
Photo from Stephen G. Warren



Yang et al (2008)

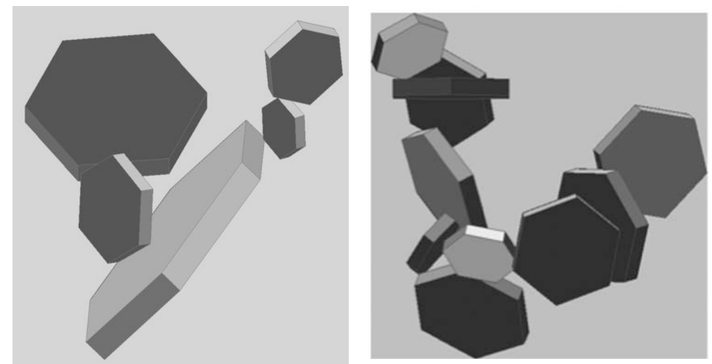


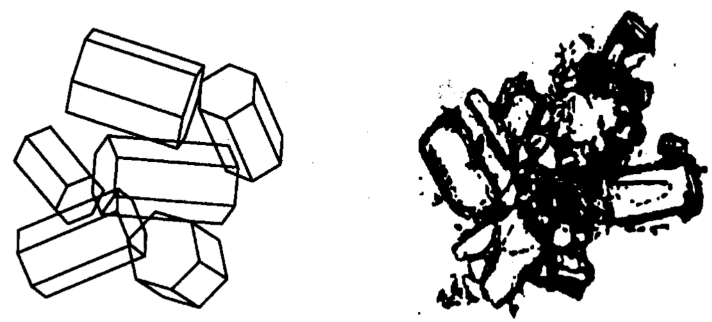
Ice Crystal Habit: Aggregates



CPI Imag (Um & McFarquhar,2009)

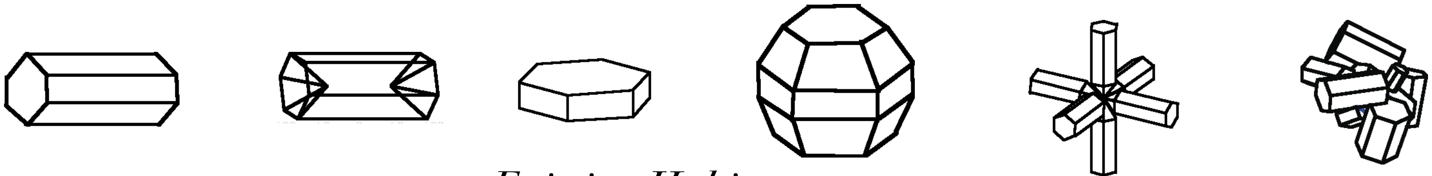
(Xie, 2011)





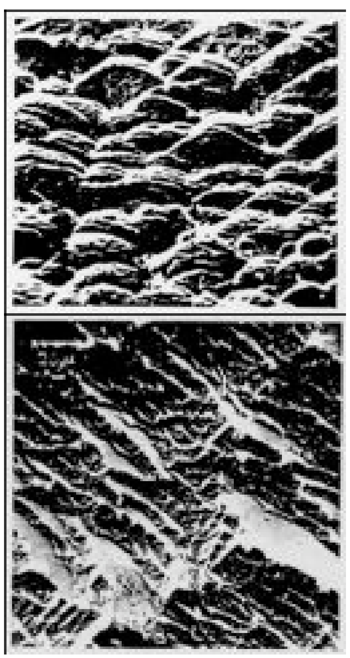
Compact aggregate of columns
(Yang et al 1998)

Ice Crystal Habits



Existing Habits

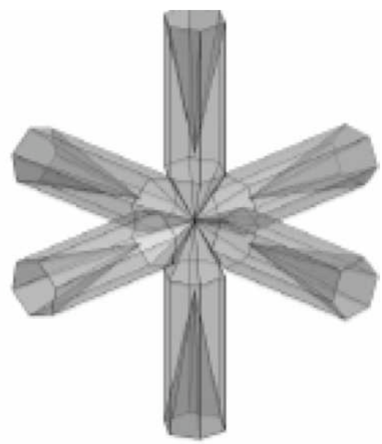
Incorporated Roughness Condition



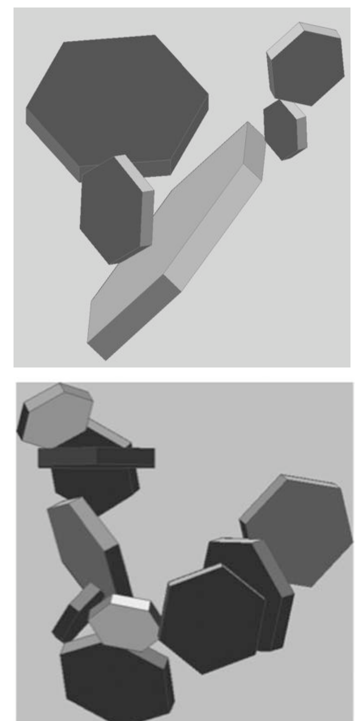
Surface roughness were observed for single crystals and polycrystalline ice by using an electronic microscope. Images adapted from Cross, 1968!

New Habits

Yang et al. (2008)



Xie et al. (2011)



Essence of Radiative Interaction

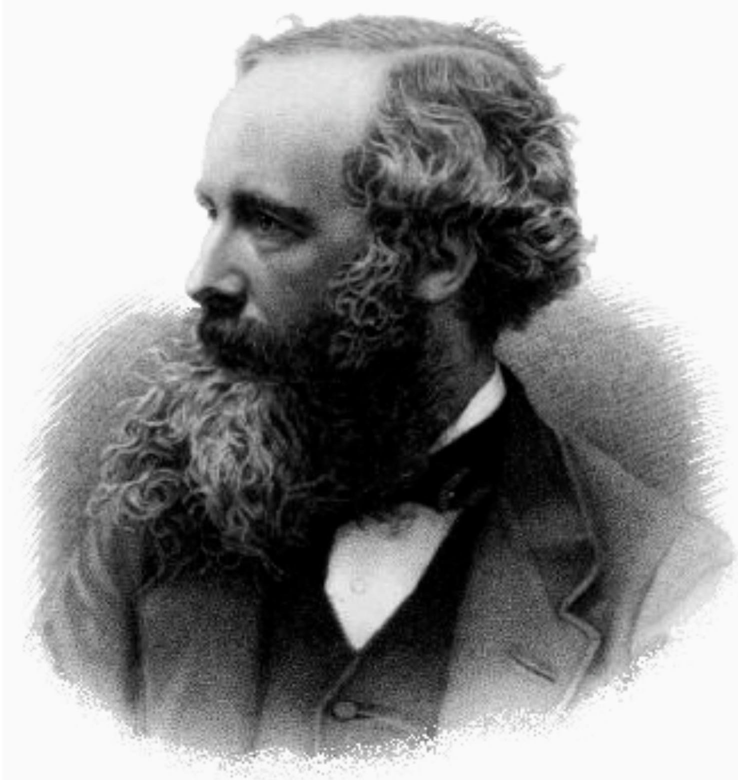
Electromagnetic wave

$$\nabla \times \mathbf{H} = \frac{\varepsilon}{c}\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{\mu}{c}\frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 0$$

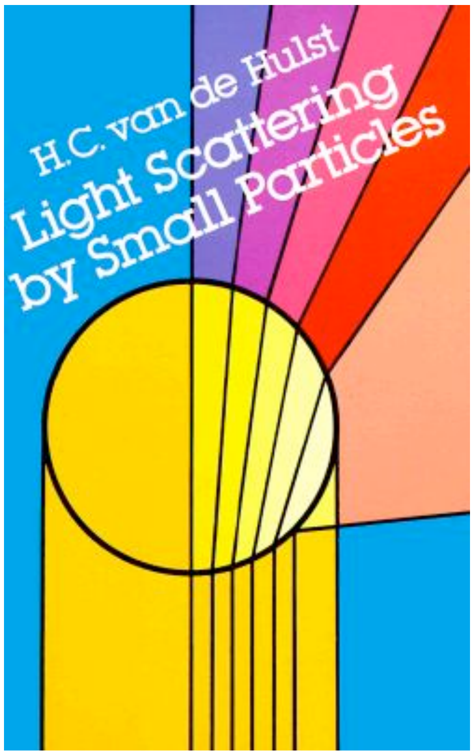
$$\nabla \cdot \mathbf{H} = 0$$

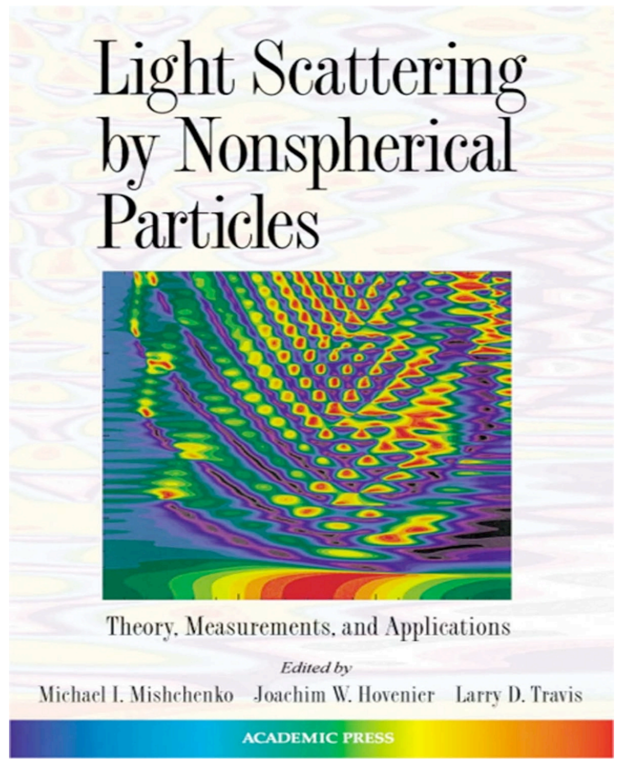


James Clerk Maxwell
(13 June 1831 – 5 November 1879)

Solution of Maxwell's Equations & Mathematically Equivalents

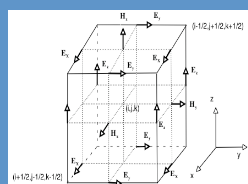
Van de Hulst (1957)

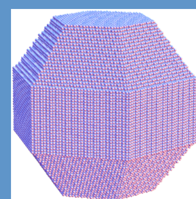




A Combination of Methods

FDTD/DDA

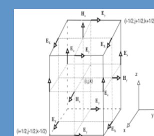


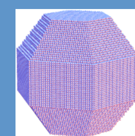


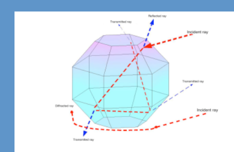
Yee grid (Yee, 1966)

Dipoles

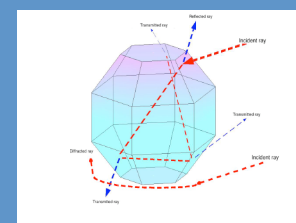
FDTD / ADDA +IGOM





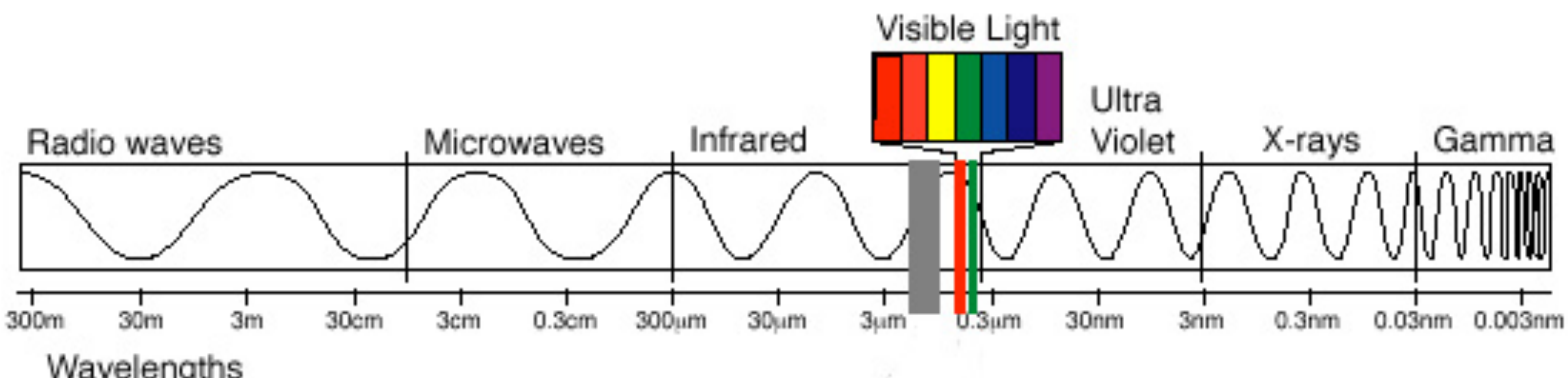


IGOM



Ray tracing

Size Parameter



Electromagnetic Spectrum (Image Credit: NASA)

Discrete-Dipole-Approximation (DDA) Method

SCATTERING AND ABSORPTION OF LIGHT BY NONSPHERICAL DIELECTRIC GRAINS

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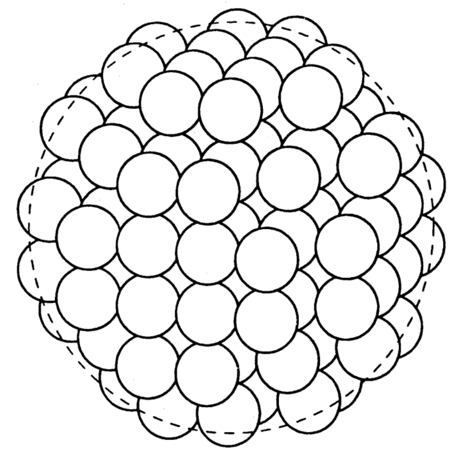
Received 1973 June 4; revised 1973 July 6

ABSTRACT

A method is described for calculating approximate extinction, absorption, and scattering cross-sections for dielectric grains of arbitrary shape, with dimensions comparable to or smaller than the wavelength of the incident radiation. The grain is modeled by an array of *N* polarizable elements in vacuum. The elements are located on a simple cubic lattice, and *N* is of order of magnitude 100. The polarizability of an element is such that an unbounded array would exhibit, according to the Clausius-Mossotti relation, the bulk dielectric constant of the grain material. The complex vector amplitude of each oscillator in the array, which is driven by the field of the incident wave and the fields of all the other oscillators, is determined by an iterative procedure. From the *N* amplitudes all the cross-sections, including differential cross-sections, are obtained. The method was tested by comparing the cross-sections computed for "spherical" clusters of oscillators with exact Mie theory values for the corresponding dielectric spheres. Computed cross-sections are presented for five different grain shapes and three different complex refractive indices.

Subject headings: interstellar matter — opacities — polarization



ApJ 333 848 (1988)

$$\vec{E}(\vec{r}) = \vec{E}_{inc}(\vec{r}) + \int_V d^3r' \vec{G}(\vec{r},\vec{r}')\chi(\vec{r}')\vec{E}(\vec{r}')$$

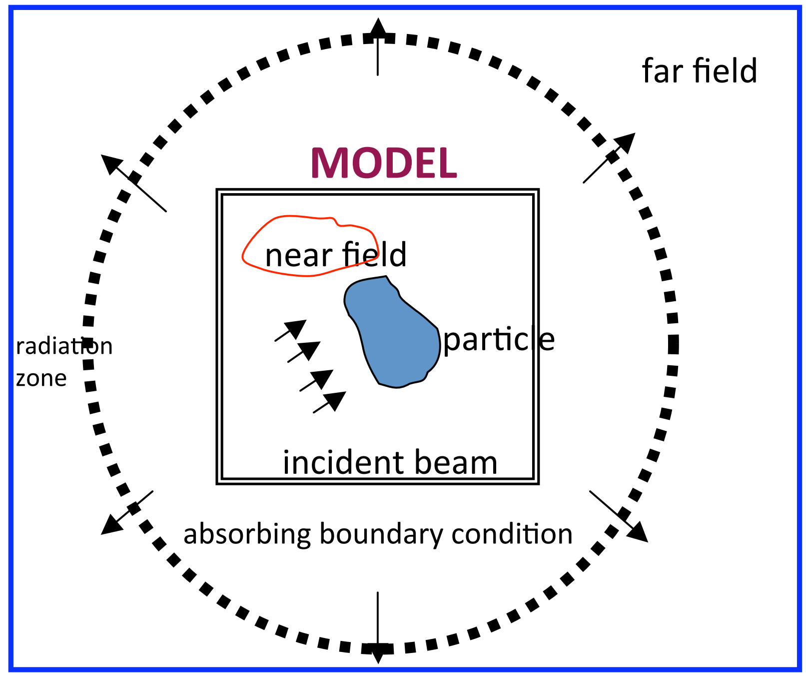
$$\vec{G}(\vec{r},\vec{r}') = [\vec{I} + \frac{1}{k^2}\nabla\nabla]\frac{\exp(ik|\vec{r}-\vec{r}'|)}{4\pi|\vec{r}-\vec{r}'|}$$

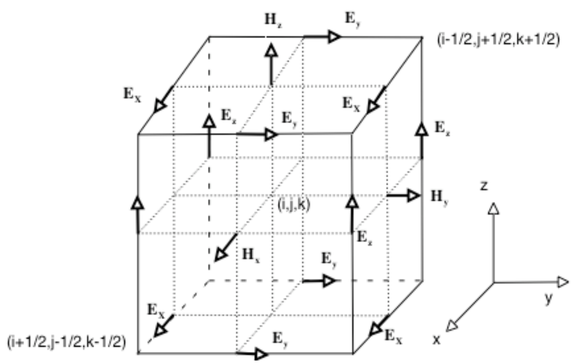
- Efficient parallel-version codes (DDSCAT, ADDA) have been designed(Draine, 2006, ;Yurkin, 2006).

Time-Domain Methods

$$\vec{\nabla} \times \vec{H}(\vec{r},t) = \frac{\varepsilon}{c}\frac{\partial \vec{E}}{\partial t},$$

$$\vec{\nabla} \times \vec{E}(\vec{r},t) = -\frac{\mu}{c}\frac{\partial \vec{H}}{\partial t}$$





Yee grid (Yee, 1966)

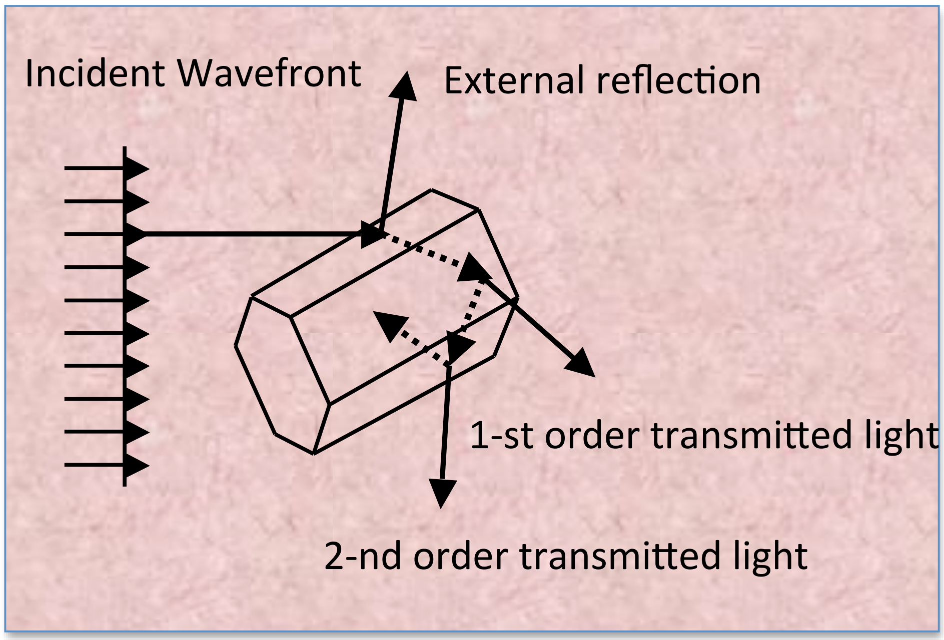
Finite-difference time-domain (FDTD):

$$\frac{\partial E_z^{sca}(r_{i+1/2,j,k},t_n)}{\partial y} = \frac{1}{\Delta y}\left[E_z^{sca}(r_{i+1/2,j,k},t_n) - E_z^{sca}(r_{i+1/2,j-1/2,k},t_n)\right]$$

Pseudo-spectral time-domain (PSTD):

$$\frac{\partial E_z^{sca}(r_{i+1/2,j,k},t_n)}{\partial y} = F^{-1}\left\{-ik_y F\left[E_z^{sca}(r,t_n)\right]\right\}$$

Geometric-Optics Method



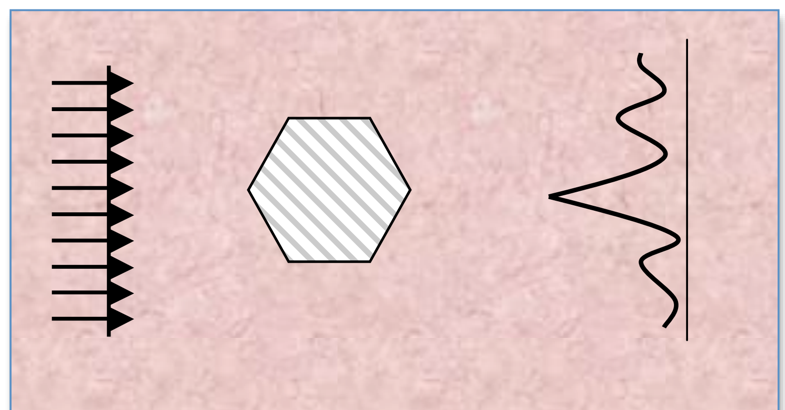
Basic Principle

Ray / Beam / "Photon",
Intensity, Polarization, Phase

Ray/Beam Tracing

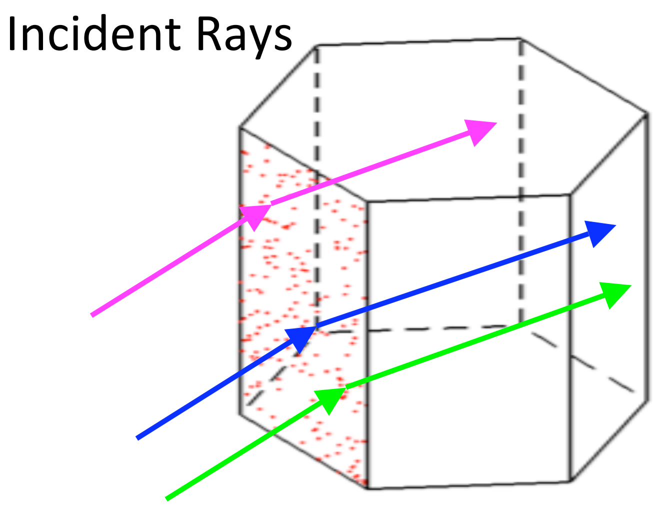
Snell's Law, Fresnel Formulas

Fraunhofer Diffraction



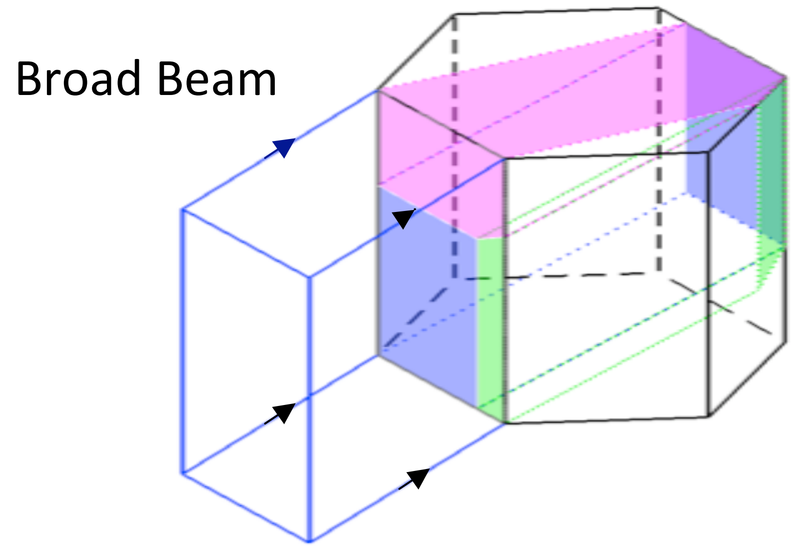
In a more rigorous sense, this method is of physics-geometric optics hybrid (PGOH).

Ray/Beam-tracing Algorithm



Conventional ray-tracing

(a)



Beam-splitting technique

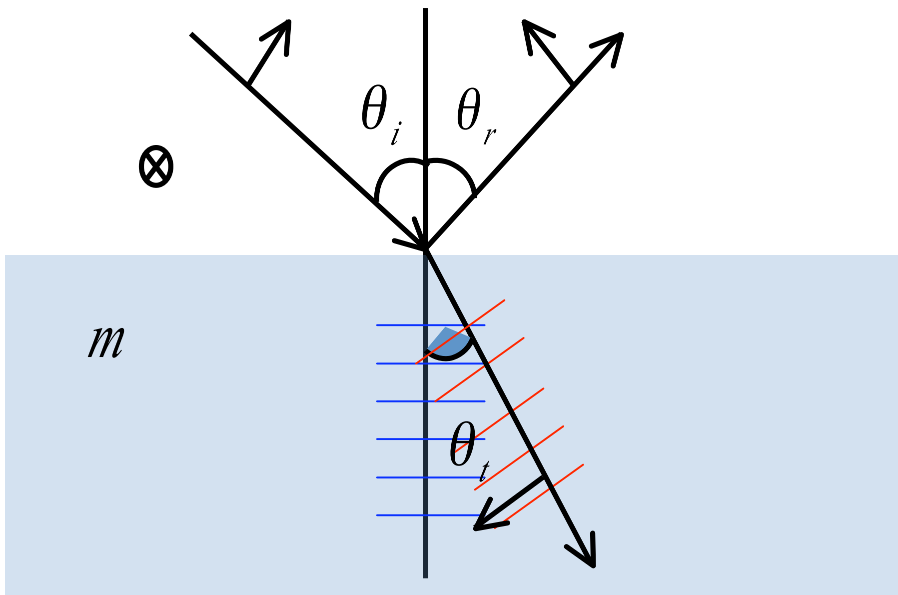
(b)

(a) Larger size parameter, larger number of rays

(b) Number of beams is irrelevant to size parameter.

Similar studies: Popov, 1996; Borovoi, 2003

Inhomogeneous Plane Waves



$$N_r = \sqrt{\left\{ m_r^2 - m_i^2 + \sin^2\theta_i + \sqrt{(m_r^2 - m_i^2 - \sin^2\theta_i)^2 + 4m_r^2 m_i^2} \right\} / 2}$$

$$N_i = \cos\theta_t \sqrt{\left\{ -(m_r^2 - m_i^2 - \sin^2\theta_i) + \sqrt{(m_r^2 - m_i^2 - \sin^2\theta_i)^2 + 4m_r^2 m_i^2} \right\} / 2}$$

$$E \exp(-kN_i l)\exp(ikN_r \hat{e}_t \cdot r)$$

$$\sin\theta_i = m\sin\theta_t$$

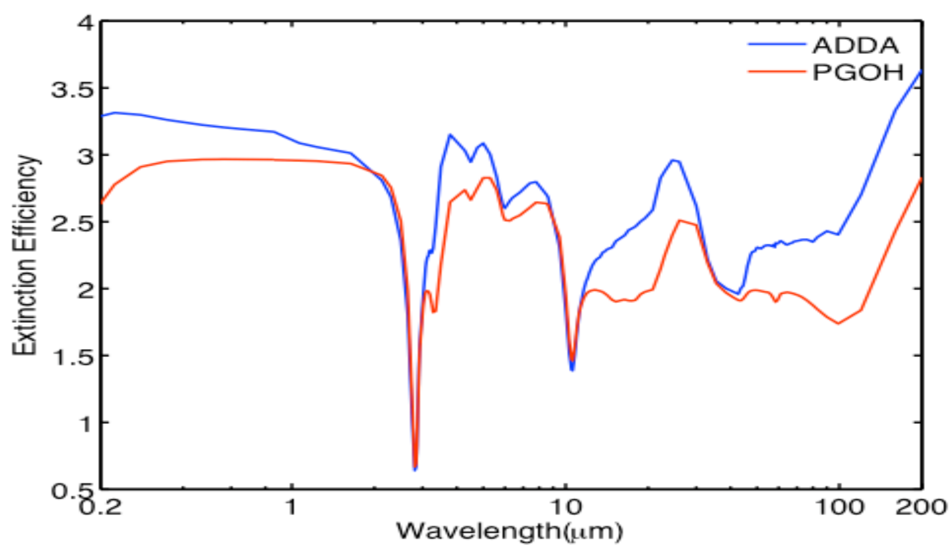
$$\sin\theta_i = N_r \sin\theta_t$$

Effective refractive index (Yang and Liou, 2009)

Edge-Effect

- <u>Question:</u>

How to understand the difference between extinction efficiency factors simulated from the PGOH and exact methods (e.g. DDA)?



Hexagonal particle. Size parameter is 15.

Localization Principle

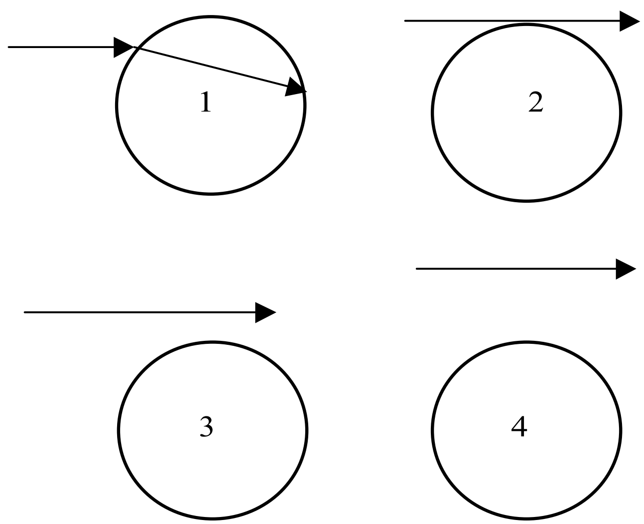
Mie formula:

$$S_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} (a_n \pi_n + b_n \tau_n)$$

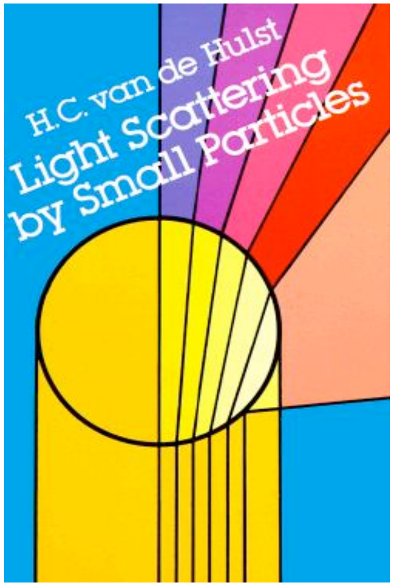
$$S_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} (a_n \tau_n + b_n \pi_n)$$

A term of the order n corresponds to a ray passing the origin at a distance

$$(n + 1/2)\,\lambda / 2\pi$$

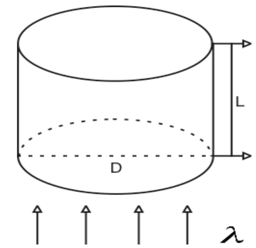


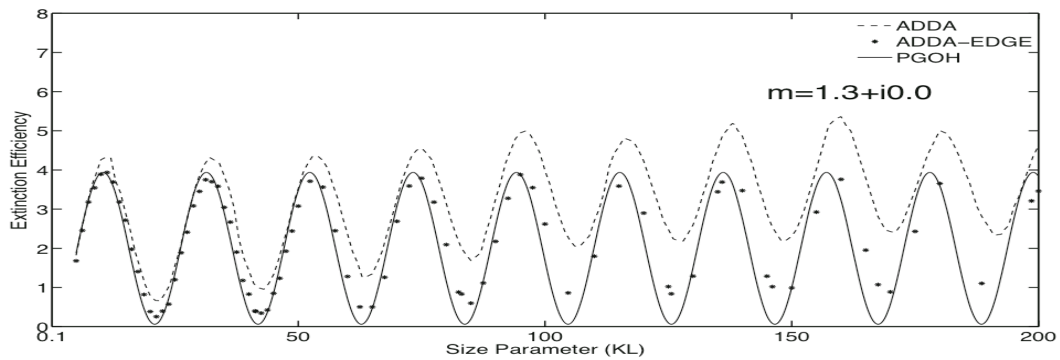
Van de Hulst (1957)

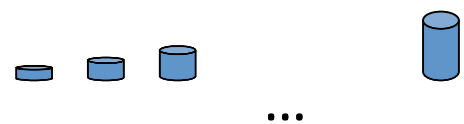


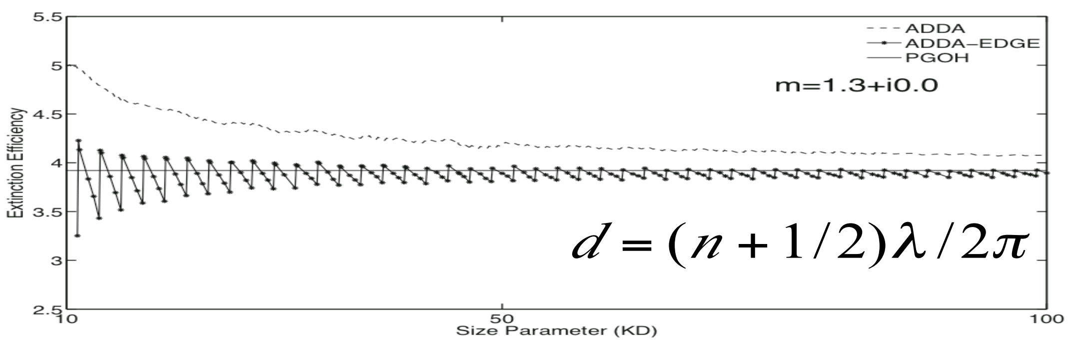
Extinction Efficiency

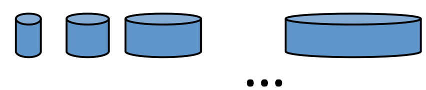
$$Q_{ext} = 2\,\mathrm{Re}\left\{1 - \frac{4m\exp\{i(m-1)kL\}}{(m+1)^2 - (m-1)^2\exp(i2mkL)}\right\}$$

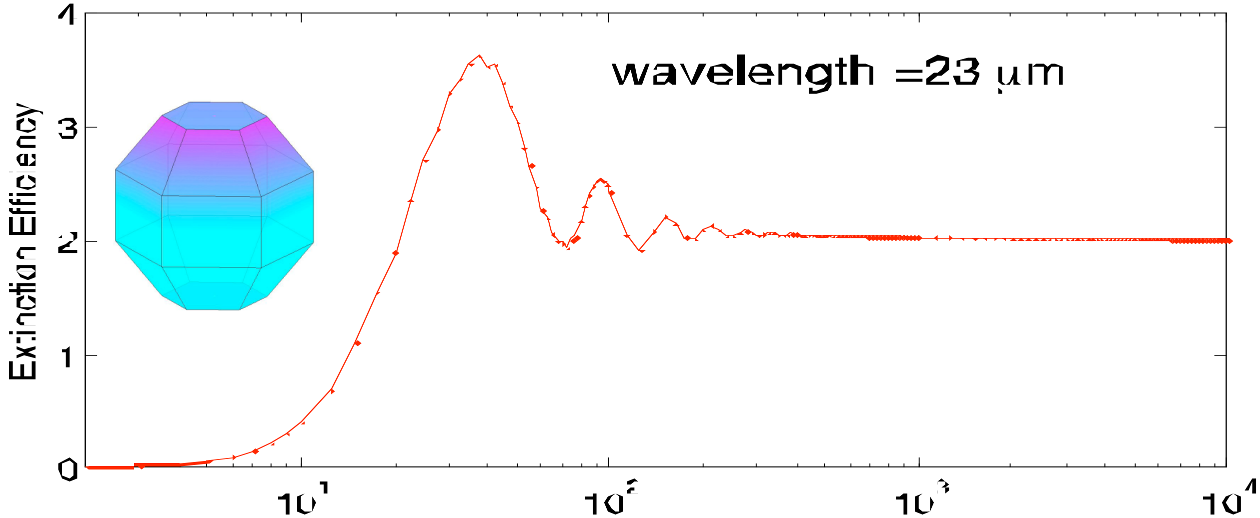






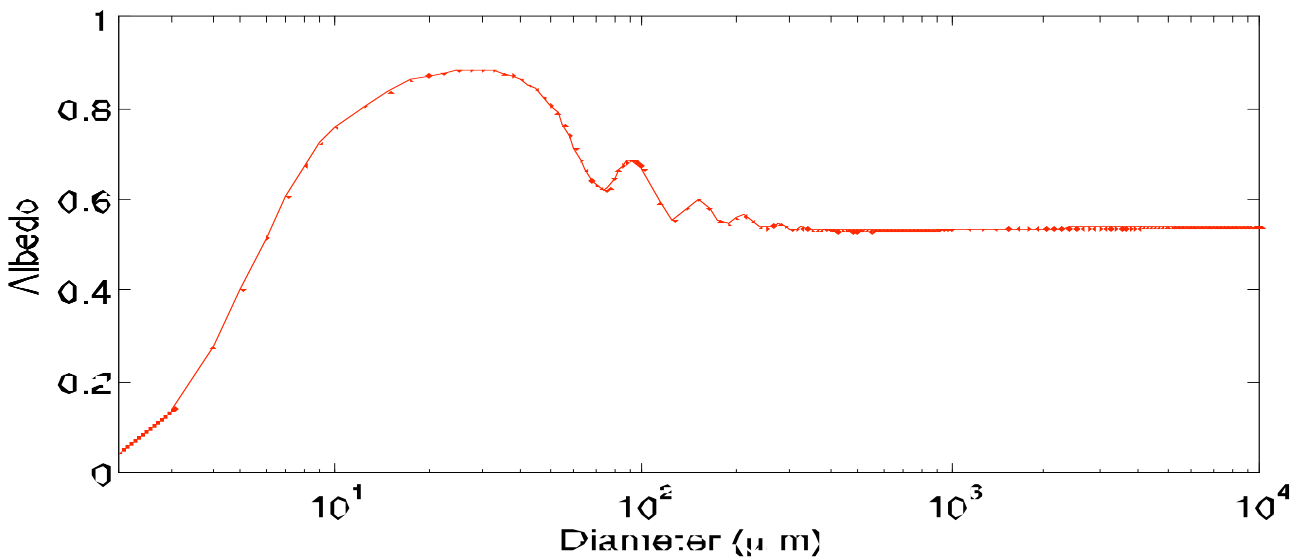






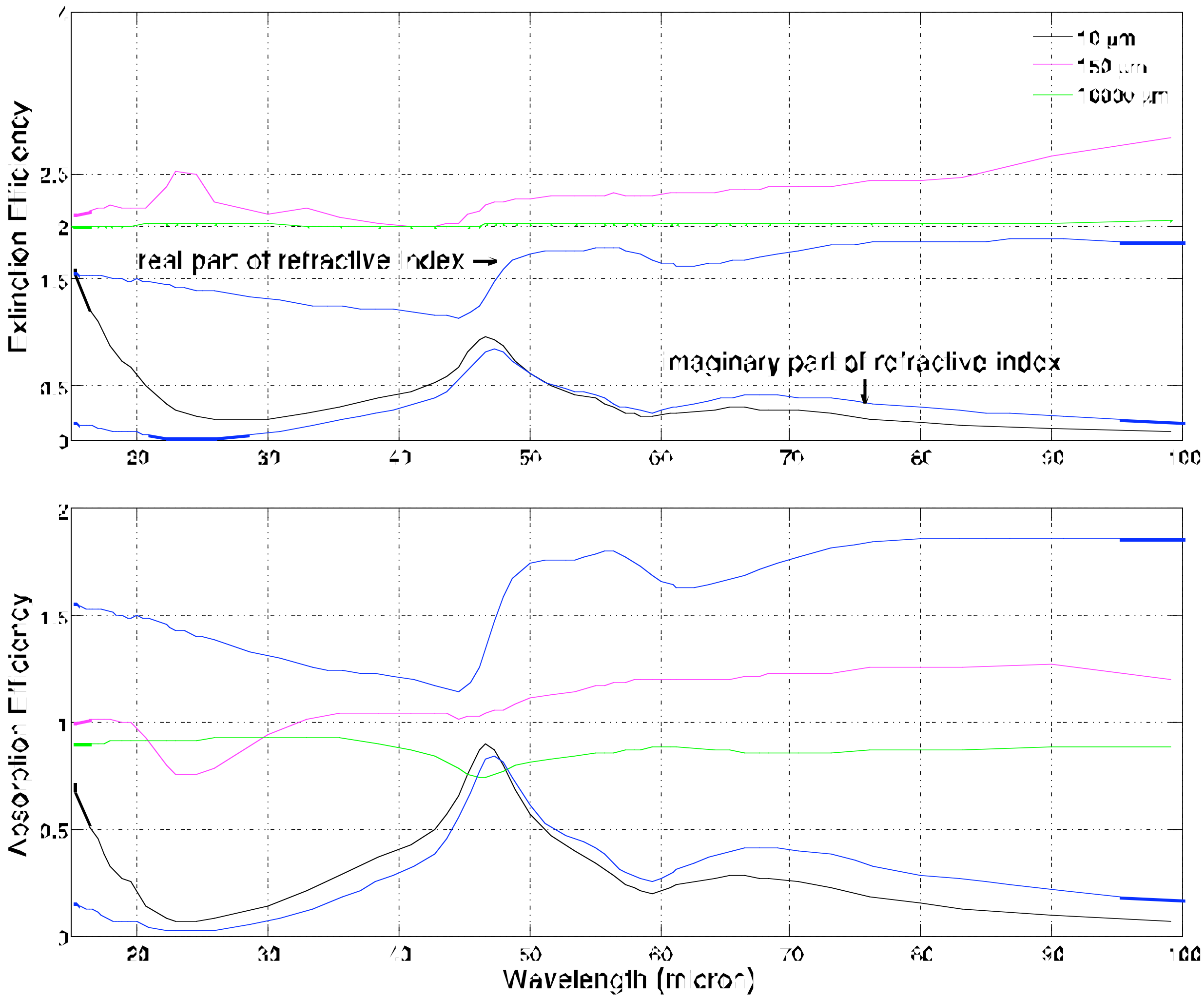
$$Q_{ext,\,edge} = \frac{f_e}{(kL)^{2/3}}$$

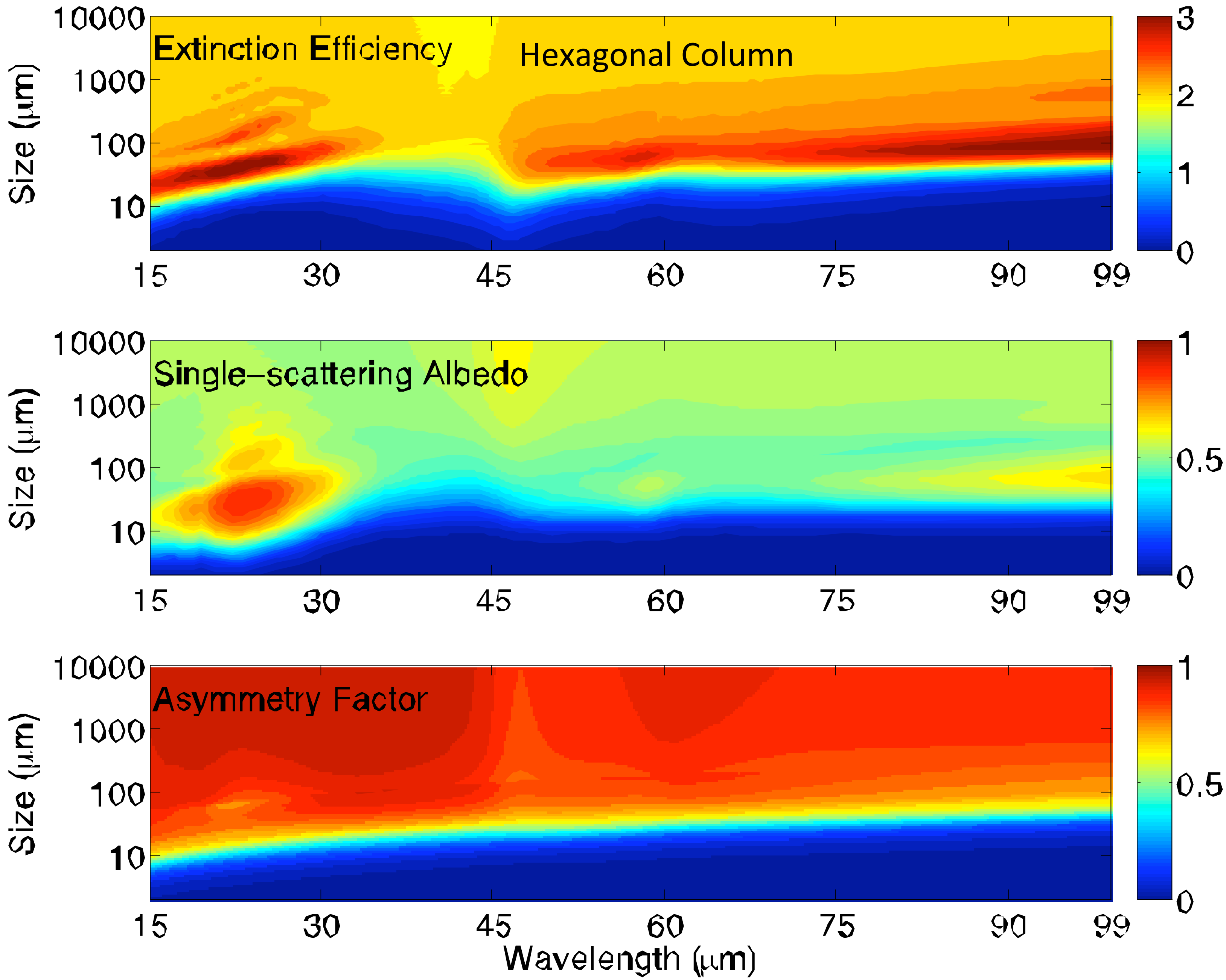
Edge effect incorporated.



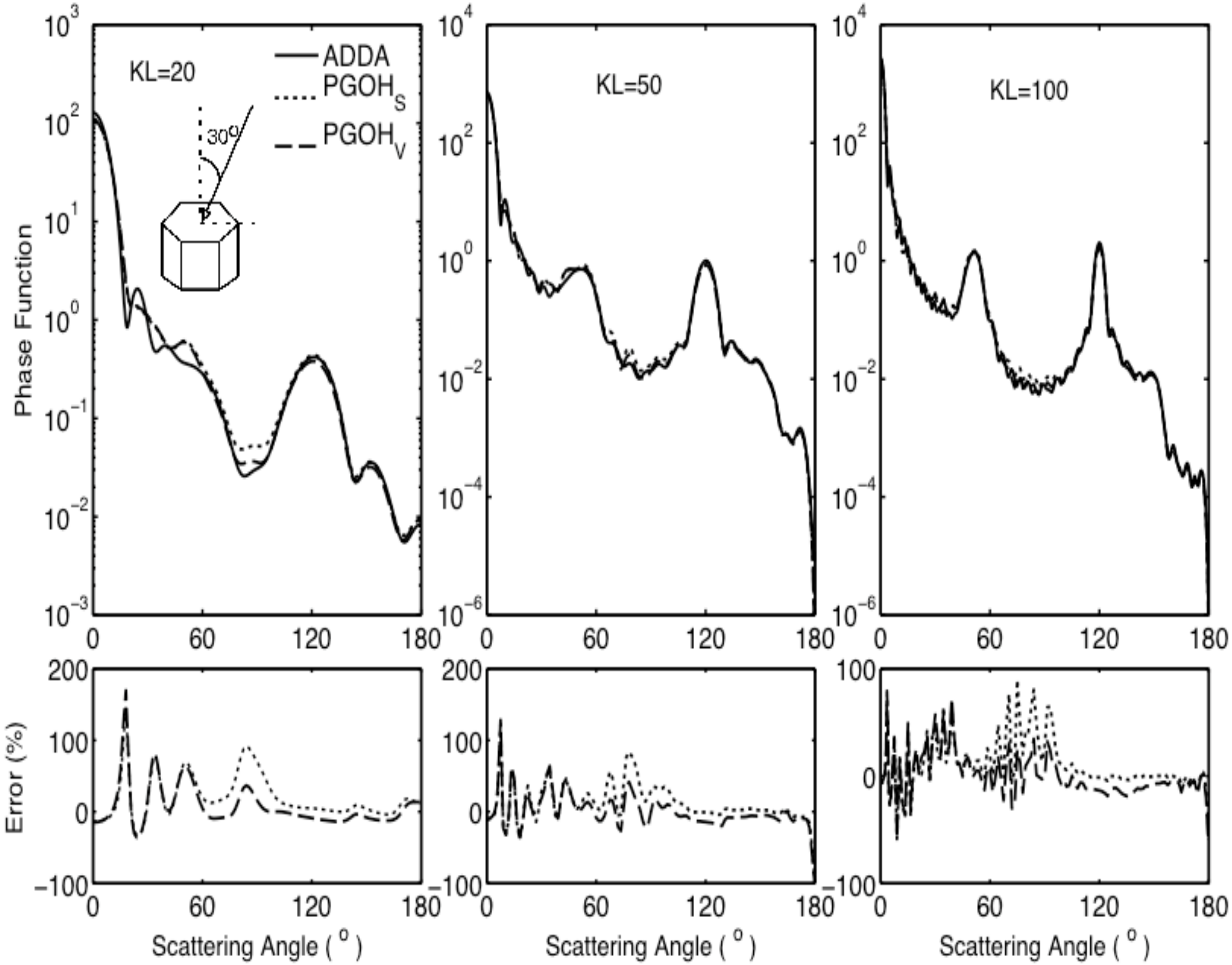
$$Q_{abs,\,edge} = \frac{f_a}{(kL)^{2/3}}$$

Extinction and Absorption



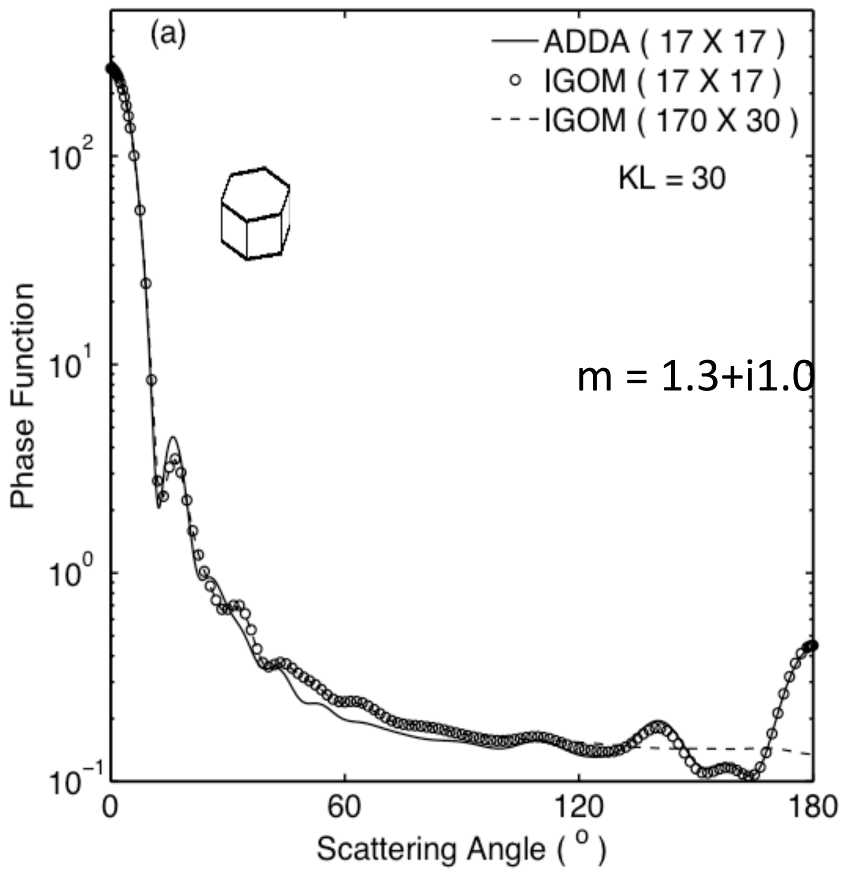

Extinction Efficiency
Hexagonal Column
Single-scattering Albedo
Asymmetry Factor
Size (μm)
10000
1000
100
10
15
30
45
60
75
90
99
3
2
1
0
0.5
Wavelength (μm)

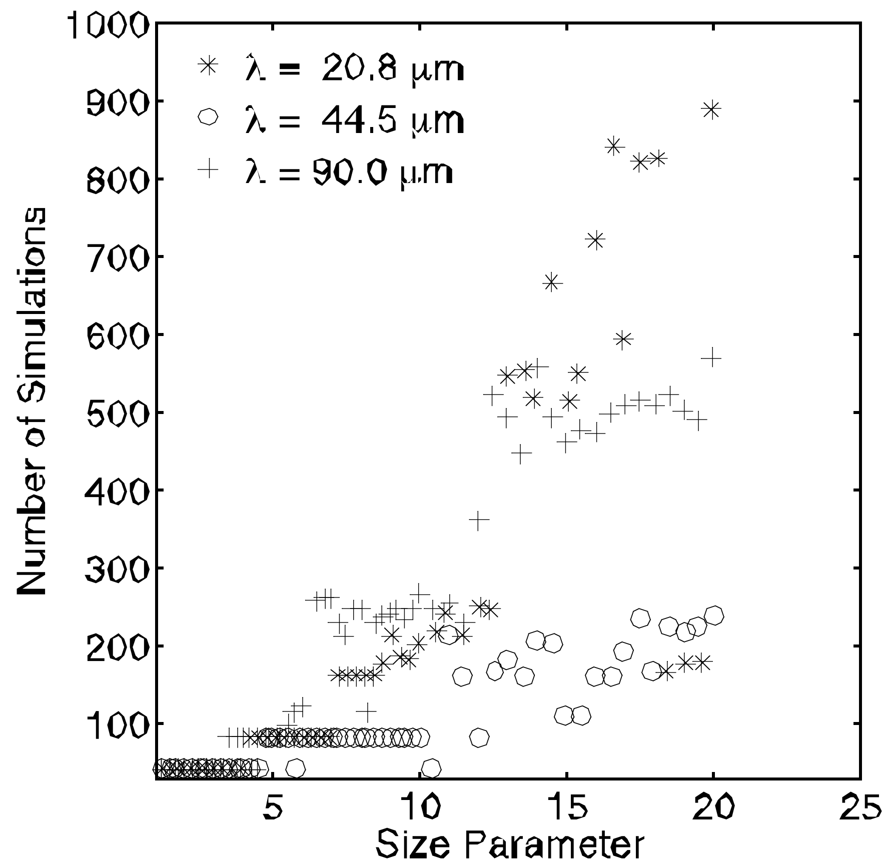
Diffraction and External Reflection



(Bi et al, 2010)

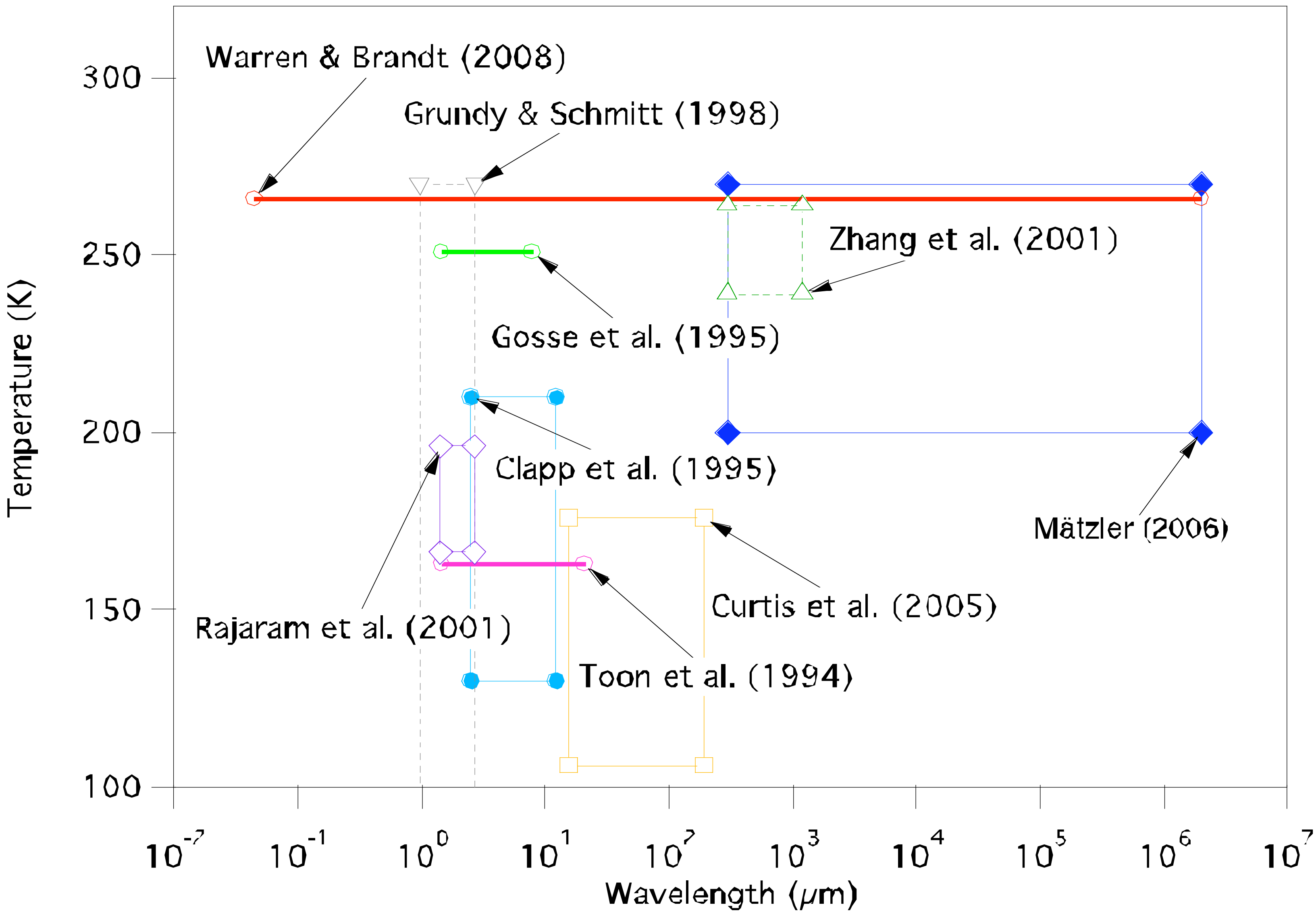
Impact of the Number of particle's Orientations



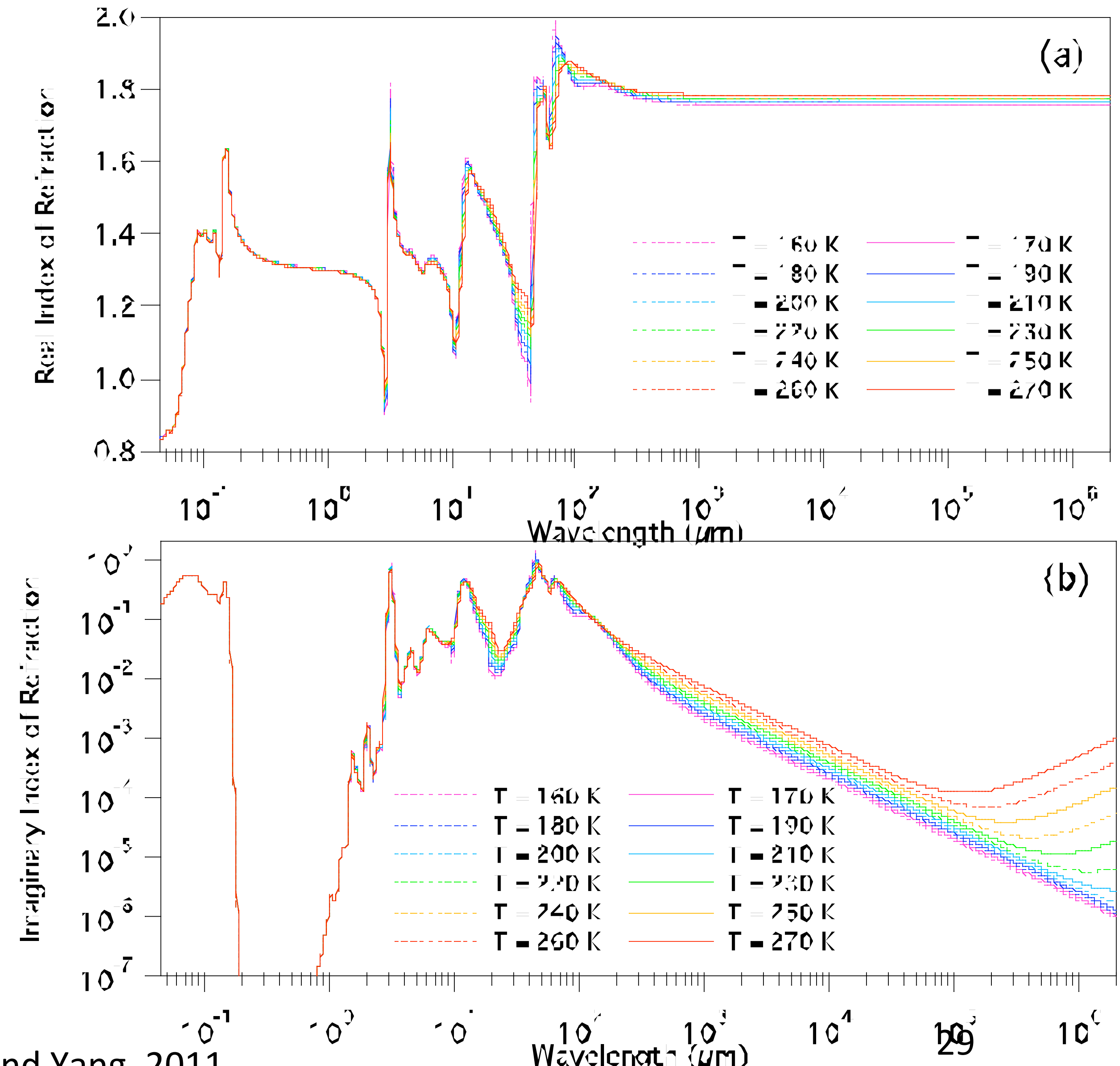


Increasing the number of orientation of model particles!

Temperature dependent refractive index



Iwabuchi and Yang, 2011



Iwabuchi and Yang, 2011

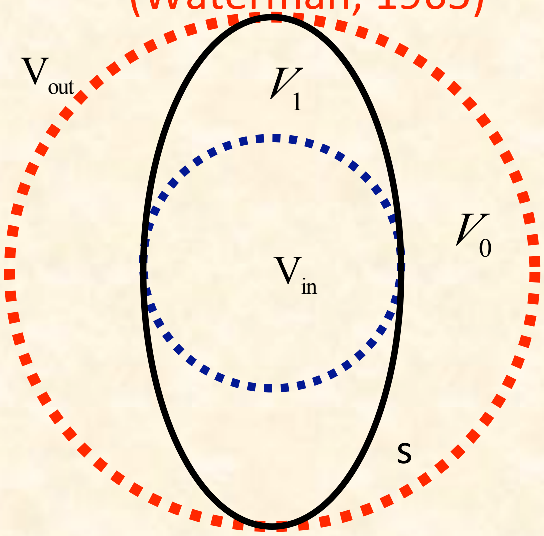
T-matrix

$$E^{inc}(r) = \sum_{n=1}^{\infty}\sum_{m=-n}^{n} a_{mn} RgM_{mn}(r) + b_{mn} RgN_{mn}(r)$$

$$E^{sca}(r) = \sum_{n=1}^{\infty}\sum_{m=-n}^{n} p_{mn} M_{mn}(r) + q_{mn} N_{mn}(r)$$

$$\begin{bmatrix} p_{mn} \\ q_{mn} \end{bmatrix} = \sum_{n'=1}^{\infty}\sum_{m'=-n'}^{n'} \begin{bmatrix} T^{11}_{mnm'n'} & T^{12}_{mnm'n'} \\ T^{21}_{mnm'n'} & T^{22}_{mnm'n'} \end{bmatrix} \begin{bmatrix} a_{m'n'} \\ b_{m'n'} \end{bmatrix}$$

Extended Boundary Condition Method
(Waterman, 1965)

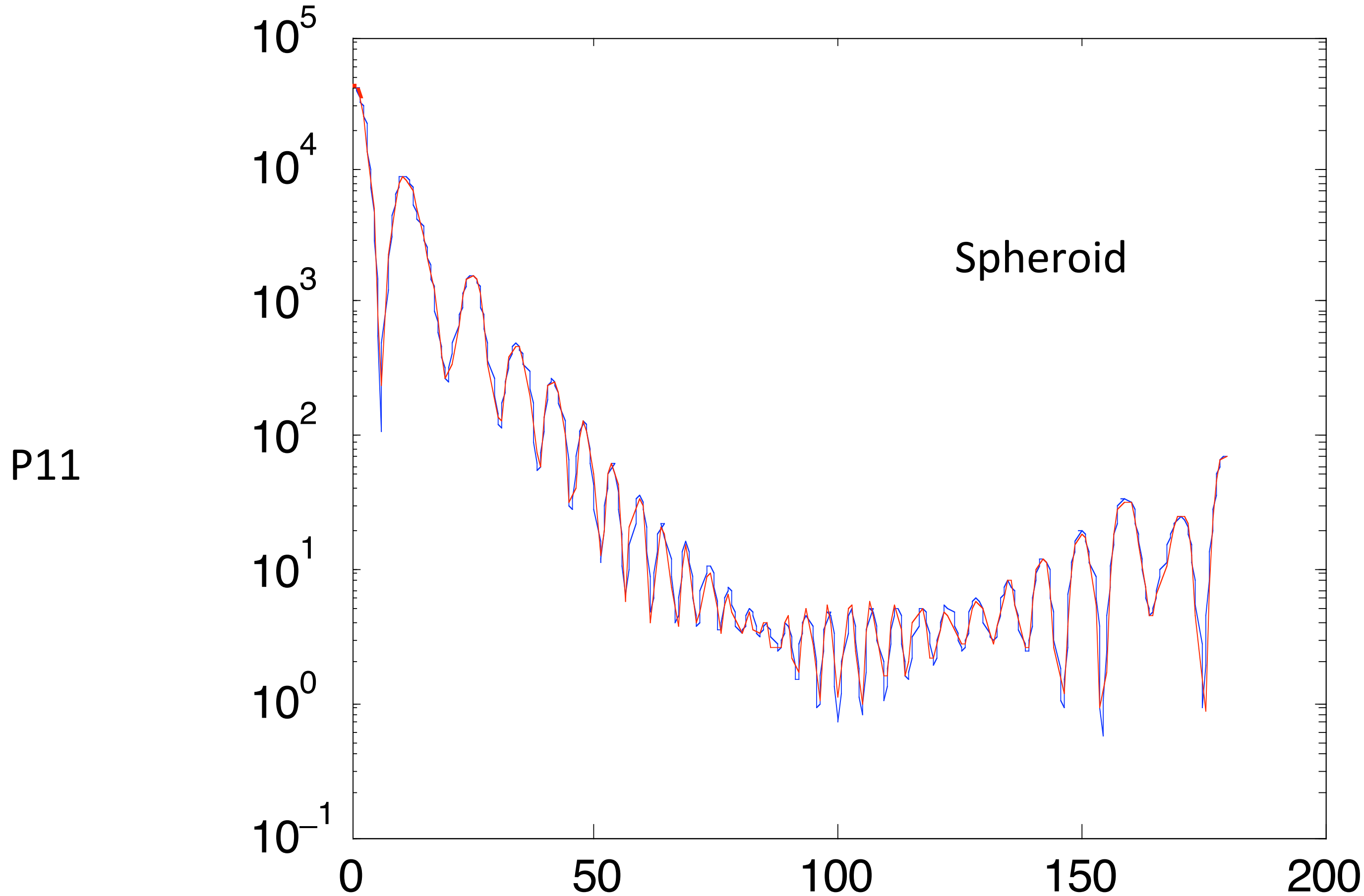


$$E(r) = E^{inc}(r) + \int_V d^3r' \, G(r,r')(m^2 - 1)E(r')$$

Mie-theory: inscribed sphere
Iteration: remaining volume

Accurate; Stable;
Efficient for random orientation

EBCM T-matrix and new T-matrix



Calculation of EBCM is from Mishchenko's code.

Summary

- Single-scattering property datasets have been computed for the wavelengths from 15~99 μm:
  - Using the updated ice index reported in Warren and Brandt;
  - Improved accuracy of scattering calculations
  - 9 representative ice crystal habits
- Perspectives:
  - Temperature dependence (ice crystal habit and refractive index)
  - Volume-integration T-matrix calculation to further improve the efficiency and accuracy