Physical Properties of Asteroid Surfaces

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Lectures

1. Introduction to asteroid UV-VIS-NIR spectrometry,
Monday, November 7, 2016

2. Novel spectrometric modeling,
Tuesday, November 8, 2016

3. Hands-on application to asteroid observations,
Monday, November 14, 2016

4. Combining spectrometric, polarimetric, and photometric observations,
Monday, November 14, 2016

Lecture 2, Contents

- Introduction
- Multiple scattering
  - Radiative transfer and coherent backscattering (RT-CB)
  - RT-CB with incoherent fields
  - Radiative transfer with reciprocal transactions (R^2T^2)
- Preliminary results
- Spectrometry revisited
  - Space weathering
  - Chelyabinsk meteorite spectral modeling
- Spectrometric inverse problem
- Conclusions

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ERC Advanced Grant No 320773 SAEMPL
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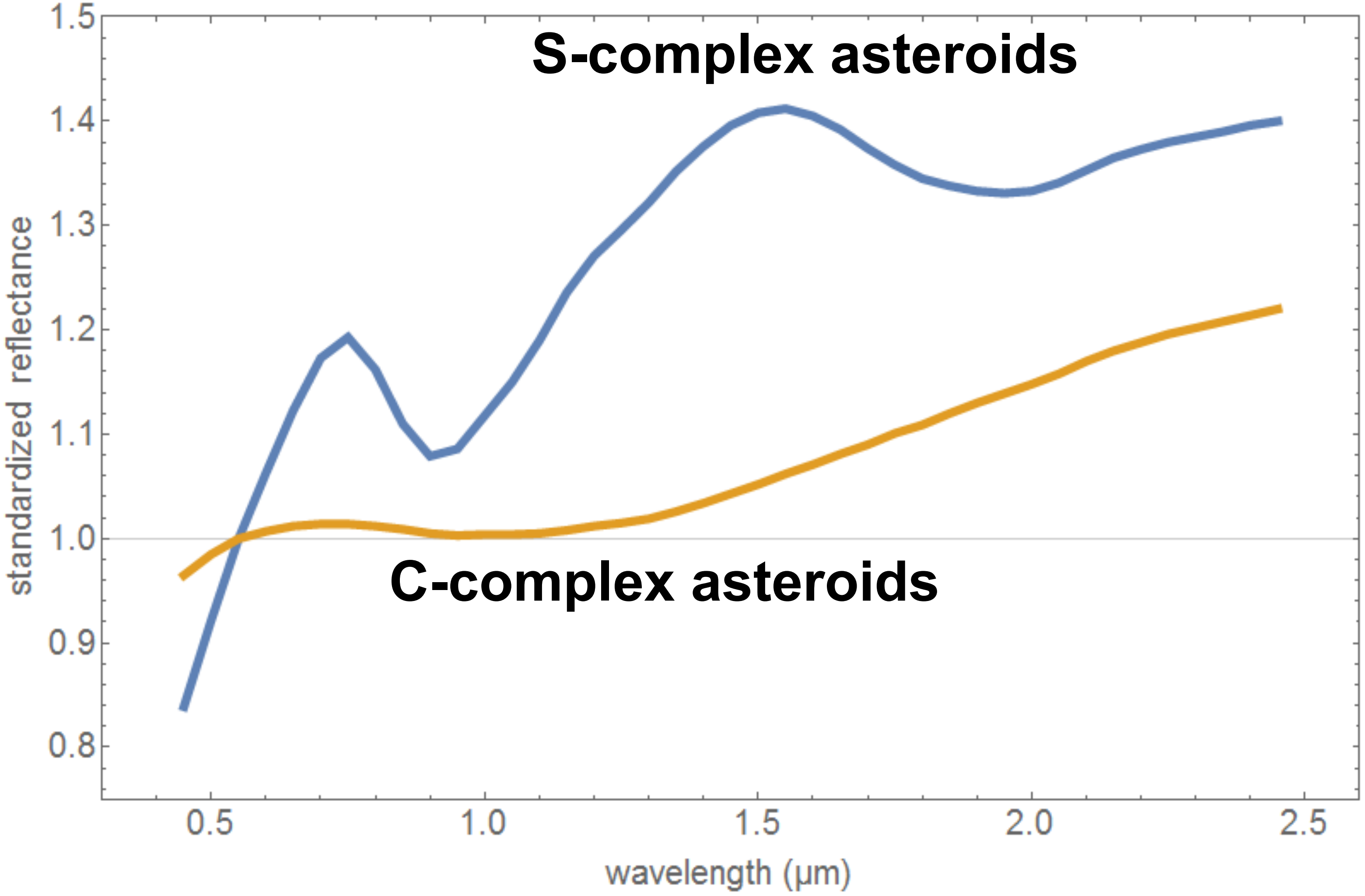
Introduction

- Physical characterization of small particles and particulate media in asteroid surfaces
- Direct problem of light scattering with varying particle size, shape (structure), and refractive index (optical properties)
- Inverse problem of retrieving physical properties of particles based on observations/measurements
- Plane of scattering, scattering angle, solar phase angle, degree of linear polarization

Bus-DeMeo spectral classification system

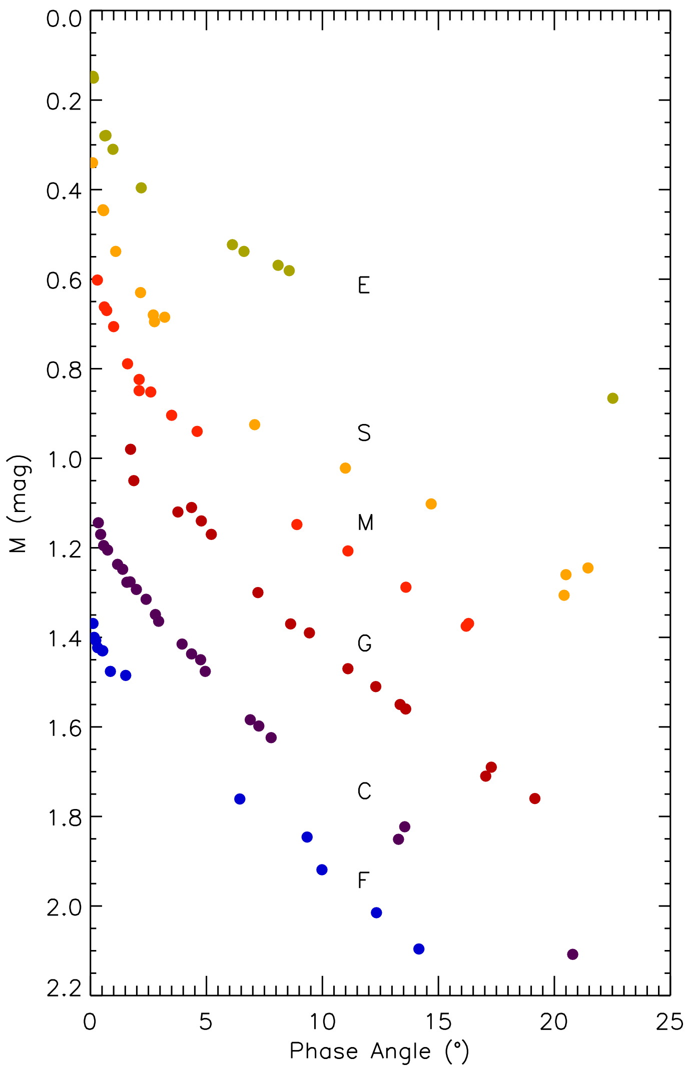


S-complex asteroids

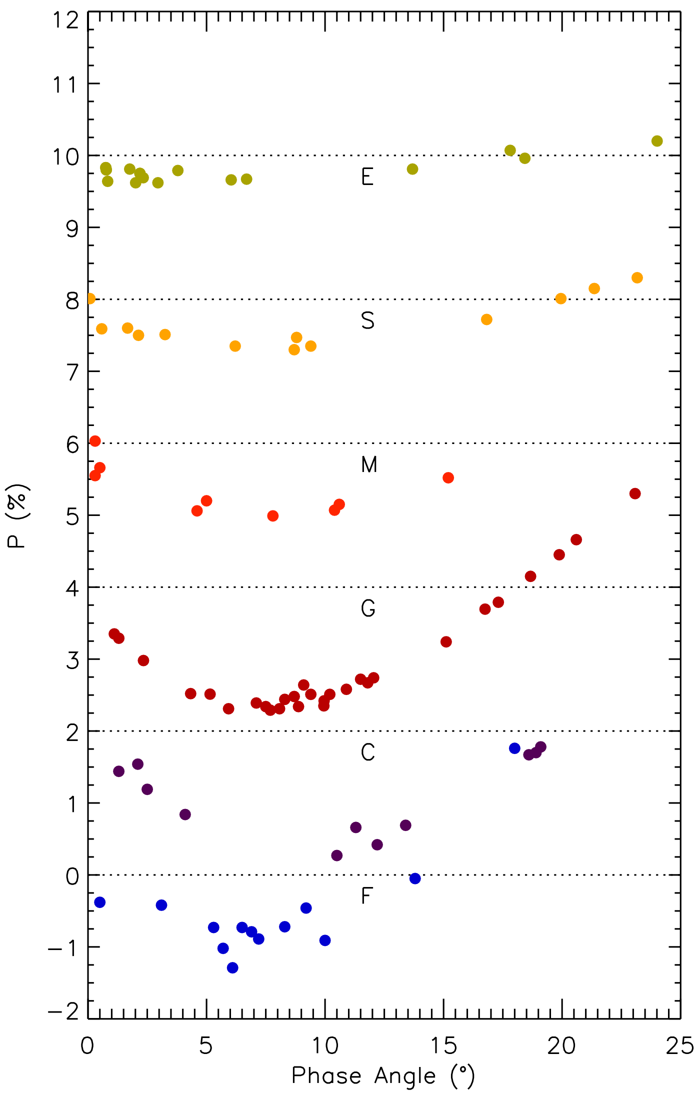
C-complex asteroids

Asteroids

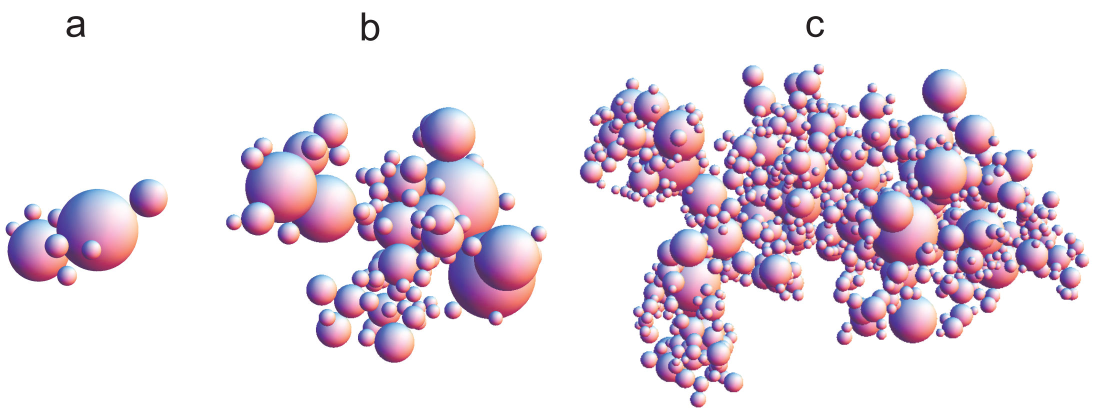
Photometry

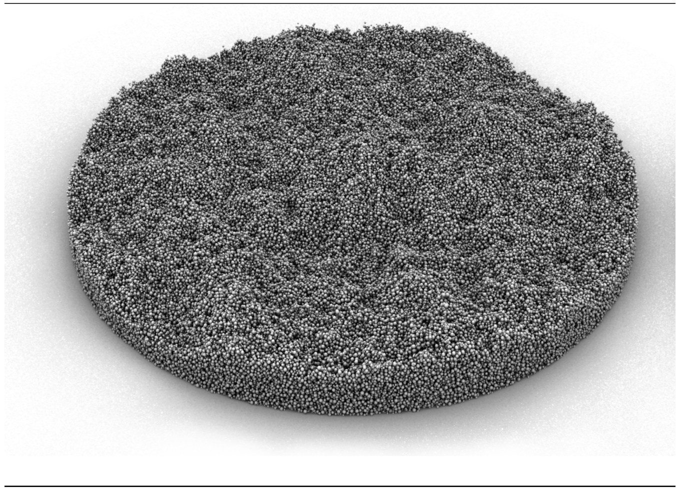


Polarimetry

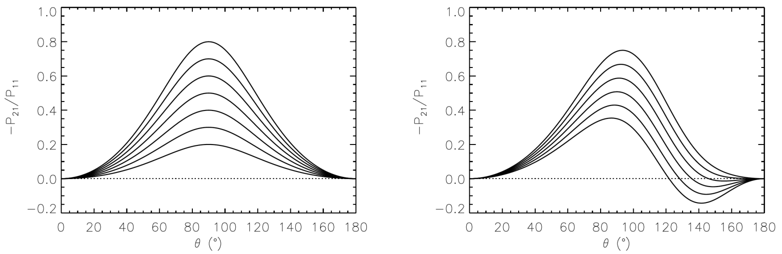


Multiple scattering





- Radiative transfer and coherent backscattering
  - Particulate medium of spherical volume elements and fBm roughness
  - Phenomenological fundamental scatterers
- References:
  - Muinonen et al., in EMTS 2016, in Polarimetry of stars and planetary systems, 2015; ApJ 2012; A&A 2011
  - Tishkovets et al., JQSRT 2011
  - Wilkman et al., JQSRT 2014
  - Muinonen & Videen, JQSRT 2012
  - Parviainen & Muinonen, JQSRT 2007 & 2009
  - Muinonen, Waves in Random Media, 2004

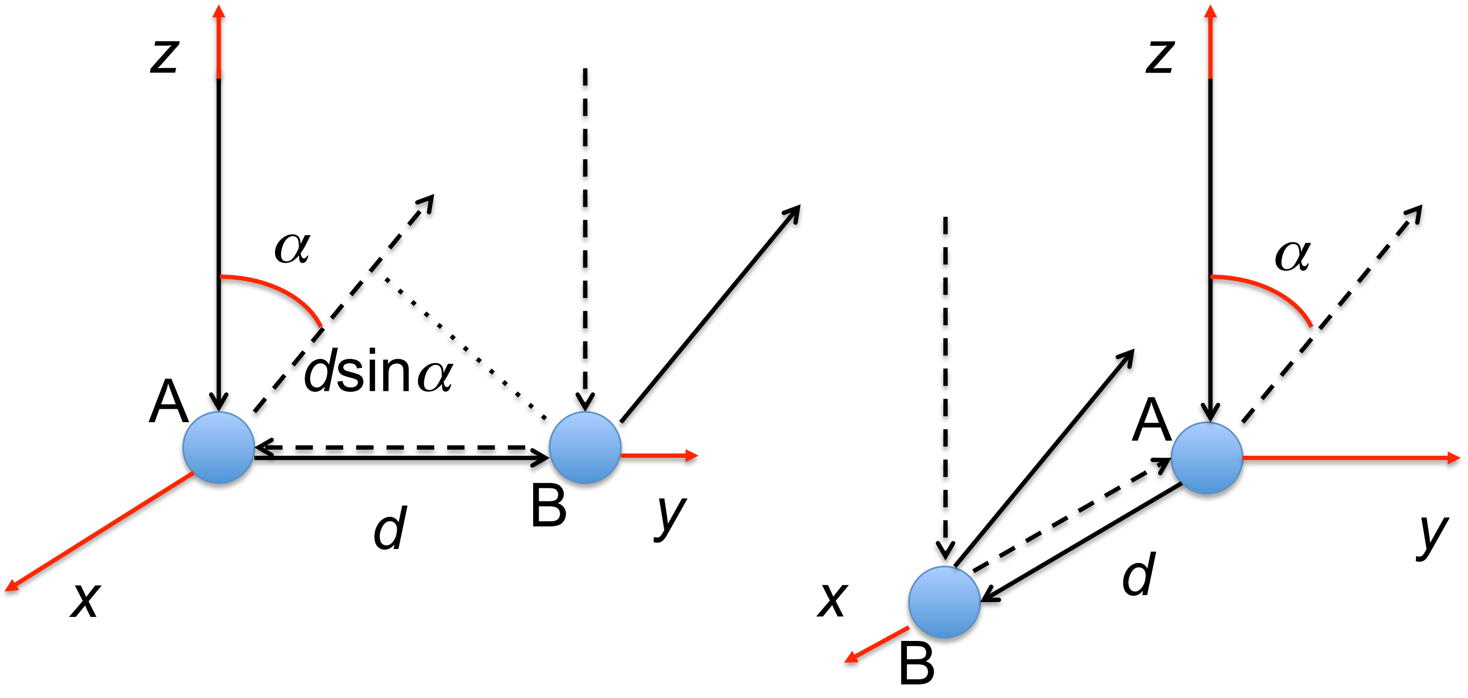


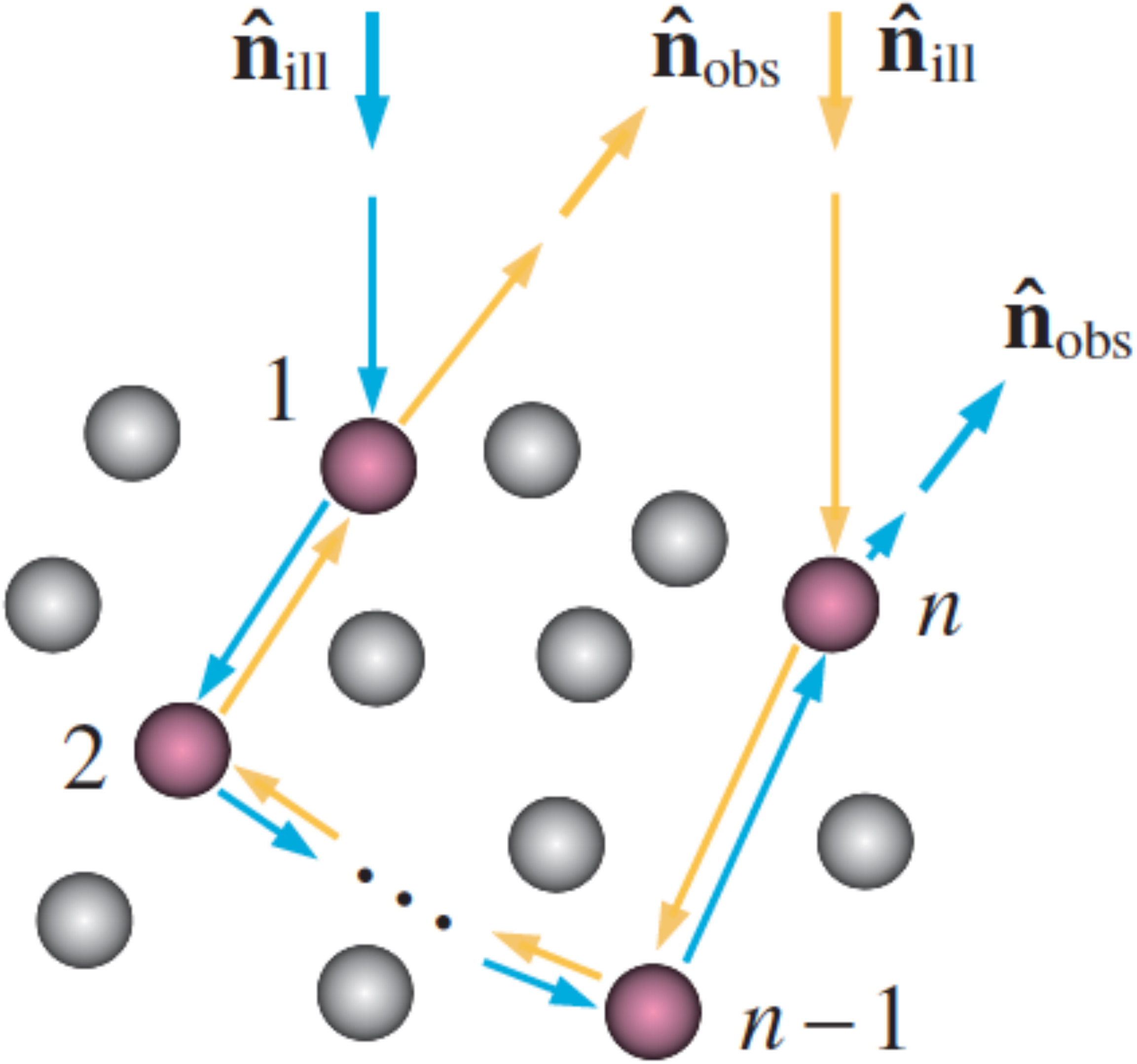
Multiple scattering from a particulate medium is a function of

- surface roughness
- volume density of the particulate medium
- size of small particles
- shape (structure) of small particles
- refractive index of small particles

Coherent backscattering mechanism

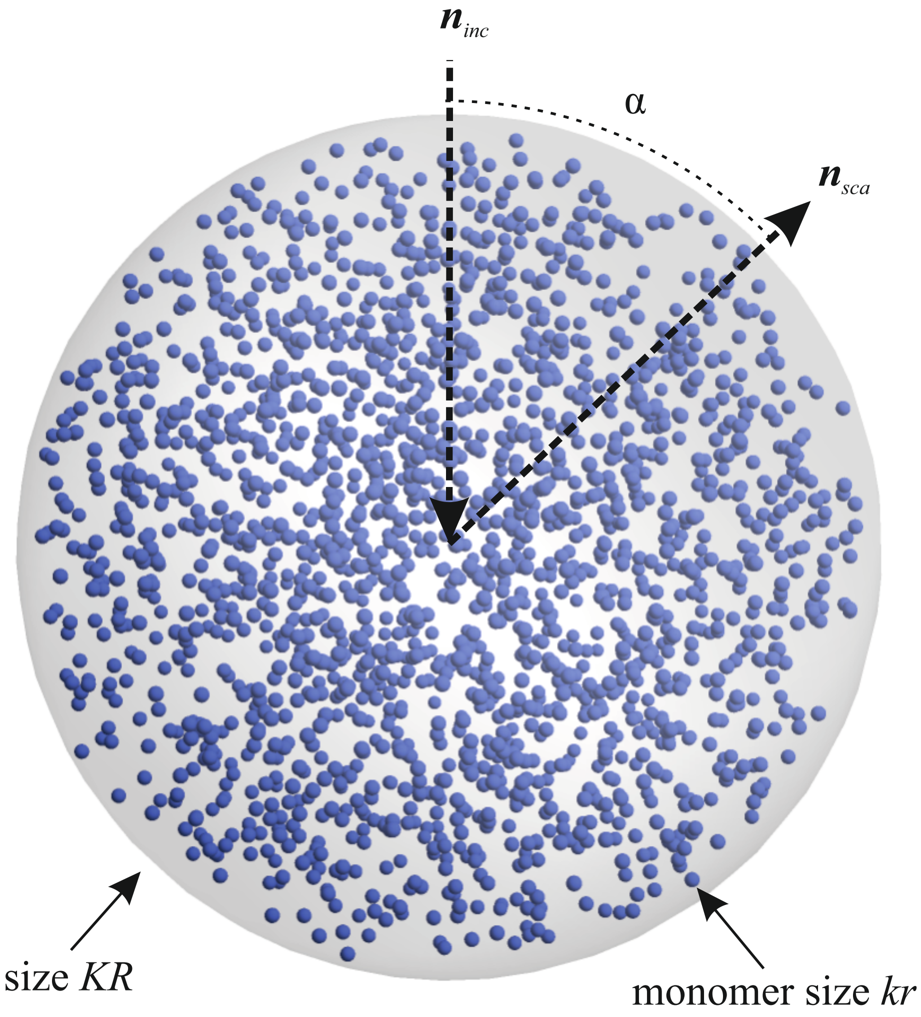
Muinonen 1989 & 1990, Shkuratov 1988 & 1989




$\hat{\mathbf{n}}_{\text{ill}}$
$\hat{\mathbf{n}}_{\text{obs}}$
$\hat{\mathbf{n}}_{\text{ill}}$
$\hat{\mathbf{n}}_{\text{obs}}$
1
2
n
$n-1$

Spherical medium of scatterers

- Radiative transfer and coherent backscattering (RT-CB; e.g., Muinonen et al., ApJ, 2012; Väisänen et al., this meeting)
- Superposition *T*-Matrix Method (STMM or MSTM; Mackowski & Mishchenko 2011; FaSTMM, Markkanen et al. 2016)
- Radiative transfer with rigorous transactions (R^2T^2; e.g., Muinonen et al., EMTS 2016, Väisänen et al., this meeting)



$$\boldsymbol{I}_{\rm i} = (I_{\rm i}, Q_{\rm i}, U_{\rm i}, V_{\rm i})^T$$

$$\boldsymbol{I}_{\rm s} = (I_{\rm s}, Q_{\rm s}, U_{\rm s}, V_{\rm s})^T$$

$$\boldsymbol{I}_{\rm s} = \frac{1}{k^2 R^2} \boldsymbol{S} \cdot \boldsymbol{I}_{\rm i}$$

(Here R is the distance between observer and scatterer.)

$$\mu_{\rm L} = \frac{P_{11} - P_{22}}{P_{11} + 2P_{21} + P_{22}}.$$

$$\mu_{\rm C} = \frac{P_{11} + P_{44}}{P_{11} - P_{44}}.$$

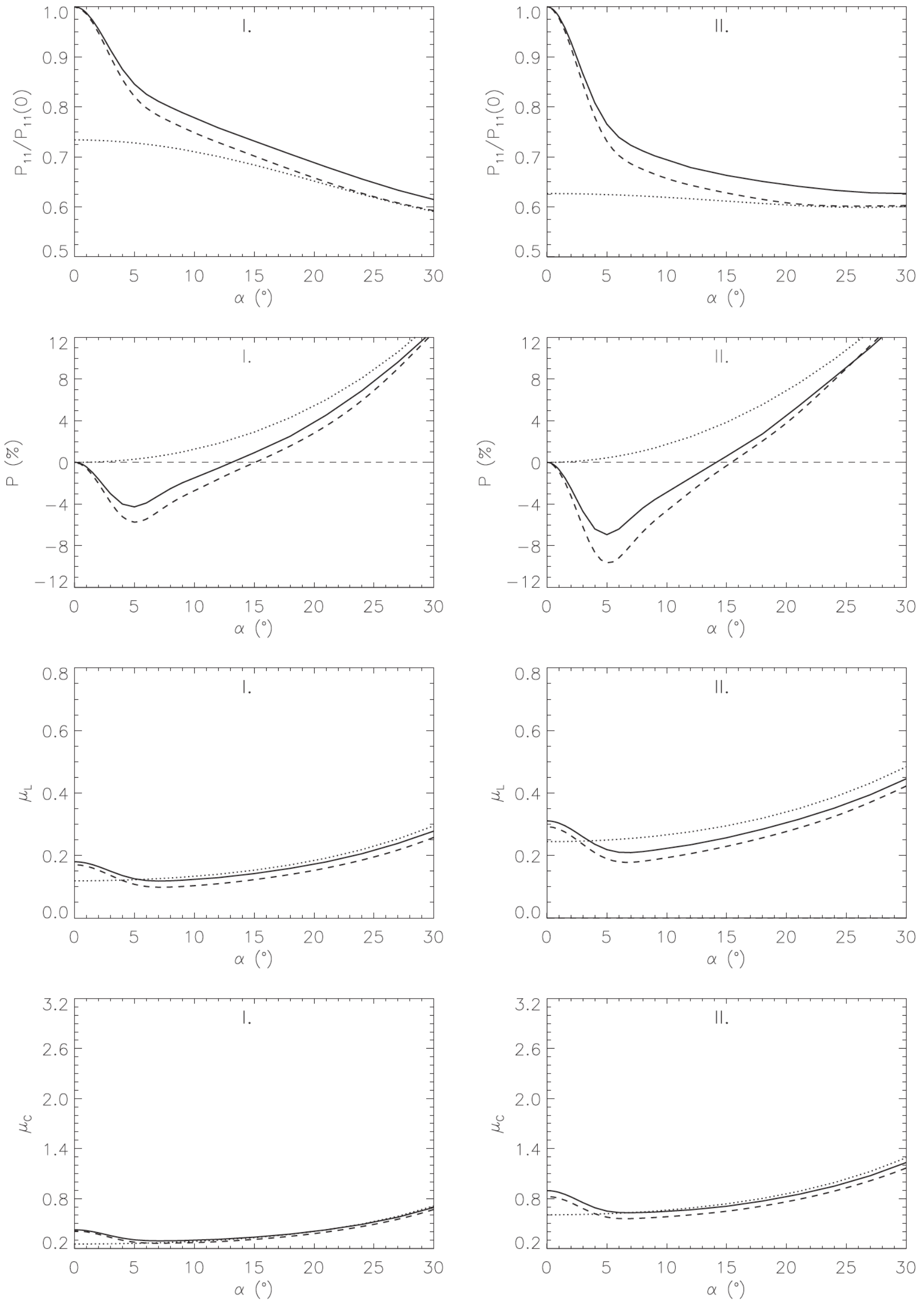


Figure 2. Scattering by a spherical volume of particulate medium with a size parameter $kR = 40$ and packing density of $v = 3.125\%$ (I) and 6.250% (II), populated with spherical particles with a size parameter $kr = 2$ and a refractive index $m = 1.31$. The solid, dotted, and dashed curves depict the RT–CB, RT-only, and STMM results, respectively. See the text.

Muinonen et al. 2012

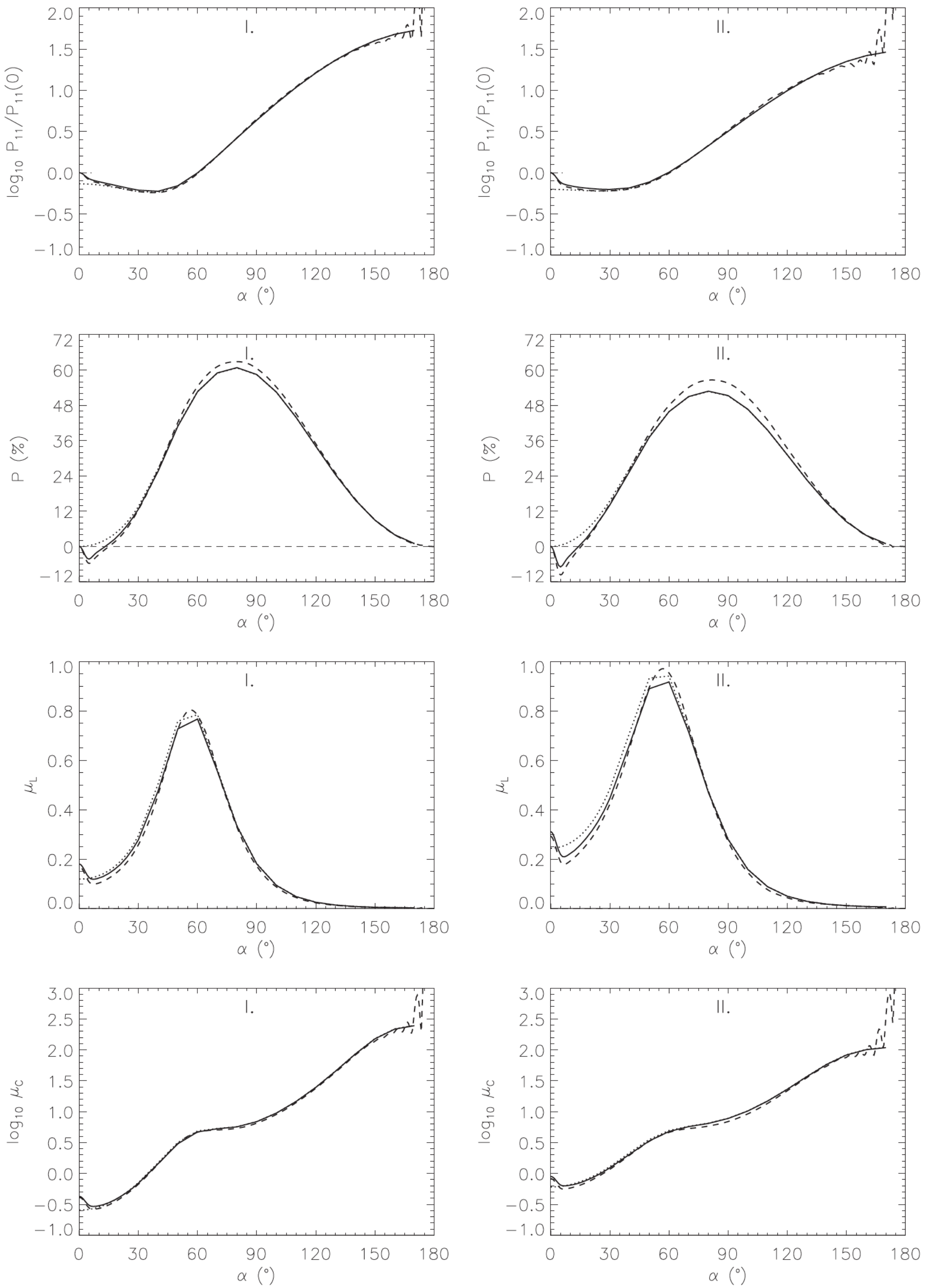


Figure 3. Same as in Figure 2, but for the full range of phase angles.

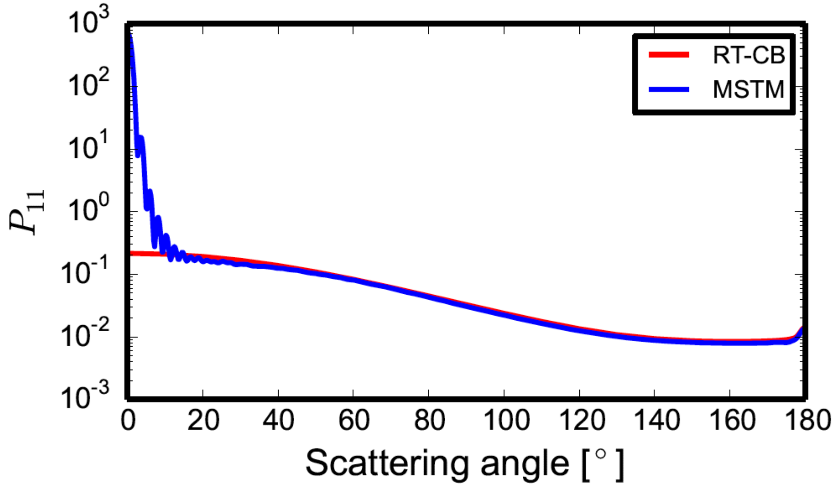


Fig. 2. Ensemble-averaged scattering-matrix element P_{11} (intensity) of a finite particulate medium with volume fraction p=0.05, size parameter kR=86.7481, mean free path $k\ell$=86.028.

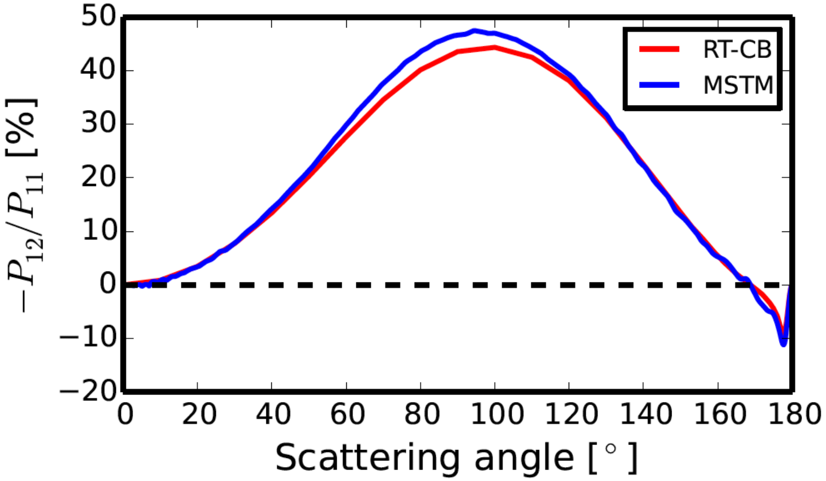


Fig. 3. Degree of linear polarization for unpolarized incident light for a finite particulate medium with volume fraction p=0.05

Väisänen et al. 2016

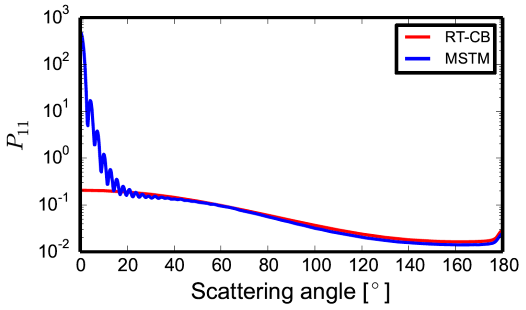


Fig. 4. Ensemble-averaged scattering-matrix element P_{11} (intensity) of a finite particulate medium with volume fraction p=0.1, kR=68.852, mean free path $k\ell$=43.013

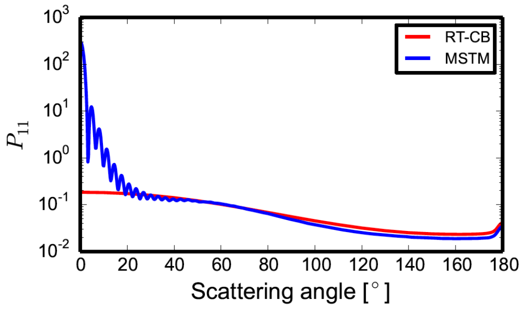


Fig. 5. Ensemble-averaged scattering-matrix element P_{11} (intensity) of a finite particulate medium with volume fraction p=0.15, kR=60.1478, mean free path $k\ell$=28.676

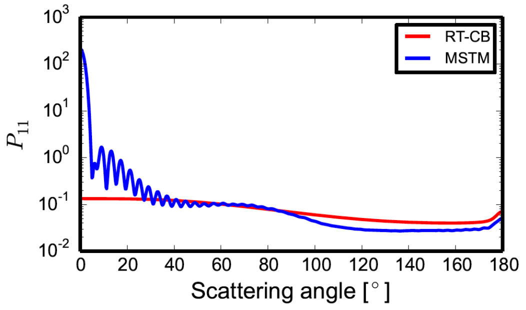


Fig. 6. Ensemble-averaged scattering-matrix element P_{11} (intensity) of a finite particulate medium with volume fraction p=0.3, kR=47.7393, mean free path $k\ell$=14.338

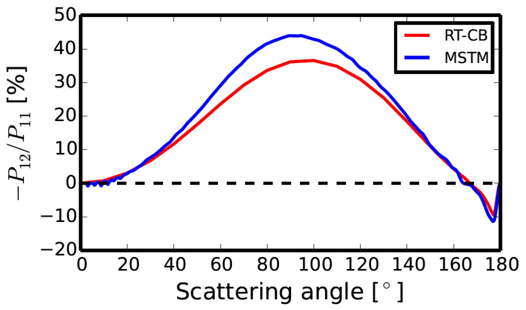


Fig. 7. Degree of linear polarization for unpolarized incident light for a finite particulate medium with p=0.1

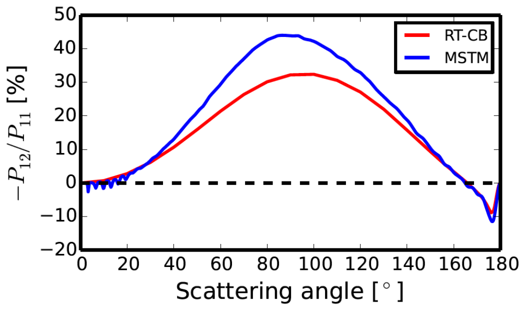


Fig. 8. Degree of linear polarization for unpolarized incident light for a finite particulate medium with p=0.15

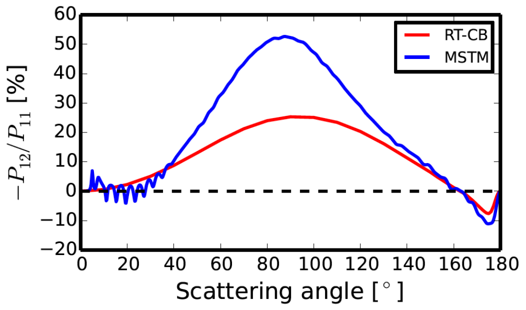


Fig. 9. Degree of linear polarization for unpolarized incident light for a finite particulate medium with p=0.3

- Coherent field equals the mean field from separate realizations (not measurable)
- Incoherent field equals the free-space field with subtraction of the mean field
- Incoherent field specifies the elementary scattering in an infinite medium
- Scattering by an infinite medium invariant: independence of elementary scattering
- Recipe: revise RT-CB input for incoherent elementary scattering by a wavelength-scale volume element

Stokes vectors, incident and scattered radiation:

$$\boldsymbol{I}_{\mathrm{i}} = (I_{\mathrm{i}}, Q_{\mathrm{i}}, U_{\mathrm{i}}, V_{\mathrm{i}})^T$$

$$\boldsymbol{I}_{\mathrm{s}} = (I_{\mathrm{s}}, Q_{\mathrm{s}}, U_{\mathrm{s}}, V_{\mathrm{s}})^T$$

Scattering matrix:

$$\boldsymbol{I}_{\mathrm{s}} = \frac{1}{k^2 R^2}\, \boldsymbol{S} \cdot \boldsymbol{I}_{\mathrm{i}}$$

Preliminary results

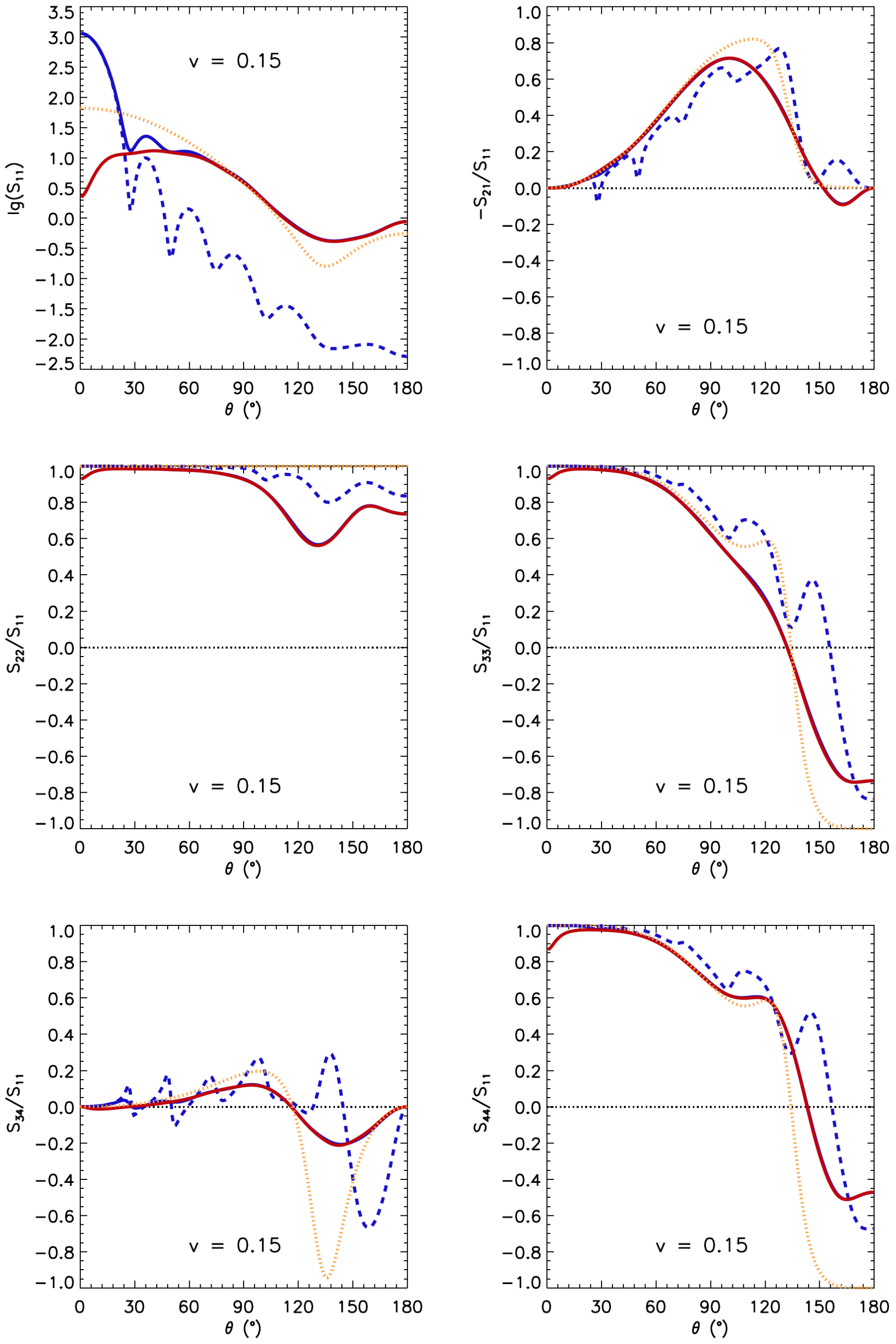
- Spherical medium of spherical scatterers:
  - – number of spheres $N = 1, 2, 20, 4080$
  - – radius $kr = 2.0$, refractive index $m = 1.31$
  - – single-scattering albedo $\omega = 1.0$
- RT-CB with incoherent input vs. STMM for $N = 4080$
- For independent scattering and volume fraction $v = 0.15$, extinction mean free path length $kl_e = 28.68$

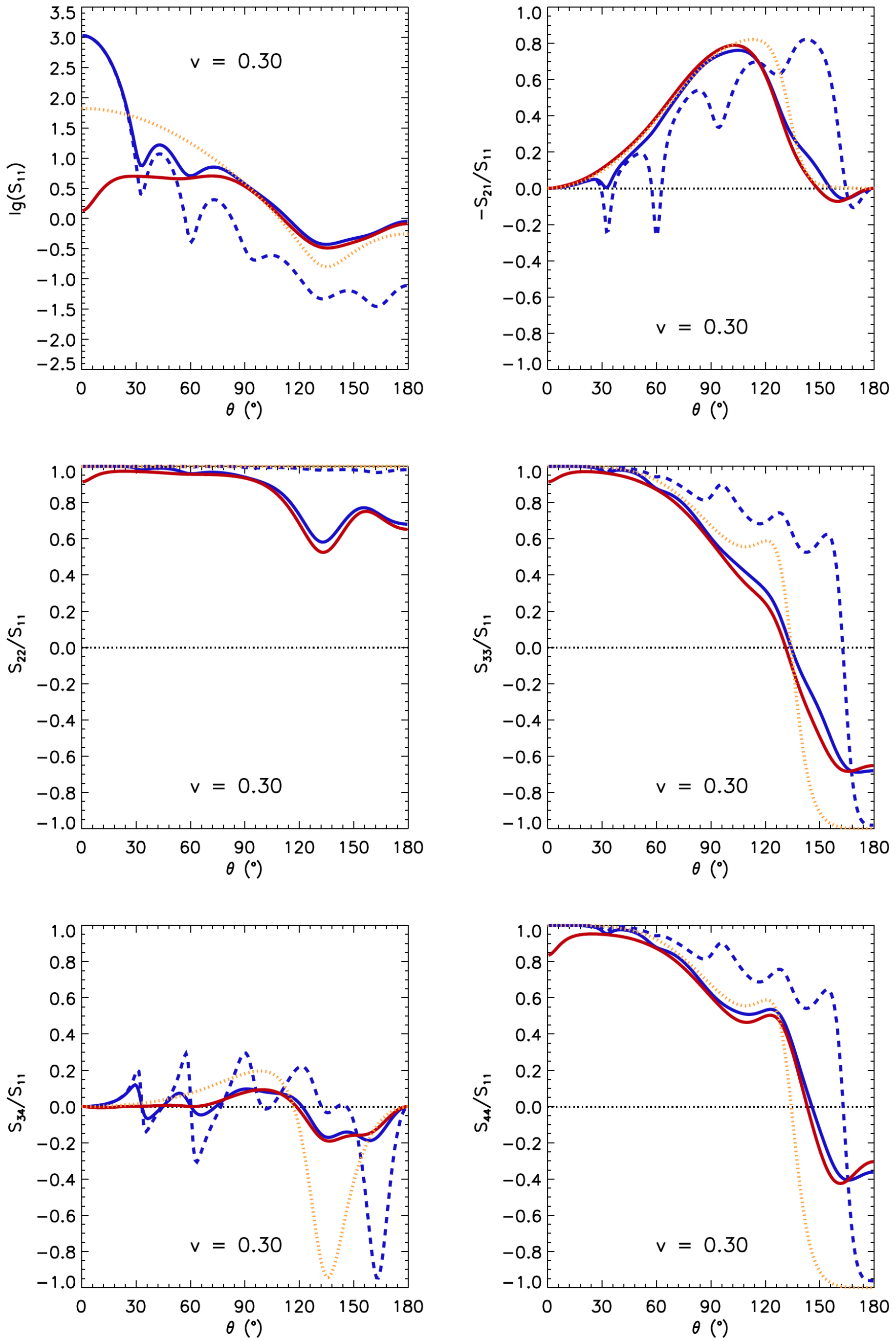
TABLE I

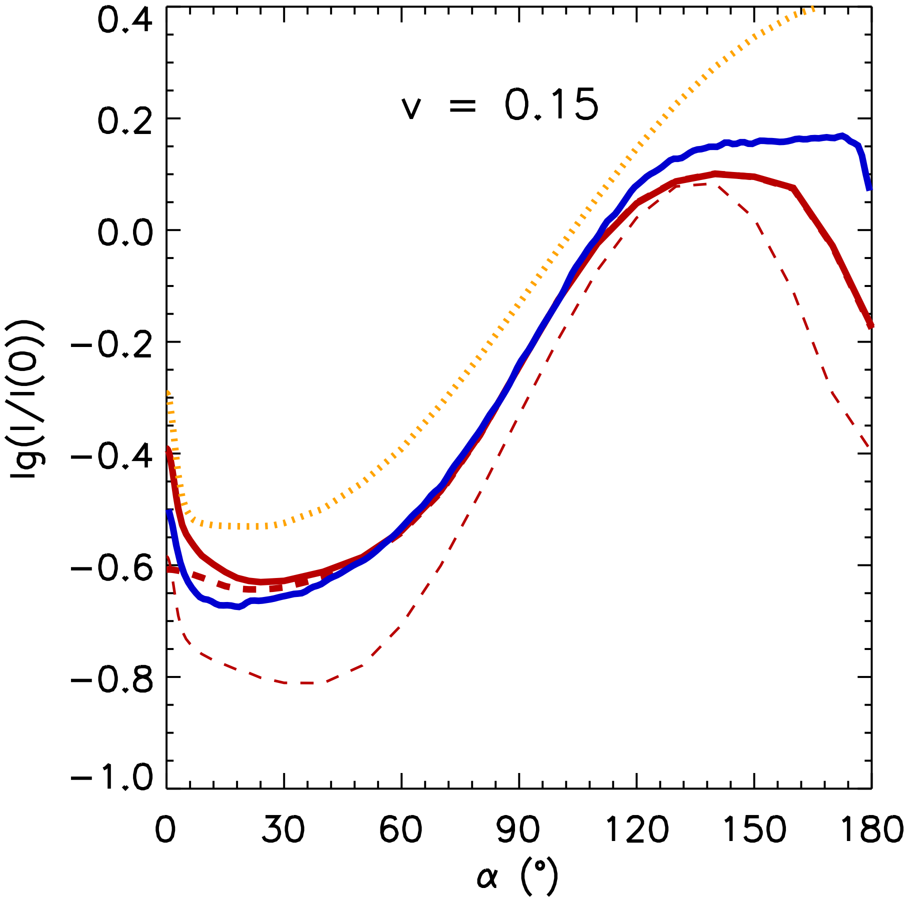
THE DIMENSIONLESS INCOHERENT EXTINCTION COEFFICIENTS $\kappa_{\rm e}/k$ (k IS THE WAVE NUMBER) AND THE CORRESPONDING EXTINCTION MEAN FREE PATH LENGTHS $k\ell_{\rm e} = k/\kappa_{\rm e}$ FOR VOLUME ELEMENTS OF SPHERICAL PARTICLES WITH TWO VALUES OF VOLUME DENSITIES v (VOLUME FRACTION OF PARTICLES). N DENOTES THE NUMBER OF SPHERES AND kR GIVES THE SIZE PARAMETER OF THE SPHERICAL MEDIUM. NOTE THAT IT IS IMPOSSIBLE TO PACK TWO SPHERICAL PARTICLES INTO A SPHERICAL MEDIUM WITH VOLUME DENSITY $v = 0.30$.

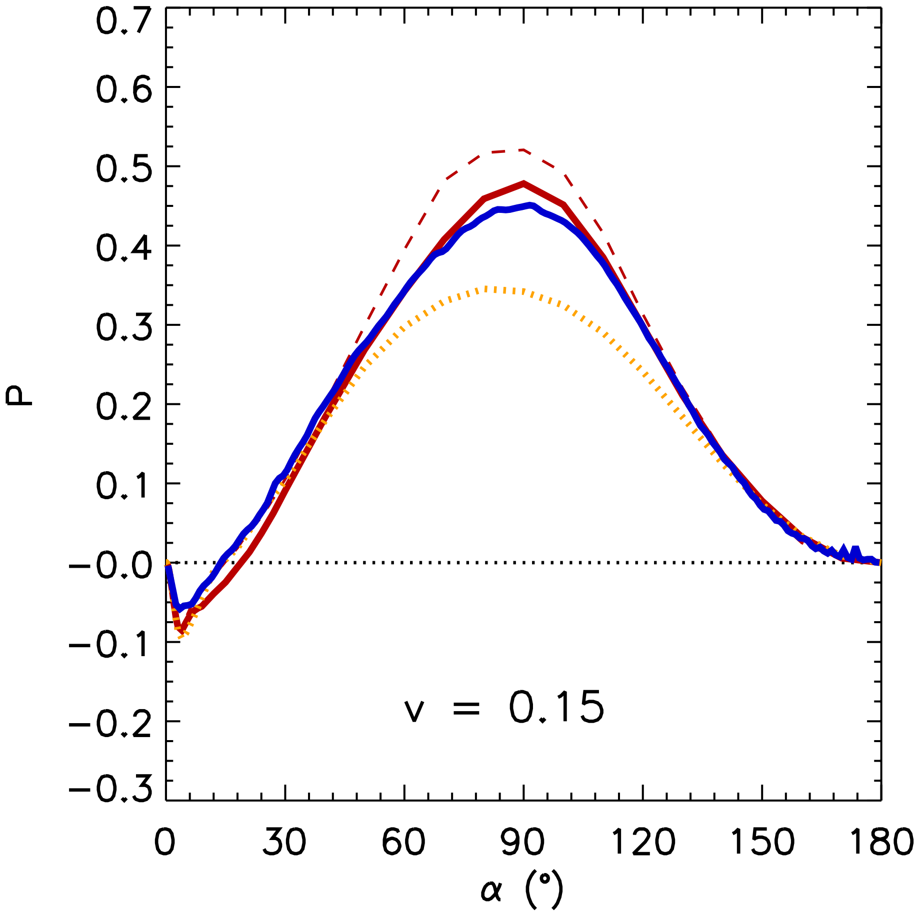
	$v = 0.15$			$v = 0.30$		
N	kR	$\kappa_{\rm e}/k$	$k\ell_{\rm e}$	kR	$\kappa_{\rm e}/k$	$k\ell_{\rm e}$
1	3.76	0.0110	90.8	2.99	0.0082	122
2	4.74	0.0131	76.5	–	–	–
20	10.2	0.0151	66.3	8.11	0.0160	62.4
200	22.0	0.0136	73.3	17.5	0.0159	62.7
4080	60.1	0.0099	101	47.7	0.0117	85.3

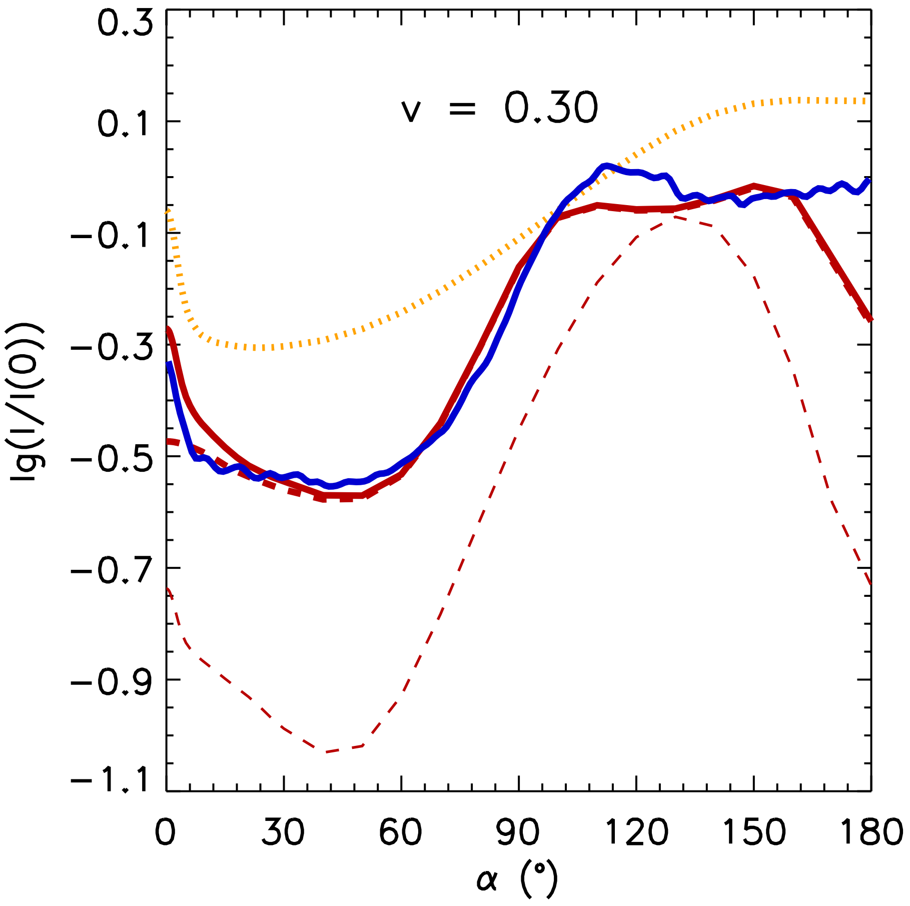
Incoherent scattering matrix,
Muinonen et al. 2016,
Markkanen et al. 2016,
in preparation

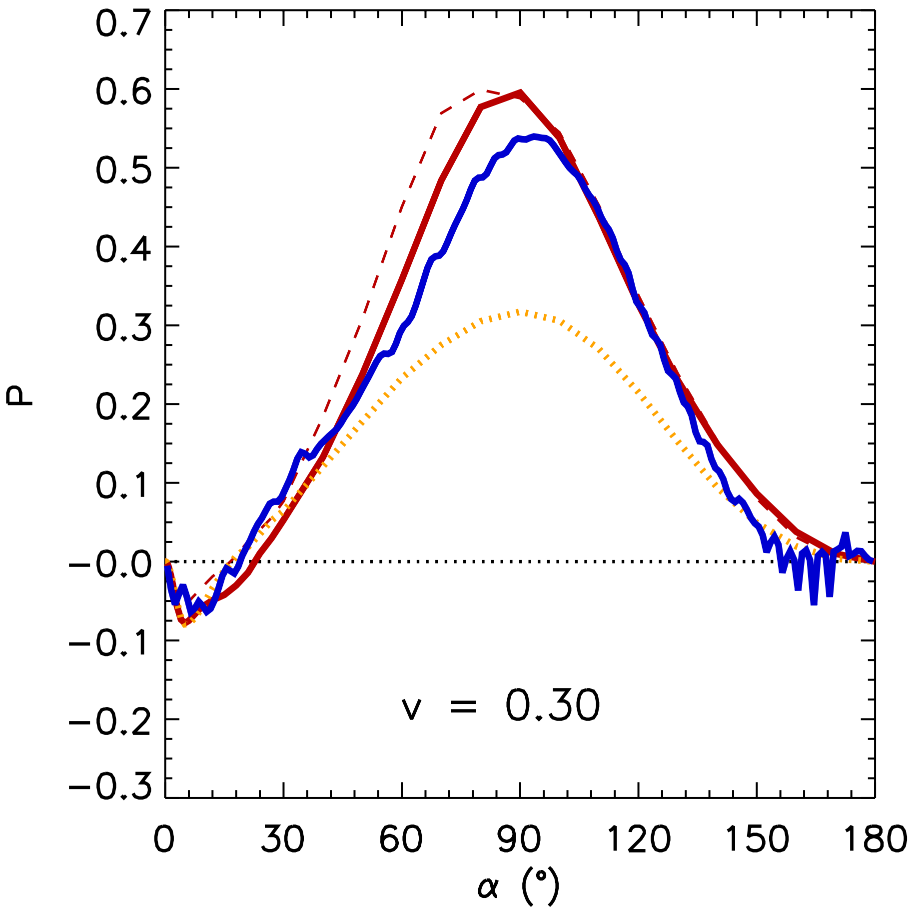



lg(S$_{11}$)
v = 0.30
$-S_{21}/S_{11}$
v = 0.30
S_{22}/S_{11}
v = 0.30
S_{33}/S_{11}
v = 0.30
S_{34}/S_{11}
v = 0.30
S_{44}/S_{11}
v = 0.30
θ (°)
0
30
60
90
120
150
180
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0.8
0.6
0.4
0.2
−0.2
−0.4
−0.6
−0.8


v = 0.15
lg(I/I(0))
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
30
60
90
120
150
180
α (°)

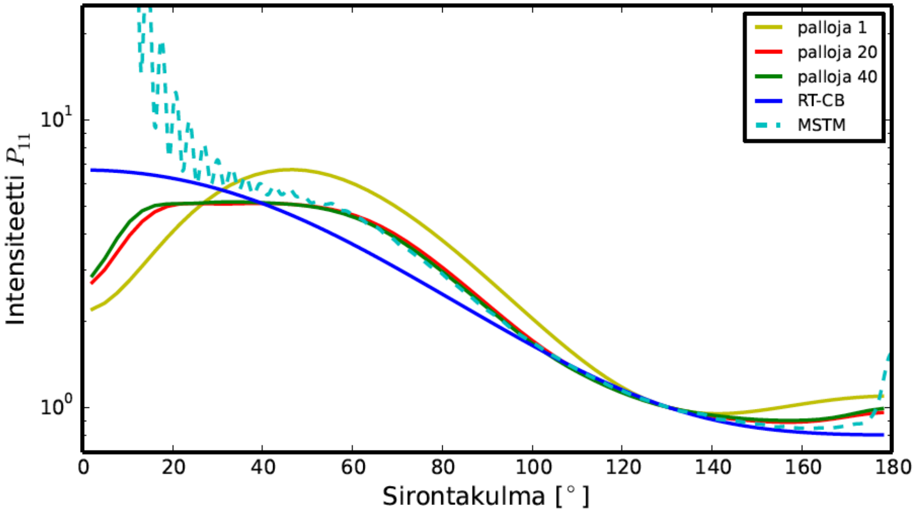

v = 0.15
P
0.7
0.6
0.5
0.4
0.3
0.2
0.1
−0.0
−0.1
−0.2
−0.3
0
30
60
90
120
150
180
α (°)

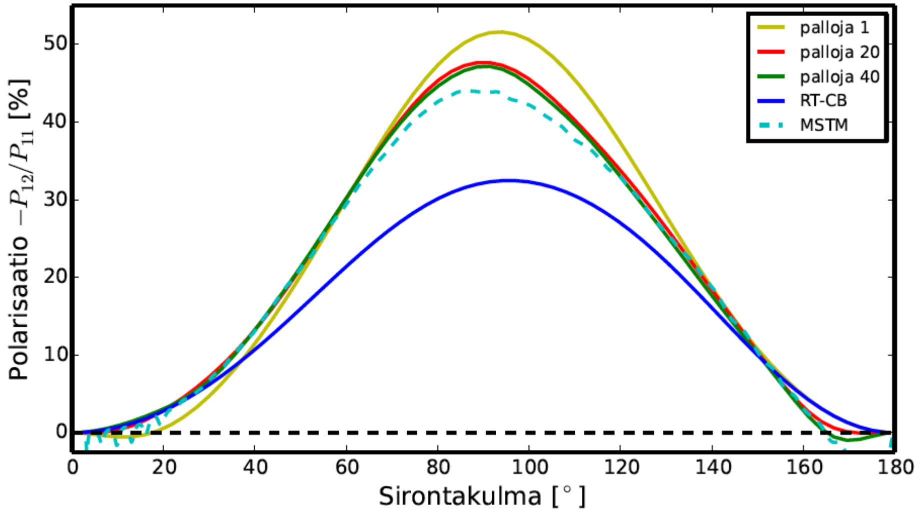

v = 0.30
lg(I/I(0))
0.3
0.1
−0.1
−0.3
−0.5
−0.7
−0.9
−1.1
0
30
60
90
120
150
180
α (°)


P
0.7
0.6
0.5
0.4
0.3
0.2
0.1
−0.0
−0.1
−0.2
−0.3
v = 0.30
0
30
60
90
120
150
180
α (°)

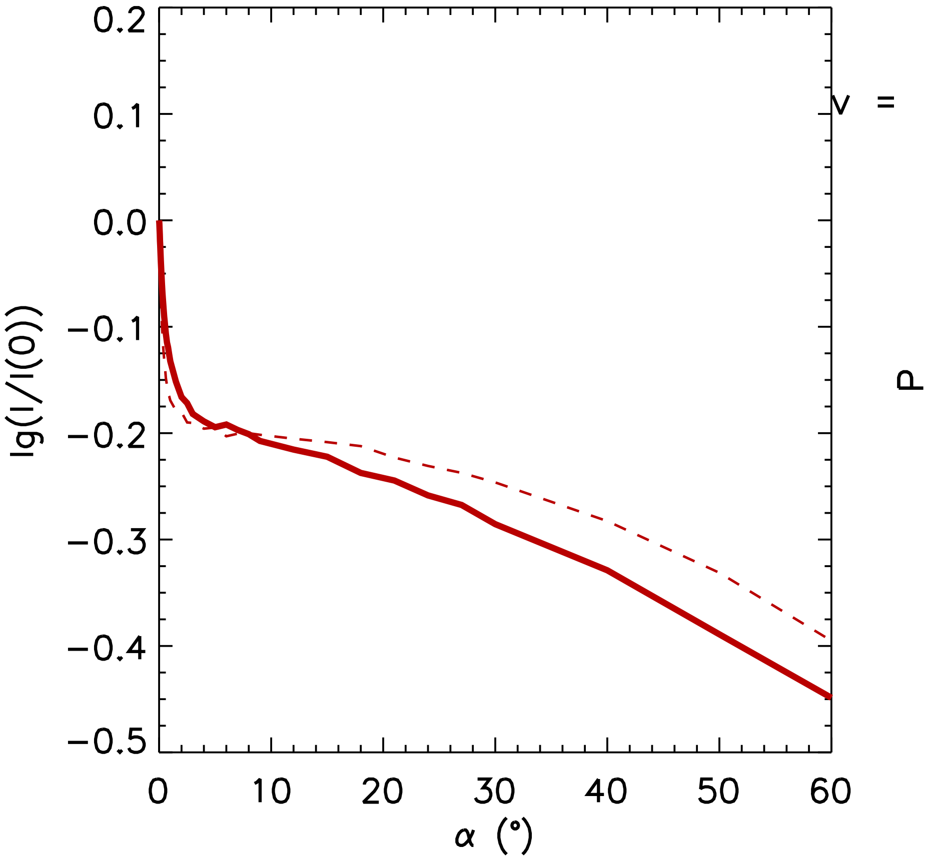
R^2T^2

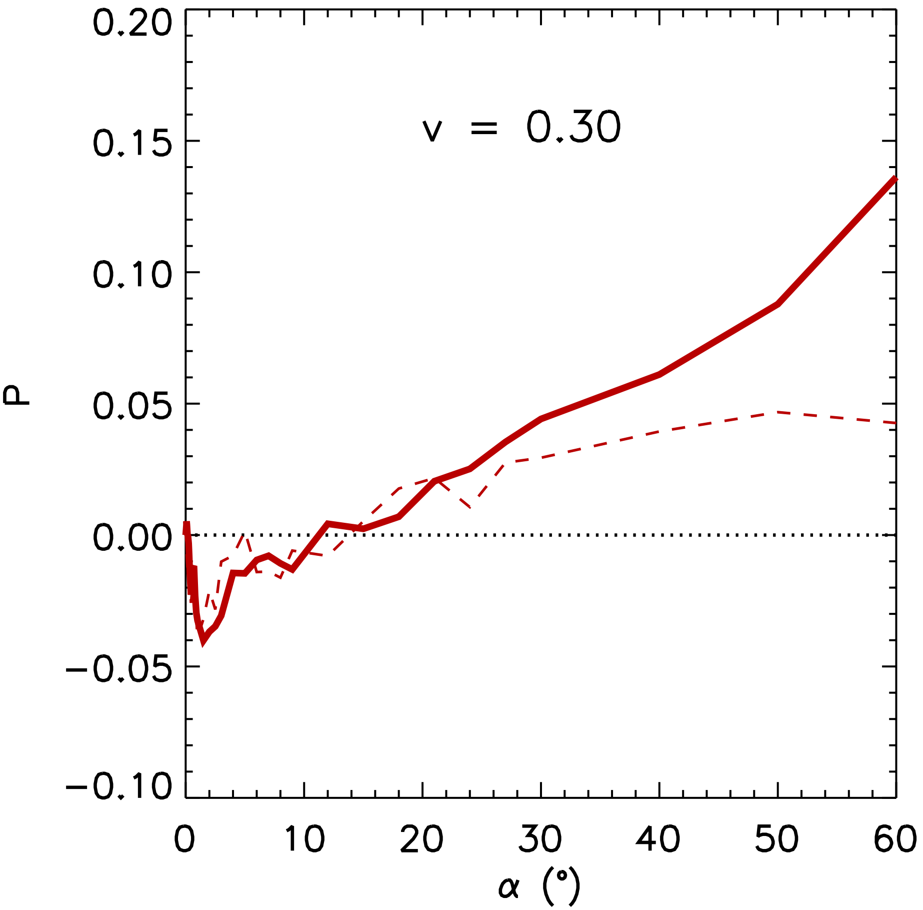
Exctract from Väisänen, M.Sc. Thesis, 2016; also Muinonen et al. and Markkanen et al., 2016, in preparation





RT-CB, incoherent input, kR = 10^4





38 billion spherical particles!

Spectrometry revisited

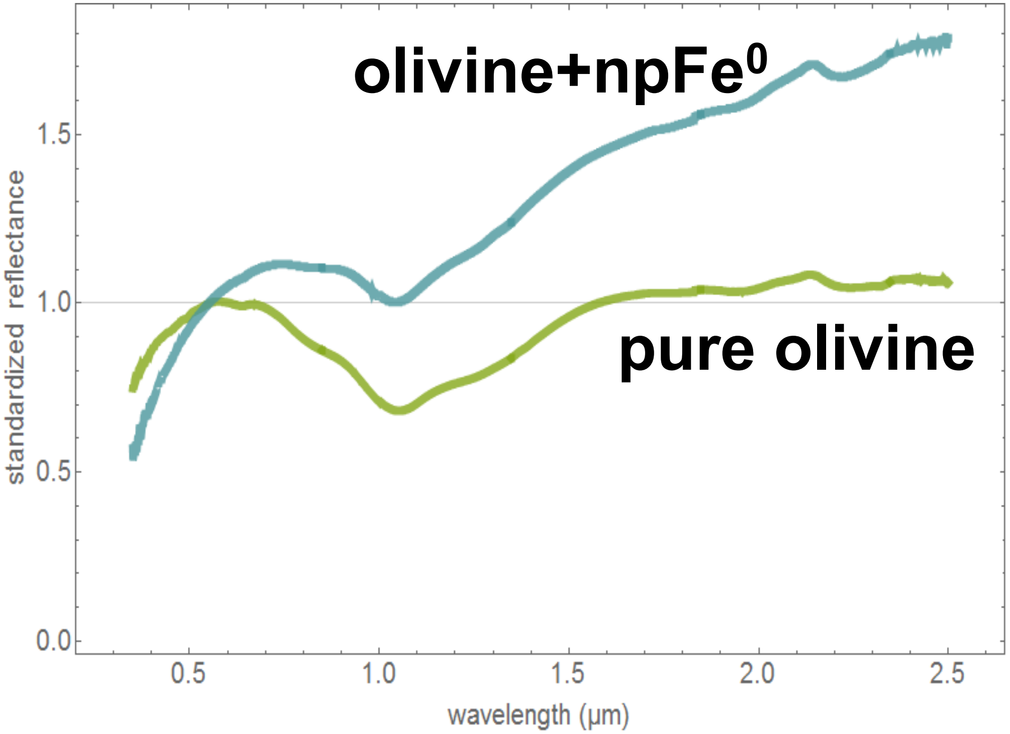
- What does the incoherent scattering imply for multiple scattering in host materials? Recipe?
- Concept of volume element extended from free space to host material
- Geometric optics for a volume element is incoherent
- Approximate the interaction between a large-particle surface element and volume element by geometric optics (can be improved)

Space weathering effects in Vis-NIR spectroscopy

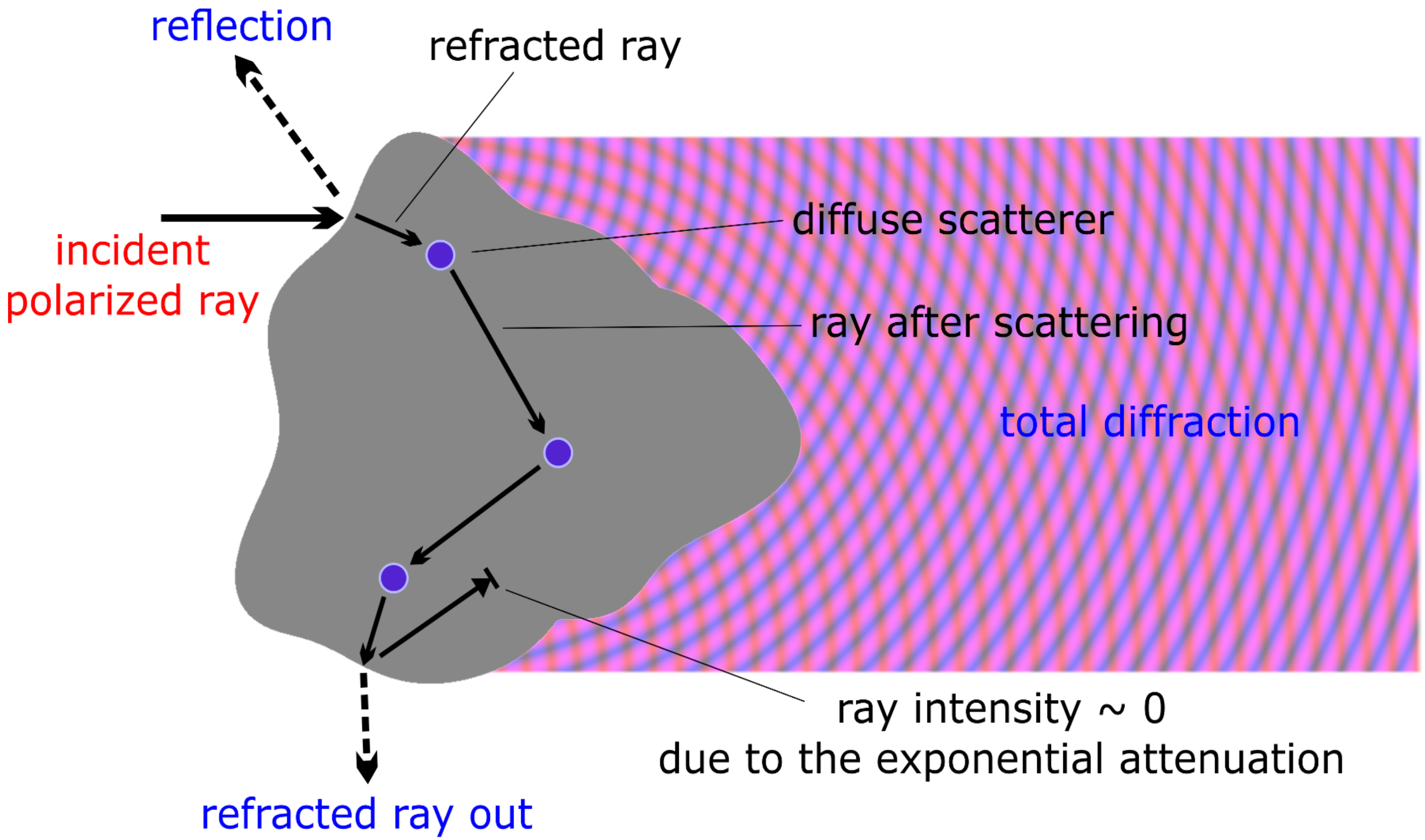
- Validated RT approach, no free parameters
- Nanophase iron ($npFe^0$) inclusions in the outer layer of mineral grains
- We have controlled sample of pure olivine and olivine+$npFe^0$, grain size ~ 20 μm in diameter
- $npFe^0$ inclusions ~ 20 nm, weight fraction 0.023%

TEM image of nanophase iron in an olivine grain

**Kohout et al. (2014), Icarus 237*.



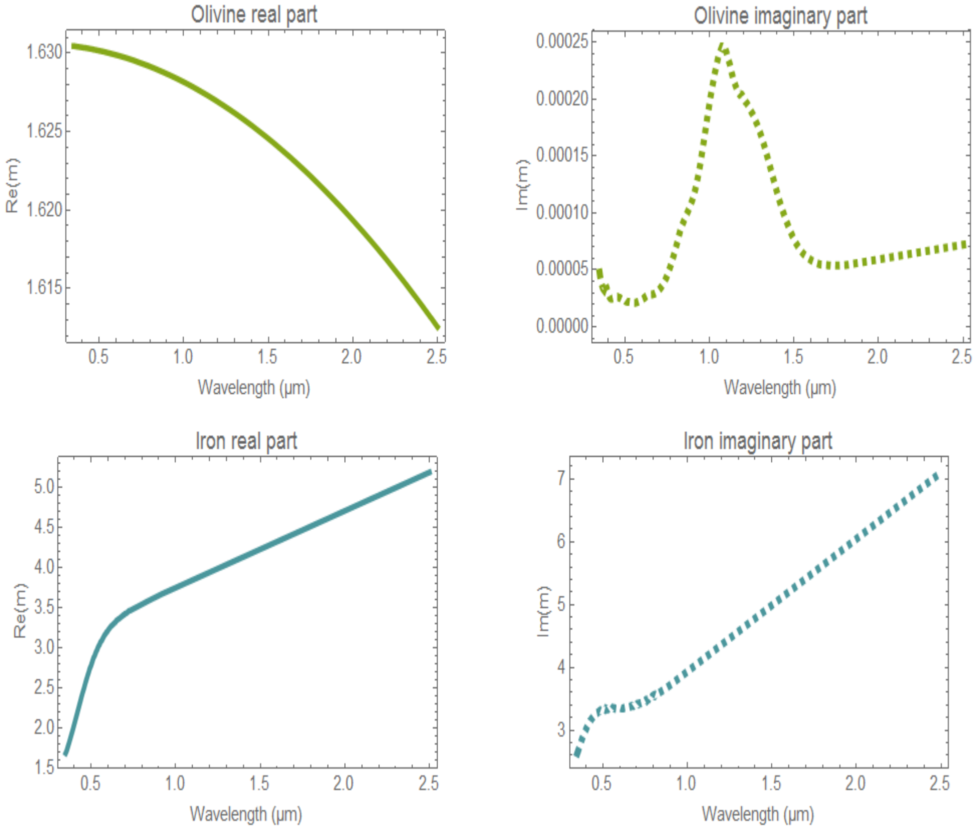
SIRIS ray-tracer in a nutshell



Muinonen et al. (2009),
JQSRT 110.

Input parameters directly from measurements

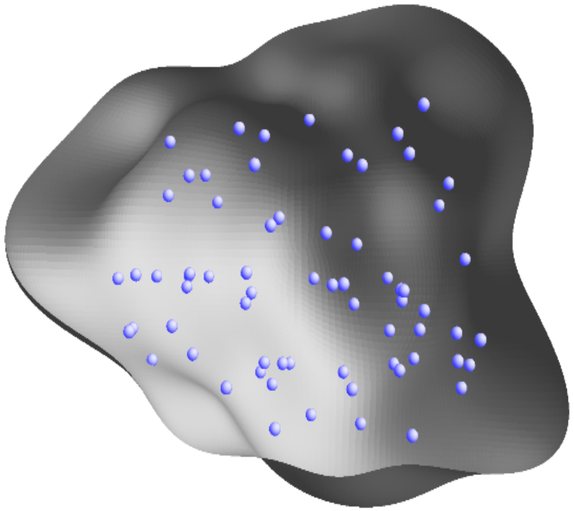
- Measured refractive indices for olivine and iron



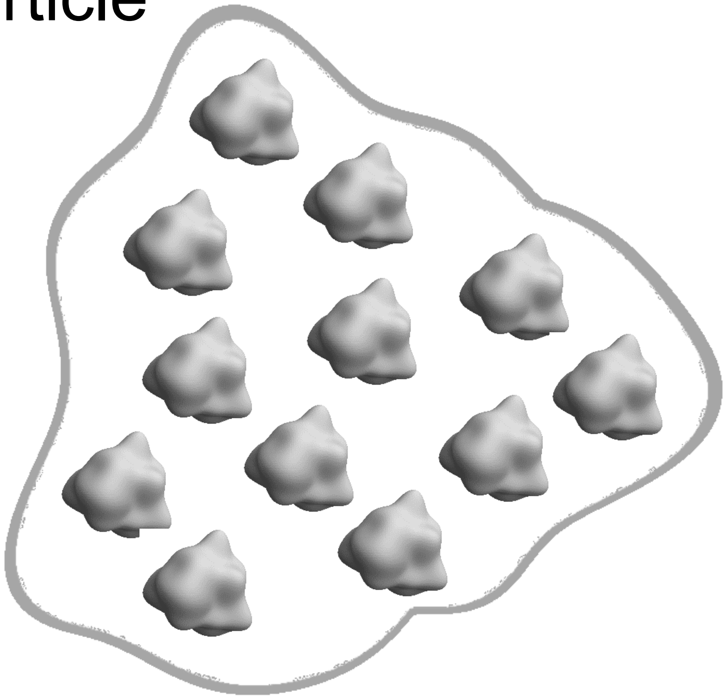
- Real grain size, diameter 20 μm
- Real npFe^0 size, 20 nm
- npFe^0 diffuse scattering matrix from Mie
- Single-scattering albedo and optical mean-free-path for diffuse scattering from Mie computations and from known weight fraction

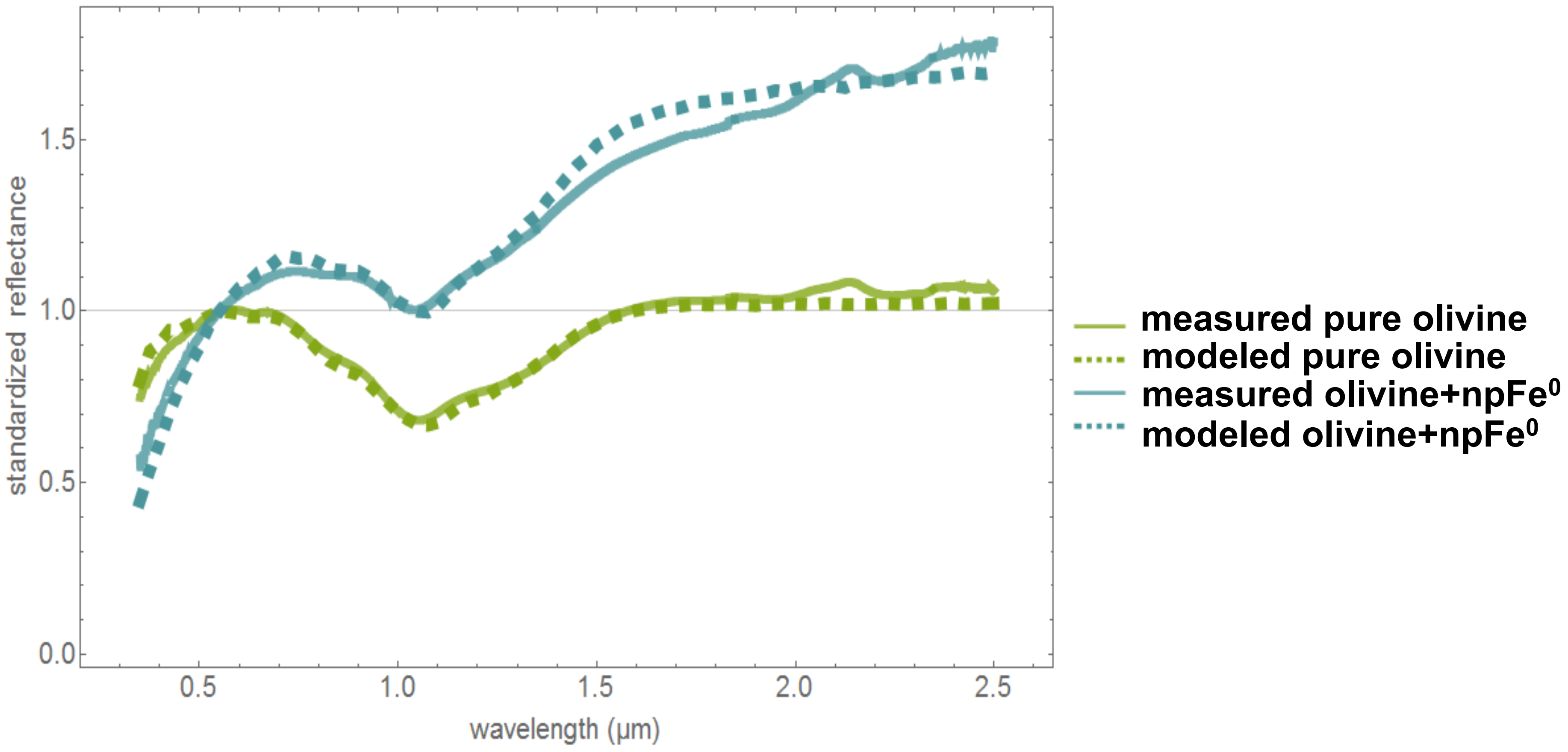
Two rounds in SIRIS to reach macroscopic medium

First round, compute single grain, with or without npFe^0 diffuse scatterer inclusions



Second round, insert scattering matrix from first round as diffuse scatterer in macroscopic ‘vacuum particle’





Penttilä et al. 2016, in preparation

- Why did the measurements and modeling match with “free-space” single-scattering input modified for the host material?
- How does multiple scattering evolve from that for dense media to that for sparse media?

Chelyabinsk meteorite spectrometry

Martikainen et al., present meeting; Kohout et al. 2014

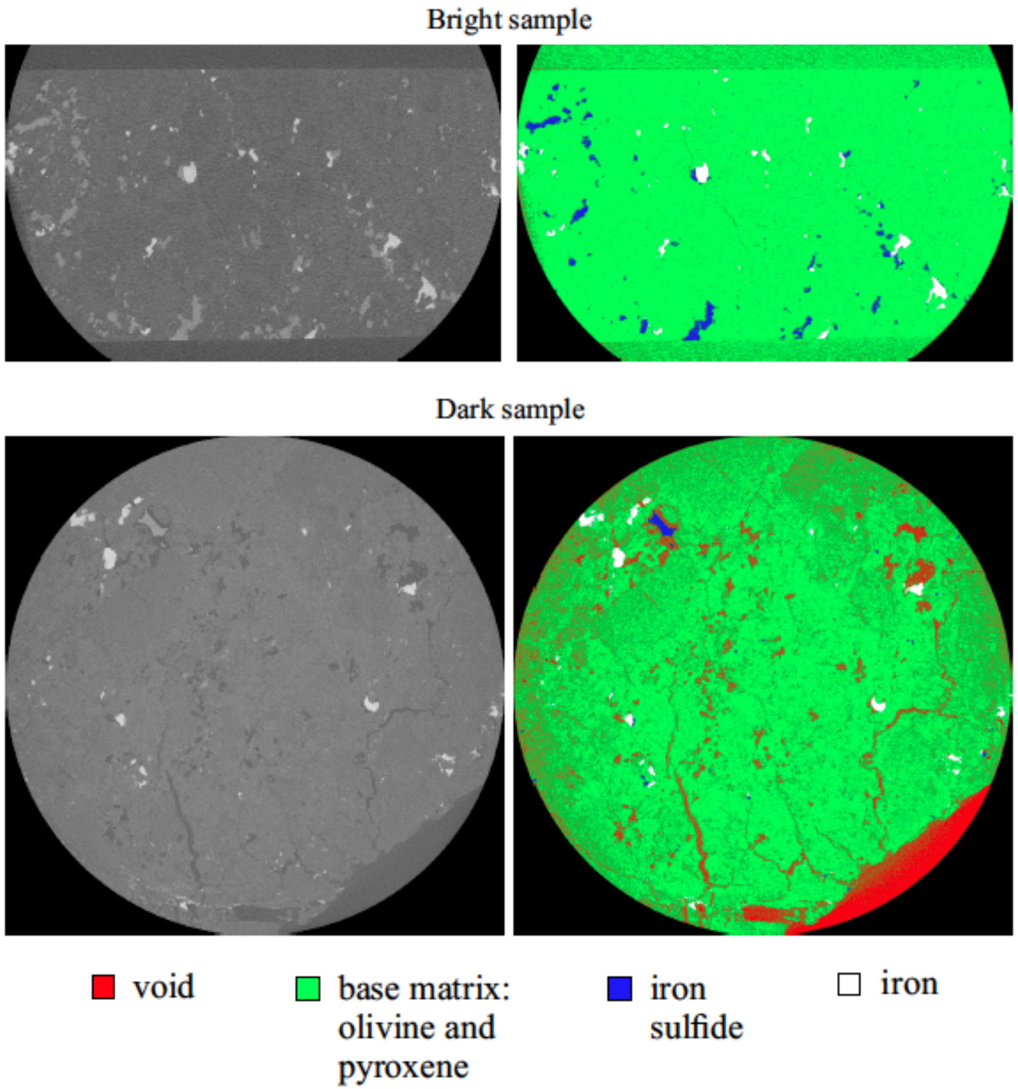


Figure 2 : Microtomography images of the light-colored and dark-colored lithologies.

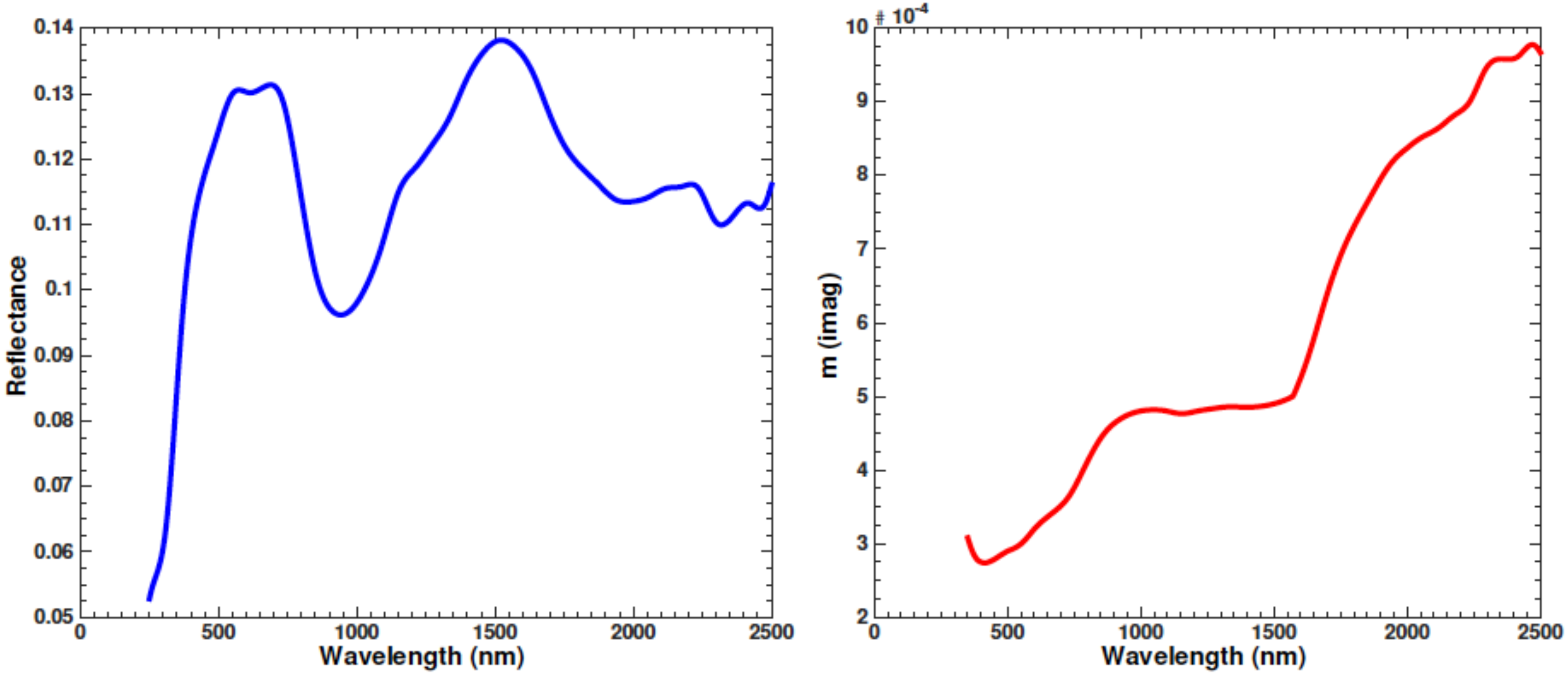


Figure 3 : The spectrum and the absorption coefficients for the light-colored lithology.

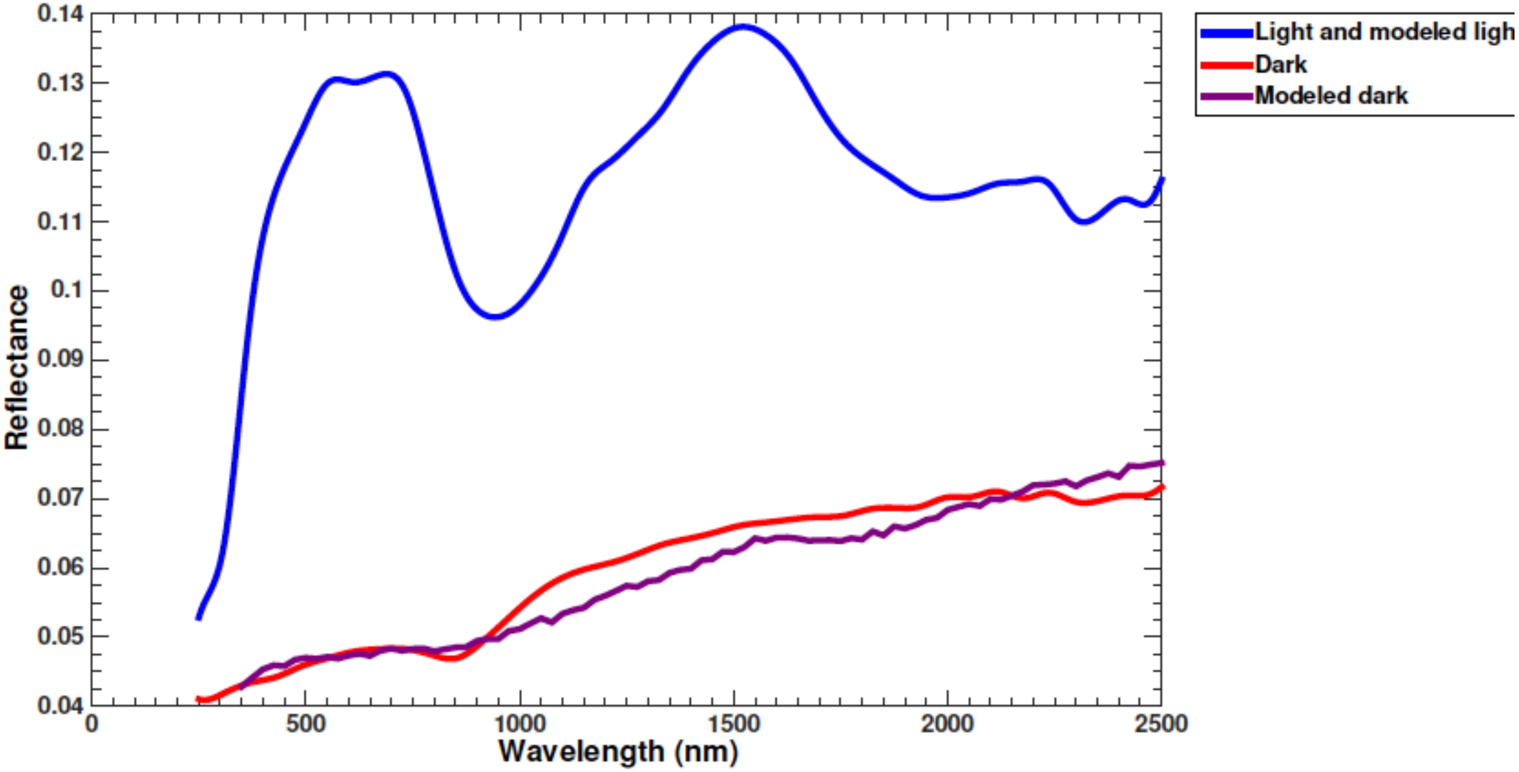


Figure 4 : The measured and the modeled spectra of the light-colored and the dark-colored lithologies.

Spectrometric inverse problem

- Derive the imaginary part of the refractive index using the Shkuratov model from a Vis-NIR spectrum for
    - a pure olivine sample
    - an olivine sample with nm-scale iron particles
    - an olivine sample with submicron-scale iron particles

  All are simulated with the SIRIS ray-tracer and provided by request tomorrow at latest with the necessary auxiliary information.
- How does the refractive index of the sample change? Why?
- Analyze the validity of the analytical Shkuratov model

Conclusions

- Numerical multiple-scattering methods matured for densely packed particulate media
- Fully-defined input allows for quantitative analyses of spectrometric, photometric, and polarimetric observations