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 3, Contents

- Introduction
- Multiple scattering
  - Preliminary results
- Spectrometry revisited
  - Space weathering
  - Chelyabinsk meteorite spectral modeling
- SIRIS ray-tracer
- Spectrometric inverse problem
- Shkuratov model
- Preliminary results
- Conclusions

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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

Multiple Scattering How-To I: Particles in Free Space

- Find the model particles that reproduce the measured scattering matrix
- Generate a model for the volume element of a particulate medium
- Compute the incoherent scattering by the volume element
- Utilize the incoherent volume-element scattering in multiple scattering computations (R^2T^2)

- 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:

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

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

Scattering matrix:

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

Preliminary results

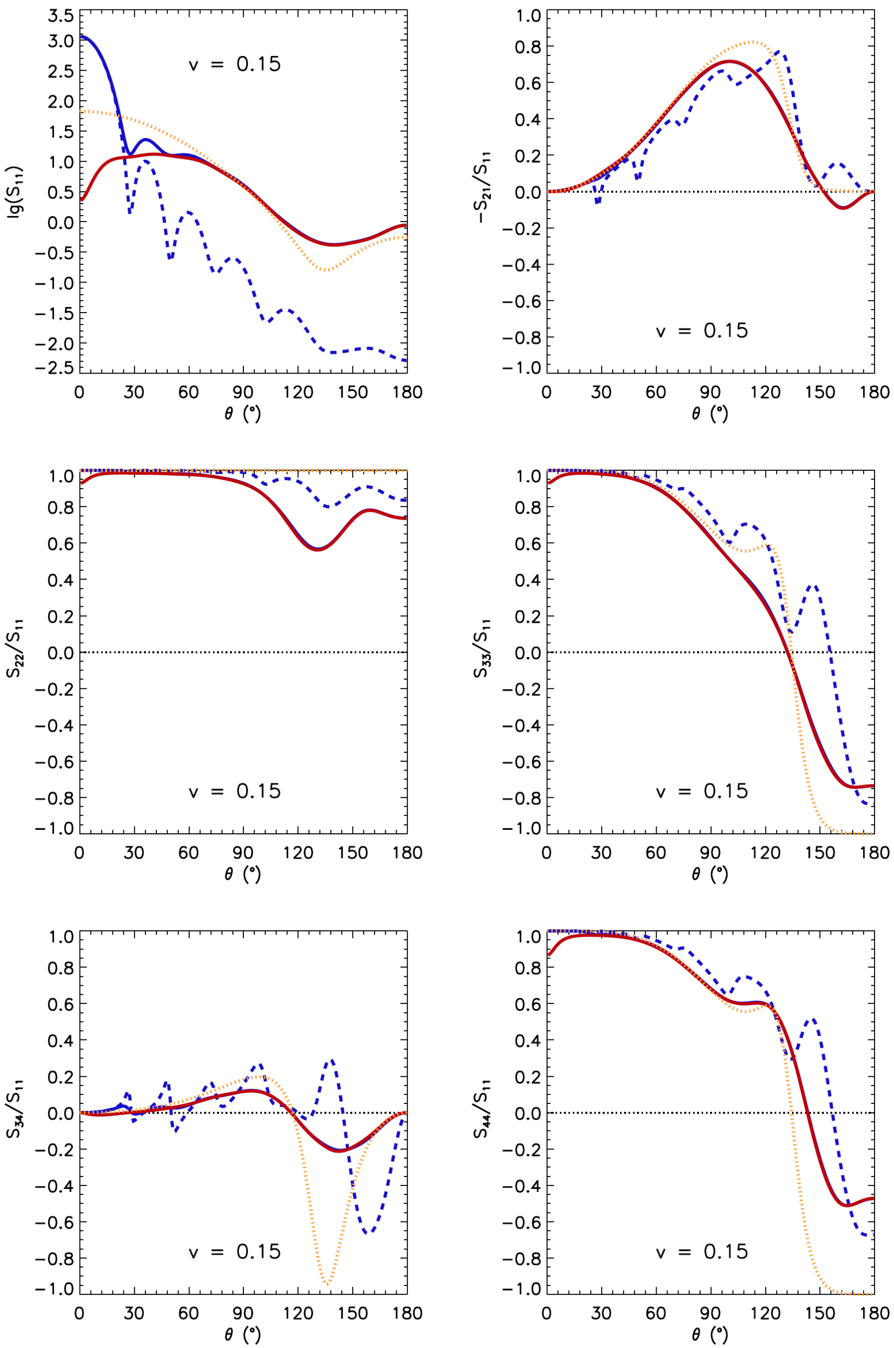
- Spherical medium of spherical scatterers:
  - number of spheres $N = 1, 2, 20, 4080$
  - radius $kr = 2.0$, refractive index $m = 1.31$
  - single-scattering albedo $\omega = 1.0$
- RT-CB with incoherent input vs. STMM for $N = 4080$
- For independent scattering and volume fraction $v = 0.15$, extinction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

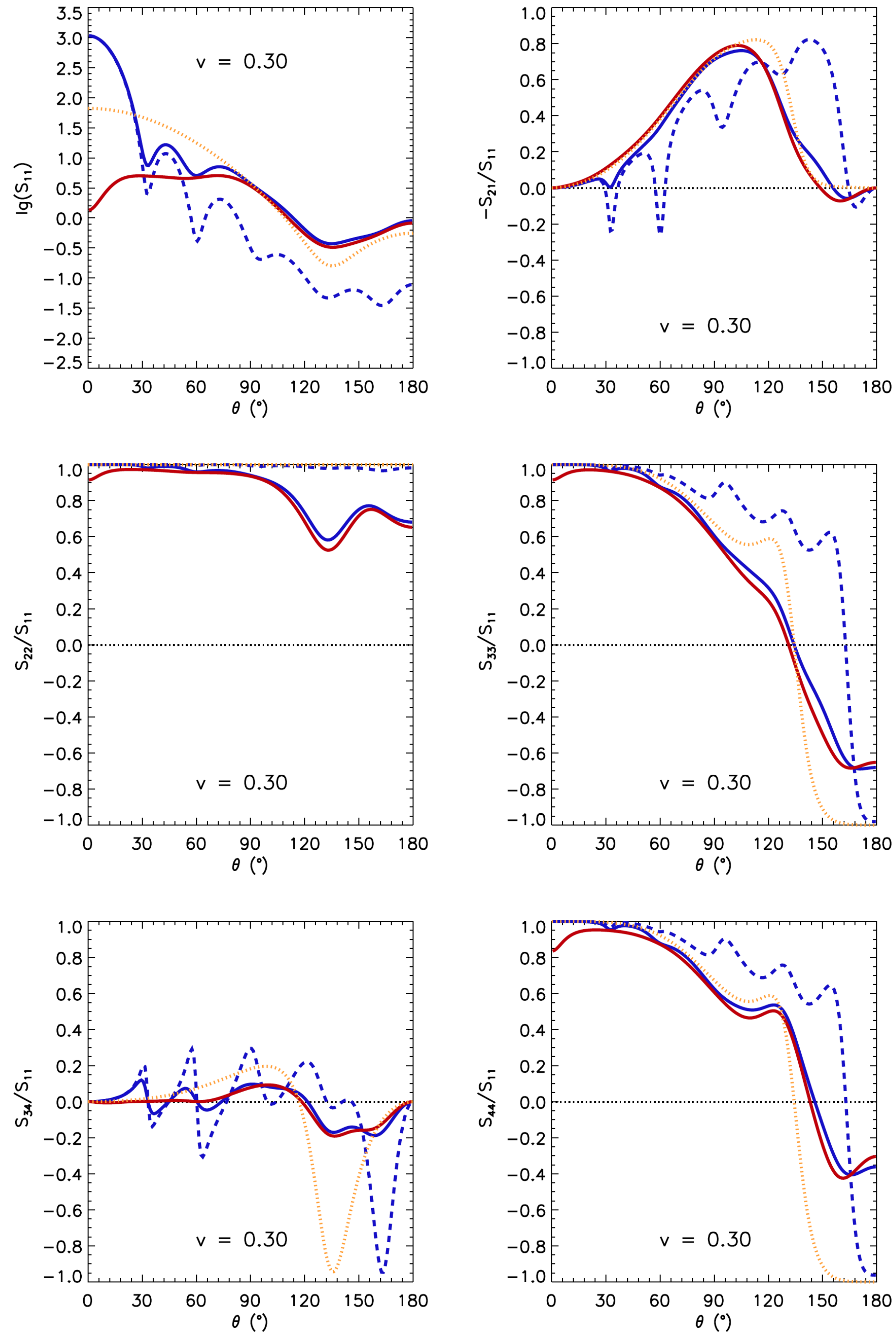
TABLE I

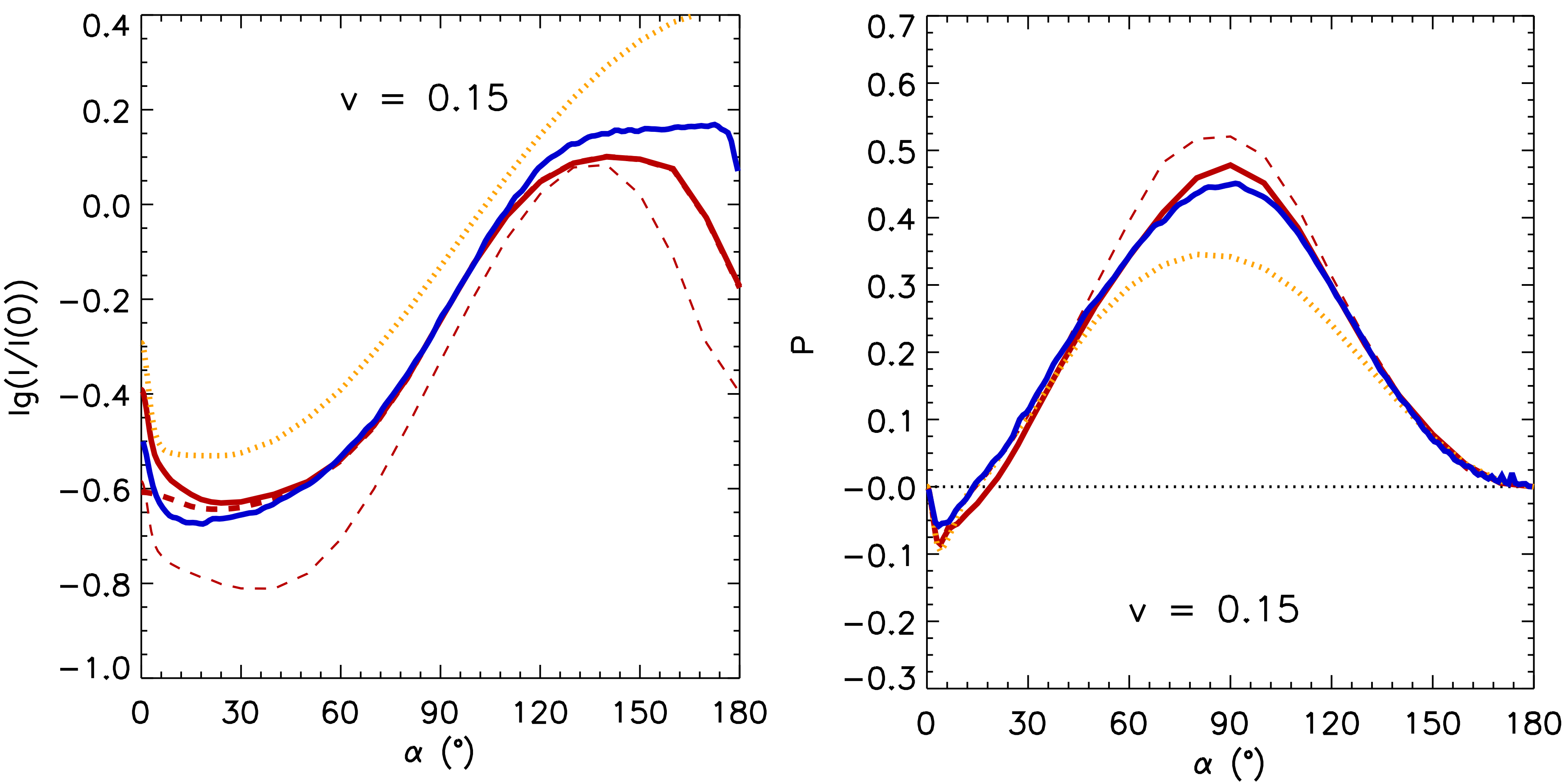
THE DIMENSIONLESS INCOHERENT EXTINCTION COEFFICIENTS κ_e/k (k IS THE WAVE NUMBER) AND THE CORRESPONDING EXTINCTION MEAN FREE PATH LENGTHS $k\ell_\mathrm{e} = k/\kappa_\mathrm{e}$ FOR VOLUME ELEMENTS OF SPHERICAL PARTICLES WITH TWO VALUES OF VOLUME DENSITIES v (VOLUME FRACTION OF PARTICLES). N DENOTES 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	κ_e/k	$k\ell_\mathrm{e}$	kR	κ_e/k	$k\ell_\mathrm{e}$
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

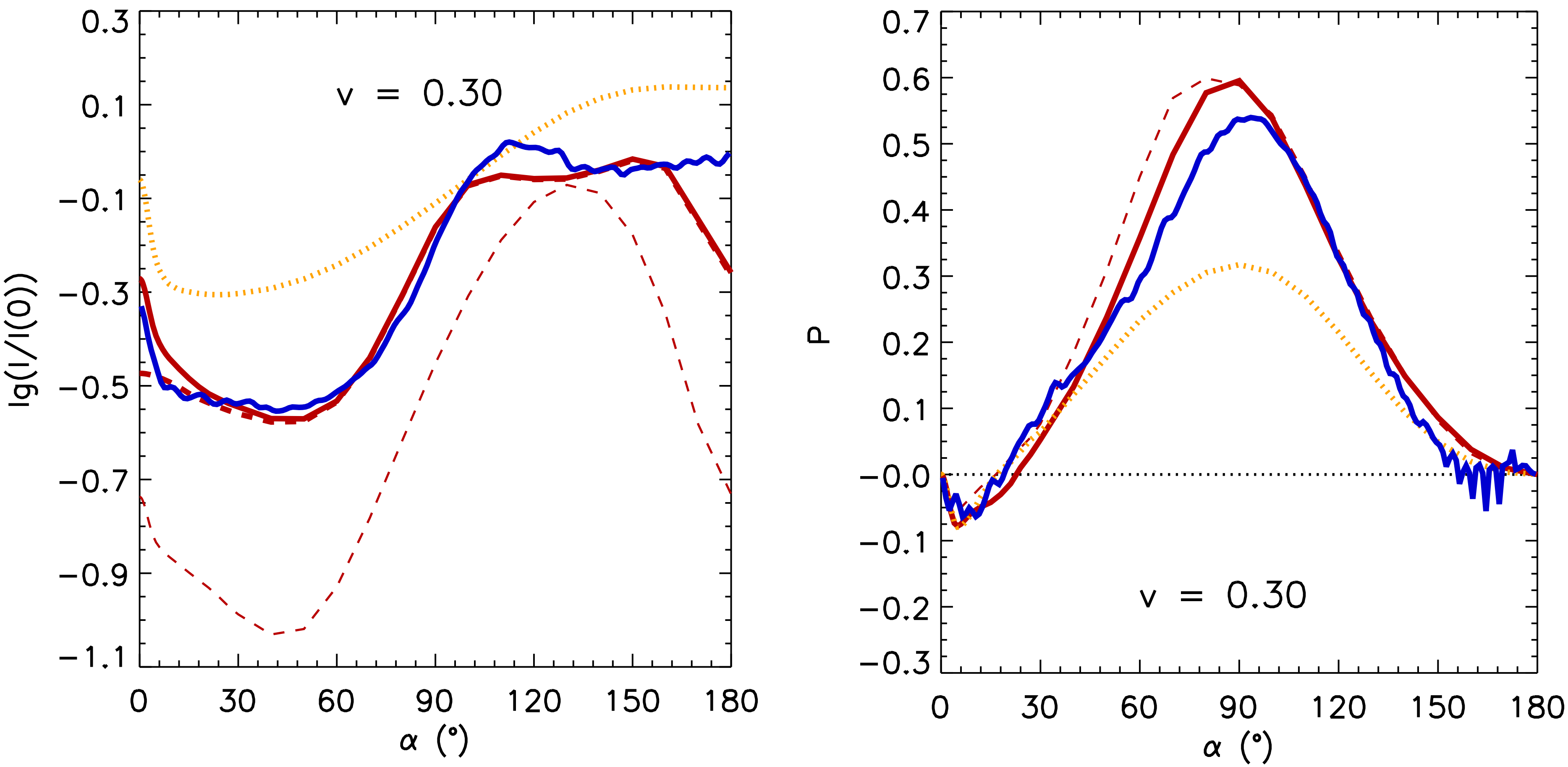
Incoherent scattering matrix,
Muinonen et al. 2016, Markkanen et al. 2016, in preparation




lg(S11)
v = 0.30
θ (°)
−S21/S11
v = 0.30
θ (°)
S22/S11
v = 0.30
θ (°)
S33/S11
v = 0.30
θ (°)
S34/S11
v = 0.30
θ (°)
S44/S11
v = 0.30
θ (°)



v = 0.15
lg(I/I(0))
α (°)
P
v = 0.15
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 (°)
v = 0.30
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 (°)

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)

Multiple Scattering How-To II: Particles Embedded in Host Material

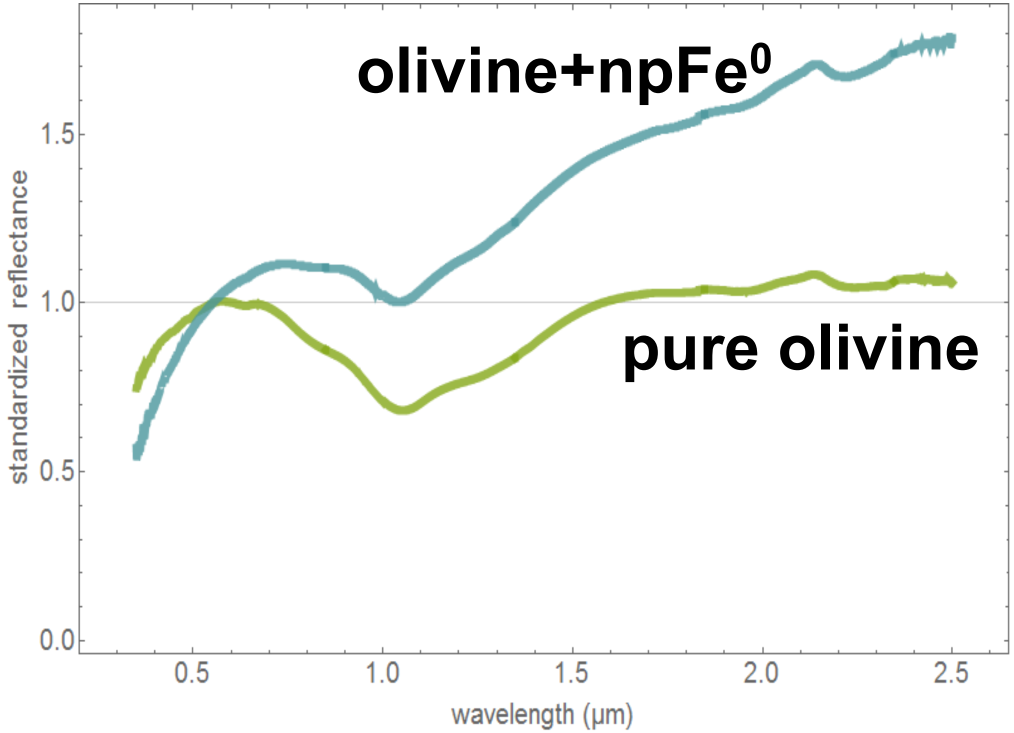
- Generate a model for the volume element of the embedded particles
- Compute the incoherent scattering by the volume element
- Utilize the incoherent volume-element scattering in multiple scattering computations (R^2T^2)
- Account for the interface between host material and free space using geometric optics

Space weathering effects in Vis-NIR spectroscopy

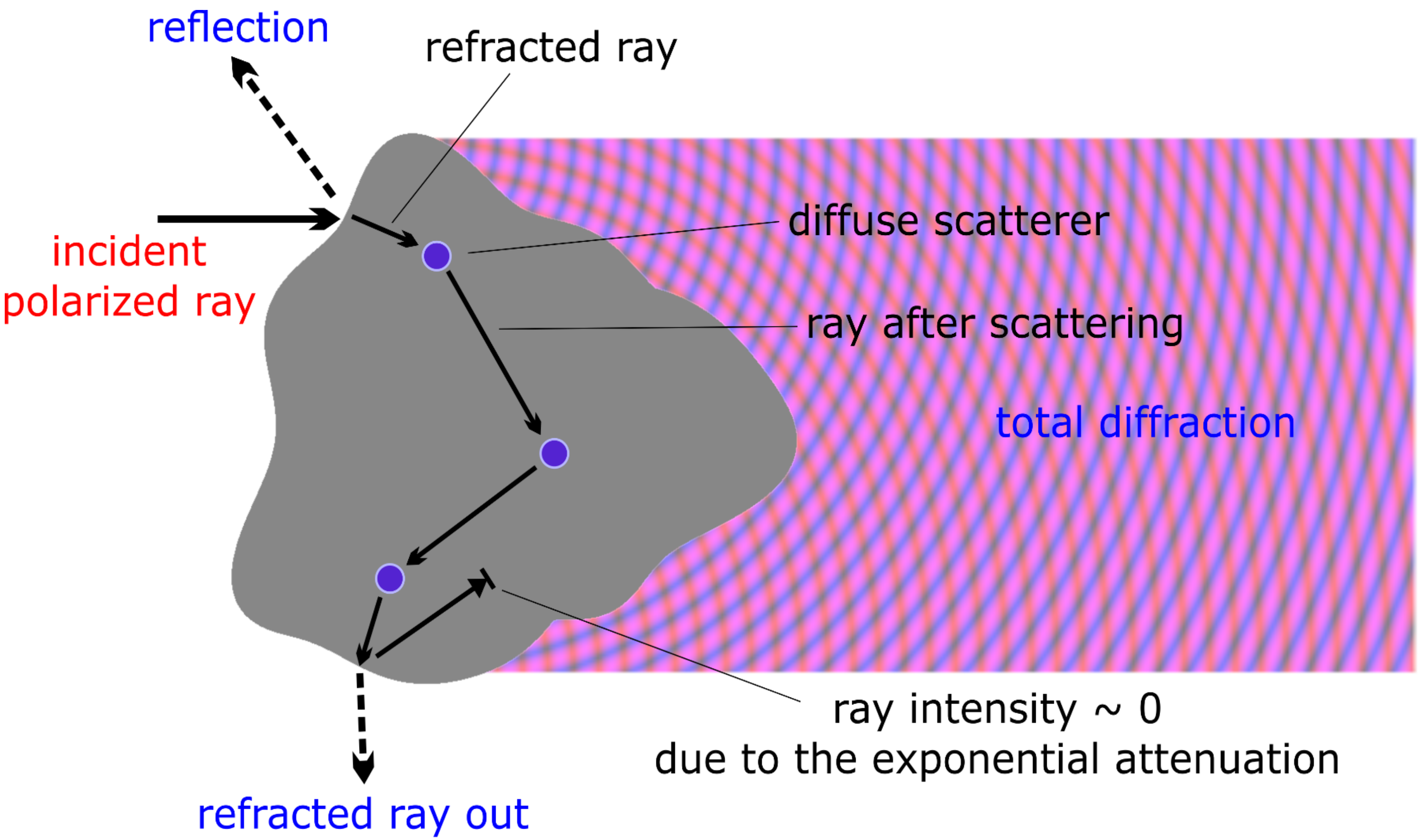
- Validated RT approach, no free parameters
- Nanophase iron ($npFe^0$) inclusions in the outer layer of mineral grains
- We have controlled sample of pure olivine and olivine+$npFe^0$, grain size ~ 20 μm in diameter
- $npFe^0$ inclusions ~ 20 nm, weight fraction 0.023%

TEM image of nanophase iron in an olivine grain

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



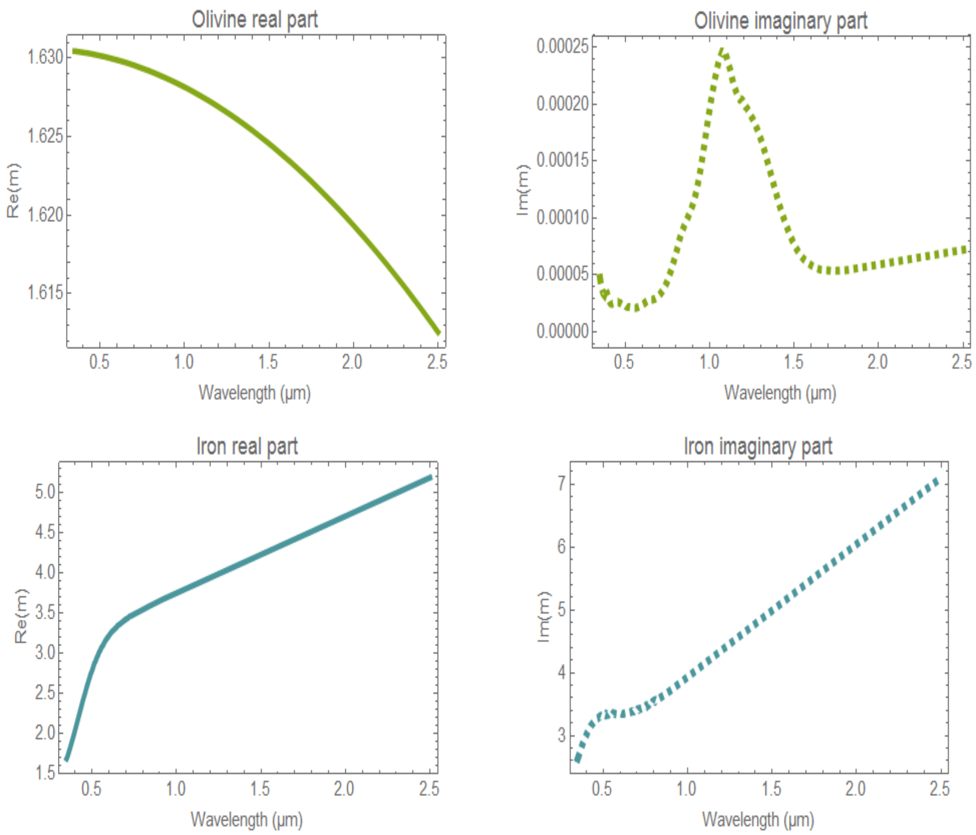
SIRIS ray-tracer in a nutshell



Muinonen et al. (2009), JQSRT 110.

Input parameters directly from measurements

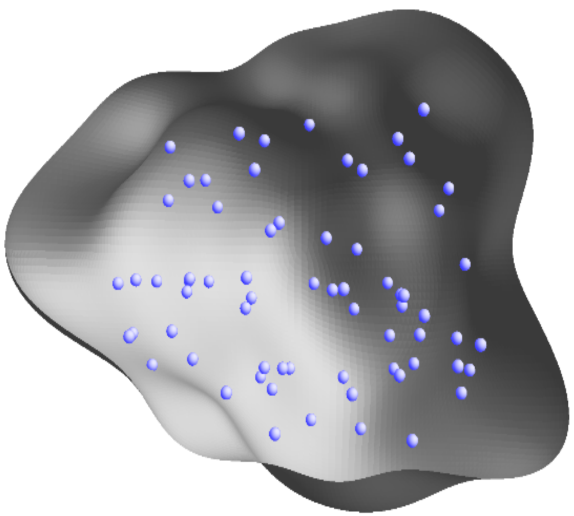
- Measured refractive indices for olivine and iron



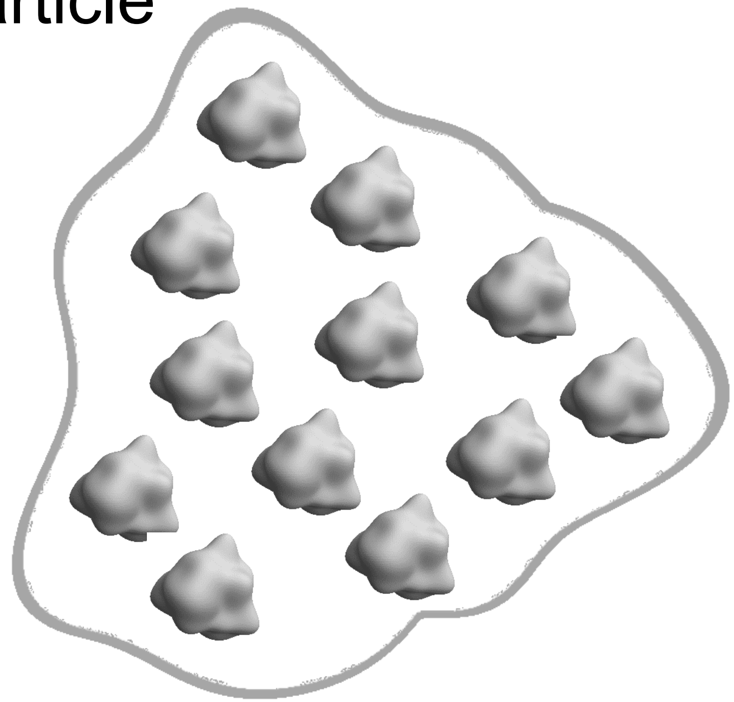
- Real grain size, diameter 20 μm
- Real $npFe^0$ size, 20 nm
- $npFe^0$ diffuse scattering matrix from Mie
- Single-scattering albedo and optical mean-free-path for diffuse scattering from Mie computations and from known weight fraction

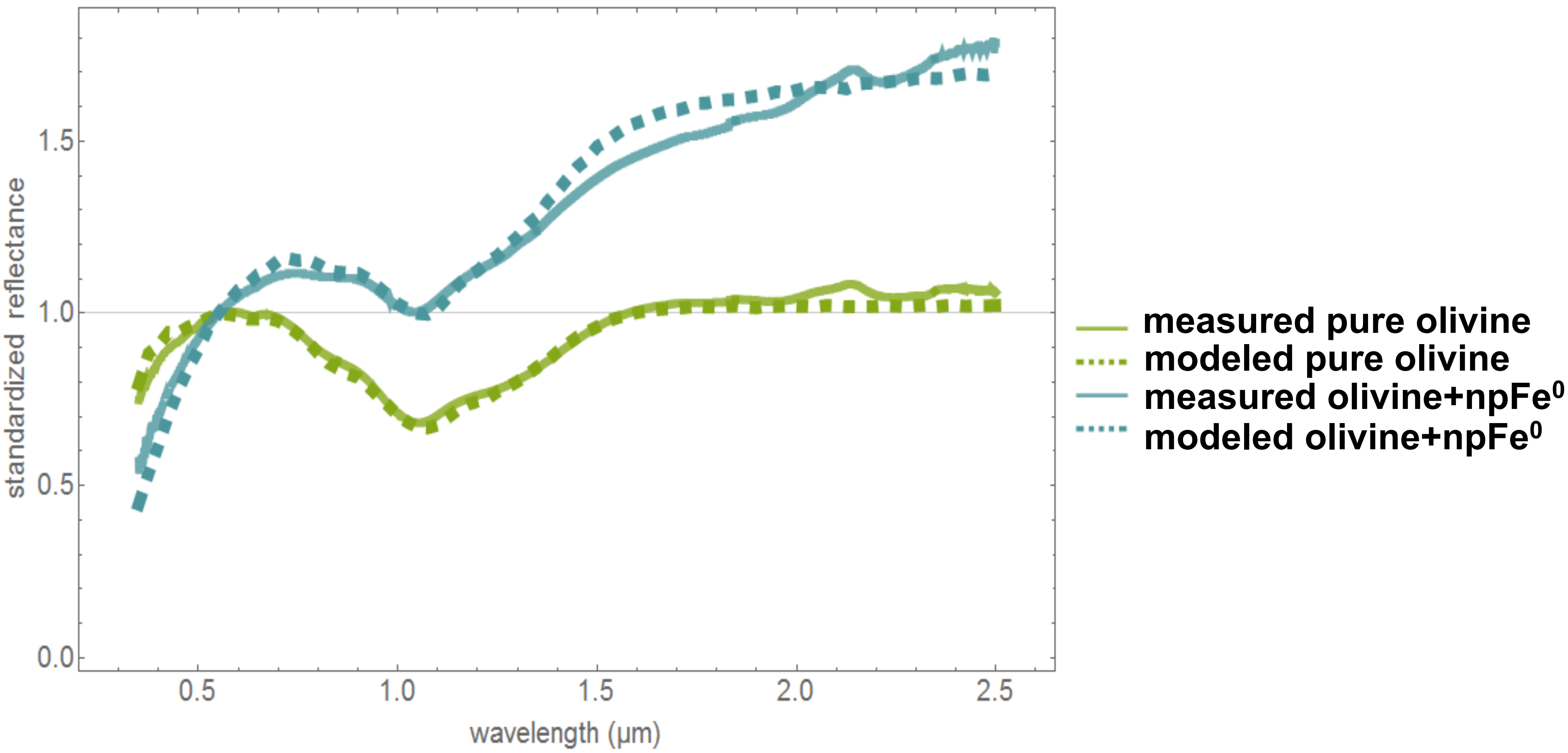
Two rounds in SIRIS to reach macroscopic medium

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?

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

Shkuratov Radiative Transfer Model

Shkuratov et al. 1999
Icarus 137, 235

- Parameters to be estimated a priori:
  - Real part of refractive index n
  - Average path length between internal reflections S
  - Volume density q (volume fraction of particles)
- Derivation for the imaginary part of refractive index κ

Forward problem, albedo of a particulate medium:

$$A = \frac{1+\rho_{\mathrm{b}}^2-\rho_{\mathrm{f}}^2}{2\rho_{\mathrm{b}}} - \sqrt{\left(\frac{1+\rho_{\mathrm{b}}^2-\rho_{\mathrm{f}}^2}{2\rho_{\mathrm{b}}}\right)^2 - 1}.$$

$$\rho_{\mathrm{b}} = q \cdot r_{\mathrm{b}}$$

$$\rho_{\mathrm{f}} = q \cdot r_{\mathrm{f}} + 1 - q.$$

$$r_{\mathrm{b}} = R_{\mathrm{b}} + \frac{1}{2} T_{\mathrm{e}} T_{\mathrm{i}} R_{\mathrm{i}} \exp(-2\tau)/(1 - R_{\mathrm{i}} \exp(-\tau)),$$

$$r_{\mathrm{f}} = R_{\mathrm{f}} + T_{\mathrm{e}} T_{\mathrm{i}} \exp(-\tau) + \frac{1}{2} T_{\mathrm{e}} T_{\mathrm{i}} R_{\mathrm{i}} \exp(-2\tau)/$$

$$(1 - R_{\mathrm{i}} \exp(-\tau)).$$

$$T_e = 1 - R_e, \qquad T_i = 1 - R_i.$$

$$R_b \approx (0.28 \cdot n - 0.20) R_e,$$

$$R_e \approx r_o + 0.05,$$

$$R_i \approx 1.04 - 1/n^2,$$

$$r_o = (n - 1)^2/(n + 1)^2$$

Optical thickness τ set to infinity

Inverse problem, imaginary part of refractive index:

$$\kappa = -\frac{\lambda}{4\pi S}\ln\left[\frac{b}{a}+\sqrt{\left(\frac{b}{a}\right)^2-\frac{c}{a}}\right],$$

$$a = T_\mathrm{e}T_\mathrm{i}(yR_\mathrm{i}+qT_\mathrm{e}),$$

$$b = yR_\mathrm{b}R_\mathrm{i}+\frac{q}{2}T_\mathrm{e}^2(1+T_\mathrm{i})-T_\mathrm{e}(1-qR_\mathrm{b}),$$

$$c = 2yR_\mathrm{b}-2T_\mathrm{e}(1-qR_\mathrm{b})+qT_\mathrm{e}^2,$$

$$y = (1-\mathrm{A})^2/2A.$$

Conclusions

- Numerical multiple-scattering methods matured for densely packed particulate media
- Fully-defined input will allow for quantitative analyses of spectrometric, photometric, and polarimetric observations
- Detailed forward models will allow mapping the ambiguities in spectrometry