Astrophysical light scattering problems (PAP316)
Lecture 2a

Spectrometry

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- Introduction to UV-Vis-NIR spectrometry
  - Asteroids
- Space weathering
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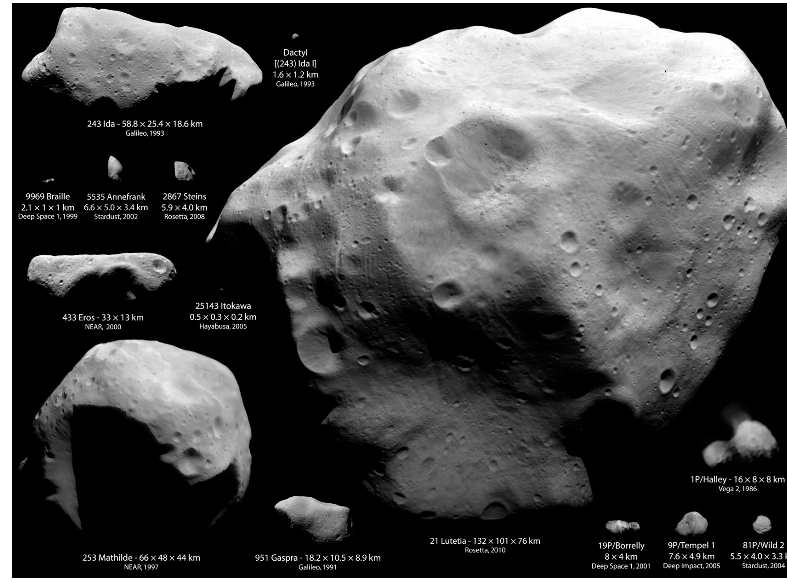
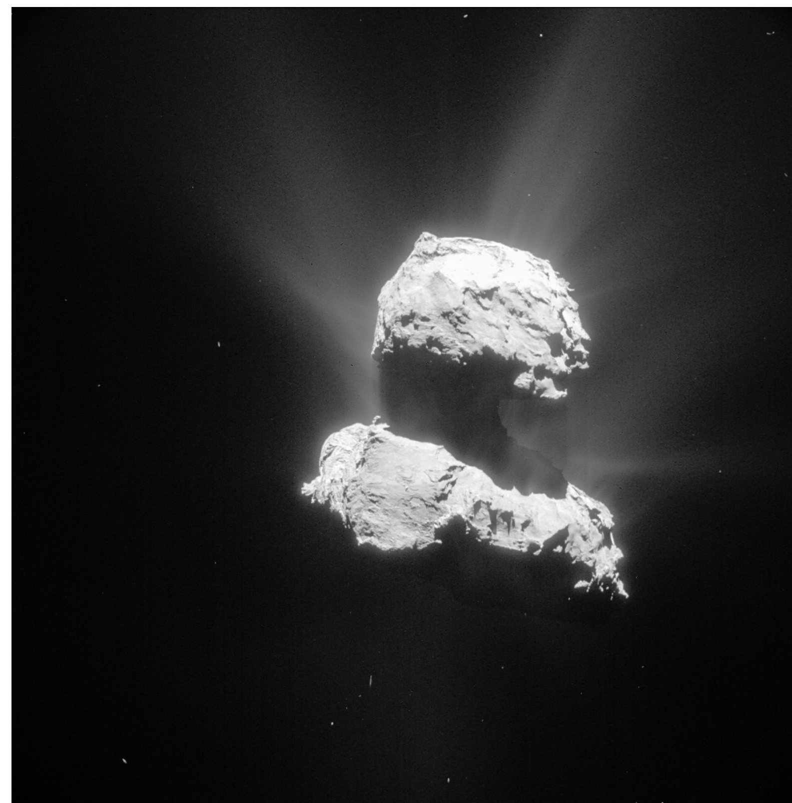
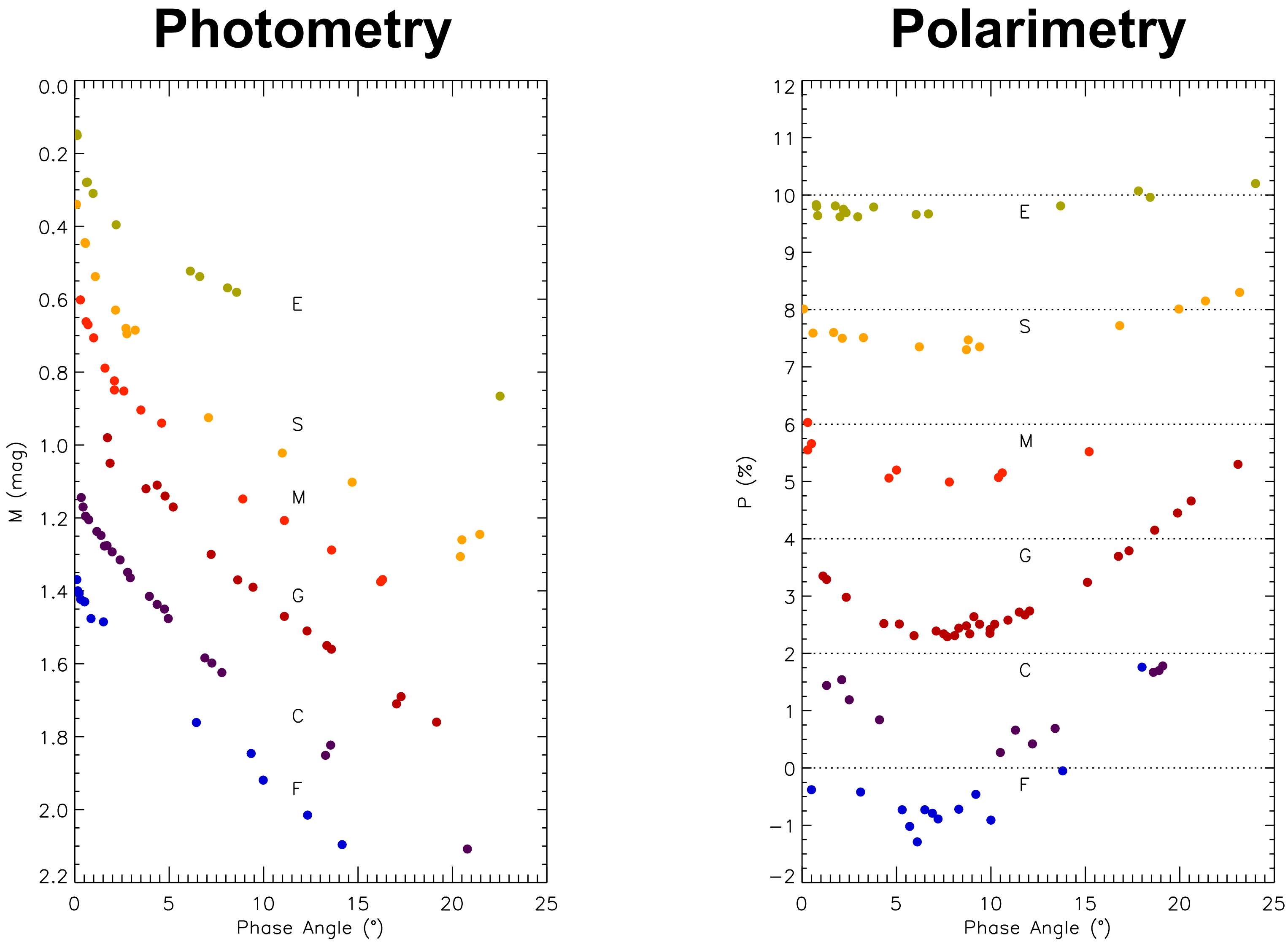


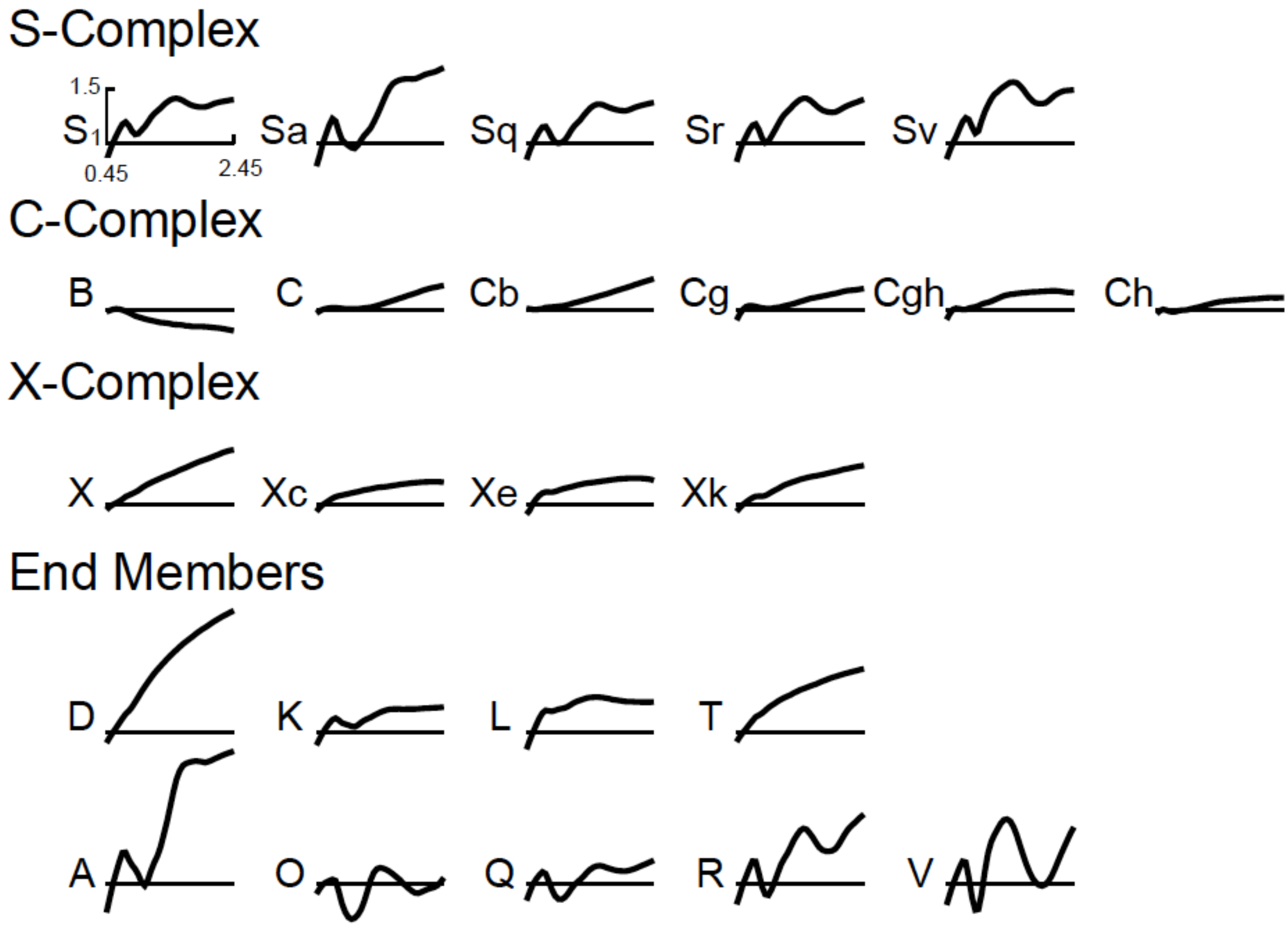


Asteroids

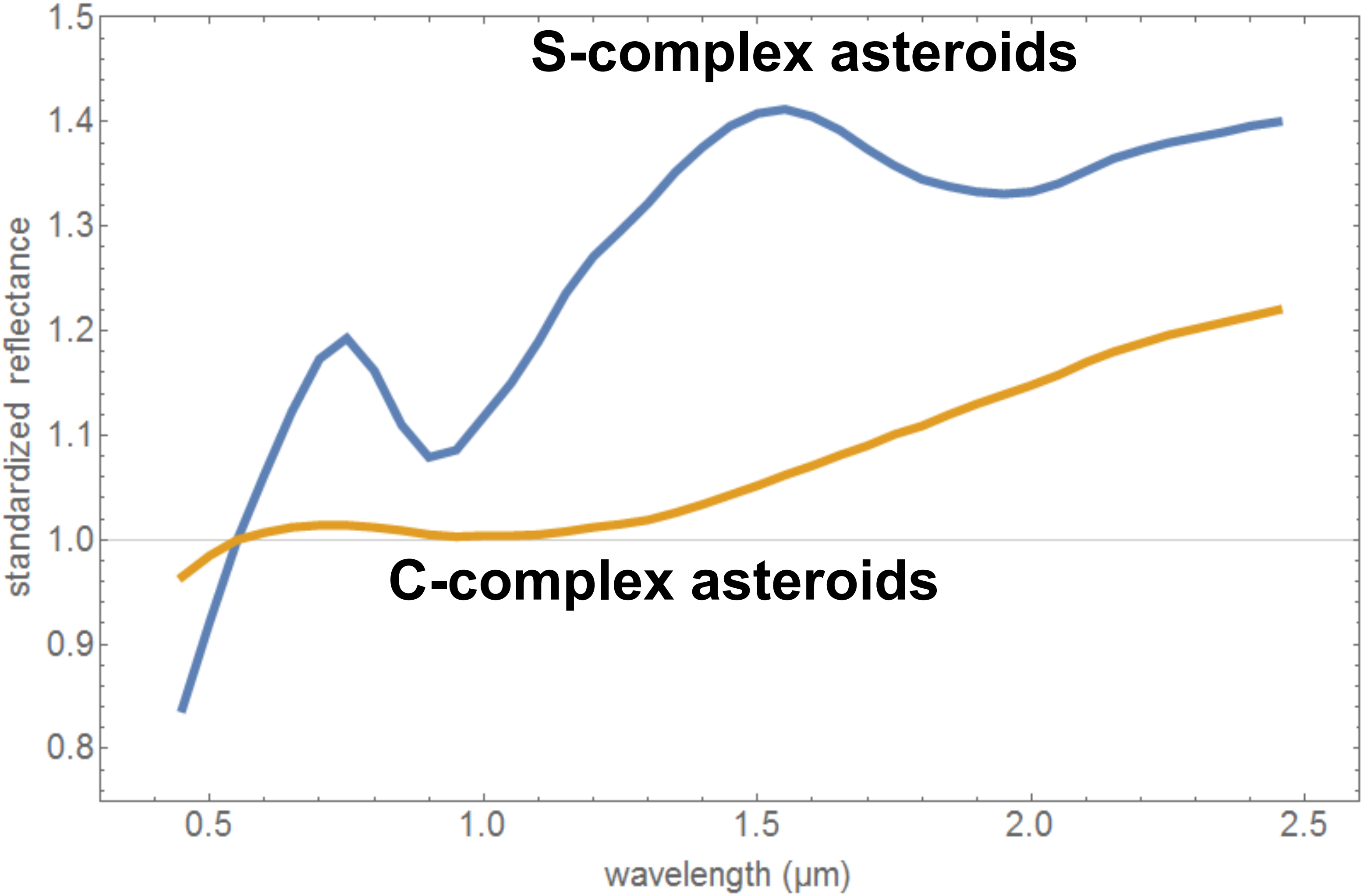


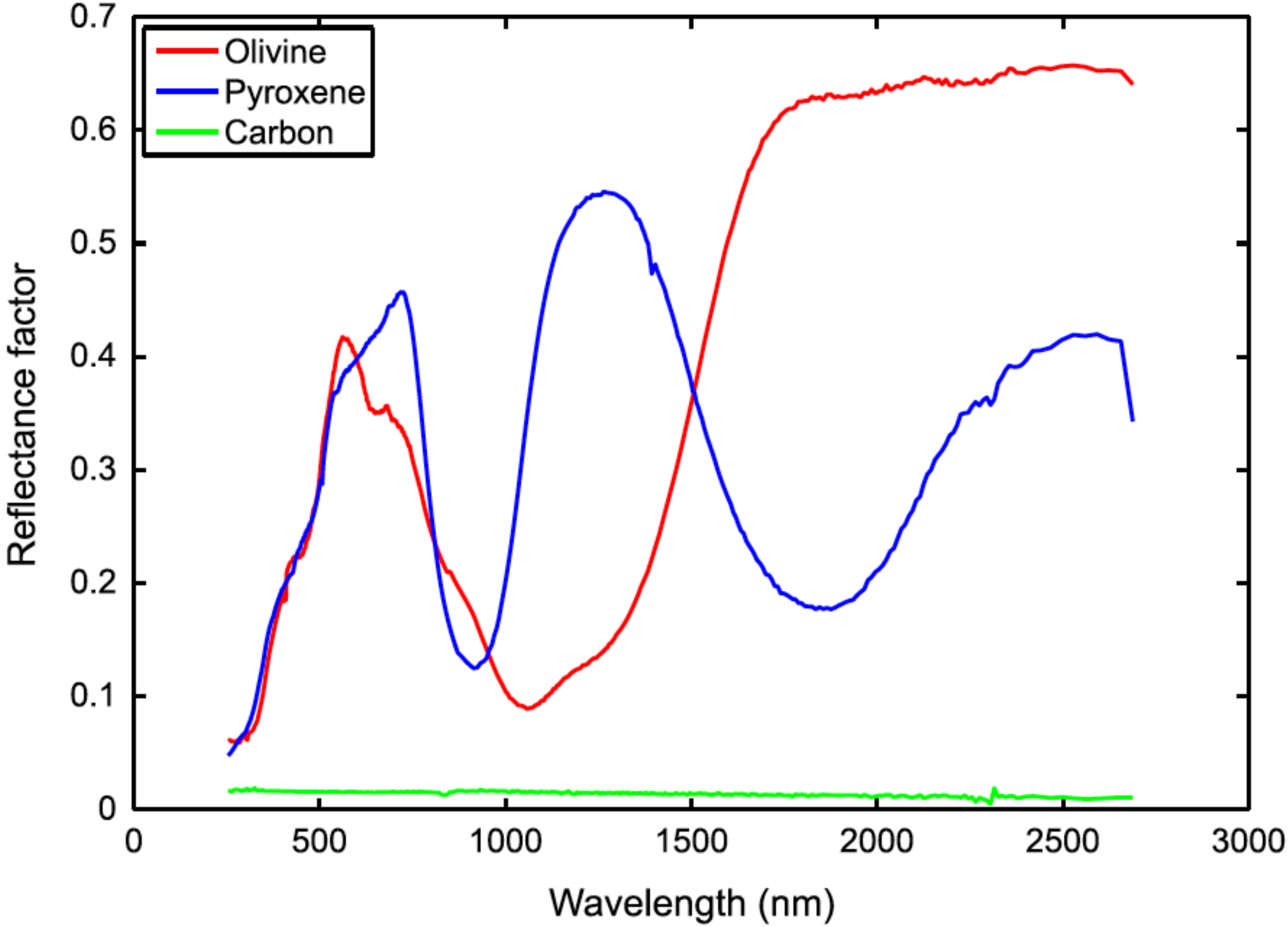
Muinonen et al., in Polarimetry of Stars and Planetary Systems, 2016 (obs. ref. therein)

Bus-DeMeo Taxonomy Key



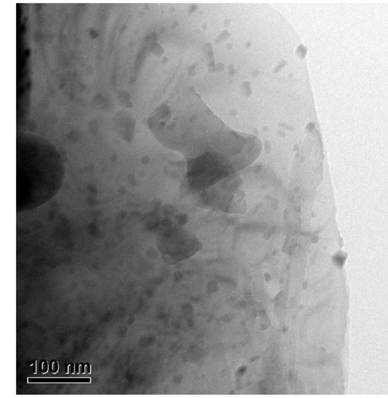
Bus-DeMeo spectral classification system

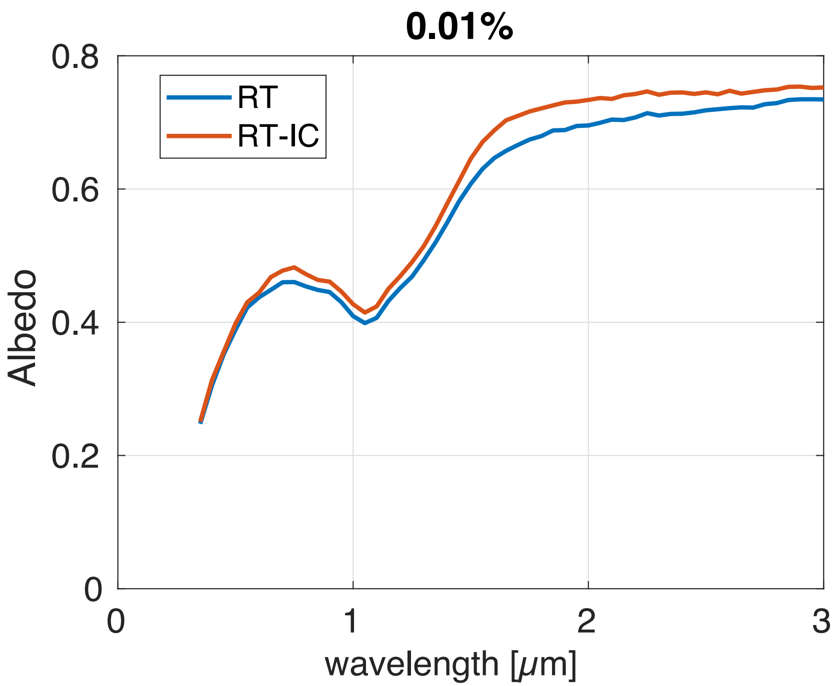


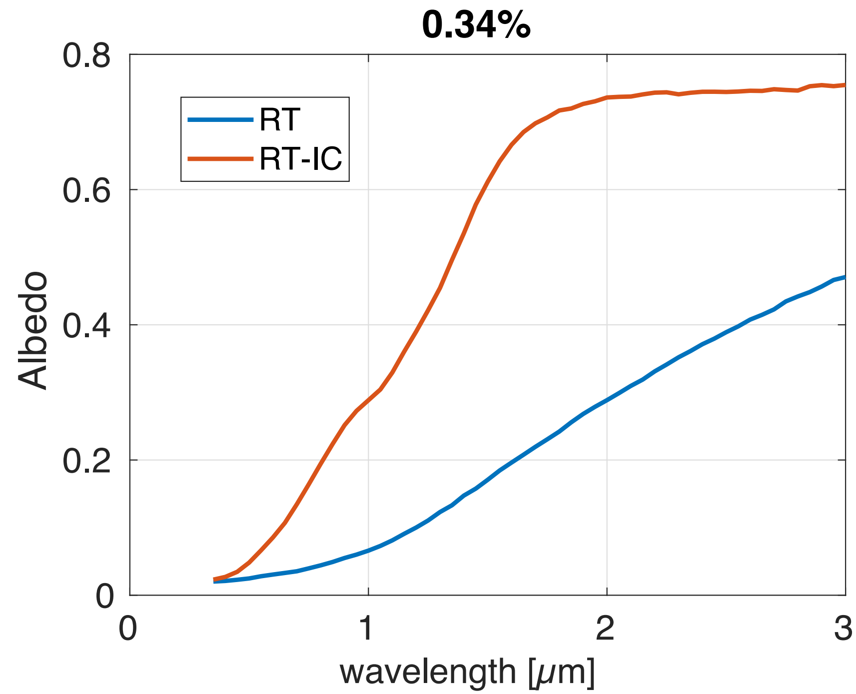


Olivine
Pyroxene
Carbon
Reflectance factor
Wavelength (nm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
2000
2500
3000

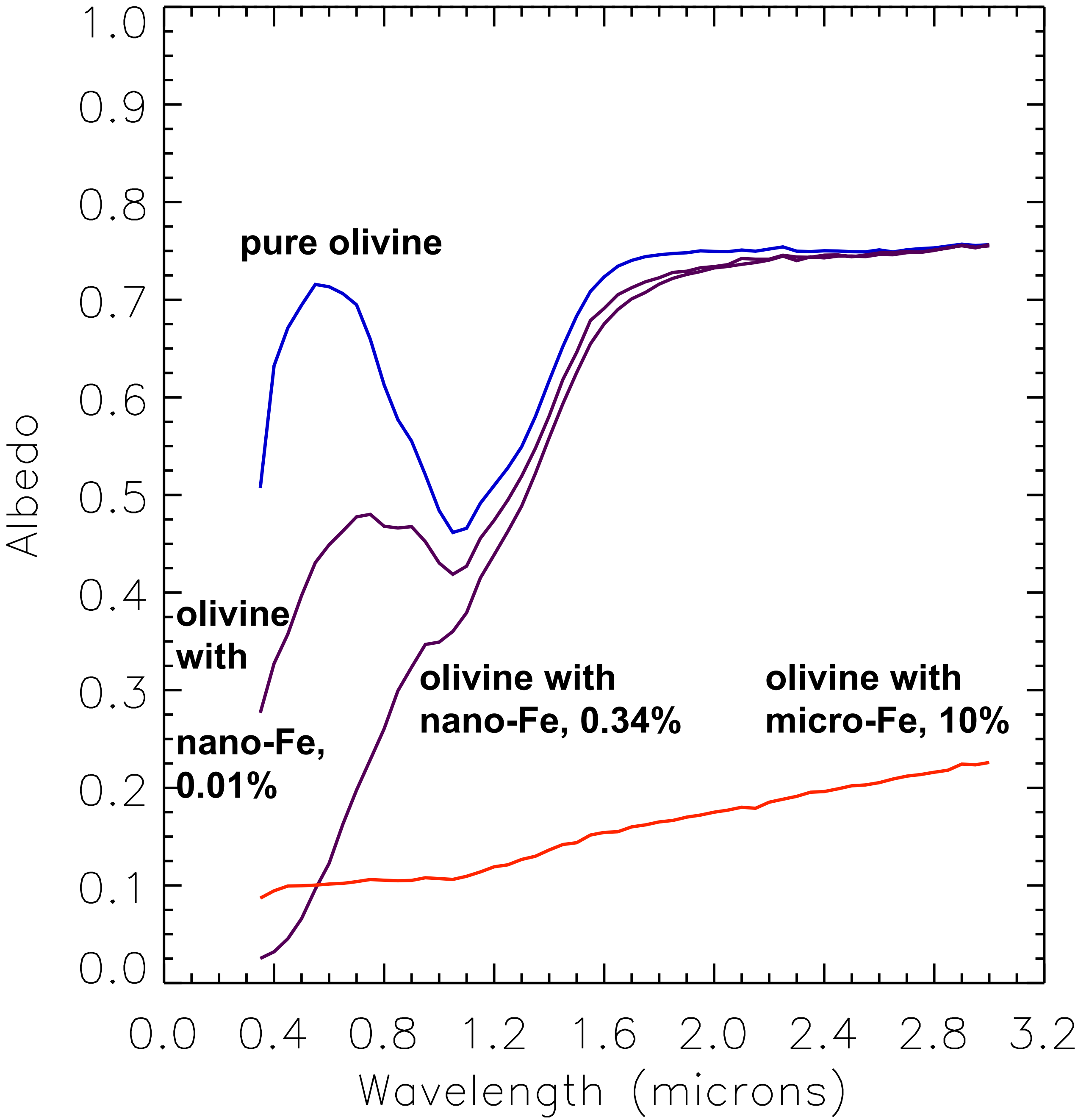
Space weathering







Muinonen et al. 2018, Lindqvist et al. 2018,
Martikainen et al. 2018, Kohout et al. 2014



pure olivine
olivine with nano-Fe, 0.01%
olivine with nano-Fe, 0.34%
olivine with micro-Fe, 10%
Albedo
Wavelength (microns)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2

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)

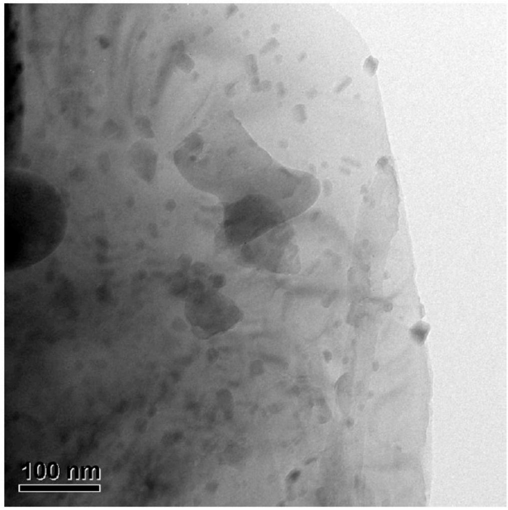
Multiple scattering how-to: Particles embedded in host material

- 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

See Muinonen et al. (2019) Jove, 148, e59607

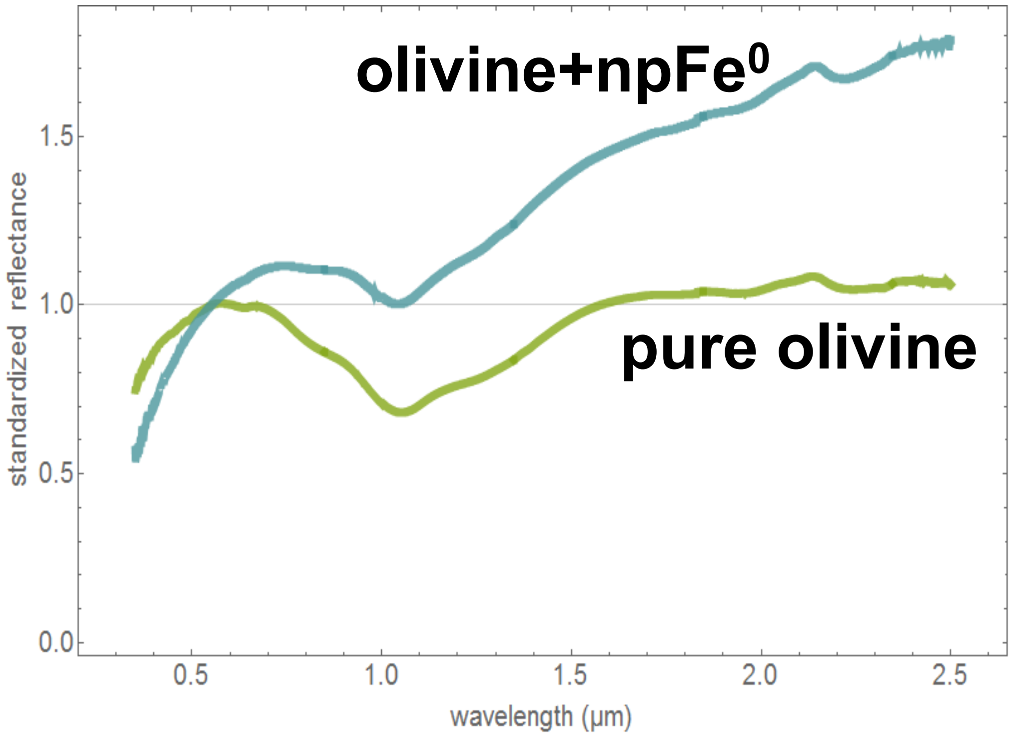
Space weathering effects in Vis-NIR spectroscopy

- 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%

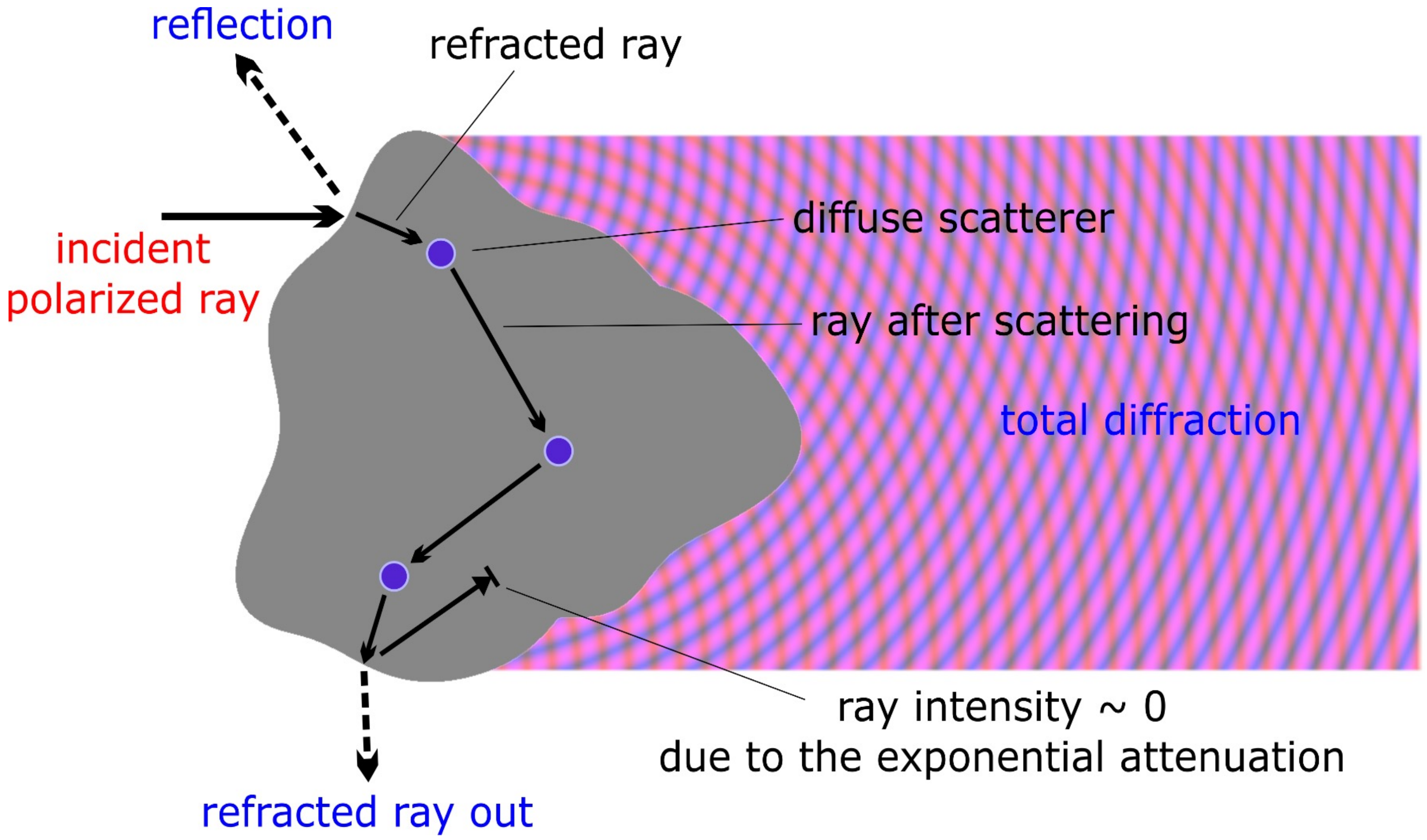


TEM image of nanophase iron in an olivine grain

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



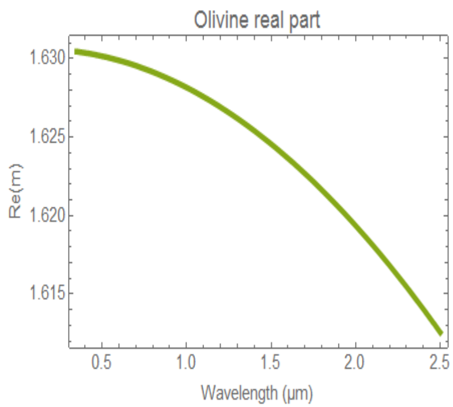
SIRIS ray-tracer in a nutshell

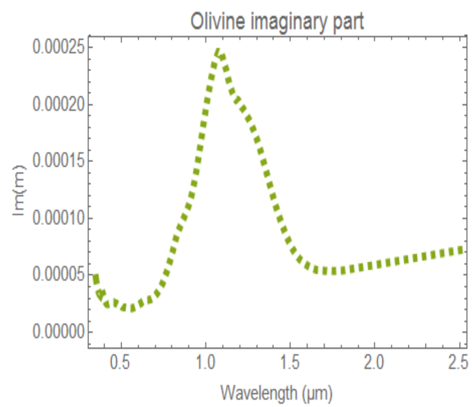


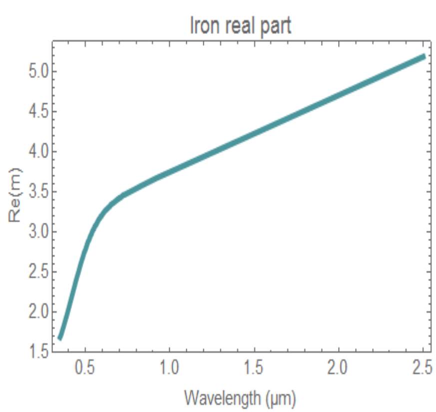
Muinonen et al. (2009), JQSRT 110.

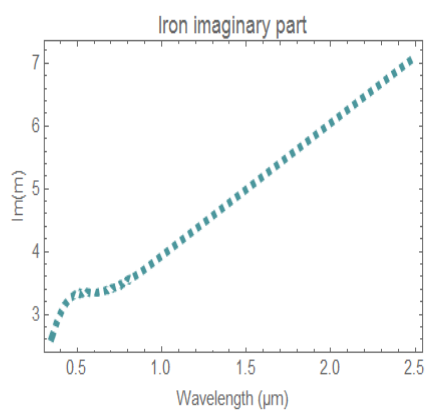
Input parameters directly from measurements

- Measured refractive indices for olivine and iron





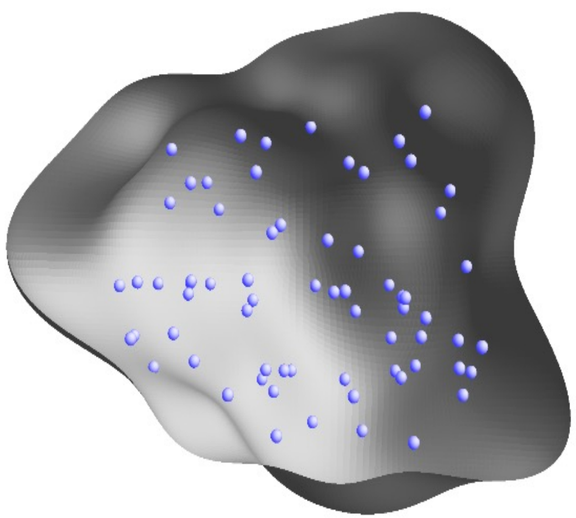




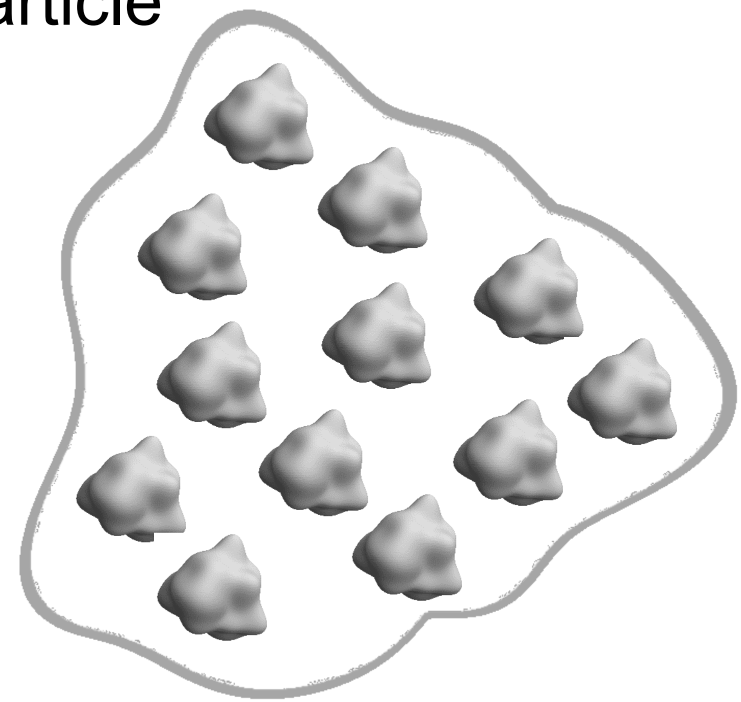
- Real grain size, diameter 20 μm
- Real $npFe^0$ size, 20 nm
- $npFe^0$ diffuse scattering matrix from Mie
- Single-scattering albedo and optical mean-free-path for diffuse scattering from Mie computations and from known weight fraction

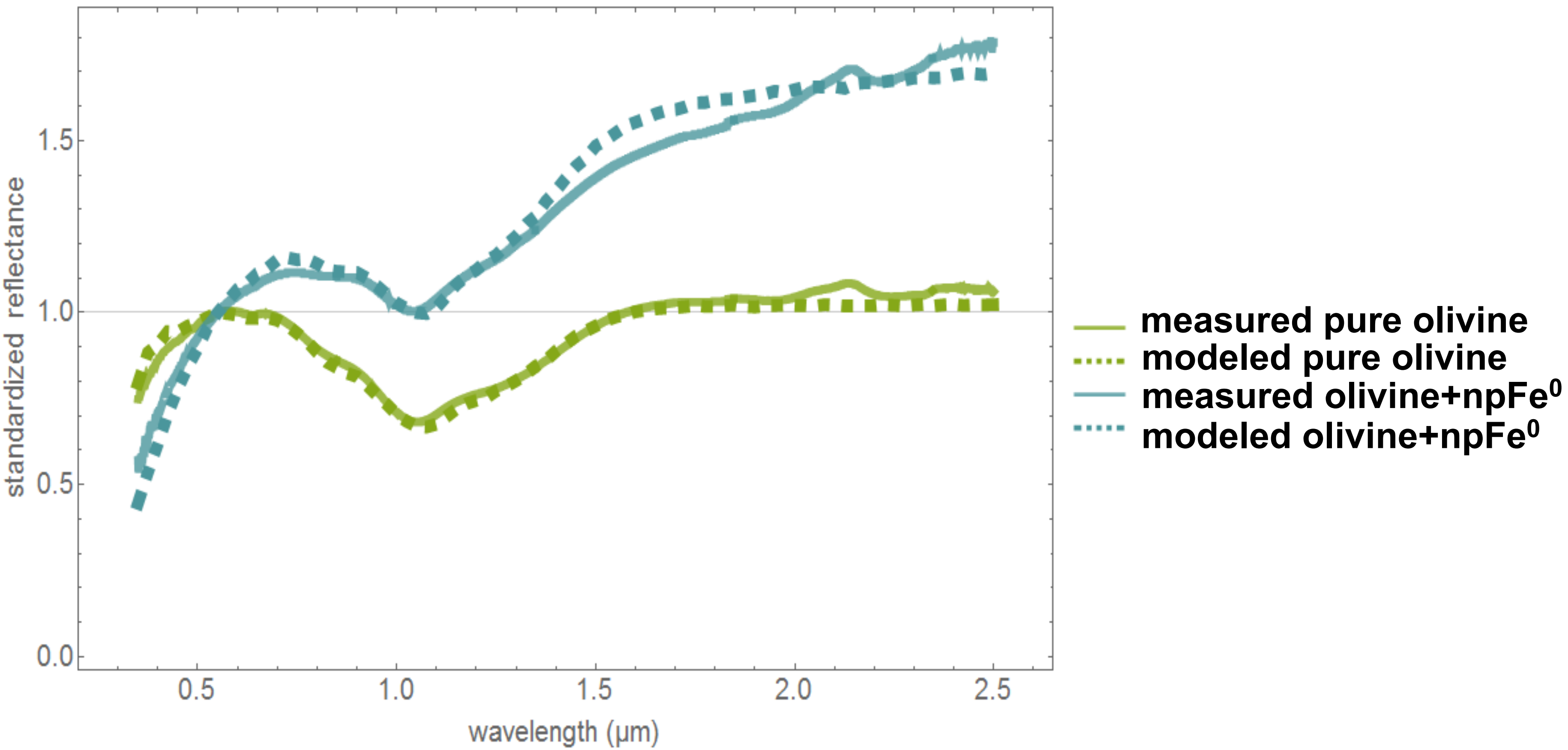
Two rounds in SIRIS to reach macroscopic medium

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’



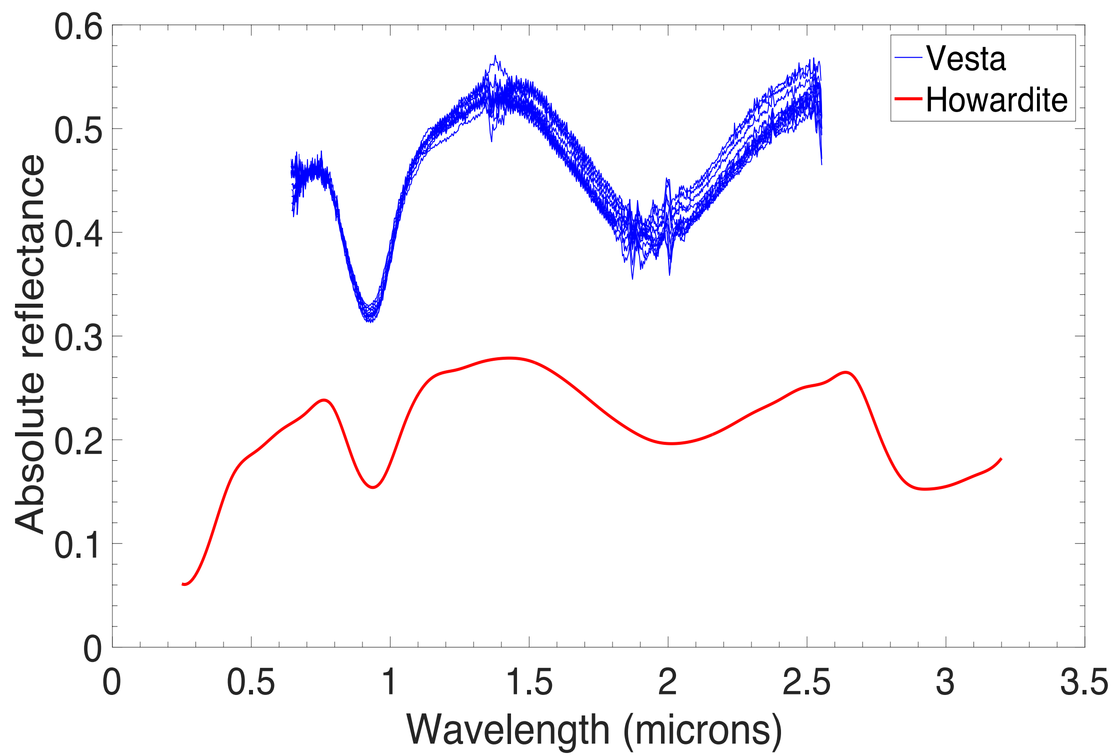


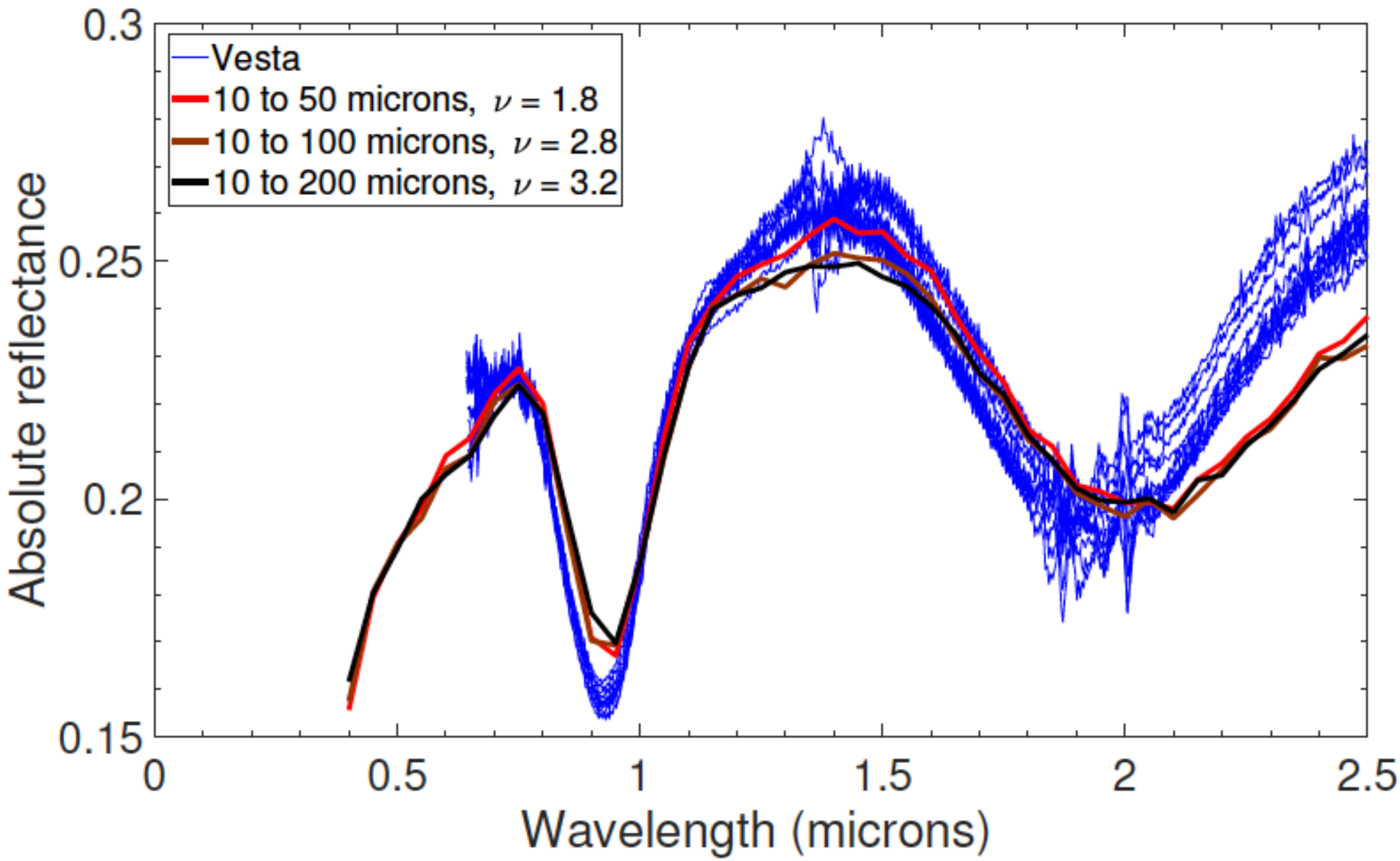
Penttilä et al. 2016

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

(4) Vesta Spectrometry

- Measured the reflectance spectrum of howardite powder with the University of Helsinki integrating-sphere spectrometer
  - Particle sizes ranging from 50 µm to 100 µm
  - Wavelength region of 0.25 to 3.2 µm
- The reflectance spectra of Vesta were obtained from Reddy 2011 (NASA Planetary Data System).
  - SpeX instrument on NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii
- Vesta's spectra scaled to an albedo value of 0.423 (Tedesco et al. 2004) at 0.55 µm



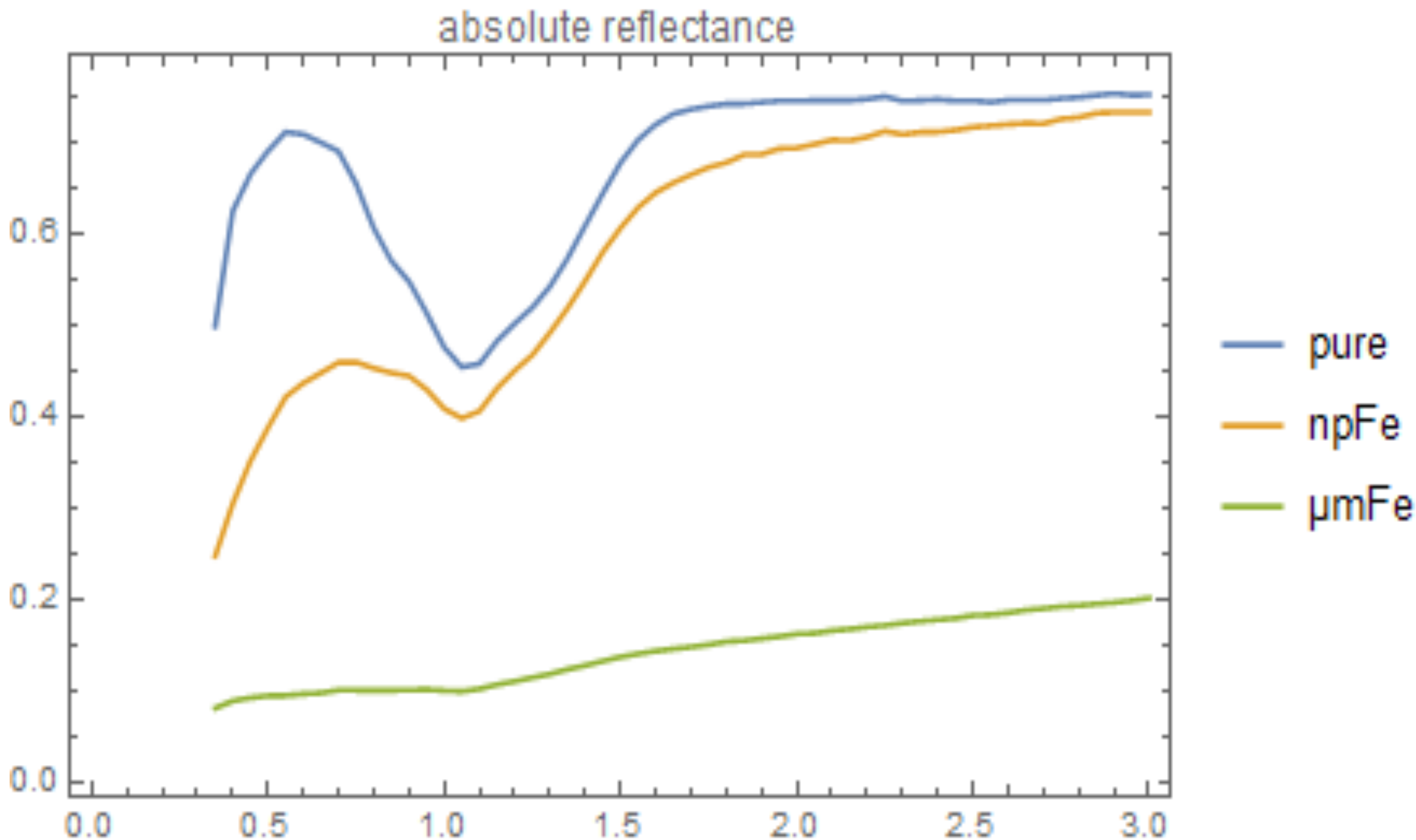


Martikainen et al. 2019

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



absolute reflectance
0.0
0.2
0.4
0.6
0.0
0.5
1.0
1.5
2.0
2.5
3.0
pure
npFe
µmFe

Shkuratov Radiative Transfer Model

Shkuratov et al. 1999
Icarus 137, 235

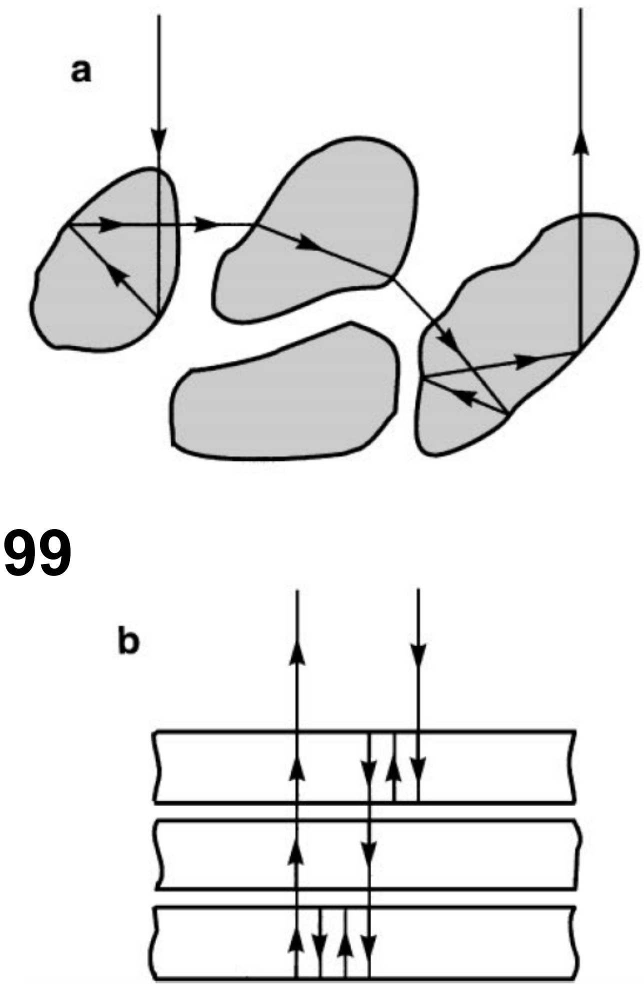


FIG. 1. A scheme of light propagation: (a) through a particulate medium and (b) through plates in a pile.

- 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:

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

$$a = T_e T_i (yR_i + qT_e),$$

$$b = yR_b R_i + \frac{q}{2} T_e^2 (1 + T_i) - T_e (1 - qR_b),$$

$$c = 2yR_b - 2T_e(1 - qR_b) + qT_e^2,$$

$$y = (1 - A)^2 / 2A.$$

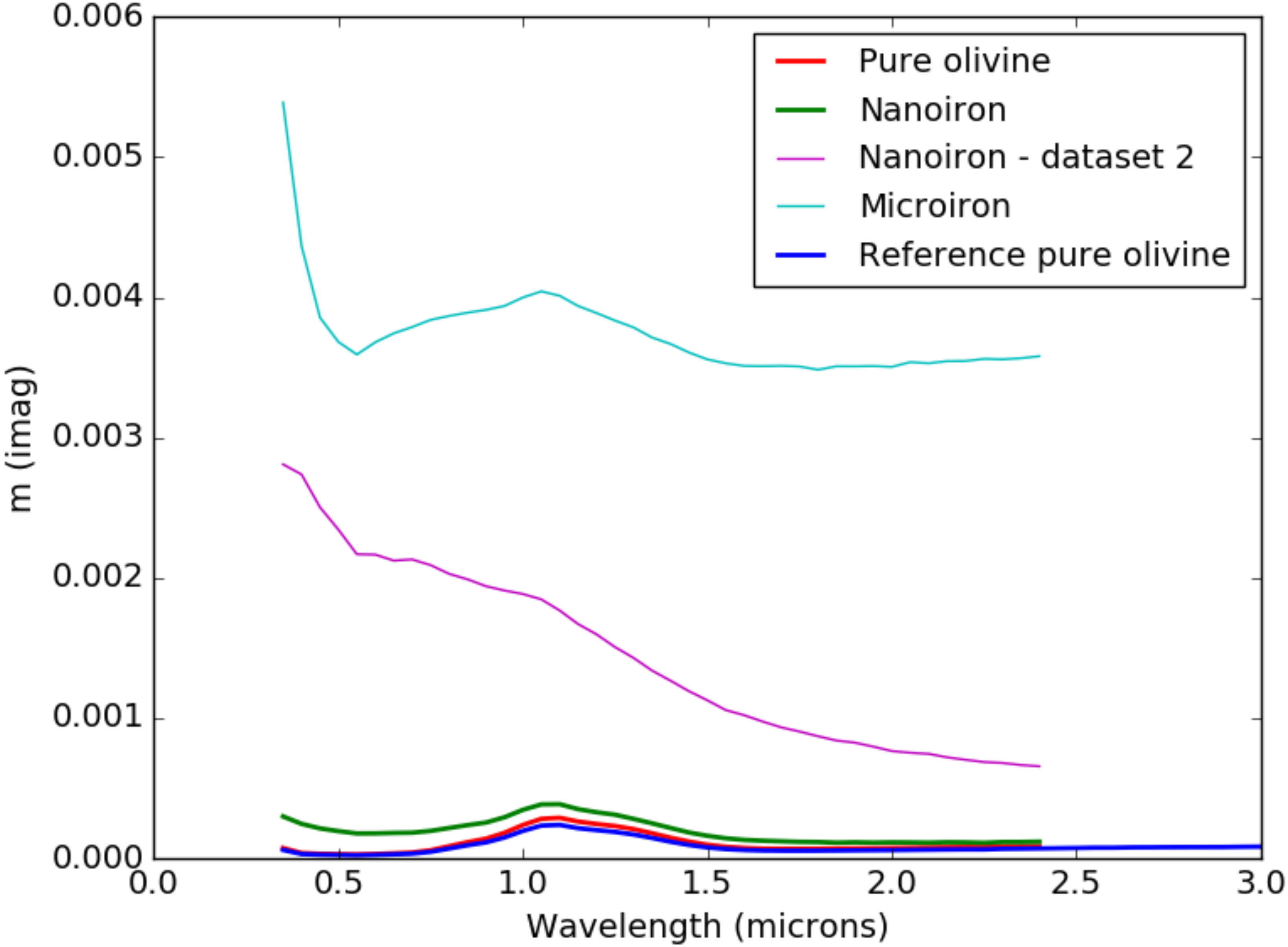
Spectrometric inverse problem - results

- Derive the imaginary part of the refractive index using the Shkuratov model from a Vis-NIR spectrum

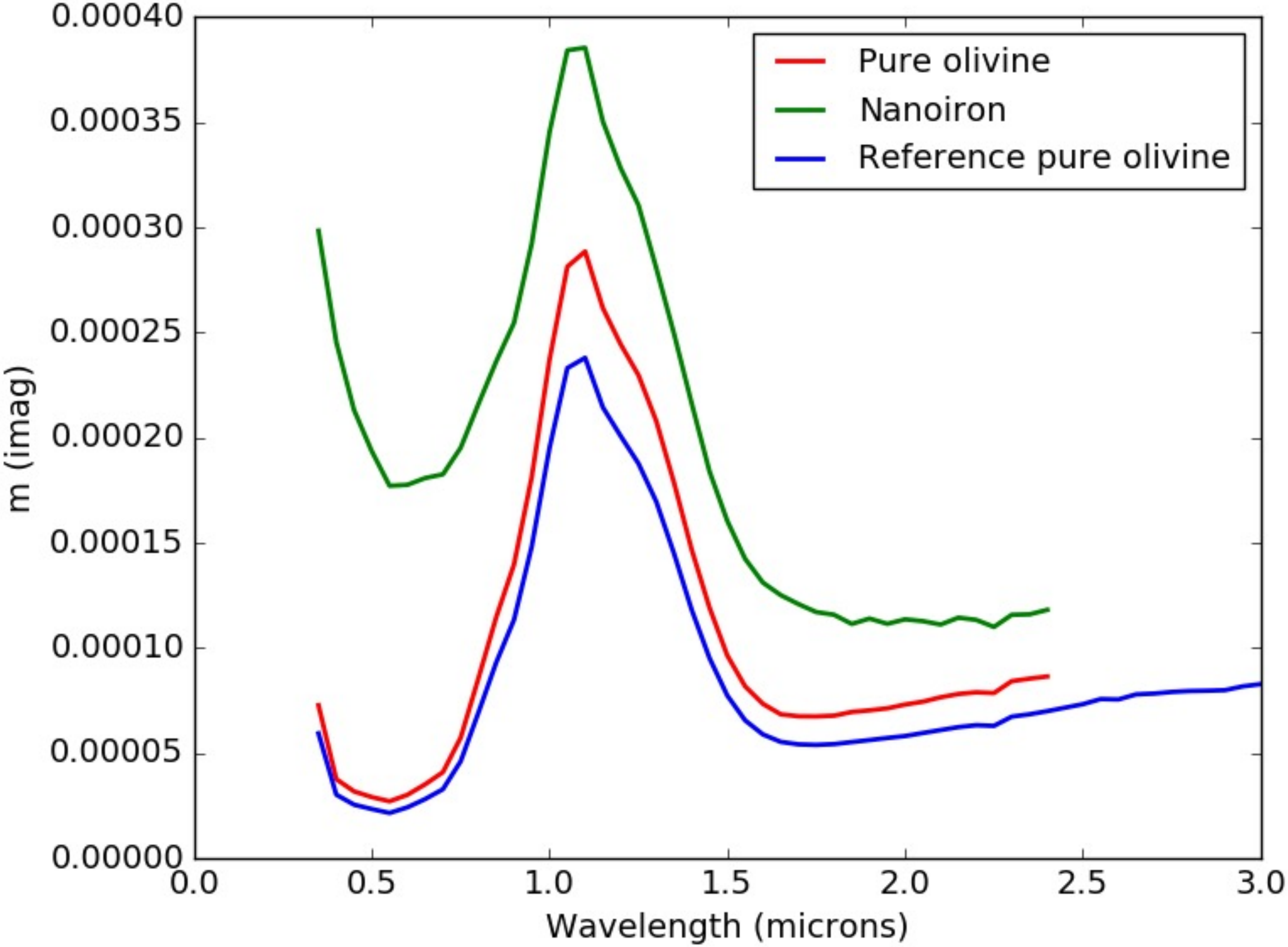
1) Pure olivine
   - radius = 10 microns
   - m_{real} = 1.62

2) Nanoiron embedded in olivine
   - Olivine particle radius = 10 microns, nanoiron particle radius = 20 nm
   - Iron complex refractive index from file

3) Microiron embedded in olivine
   - Olivine particle radius = 20 microns, microiron particle radius = 3 microns
   - iron complex refractive index from file



Pure olivine
Nanoiron
Nanoiron - dataset 2
Microiron
Reference pure olivine
m (imag)
Wavelength (microns)
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.0
0.5
1.0
1.5
2.0
2.5
3.0

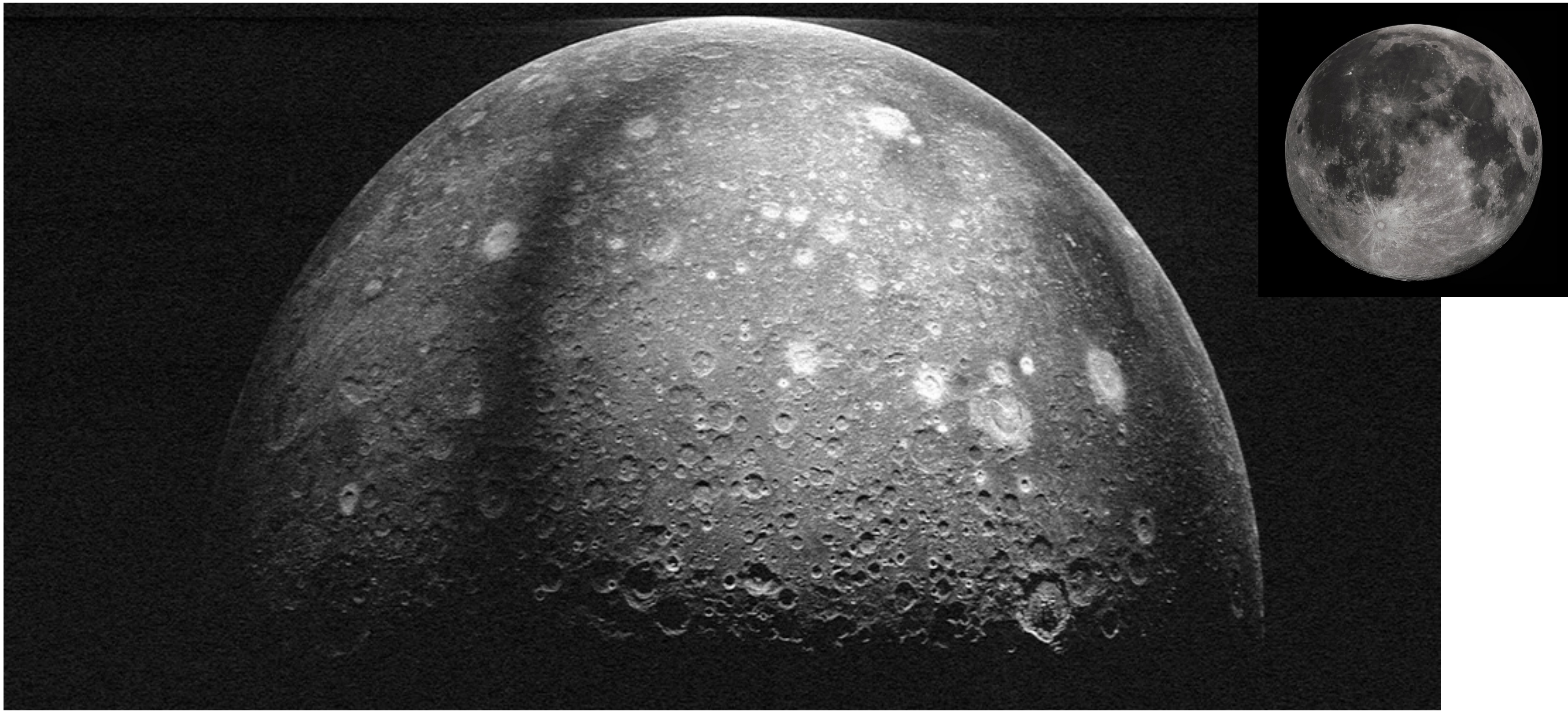


Pure olivine
Nanoiron
Reference pure olivine
m (imag)
Wavelength (microns)
0.00040
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Microwave (radar) scattering

- Multiwavelength analysis can be extended to cm-scale: microwave scattering
- Longer wavelengths can probe information from below the surface and interact with the surface different from the shorter wavelengths
- Radar albedo is equal to the Fresnel reflectivity at normal incidence for a spherical object with no diffuse scattering
- Also allows better imaging resolution through delay-Doppler imaging

The Moon in radar



What is different from an optical image?

Intermediate conclusions

- Mature numerical multiple-scattering methods for densely packed particulate media exist
- Well-defined input allows for quantitative analyses of spectrometric, photometric, and polarimetric observations
- Detailed forward models allow mapping the ambiguities in spectrometry