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 4, Contents

- Introduction
- Laboratory measurements
  - IAA Cosmic Dust Laboratory
  - Scattering by volcanic particles
  - Scattering by olivine and meteorite particles
- Scattering by Gaussian particles
- Feldspar as agglomerated debris
- Multiple scattering by a feldspar medium
- Application to asteroids
- Laboratory measurements
  - UH-Physics Scattering Laboratory
- Optical Constants How-To
- 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

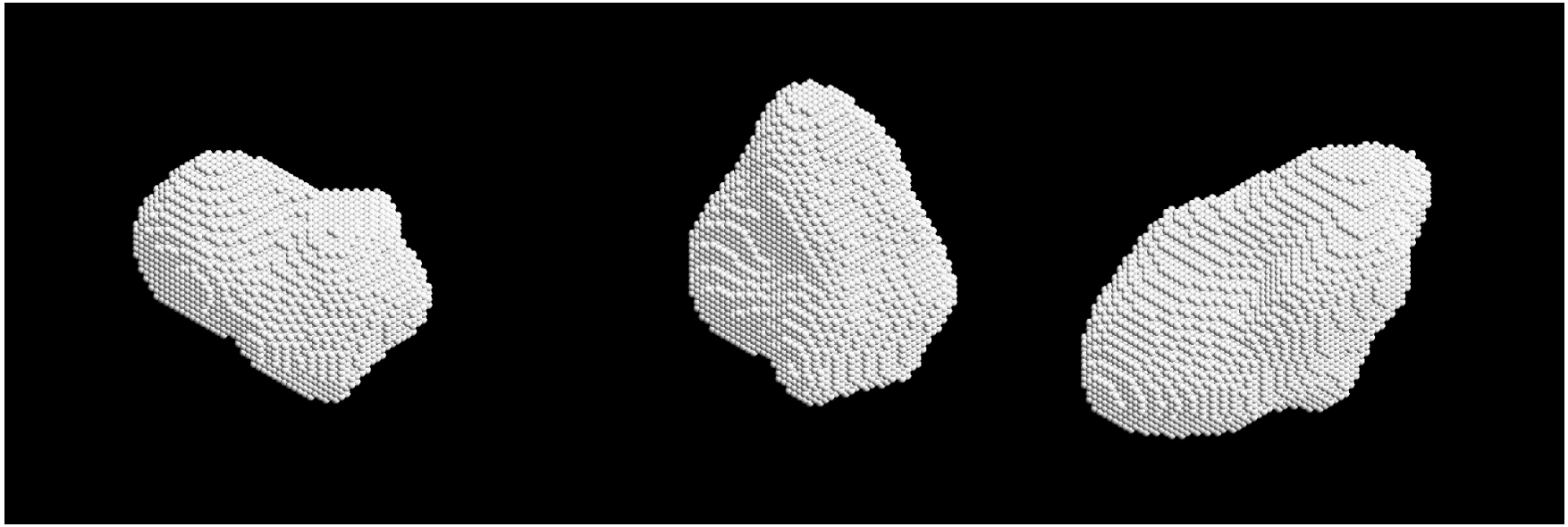
IAA Cosmic Dust Laboratory

- Complete scattering matrix as a function of the scattering angle of aerosol particles
- Wavelengths of 483, 488, 520, 568, or 647 nm
- Scattering angle range from 3 to 177 degrees
- Munoz et al. 2010, JQSRT

Scattering by Gaussian spheres

- Radial distance lognormal, size described by mean distance
- Logarithm of distance Gaussian and given in spherical harmonics (Muinonen et al., JQSRT 1996)
- Correlation between two logarithmic distances depends on the angular distance and is given as series of Legendre polynomials
- Variance of radial distance (σ^2) controls the mountain heights and valley depths
- Power-law correlation function (Legendre coefficients proportional to $l^{-\nu}$ where l is degree) results in only two shape parameters: power-law index ν and standard deviation of radial distance σ

- Simulations with the Discrete-Dipole Approximation (DDA; Muinonen et al. 2007, Zubko et al. 2008 & 2003)
- Radial-distance standard deviations 0.05, 0.10, 0.15, 0.20, 0.245; power-law index 4.0
- Refractive indices 1.6+i0.0005 (silicates) and 1.313 (ice)



Scattering theory

Stokes vectors

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

scattering matrix $\boldsymbol{S}$

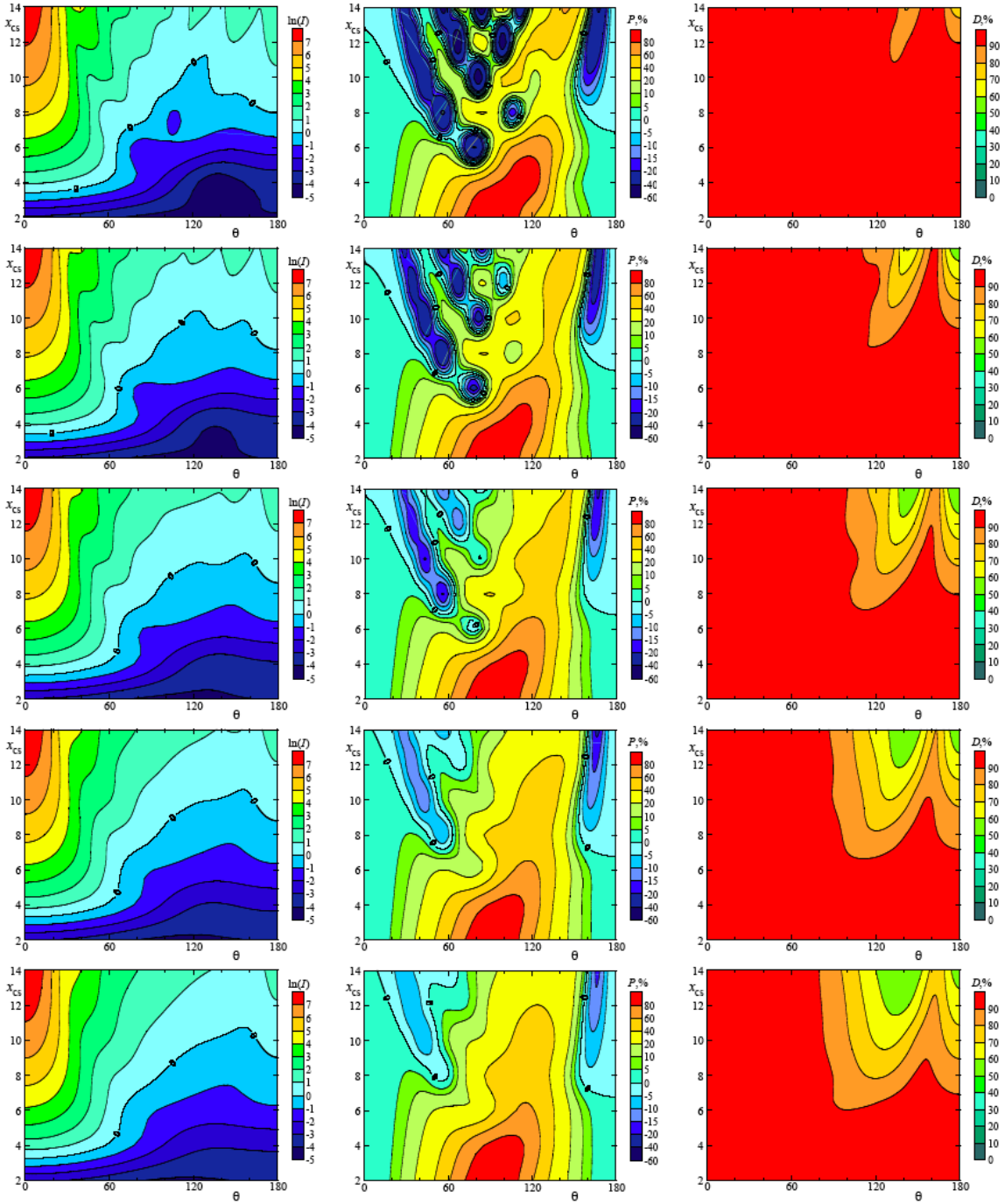
$$\boldsymbol{I}_\mathrm{s} = \frac{1}{k^2 R^2}\, \boldsymbol{S} \cdot \boldsymbol{I}_\mathrm{i}$$

$$I_\parallel(\theta) = S_{11}(\theta) + S_{12}(\theta),$$
$$I_\perp(\theta) = S_{11}(\theta) - S_{12}(\theta),$$
$$P(\theta) = -\frac{S_{12}(\theta)}{S_{11}(\theta)},$$
$$D(\theta) = 1 - \frac{S_{22}(\theta)}{S_{11}(\theta)},$$

where θ is the scattering angle.

1.313

Qualitative explanations? See Muinonen et al. 2011.



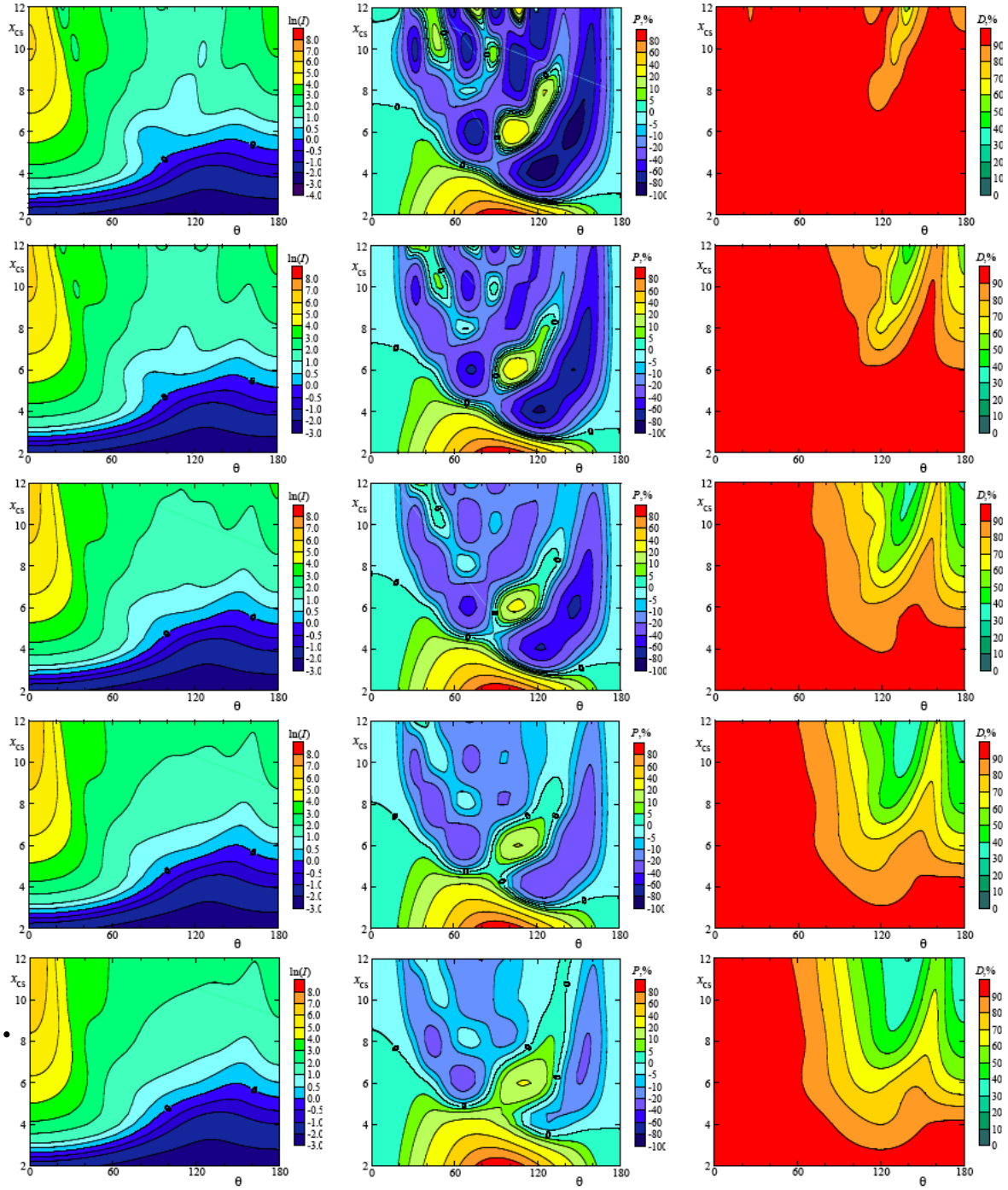
1.6+i0.0005

Qualitative explanations? See Muinonen et al. 2011.

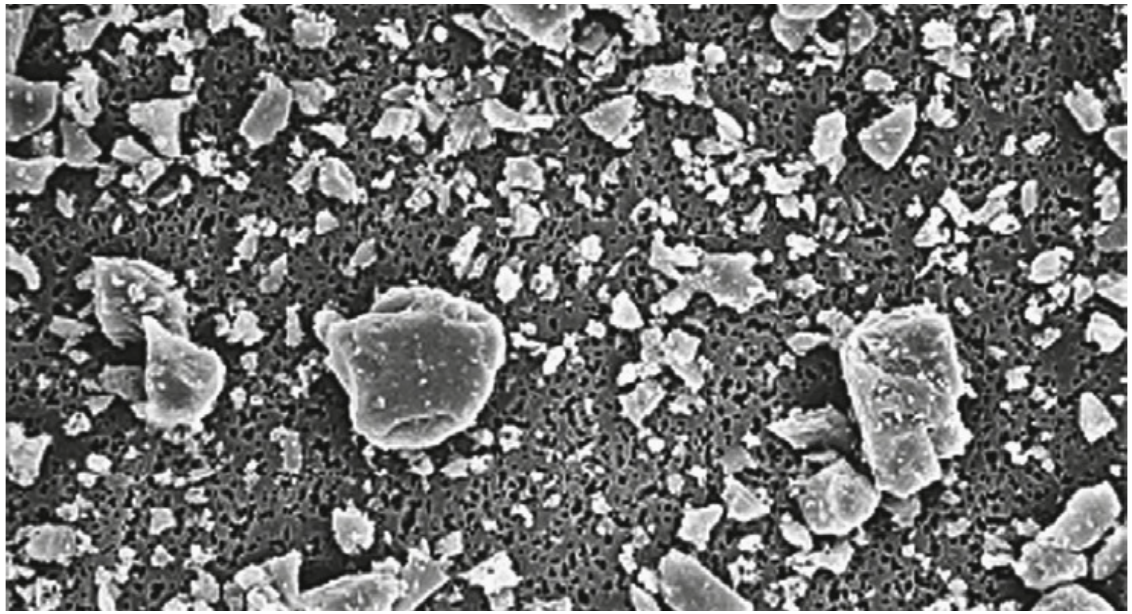
Muinonen et al. 2007,

Tyynelä et al. 2007 & 2008,

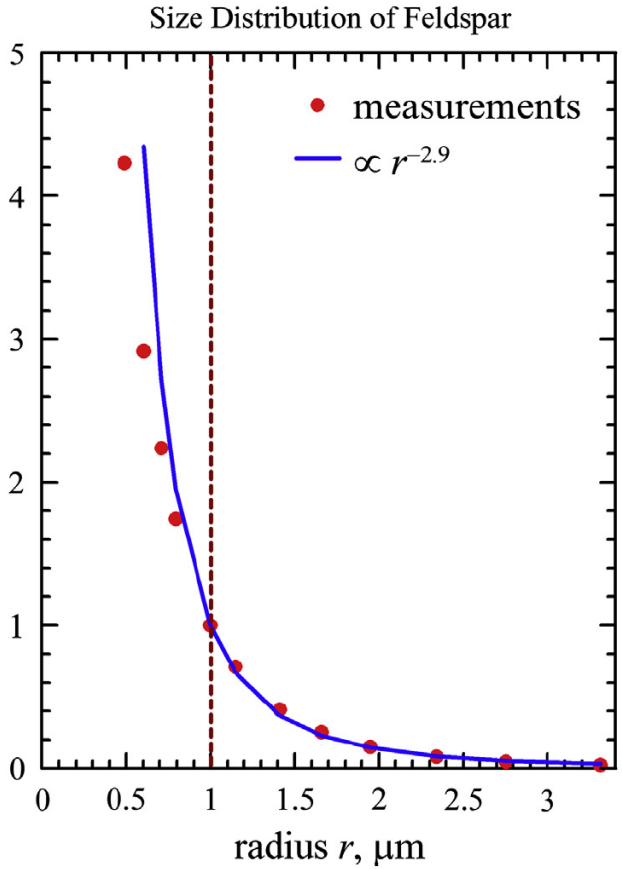
Lindqvist et al. 2009

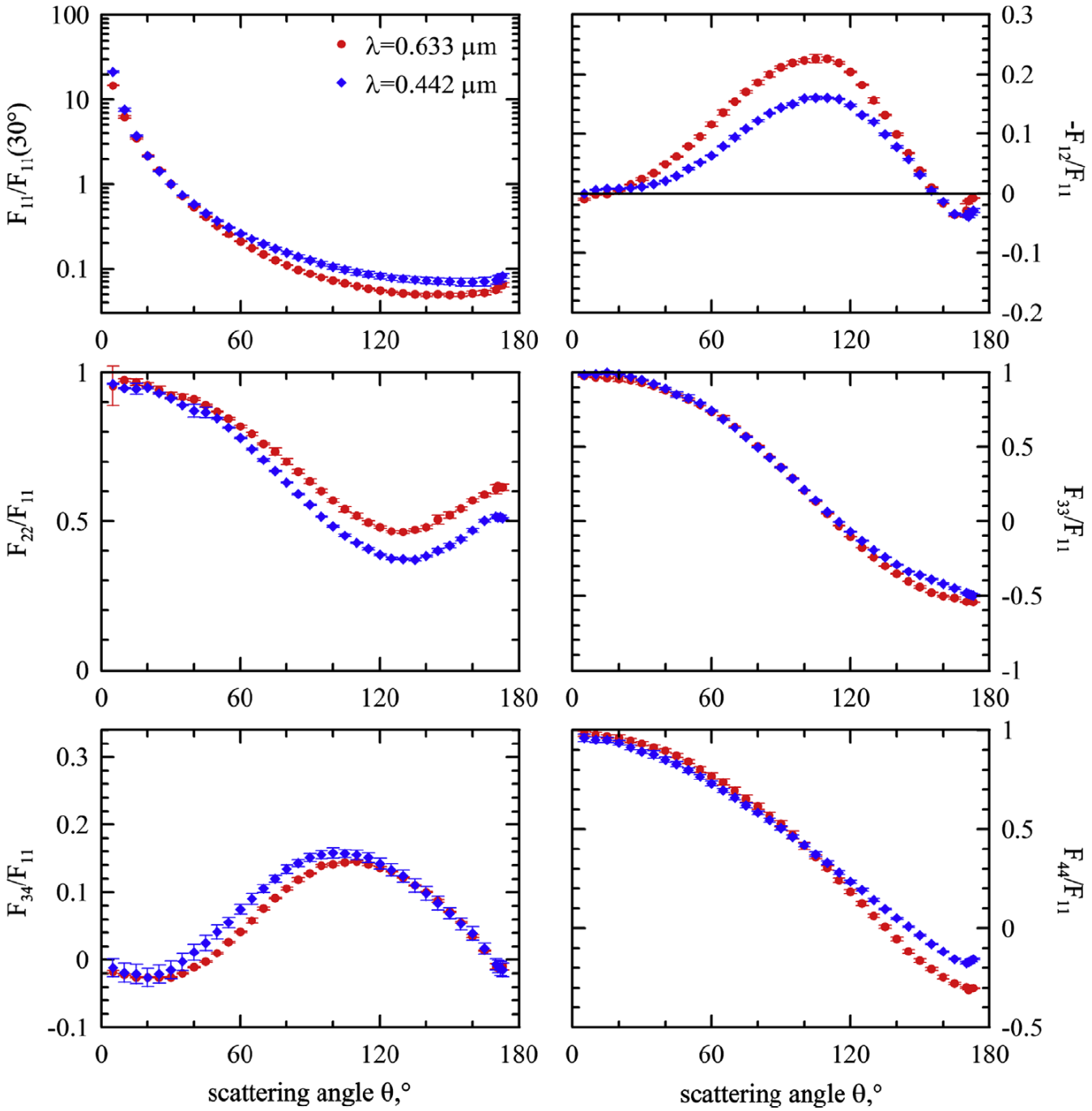


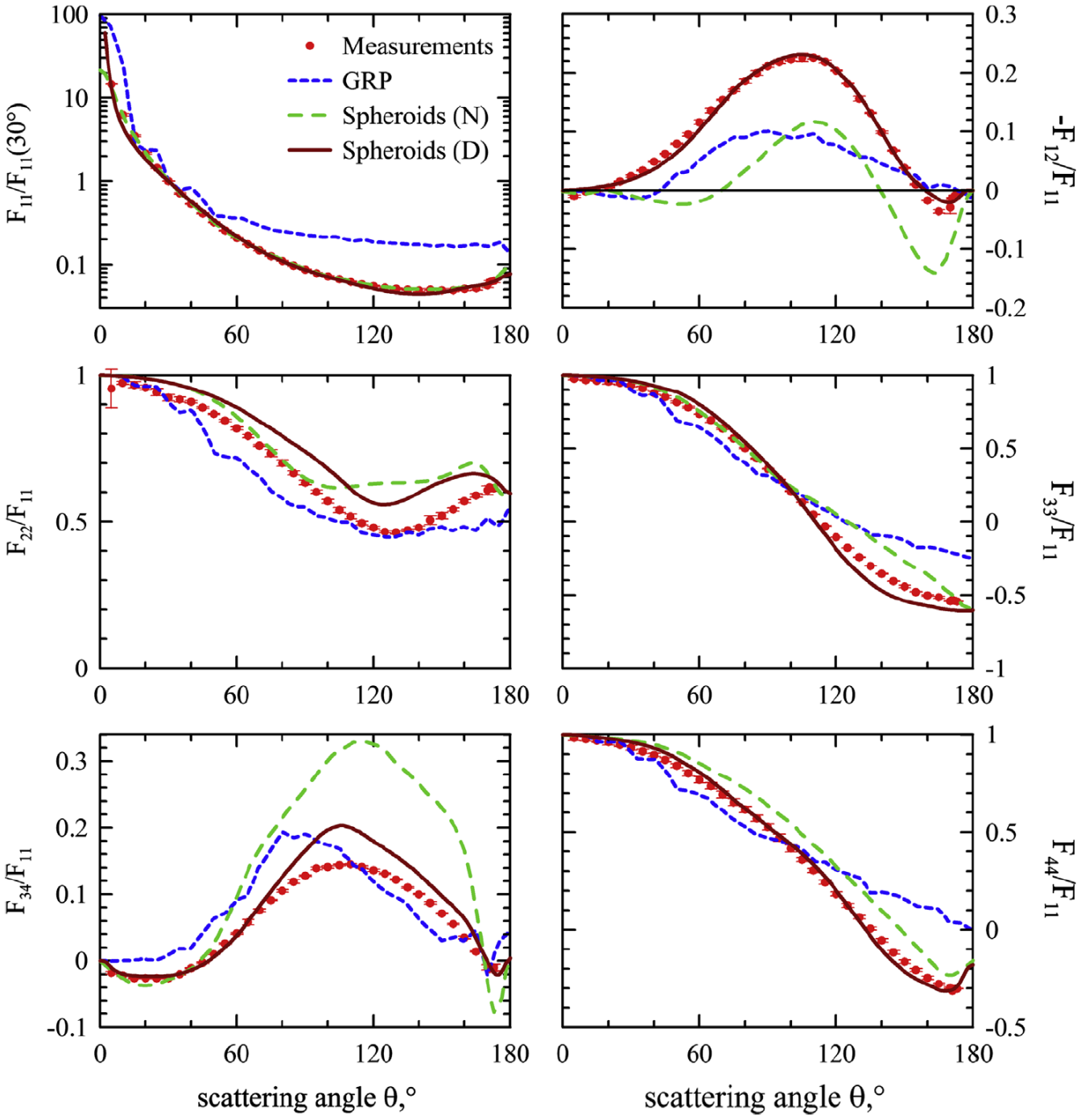
Feldspar as agglomerated debris

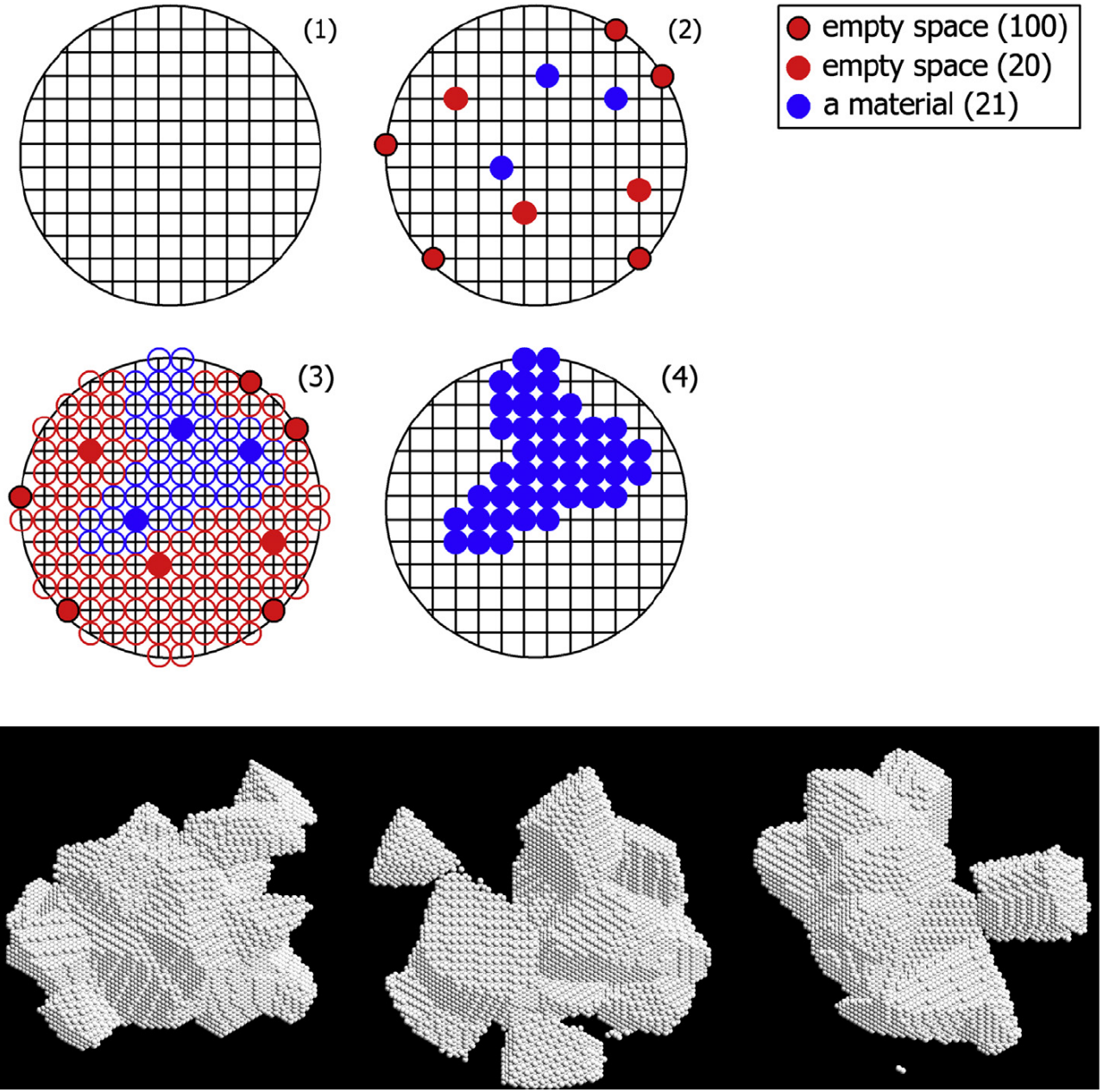


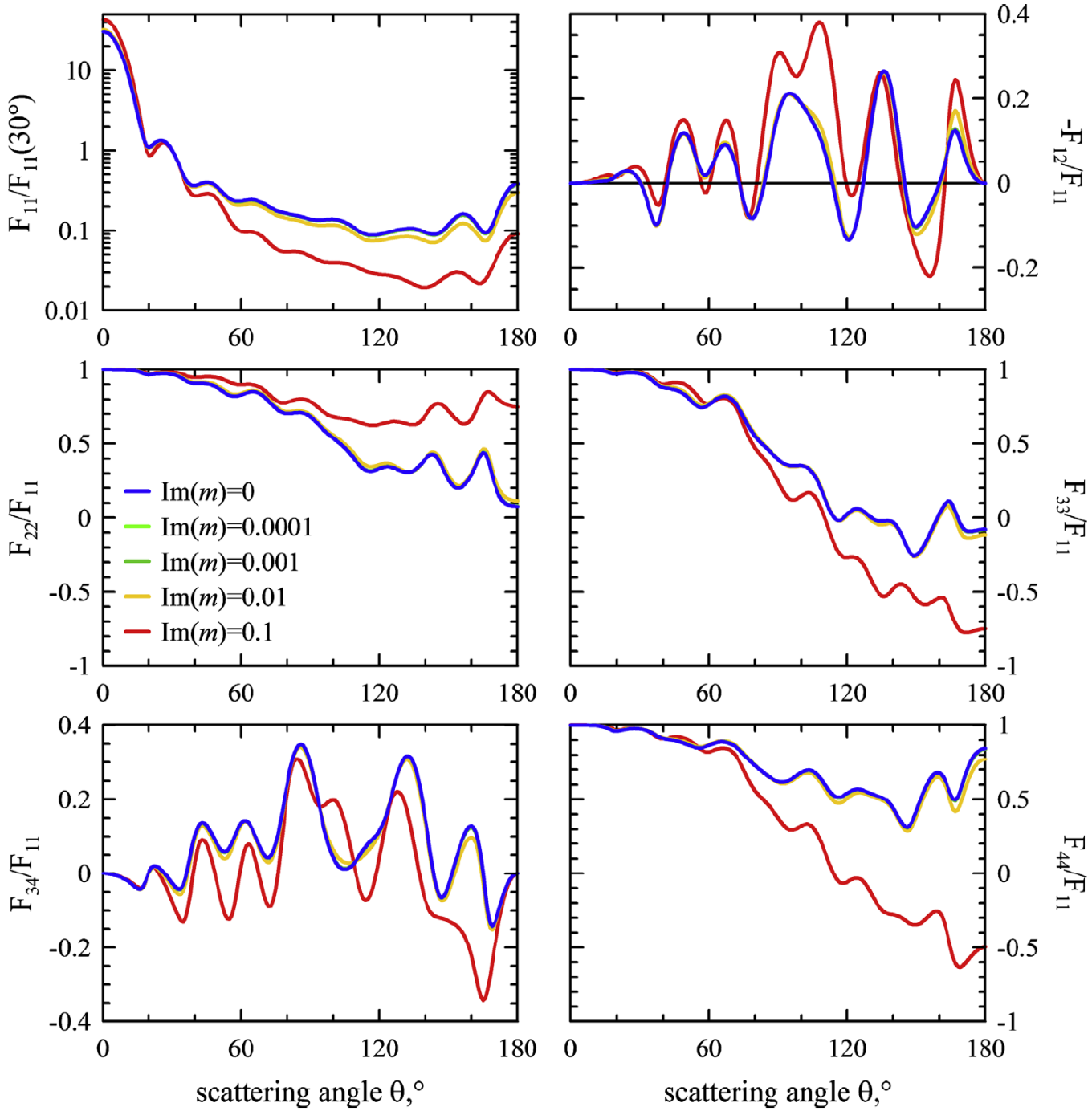
Zubko et al., JQSRT, 2013

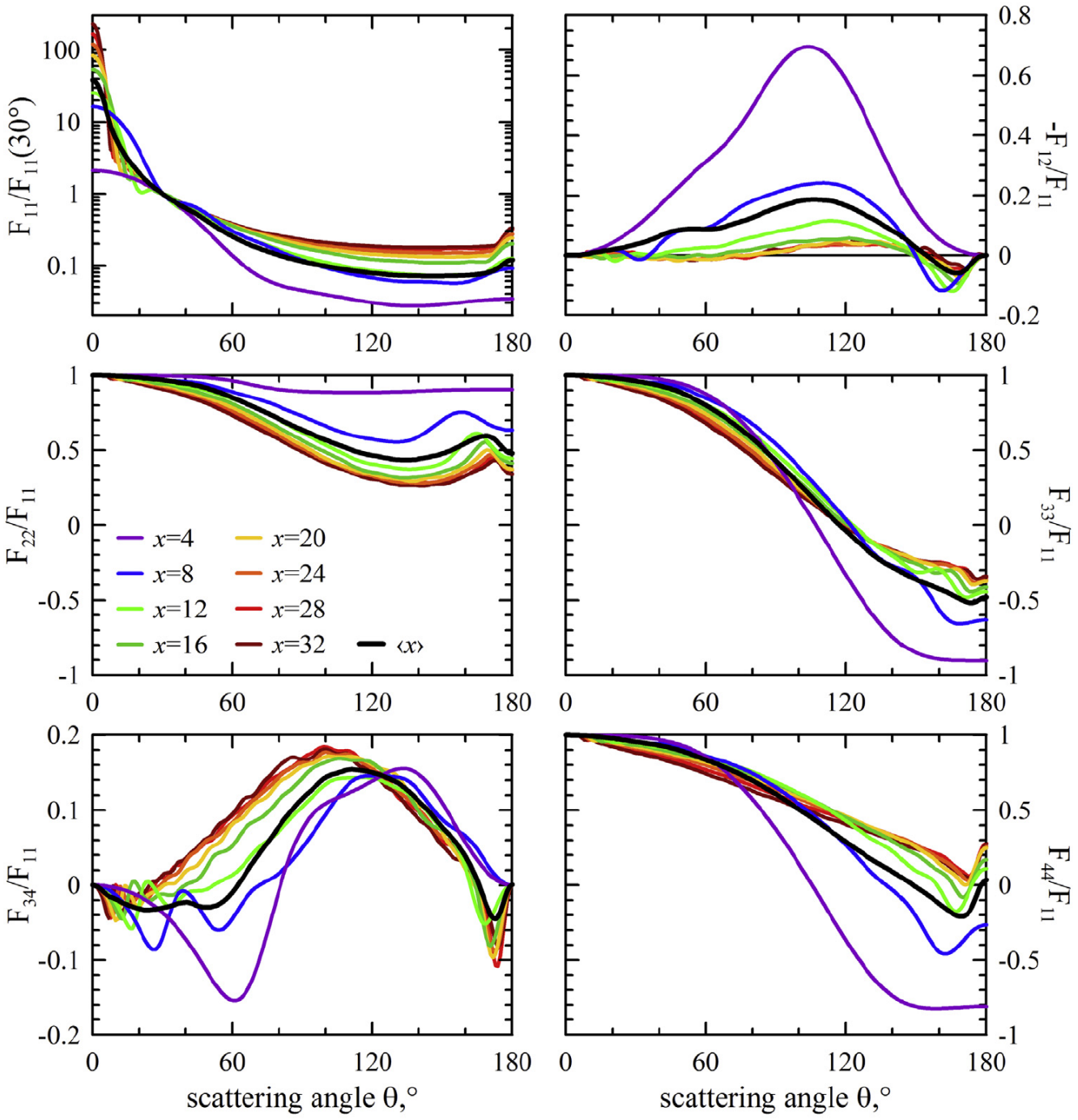


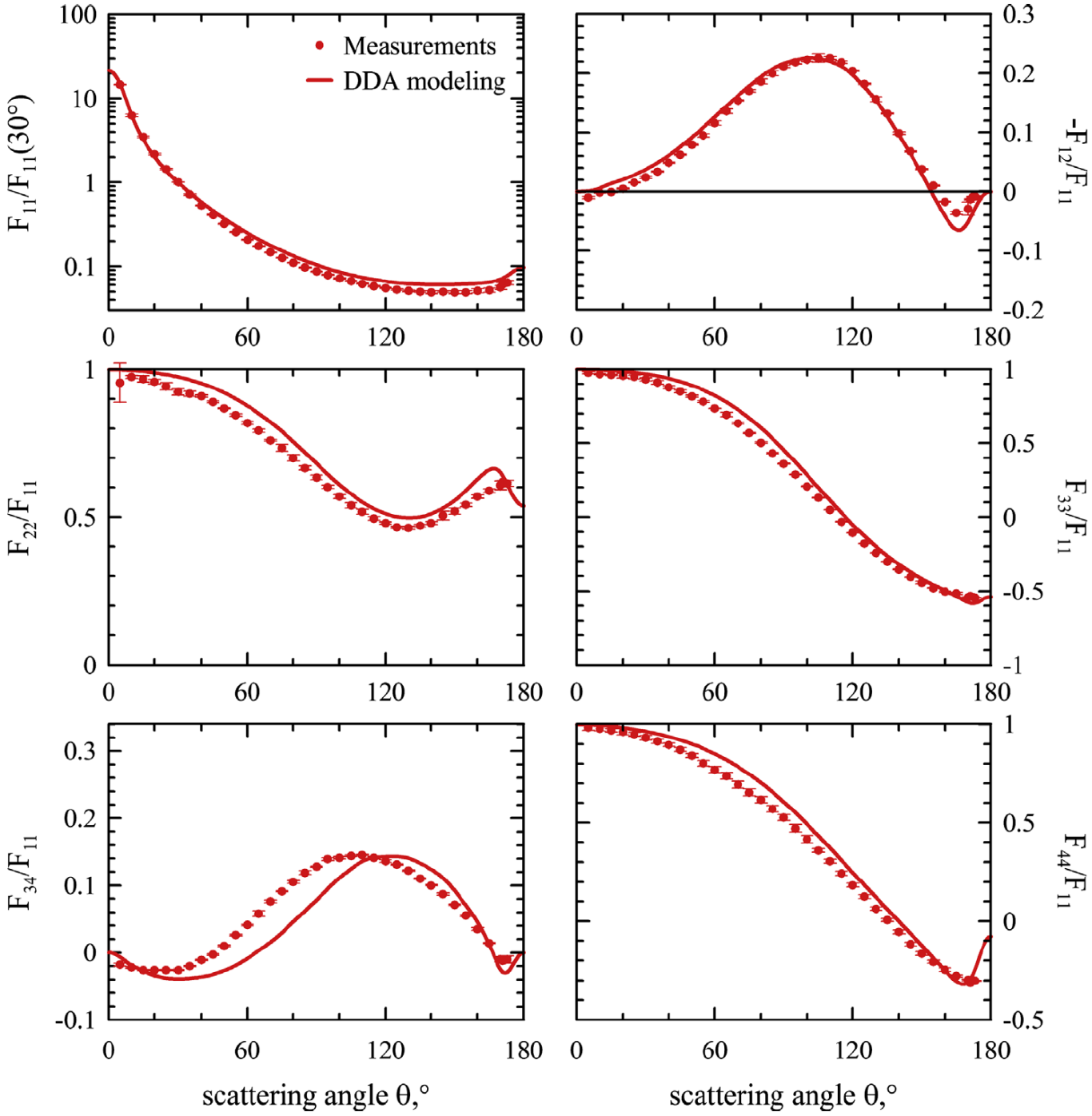

λ=0.633 μm
λ=0.442 μm
F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
scattering angle θ,°
scattering angle θ,°

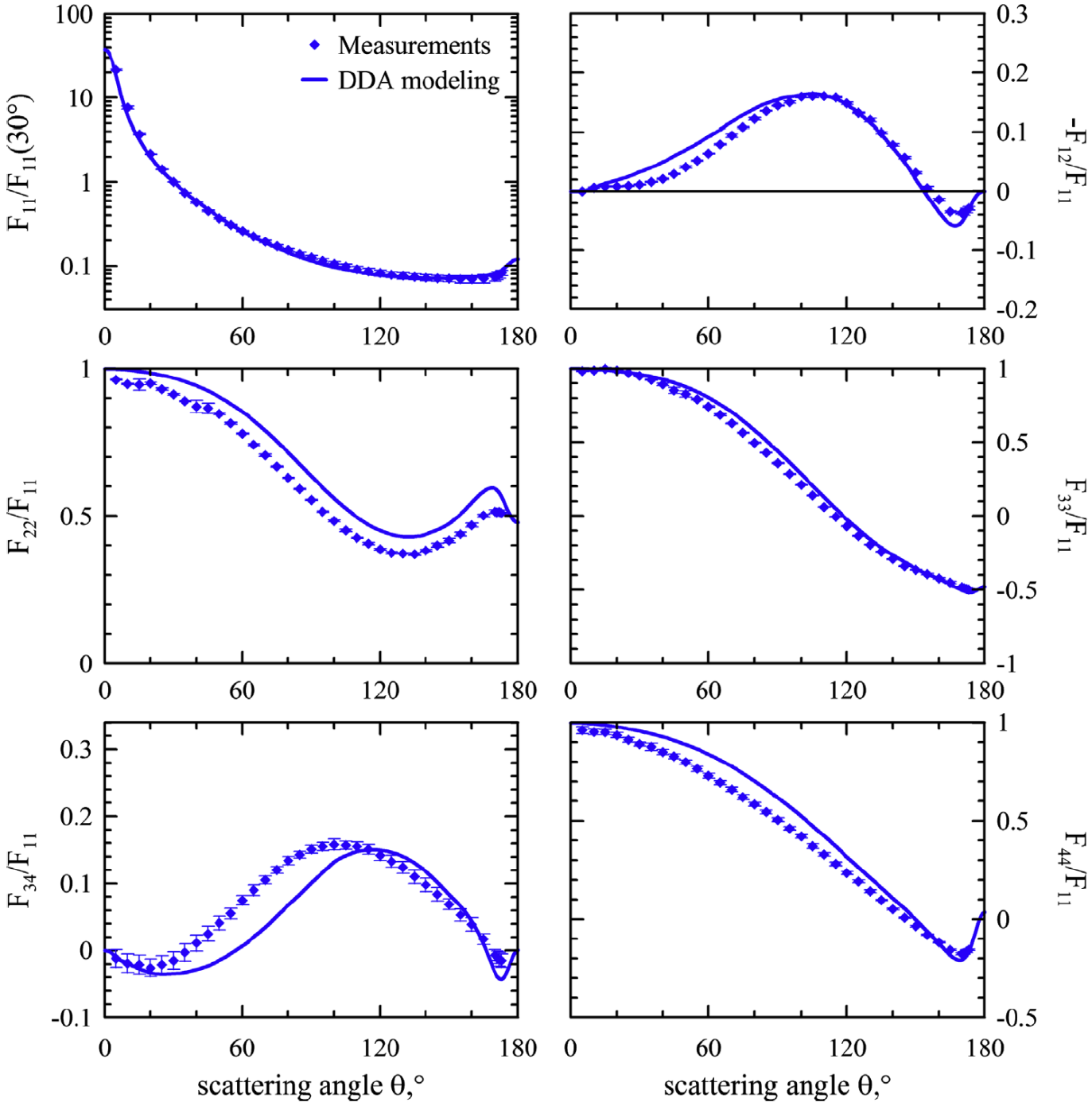

Measurements
GRP
Spheroids (N)
Spheroids (D)
F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
scattering angle θ,°
scattering angle θ,°


(1)
(2)
(3)
(4)
empty space (100)
empty space (20)
a material (21)

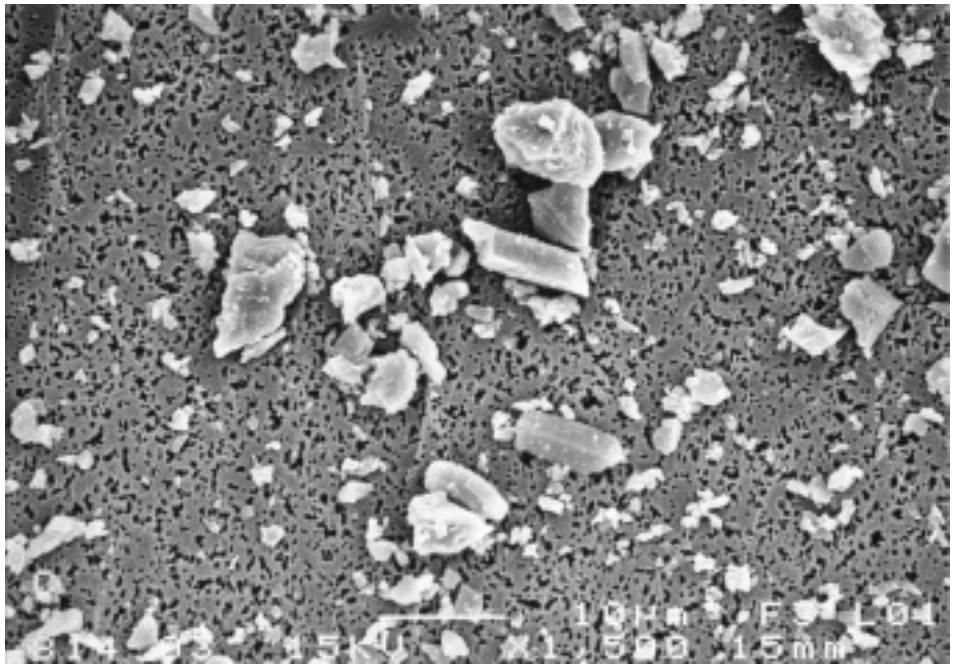

F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
Im(m)=0
Im(m)=0.0001
Im(m)=0.001
Im(m)=0.01
Im(m)=0.1
scattering angle θ,°
scattering angle θ,°

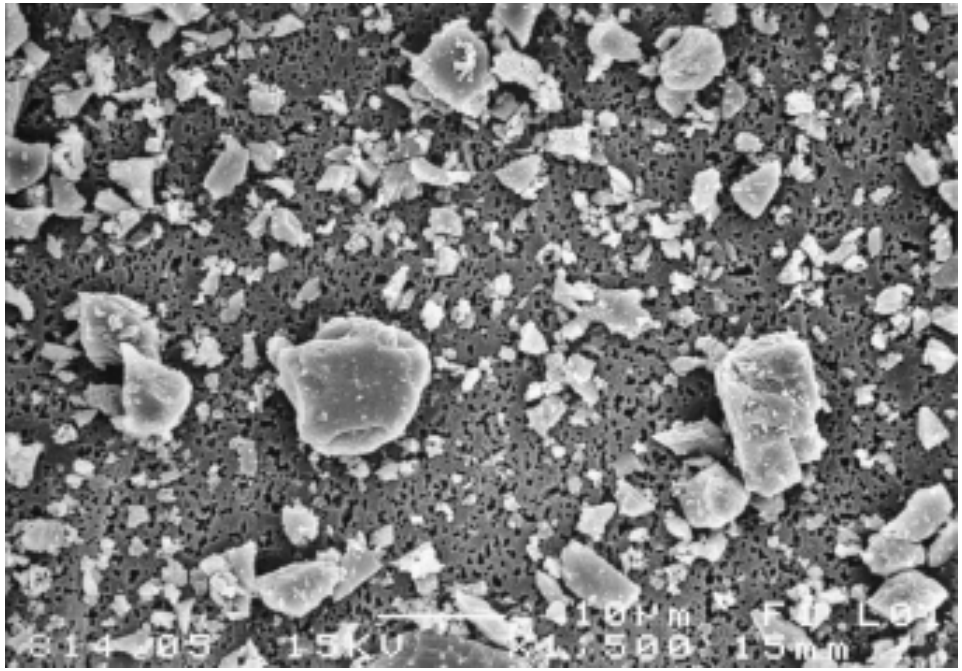

F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
x=4
x=8
x=12
x=16
x=20
x=24
x=28
x=32
‹x›
scattering angle θ,°
scattering angle θ,°


Measurements
DDA modeling
F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
scattering angle θ,°
scattering angle θ,°


Measurements
DDA modeling
F11/F11(30°)
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
scattering angle θ,°
scattering angle θ,°

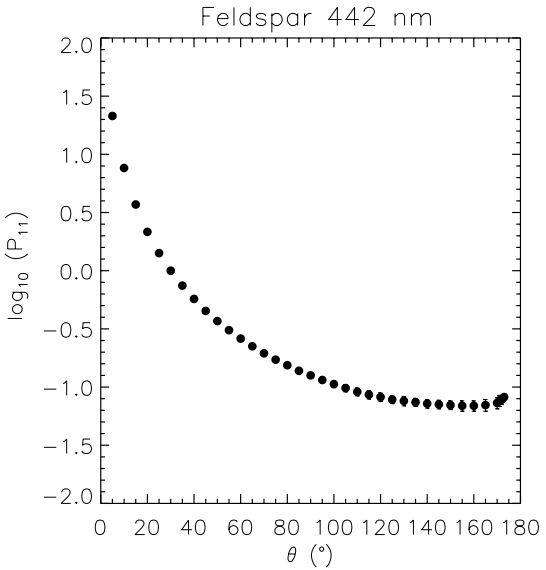
Multiple scattering by a medium of feldspar particles

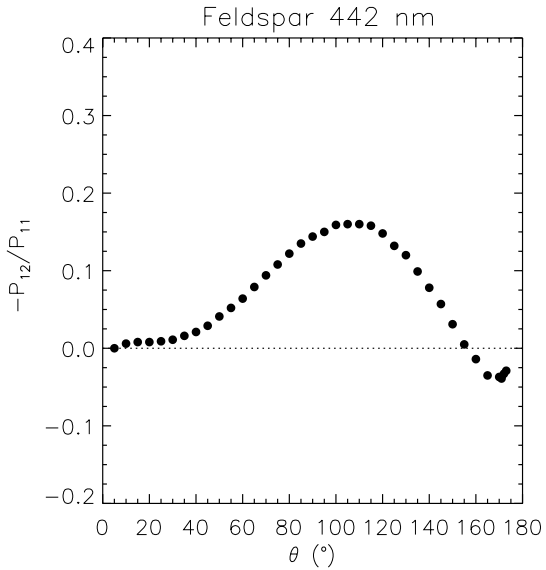


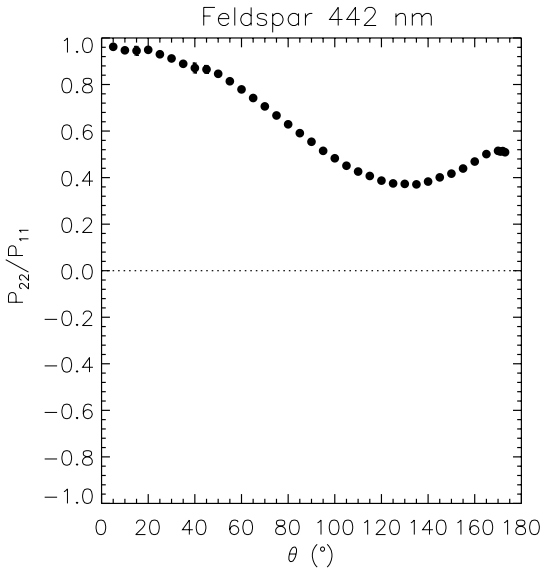


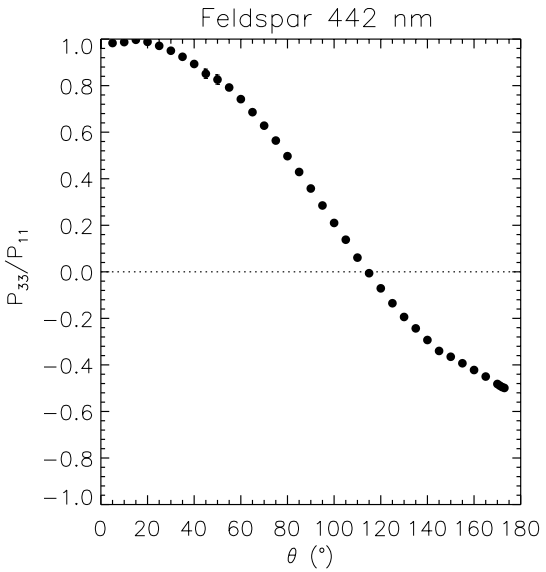
Laboratory measurements for feldspar particles:
Single scattering: Volten et al. 2001, Munoz et al. 2012
Multiple scattering: Shkuratov et al. 2004

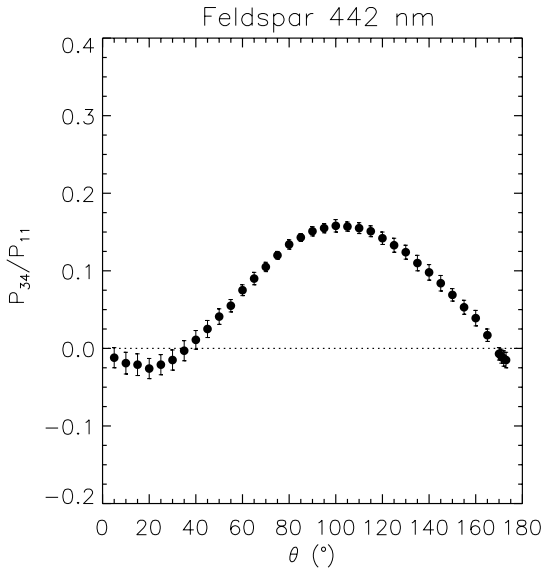
Feldspar at 442 nm

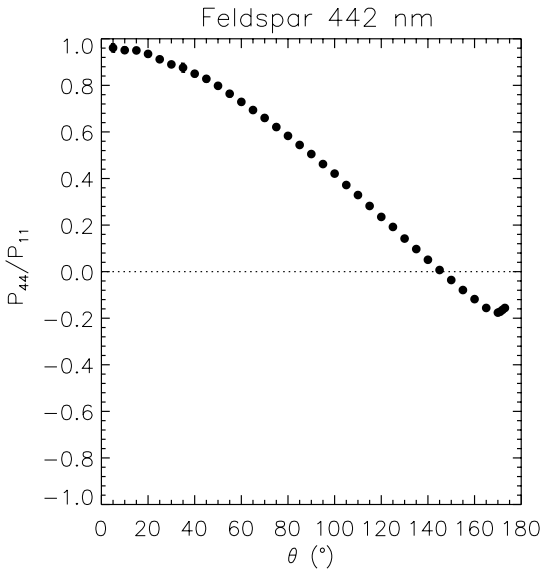




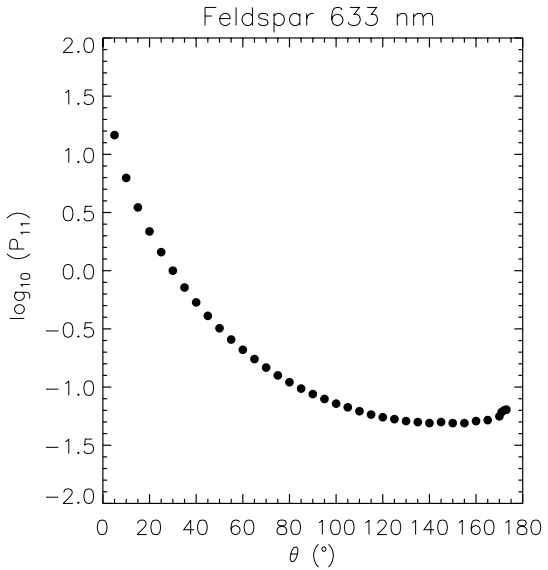


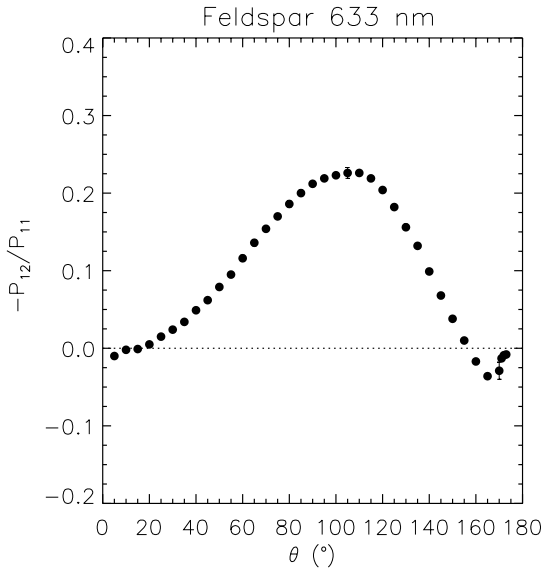


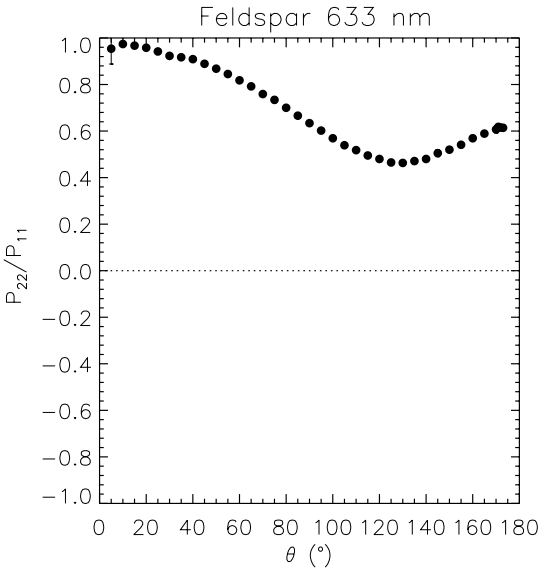


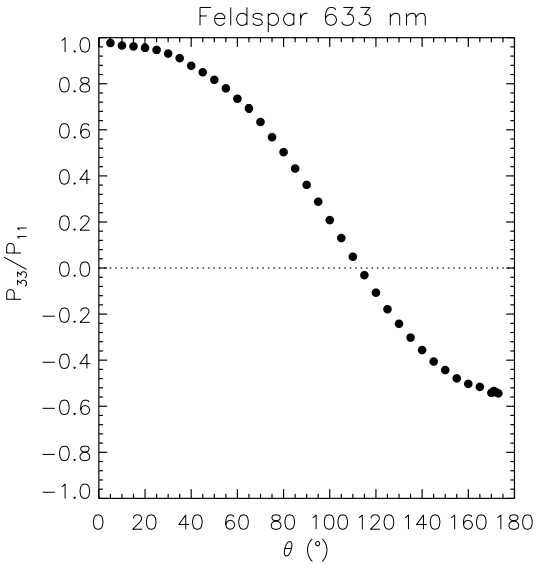


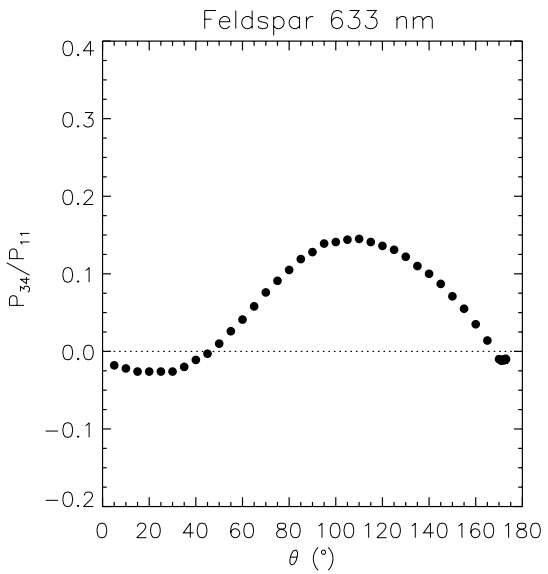
Feldspar at 633 nm

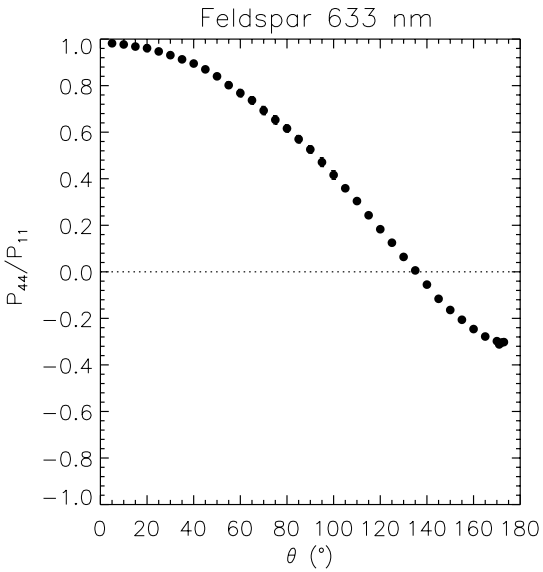








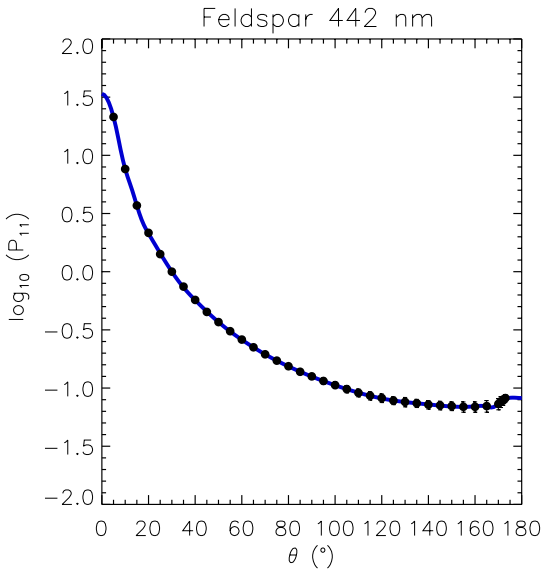


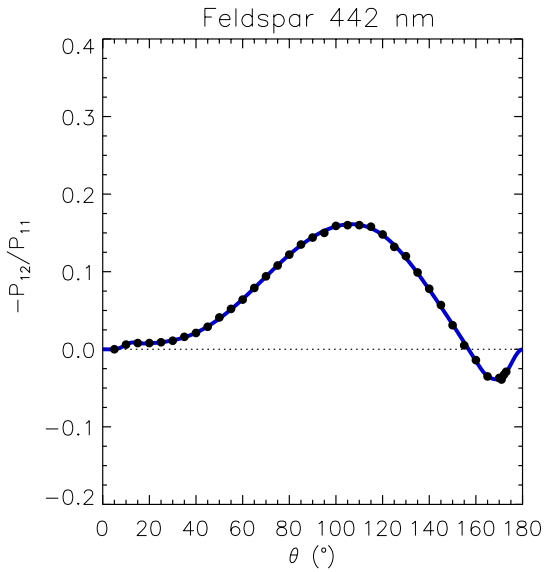


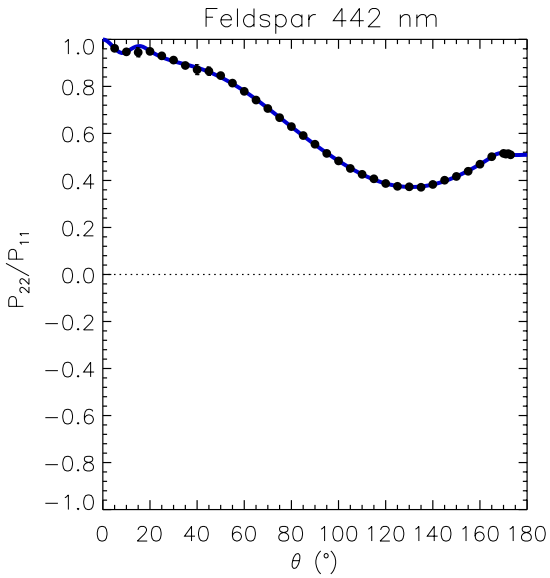
Feldspar scattering matrix model

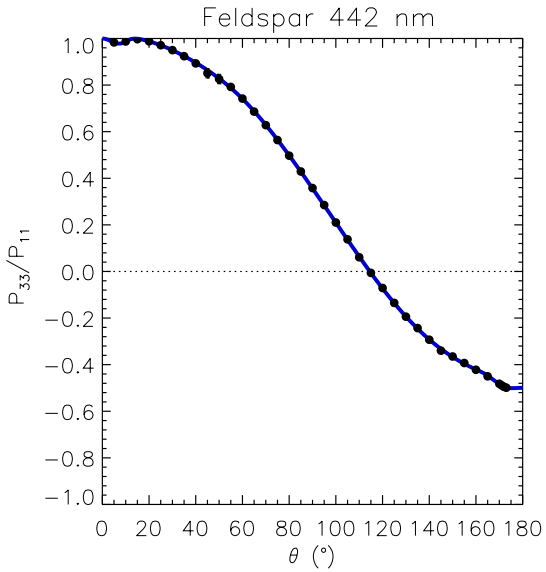
- Feldspar particle scattering matrix modeled using interacting phenomenological fundamental scatterers
- Three phenomenological components expressed using splines:
  - Forward scatterer
  - Positively linearly polarizing scatterer
  - Negatively linearly polarizing scatterer
- Conjugate gradient optimization with splines (future)
- Ultimate goal: spectropolarimetric modeling

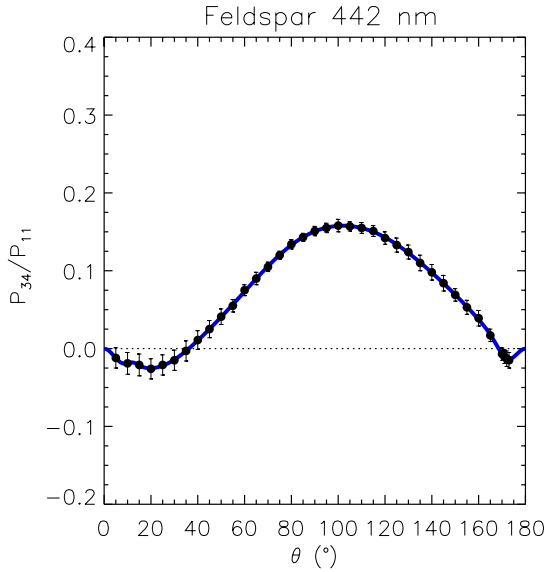
Feldspar at 442 nm

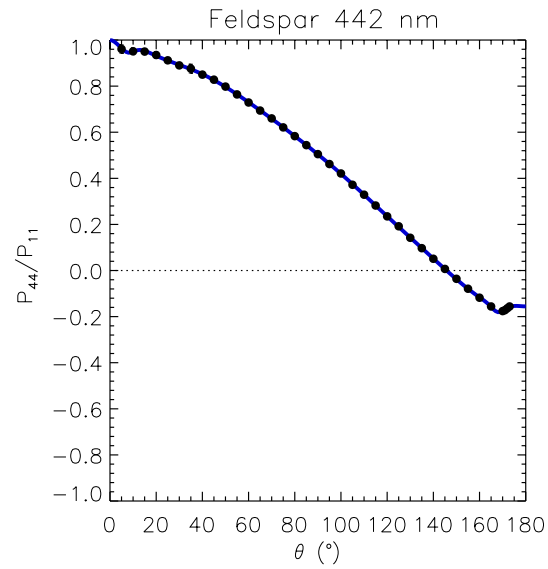




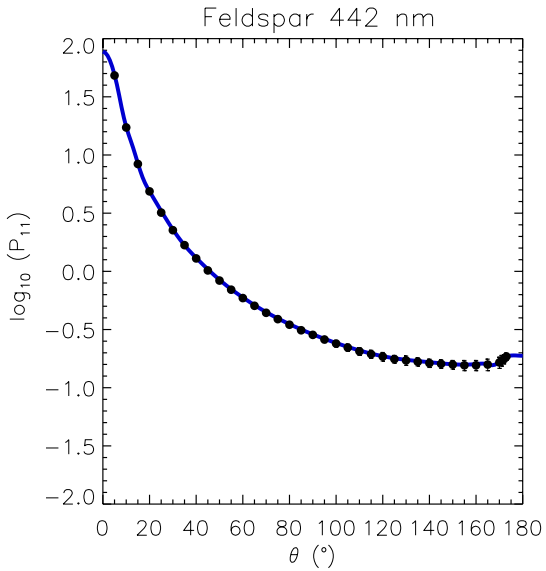


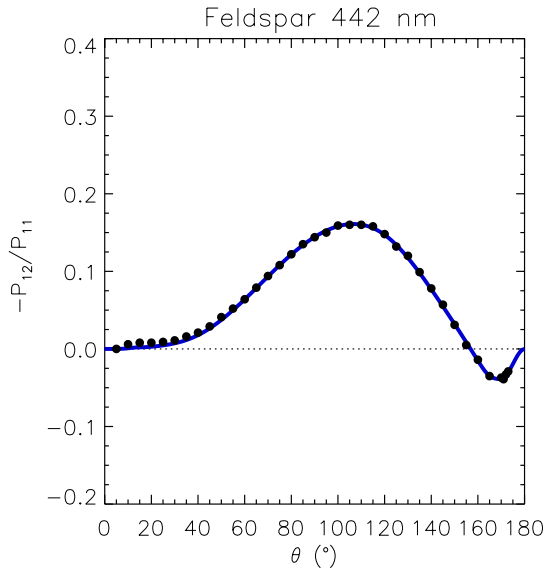


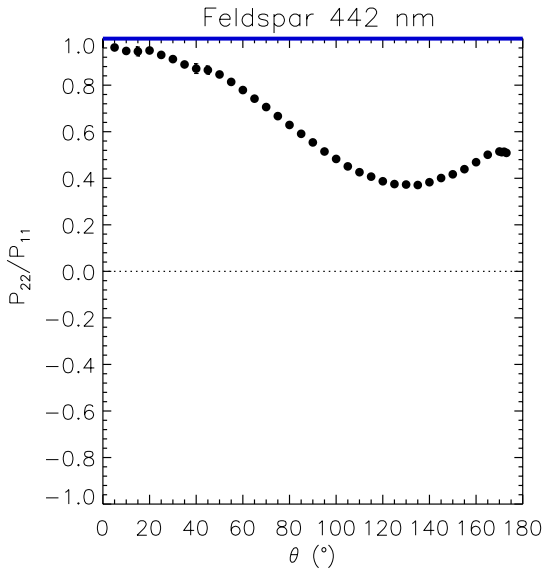


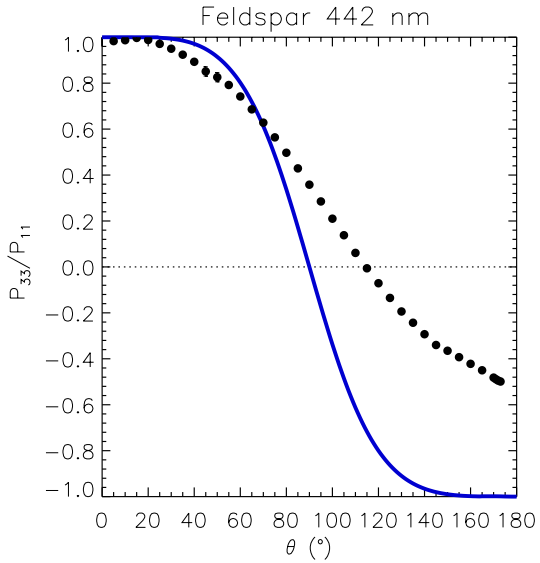


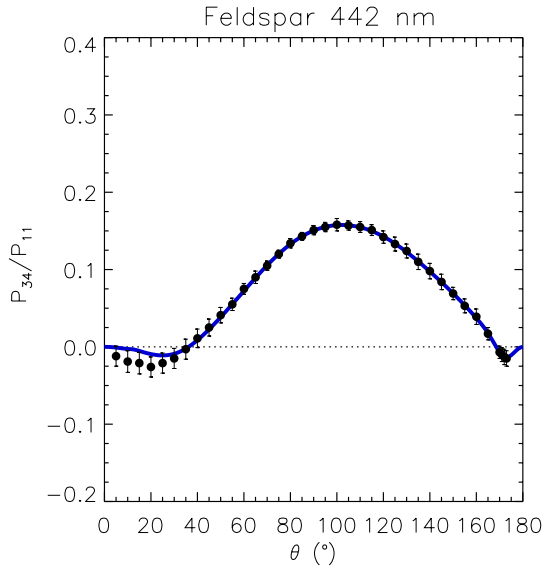
Feldspar at 442 nm

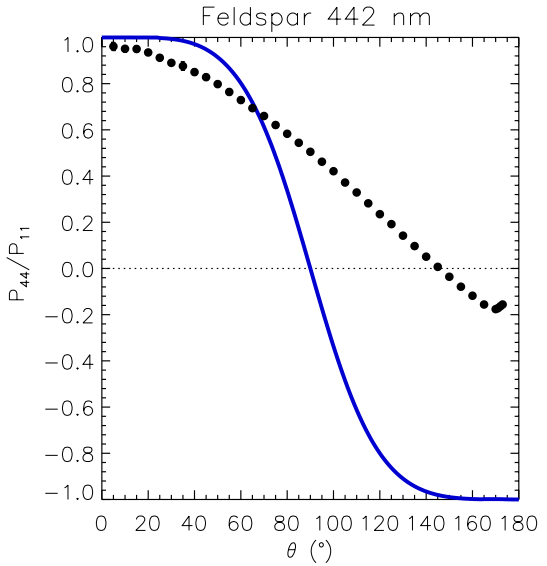




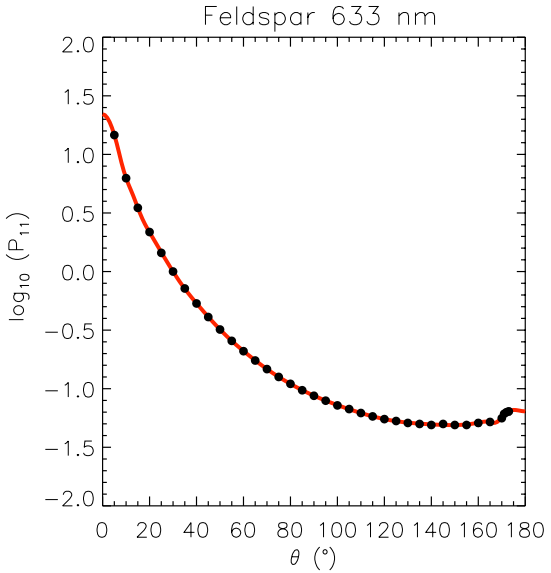


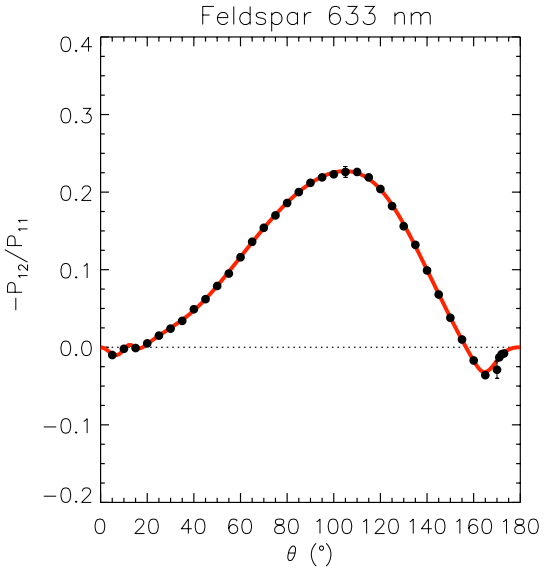


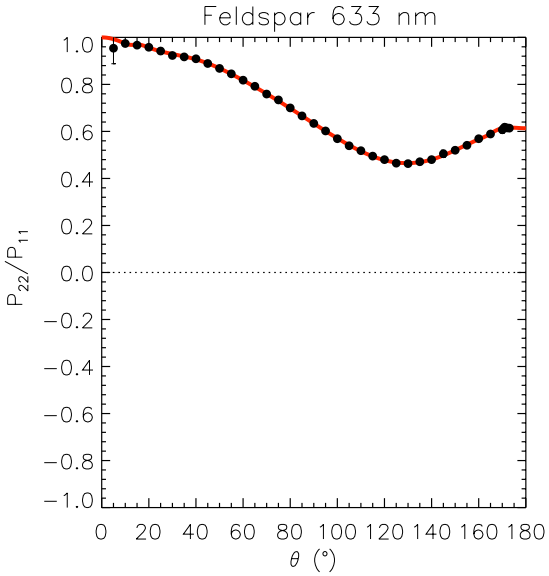


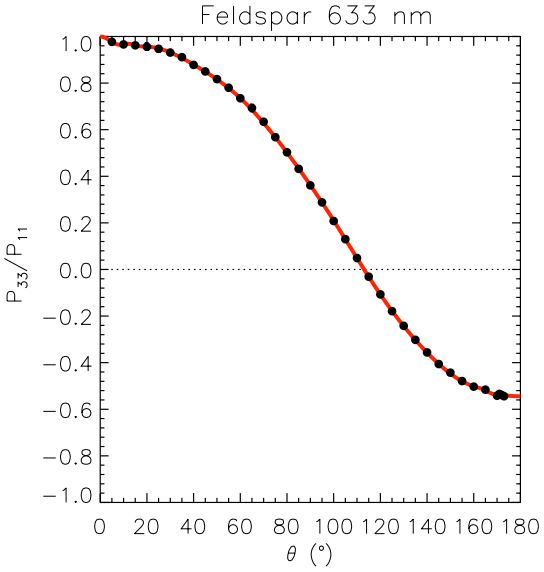


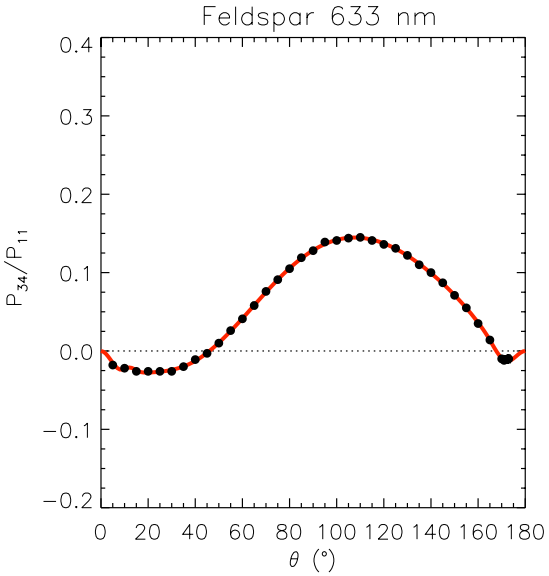
Feldspar at 633 nm

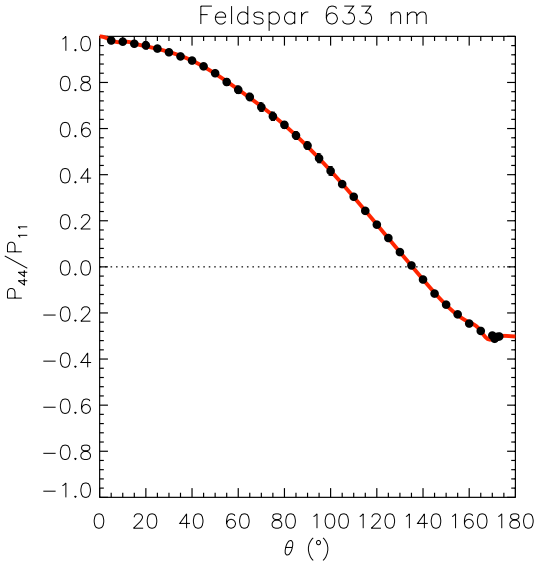




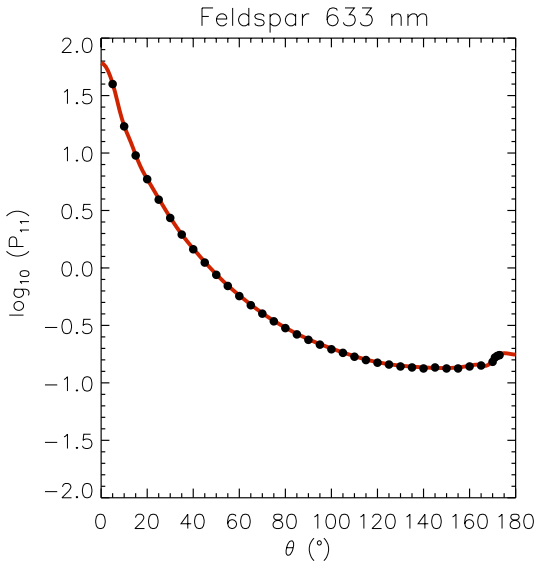


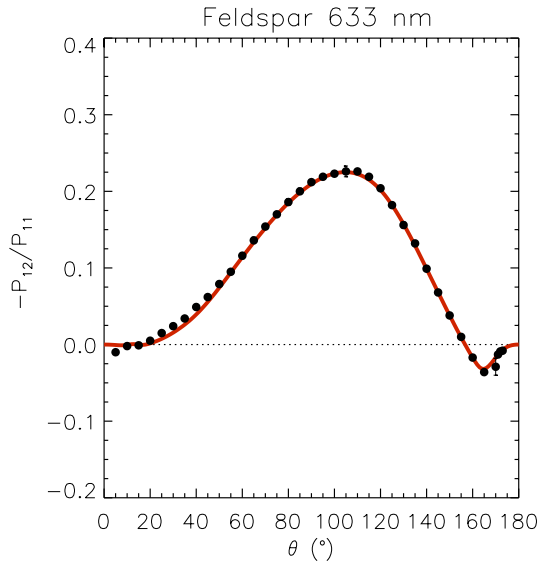


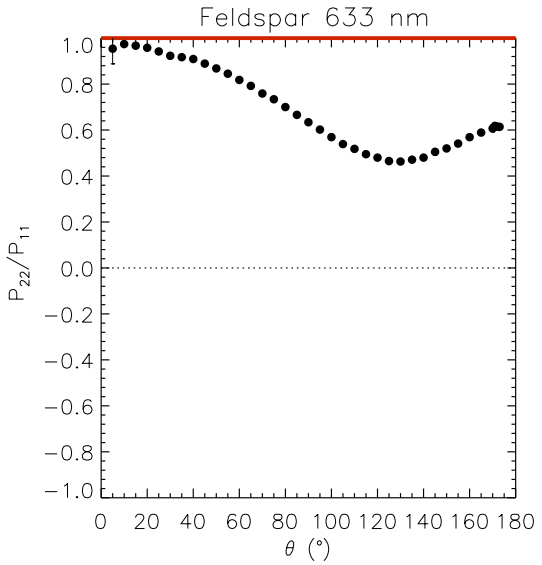


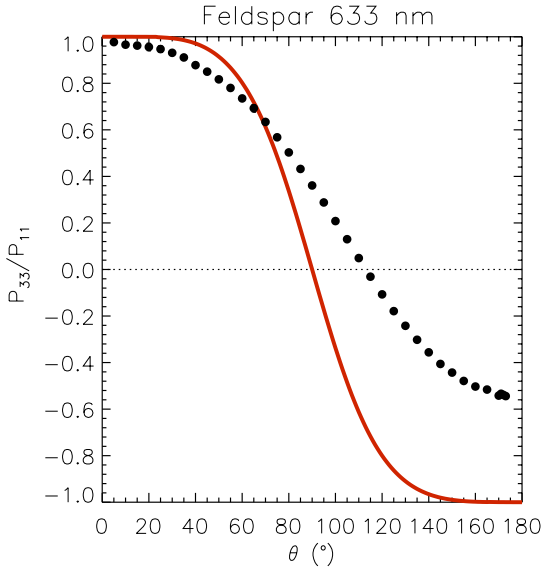


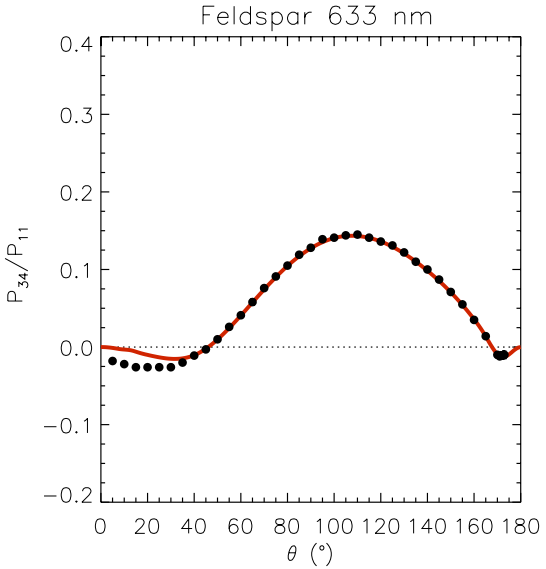
Feldspar at 633 nm

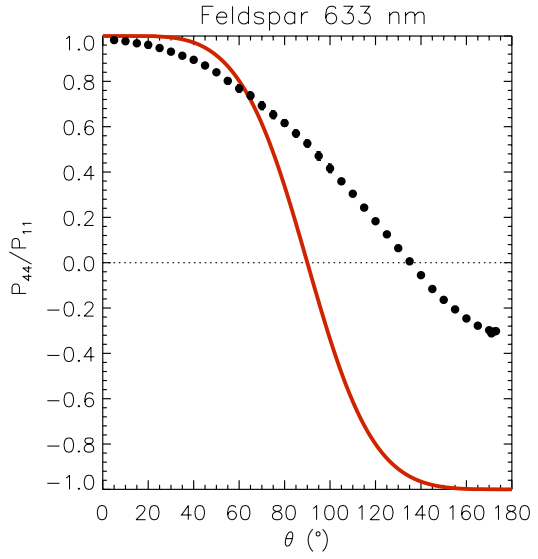




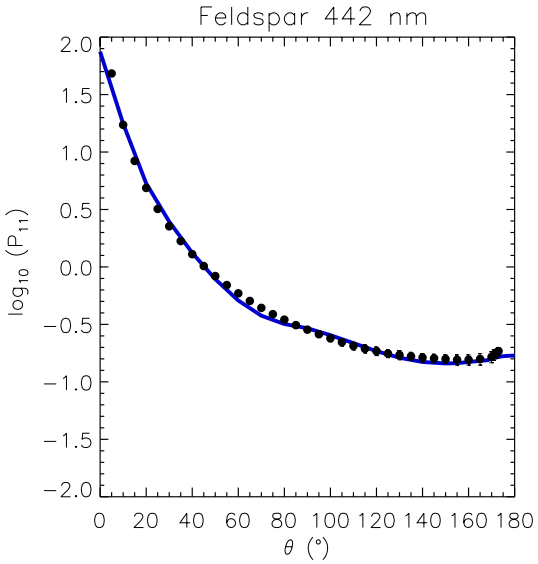


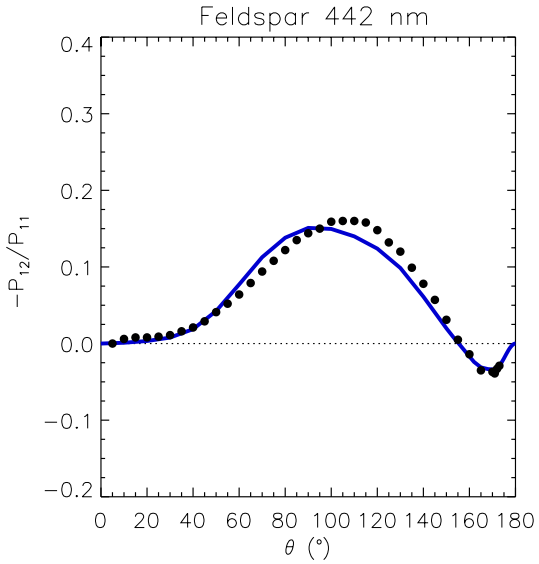


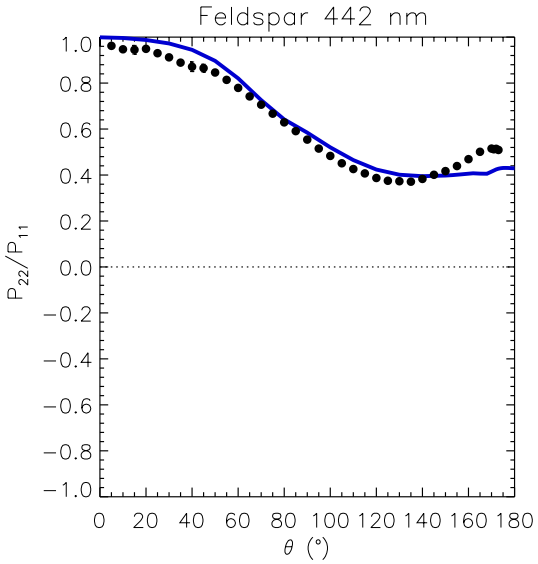


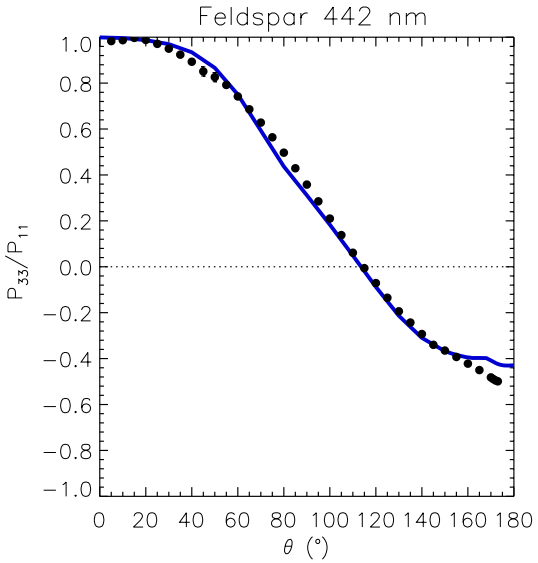


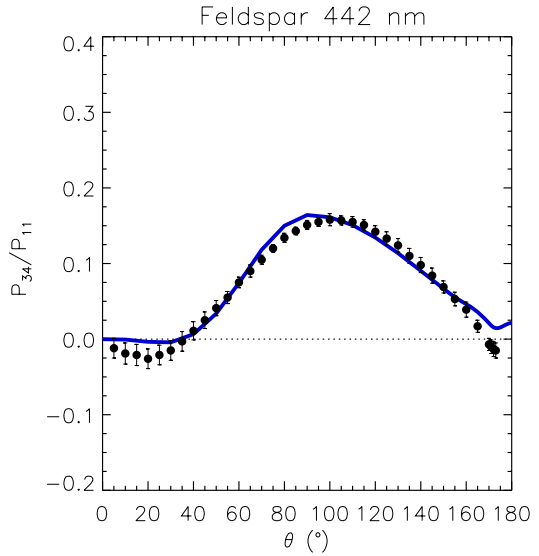
Feldspar at 442 nm

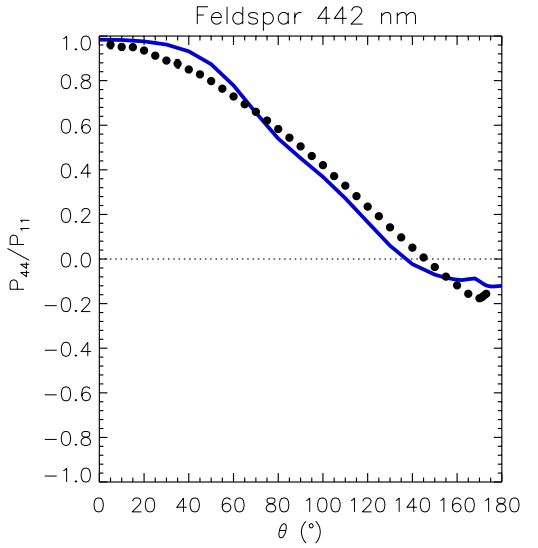




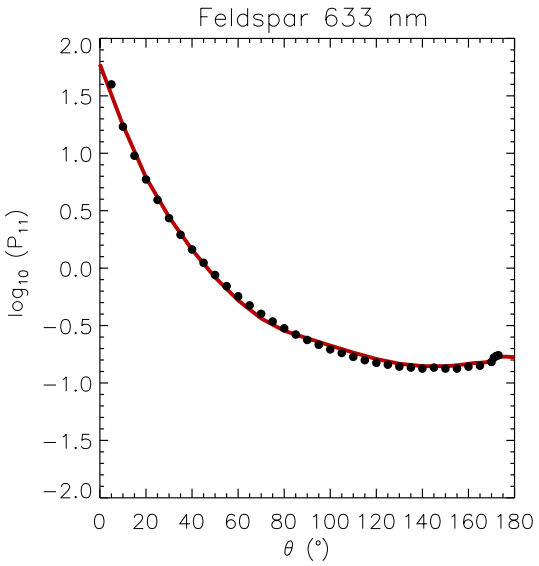


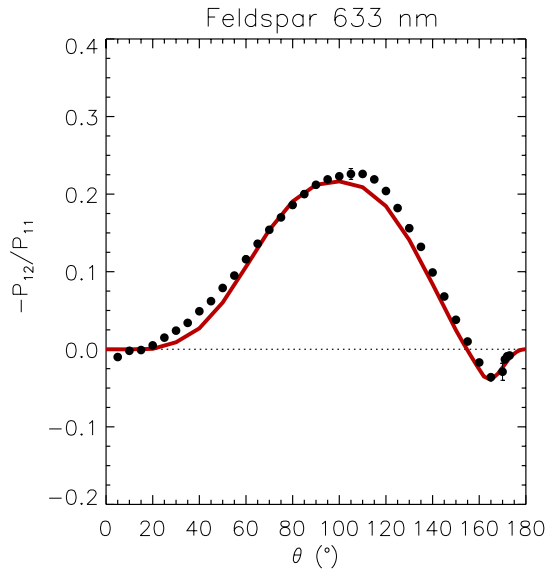


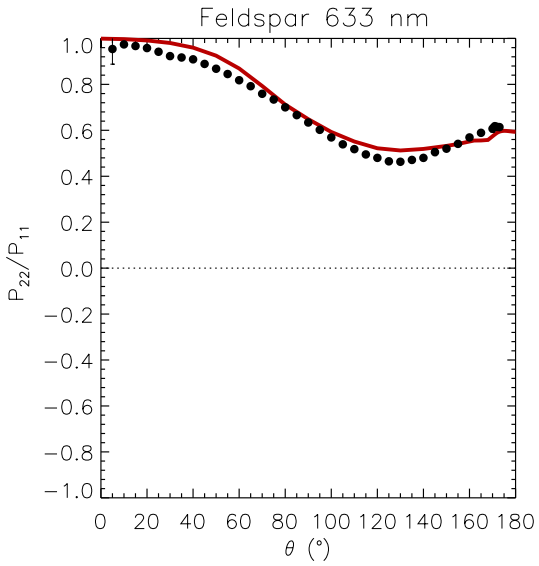


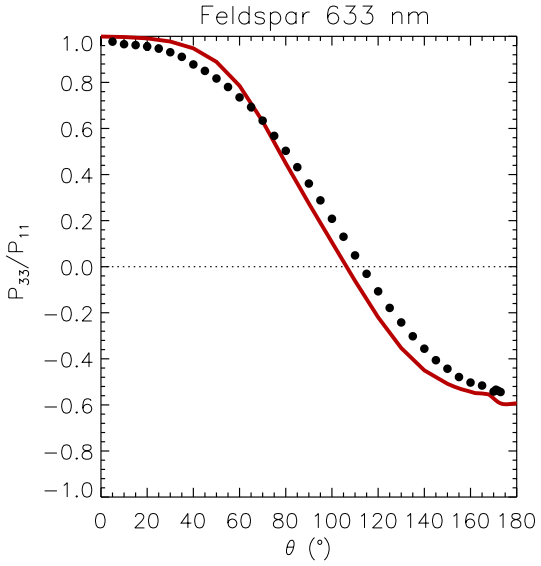


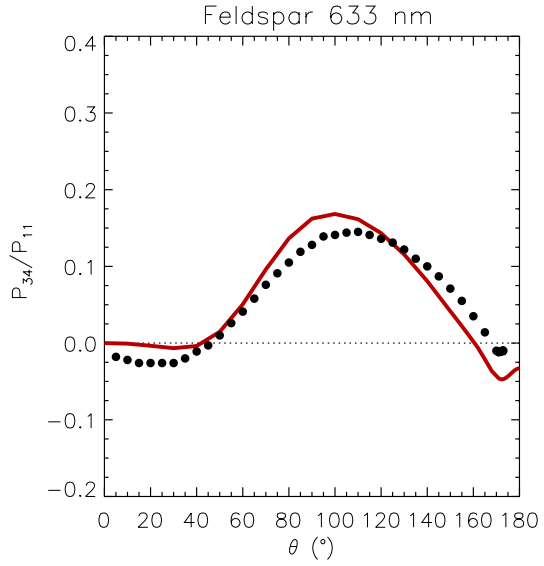
Feldspar at 633 nm

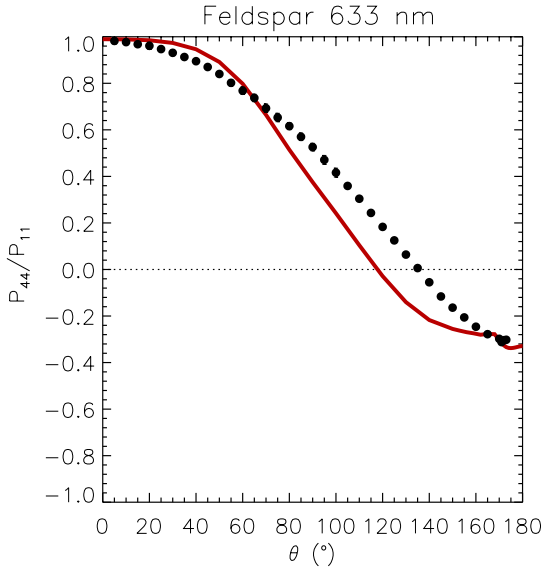




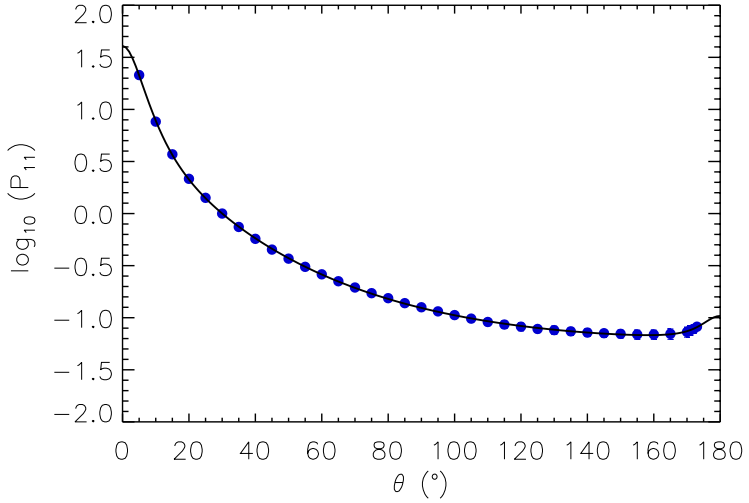


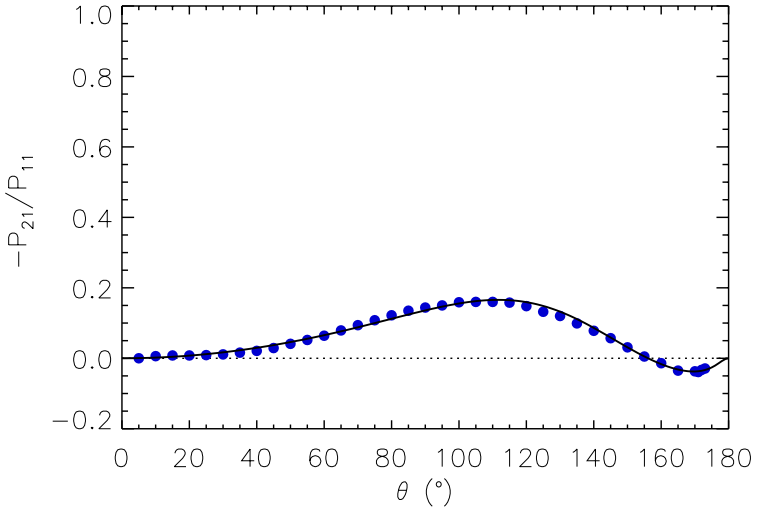




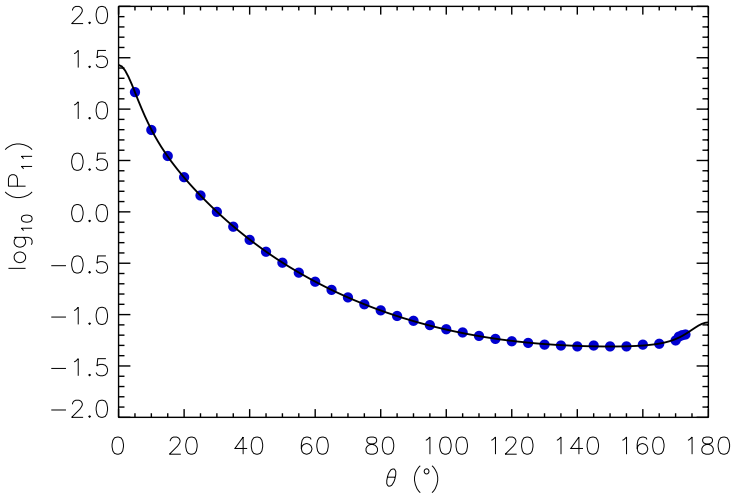


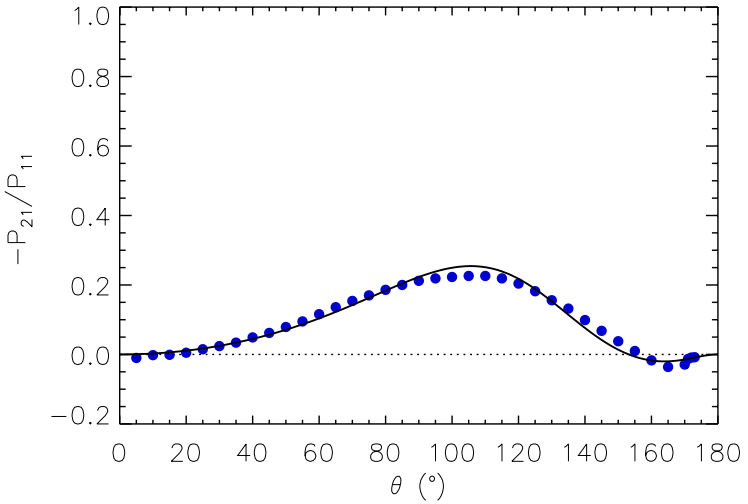
Application to asteroids

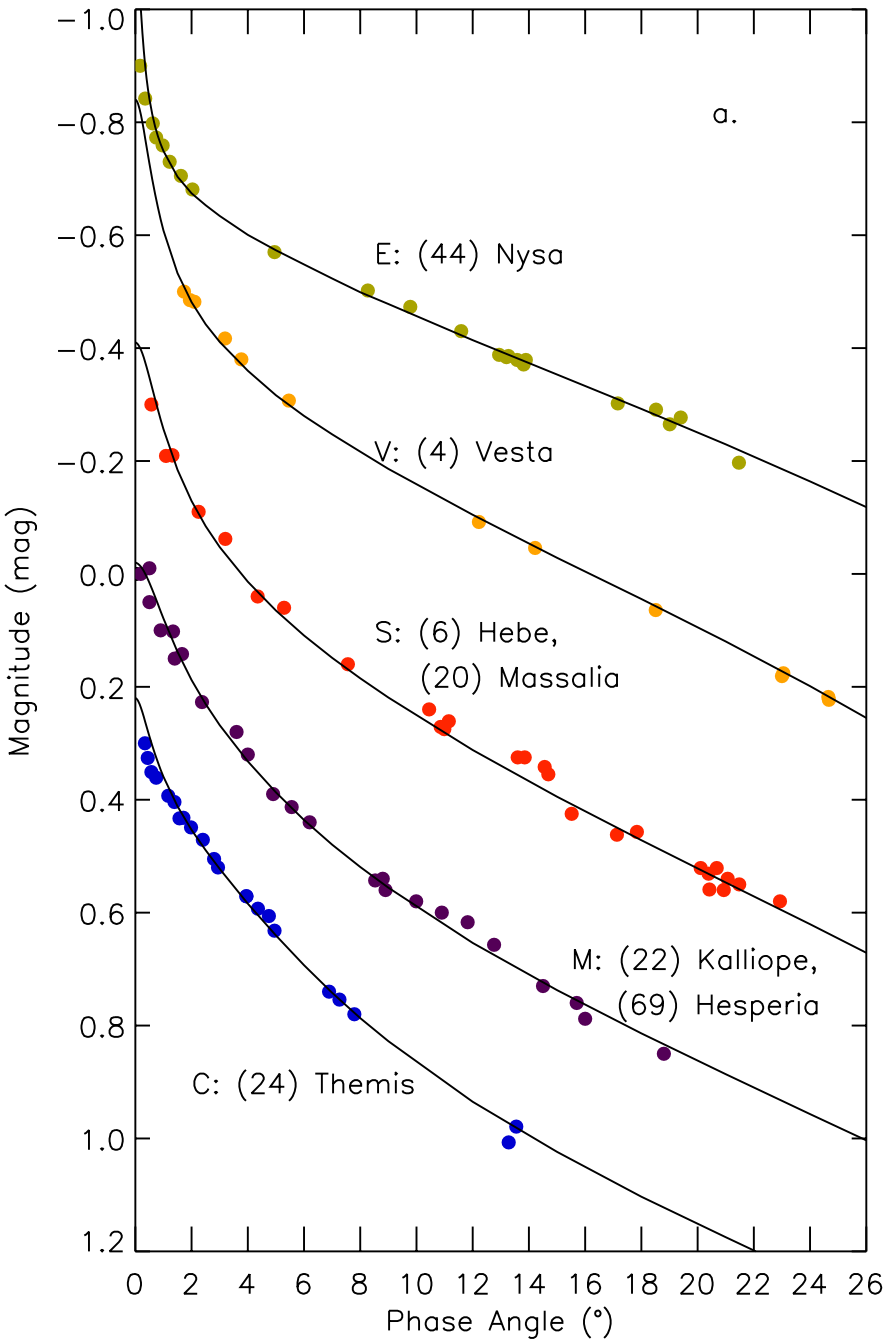




Laboratory Measurements: Volten et al. 2001, Munoz et al. 2012



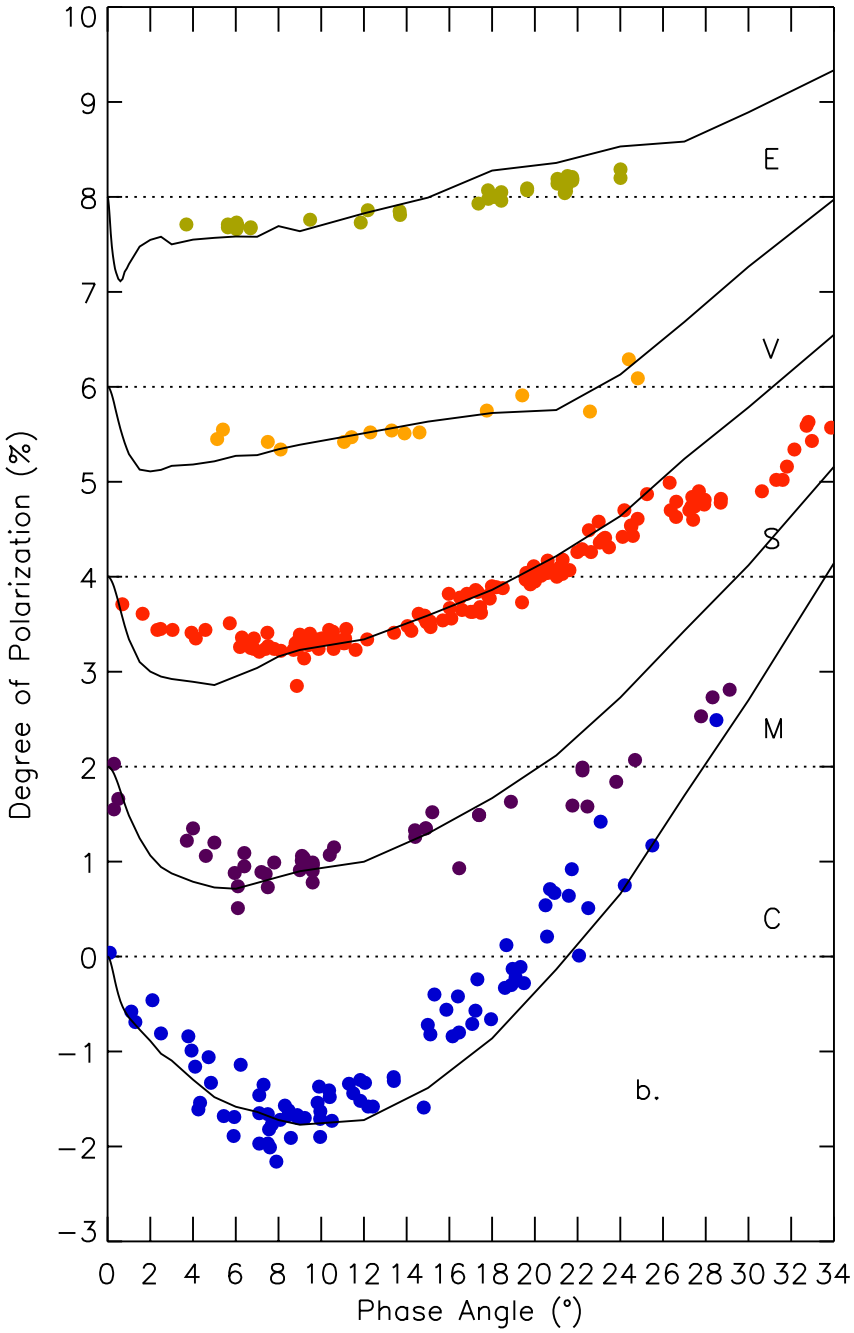




Theoretical modeling:
Muinonen et al.,
in preparation

Spherical volume of scatterers, geometric albedo matched with the observed one

Shadowing assumed linear in brightness



Theoretical modeling:
Muinonen et al.,
in preparation

No shadowing effects

UH-Physics Scattering Laboratory

- Scattering measurements for levitating particles with sizes 10^1-10^4 microns
- Ultrasonic levitation and control of sample orientation
- Verification of numerical multiple scattering methods
- Alignment of optics and calibration measurements ongoing
- National Instruments Young Scientist Prize in Northern Europe for Mr. Göran Maconi

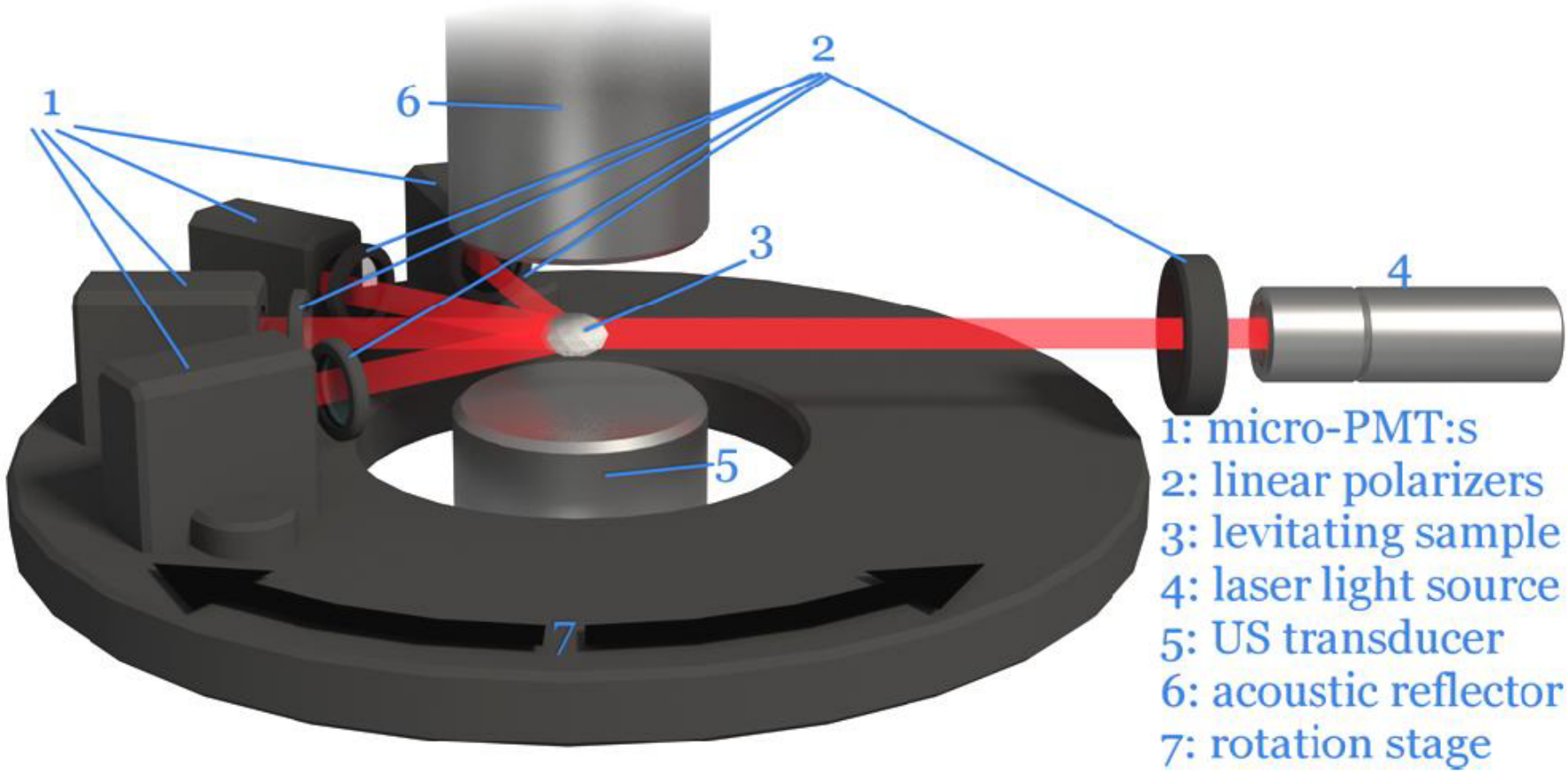


Fig. 1: Simplified schematic of the final setup

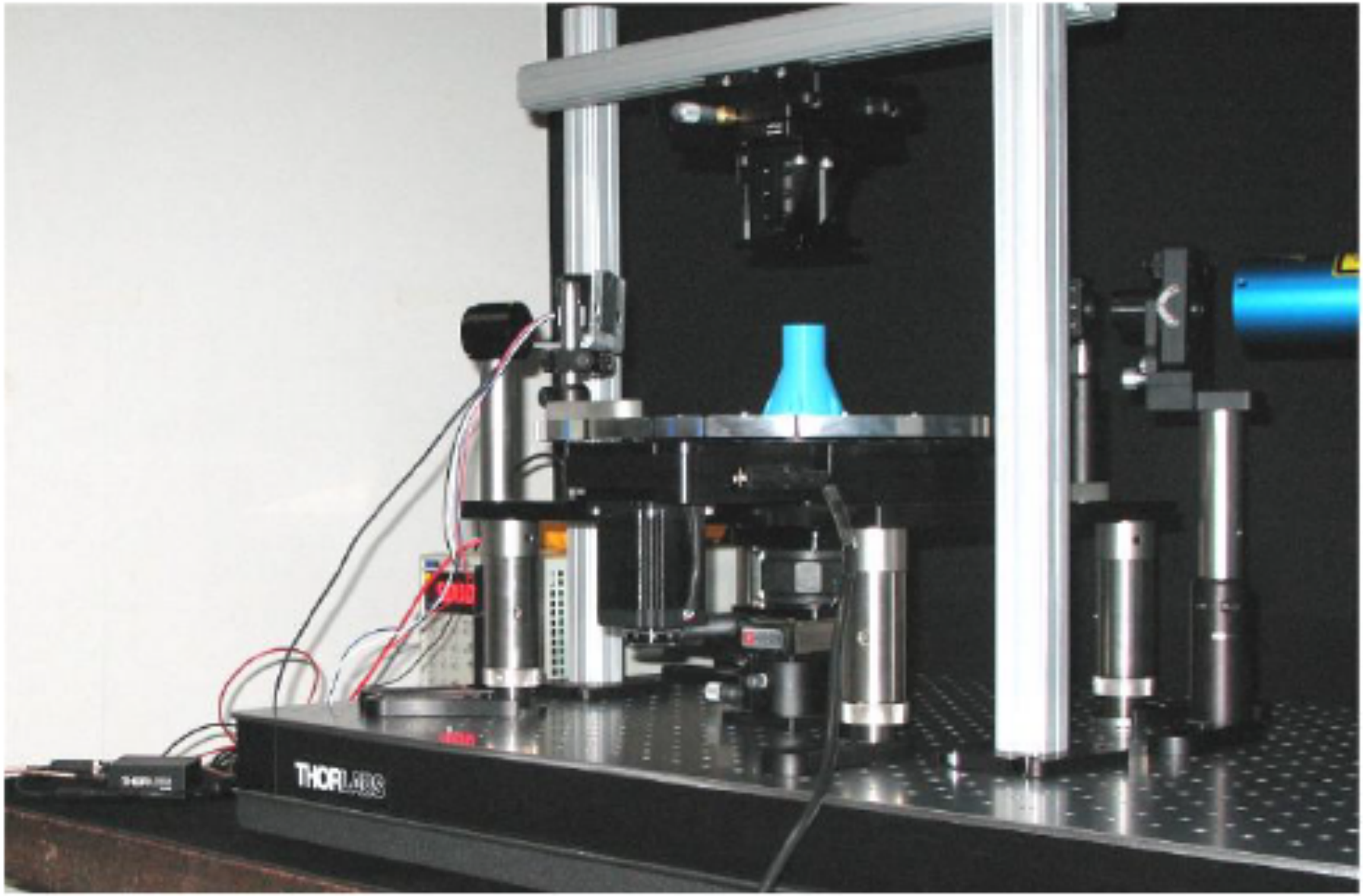


Fig. 2: Photograph of setup with prototype acoustic levitator installed

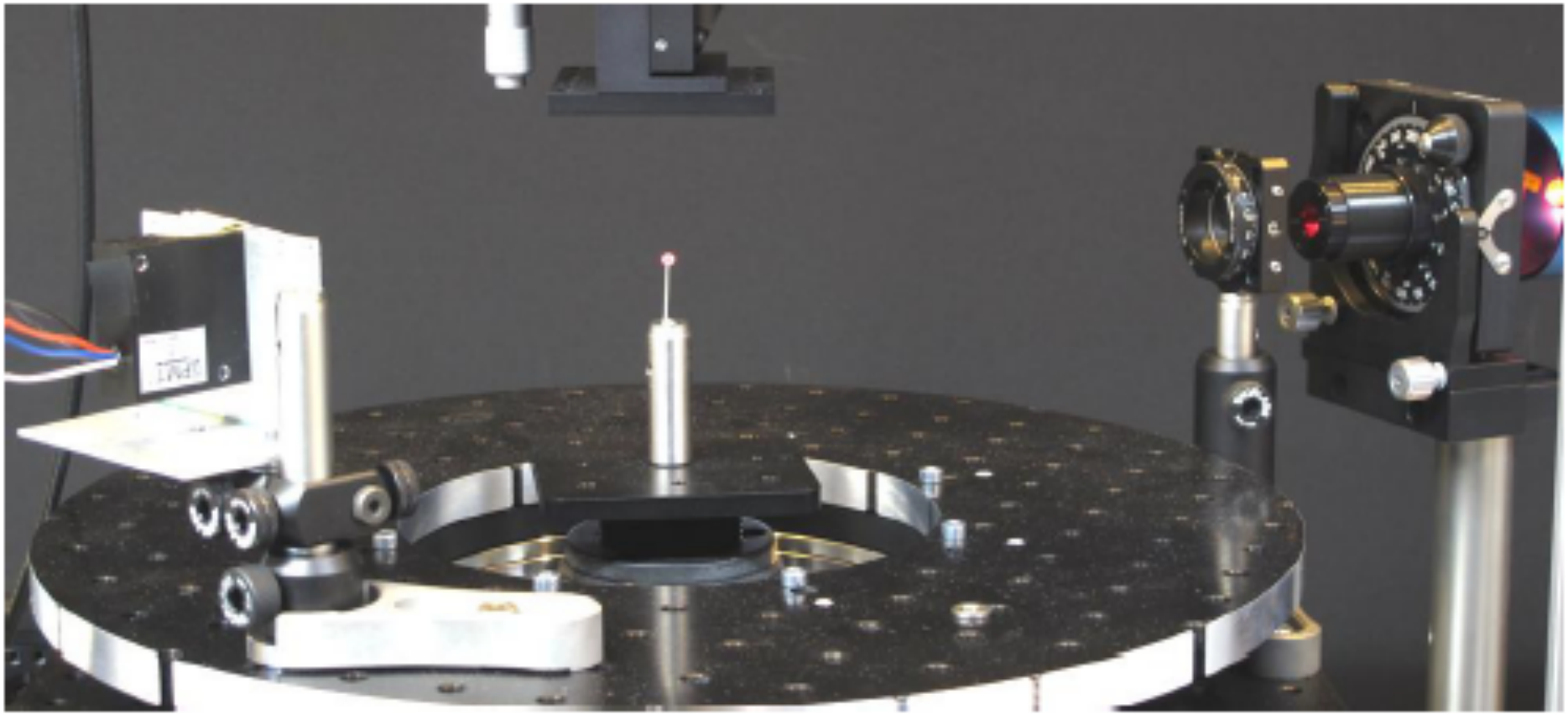


Fig. 3: Test measurement with a 3 mm glass sphere

Optical Constants How-To

- Measure the scattering matrix for a single particle in controlled orientation
- Measure the size, shape, and structure of the particle
- Using numerical methods, find the real part of the refractive index and constrain the imaginary part of the refractive index
- Increasing the sample size, find the imaginary part of the refractive index
- When necessary, move to consider semi-infinite layers of particles

Conclusions

- RT-CB with phenomenological scatterers explains the photometric and polarimetric observations of asteroids
- Depolarizing scatterers successfully incorporated into RT-CB
- Regolith geometry to be accounted for, including shadowing effects

- Interactions among scatterers to be accounted for exactly (SAEMPL R^2T^2)
- Multiple-scattering modeling for large atmospheric particles
- Scattering laboratory for levitating particles (10^0-10^4 microns) in fixed orientation (first measurements in 2016)