Multiple Scattering of Light in Planetary Regoliths

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Contents

Introduction

- Direct problem of light scattering by regolith particles with varying size, shape (structure), and refractive index (optical properties)
- Inverse problem of retrieving physical properties of particles based on observations
- Plane of scattering, scattering angle, solar phase angle
- Physical properties of transneptunian objects

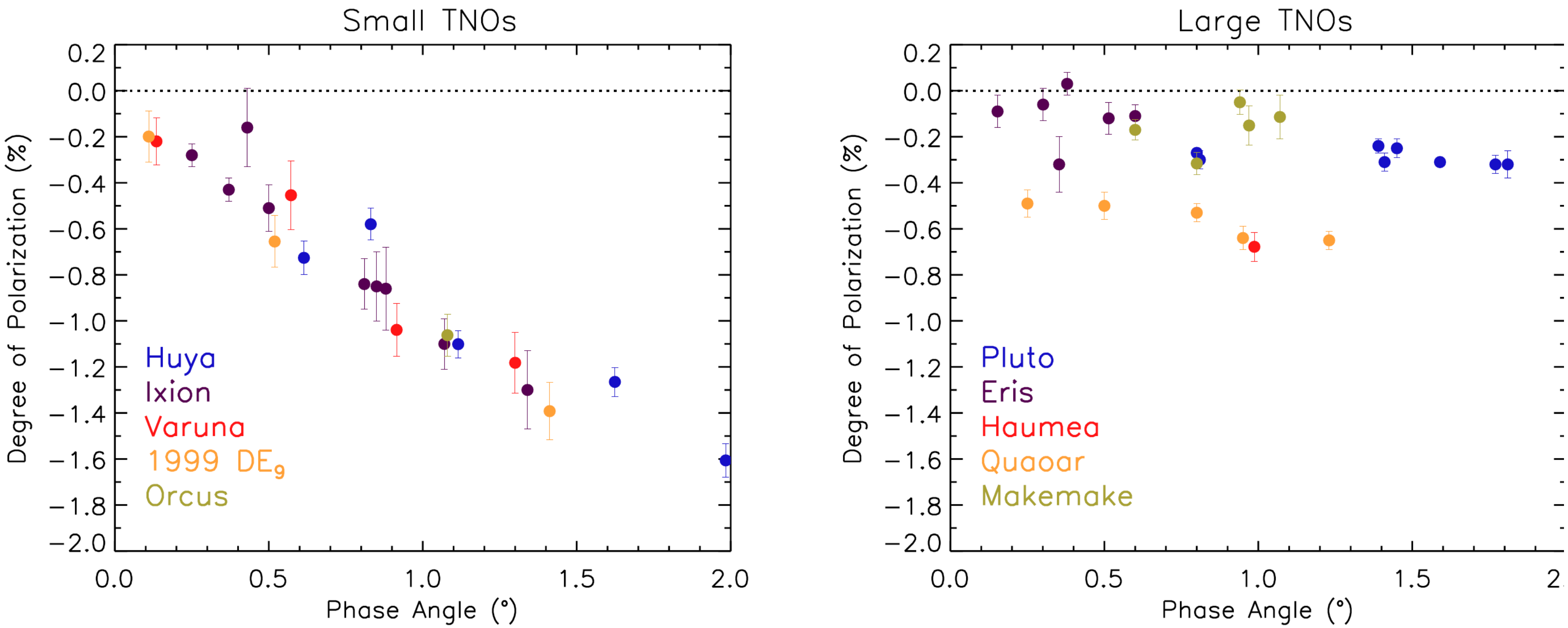
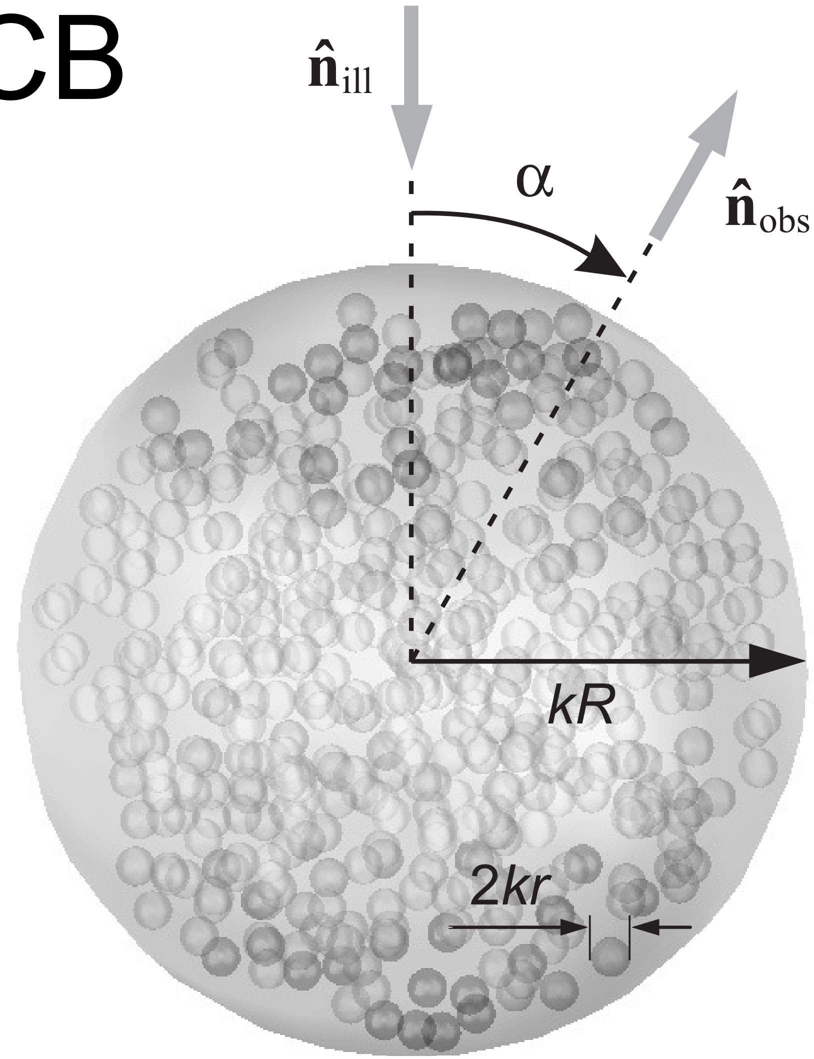


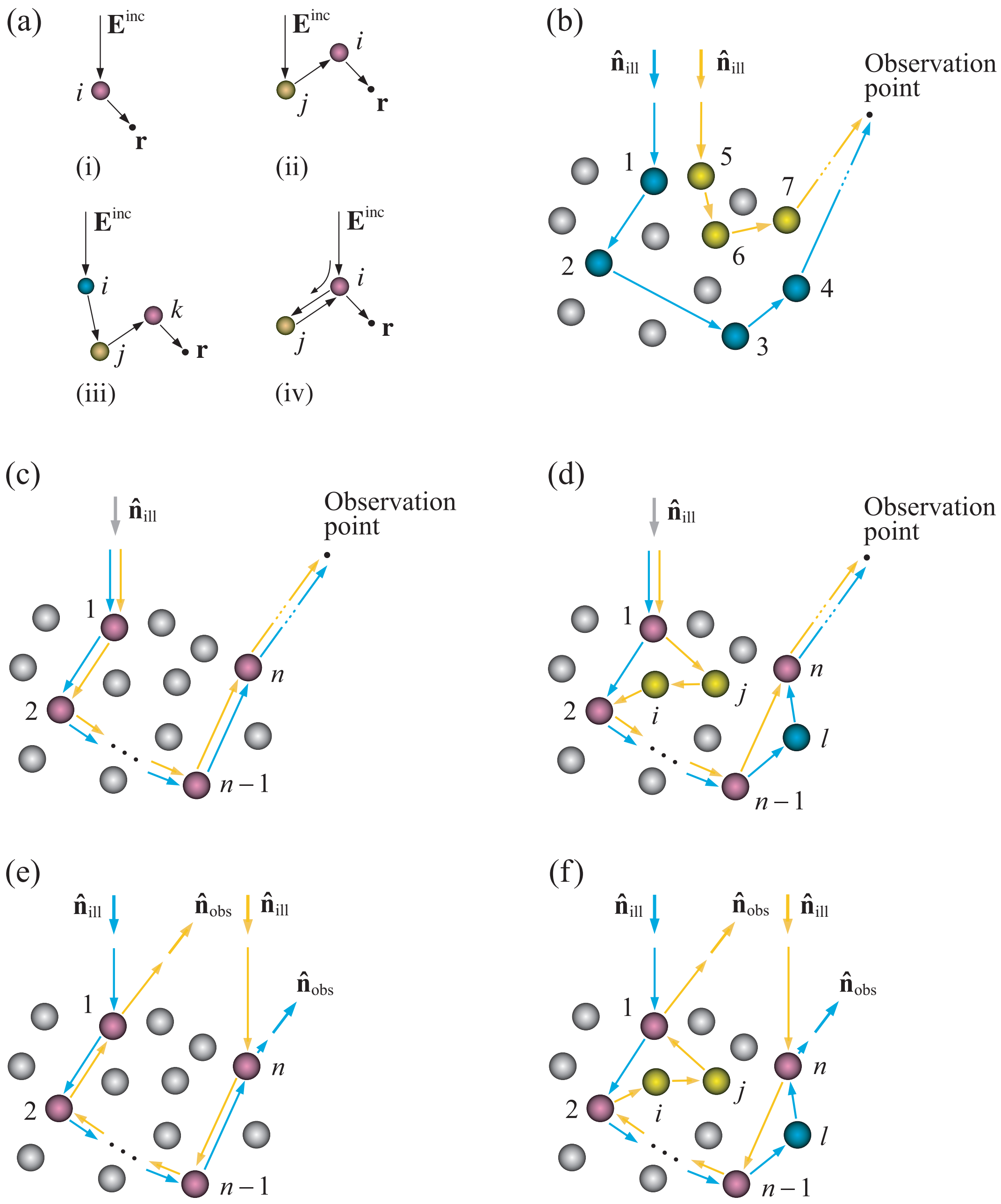
Figure 1: Polarimetry for small TNOs (left—Boehnhardt et al. 2004; Bagnulo et al. 2008; Belskaya et al. 2012) and large TNOs (right—Kelsey and Fix 1973; Breger and Cochran 1982; Avramcuk et al. 1992; Bagnulo et al. 2006, 2008; Belskaya et al. 2008, 2012). Observations mainly obtained at the ESO Very Large Telescope.

RT-CB

- Polarization and intensity surges due to interference in multiple scattering for a spherical medium
- Monte Carlo computation
- Full angular profiles for the complete scattering matrix



Muinonen et al., ApJ, 2012
Penttilä et al., this meeting



(a)
$\mathbf{E}^{\mathrm{inc}}$
i
$\mathbf{r}$
(i)
j
(ii)
k
(iii)
(iv)
(b)
$\hat{\mathbf{n}}_{\mathrm{ill}}$
Observation point
1
2
3
4
5
6
7
(c)
n
$n-1$
(d)
l
(e)
$\hat{\mathbf{n}}_{\mathrm{obs}}$
(f)

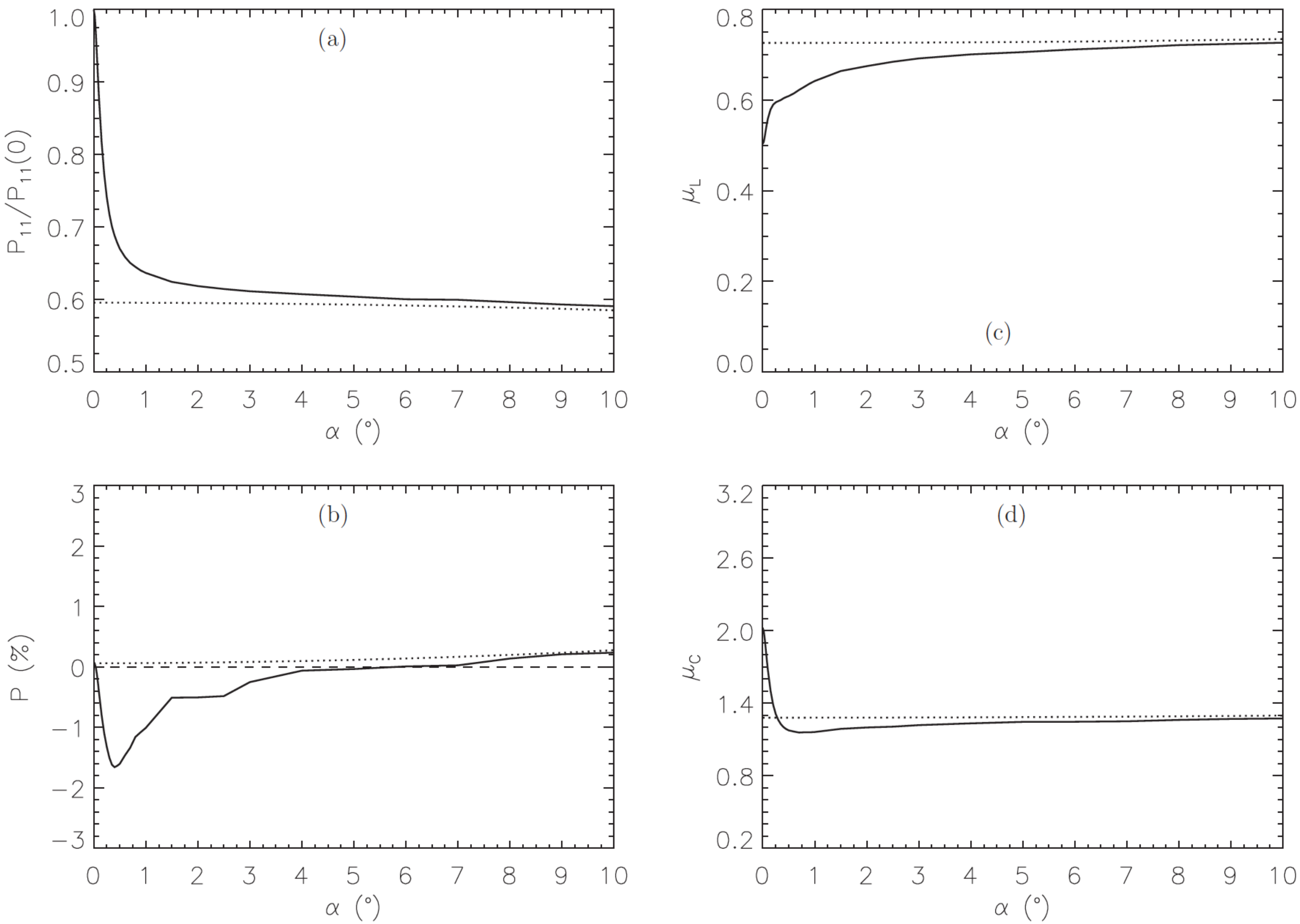


Figure 6. RT–CB (solid lines) and RT-only computations (dotted lines) for a macroscopic medium with $kR = 10^7$ composed of a power-law size distribution (index $\nu = 3$) of spherical monomers with sizes within $kr \in [2.0, 3.0]$. The refractive index of the monomers is $m = 1.31 + i10^{-3}$ and the volume density is $v = 3.125\%$. (a) $P_{11}/P_{11}(0)$, (b) $P = -P_{21}/P_{11}$, (c) $\mu_L = (P_{11} - P_{22})/(P_{11} + 2P_{21} + P_{22})$, and (d) $\mu_C = (P_{11} + P_{44})/(P_{11} - P_{44})$.

RT-CB scattering model

- Radiative transfer, coherent backscattering
- Particulate medium of spherical volume elements and fBm roughness
- Phenomenological fundamental scatterers
- References:
  - Muinonen & Videen, JQSRT; Wilkman et al., ELS XIV; Penttilä et al., ELS XIV
  - Muinonen et al., A & A 531, A150, 2011
  - Parviainen & Muinonen, JQSRT 2007 & 2009
  - Muinonen, Waves in Random Media 14, 365, 2004

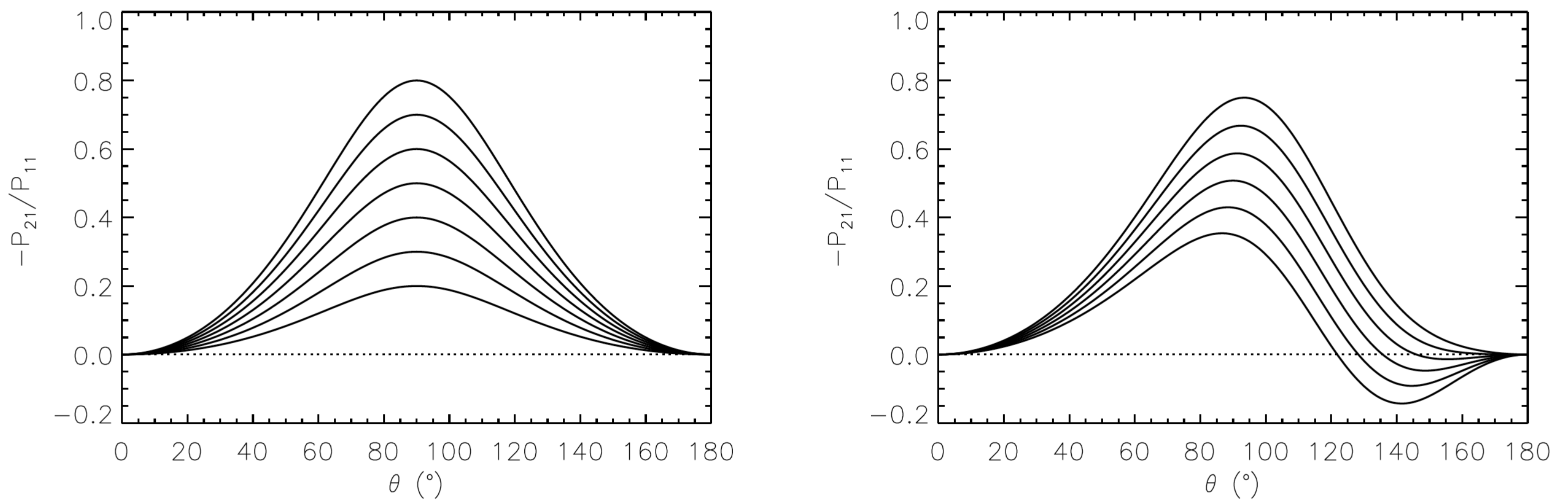
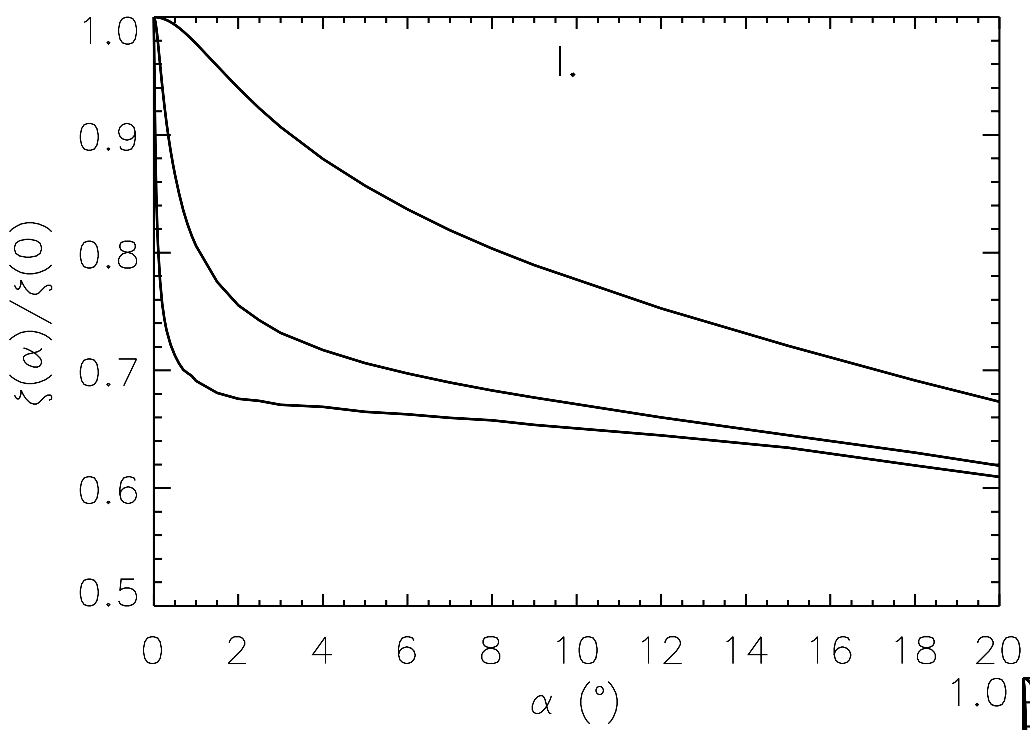
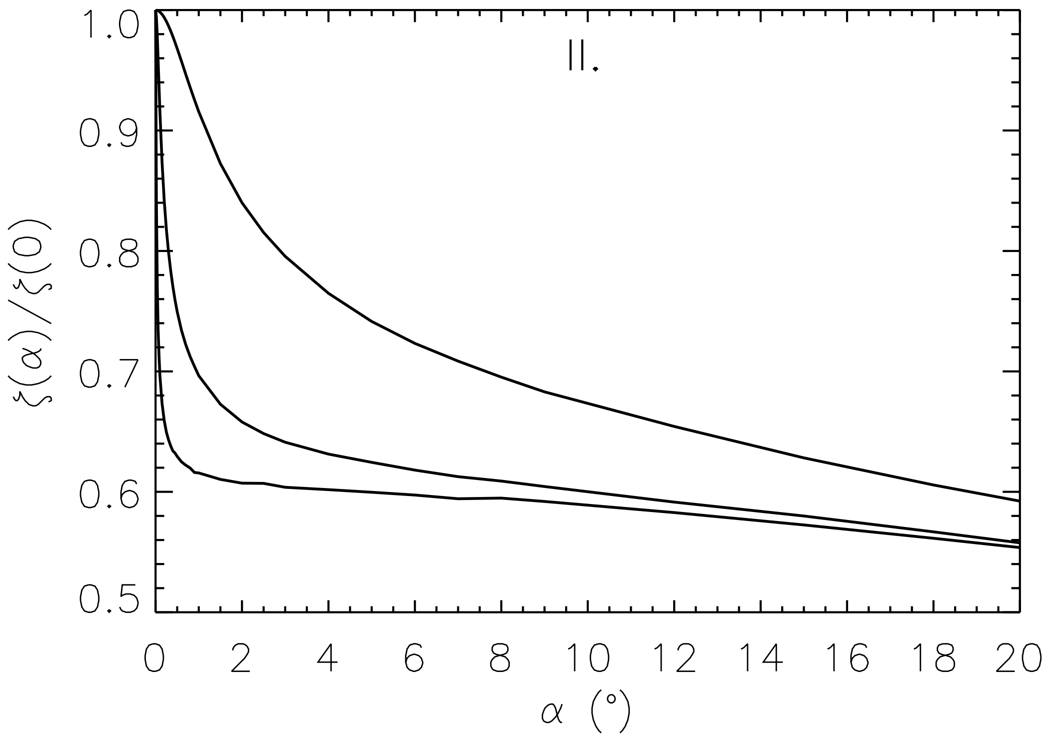


Figure 2: For the single-scatterer polarizations $-P_{12}/P_{11}$ on the left, we have $e_+ = e_- = 0$ and $P_{\mathrm{max}} = 0.2, 0.3, \ldots, 0.8$. For $-P_{12}/P_{11}$ on the right, the eccentricities are $e_+ = -0.1$ and $e_- = -0.6$ and the weights are $w_+ = 1 - w_- = 0.60$, $0.65, 0.70, \ldots, 0.85$. With increasing w_+ , the polarization $-P_{12}/P_{11}$ increases.



$\tilde{\omega} = 0.6$

$\tilde{\omega} = 0.9$

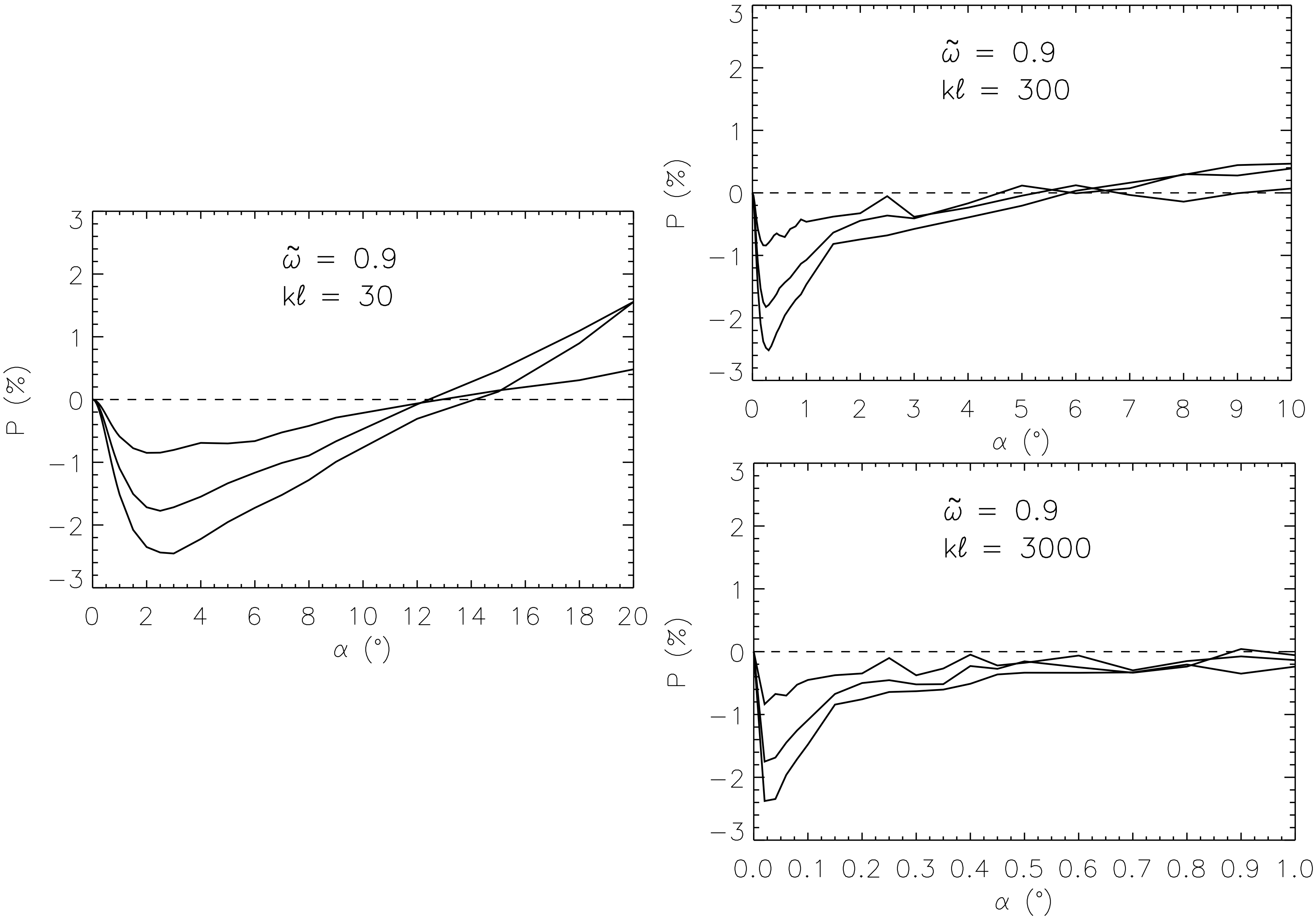


$X = 10^7$

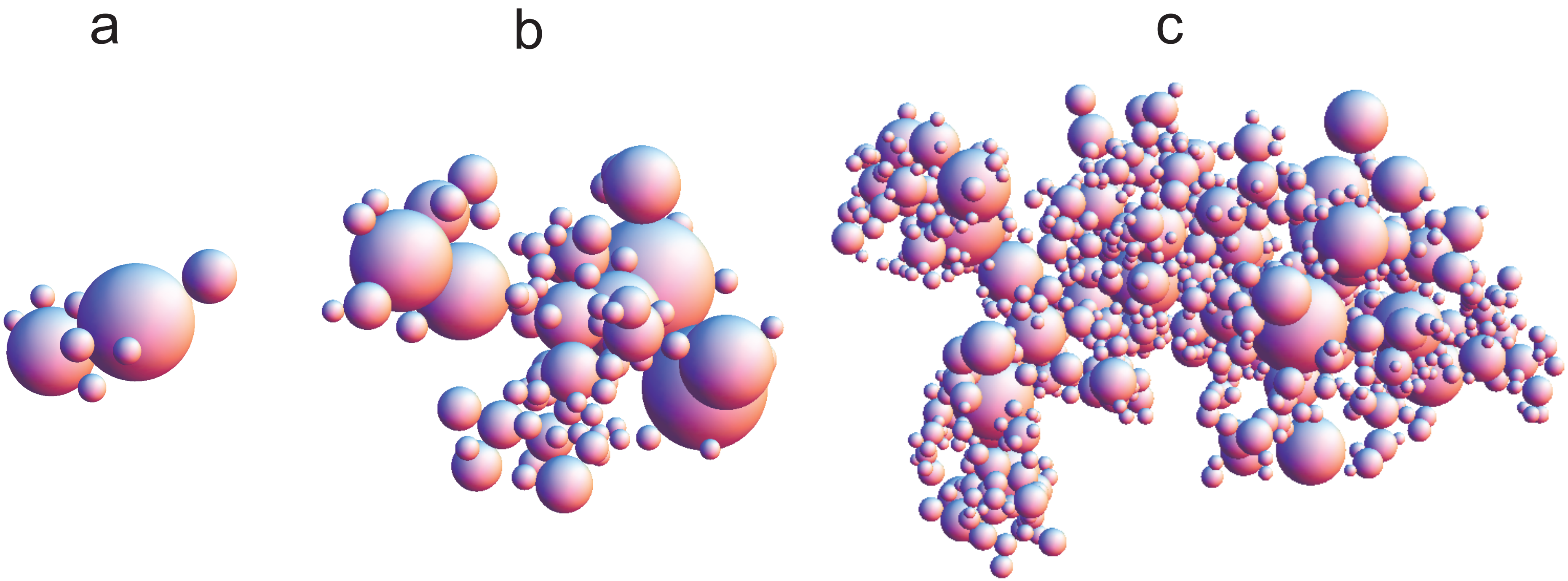
$g = 0.6$

$g_1 = 0.8$

$g_2 = -0.1$



$\tilde{\omega}$ = 0.9
kℓ = 30
P (%)
α (°)
$\tilde{\omega}$ = 0.9
kℓ = 300
P (%)
α (°)
$\tilde{\omega}$ = 0.9
kℓ = 3000
P (%)
α (°)



Muinonen et al., RT-CB for close-packed spherical volumes of scatterers, ELS XIV

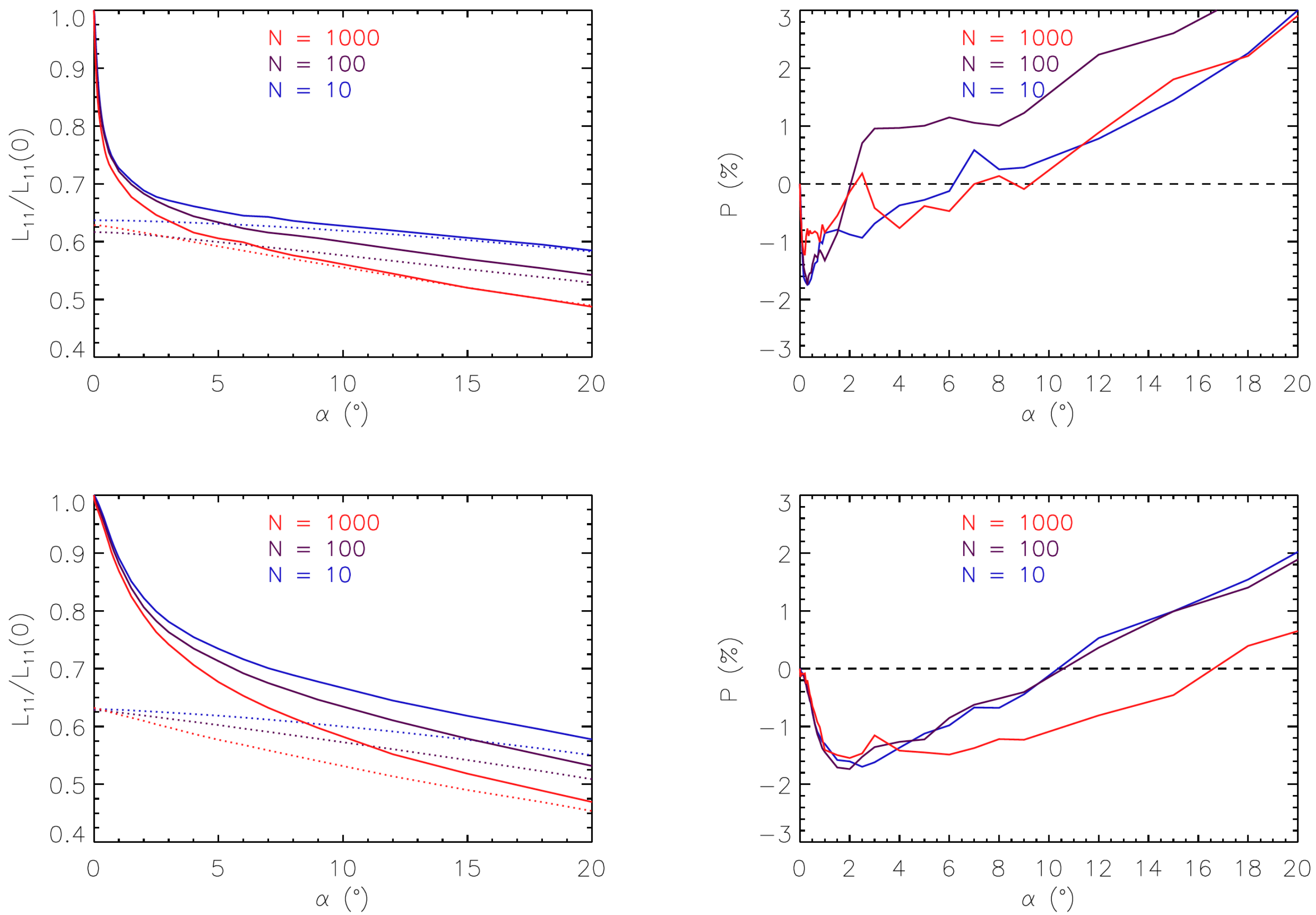


Figure 3: Phase functions (left; dotted lines for RT-only) and degrees of linear polarization (right) for $\tilde{\omega} = 0.9$ in the case of $k\ell = 500$ (top) and $k\ell = 50$ (bottom) for a ballistic aggregate of spherical volumes of scatterers.

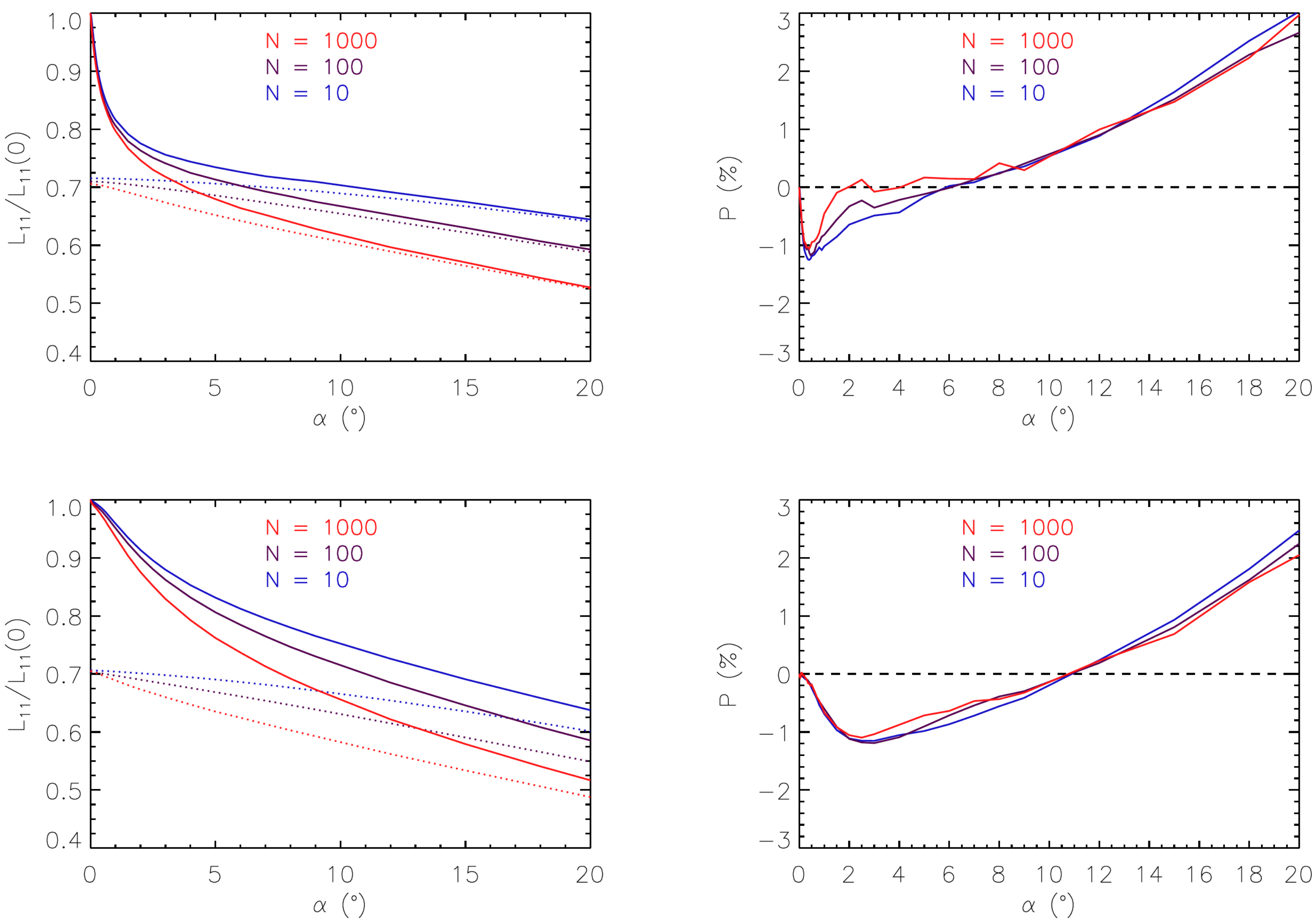
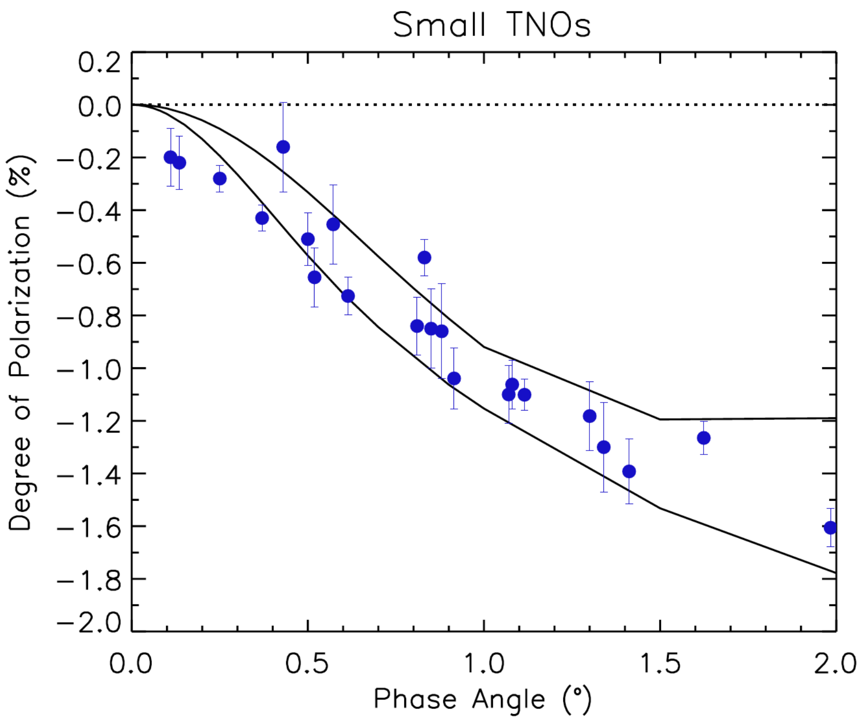
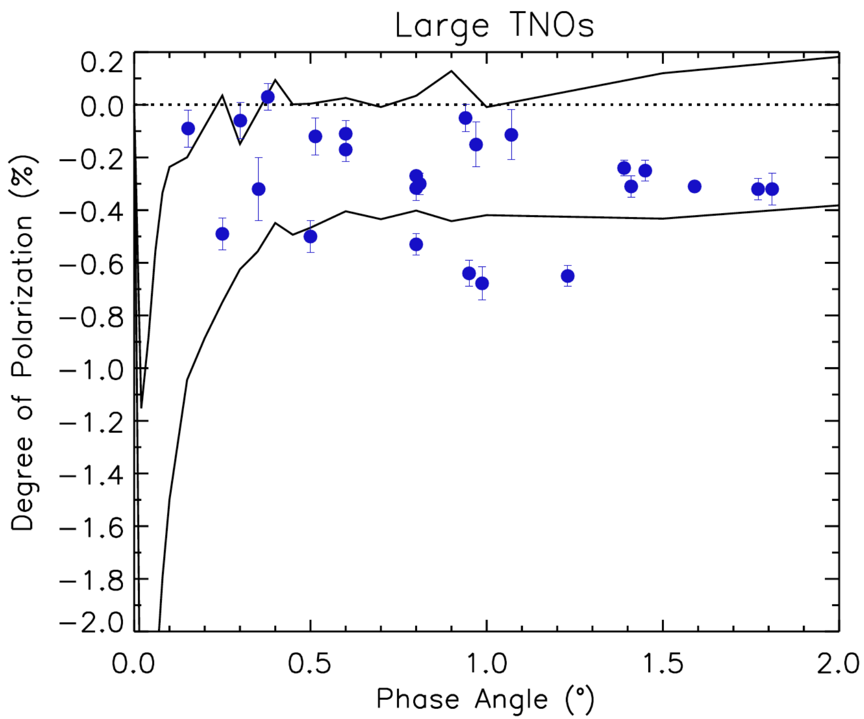


Figure 4: As in Fig. 3 for $\tilde{\omega} = 0.6$.

RT-CB-DDA Inverse Method

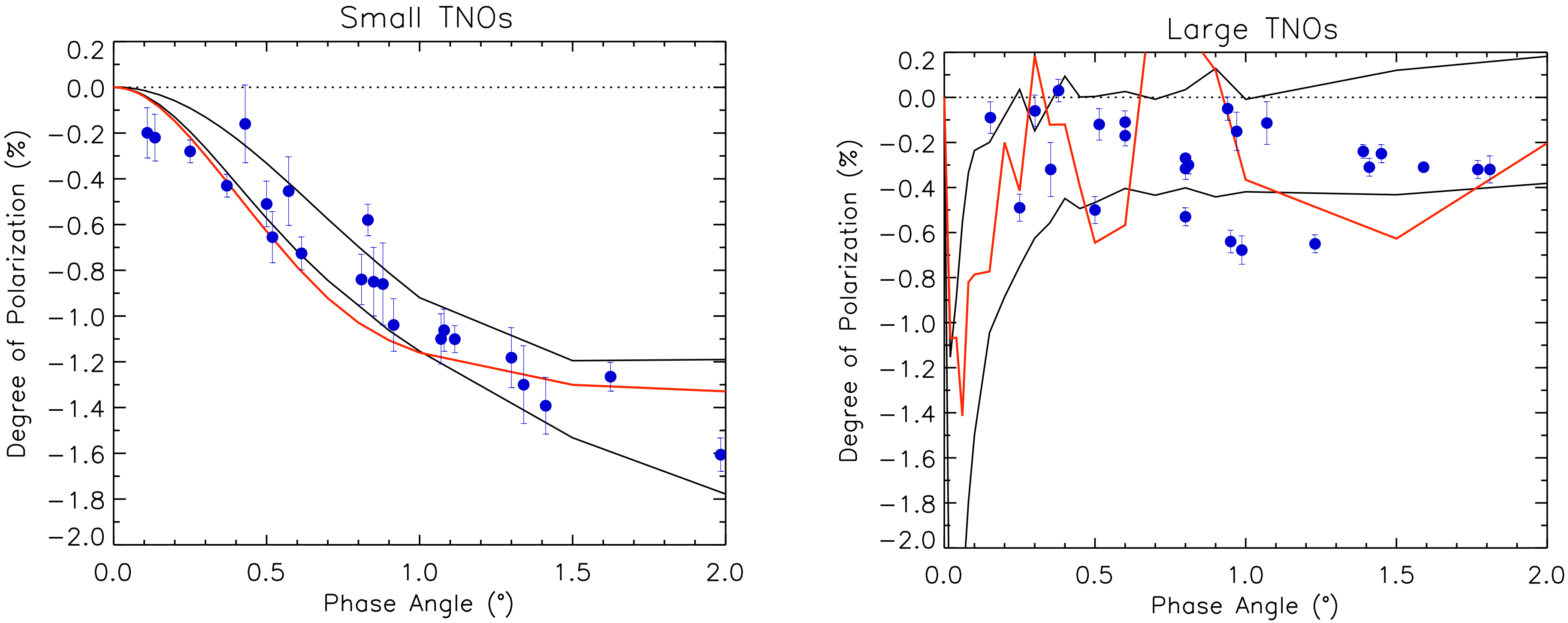
- Step 1: Fit the observations using the phenomenological RT-CB model
- Step 2: Fit the phenomenological scatterer using the DDA model (Zubko et al., ELS XIV and this meeting, ADP = agglomerated debris particle)
- Step 3: Optimize the phenomenological against the DDA model
- Convergence
  - NO: Go to Step 1
  - YES: Done





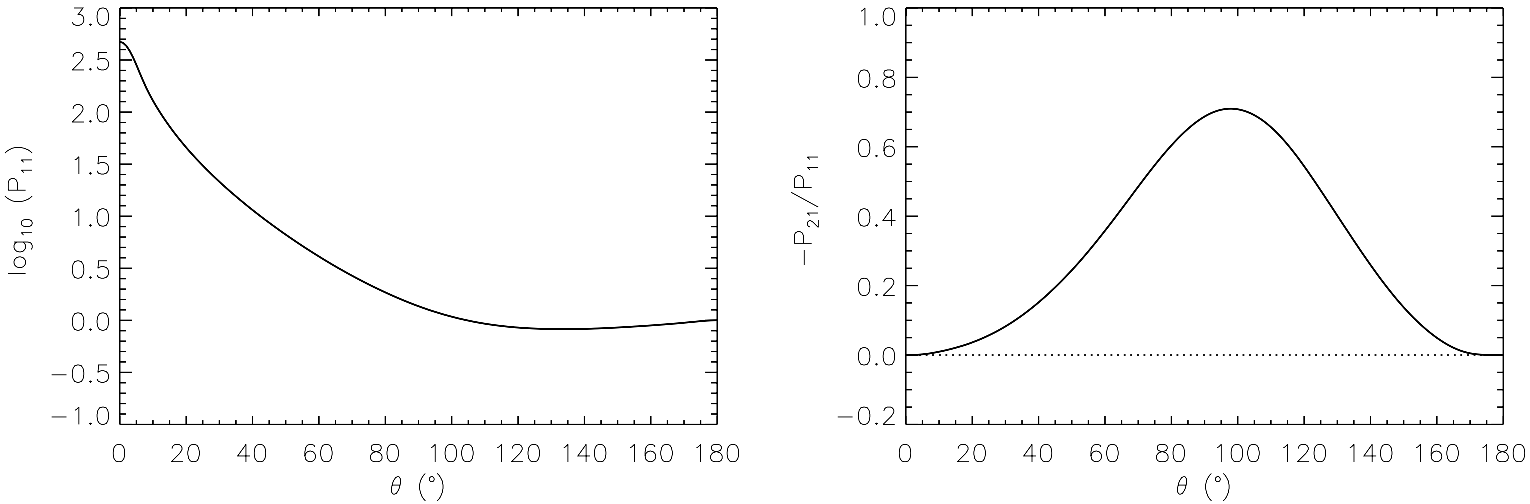
The geometrical albedos p corresponding to the best fits for the small and large TNOs are $p \approx 0.2$ and $p \approx 0.4$. Based on the first analysis, we have $\tilde{\omega} \approx 0.6$, $k\ell \approx 60$ for the small TNOs and $\tilde{\omega} \approx 0.9$, $k\ell \approx 4000$ for the large TNOs. The difference can be due to the presence and absence of volatiles in the surfaces of large and small TNOs, respectively (cf. Bagnulo et al. 2008).

Muinonen et al., DPS 2012



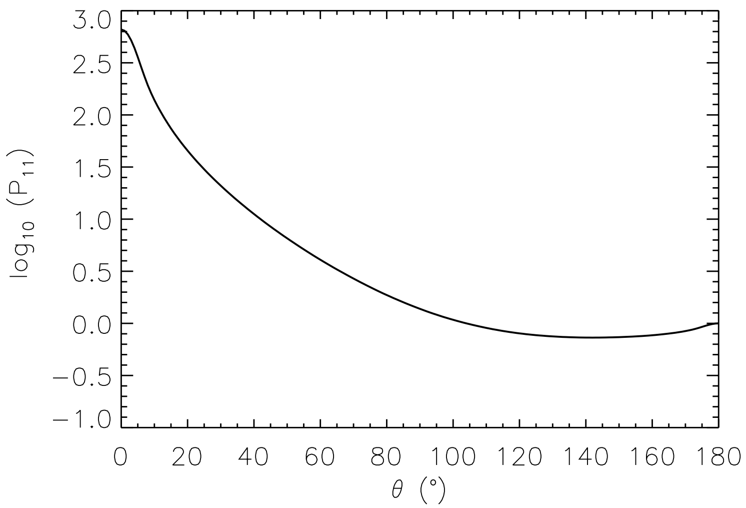
Small TNOs
Degree of Polarization (%)
Phase Angle (°)
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
0.0
0.5
1.0
1.5
2.0
Large TNOs
Degree of Polarization (%)
Phase Angle (°)

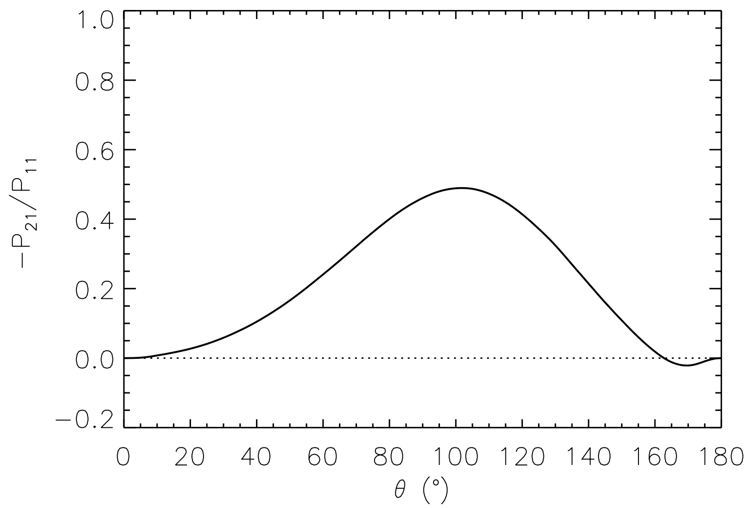
ADP-model for small TNOs



Dirty ice, m = 1.40 + i 0.05, power law index 3.9

ADP-model for large TNOs

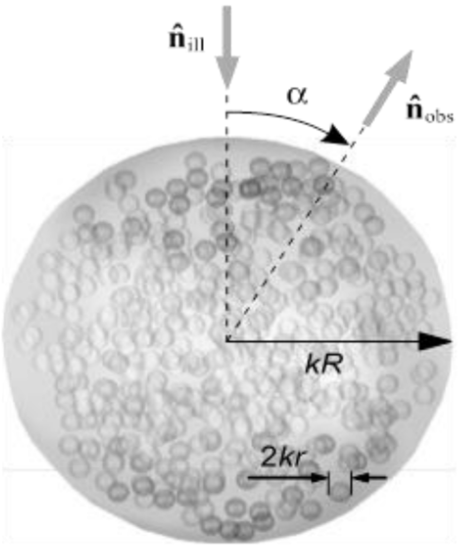


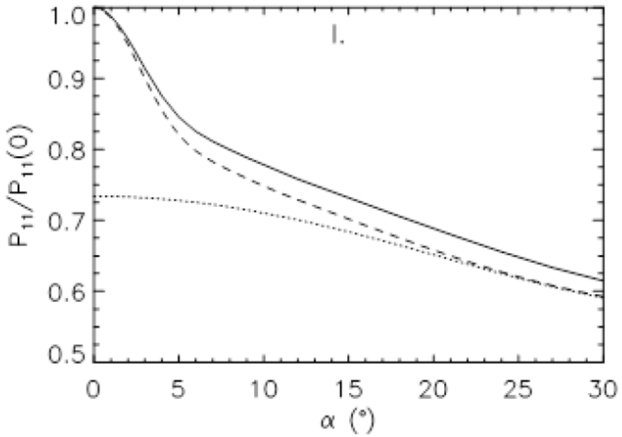


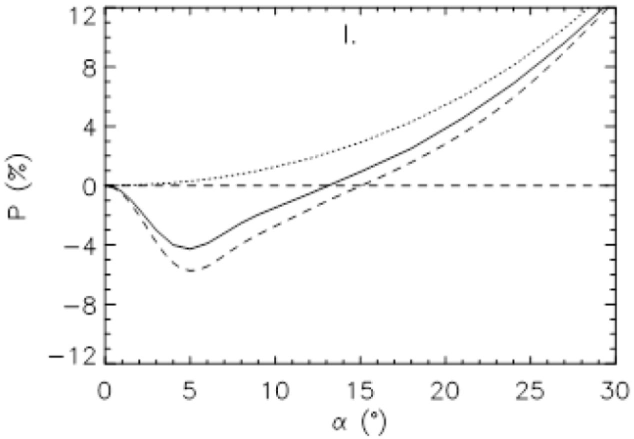
Dirty ice, m = 1.40 + i 0.02, power law index 3.4

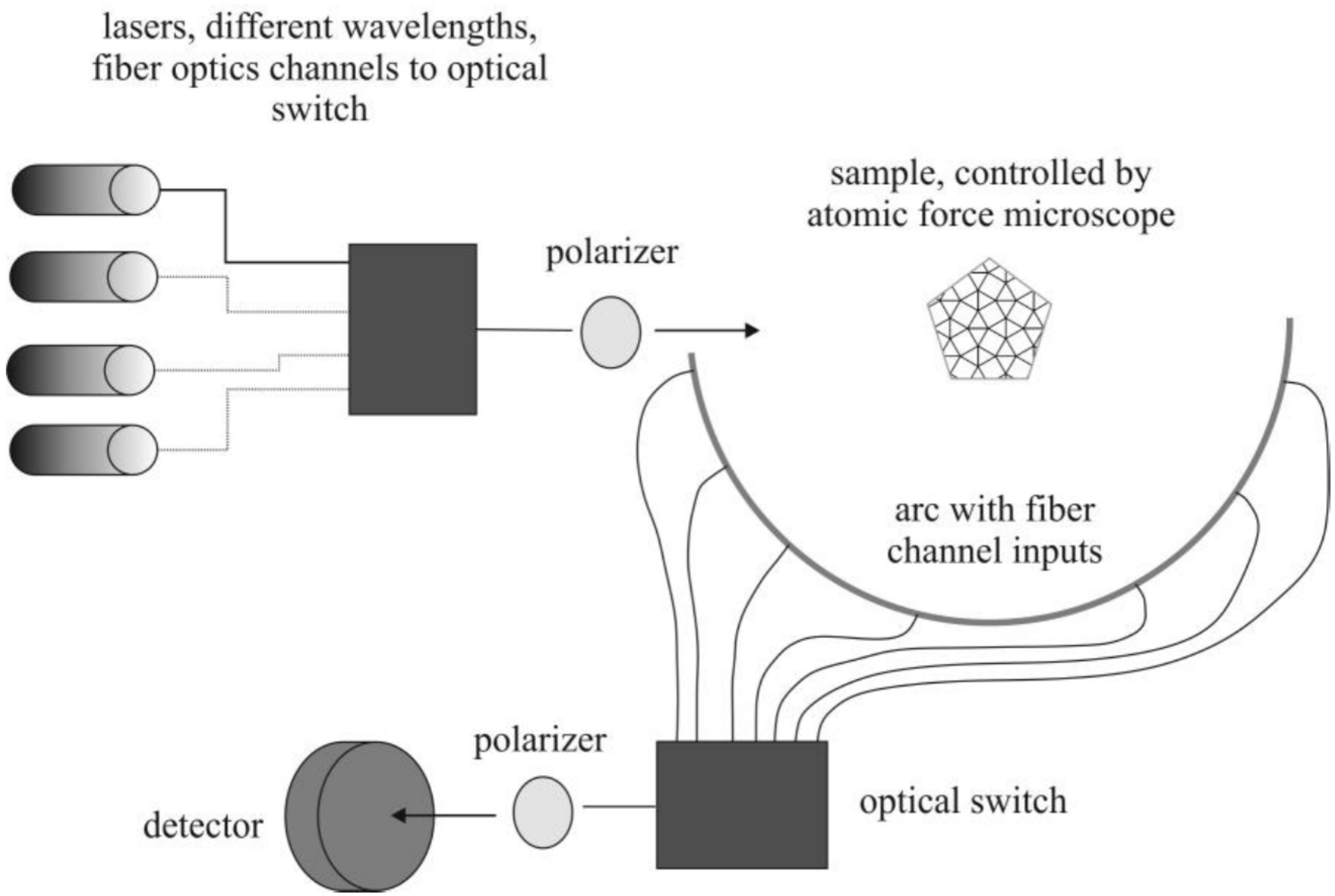
Scattering and Absorption of Electromagnetic Waves in Particulate Media (SAEMPL)

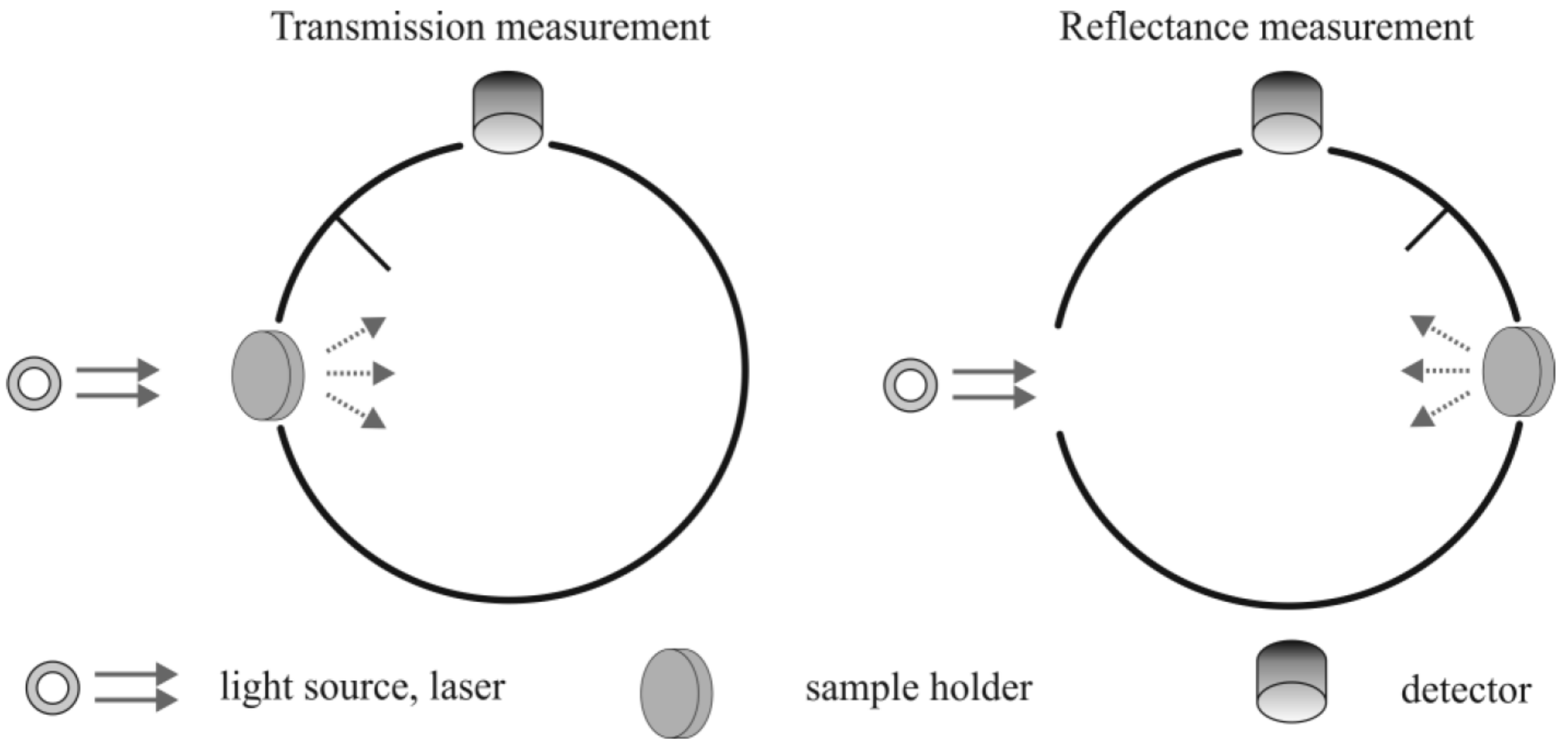
Karri Muinonen & Planetary-System Research -group








lasers, different wavelengths, fiber optics channels to optical switch
sample, controlled by atomic force microscope
polarizer
arc with fiber channel inputs
polarizer
optical switch
detector


Transmission measurement
Reflectance measurement
light source, laser
sample holder
detector

Conclusions

- RT-CB numerically verified for a finite volume of spherical scatterers using MSTM
- Phenomenological RT-CB scattering model capable of fitting the observations
- Iterative DDA modeling of the phenomenological single scatterer allows for the retrieval of optical properties of single scatterers
- Future prospects: regolith geometry to be accounted for, including shadowing effects
- New experimental setup for single-particle scattering measurements (ERC/SAEMPL)

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