Multiple Scattering in the Surfaces of Small Solar System Bodies

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Topics: Numerical verification of coherent backscattering, Physical scattering model

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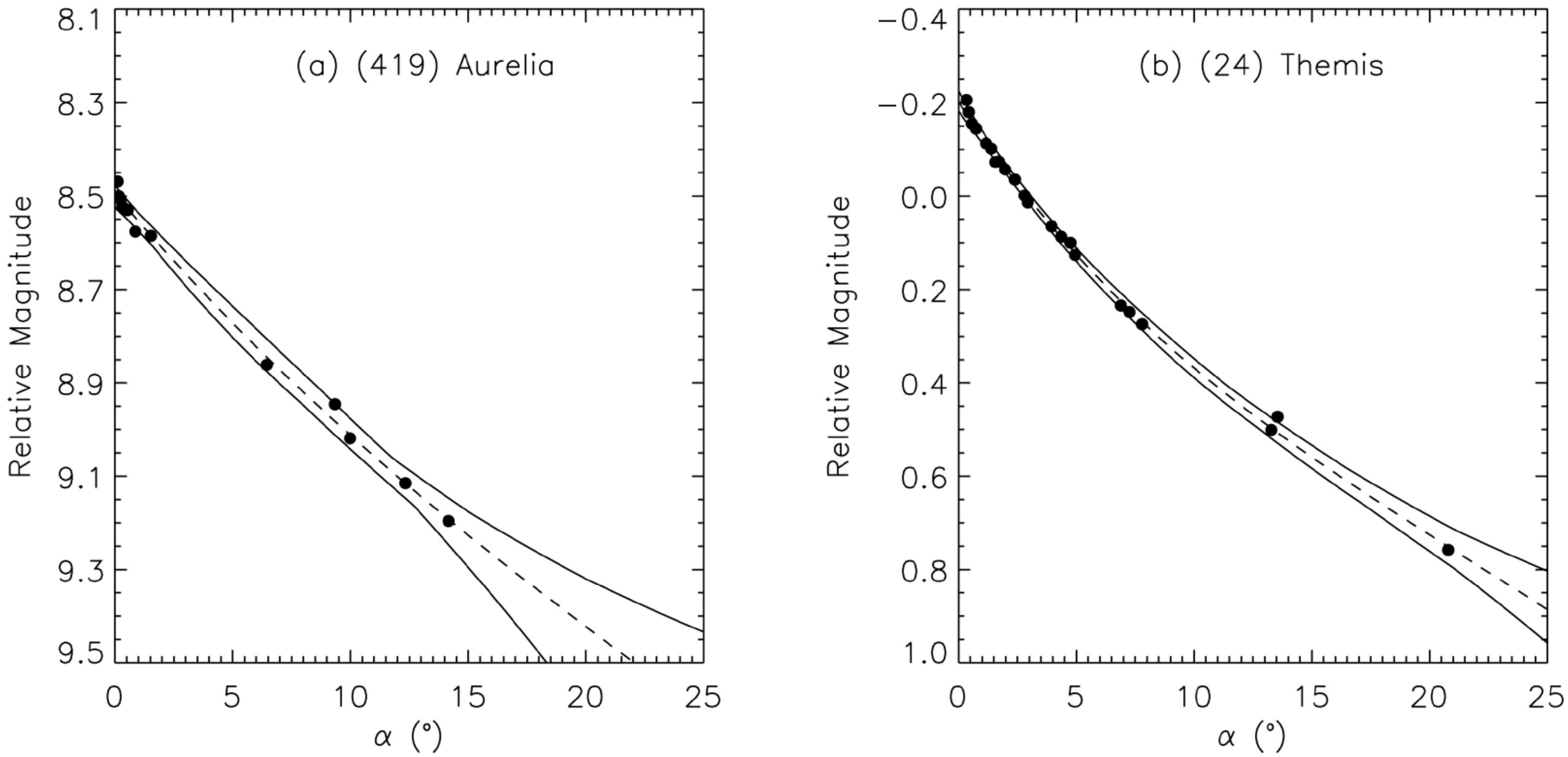
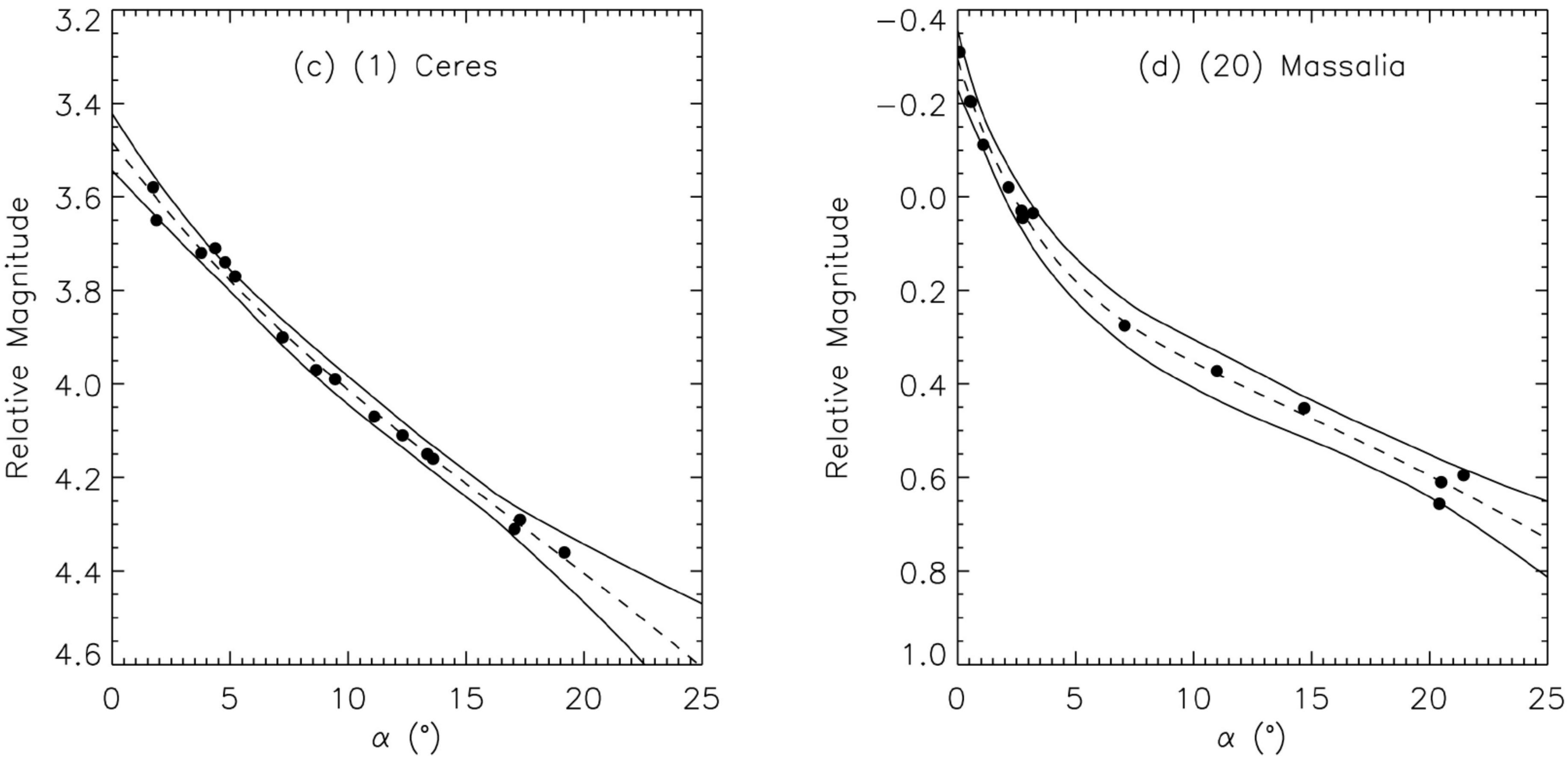
Introduction

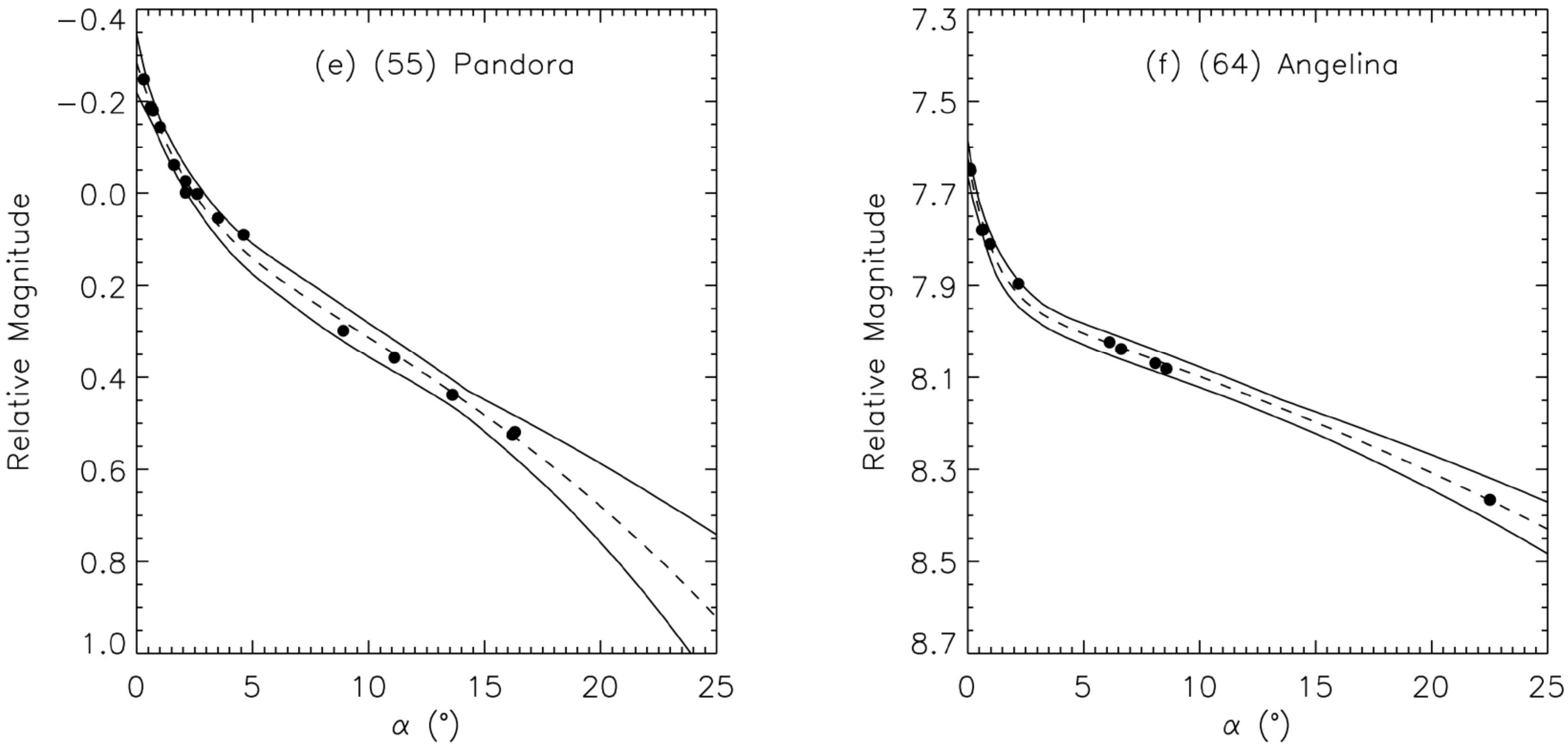
- Direct problem of light scattering from planetary-system regoliths
  - particle size, shape, and composition
  - volume density in particulate medium
  - rough interface between particulate medium and free space
- Inverse problem based on photometric and polarimetric observations
- Opposition effect, negative polarization



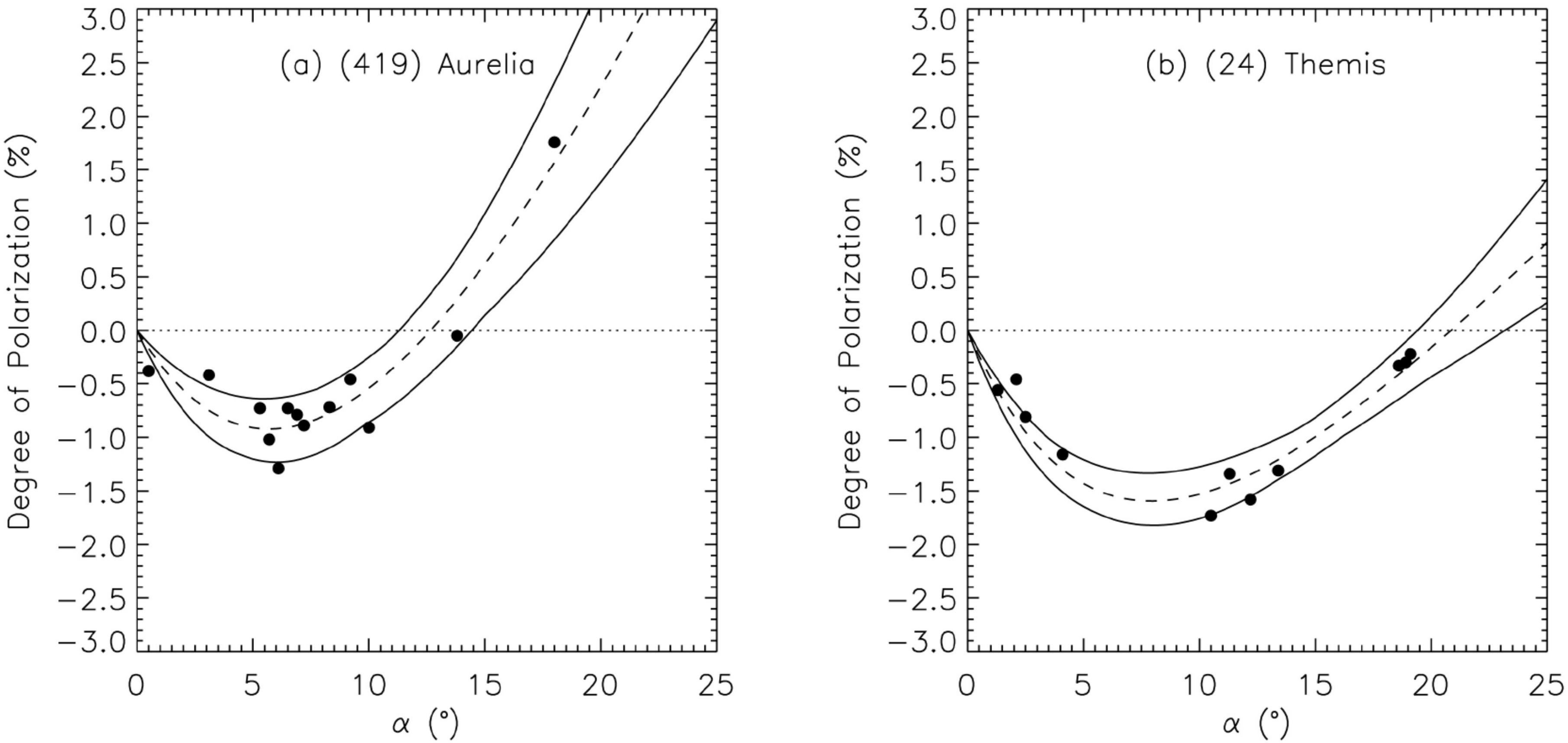
Muinonen et al., MAPS 44, 1937, 2009, obs. ref. therein



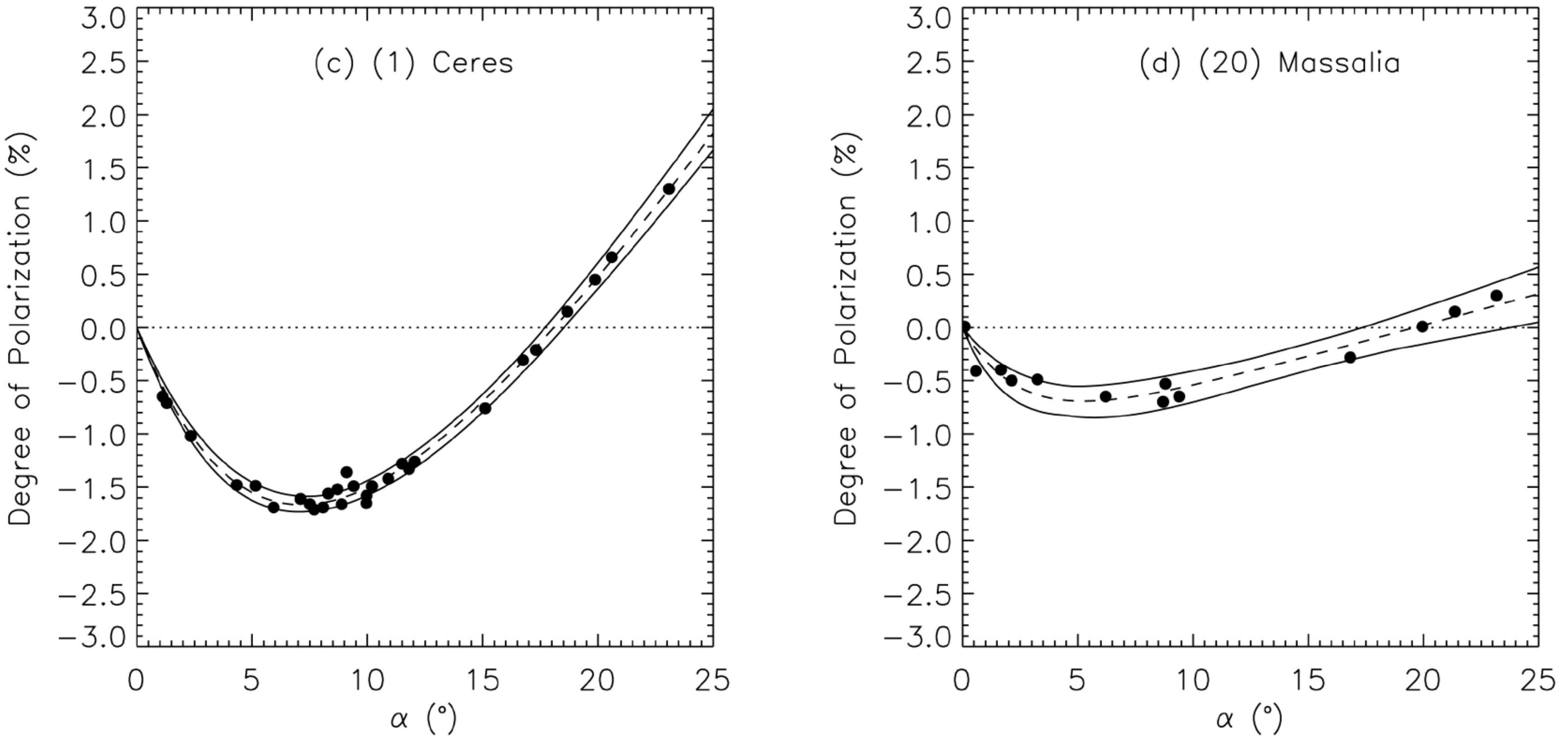
(c) (1) Ceres
Relative Magnitude
α (°)
(d) (20) Massalia
Relative Magnitude
α (°)

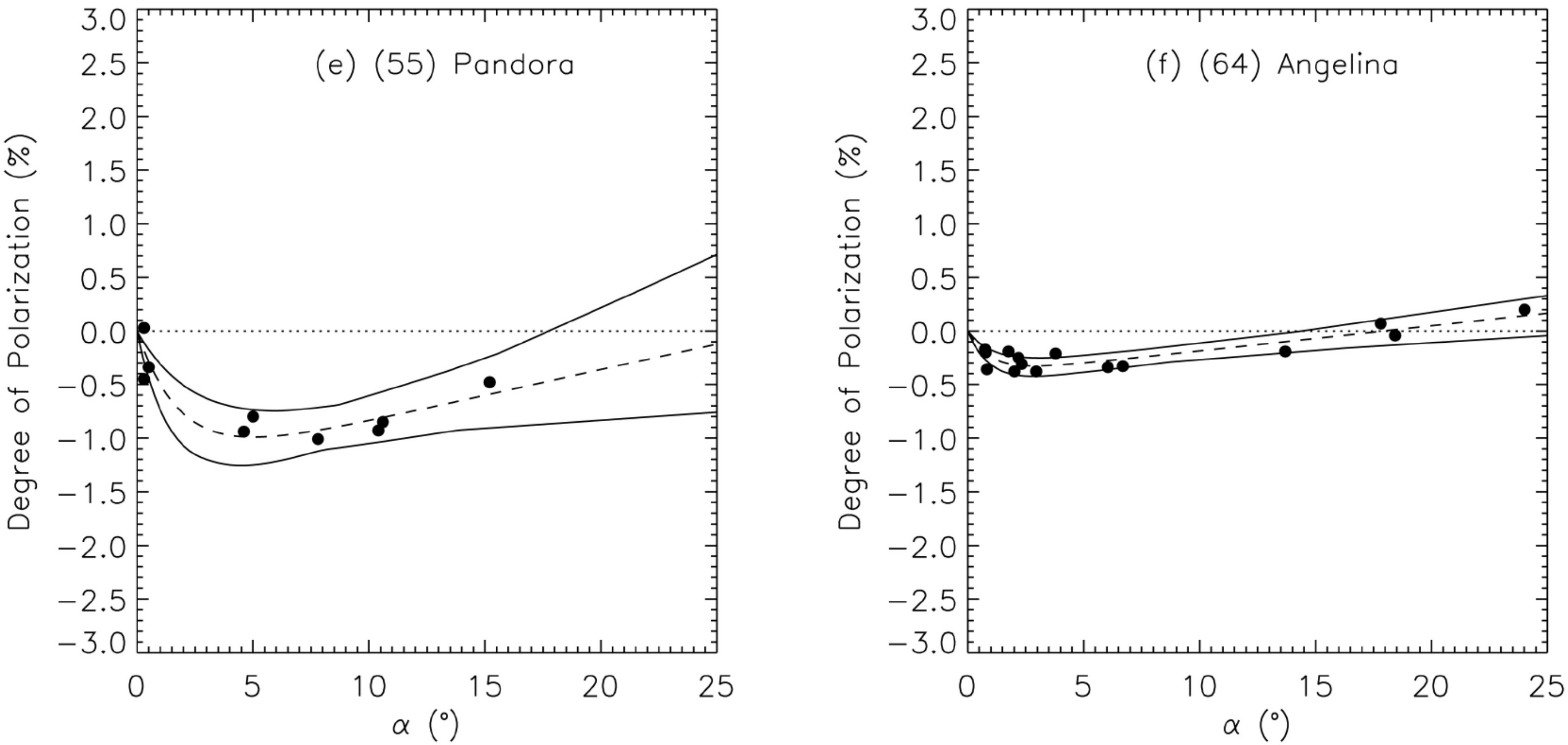


(e) (55) Pandora
Relative Magnitude
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
α (°)
(f) (64) Angelina
7.3
7.5
7.7
7.9
8.1
8.3
8.5
8.7



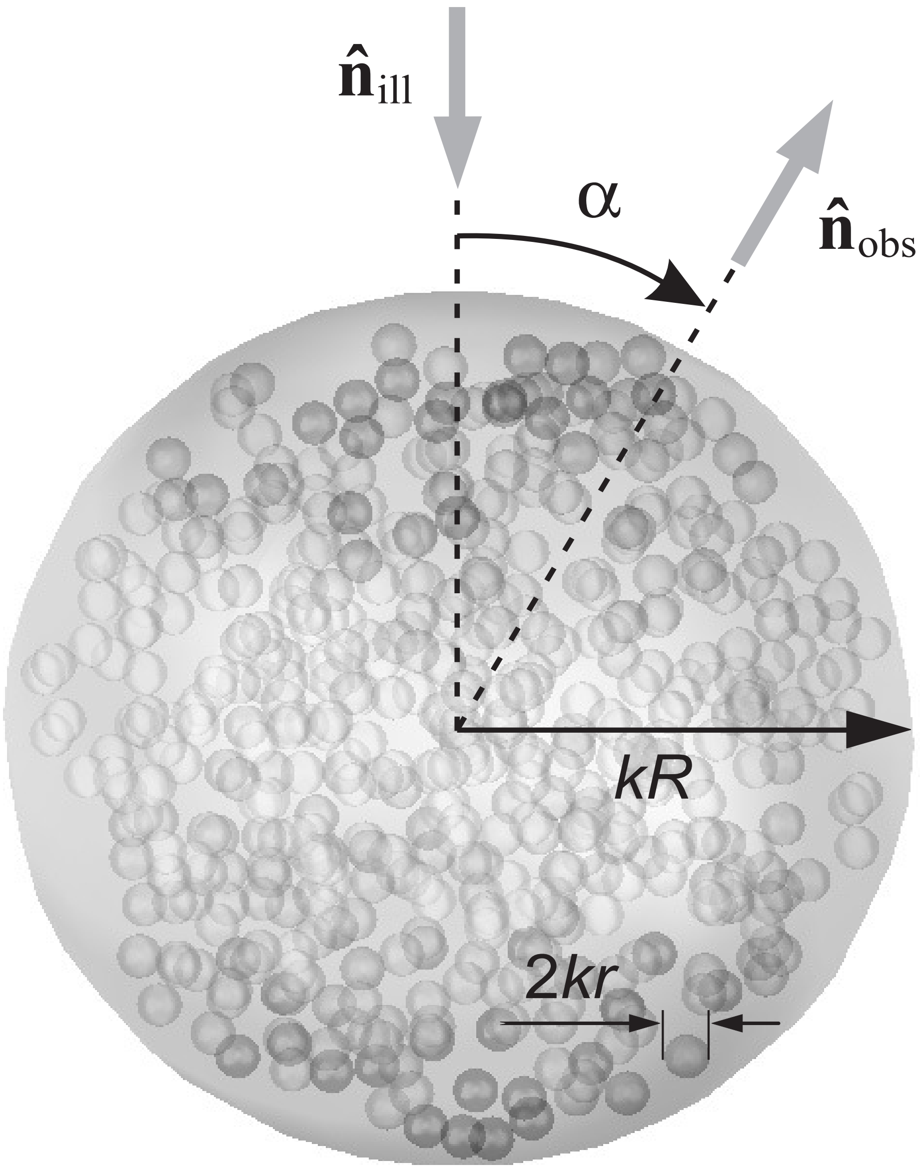
(a) (419) Aurelia
(b) (24) Themis
Degree of Polarization (%)
α (°)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0
5
10
15
20
25


(c) (1) Ceres
(d) (20) Massalia
Degree of Polarization (%)
α (°)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0
5
10
15
20
25


(e) (55) Pandora
(f) (64) Angelina
Degree of Polarization (%)
α (°)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0
5
10
15
20
25

Numerical verification of coherent backscattering

- Intensity and polarization of light backscattered by a finite volume of spherical particles
- Superposition *T*-matrix method (STMM, exact)
  - Mackowski and Mishchenko, JQSRT 2011
  - Mishchenko et al., ApJ 2009
- Coherent-backscattering radiative-transfer method (RT-CB, ladder & cyclical interaction diagrams in multiple scattering)
  - Muinonen, Waves in Random Media 2004
  - Muinonen and Zubko, ELS XII 2010
  - Muinonen et al., ApJ 2012, submitted



$\hat{\mathbf{n}}_{\text{ill}}$
α
$\hat{\mathbf{n}}_{\text{obs}}$
kR
2kr

Stokes vectors

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

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

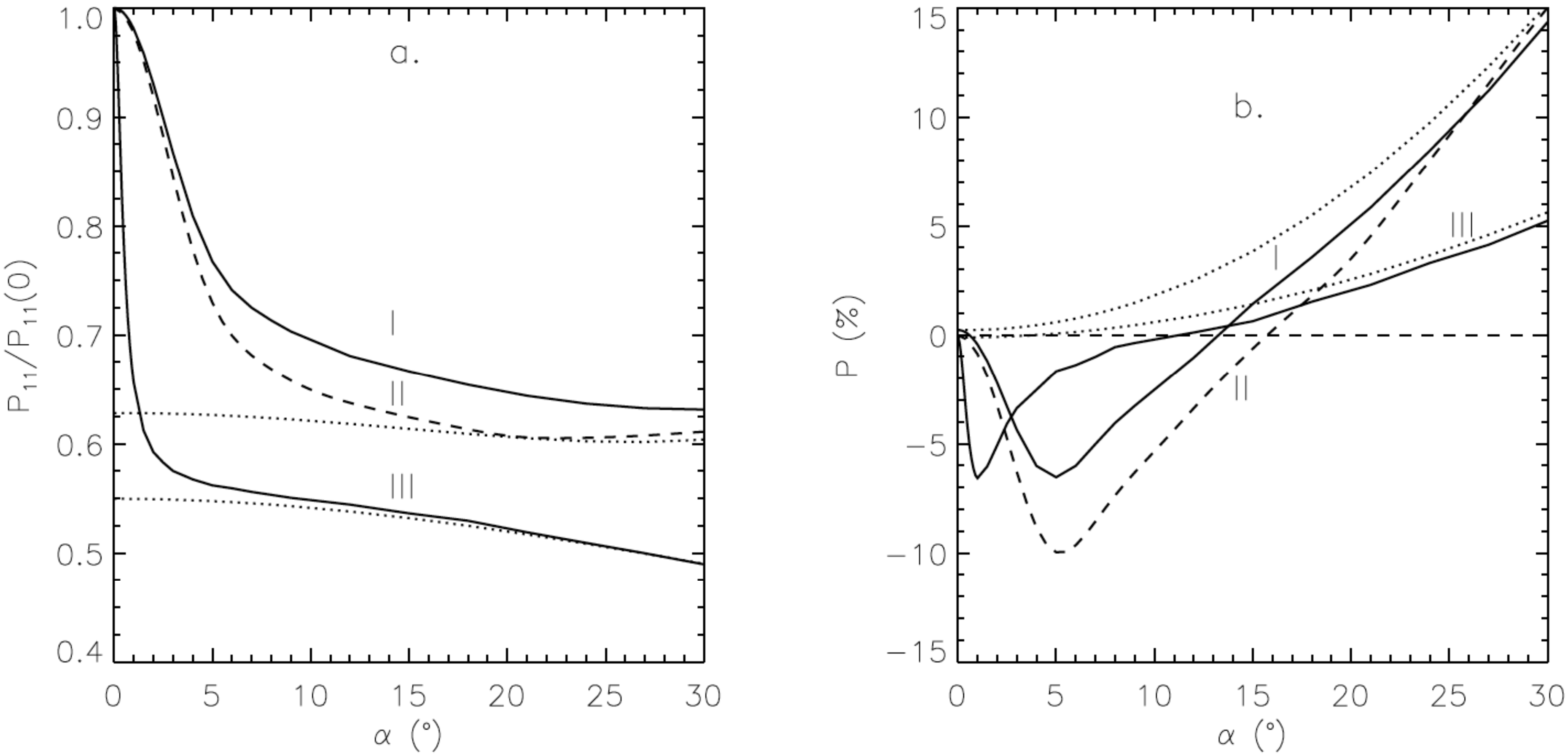
scattering matrix $\boldsymbol{S}$

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

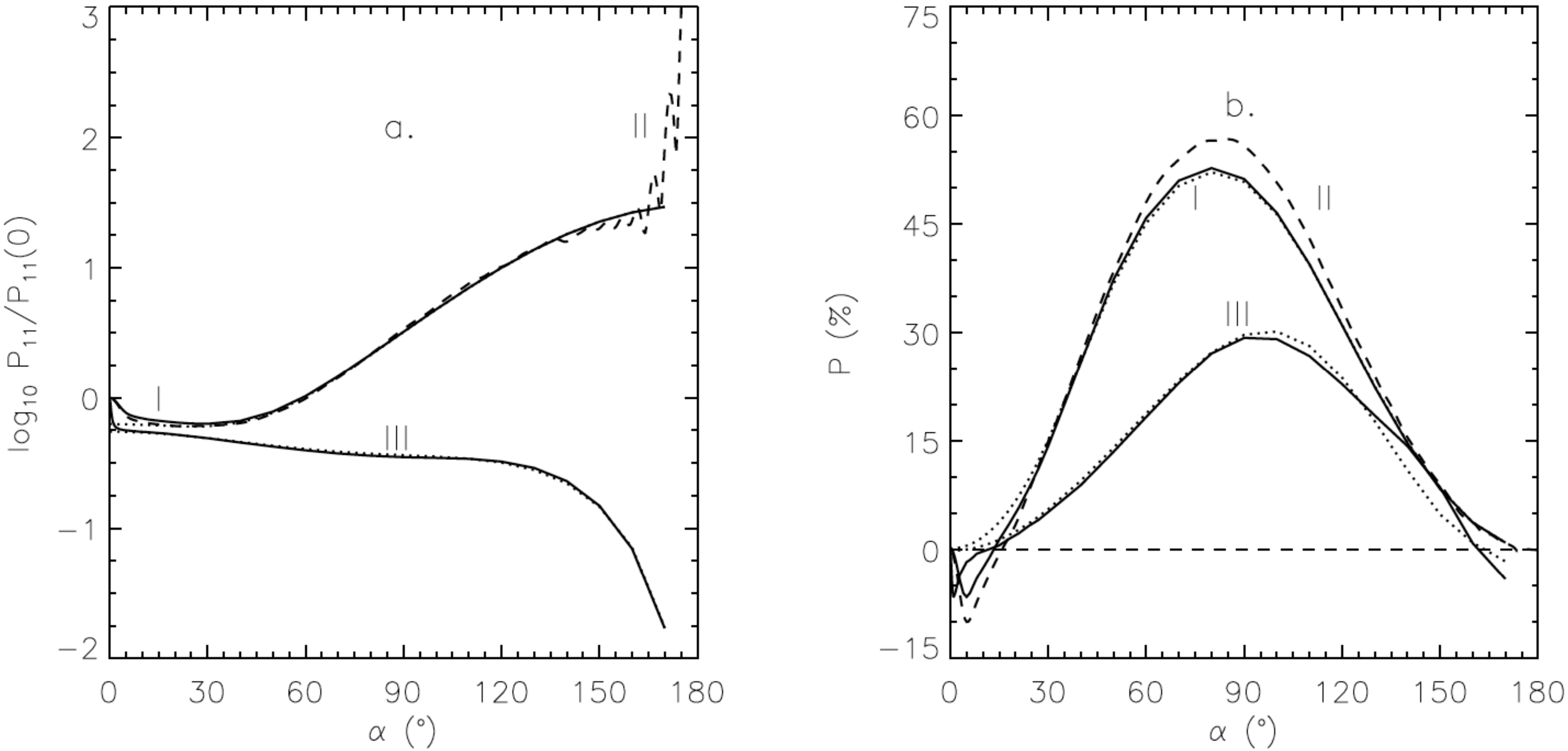
(Here *R* is the distance between observer and scatterer.)

- Finite volume of 500 spheres with volume density of 6.25%
- Volume size parameter
  - X = kR = 40 (STMM & RT-CB)
  - X = 10^7 (RT-CB)
- Properties of constituent spheres
  - size parameter x = kr = 2
  - refractive index 1.31 for X = 40
  - refractive index 1.31+i0.01 for X = 10^7

I: X = 40, m = 1.31, RT-CB
II: X = 40, m = 1.31, STMM
III: X = 10^7, m = 1.31+i0.01, RT-CB



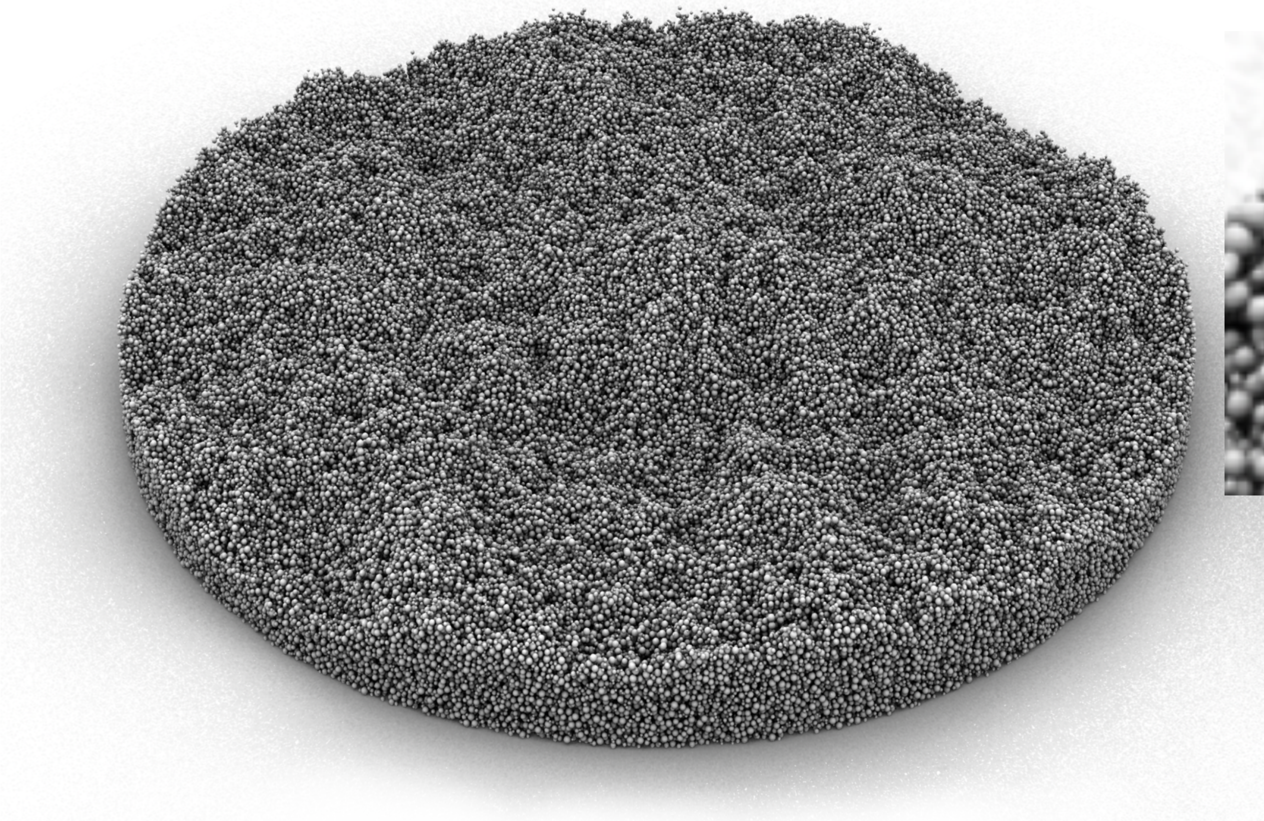
$$P = -P_{21}/P_{11}$$

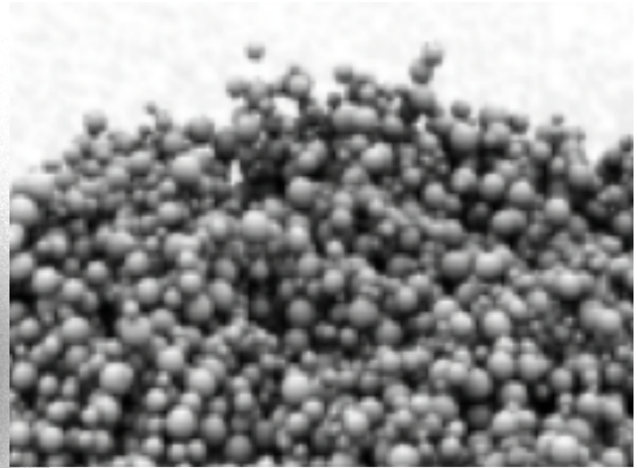


a.
log10 P11/P11(0)
α (°)
I
II
III
b.
P (%)

Physical scattering model

- Model based on coherent backscattering and radiative transfer
- Particulate medium modeled using spheres and fBm roughness
- Semiempirical single scatterers
- References:
  - Muinonen & Videen, JQSRT, in preparation
  - Wilkman et al., A & A, in preparation
  - Muinonen et al., A & A 531, A150, 2011
  - Parviainen & Muinonen, JQSRT 2007 & 2009
  - Muinonen, Waves in Random Media 14, 365, 2004





H. Parviainen,
K. Muinonen,
JQSRT 2009

Wilkman et al.,
in preparation

Densely-packed random media of spheres,
fractional-Brownian-motion boundary
surface (fBm)

- Single-scattering albedo, three asymmetries, maximum polarization:

$$\tilde{\omega},\ g,\ g_1,\ g_2,\ \text{and}\ P_{\max}$$

- Extinction mean free path length:

$$\tau_s = \int_0^s ds\ k_{\rm e} = k_{\rm e} s = \frac{s}{\ell}, \qquad \ell = \frac{1}{k_{\rm e}}$$

$$\boldsymbol{P}(\theta) \propto \frac{f(\theta)}{\frac{3}{4}(1+\cos^2\theta)} \left[w_+ \boldsymbol{P}_+(\theta) + (1-w_+)\boldsymbol{P}_-(\theta) \right]$$

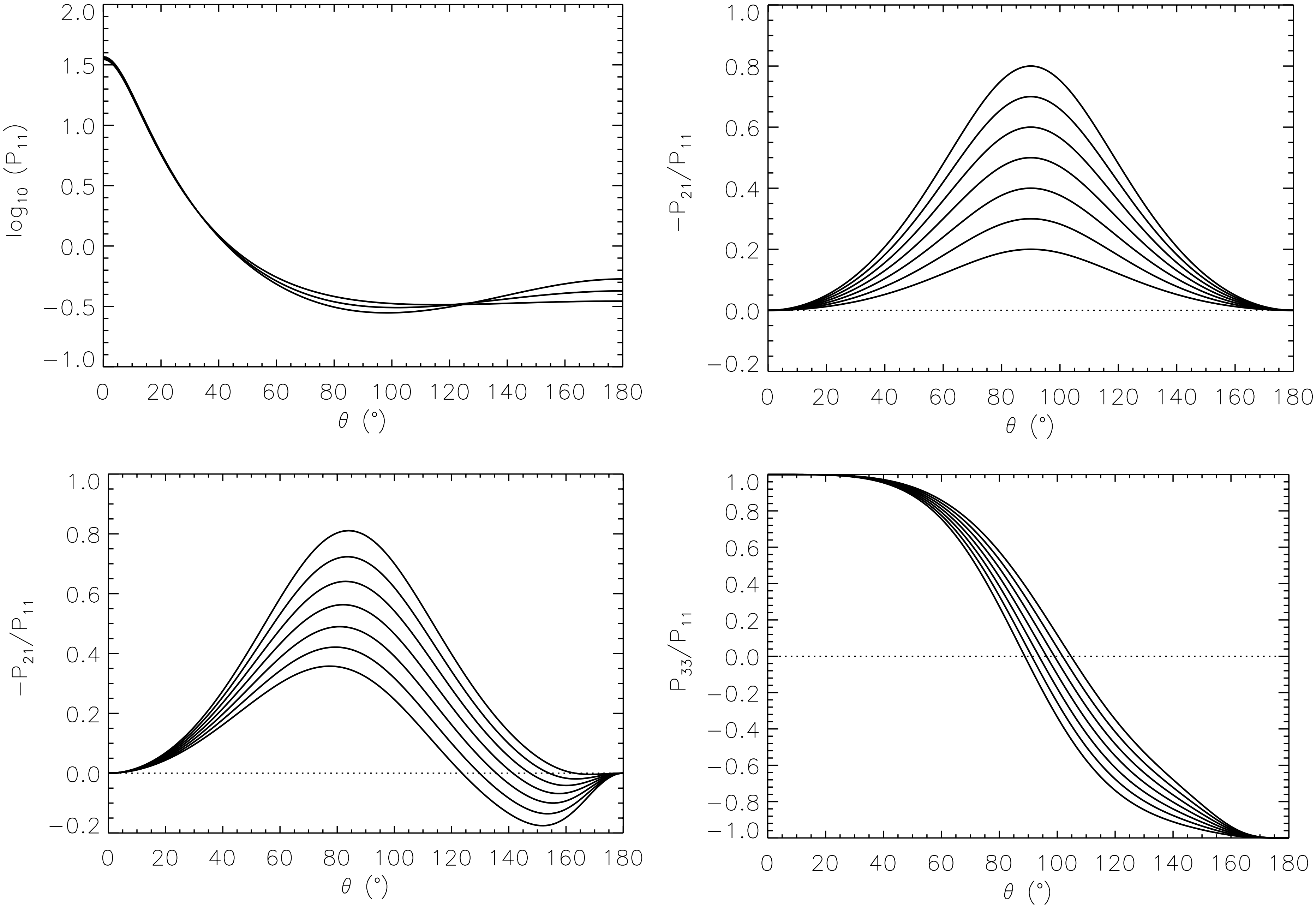
$$w_+ = \frac{1}{2}(P_{\max} + 1)$$

$$\boldsymbol{P}_\pm = \frac{3}{2} \begin{pmatrix} \frac{1}{2}(1+\cos^2\theta) & \mp\frac{1}{2}\sin^2\theta & 0 & 0 \\ \mp\frac{1}{2}\sin^2\theta & \frac{1}{2}(1+\cos^2\theta) & 0 & 0 \\ 0 & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & \cos\theta \end{pmatrix}$$

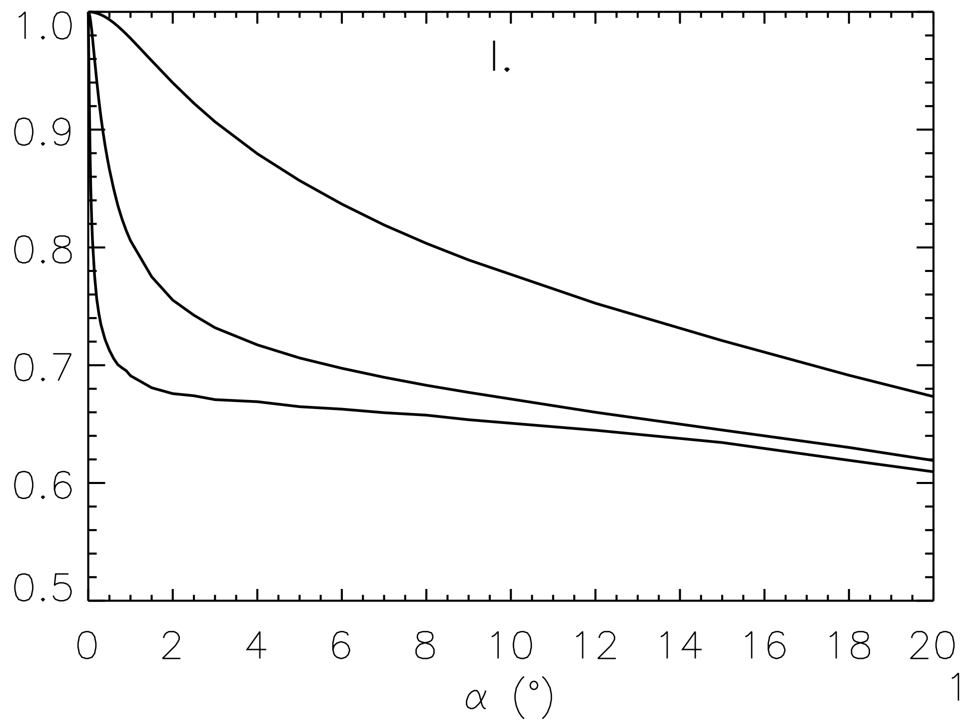
$$f(\theta) = w \frac{1-g_1^2}{(1+g_1^2-2g_1\cos\theta)^{\frac{3}{2}}} + (1-w) \frac{1-g_2^2}{(1+g_2^2-2g_2\cos\theta)^{\frac{3}{2}}}$$

$$g = w g_1 + (1-w) g_2,$$

$$w = \frac{g-g_2}{g_1-g_2},$$



(cf. Tyynelä, Ph.D. thesis, 2011)



$$\tilde{\omega} = 0.6$$

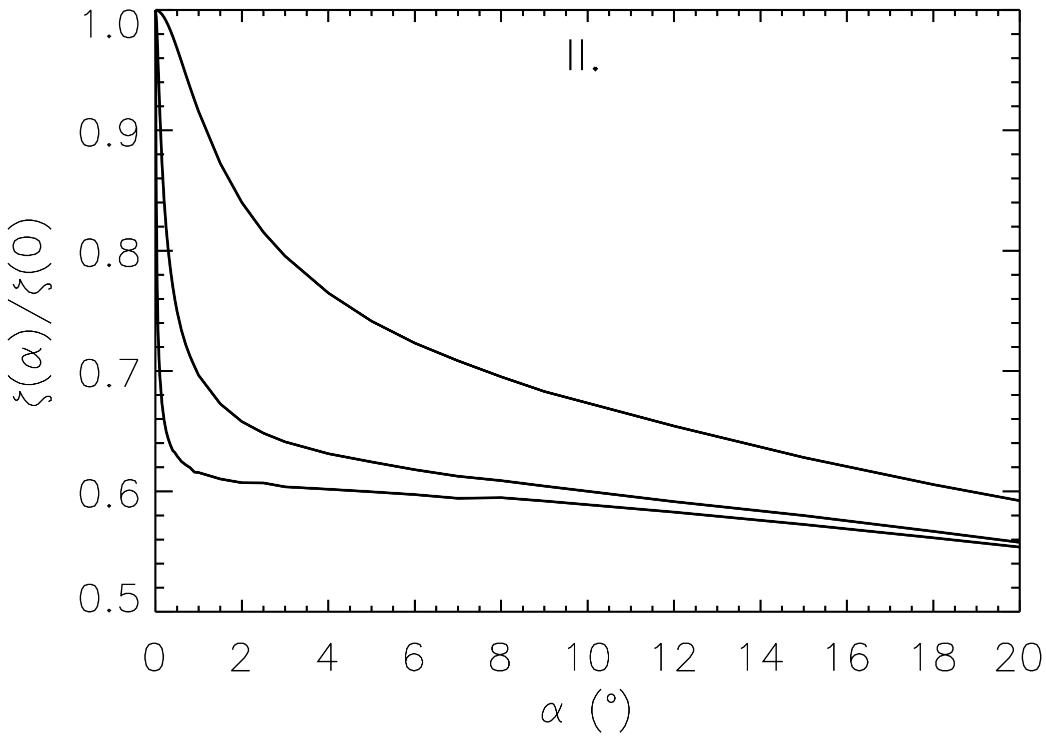
$$X = 10^7$$

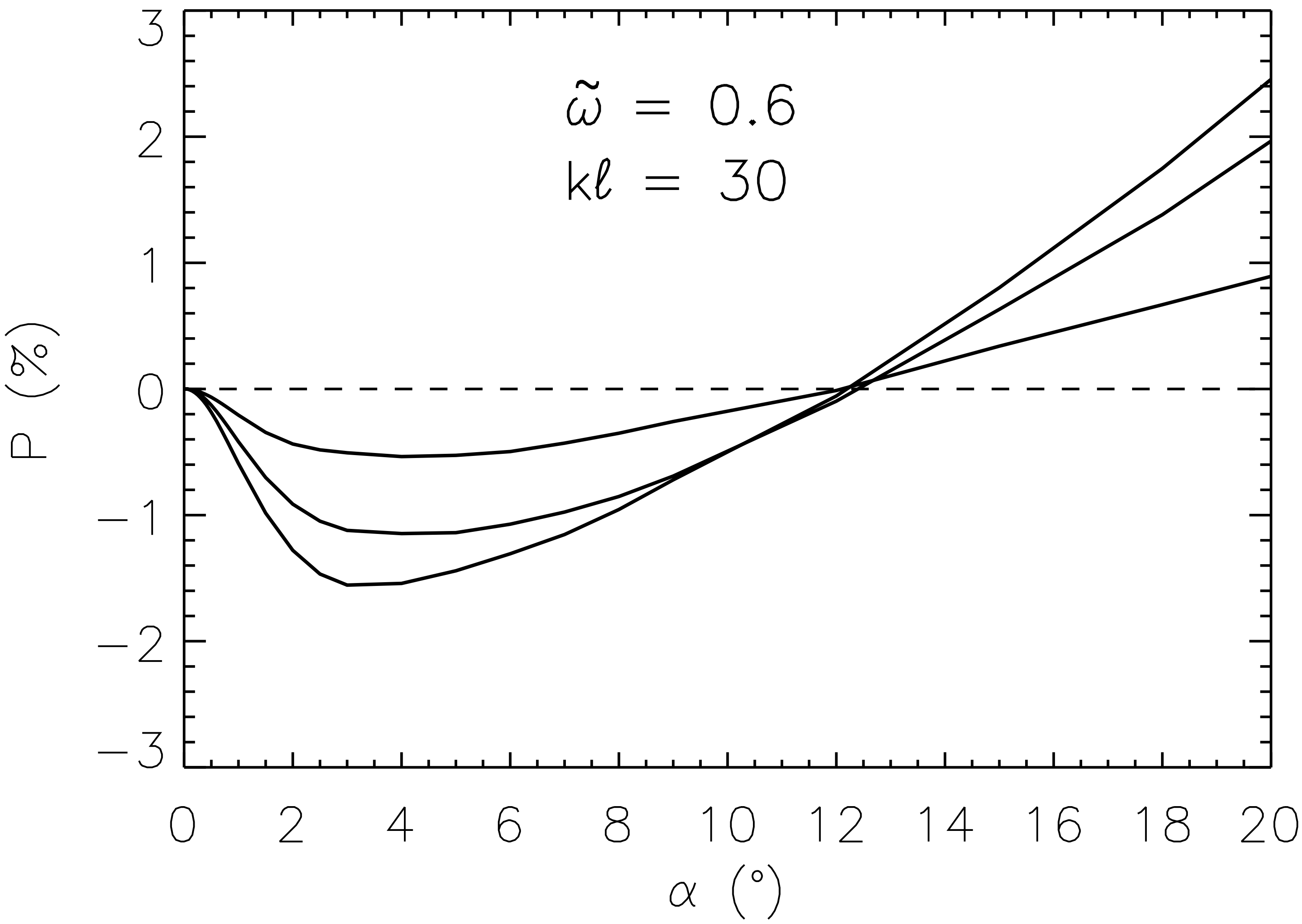
$$g = 0.6$$

$$g_1 = 0.8$$

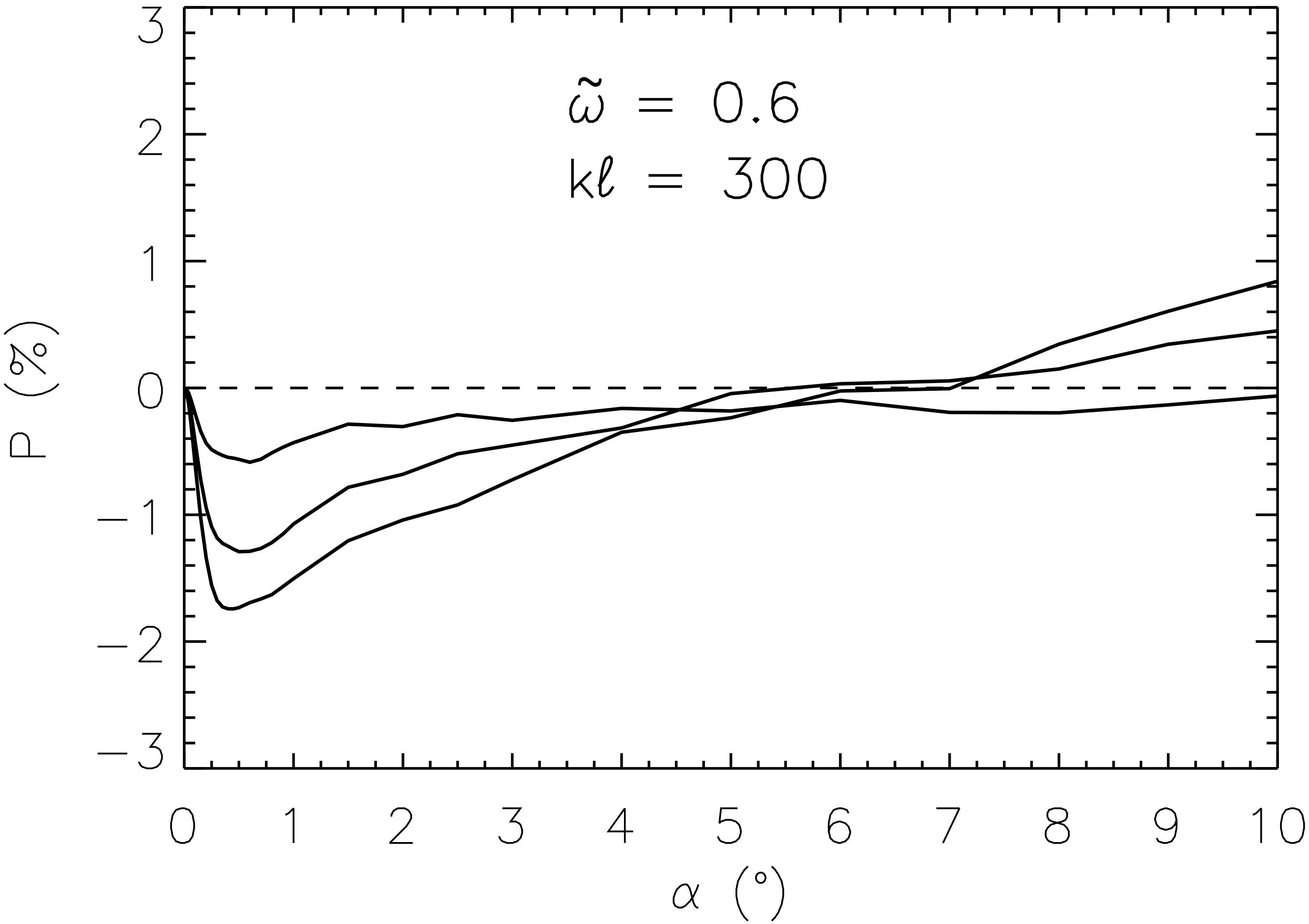
$$g_2 = -0.1$$

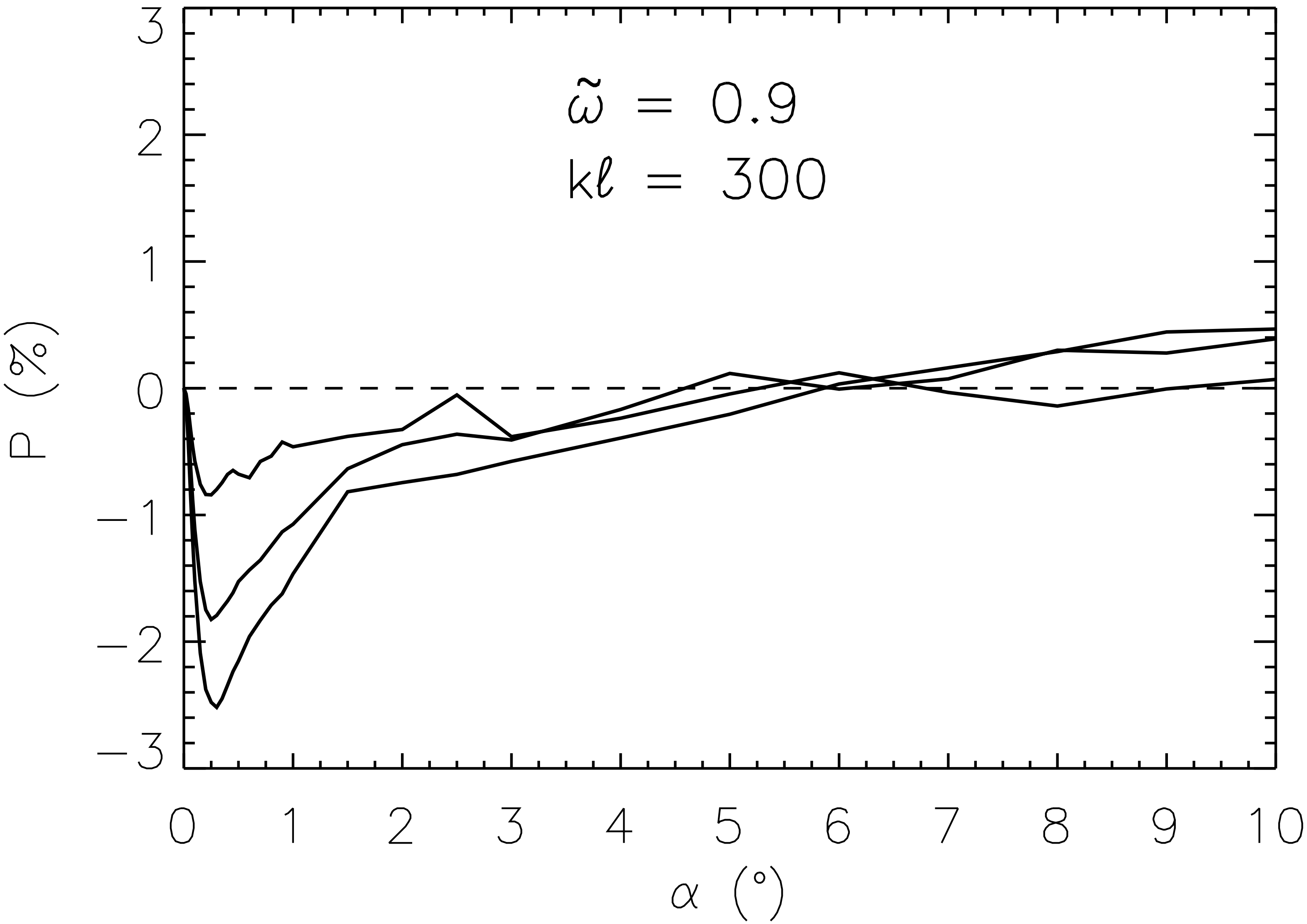
$$\tilde{\omega} = 0.9$$



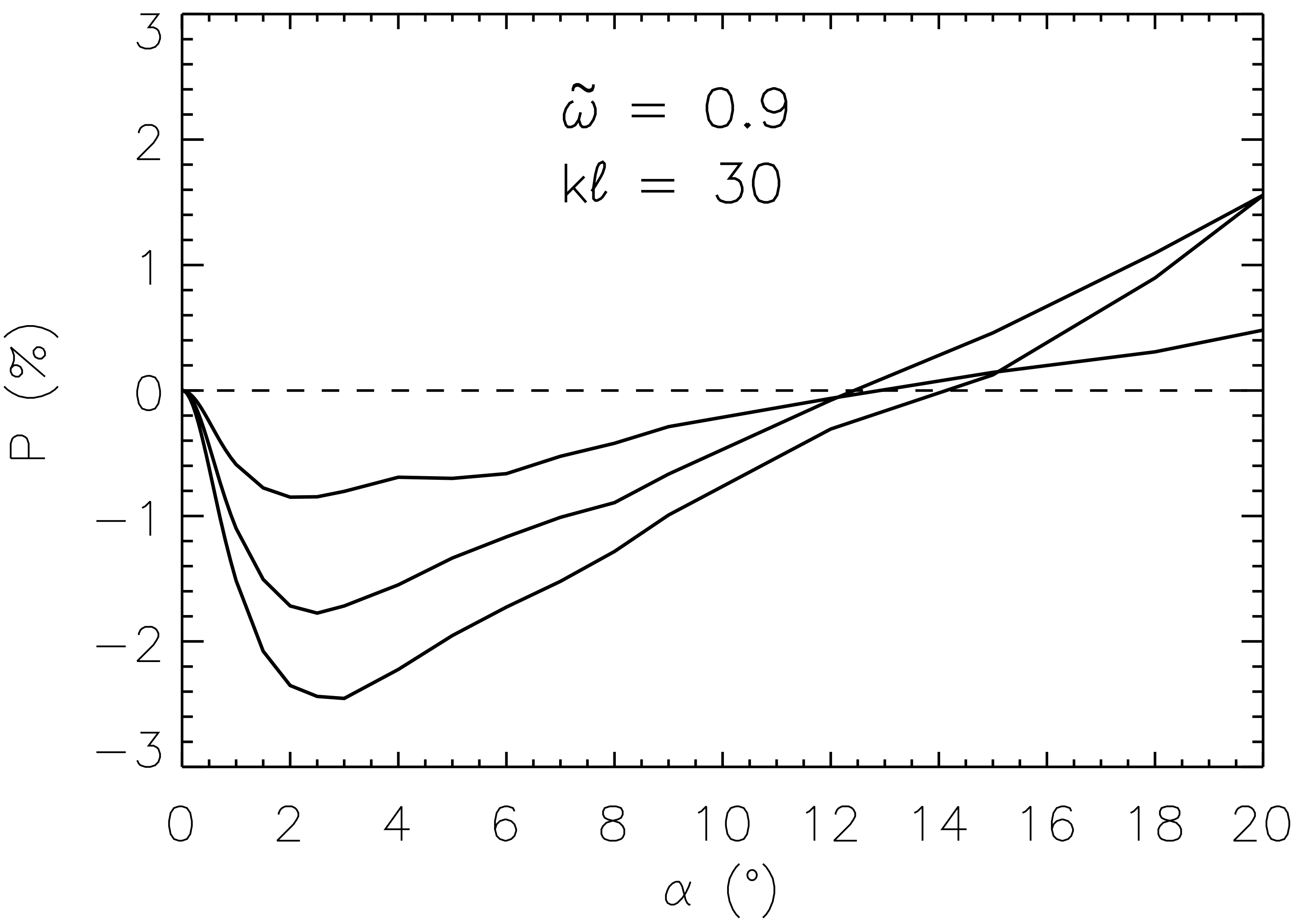


$\tilde{\omega}$ = 0.6
$k\ell$ = 30
P (%)
α (°)
3
2
1
0
−1
−2
−3
0
2
4
6
8
10
12
14
16
18
20

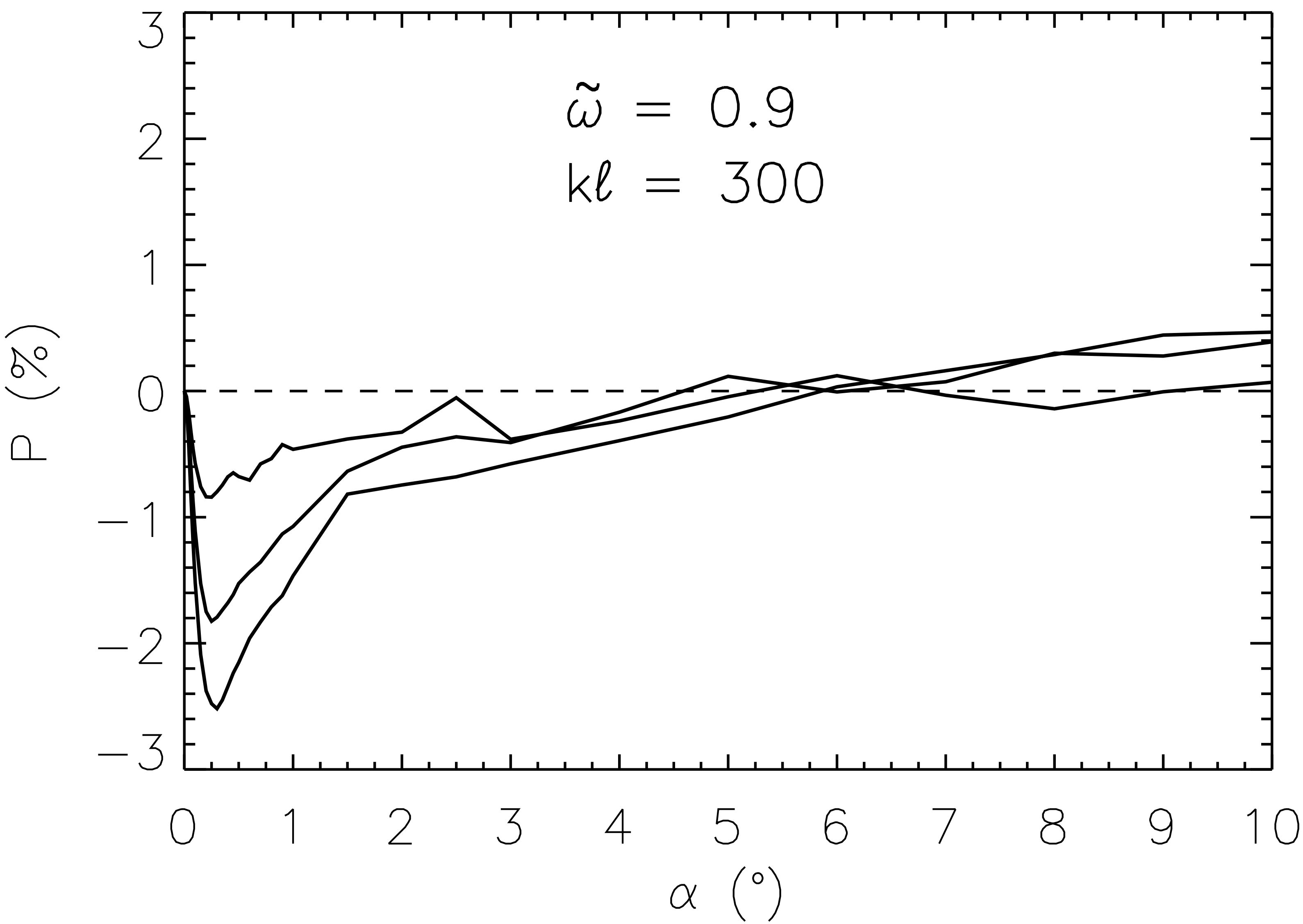

$\tilde{\omega}$ = 0.6
kℓ = 300
P (%)
α (°)
3
2
1
0
−1
−2
−3
0 1 2 3 4 5 6 7 8 9 10



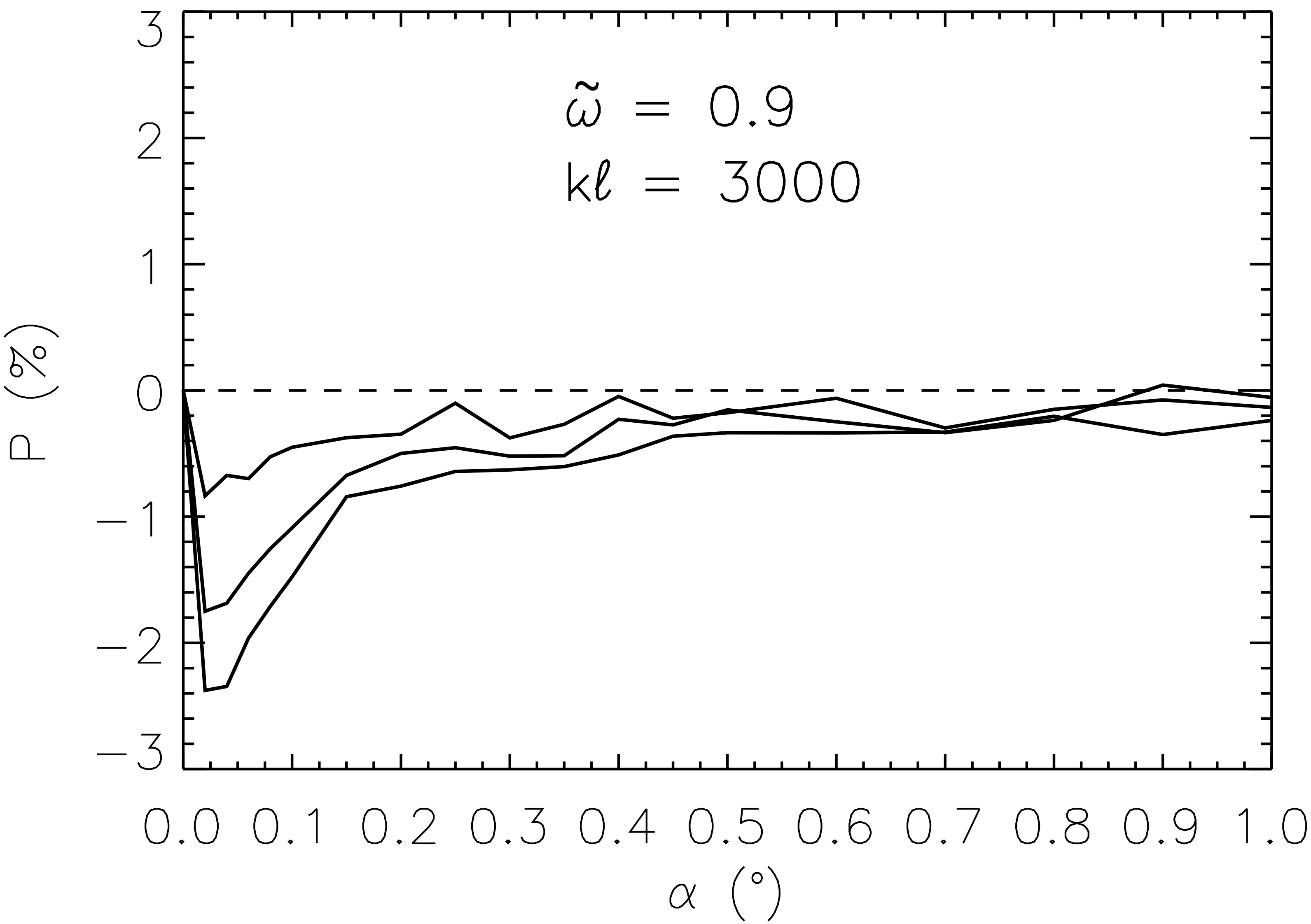
$\tilde{\omega}$ = 0.9
kℓ = 300
P (%)
α (°)



$\tilde{\omega}$ = 0.9
kℓ = 30
P (%)
α (°)
3
2
1
0
−1
−2
−3
0
2
4
6
8
10
12
14
16
18
20

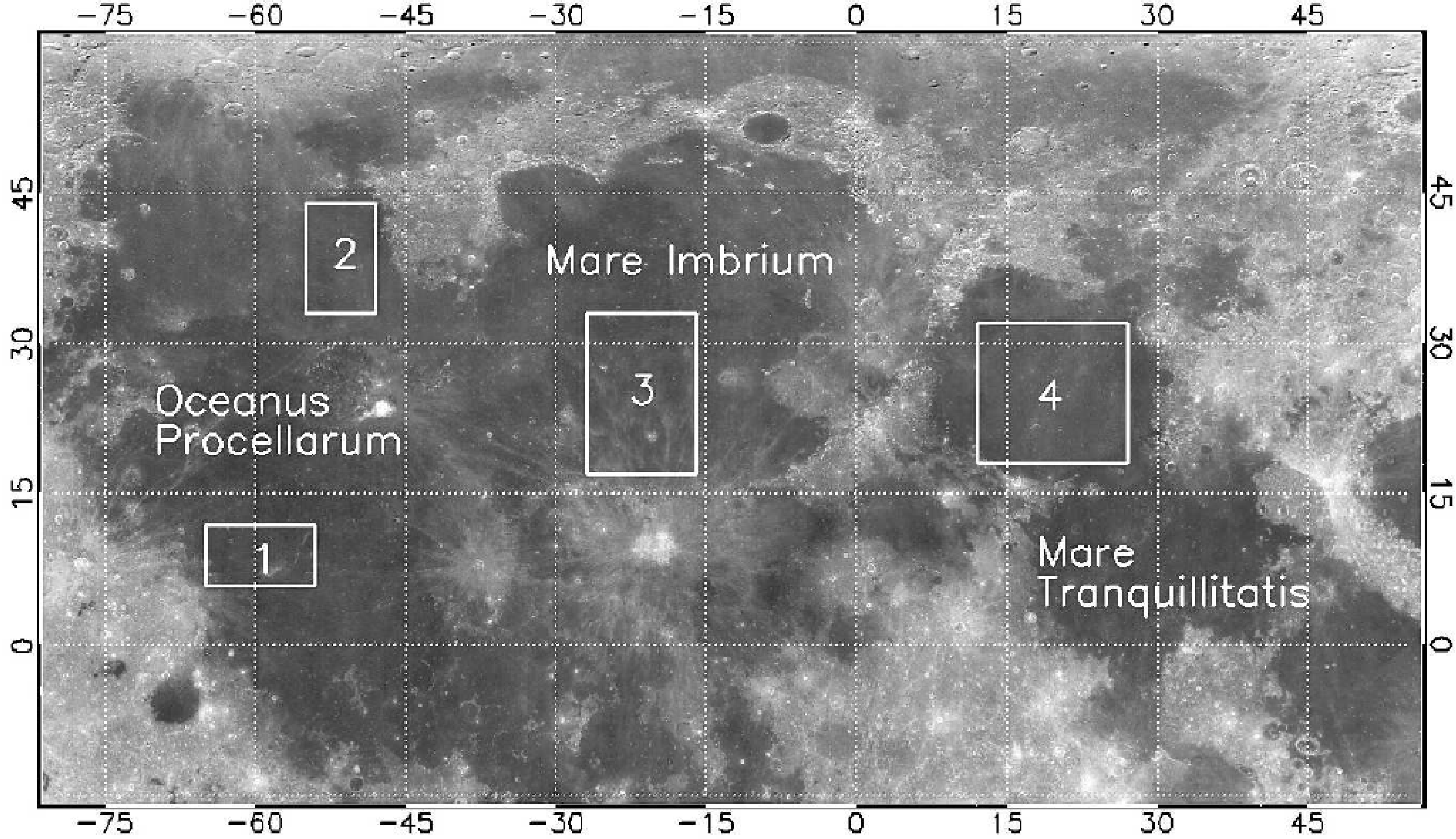


$\tilde{\omega}$ = 0.9
kℓ = 300
P (%)
α (°)
3
2
1
0
−1
−2
−3
0
1
2
3
4
5
6
7
8
9
10

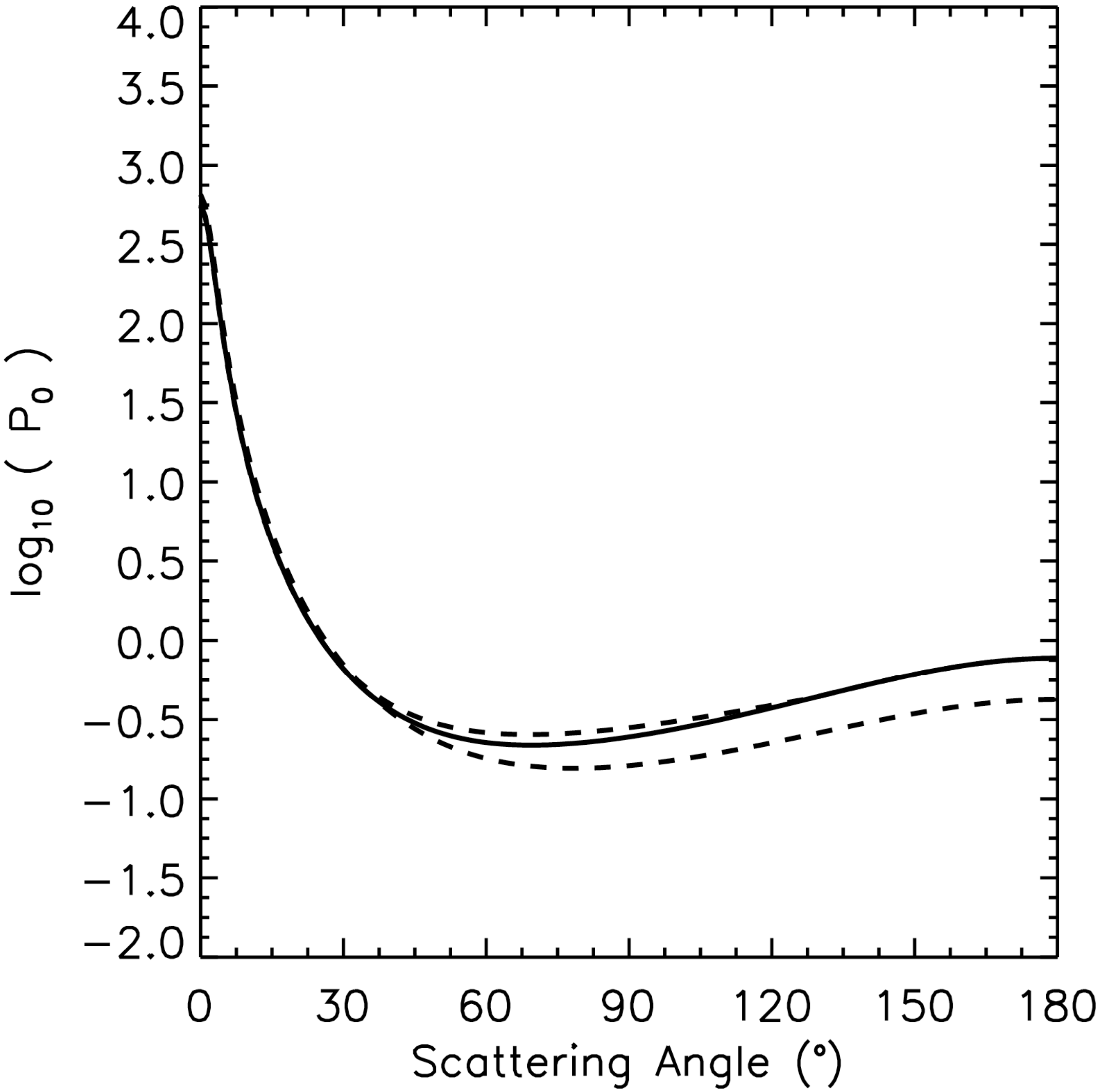


$\tilde{\omega}$ = 0.9
kℓ = 3000
P (%)
3
2
1
0
−1
−2
−3
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
α (°)

Application to lunar imaging data



SMART-1/AMIE Muinonen et al., A&A 531, A150, 2011



Double Henyey-Greenstein phase function for fundamental scatterers

Conclusions

- Coherent backscattering numerically verified for a finite volume of spherical scatterers
- Scattering by Solar System regoliths modeled on the basis of first principles
- Practical strategies for space-based imaging of Solar System objects
- Application to lunar photometry (Wilkman et al.), Iapetus polarimetry (Ejeta et al.), and transneptunian objects