Coherent backscattering in planetary regoliths

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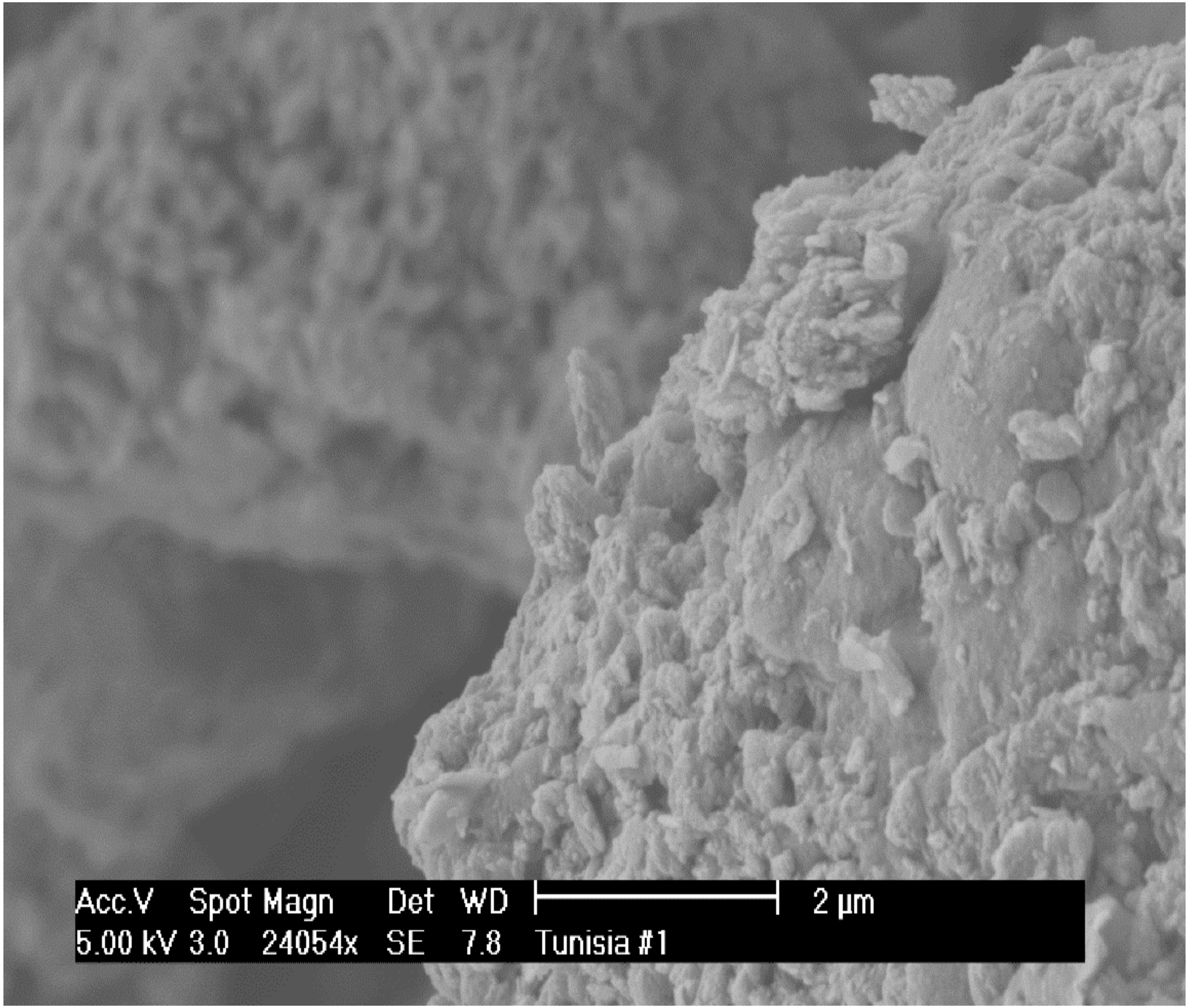
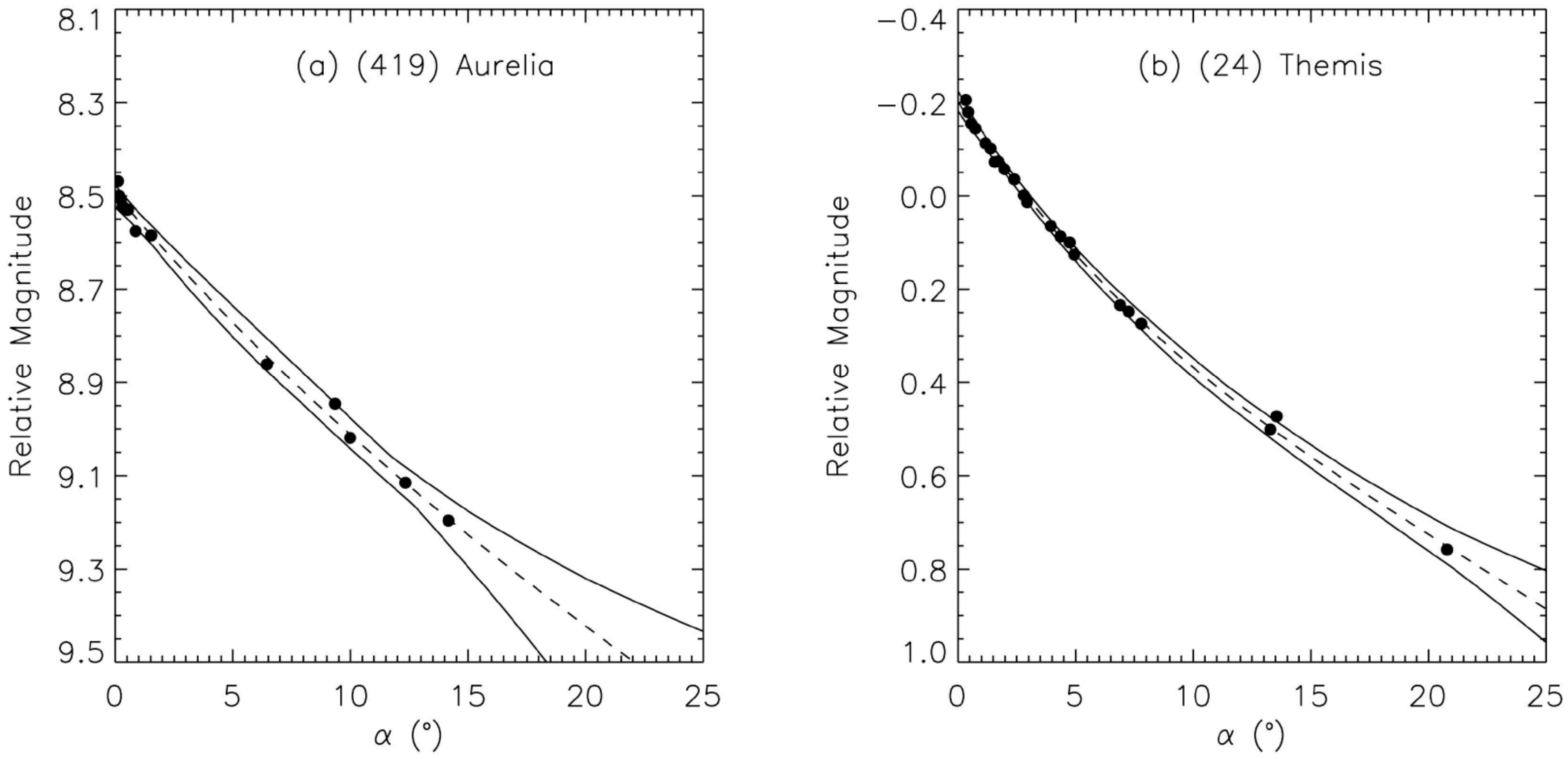
- Introduction to single and multiple scattering
- Radiative-transfer coherent-backscattering method (RT-C)
- Modeling for transneptunian objects (TNOs) and Centaurs
- Modeling for lunar disk-resolved photometry from SMART-1/AMIE
- RT-C vs. *T*-matrix method
- Conclusions

Introduction

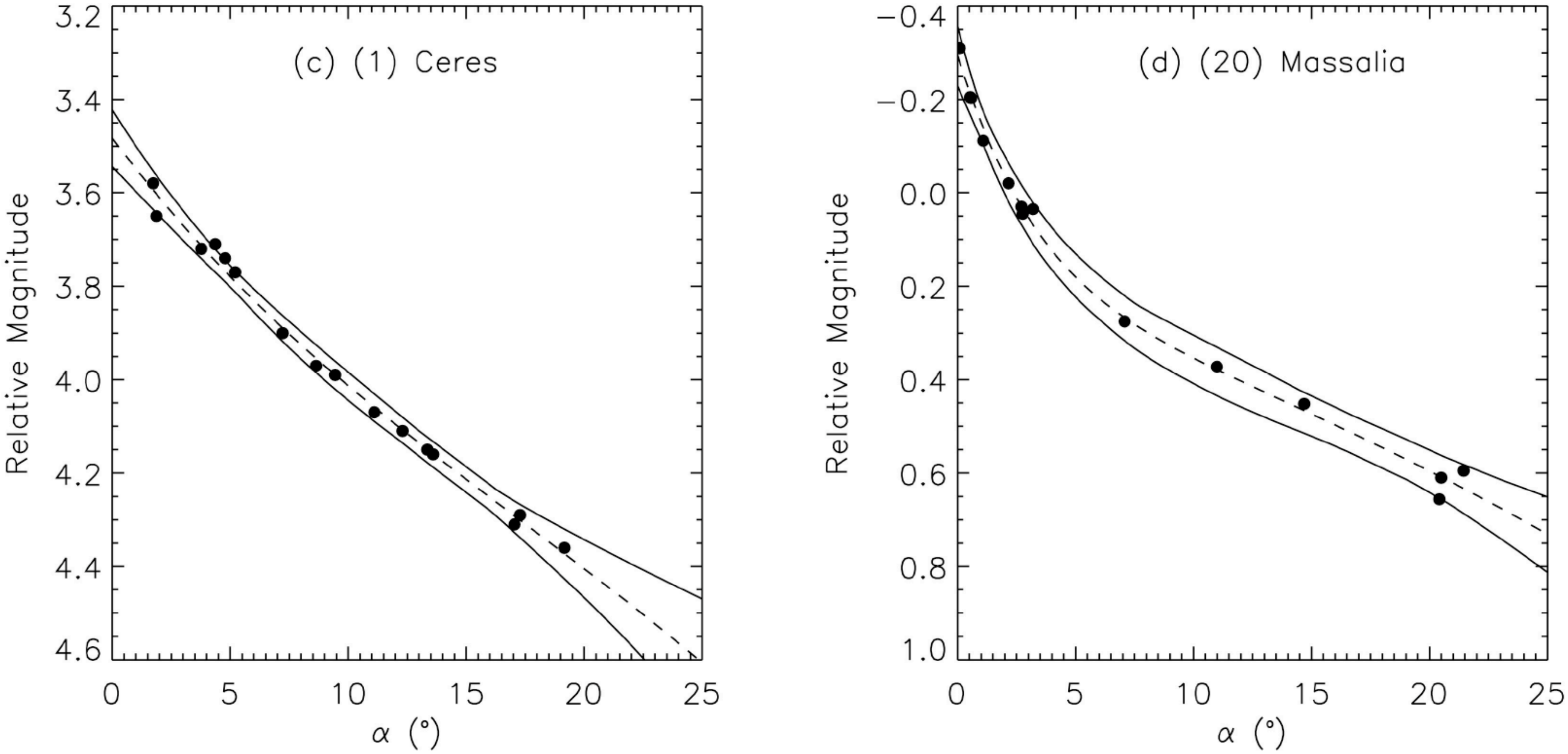
- Physical properties of atmosphereless solar-system objects (asteroids, Moon, transneptunian objects)
- Polarimetric and photometric observations
- Direct problem of computing scattering by regolith particles with varying size, shape (structure), and refractive index (optical properties)
- Inverse problem of retrieving physical properties of particles based on observations



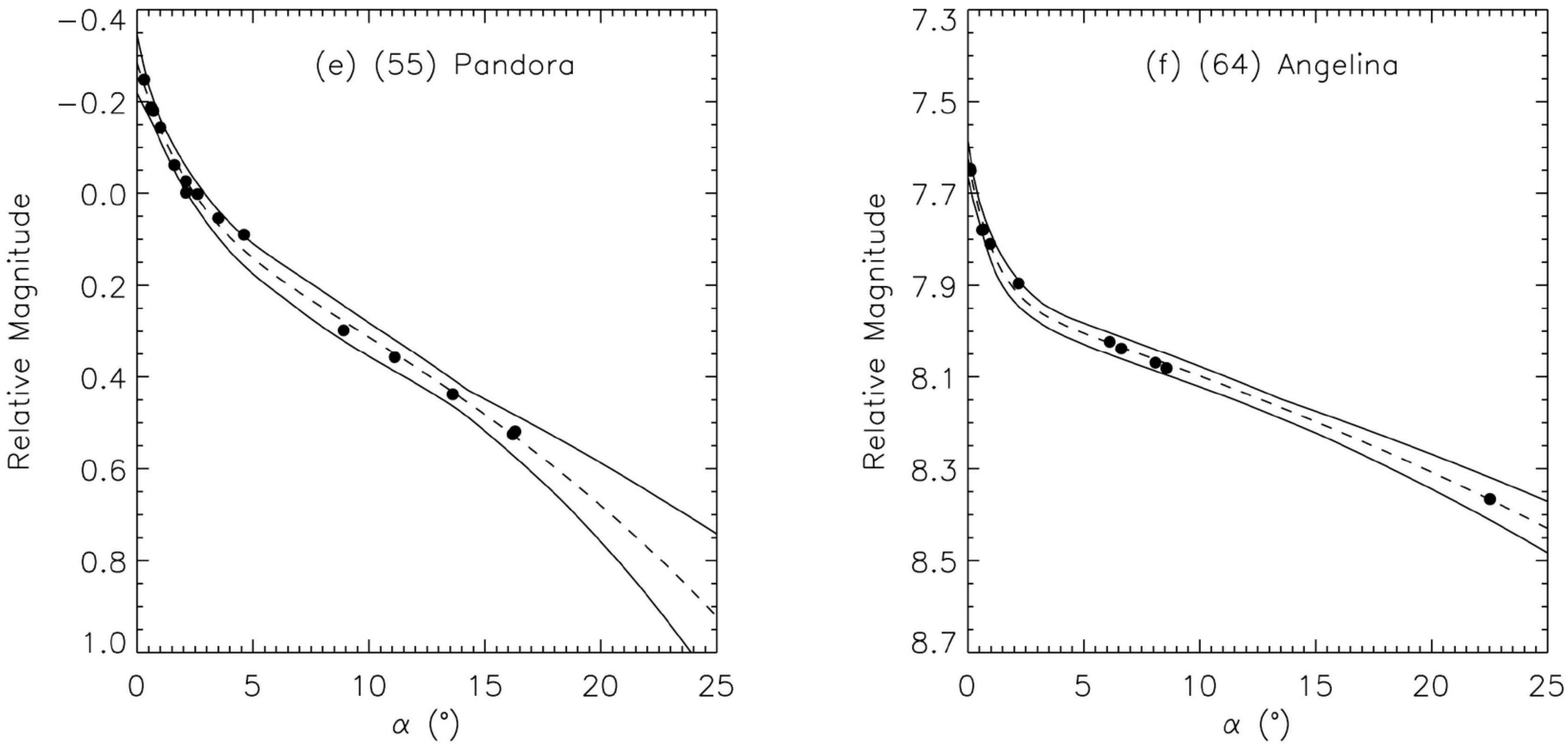
Courtesy: Timo Nousiainen

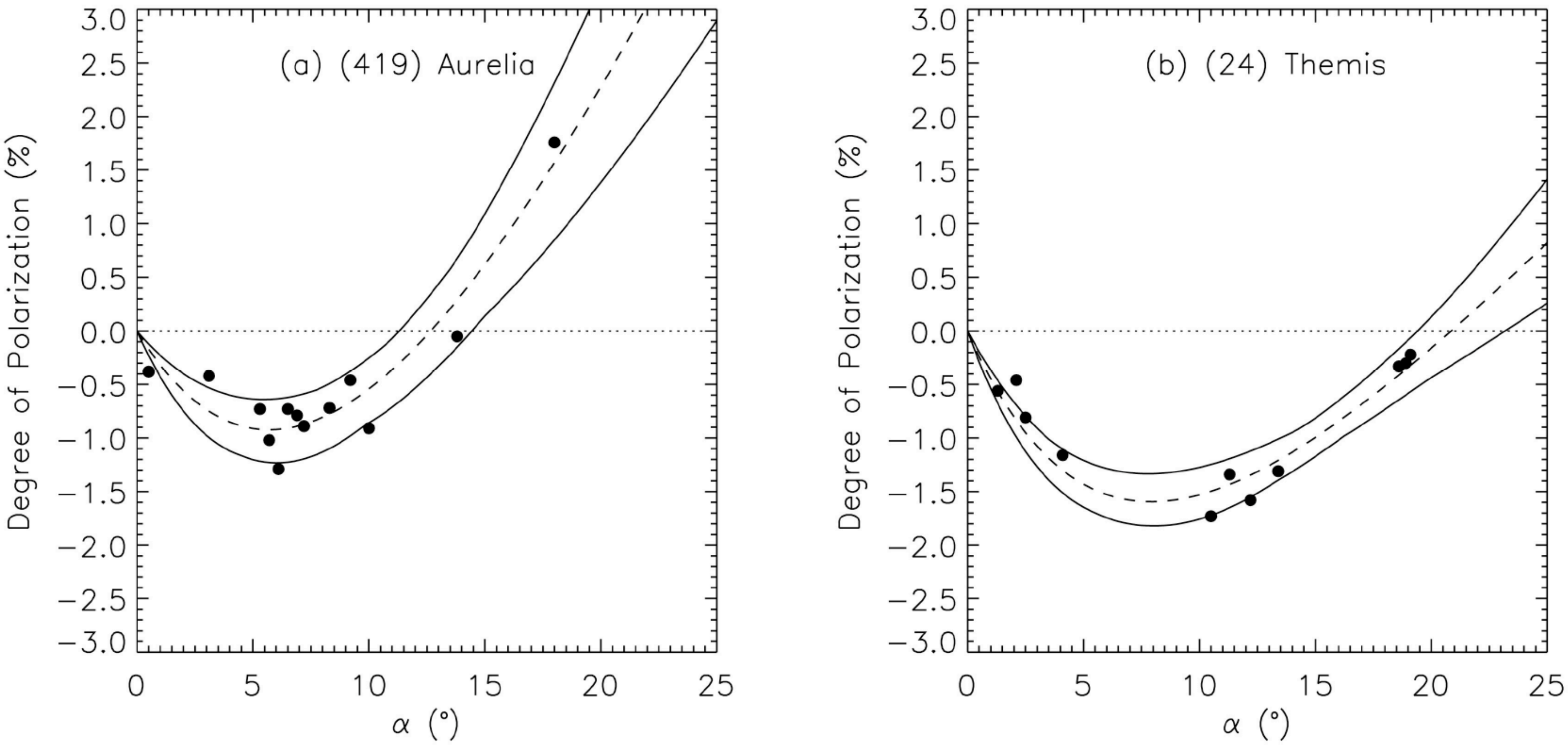


Muinonen et al., MAPS 44, 1937, 2009, obs. ref. therein

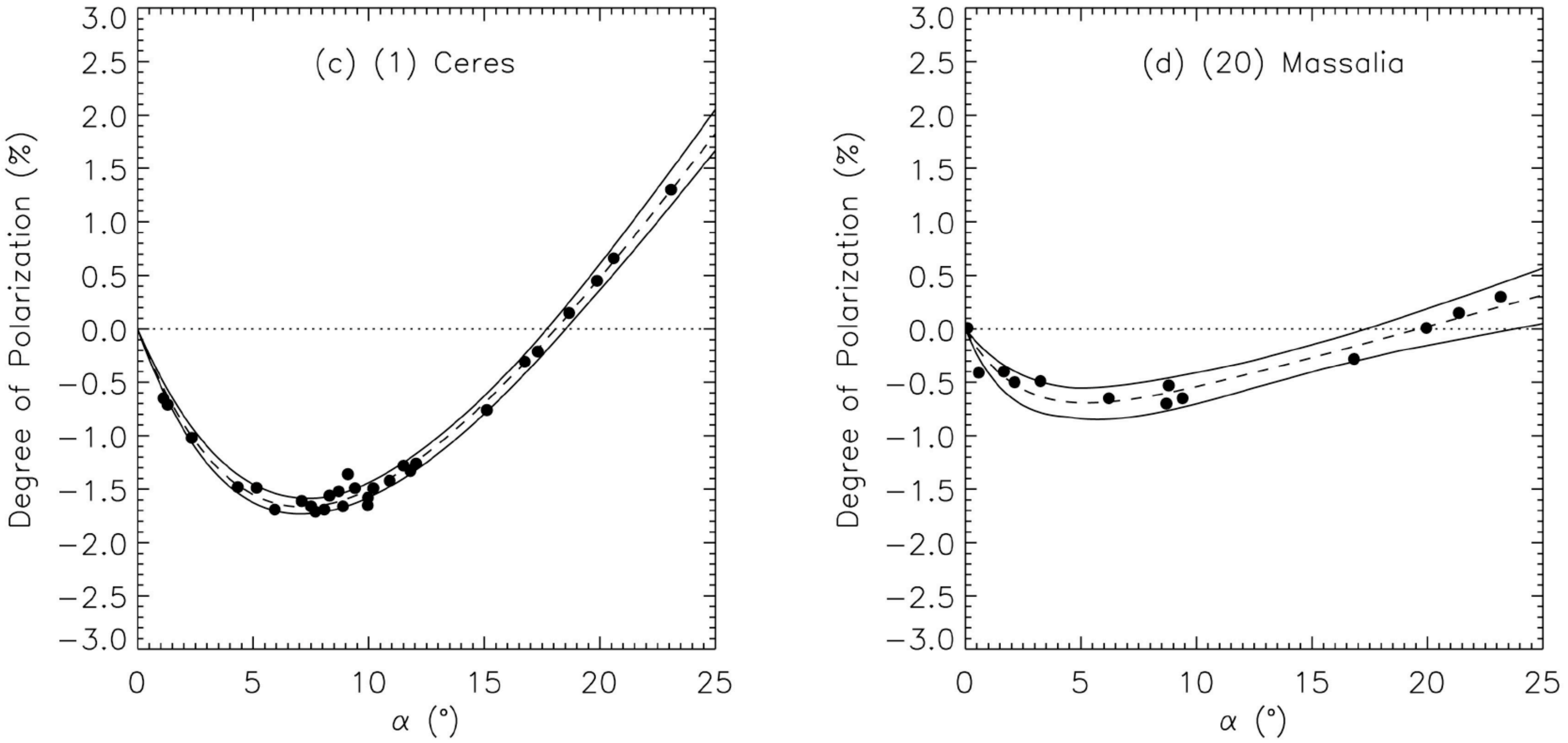


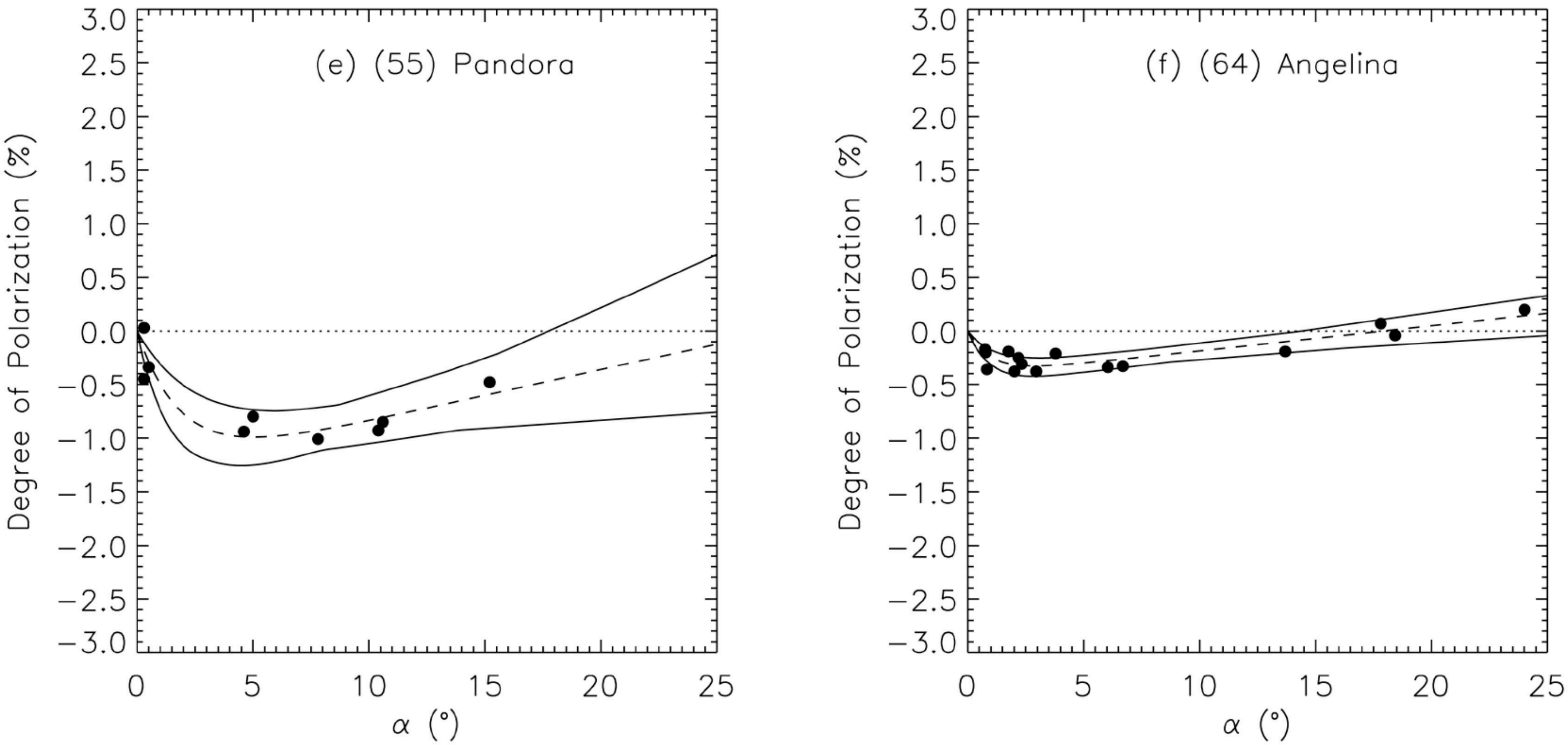
(c) (1) Ceres
Relative Magnitude
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
0
5
10
15
20
25
α (°)
(d) (20) Massalia
Relative Magnitude
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
α (°)


(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
Relative Magnitude
7.3
7.5
7.7
7.9
8.1
8.3
8.5
8.7
0
5
10
15
20
25
α (°)



(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 (%)
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
α (°)



(e) (55) Pandora
(f) (64) Angelina
Degree of Polarization (%)
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
α (°)

- Model based on coherent backscattering and radiative transfer
- References:
  - Muinonen et al., Light Scattering Reviews 5, 377, 2010
  - Muinonen, Waves in Random Media 14, 365, 2004

Multiple scattering from a particulate medium is a function of

- surface roughness
- volume density of the particulate medium
- size of small particles
- shape (structure) of small particles
- refractive index of small particles

Interpreting polarization:

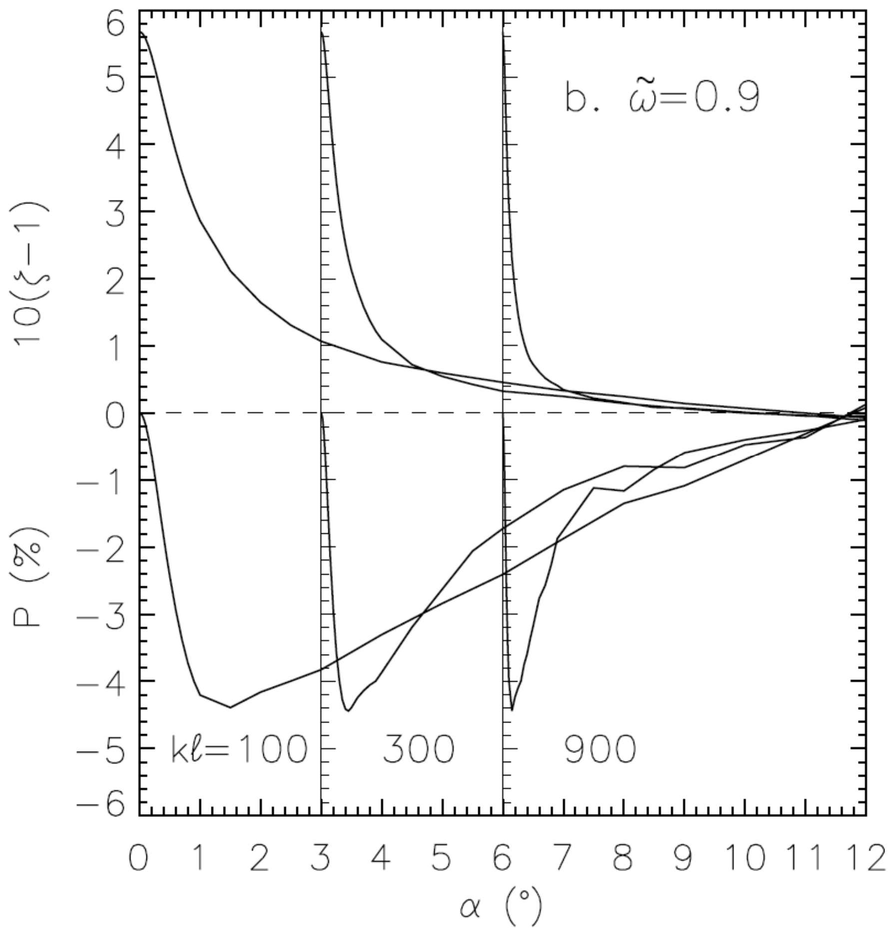
- Phase angles ~0-30^o: interference in transverse internal fields of single scatterers
- ~30-150^o: interference in longitudinal internal fields of single scatterers
- ~0-180^o: Rayleigh scattering (small scatterers)
- ~0-180^o: Fresnel reflection/refraction (large scatterers)
- ~0-20^o: coherent backscattering (multiple scattering; wider angular range for embedded media)
- ~20-180^o: multiple scattering (interference omitted)

Interpreting brightness:

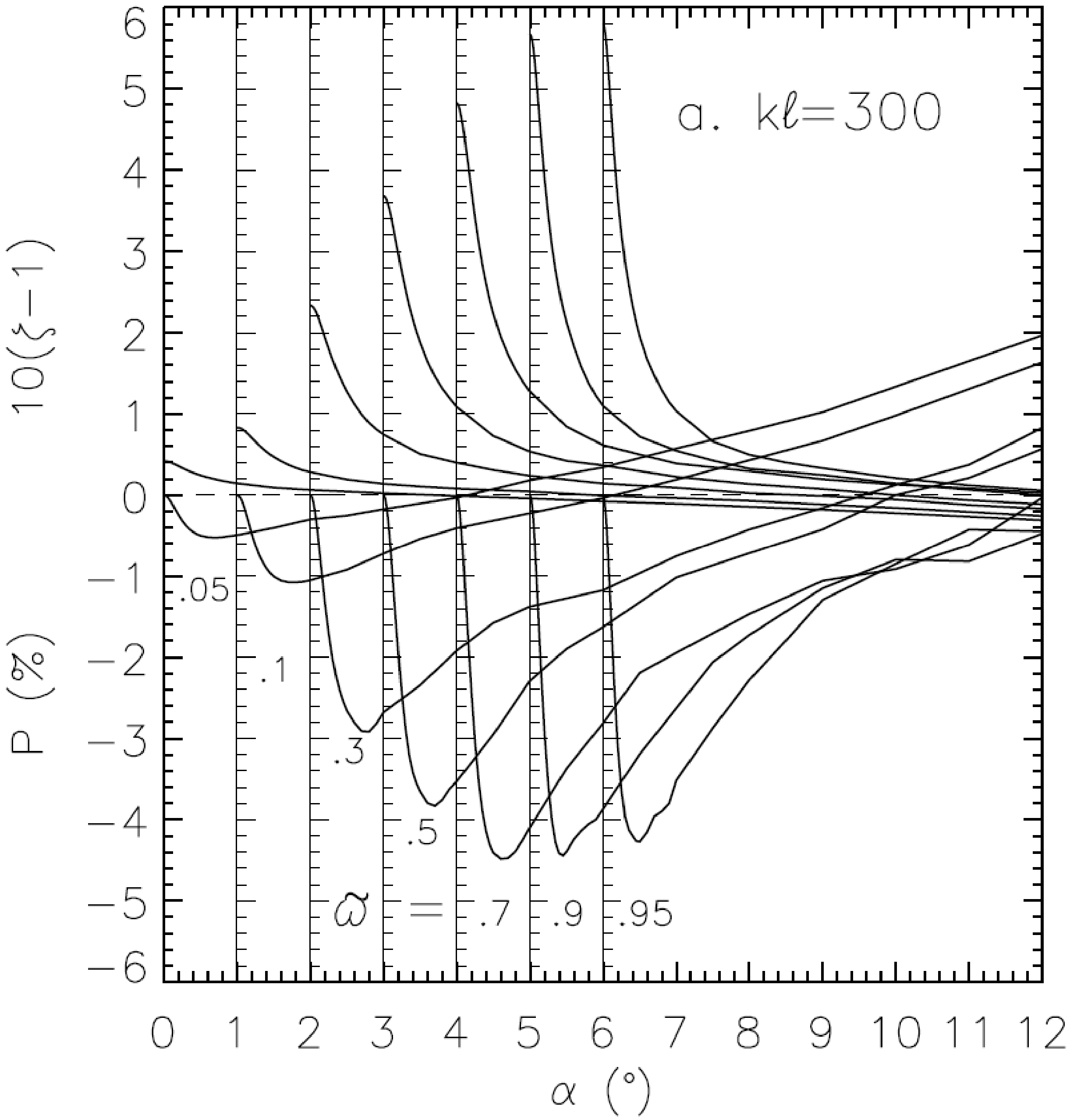
- Phase angles ~0-10^o: mutual shadowing among particles
- ~0-180^o: shadowing due to surface roughness
- ~0-20^o: coherent backscattering (multiple scattering)
- ~20-180^o: multiple scattering (interference omitted)
- ~0-30^o: interference in transverse internal fields of single scatterers
- ~30-150^o: interference in longitudinal internal fields of single scatterers

RT-C with polarization

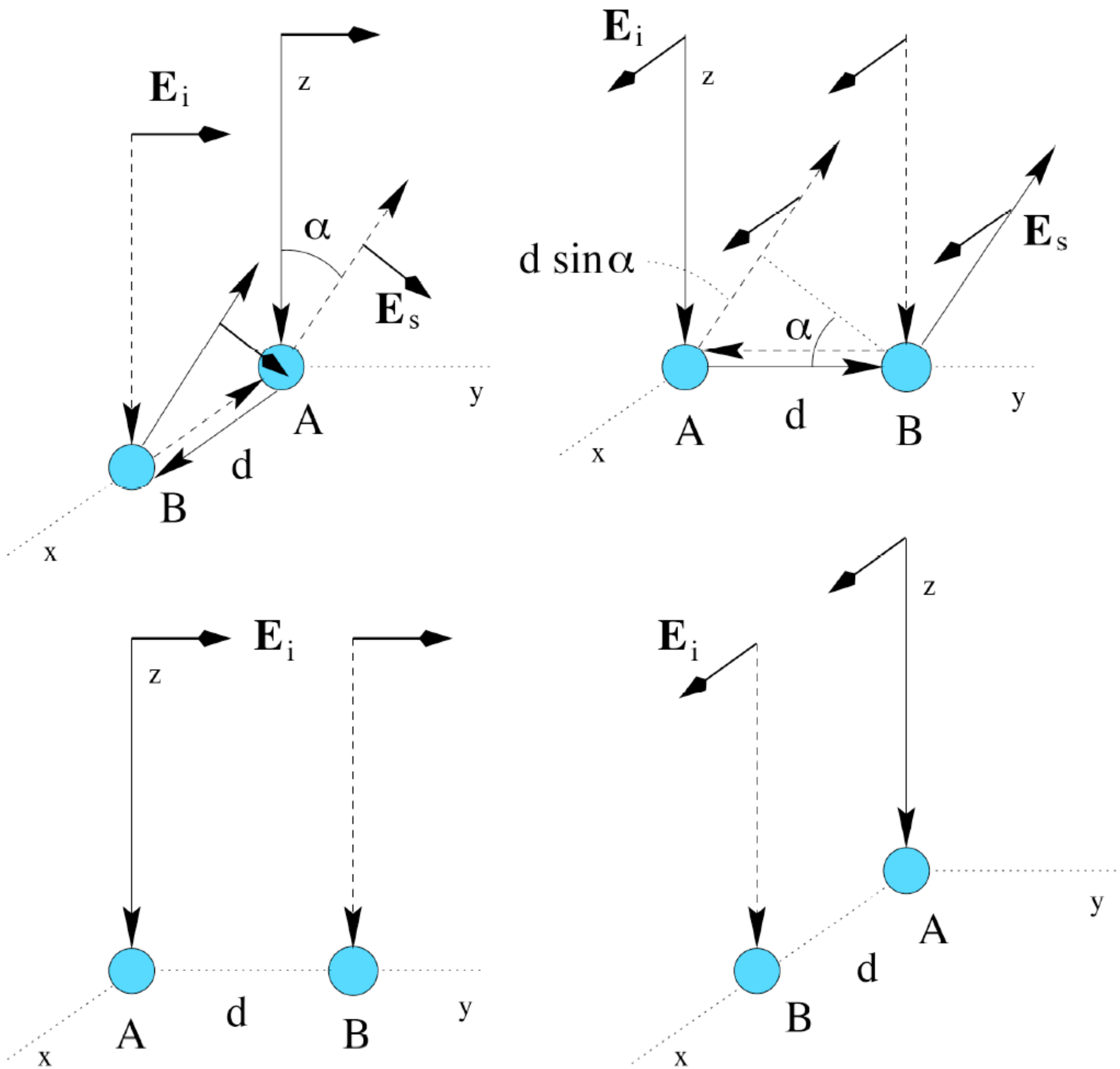
- Polarization and intensity surges due to interference in multiple scattering for a spherical medium
- Monte Carlo for radiative transfer and coherent backscattering
- Full angular profiles for the complete scattering matrix
- Diametrical optical thickness approaching infinity



Muinonen et al., Light Scattering Reviews 5, 377, 2010

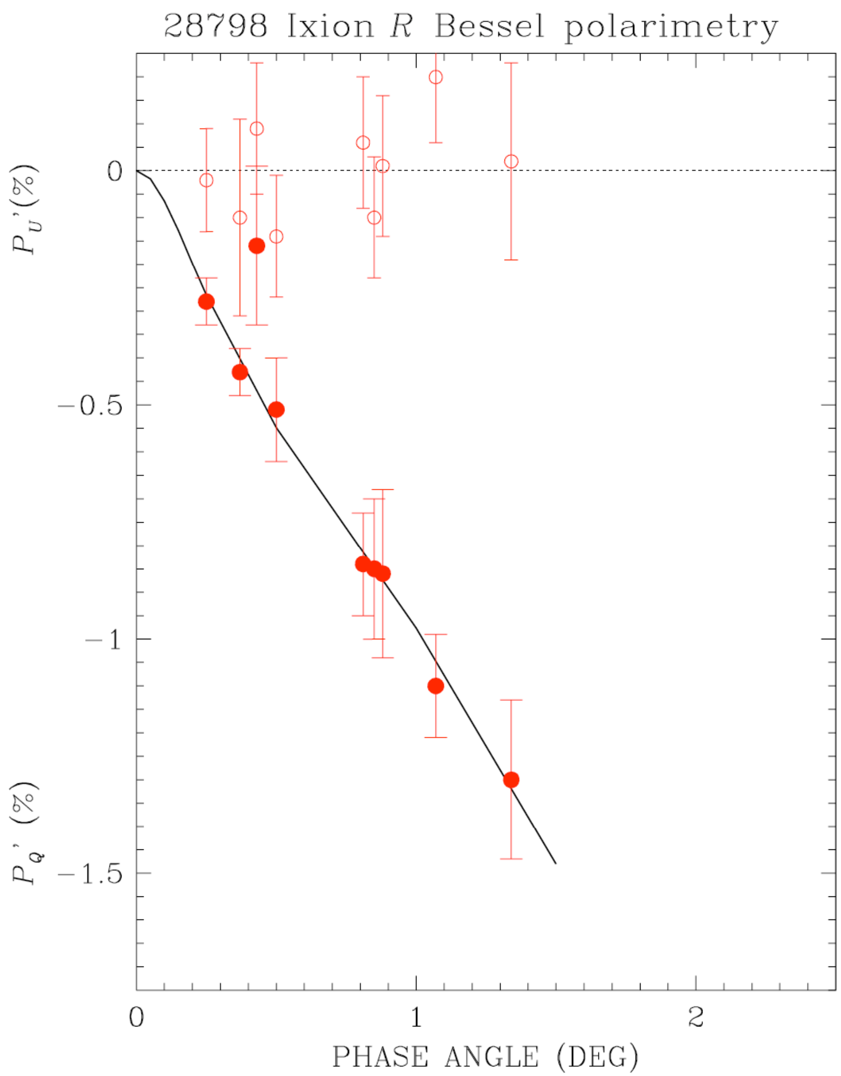


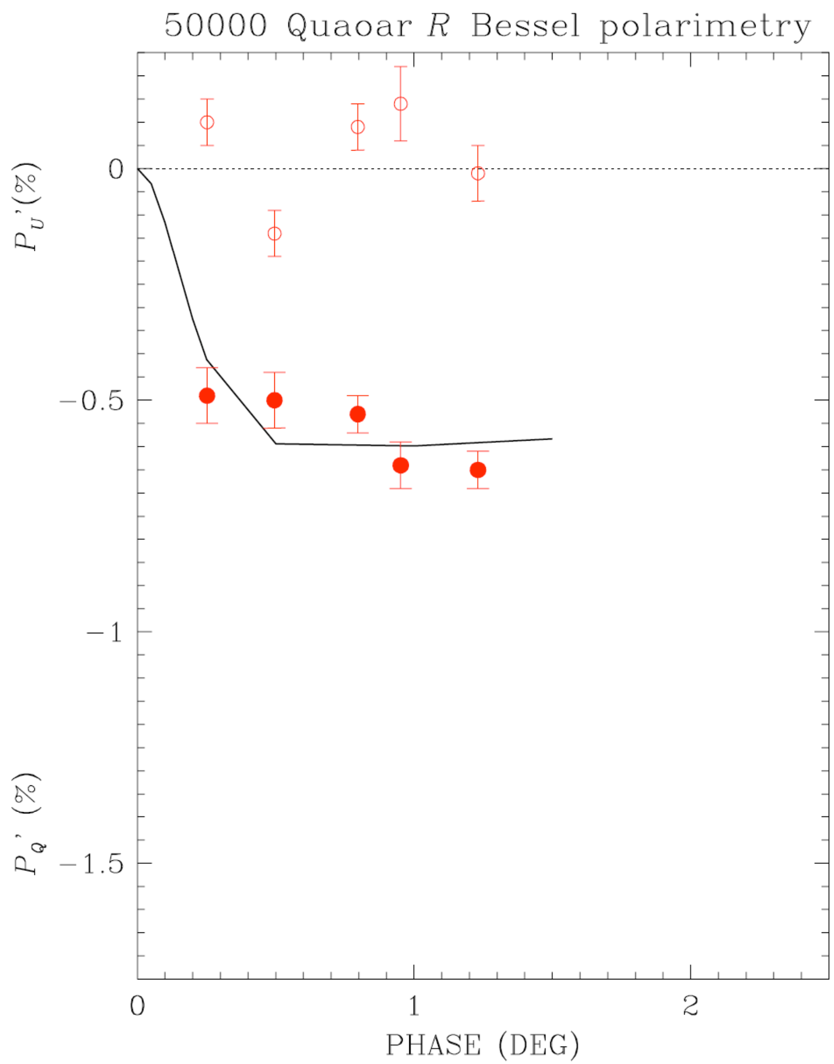
a. kℓ=300
10(ζ−1)
P (%)
α (°)
ϖ =
.05
.1
.3
.5
.7
.9
.95
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0 1 2 3 4 5 6 7 8 9 10 11 12



E_i
z
α
E_s
A
B
d
x
y
d sin α

Ixion and Quaoar





Bagnulo et al., A&A 450, 1239, 2006

Chiron

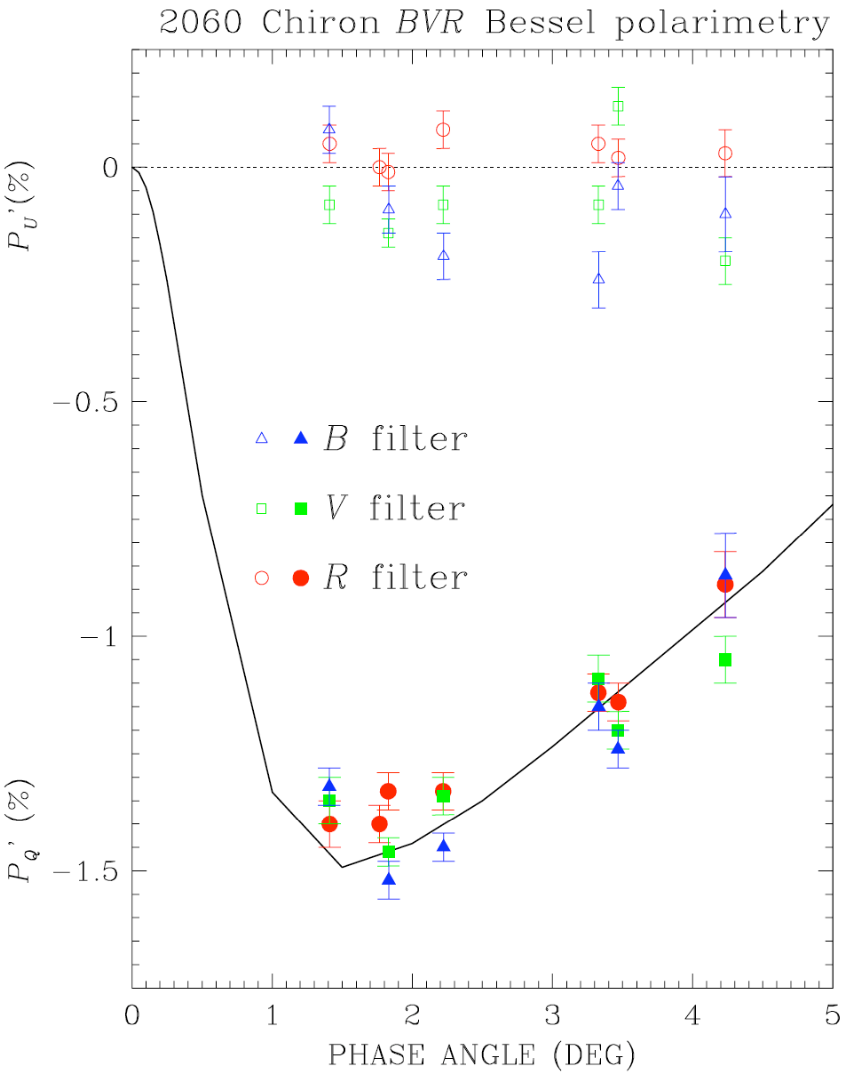
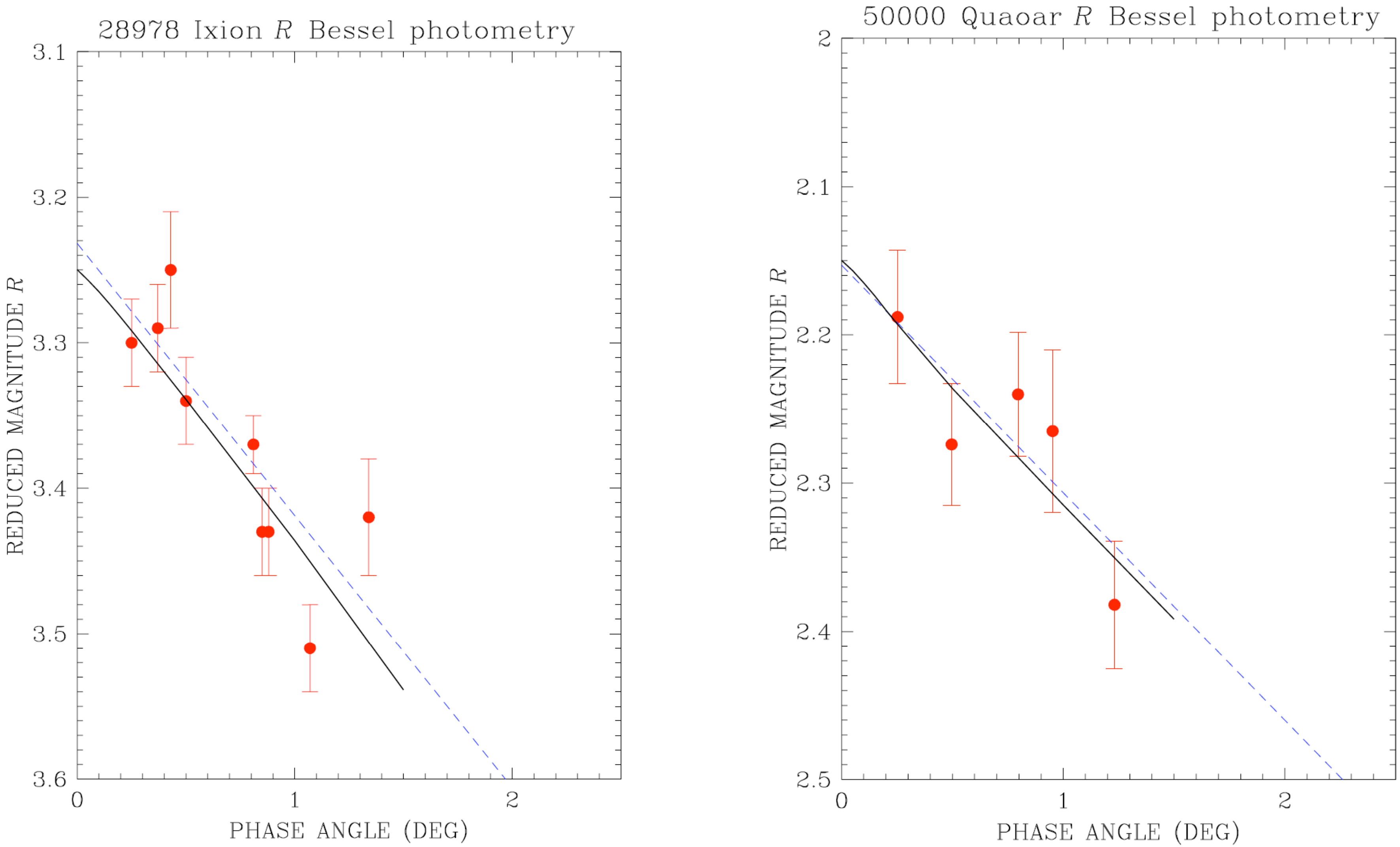


Table 5. The best-fit coherent-backscattering model parameters for Ixion, Quaoar, and Chiron. We give the single-scattering albedos $\tilde{\omega}$ and dimensionless mean free paths $k\ell$ for the dark (subscript d) and bright components (b), the weight of the dark component w_d, the rms values of the polarimetric fits, as well as the R-band absolute magnitudes H_R and slope parameters k_R.

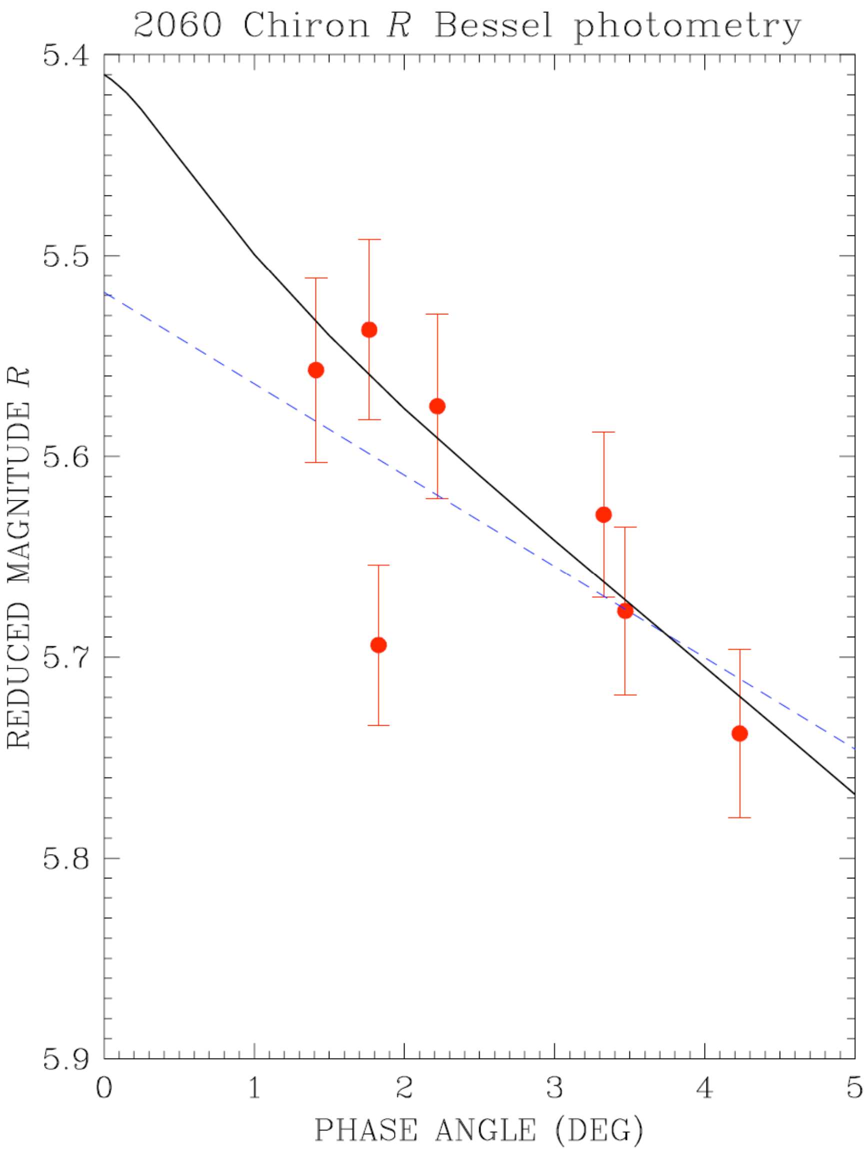
	Ixion	Quaoar	Chiron
$\tilde{\omega}_d$	0.45	0.35	0.15
ℓ_d	250	300	120
$\tilde{\omega}_b$	0.80	0.50	0.60
ℓ_b	20	10	500
w_d	0.74	0.46	0.14
rms	0.029 %	0.069 %	0.067 %
H_R	3.25	2.15	5.41
k_R	0.12/deg^{-1}	0.11/deg^{-1}	0.041/deg^{-1}

Ixion and Quaoar



Bagnulo et al., A&A 450, 1239, 2006

Chiron


2060 Chiron R Bessel photometry
REDUCED MAGNITUDE R
PHASE ANGLE (DEG)
5.4
5.5
5.6
5.7
5.8
5.9
0
1
2
3
4
5