

Scattering, Absorption, and Emission of Light by the Mercury Regolith

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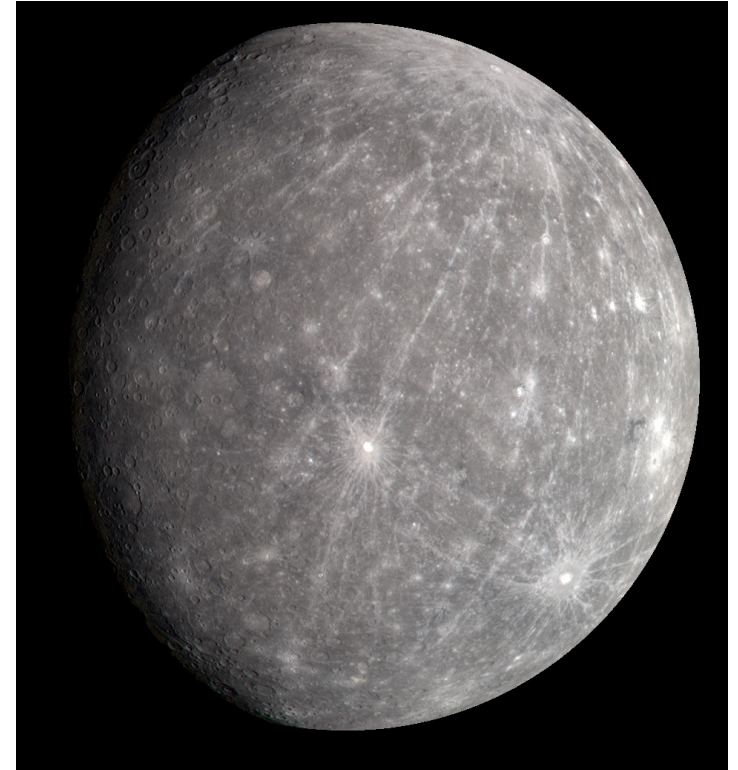
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Introduction

- ESA/JAXA BepiColombo mission at Mercury in fall 2026
- Why does spectroscopy fail to reveal significant **iron** on the surface, despite it being a major interior constituent?
- Do the permanently shadowed craters in the polar regions contain **water ice or sulfur**?
- What are the mechanisms producing Mercury's thin **exosphere**?
- How have **tectonism, volcanism, and cratering** shaped the surface?



Mercury in true colors by MESSENGER

By NASA/Johns Hopkins University Applied Physics Laboratory/
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- Physical characterization of Mercury surface regolith
- Forward and inverse scattering problems concerning regolith particle sizes, shapes, and refractive indices, as well as spatial distribution
- Plane of scattering, scattering angle, solar phase angle
- Stokes parameters, scattering Mueller matrix
- Disk-integrated brightness L (often in magnitude scale, $-2.5 \log_{10} L$)
- Degree of linear polarization $(L_r - L_l)/(L_r + L_l)$

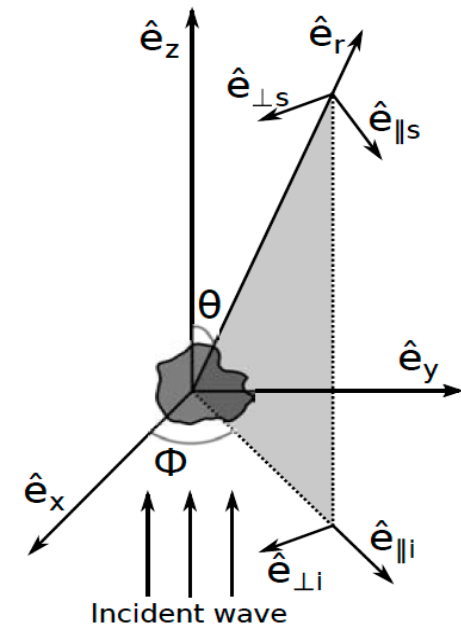


Figure 2.2: Illustration of the incident wave and the scattering plane. (Bohren and Huffman, 1983)

Mercury photometric phase curve

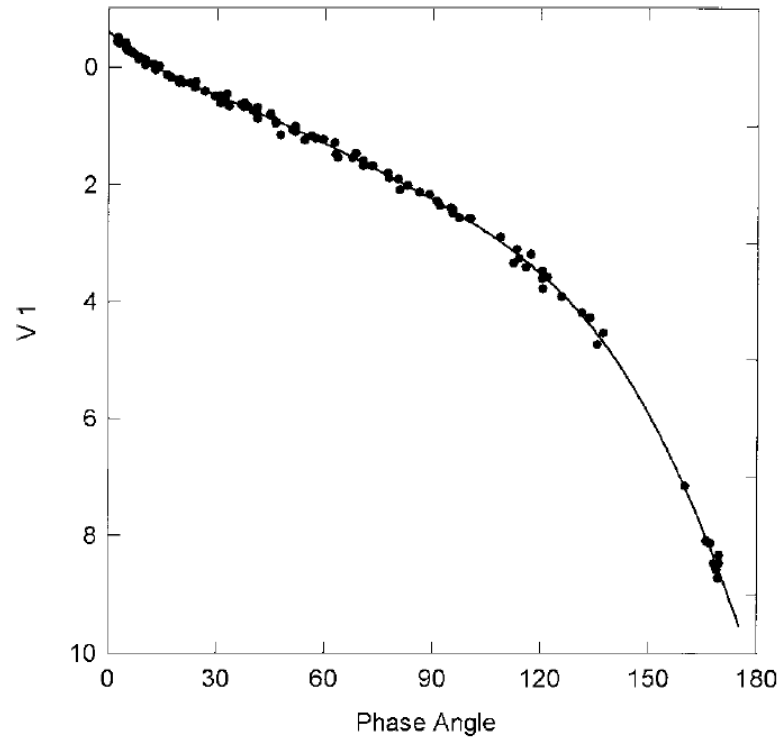
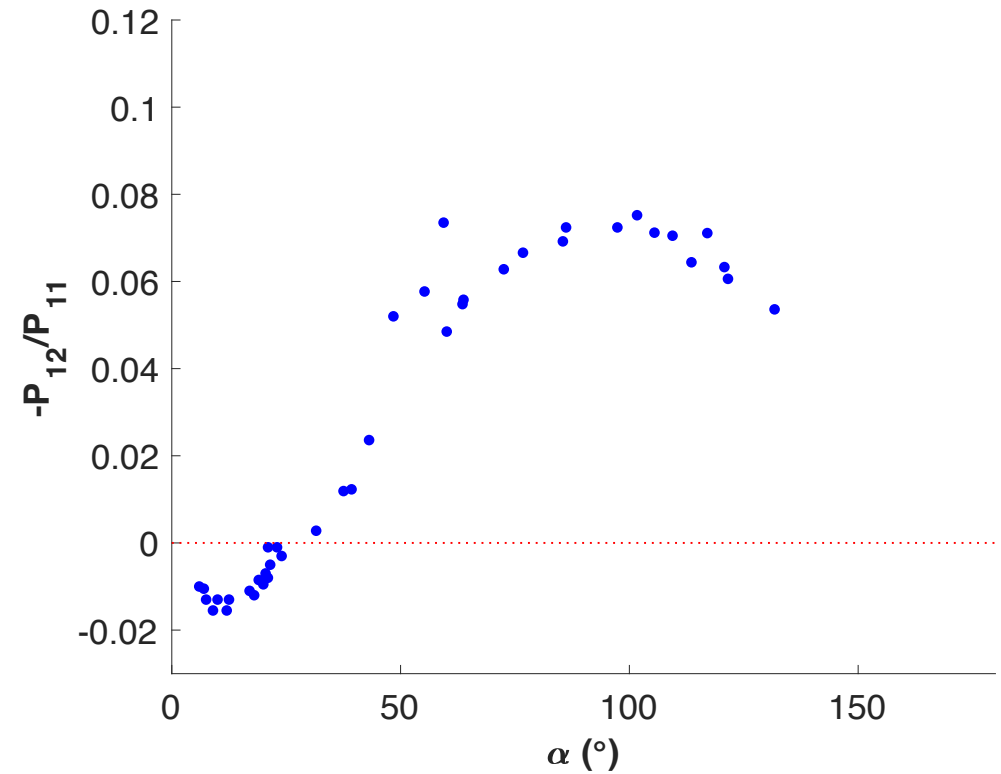


FIG. 6. The observed phase function of Mercury in V . The solid line represents the polynomial whose coefficients are listed in Table V.

Mallama et al., *Icarus* 155, 253, 2002

Mercury geometric albedo $p_V = 0.12-0.14$

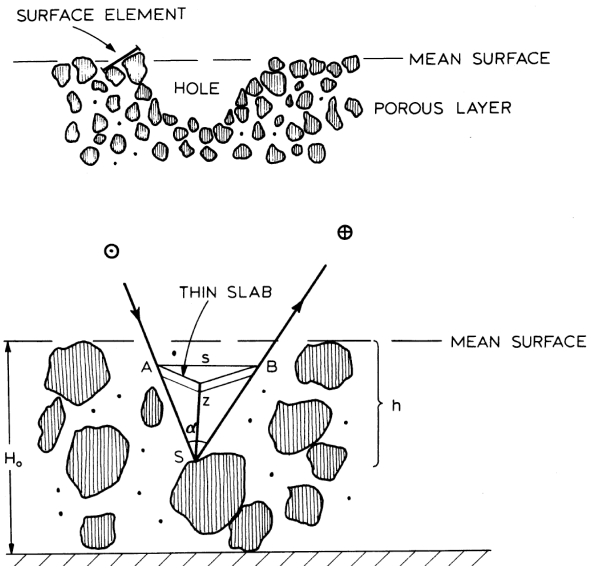
Mercury polarimetric phase curve



Lyot, *Comptes Rendus Acad. Sci.* 1930

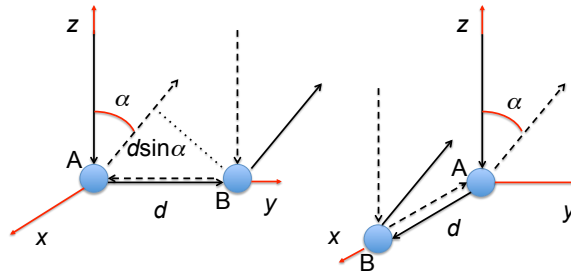
Dollfus, *Icarus* 23, 465, 1974

Shadowing mechanism



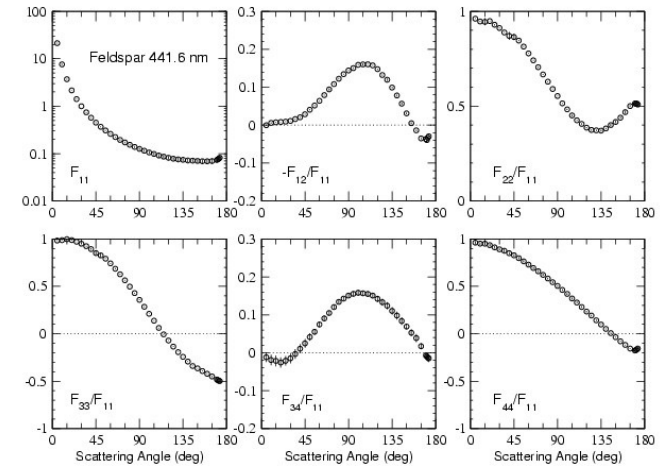
e.g., Lumme & Bowell (1981),
Hapke (1963), Seeliger (1887),
Russell (1916)

Coherent backscattering mechanism



Muinonen (1989, 1990)
Shkuratov (1985, 1988, 1989)

Nonspherical particle mechanism

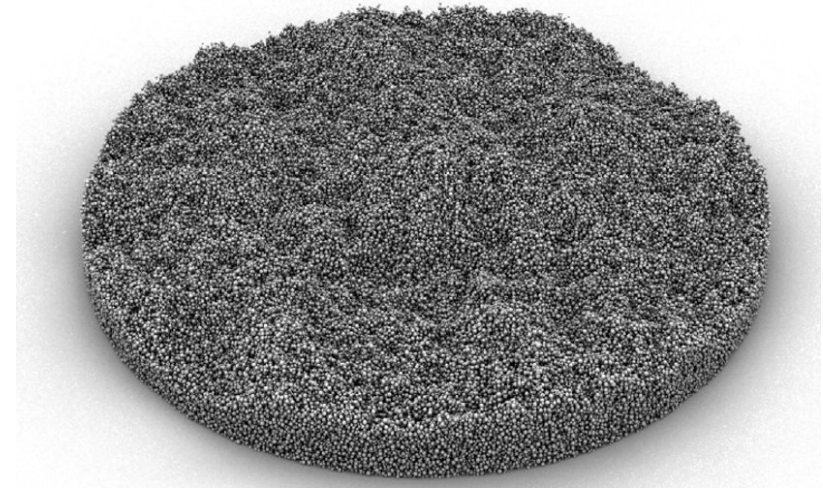


Feldspar measurements; Volten et al. (2001), Muñoz et al. (2012)

Computations, e.g.,
Lumme and Rahola (1998),
Muinonen et al. (2007, 2011),
Zubko et al. (2007)

Particulate-medium model: Realistic regolith properties

- Theoretical particulate medium model (PM; Muinonen et al. 2011, Wilkman et al. 2015, Björn et al. 2024)
 - Fractal surface with three geometry parameters:
 - Packing density ν , fractal Hurst exponent H , amplitude σ
 - Reflection coefficient (reflectance):
 - $R_{PM} = 2p\Phi_{11}(\alpha)\Phi_S(\mu, \mu_0, \varphi_{az}) \frac{1}{\mu + \mu_0}$,
where
 - $2p\Phi_{11}(\alpha) \sim a + b\alpha$ is a linear phase function, and
 - $\Phi_S(\mu, \mu_0, \varphi_{az})$ is the shadowing correction from the database by Wilkman et al. 2015
 - <https://wiki.helsinki.fi/display/PSR/Numerical+Scattering+Law>



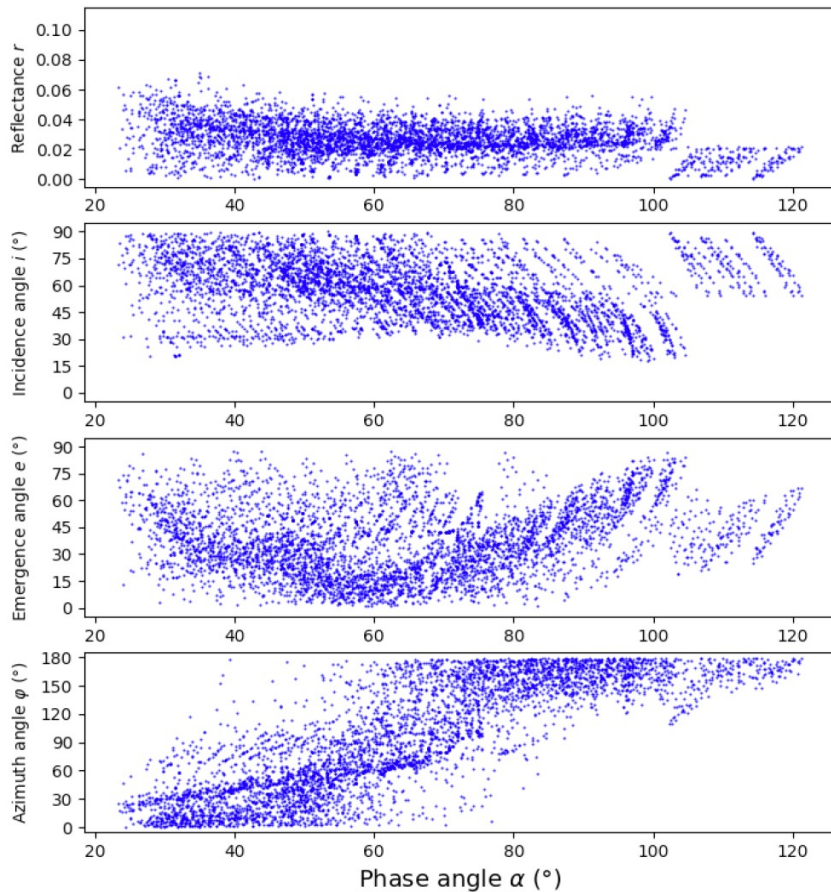
Parviainen et al. 2011

Parameter	Values
ν	0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55
H	0.20, 0.40, 0.60, 0.80
σ	0.00, 0.02, 0.04, 0.06, 0.08, 0.10

Wilkman et al. 2015

MDIS spectrophotometry

Filter C (479.9 nm)



- Reflection coefficient / cosine of incidence angle observed for Mercury as a function of the angle of incidence, angle of emergence, azimuthal angle, and the phase angle
- Eight colors, see Domingue et al., Icarus, 2016, and references therein (filters given below)
- Comparison of multiple photometric models

Filter	Wavelength (nm)
F	433.2
C	479.9
D	558.9
E	628.8
G	748.7
L	828.4
J	898.8
I	996.2

Regolith geometry (Björn et al. 2024)



Figure 7. Example realization of a surface with the geometry parameters having the median values from the MCMC samples. The Hurst exponent has a value of $H = 0.606$ and the surface amplitude $\sigma = 0.0998$. Packing density ν is approximately 0.55, and the particles are as in Figure 4.

- Median \pm interquantile values:
 - $\nu = 0.547 \pm 0.004$,
 - $H = 0.606 \pm 0.009$,
 - $\sigma = 0.0998 \pm 0.0003$

Phase reddening (Björn et al. 2024)

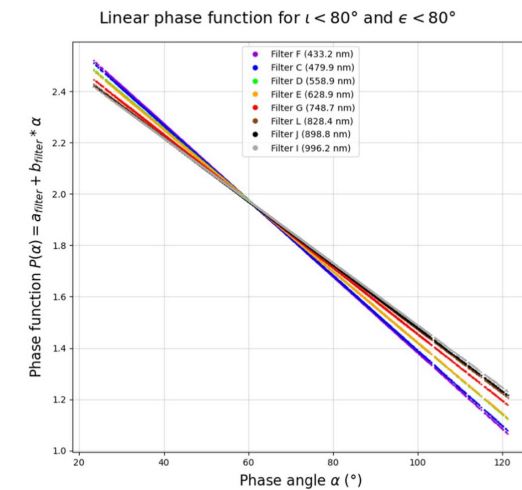
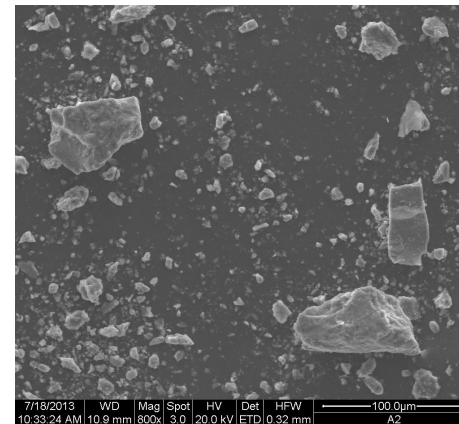
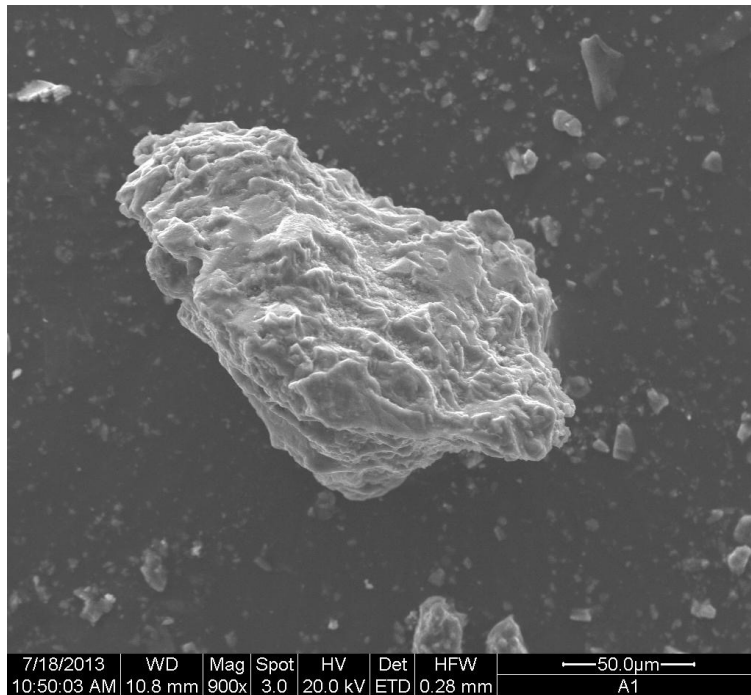
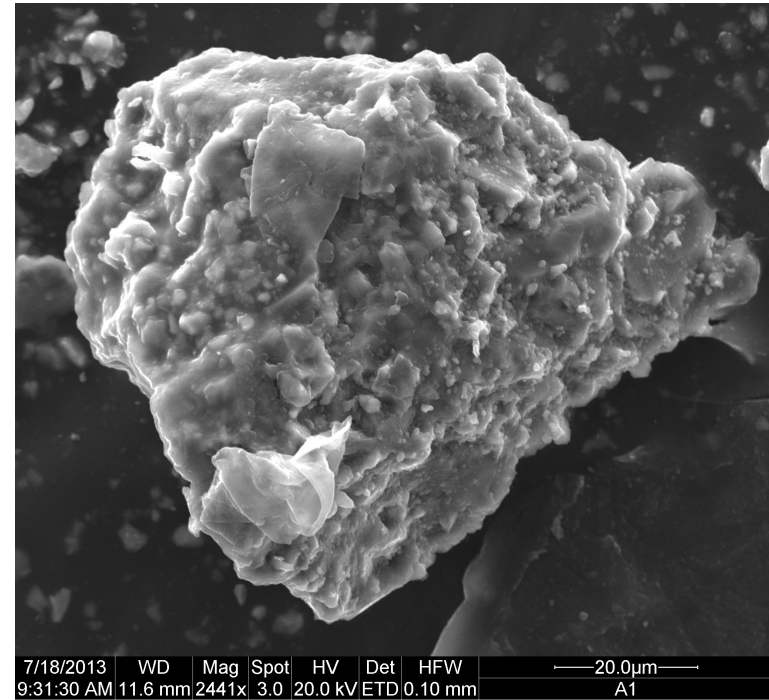
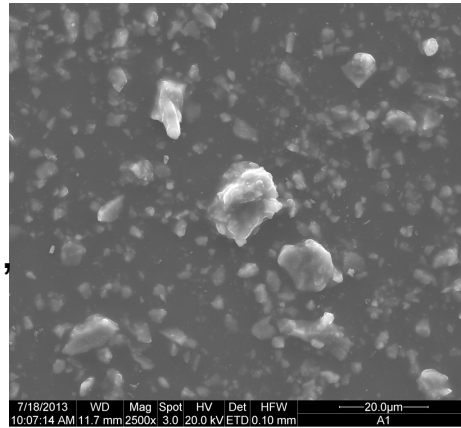


Figure 9. Phase function $P(\alpha)$.

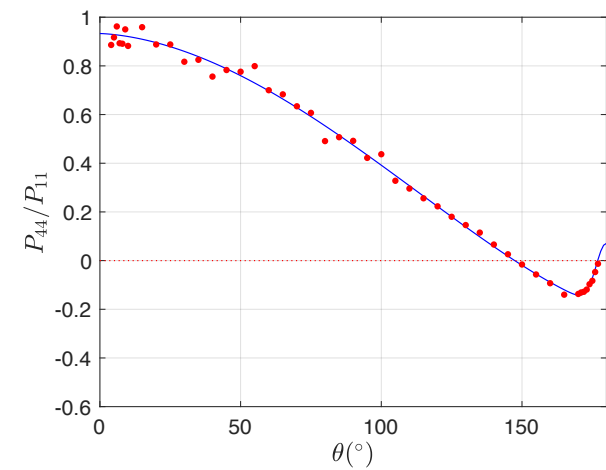
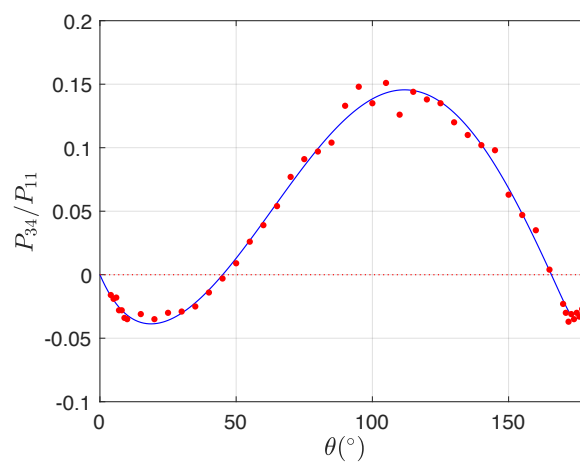
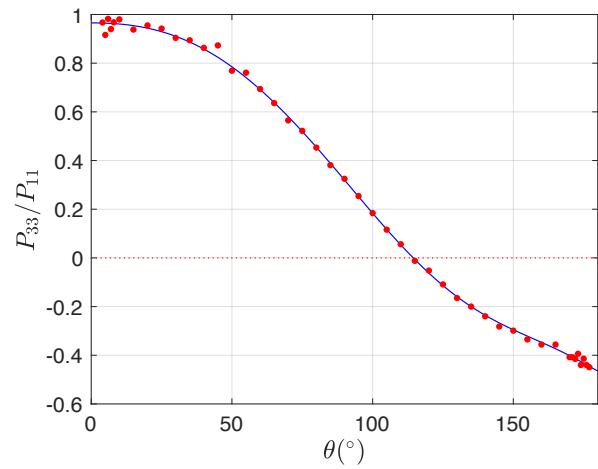
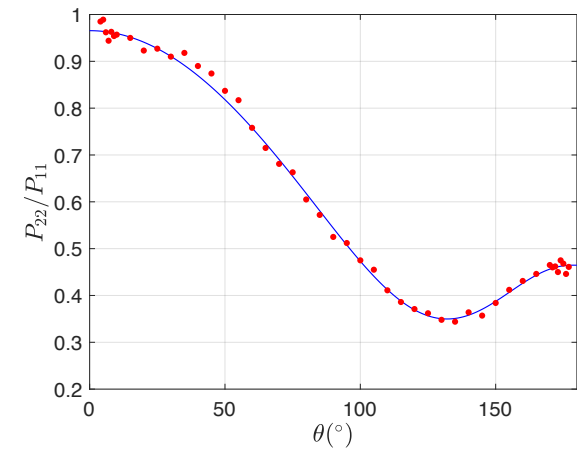
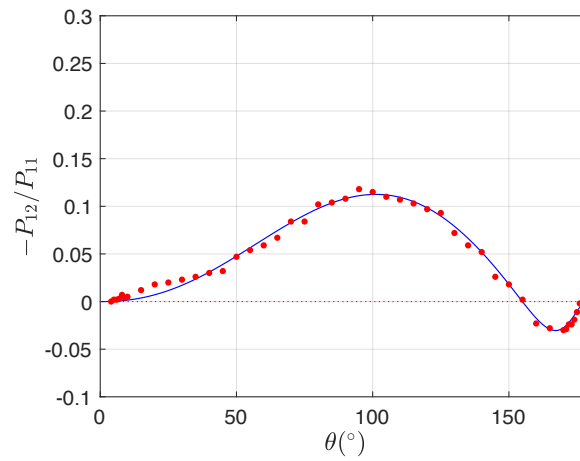
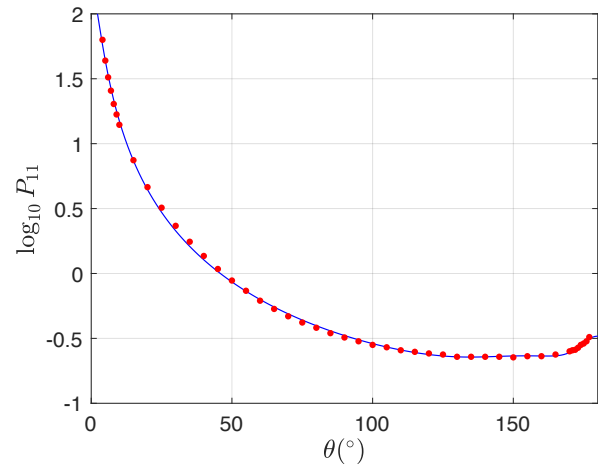
Radiative-transfer coherent-backscattering modeling (RT-CB)

- Fix geometric parameters (Björn et al., PSJ 5, 260, 2024):
 - Volume density $v = 0.550$
 - Hurst exponent $H = 0.597$
 - Roughness amplitude $\sigma = 0.0999$
- Obtain **single-element phase function** P_{11} (or $\sim p\Phi_{11}$) by dividing the Mercury phase function by the intrinsic phase function from the shadowing correction
- Make use of **RT-CB recently extended for ensemble-averaged scattering and absorption properties** (Muinonen et al. 2025, Muinonen & Penttilä 2024)
- Make use of **empirical scattering matrix system** (Muinonen & Leppälä 2025; Leppälä et al. 2026, submitted)

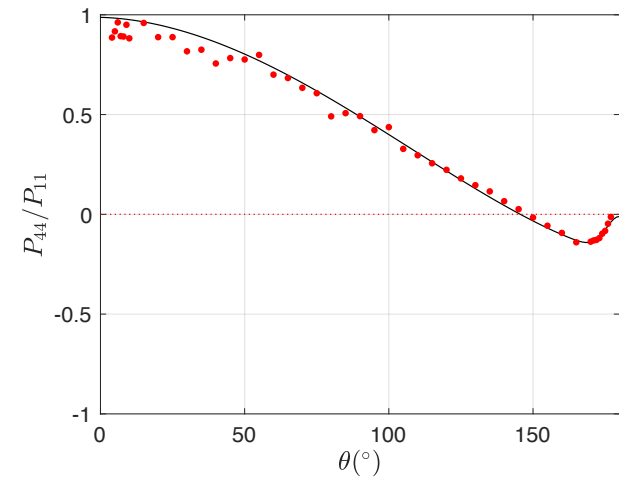
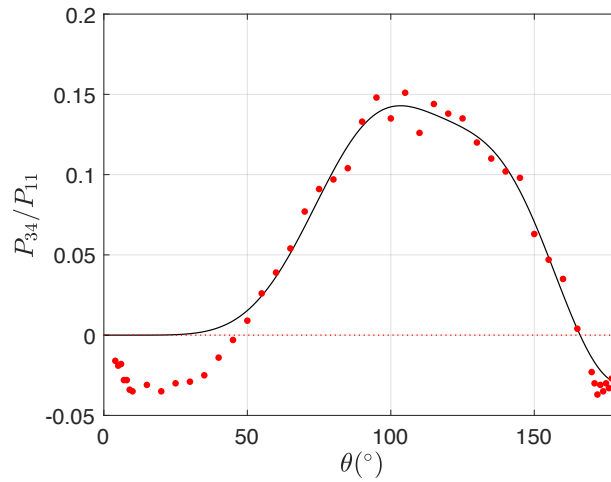
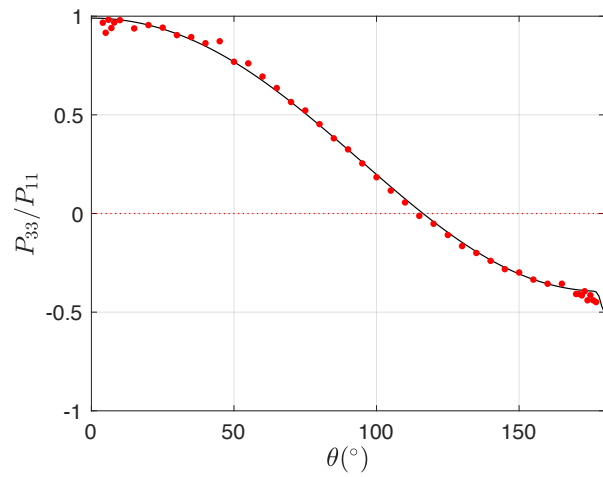
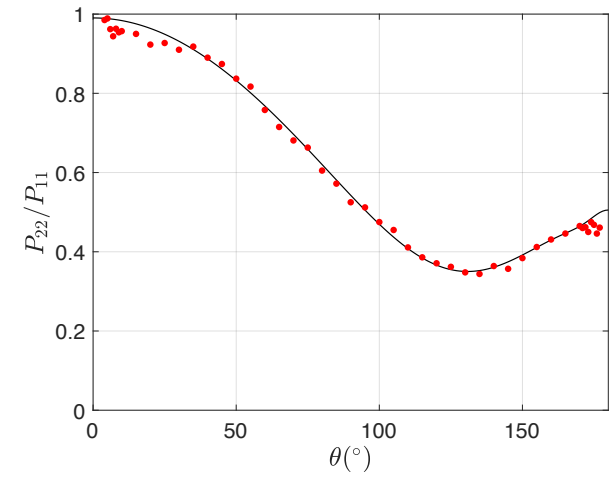
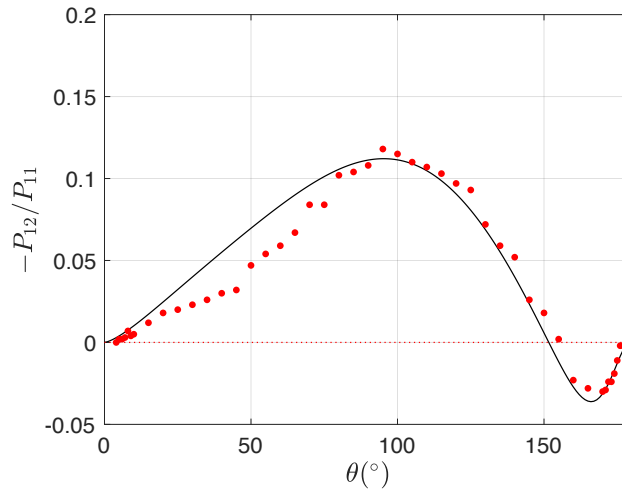
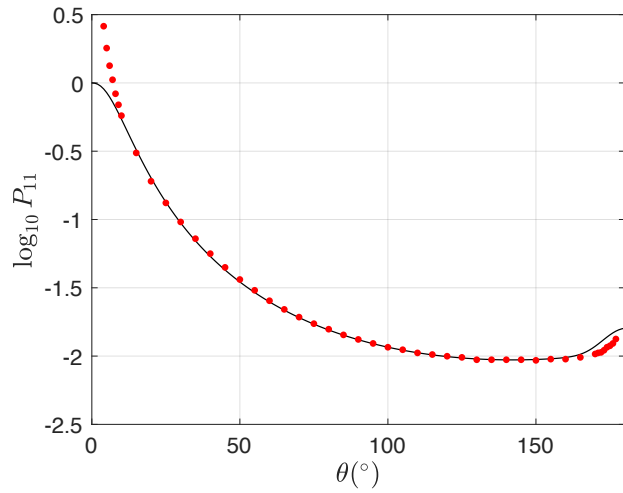
RT-CB input:
basalt sample,
Dabrowska et al. (2015),
Muñoz et al. (2025),
Granada-Amsterdam
scattering database



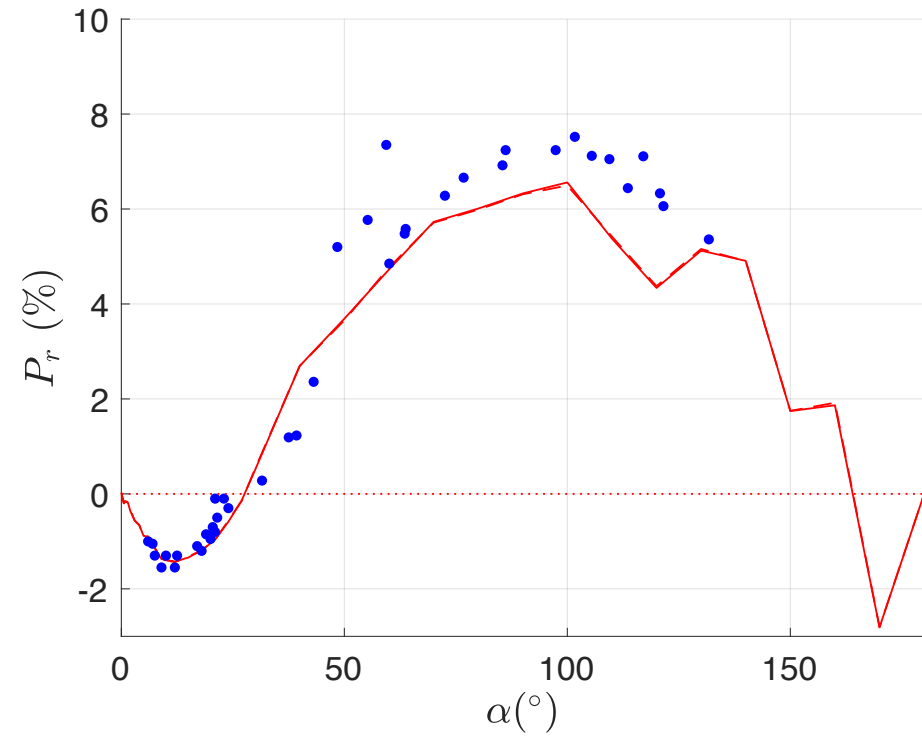
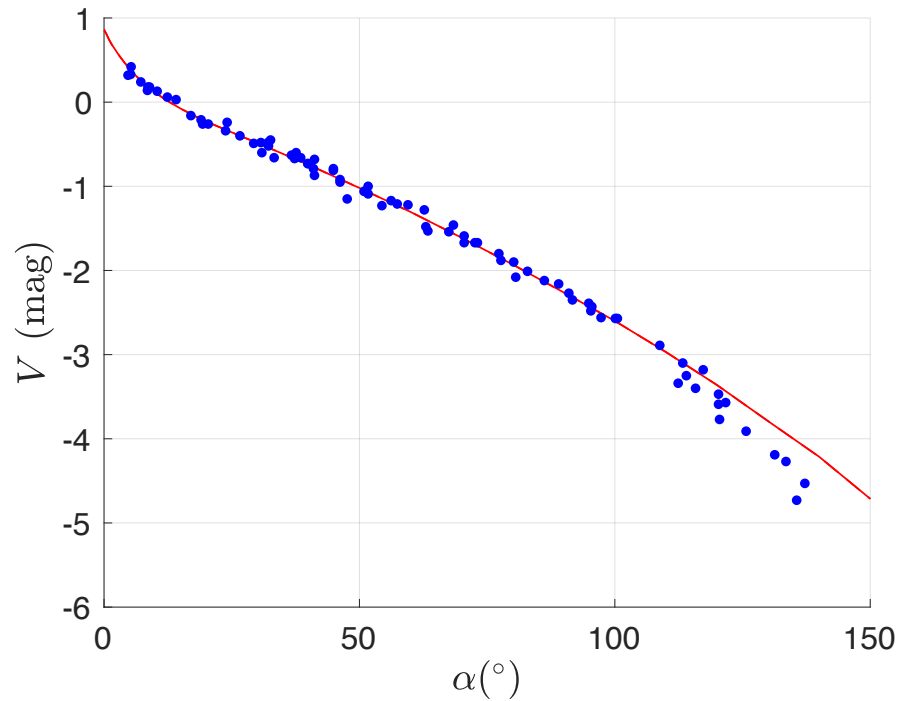
Scattering matrix measured, fit by Leppälä et al.



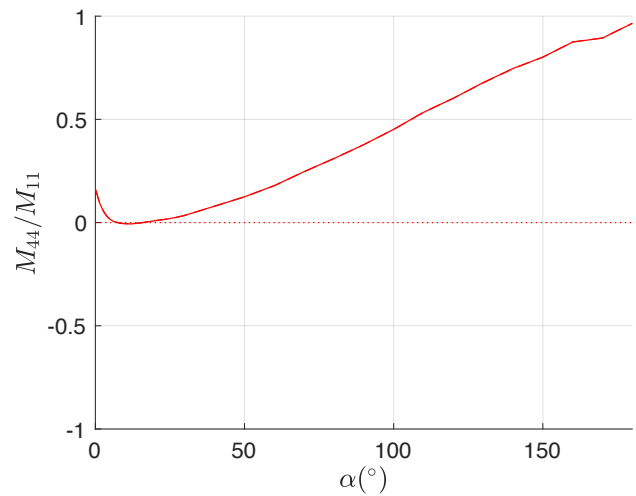
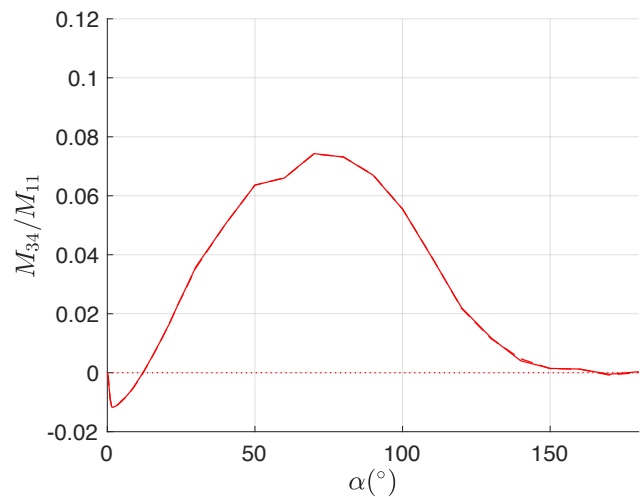
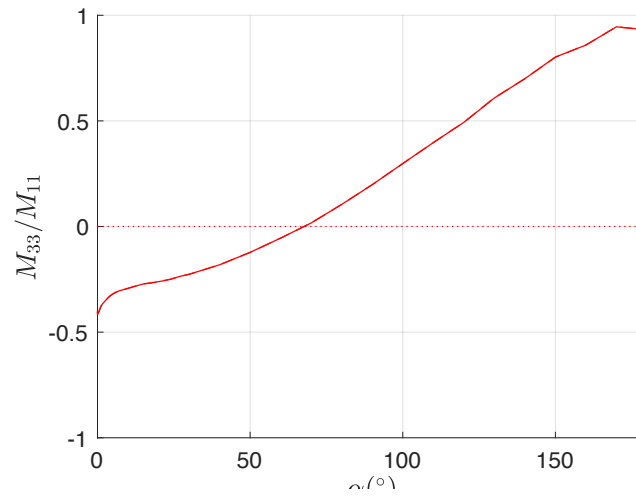
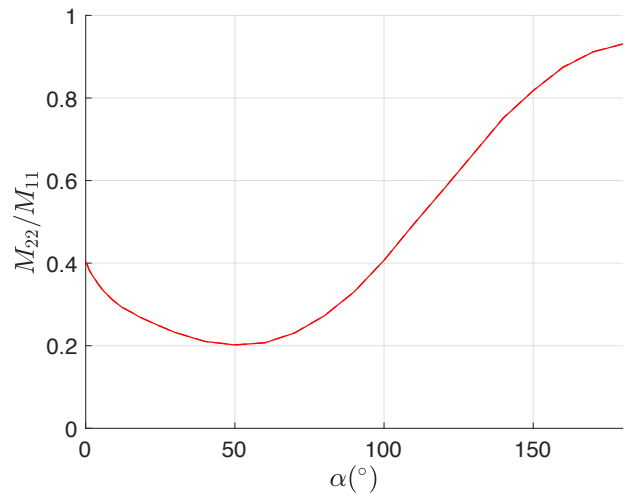
Scattering matrix optimized, Muinonen et al., in prep.



Mercury scattering model



Mueller matrix elements observable, M_{11} and $-M_{21}/M_{11}$
(Muinonen et al., in prep.)



Remaining Mercury Mueller matrix elements (Muinonen et al., in prep.), measurements by a [future lander or sample return mission](#) to Mercury

Conclusions

- RT-CB scattering modeling with **realistic regolith geometry and single-particle scattering phase matrices**
- Synoptic light scattering modeling from first principles to be continued by
 - improving the treatment of particle and volume-element size distributions
 - incorporating computed single-particle scattering properties (cf., Pentikäinen et al., Leppälä et al., Vuori et al., present meeting)
- BepiColombo **SIMBIO-SYS UV-Vis-NIR scattering and absorption modeling** and **MIXS/SIXS X-ray fluorescent emission modeling** will yield strong constraints on regolith geometry as well as on mineral and elemental composition (cf., Björn et al., present meeting)