PHOTOMETRIC MODELING OF THE REGOLITH IN TWO LUNAR SWIRLS

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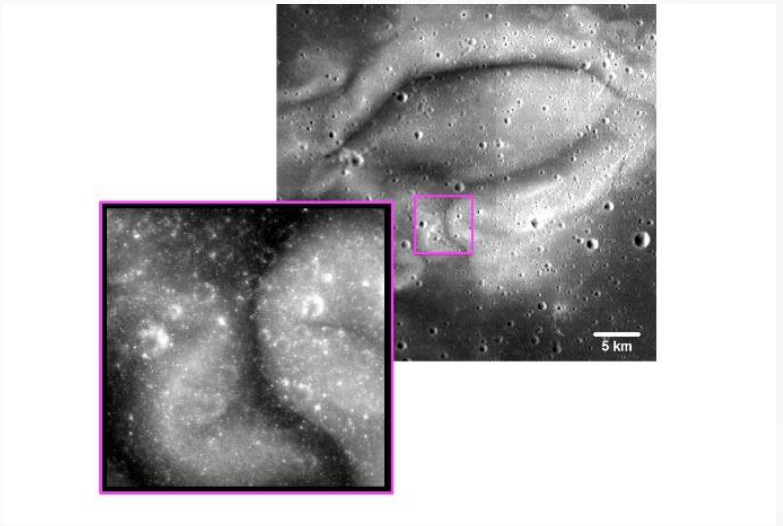
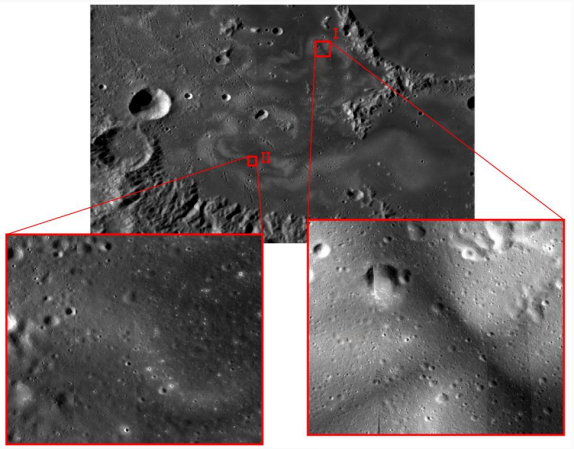
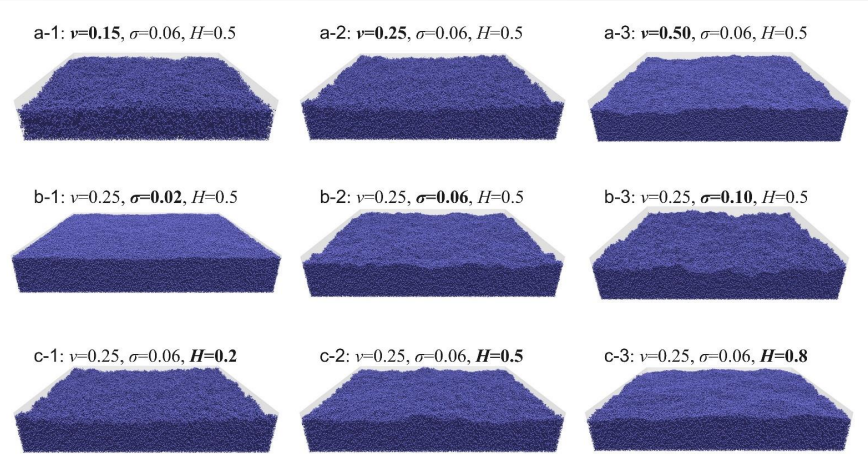


Weirich et al. 2023



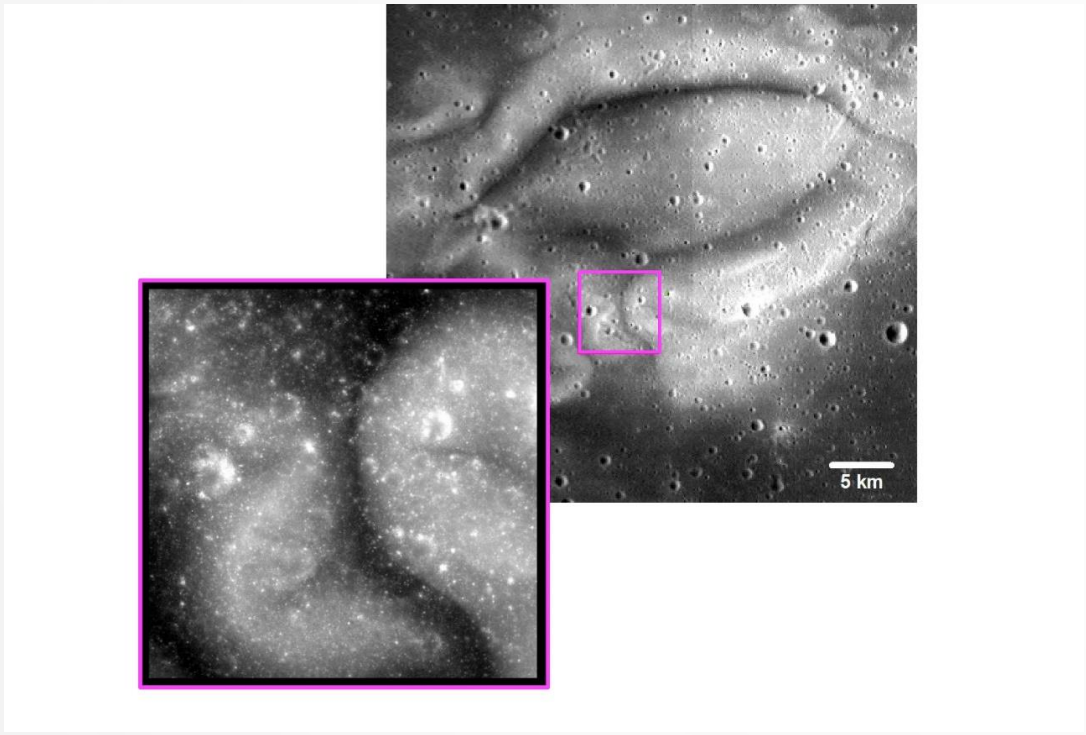
Domingue et al. 2023



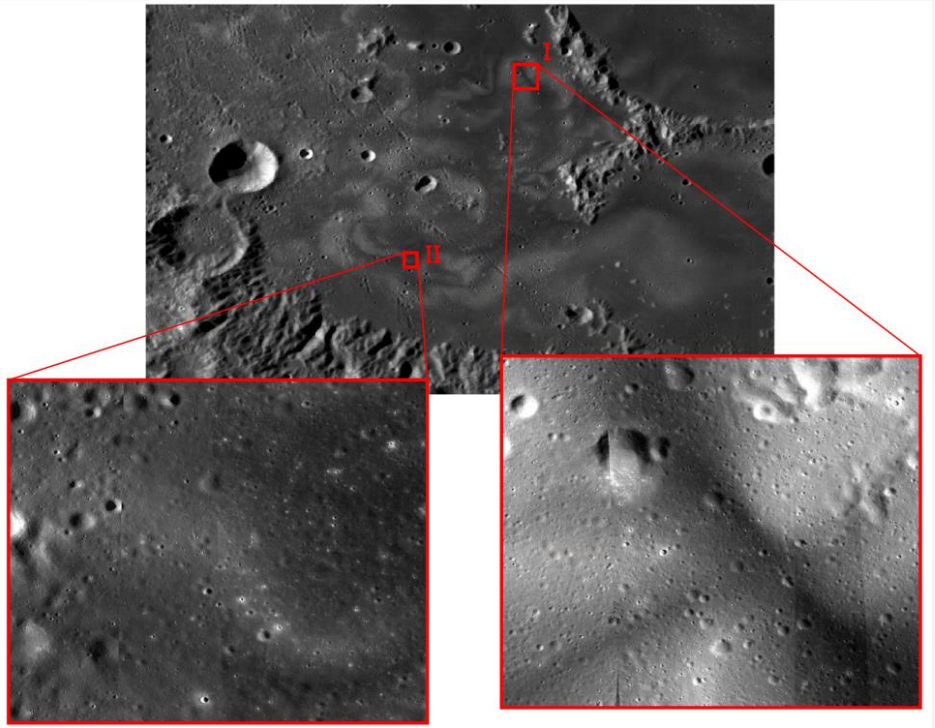
Björn et al. 2024

BACKGROUND: LUNAR SWIRLS

- ‘Lunar swirl’: a twisting bright-albedo area on the surface of the Moon



The Reiner Gamma swirl (Weirich et al. 2023)



The Mare Ingenii swirl (Domingue et al. 2023)

BACKGROUND: LUNAR SWIRLS

- ‘Lunar swirl’: a twisting bright-albedo area on the surface of the Moon

Reiner Gamma photometric data area (Weirich et al. 2023)

Mare Ingenii photometric data area, Site II (Domingue et al. 2023)

DATA: REINER GAMMA SWIRL

- The photometric data area is centered at $7.11°\mathrm{N}$, $301.18°\mathrm{E}$ (Weirich et al. 2023, Domingue et al. 2024)
  - Nearside of the Moon
- Photometric data: reflectance R, viewing angles ι, ϵ, α
- Different units classified by Chuang et al. 2022

Reiner Gamma photometric data area (Weirich et al. 2023)

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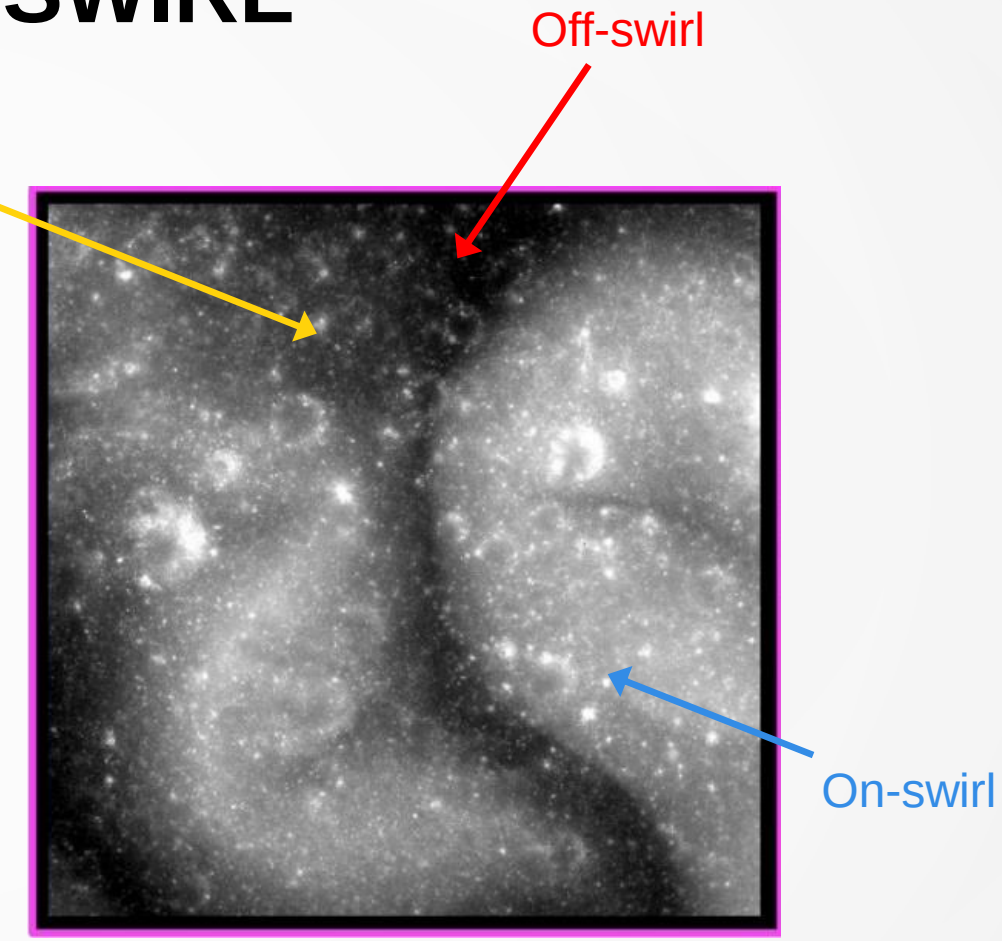
- Different units classified by Chuang et al. 2022
  - On-swirl, off-swirl, diffuse-swirl



Reiner Gamma photometric data area (Weirich et al. 2023)

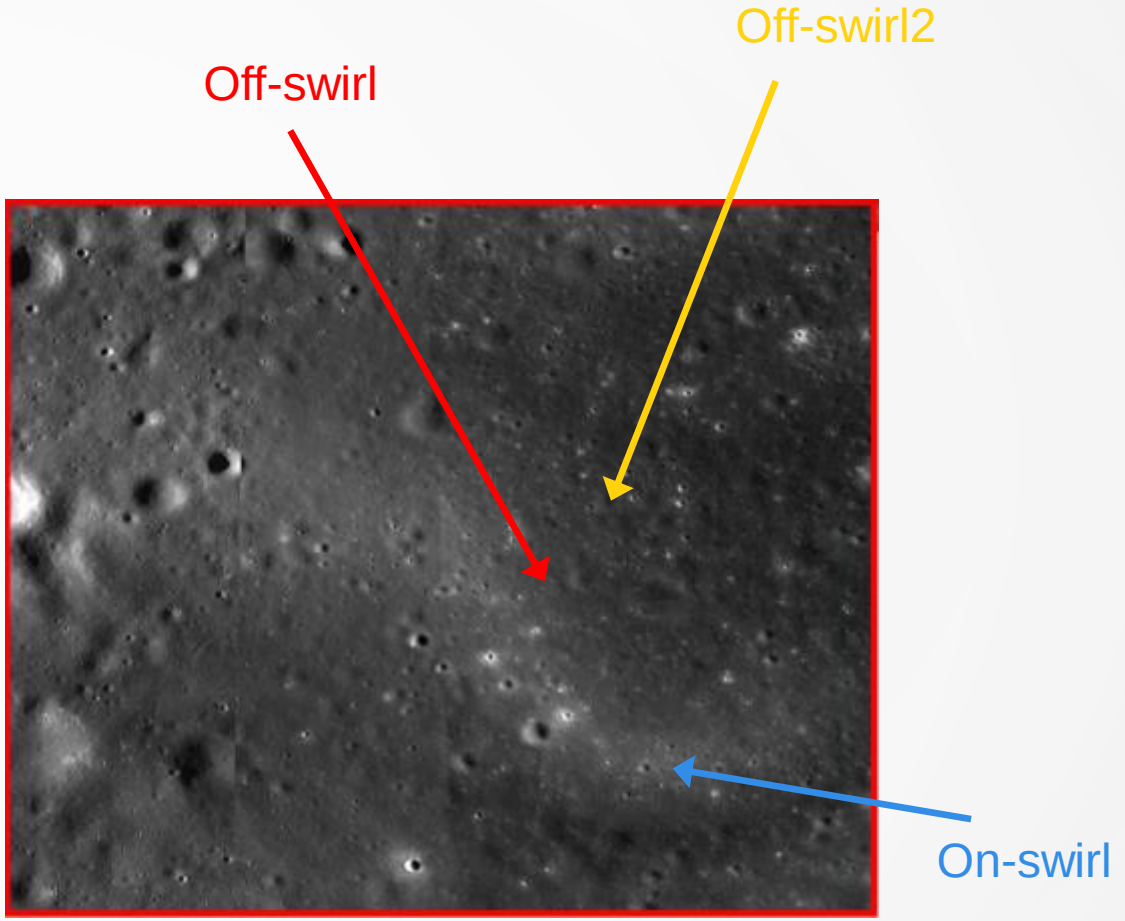
DATA: MARE INGENII

- The photometric data area II is centered at $35.8°\mathrm{S}$, $161.8°\mathrm{E}$ (Domingue et al. 2022, 2023)
  - Far side of the Moon
- Photometric data: reflectance R, viewing angles ι, ϵ, α
- Different units classified by Chuang et al. 2022

Mare Ingenii photometric data area, Site II (Domingue et al. 2023)

DATA: MARE INGENII

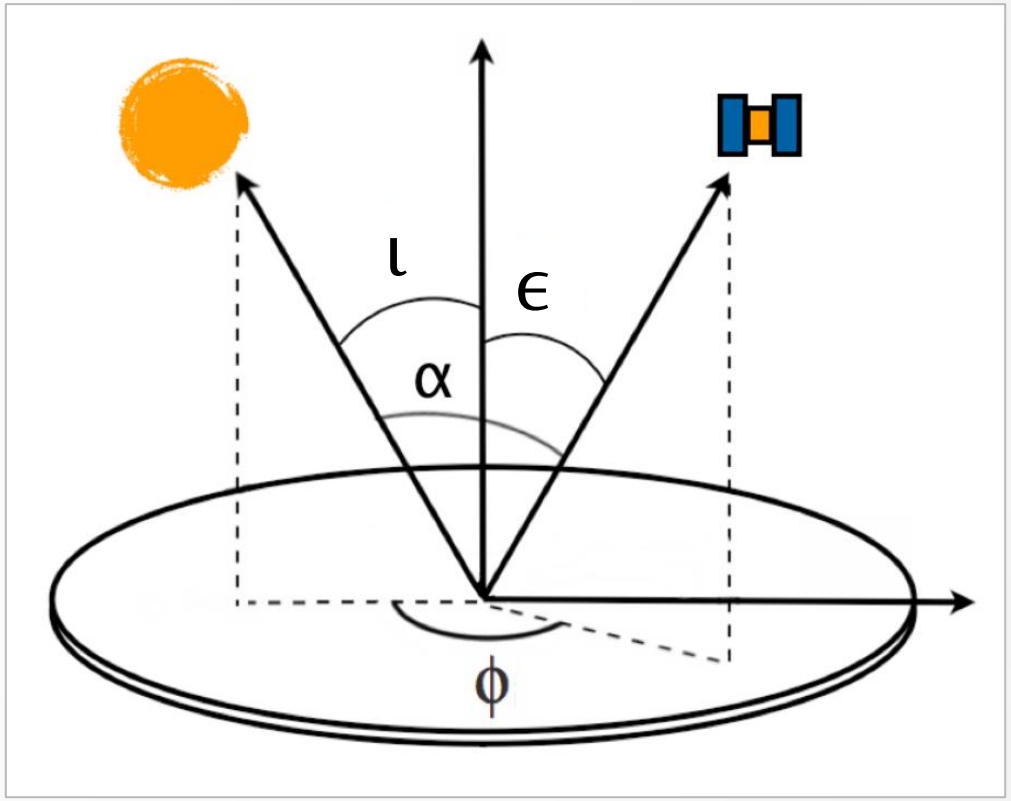
- The photometric data area II is centered at $35.8°\mathrm{S}$, $161.8°\mathrm{E}$ (Domingue et al. 2022, 2023)
  - Far side of the Moon
- Photometric data: reflectance R, viewing angles ι, ϵ, α
- Different units classified by Chuang et al. 2022
  - On-swirl, off-swirl, off-swirl2



Mare Ingenii photometric data area, Site II (Domingue et al. 2023)

THEORY: VIEWING GEOMETRY IS DEFINED BY FOUR ANGLES

- Angles of incidence ι, emergence ϵ, phase α, azimuth ϕ
  - Shorthand terms: $\mu_0 = \cos\iota$, $\mu = \cos\epsilon$
  - Incidence and emergence angles now constrained to $< 80°$
    - Removes outliers due to unaccounted topography
- Now: the surface element is a portion of the Moon's regolith



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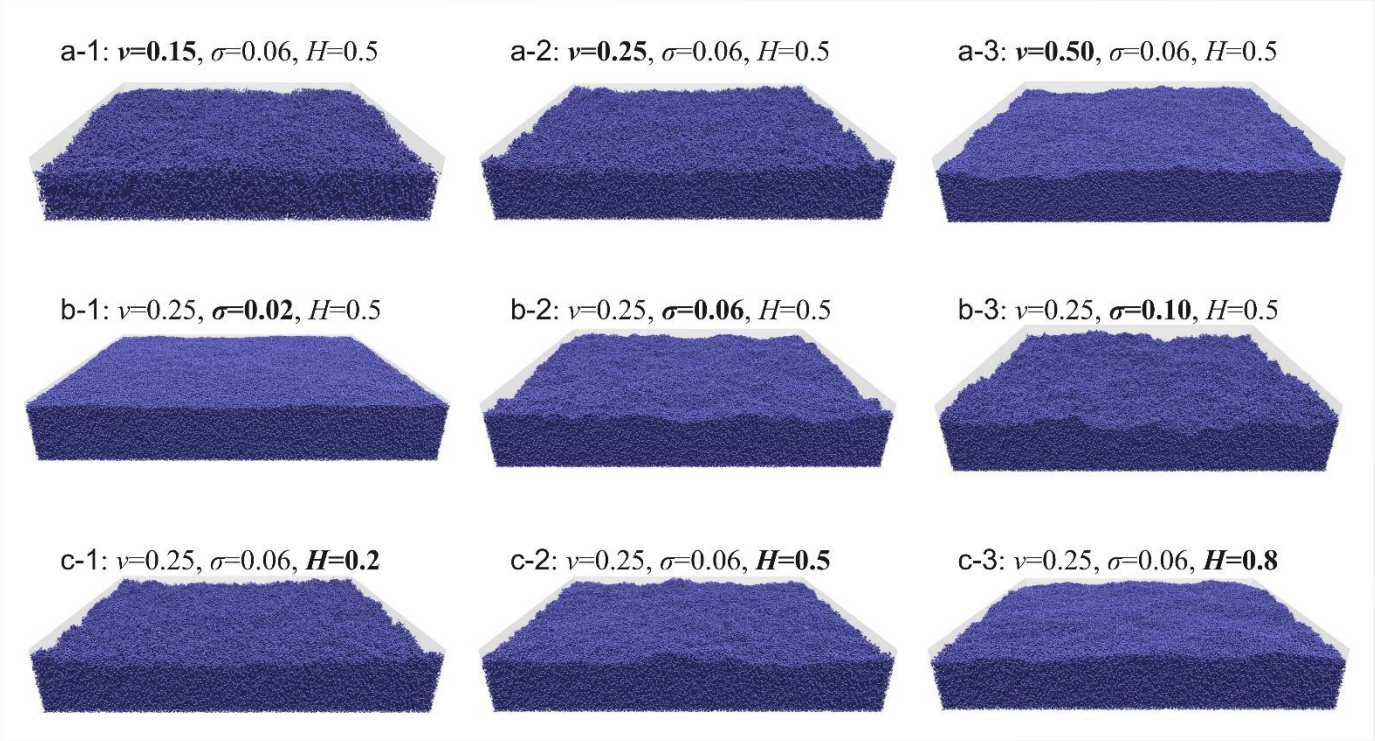
THEORY: FRACTIONAL BROWNIAN MOTION PARTICULATE MEDIUM (FBM-PM) MODEL

- Realistic regolith geometries (Muinonen et al. 2011, Wilkman et al. 2015, Björn et al. 2024)
- Three geometry parameters:
  - Packing density v
  - Fractional Brownian motion (fBm) surface roughness:
    - Hurst exponent H
    - Amplitude of height variation σ



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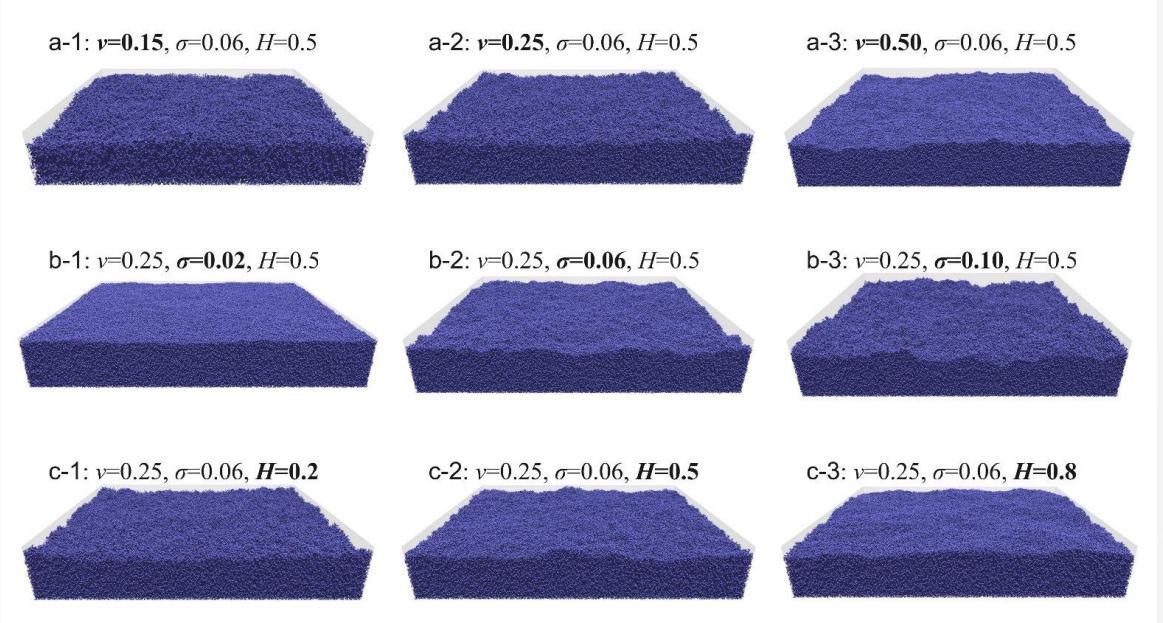
THEORY: FBM-PM MODEL

- Reflection coefficient (**reflectance**):
  - $R_{\mathrm{fBm-PM}} = 2p\Phi_{11}(\alpha)\Phi_S(\mu, \mu_0, \phi)\frac{1}{\mu+\mu_0}$, where
    - $2p\Phi_{11}(\alpha) \sim a + b\alpha$ is a linear phase function, and
    - $\Phi_S(\mu, \mu_0, \phi)$ is the shadowing correction



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THEORY: LEAST-SQUARES FIT AND MCMC SAMPLING

- Fit the fBm-PM model to observed reflectance R_{obs}
  - Least-squares fit => linear parameters a, b
- Vary the geometry parameters (v, H, σ) and quantify the goodness of fit
  - $\chi^2(\boldsymbol{P}) = \Sigma_{j=1}^{N} W_j \left[R_{\mathrm{obs},j} - R_j(\boldsymbol{P})\right]^2$, where $\boldsymbol{P} = (v, H, \sigma, a, b)^{\mathsf{T}}$
- Sample the parameter space using a Markov chain Monte Carlo (MCMC) approach
  - Histograms of the MCMC samples $\propto$ Bayesian probability distributions of the parameters

RESULTS: PARAMETER VALUES DIFFER FOR THE TWO SWIRLS

- MCMC median ± interquantile range values:
  - Reiner Gamma:

Unit	v	H	σ	a	b
On-swirl	0.413 ± 0.016	0.599 ± 0.005	0.0998 ± 0.0003	3.480 ± 0.036	-1.256 ± 0.019
Off-swirl	0.411 ± 0.030	0.591 ± 0.011	0.0998 ± 0.0002	3.489 ± 0.056	-1.255 ± 0.026
Diffuse-swirl	0.426 ± 0.009	0.598 ± 0.004	0.0998 ± 0.0002	3.429 ± 0.019	-1.217 ± 0.011

  - Mare Ingenii, Site II:

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Unit	v	H	σ	a	b
On-swirl	0.548 ± 0.004	0.234 ± 0.042	0.0402 ± 0.0017	3.431 ± 0.056	-1.345 ± 0.024
Off-swirl	0.547 ± 0.004	0.253 ± 0.064	0.0434 ± 0.0061	3.693 ± 0.062	-1.509 ± 0.025
Off-swirl2	0.547 ± 0.004	0.592 ± 0.029	0.0862 ± 0.0064	3.364 ± 0.044	-1.281 ± 0.027

RESULTS: PHYSICAL IMPLICATIONS

- Packing density of the regolith:
  - Reiner Gamma: moderate-to-high, regardless of the unit ($v \approx 0.41$)
  - Mare Ingenii, Site II: high, regardless of the unit ($v \approx 0.55$)

- Surface roughness:
  - Reiner Gamma:
    – All units: moderate horizontal roughness ($H \approx 0.6$), large vertical roughness ($\sigma \approx 0.10$)
  - Mare Ingenii, Site II:
    – On-swirl and off-swirl: low horizontal roughness ($H \approx 0.2$), moderate vertical roughness ($\sigma \approx 0.04$)
    – Off-swirl2: moderate horizontal roughness ($H \approx 0.6$), large vertical roughness ($\sigma \approx 0.09$)

SUMMARY

- We utilized photometric data of two lunar swirls: Reiner Gamma and Mare Ingenii
- The fBm-PM model describes regolith structure with realistic and physically relevant parameters
- The regolith in Reiner Gamma differs from that in Mare Ingenii, but the regolith within a swirl is similar

THANK YOU!

CITATIONS

- Björn et al. 2024, Planet. Sci. J. 5, 260
- Chuang et al. 2022, Planet. Sci. J. 3, 231
- Domingue et al. 2022, Geophys. Res. Lett. 49, e95285
- Domingue et al. 2023, Planet. Sci. J. 4, 240
- Domingue et al. 2024, Planet. Sci. J. 5, 161
- Górski et al. 2005, Astrophys. J. 622, 759
- Muinonen et al. 2011, Astron. Astrophys. 531, A150
- Weirich et al. 2023, Planet. Sci. J. 4, 212
- Wilkman et al. 2015, Planet. Space Sci., 118, 255

DATA: COMPARISON WITH BJÖRN ET AL. 2024

- Comparing to our earlier study for the average surface of Mercury (Björn et al. 2024)
  - Data reduction for Reiner Gamma: HEALPix discretization (Górski et al. 2005) of the emergence and azimuth angles

Aspect	Mercury (V. Björn et al. 2024)	The Moon (this study)
Extent of photometric data area	Average surface of Mercury	A portion of the Reiner Gamma swirl
Separation of data points	Eight filters at different wavelengths	Photometric area divided into three units
Total # of data points	37,752	29,648,391
# of data points after reduction	33,583	16,997

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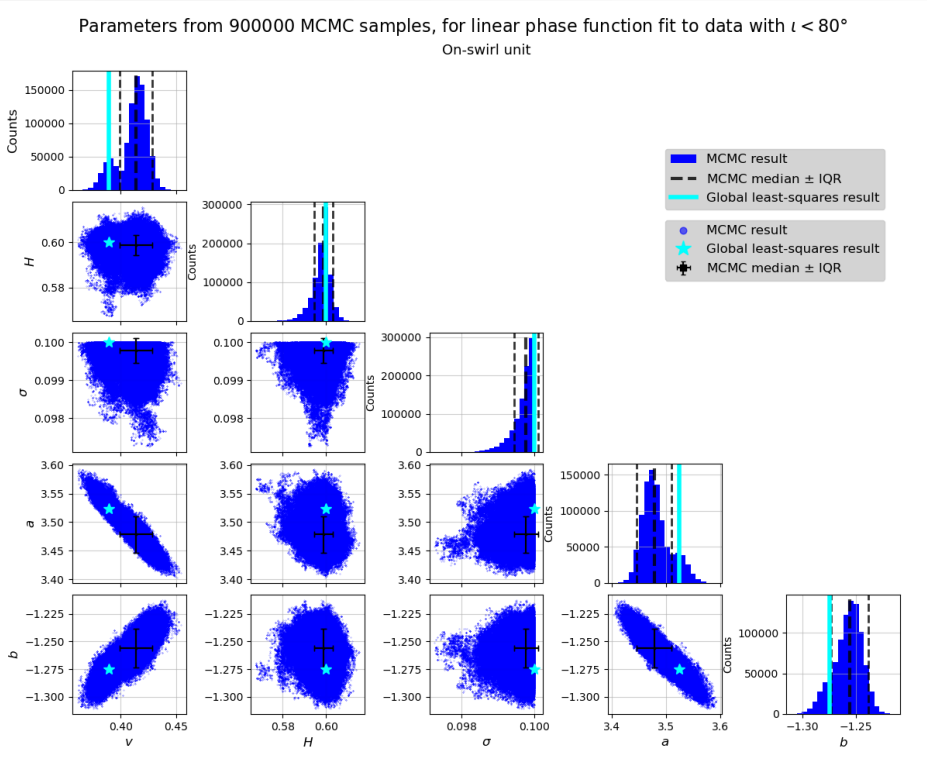
RESULTS: MCMC CORNER PLOTS FOR ON-SWIRL UNIT

Reiner Gamma



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Mare Ingenii, Site II