Imaging Polarimetry as a Powerful Tool for Lunar Science

Sungsoo S. Kim[1], Minsup Jeong[1,2], Ian Garrick-Bethell[1,3], So-Myoung Park[1], Chae Kyung Sim[1], Ho Jin[2], Kyoung Wook Min[4], and Young-Jun Choi[2]

[1]Kyung Hee University,
[2]Korea Astronomy and Space Science Institute,
[3]University of California, Santa Cruz, and
[4]Korea Advanced Institute of Science and Technology

Korea's Lunar Exploration Missions

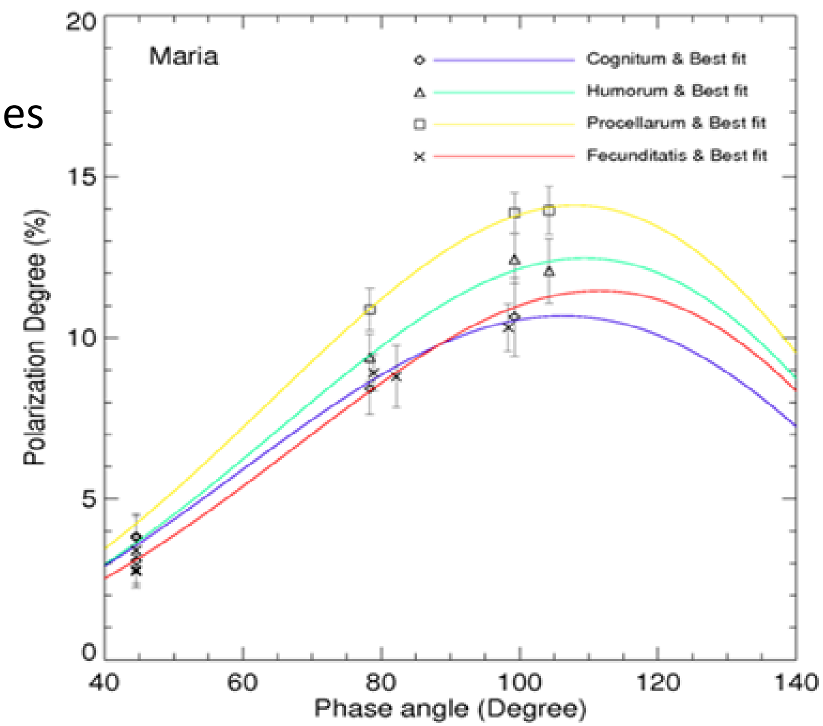
- Korea's Plans for Lunar exploration
  - 2018-19: Test orbiter
  - >2020: Orbiter/Lander/Sampler returner

- Need to find original science missions for the KLE
  - Almost all kinds of explorations have been tried in the lunar orbit.
  - Korea still needs to find original missions.
  - Simple, fail-safe missions are appropriate for the test orbiter.

- Polarimetric observations
  - Nearly the only major observational method that has not been tried in the lunar orbit.
  - The polarimeter can share the focal plane of the main camera.
  - Very simple equipment: 2 linear CCDs with polarimetric and color filters

Polarimetric Survey of the Lunar Regolith

- As a Korea's lunar exploration mission, we propose
  - Multi-band polarimetric survey from the Lunar orbit, which will be an original science mission that has never been tried before.
  - Polarimeter is a simple instrument, and can share the focal plain of the main camera.
- Advantages of observations from the Lunar orbit
  - Can survey the whole surface
  - Can have a wider range of phase angles



Polarimetric Survey of in the Lunar Orbit

- Polarimetry has not been tried in the Lunar orbit, because
  - In-situ measurement is preferred to remote-sensing in the early times of exploration
    - ➢ Time to pay more attention to remote-sensing missions now?
  - Traditional perception: Lunar science = Geology
    - ➢ The only scientist on the Moon = Geologist (Apollo 17)
    - ➢ Most of the remote-sensing science missions were for mineralogy, petrology and geophysics.
  - Polarimetry has been used to study dust and aerosol, or remove the effects by them.
    - ➢ Polarization of light reflected off particulate surfaces are not well understood, although quite a number of studies have been done recently.

- Study of surface polarimetry = **Blue Ocean**
  - In terms of observation, theory and lab experiments!

Scientific & Exploratory Values of the Lunar Surface Polarimetry

Observations

Polarization, Albedo

↓

Grain size, composition, and roughness of the regolith

↓

Science

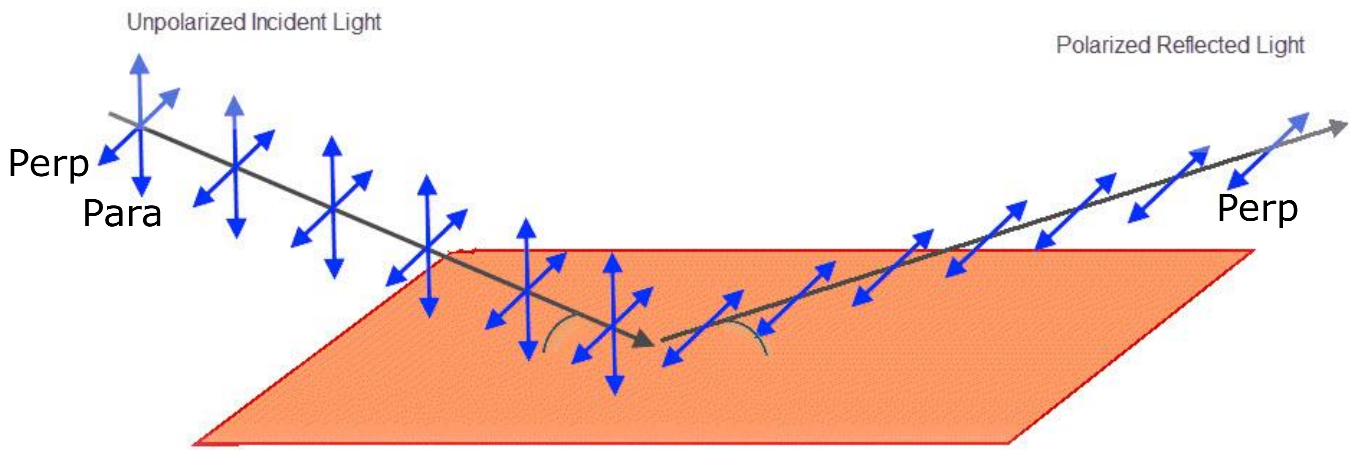
- Can estimate the exposure timescale
- Can trace the evolution of small bodies in the SS

Exploration

- Can be used in designing the rover missions
- Exploitation of resources in the regolith

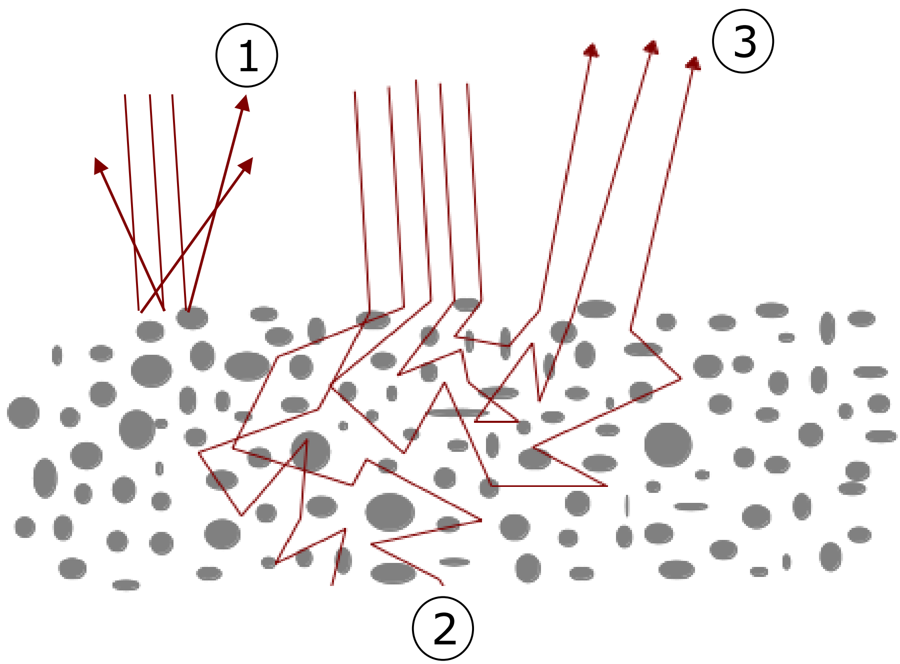
Polarization and Grain Size (1/4)

- Light reflected off a surface is partially polarized.



Polarization and Grain Size (2/4)

- Light that hits a particulate surface
  1. is partially reflected off the surface (perpendicularly polarized),
  2. is partially absorbed by the grains, or
  3. partially escapes after multiple scattering between grains (randomly polarized).



Polarization and Grain Size (3/4)

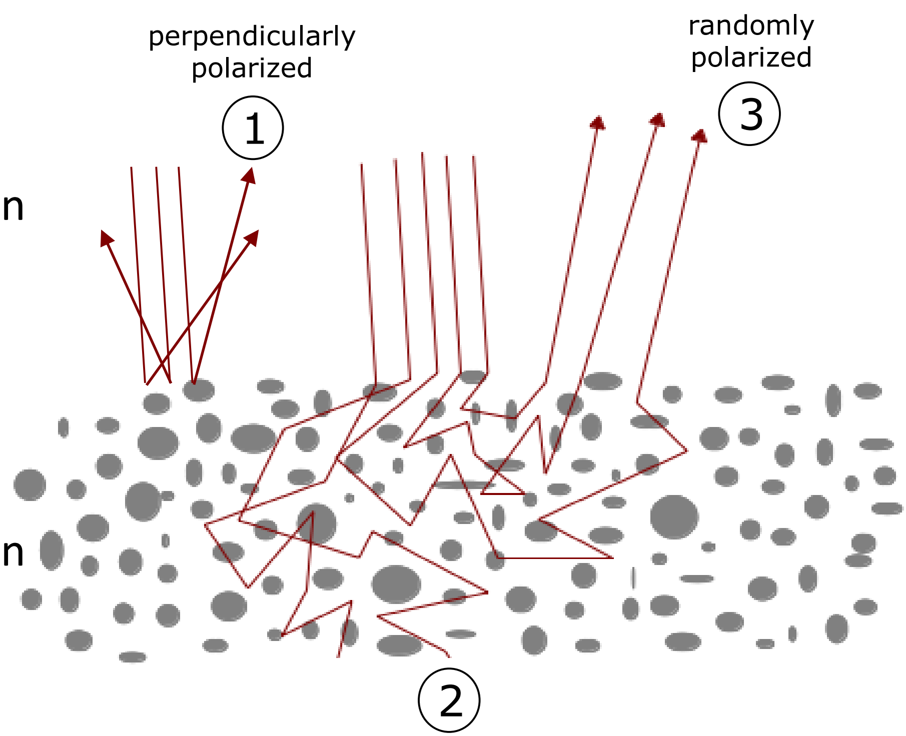
- Thus the degree of polarization is
  - determined by the ratio between the absorption and scattering,
  - and this ratio depends on the size and composition of the particles.

- Large grains have
  - greater absorption
  - smaller albedo, larger polarization

    ① > ③

Small grains have
  - smaller absorption
  - larger albedo, smaller polarization

    ① < ③



Polarization and Grain Size (4/4)

- Umov's Law (1905)

$$PA^{1.37} = f(d)$$

$$P = \text{Polarization}$$
$$A = \text{Albedo}$$
$$d = \text{Grain size}$$

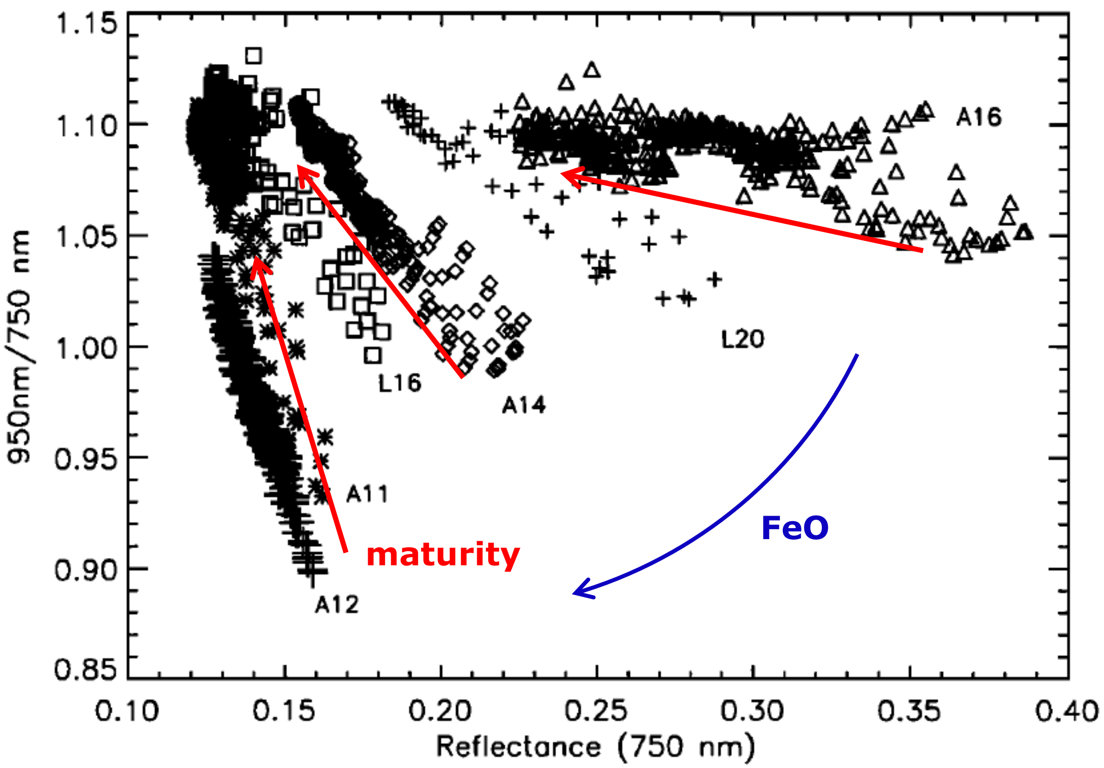
- Recent research showed that f is determined by:
  - Size, composition, and shape of the grains
  - Roughness of the surface

Space Weathering of the Lunar Regolith

- As the lunar regolith matures, the regolith grains become
  - darker
  - redder
  - smaller in size (comminution).
- These are the results of space weathering by the solar-wind particles and micrometeorites.
- Darkening and Reddening
  - Caused by the accumulation of nanophase iron (npFe) particles in the regolith grains.
  - npFe particles are produced by the solar wind particles and/or micrometeorites.
- Comminution
  - Caused by the bombardment of micrometeorites.

Two Important Maturity Indices

- Optical Maturity (OMAT)
  - Developed by Lucey et al. (1995, 1998, 2000)
  - Maturity & FeO content can be estimated by albedos at 7500Å & 9500Å.
  - Reflects the degree of darkening and reddening



Two Important Maturity Indices

- Optical Maturity (OMAT)
  - Developed by Lucey et al. (1995, 1998, 2000)
  - Maturity & FeO content can be estimated from albedos at 7500Å & 9500Å.
  - Reflects the degree of darkening and reddening

- Median Grain Size (<d>)
  - Estimated from P_{max} and A (developed by Dollfus 1971, Shkuratov 1981).
  - Dependent on the total dose of micrometeorite
  - Can be used as a supplementary and independent maturity index.
  - Comminution timescale may be different from darkening and reddening timescale.
  - Much less observed, and thus much less studied.

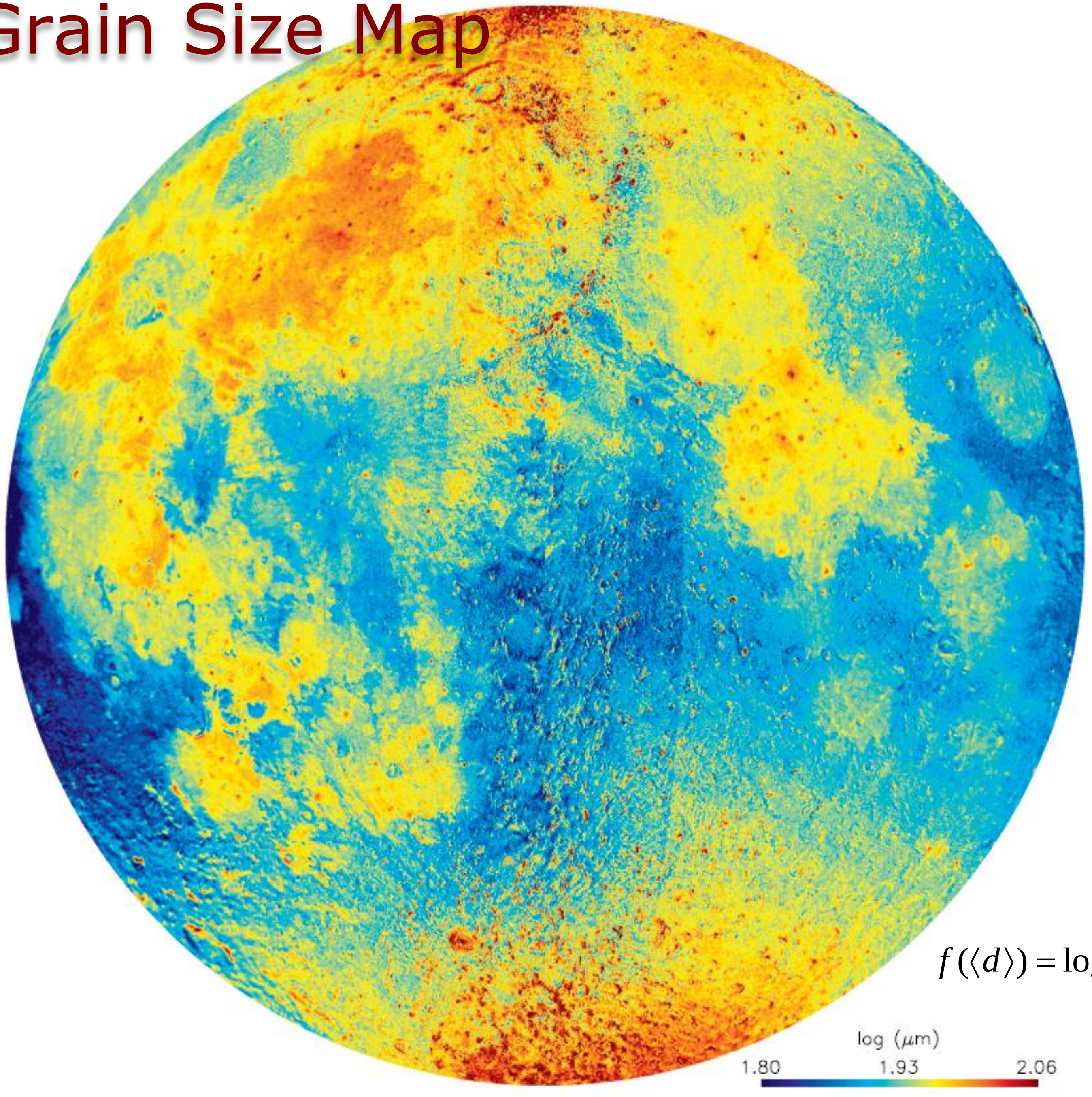
Preliminary Studies

- Ground observations
  - 3 weeks in July 2013 at Lick Observatory
  - Phase angle between 22° and 121°
  - U, B, V, R and I bands
  - ~1.2” seeing (1.6 pixel, 2.2 km at the center of the lunar disk center)
  - First CCD polarimetry of the whole near-side of the Moon

- Main results
  - <d> is latitude-dependent.
  - At the same latitude, <d> is larger in the maria than in the highlands.
  - <d> reaches saturation earlier than OMAT does.

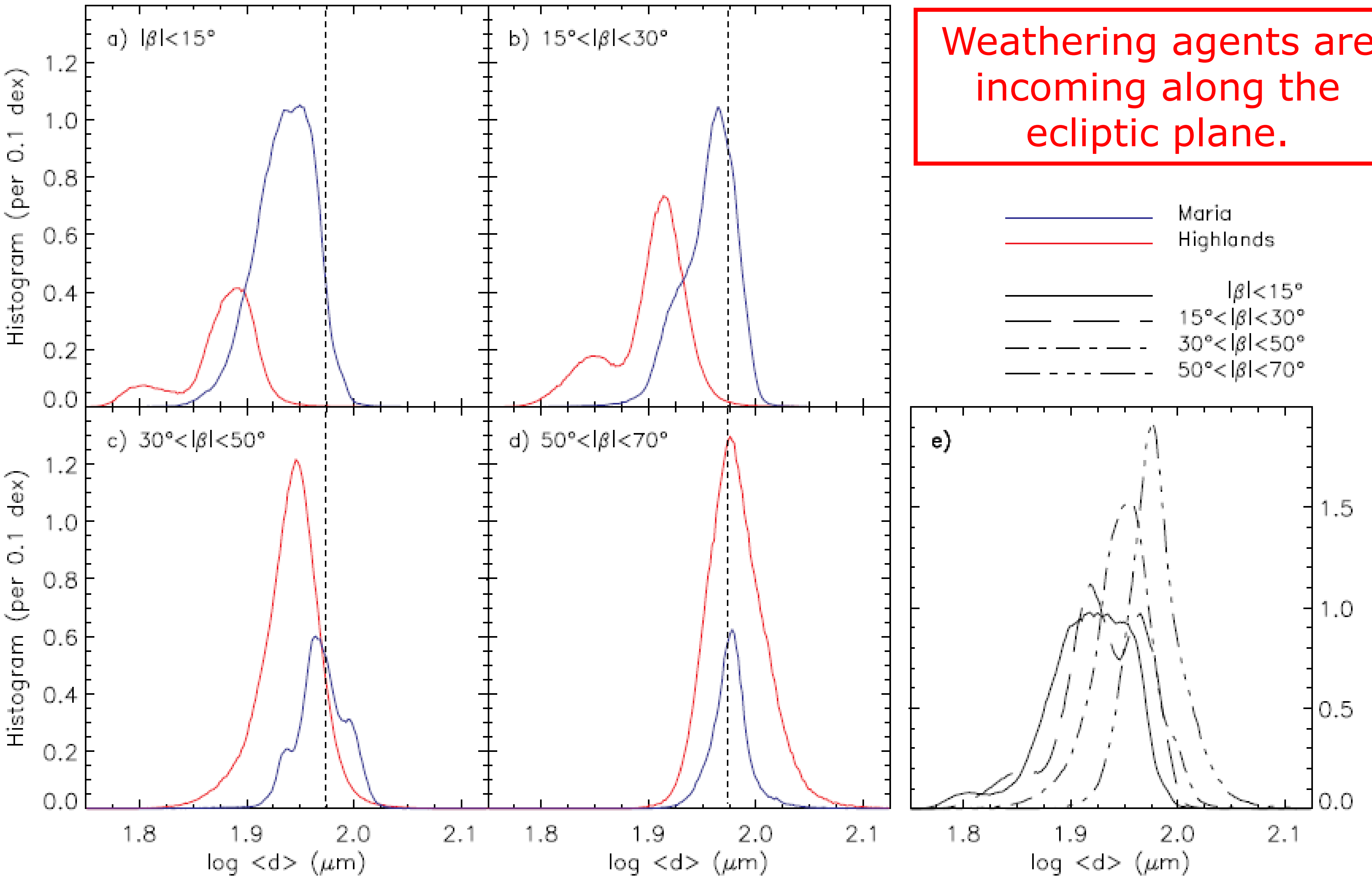
- First paper was published in the ApJS last November.
  - More than four papers from these data are currently being prepared.

The Grain Size Map



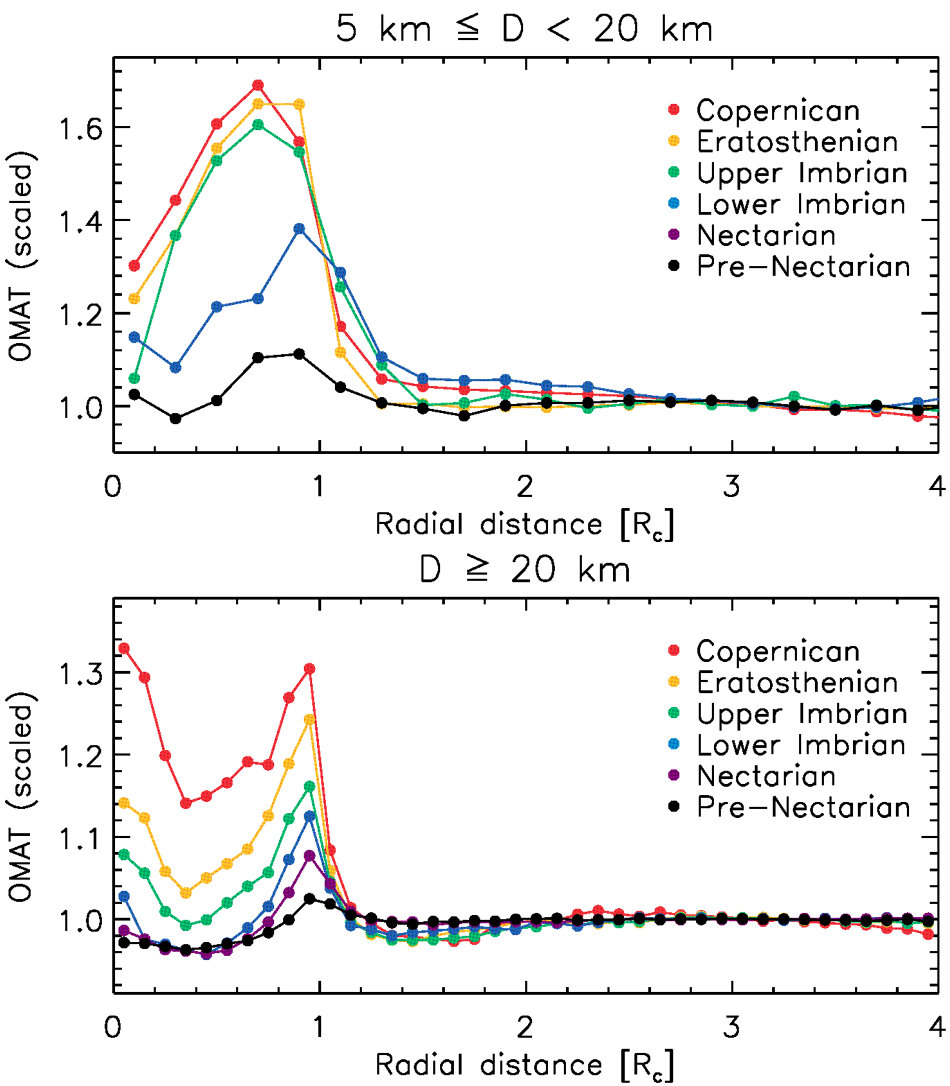
$$f(\langle d \rangle) = \log A + a \log P_{\max}$$

Latitude-Dependence of <d>



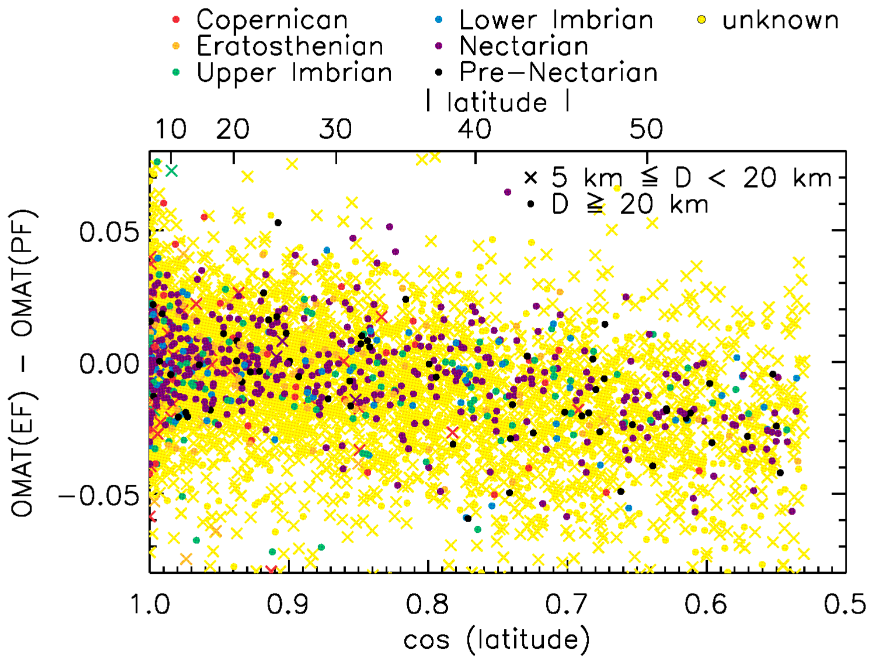
Weathering agents are incoming along the ecliptic plane.

OMAT Profiles of Craters

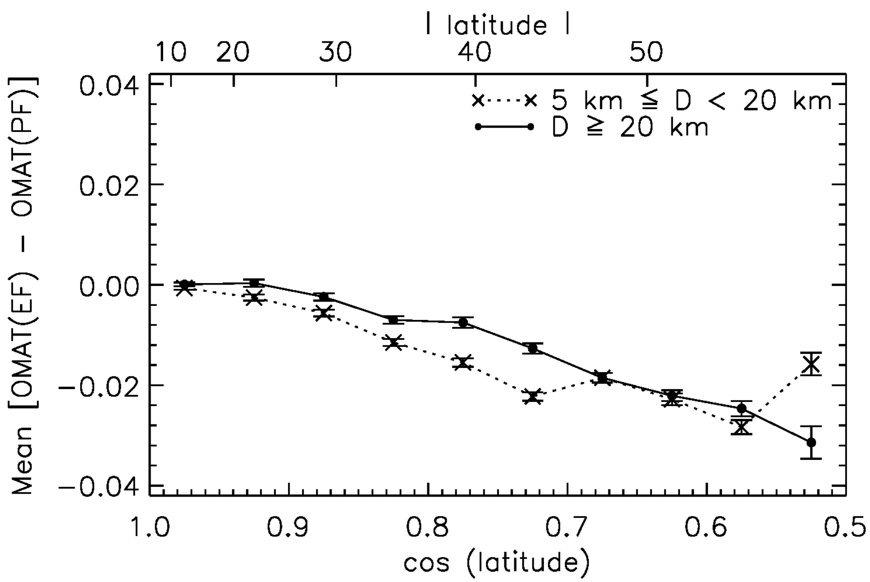


Inclined areas mature less rapidly.

OMAT of Crater Inner Walls: EF vs. PF



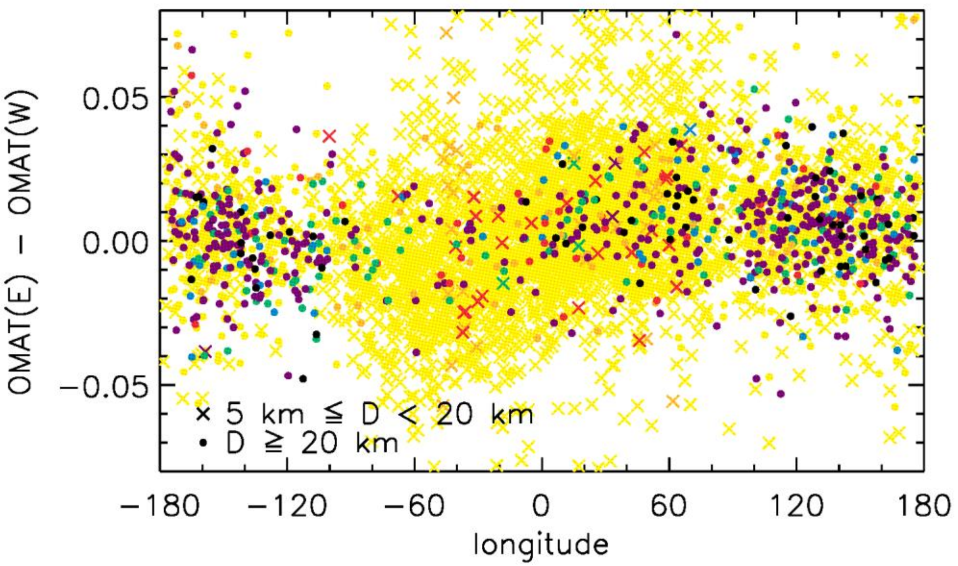
Crater inner walls also show latitude-dependence.



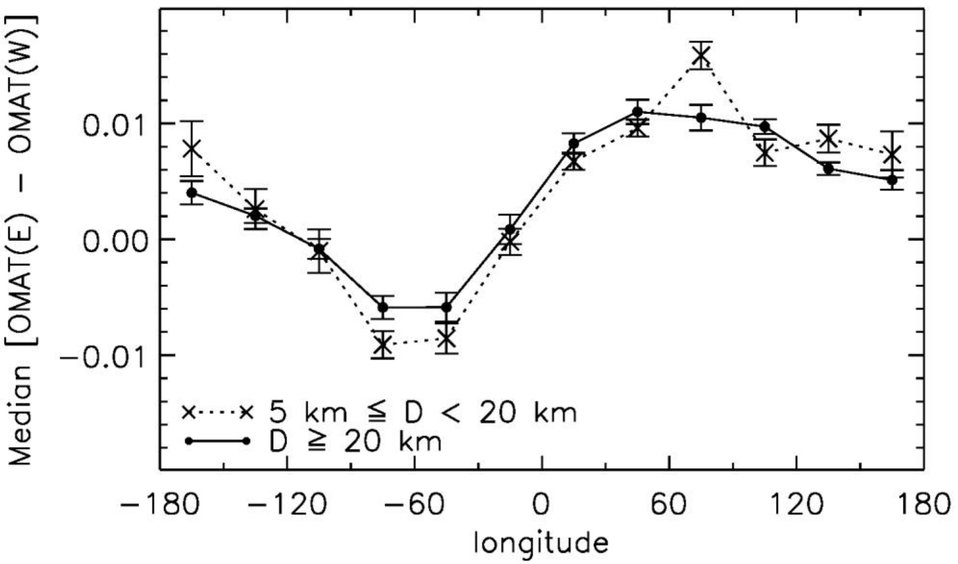
PF walls are maturer.

EF walls are maturer.

OMAT of Crater Inner Walls: E vs. W



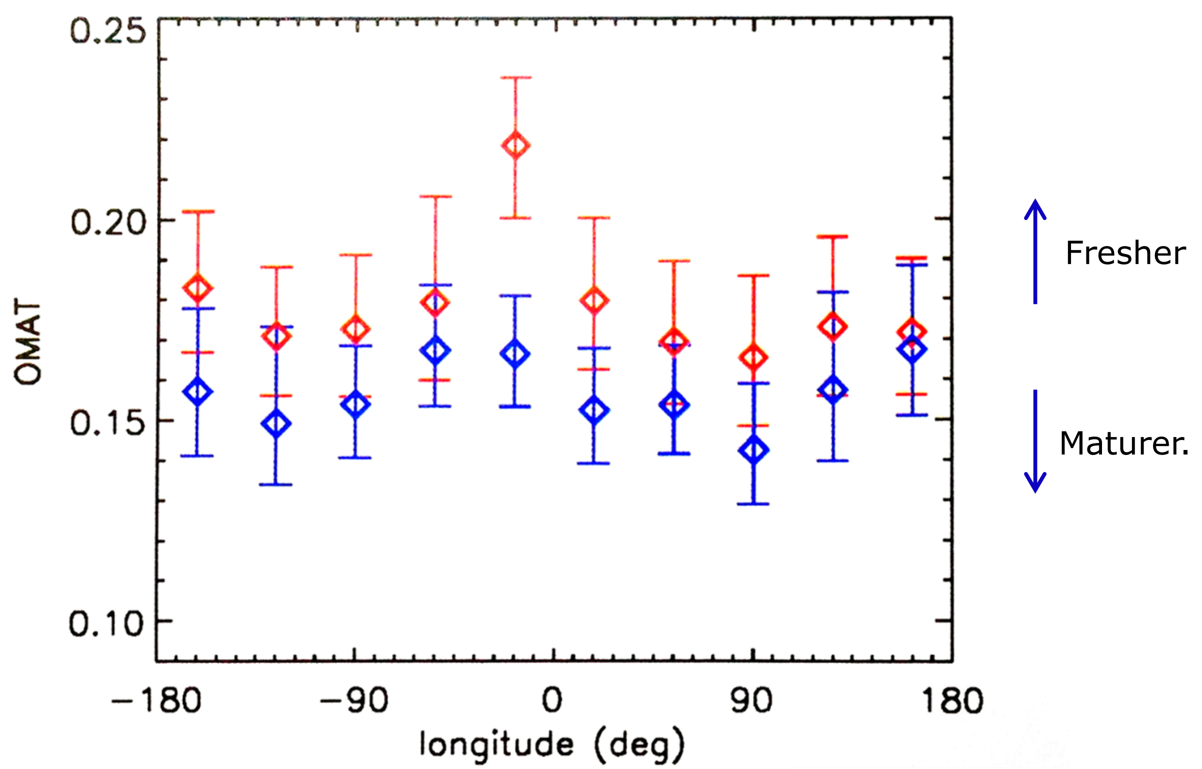
Gravitational focusing or Earth's shielding of micrometeoroids?

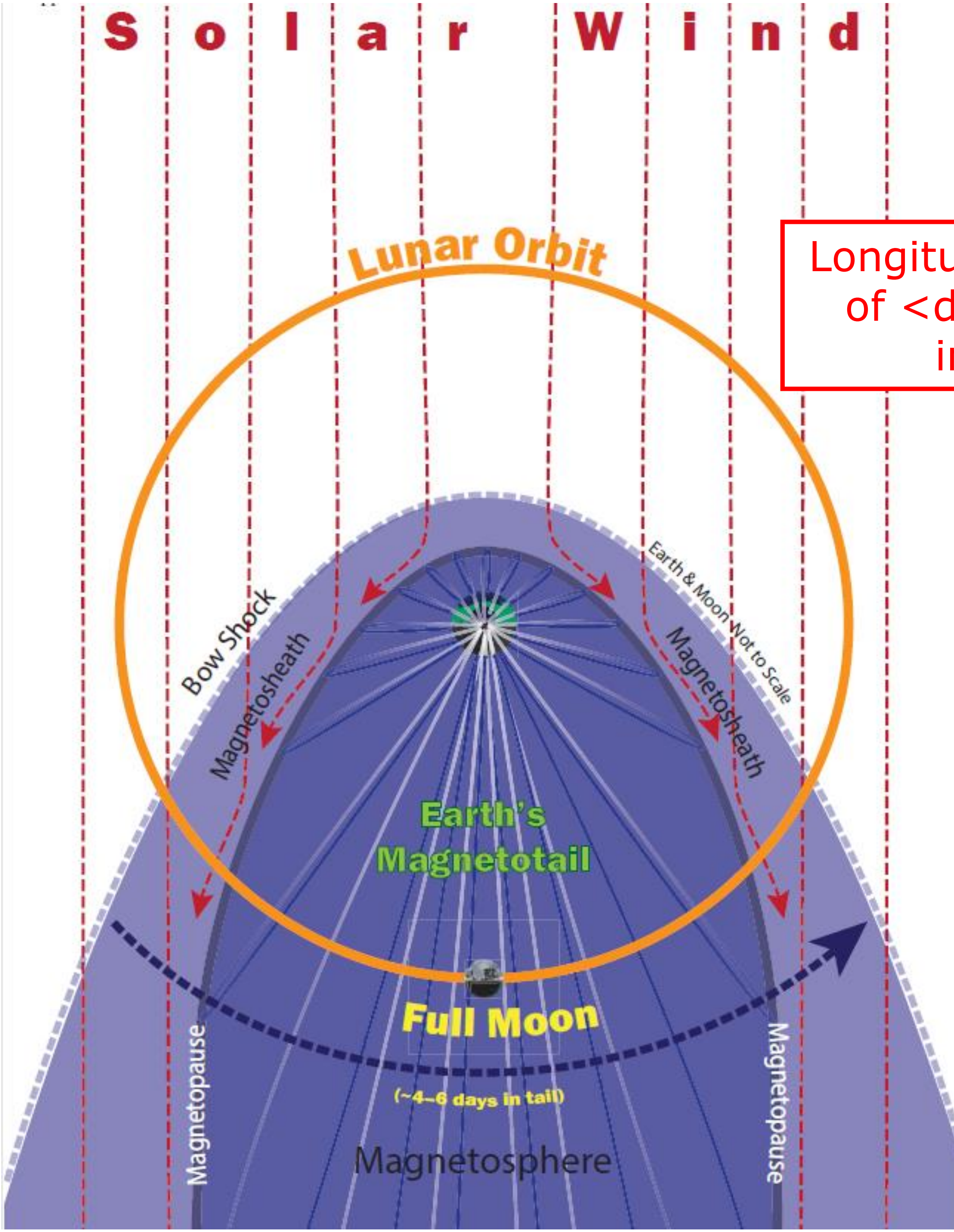


W walls are maturer.

E walls are maturer.

OMAT of the Lunar Surface





Longitude-dependence of <d> will be very important!

Our Proposal for the Science Payload

- Consortium of KASI, KHU and KAIST (SaTReC)

- The instrument
  - Wide-field cameras in the optical and infrared
  - Polarimetric survey of the whole lunar surface

- Due February 22nd
  - Selection process in March

Second Campaign of Ground Observations

- Speckle polarimetric imaging!
  - Dedicated 24-inch telescope
  - High-speed camera (down to 1 ms)
  - To be installed at the Sierra Remote Observatory in California
  - Collaboration with KASI (Young-Jun Choi)

- Highest-resolution polarimetry of the Moon
  - Speckle polarimetric imaging of the Moon works because we already have hyper-resolution imaging data of the Moon.
  - Nyquist sampling with a pixel scale of 0.2” (3-4 times enhancement)
  - Expected to reach GSD of ~300 m

- Will observe Mars and a few asteroids as next targets.