Imaging Polarimetry as a Powerful Tool for Lunar Science

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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
• 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).
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
  \[ 1 \geq 3 \]

Small grains have
- smaller absorption
- larger albedo, smaller polarization
  \[ 1 \leq 3 \]
Umov’s Law (1905)

\[ PA^{1.37} = f(d) \]

- \( P \) = Polarization
- \( A \) = Albedo
- \( d \) = Grain size

Recent research showed that \( f \) is determined by:
- Size, composition, and shape of the grains
- Roughness of the surface
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)**
  - Maturity & FeO content can be estimated by albedos at 7500Å & 9500Å.
  - Reflects the degree of darkening and reddening
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- **Median Grain Size (<d>)**
  - Estimated from $P_{\text{max}}$ 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

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

PF walls are maturer.

EF walls are maturer.

Crater inner walls also show latitude-dependence.
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

Fresher

Maturer.
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 22\textsuperscript{nd}
  – 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.