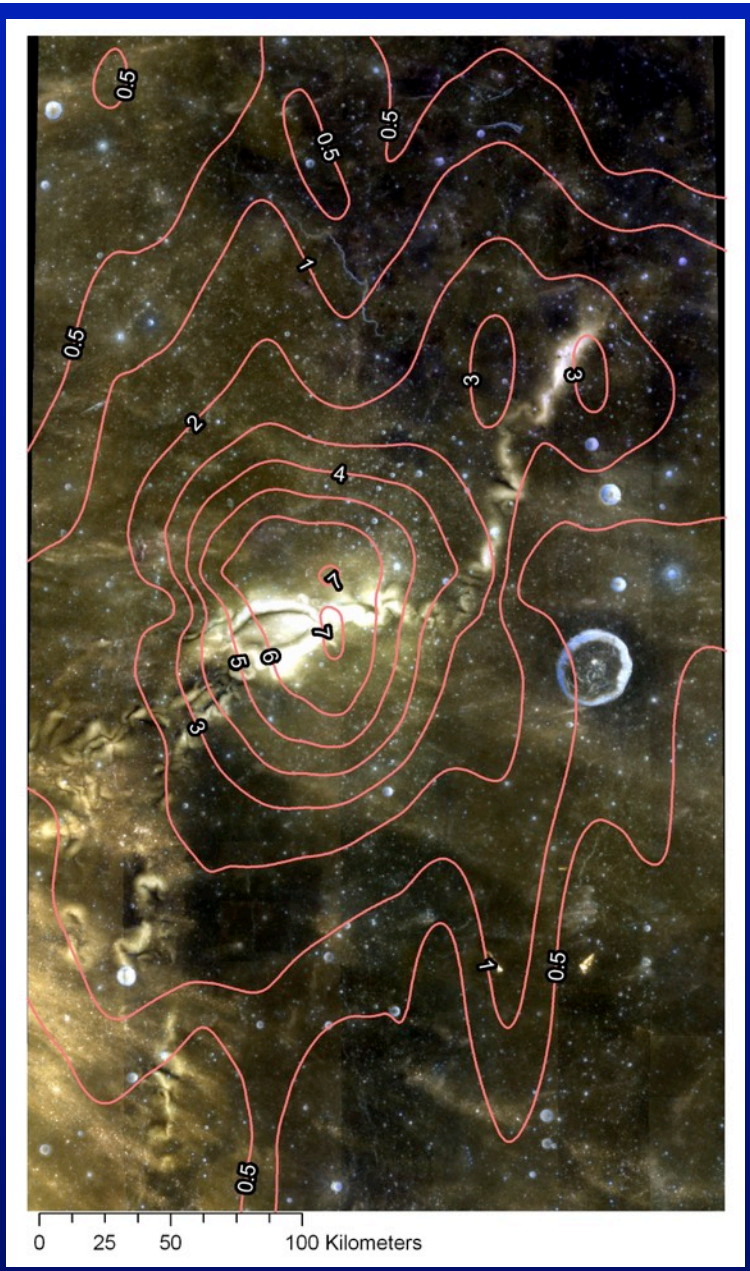

The Reiner Gamma swirl and magnetic anomaly. *Clementine* mosaic centered at 7.5° N, 302.5° E, with contours of *Lunar Prospector* total magnetic field strength (nT) at 35.5 km altitude. Blewett et al. (2007) *GRL*.

Lunar crustal magnetic anomalies: The intersection of space plasmas and geology

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Applied Physics Laboratory

Exploration Science Forum
Ames Research Center
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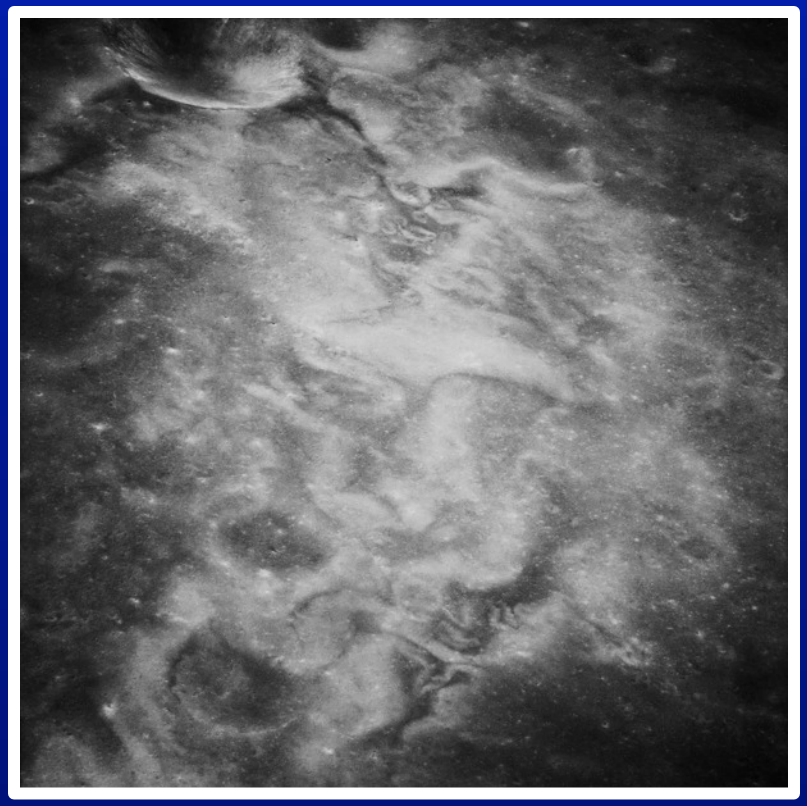
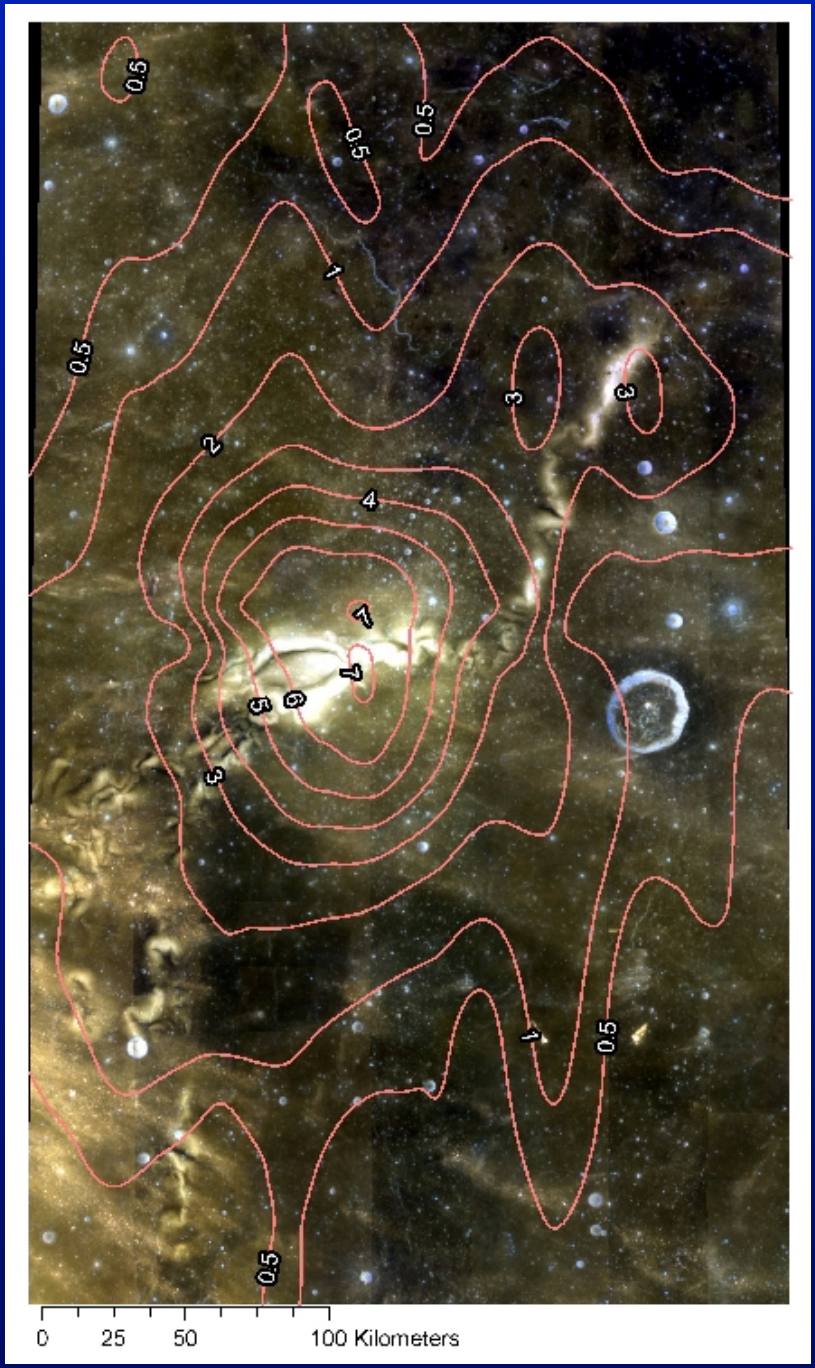
APL JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Talk Outline



Firsov. Oblique view looking approximately north. The swirls appear to drape the topography. The crater at the top left is ~7 km in diameter. AS10-30-4365, an (Blewett et al., 2011 JGR-Planets).

- Describe the features and processes that are associated with regions of magnetized crustal rocks on the Moon.
- Review the hypotheses for the origin of the magnetic anomalies and the associated swirls.
- Look at recent data that bears on the problem.
- Argue that the lunar magnetic anomalies are unique natural laboratories that provide opportunities for studying a wealth of interesting phenomena – from geology to space plasma physics.



Swirls

- Sinuous, high albedo markings.
- No topographic relief.
- Dark lanes sometimes found within the bright portions.
- Type example is the *Reiner Gamma swirl* in Oceanus Procellarum.
- Magnetic anomalies are associated with swirls.

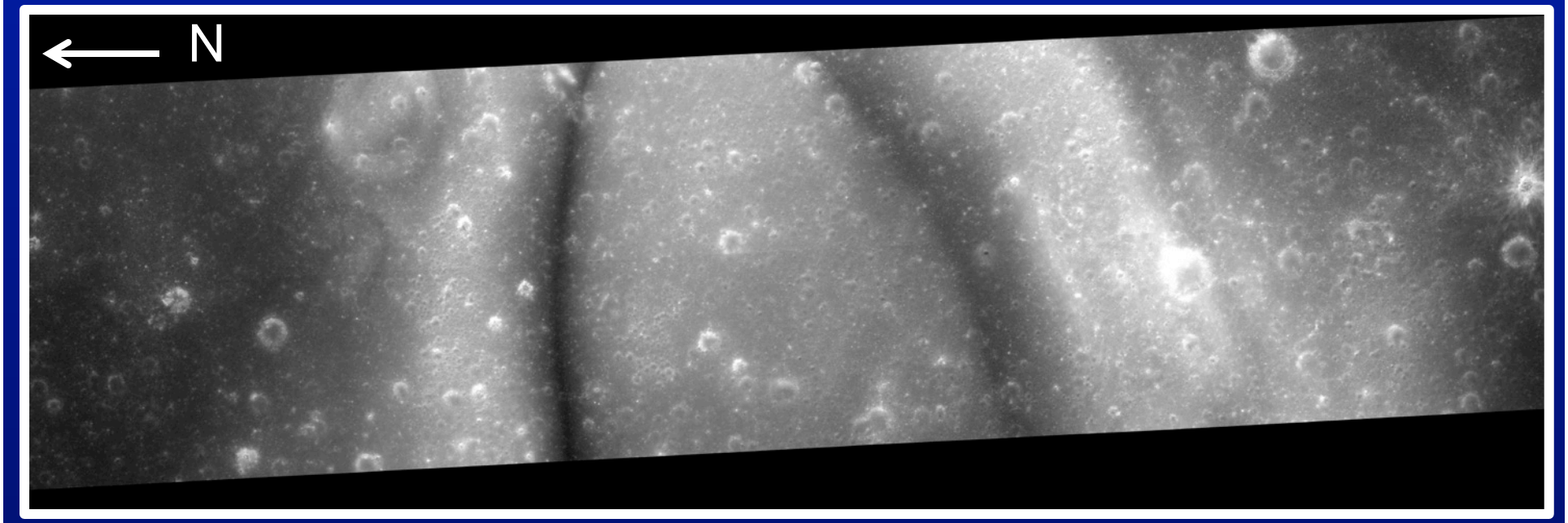
Clementine pseudo true color composite, with contours of LP total field strength at 35.5 km altitude. Blewett et al. (2007) GRL

Hypotheses for Origin

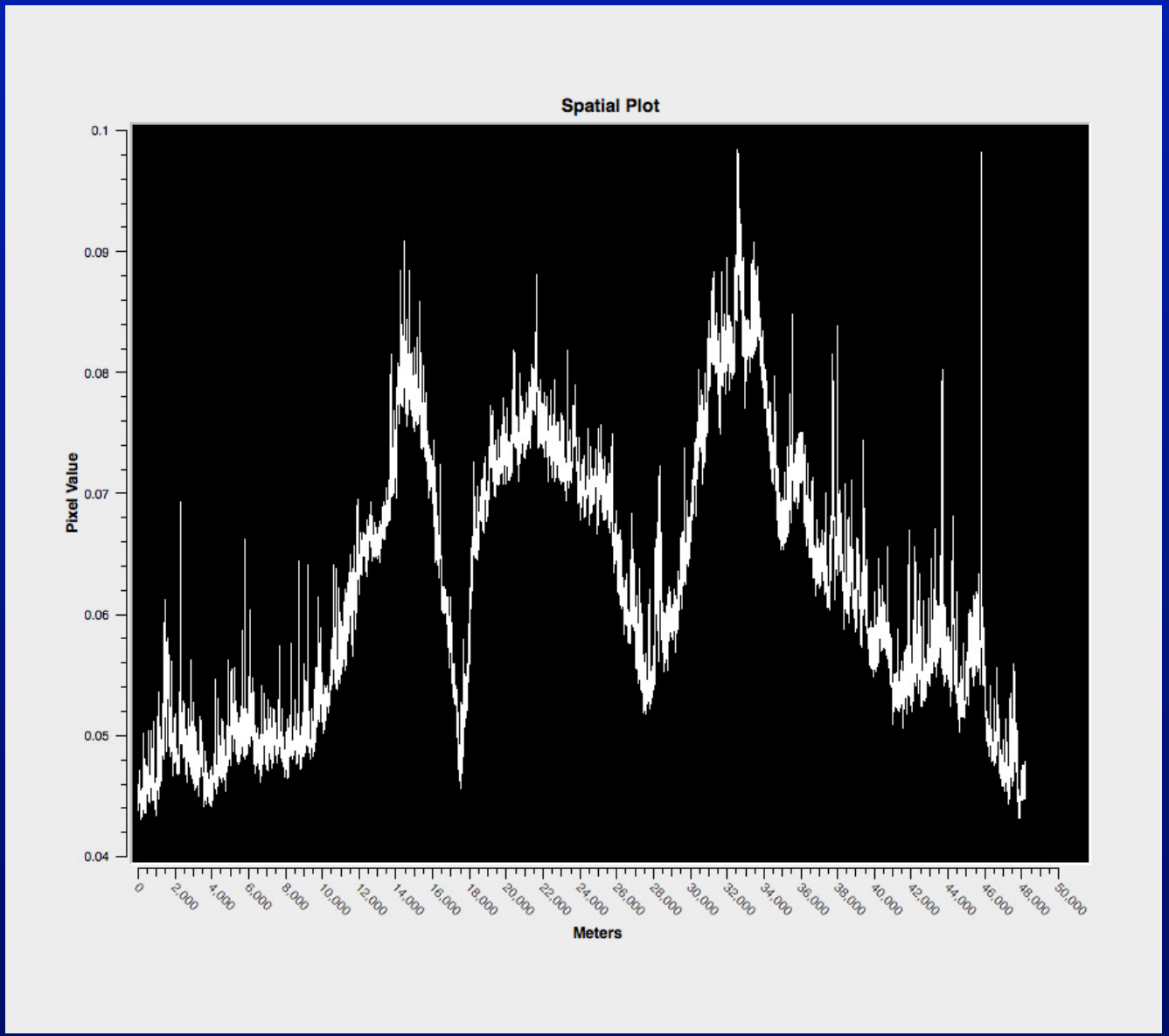
- Abnormal space weathering – magnetic field protection
  - Magnetized antipodal basin ejecta, primary magnetization, cometary impact
- Recent impact by comet / cometary swarm
- Accumulation of bright, fine-grained dust
- Collapse of "fairy castle" soil structure

Reiner Gamma

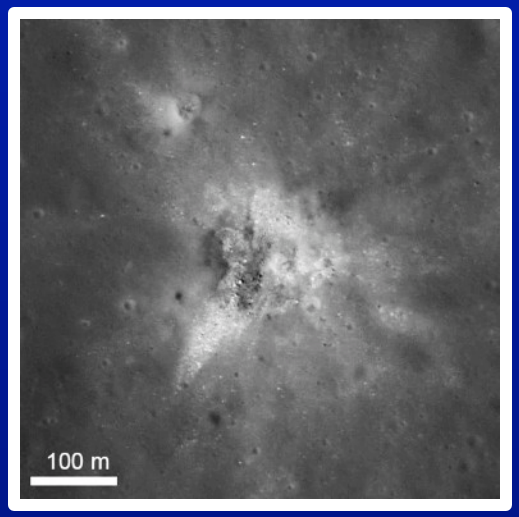
Reiner Gamma

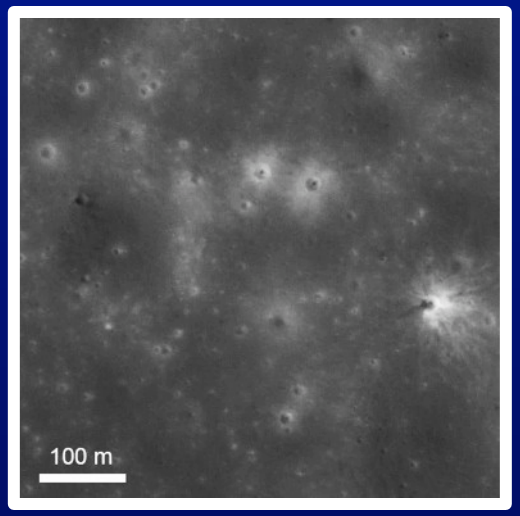


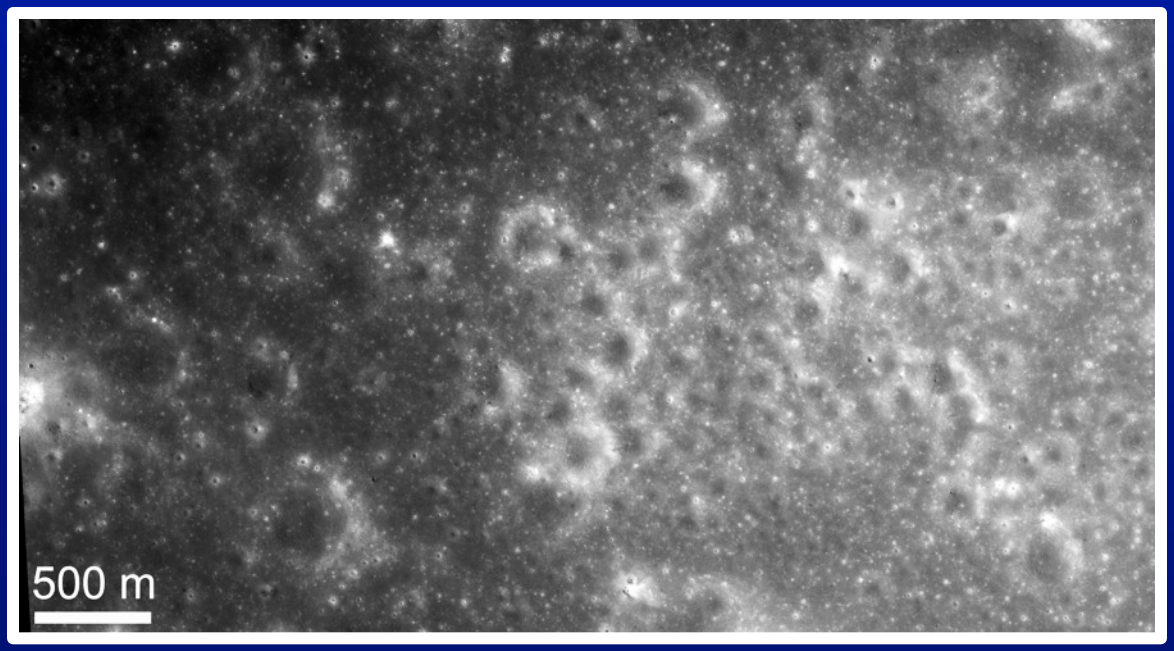
Reiner Gamma



Reiner Gamma

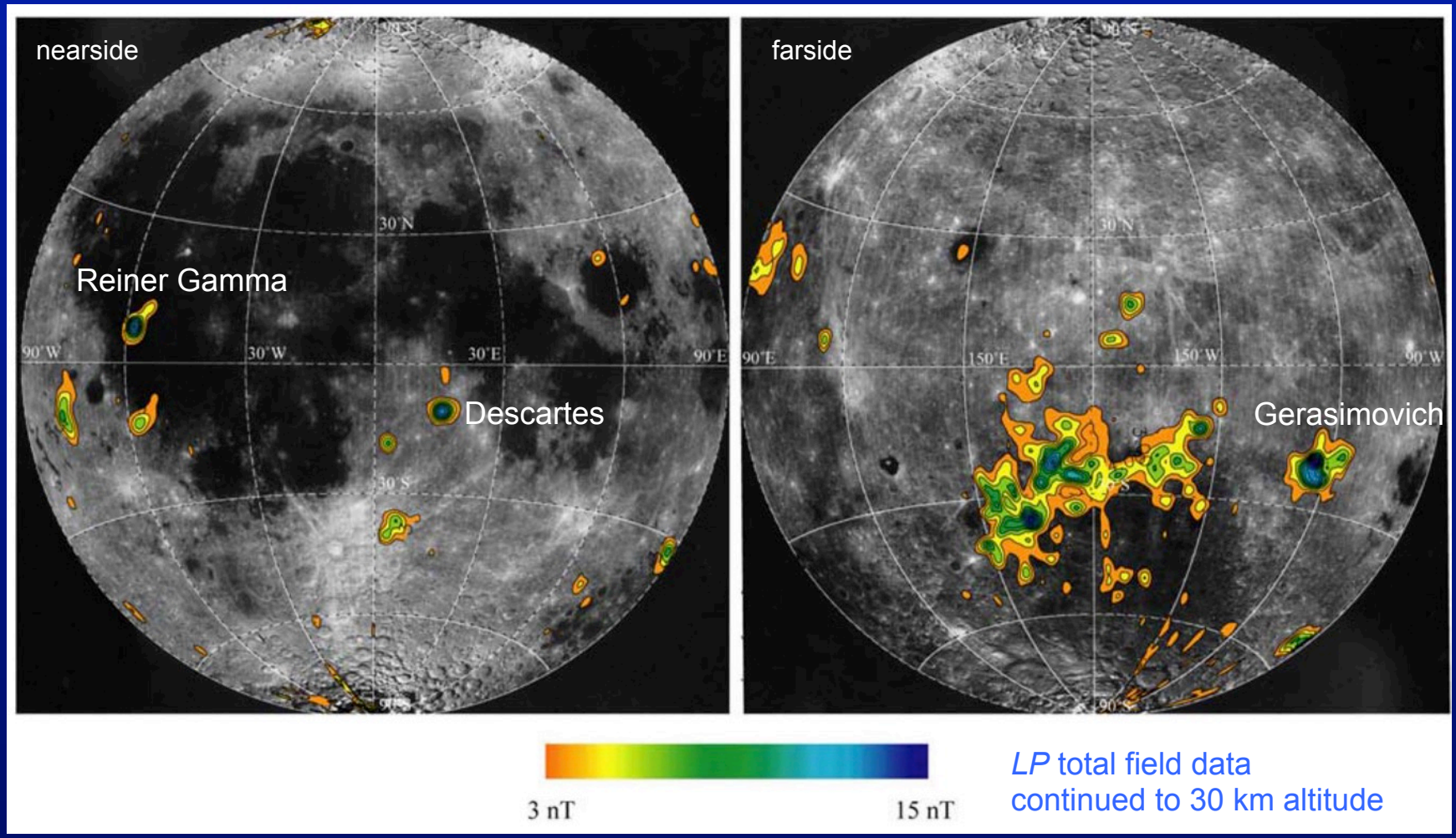






Lunar Prospector Total Magnetic Field

Strongest anomalies are ~20 nT at 30 km, perhaps 100s-1000 nT at surface.

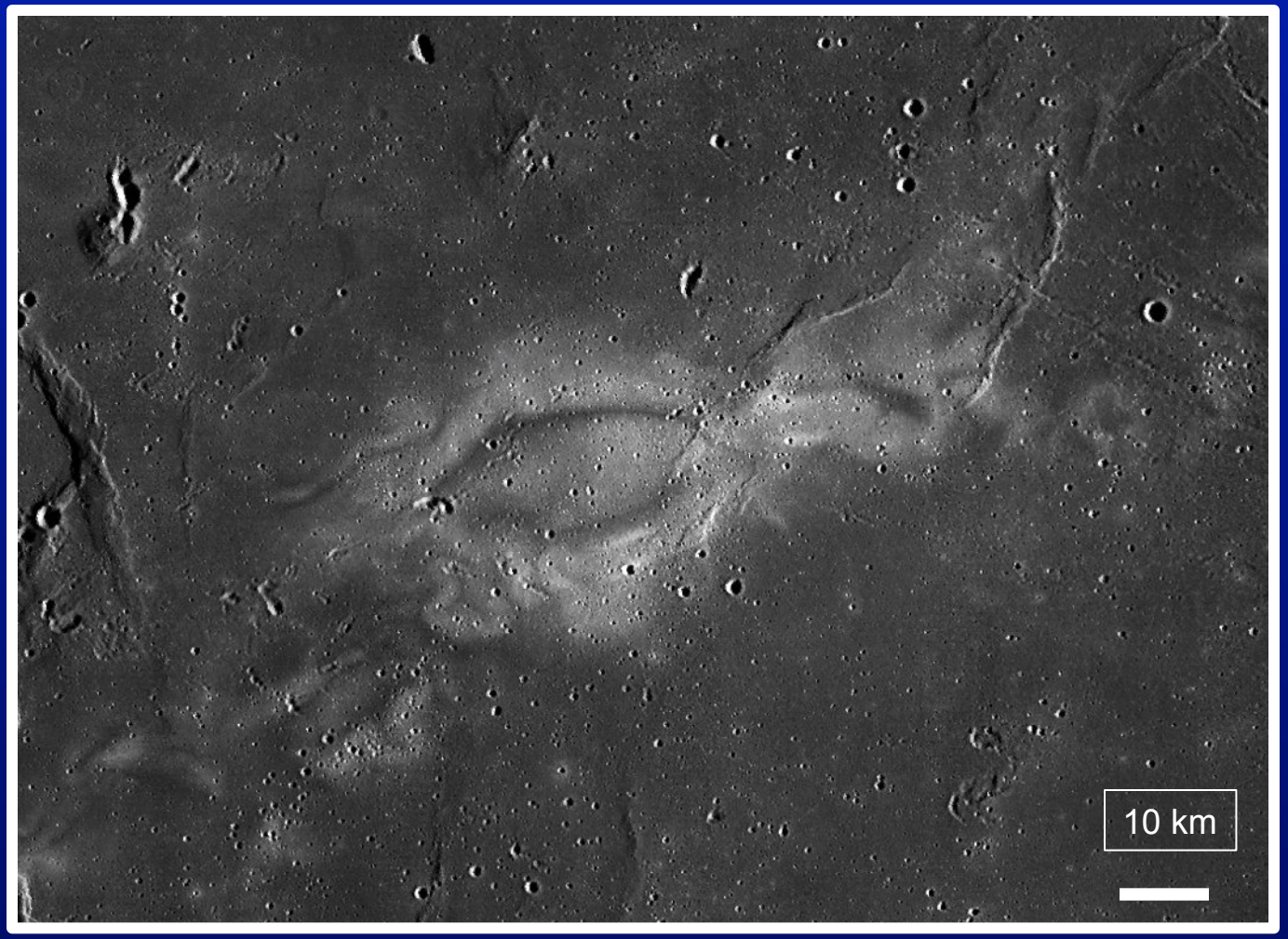


Descartes is the strongest nearside anomaly.
Gerasimovich (Crisium antipode) is strongest overall.

Richmond and Hood (2008) *JGR*

Space Weathering

Abnormal space weathering caused by magnetic anomaly

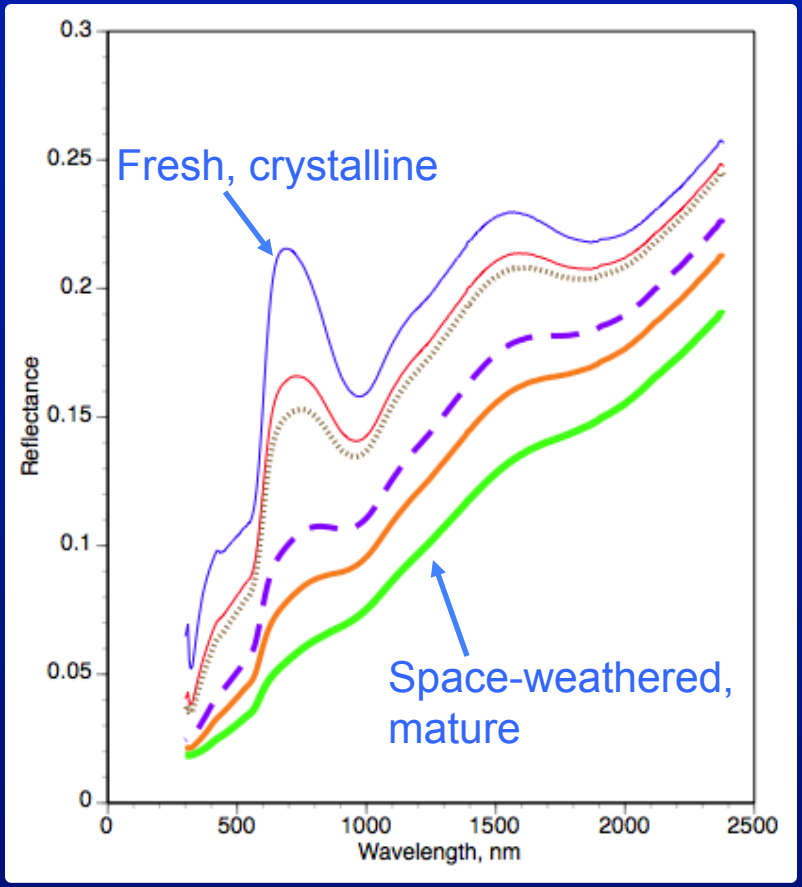


Reiner Gamma swirl
LROC WAC basemap

- Dark lanes are narrow with respect to the bright regions.
- If ion bombardment darkens regolith, there are large regions protected from the solar wind interspersed with regions connected to the solar wind.
- Suggests magnetized source has a complicated structure, not a simple dipole.

Space Weathering

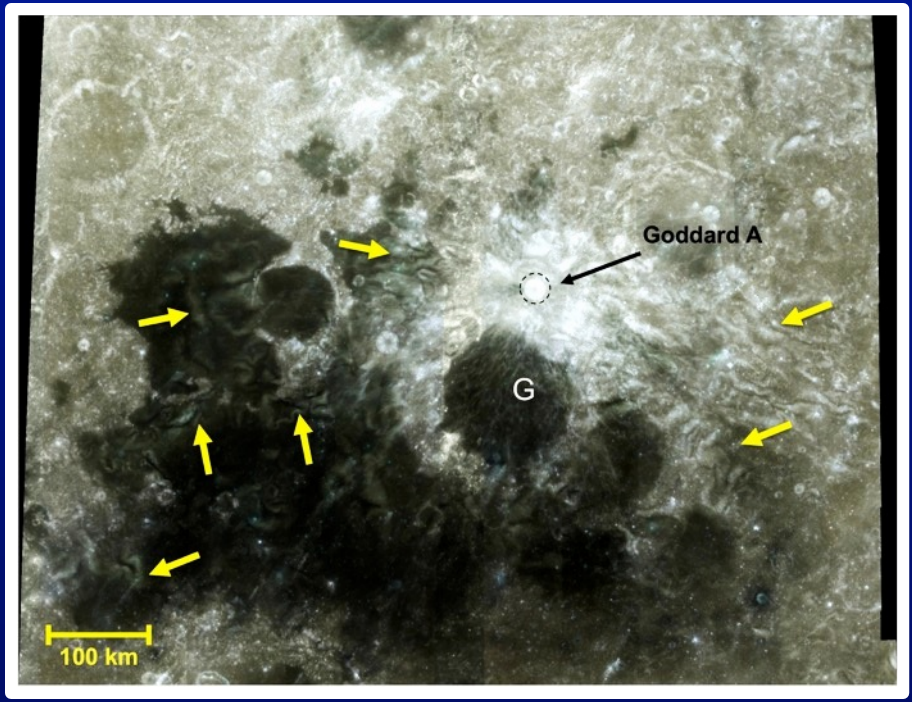
- Abnormal space weathering caused by magnetic anomaly
- Space weathering is the process(es) that cause bright crater rays to fade away with time.
  - With age, the surface becomes darker, reflects relatively more light at longer wavelengths ("reddens"), and mineralogical absorption bands lose contrast.
  - These spectral changes are caused by the accumulation of "nanophase" blebs and coatings of metallic iron on and within soil particles.



Hapke model reflectance spectra for soils of the same composition illustrate the optical effects of increasing nanophase Fe.

Cometary Impact

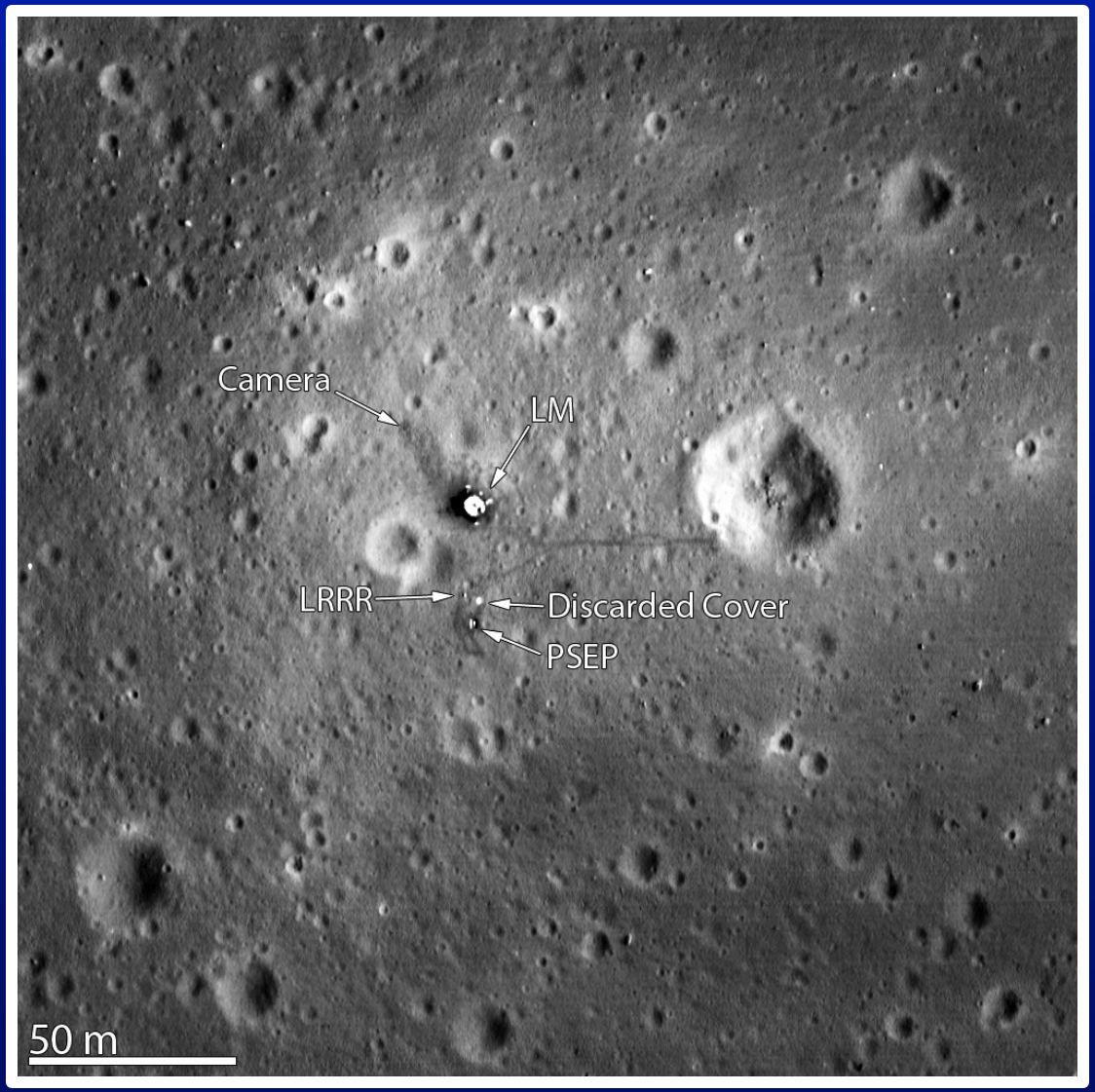
- Scouring/plowing of regolith by meteoroids, cometary nucleus fragments or gas/dust in the coma exposes fresh subsurface soils.
- Magnetic anomaly possibly created by plasma effects in coma.
- Swirls are very young features.
  - Schultz and Srnka (1980); Pinet et al. (2000); Starukhina and Shkuratov (2004); Bruck Syal and Schultz (2015).



Goddard A crater and Mare Marginis swirl belt (arrows): proposed by Schultz & Srnka (1980 Nature) to be the result of a comet impact. This is in the vicinity of the Orientale basin antipode.

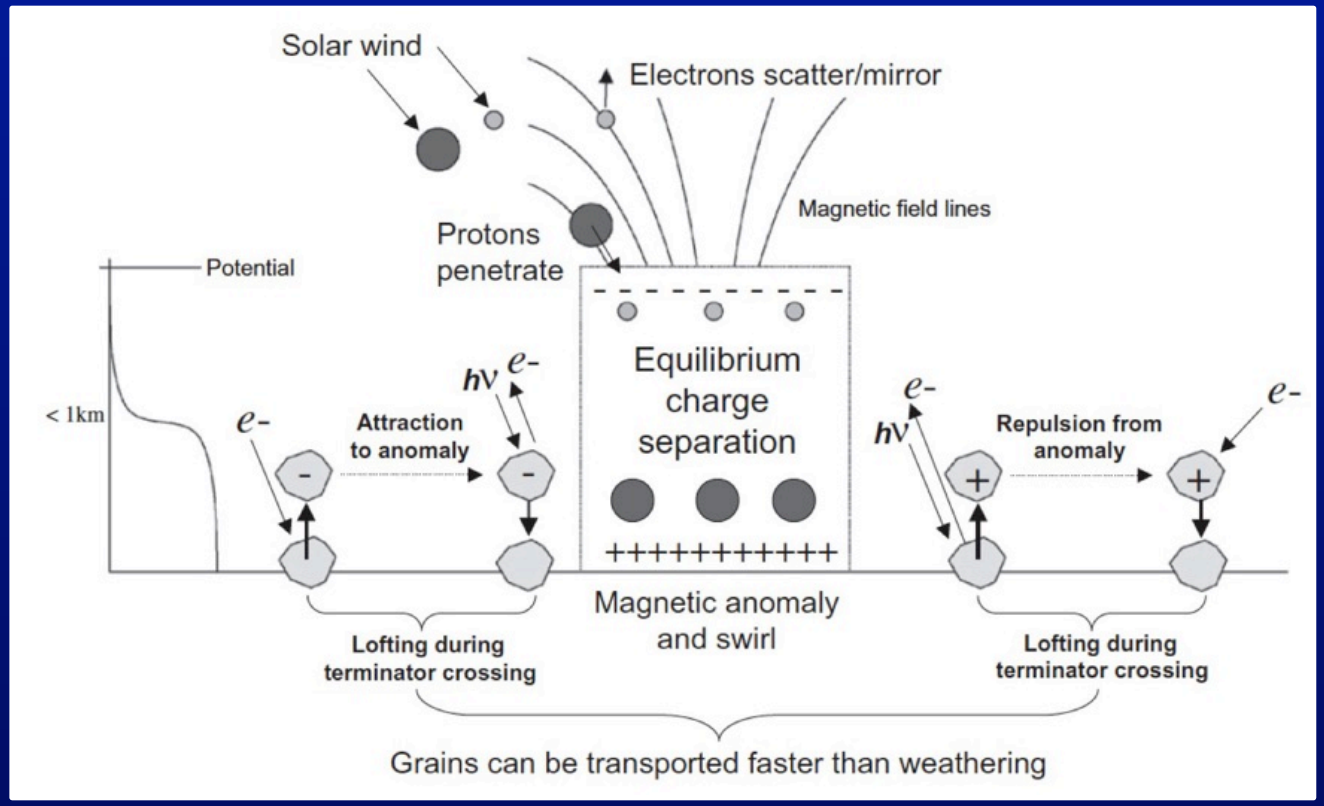
Clementine mosaic, figure from Blewett et al. (2011 JGR-Planets)

Cometary Impact



Accumulation of bright, fine-grained dust

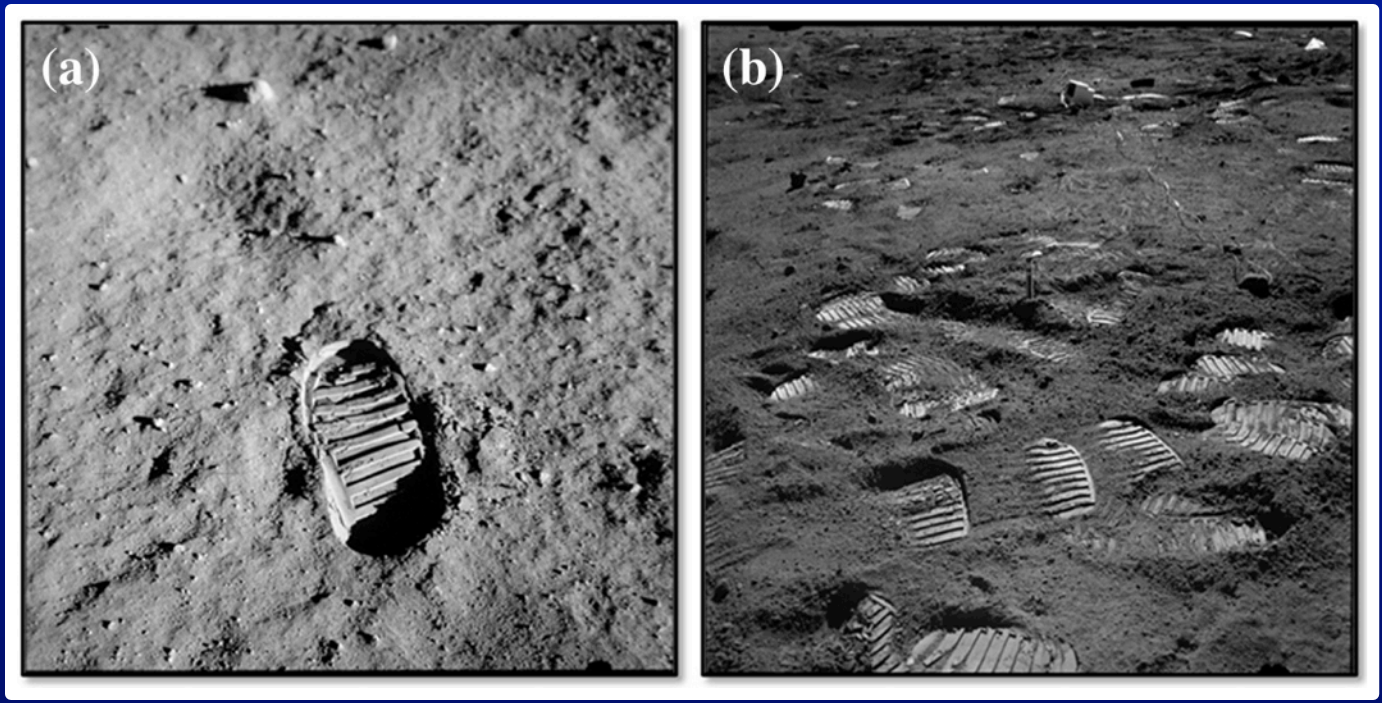
- Charge separation between solar-wind protons and electrons (plasma "double layer") above a magnetic anomaly creates an electric field that influences the motions of electrostatically charged dust grains.
- Fine-grained, feldspar-rich dust grains have high albedo.
- Garrick-Bethell et al. (2011) *Icarus*.



Garrick-Bethell et al. 2011 *Icarus*

Collapse of "fairy castle" soil structure

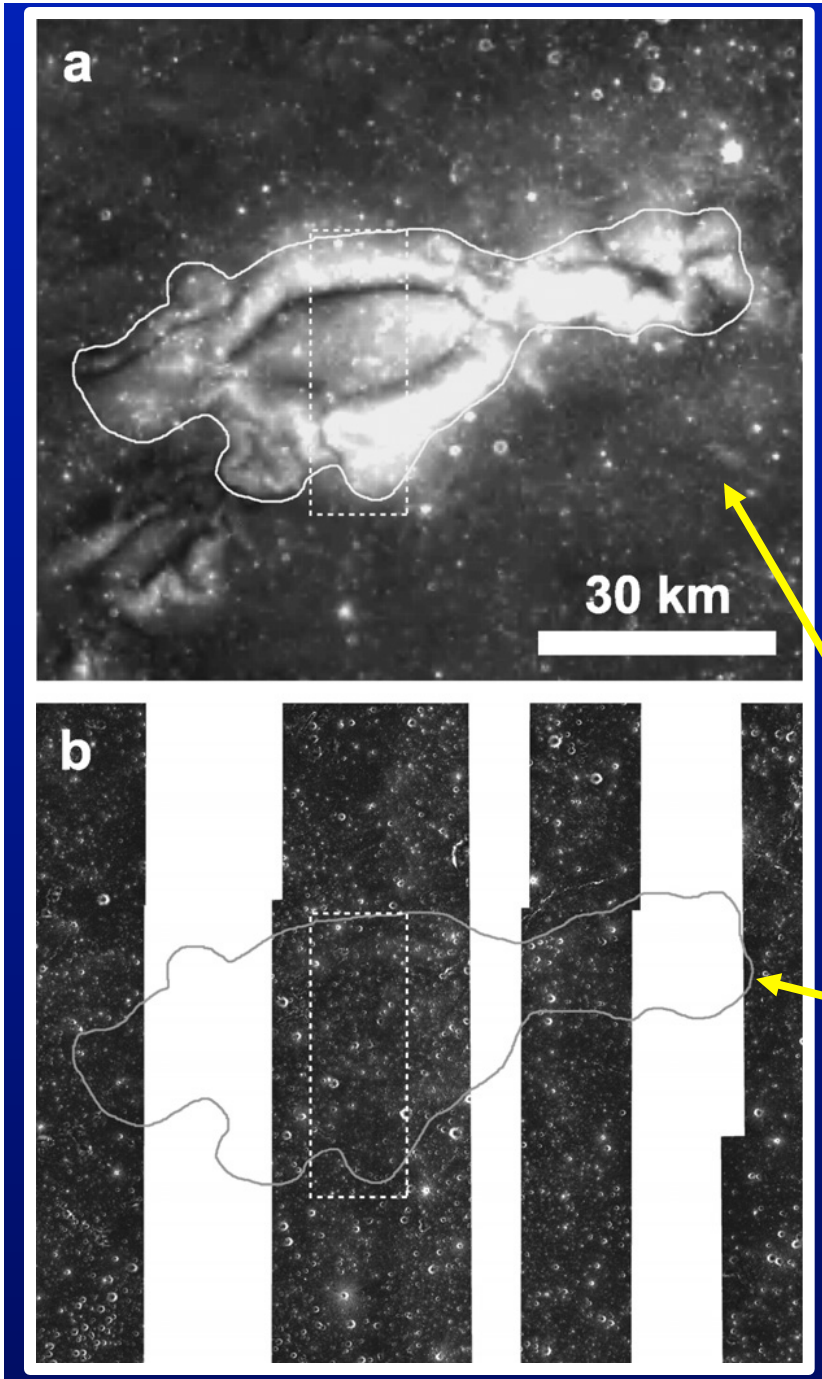
- The electric fields and dust hopping (Garrick-Bethell) modify the normal regolith texture. Causes surface to be brighter.
- Pieters et al. (2014) *LPSC*



Clegg et al. 2014 *Icarus*

Compacted soil has higher reflectance.

Recent data for swirls

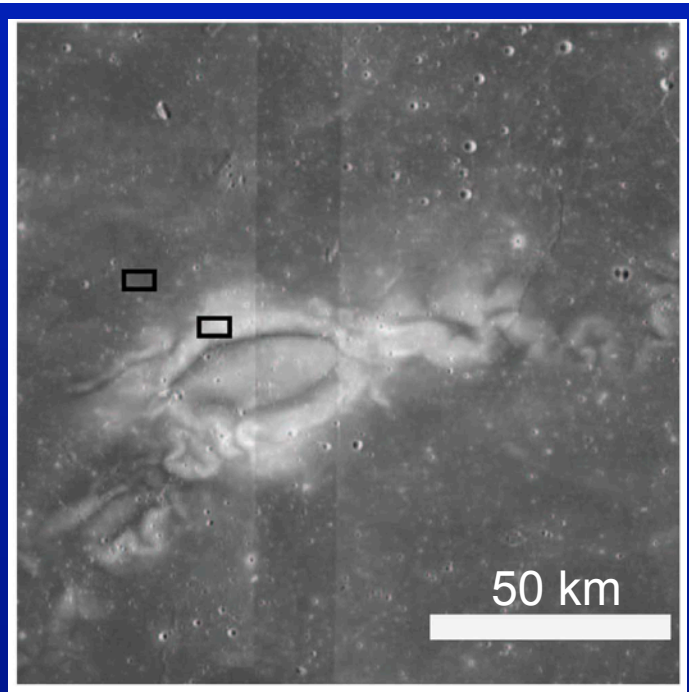


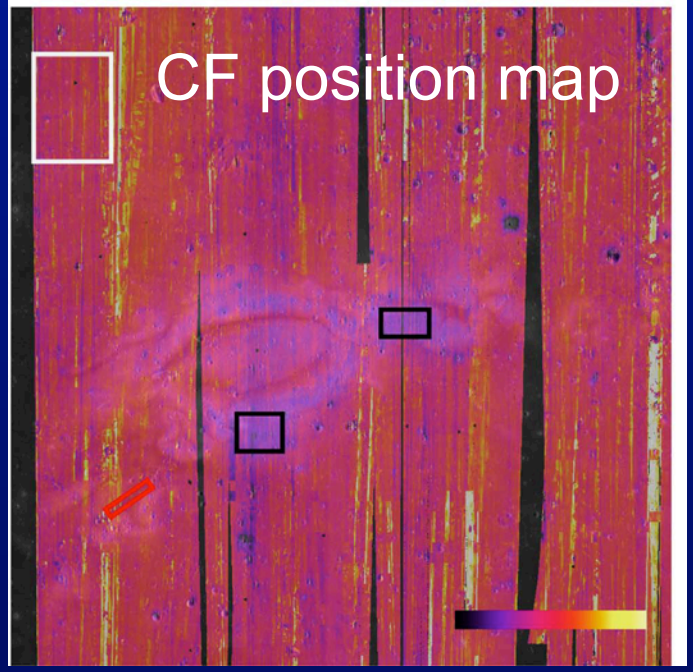
- *Lunar Reconnaissance Orbiter* Mini-RF radar roughness shows that swirls don't differ from nearby areas, suggesting they are thin, surficial features.

(a) *Clementine* 750-nm image of central Reiner Gamma swirl.

(b) Mini-RF total S-band backscattered power. No change in radar properties associated with optically bright swirl. No difference in wavelength-scale roughness.

Neish et al., 2011 *Icarus*

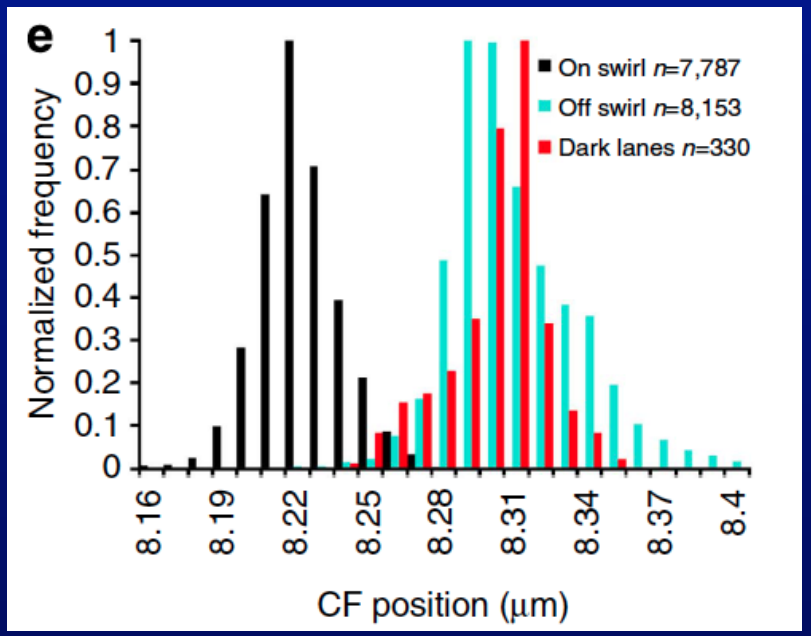


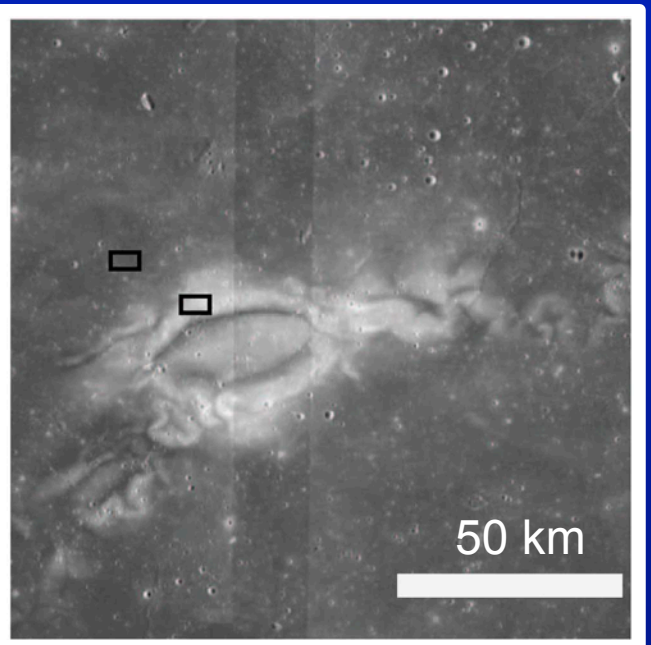


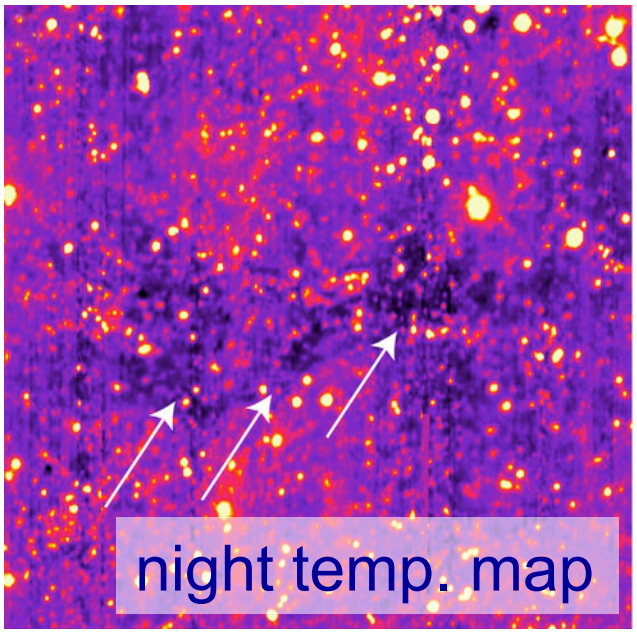
Glotch et al., 2015 *Nature Comm.*

Recent data for swirls

- *Lunar Reconnaissance Orbiter* Diviner radiometer - two findings that bear on the nature of swirls:
- Christansen feature wavelength shift is like that in other immature materials – suggests decreased space weathering in bright parts of swirls. Wavelength shift is too great to be caused by mixing of feldspar-rich dust.







-3.6 ΔK +7 ΔK

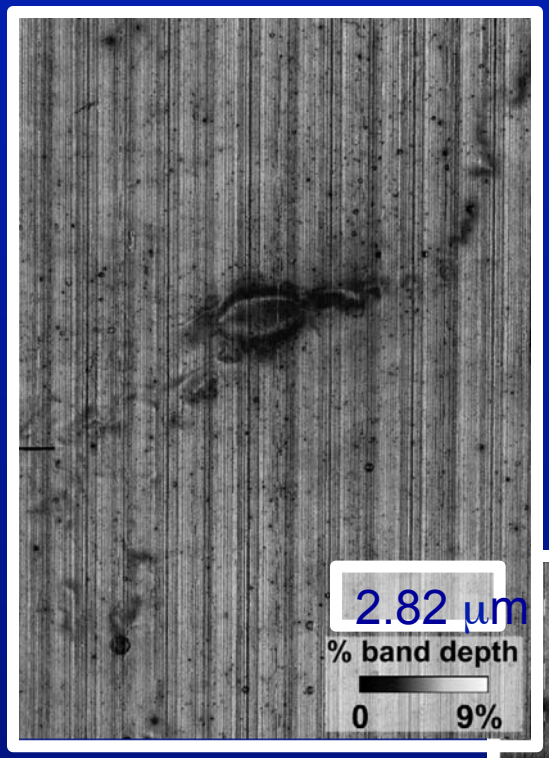
Recent data for swirls

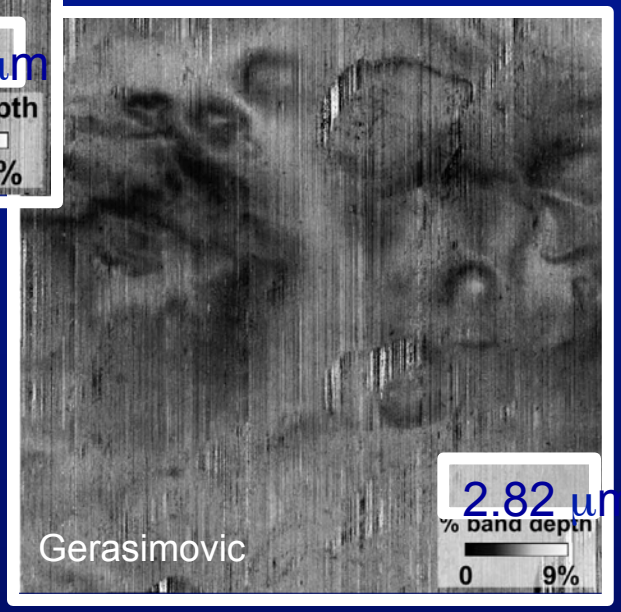
- *Lunar Reconnaissance Orbiter* Diviner radiometer - two findings that bear on the nature of swirls:
- Small nighttime temperature difference can be accounted for by the albedo difference.
- No temperature anomalies (thermal inertia difference) that would be consistent with dust accumulations.
- These findings appear to rule out the dust-accumulation model, and support the solar-wind shielding model.

Glotch et al., 2015 *Nature Comm.*

Recent data for swirls

Reiner Gamma





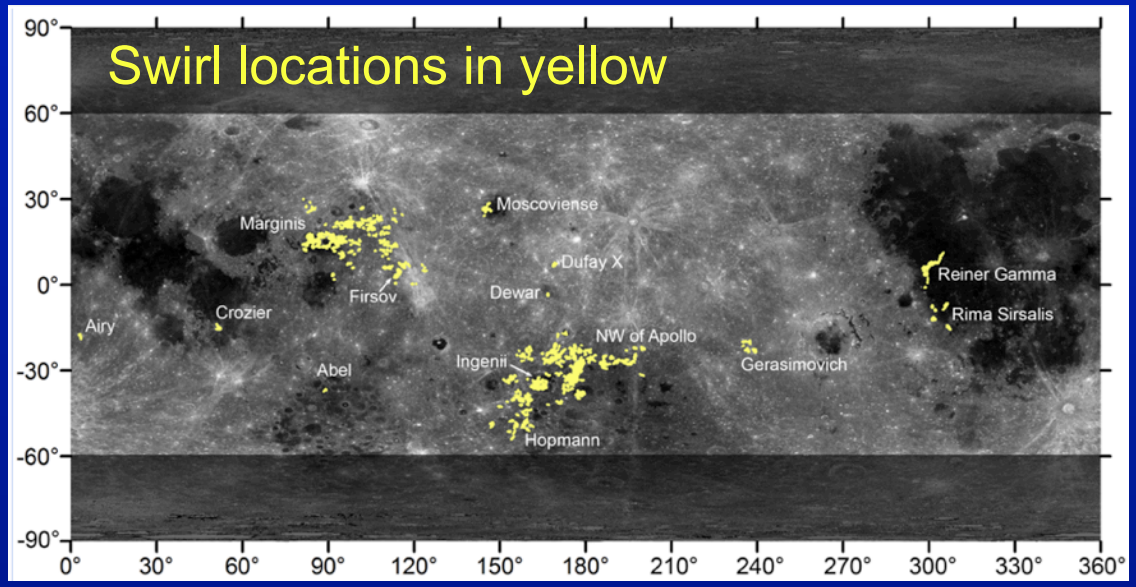
- *Chandrayaan* Moon Mineralogy Mapper (M3) data:
- 2.82 μm hydroxyl (OH) absorption.
- 2.82 μm band is weaker in bright parts of swirls.
- Suggests that decreased proton flux is reaching the surface.
- Limits space weathering and production of nanophase iron.

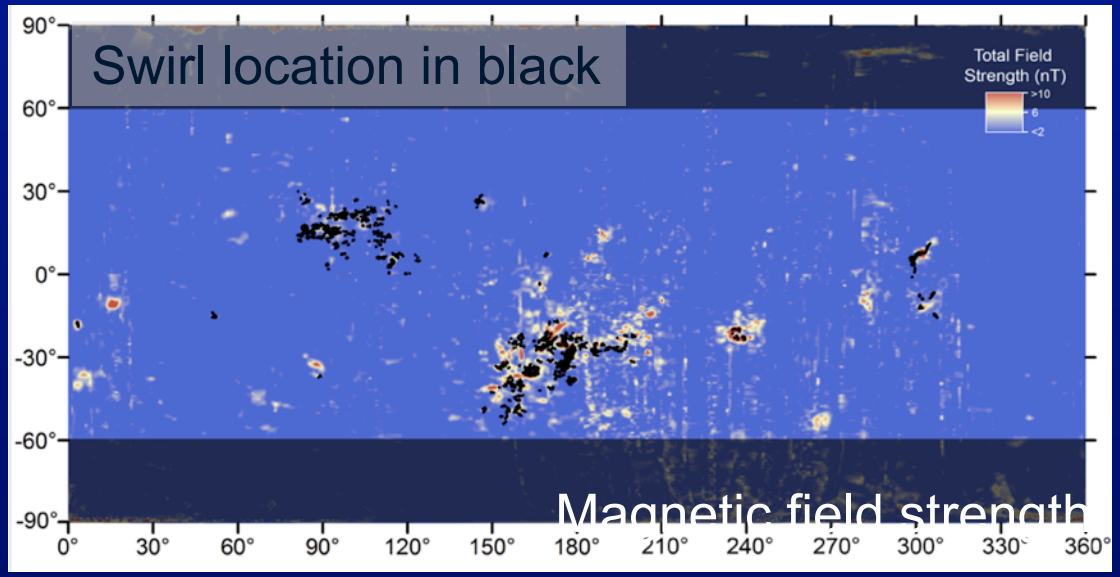
Kramer et al., 2011 *JGR-Planets*

New Swirl Mapping: Ultraviolet

- Hendrix and Vilas (2006 *Astron. J.*): UV is sensitive to early stages of space weathering, presence of small amounts of nanophase Fe
- Surface scattering dominates in UV, so more sensitive to coatings on regolith particles.

- LROC WAC has two UV filters: 320-nm, 360-nm
- Denevi et al. (2014 *JGR-Planets*) examined surface maturity and space weathering with WAC ratio images.

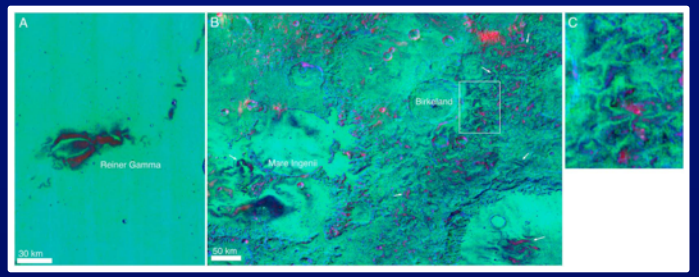




New Mapping

- Denevi et al. (2015, submitted) used LROC WAC UV images to map swirls over the entire Moon.
- All swirls are associated with magnetic anomalies.

R = 415 nm reflectance
G = 321/415nm ratio
B = 321/360nm ratio



Denevi et al., 2015, submitted

Thank You