SPACE WEATHERING ACROSS THE SOLAR SYSTEM:

Lessons from the Moon and Outstanding Questions

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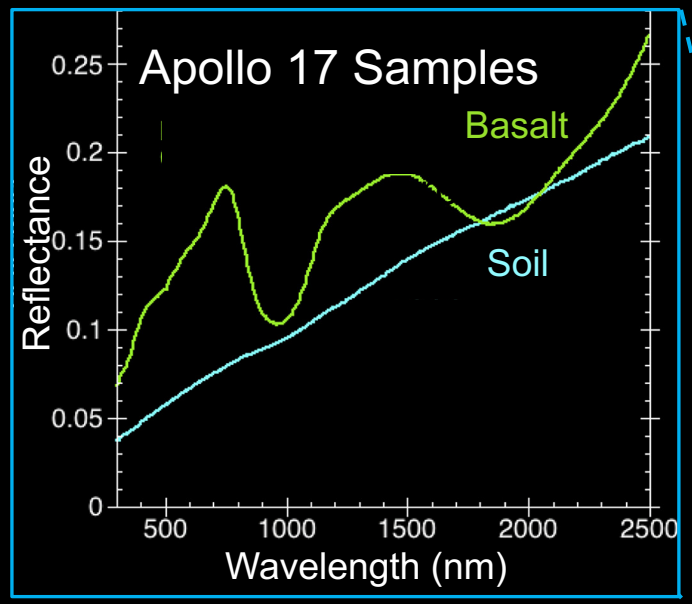
Space weathering alters the chemistry, microstructure, and spectral properties of surface soils.



(Adapted from Pieters and Noble 2016)

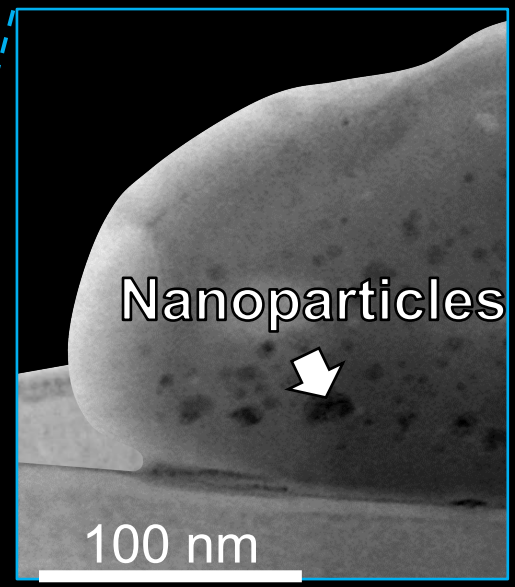
Impacts

Radiation Processes

Micrometeorites

Solar Wind

H^+ & He^+



(Adapted from Thompson et al. 2019)

Understanding space weathering is critically important for exploration of the solar system by robotic and crewed missions.

- *Interpretation of remote sensing data from any airless surface relies on properly understanding the signatures and history of space weathering*
- *Space weathering may play an important role in the production and cycling of volatiles on the surface of the Moon and other airless bodies*
- *Matching of meteorites to their parent bodies (e.g., ordinary chondrites and S-type asteroids)*
- *The Moon, Mercury, moons of Mars, near-Earth and main-belt asteroids are all affected by space weathering*

BepiColombo

Coordinated analysis of lunar samples and data has given us a framework for understanding space weathering processes.

Spectral Analyses

Visible-near infrared (VNIR):

→ Darker (⇩ reflectance)

→ Redder (reflectance ⇧ as λ ⇧)

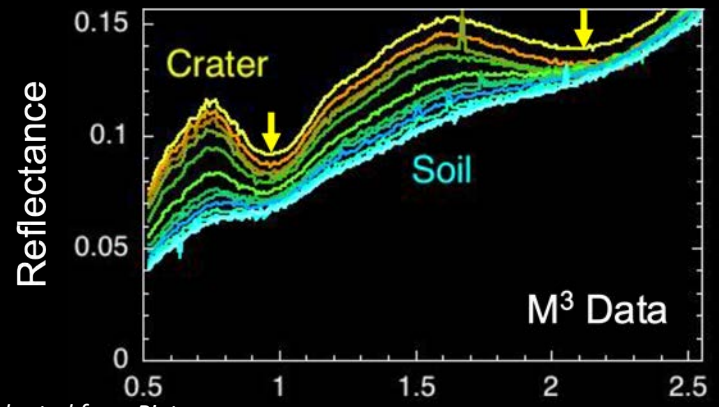
→ Attenuated absorption bands

Mid-infrared (MIR):

→ Christiansen feature ⇨ longer λ

→ Restrahlen band ⇩

→ Look for the cause of spectral changes in returned samples



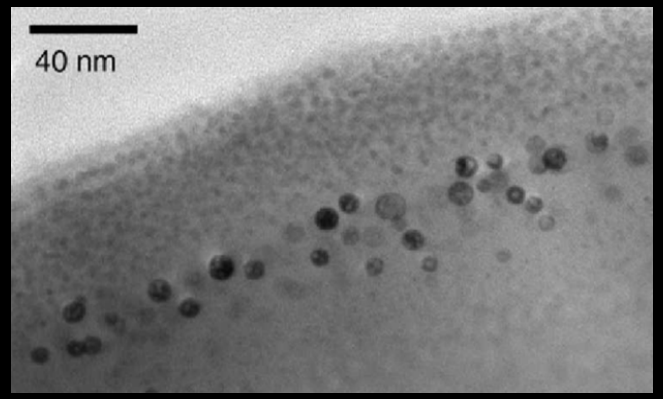
(Adapted from Pieters and Noble 2016)

Sample Analysis

→ Nanophase Fe (npFe) particles are driving spectral changes

→ Agglutinates, vesicles, amorphous rims, solar flare tracks, vapor deposits

→ Can link these characteristics to formation mechanisms through laboratory experiments



Space weathered lunar soil grain

Experimental Simulations

→ Simulate micrometeoroid bombardment through pulsed laser irradiation

→ Simulate solar wind through ion irradiation

→ Typical targets are silicate minerals common in lunar samples

→ Reproduces microstructural and spectral features

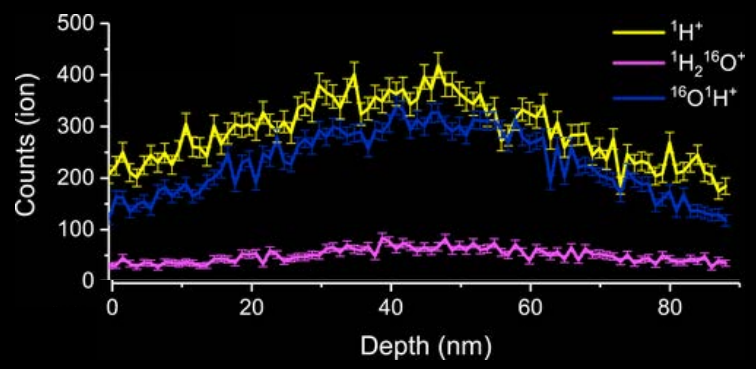
Ion irradiation chamber at UVa

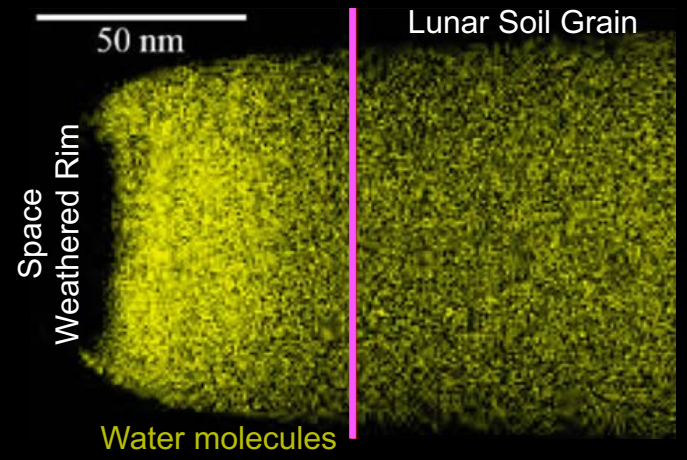
Despite a working model for lunar space weathering, mysteries persist in our understanding of how these processes affect the Moon.

How does space weathering contribute to the volatile inventory of the Moon?

- → The spatial distribution and abundance of water on the Moon is an outstanding question in lunar science
- → Sample measurements and laboratory experiments show that solar wind implanted H^+ can combine with O in surface minerals to form OH and H_2O
- → How efficient is the solar wind at producing water?
- → Is that efficiency influenced by Mineralogy? Location? Latitude?
- → Other volatile species, e.g., He^3 could prove important for ISRU applications

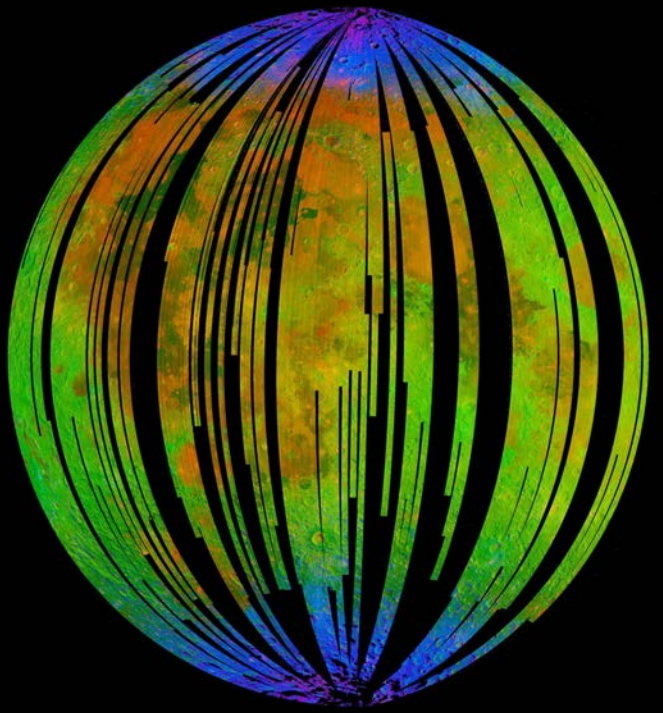
(Adapted from Greer et al. 2020)





(Adapted from Daly et al. 2018)

Water at the poles



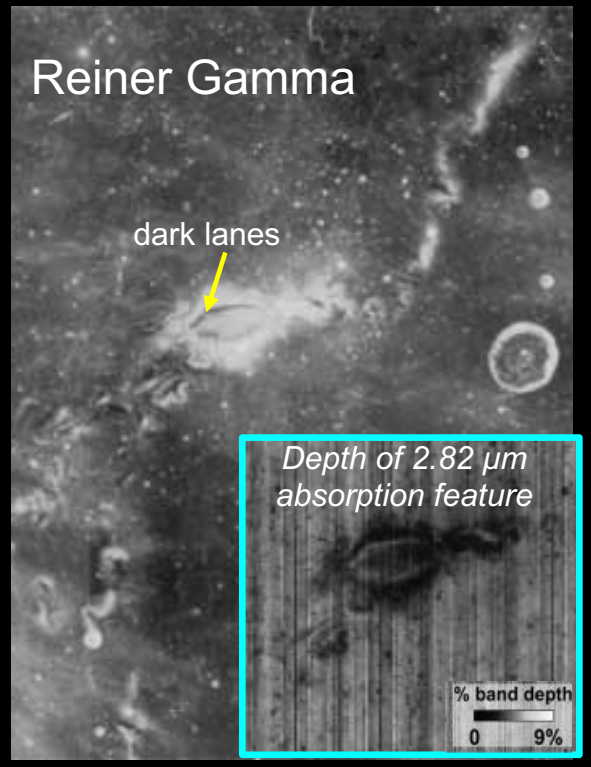
(NASA)

Recommendation: *Invest in studies exploring links between space weathering and the production and cycling of volatiles*

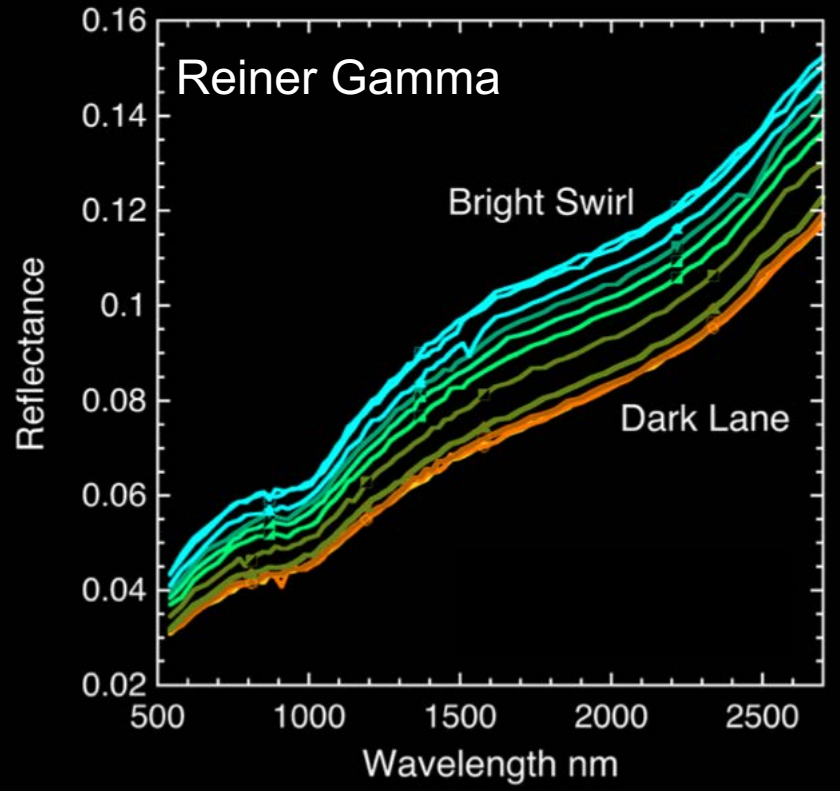
Despite a working model for lunar space weathering, mysteries persist in our understanding of how these processes affect the Moon.

What are the relative contributions of solar wind irradiation vs. micrometeoroid bombardment?

- → Solar wind irradiation and micrometeoroid impacts generate different microstructural and chemical characteristics, which affect spectral properties
- → Knowing their relative contributions will enable the prediction of optical changes on new planetary surfaces
- → Lunar swirls are locations where magnetic fields shield the surface from solar wind - a natural laboratory for understanding space weathering environments



(Adapted from Kramer et al. 2011)



(Adapted from Pieters and Noble 2016)

Recommendation: *Consider missions focused on lunar swirls to better constrain the contributions of various constituent processes to space weathering*

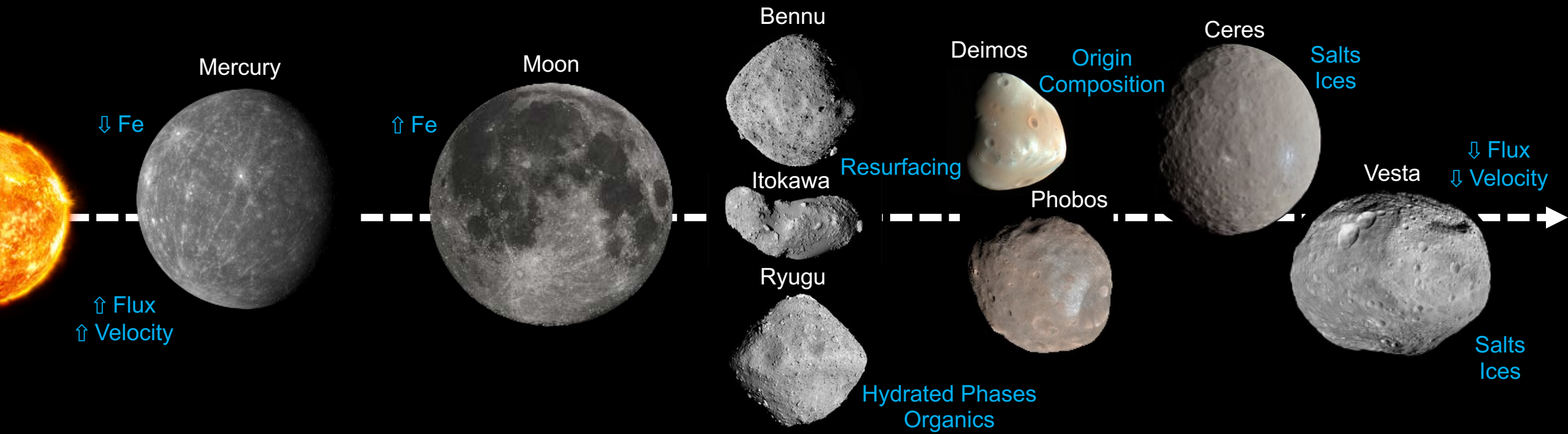
Our understanding of space weathering is built on observations of the Moon, but it is critical to expand our model beyond the lunar surface.

Variables related to heliocentric distance

→Solar wind flux
→Micrometeoroid flux and impact velocity

Other relevant variables

→Resurfacing rates
→Starting composition, mineralogic diversity



Space weathering of chondrites reveals microstructural, chemical, and spectral characteristics depend strongly on target composition.

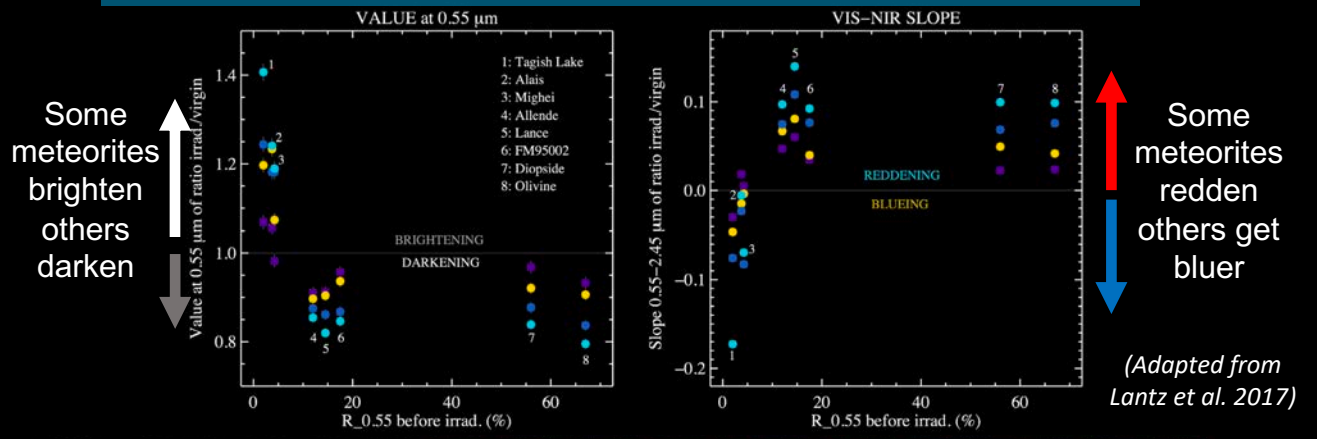
How does asteroid Itokawa experience weathering?

→ Novel space weathering characteristics, including npFeS and npMgS phases
→ Short exposure timescales

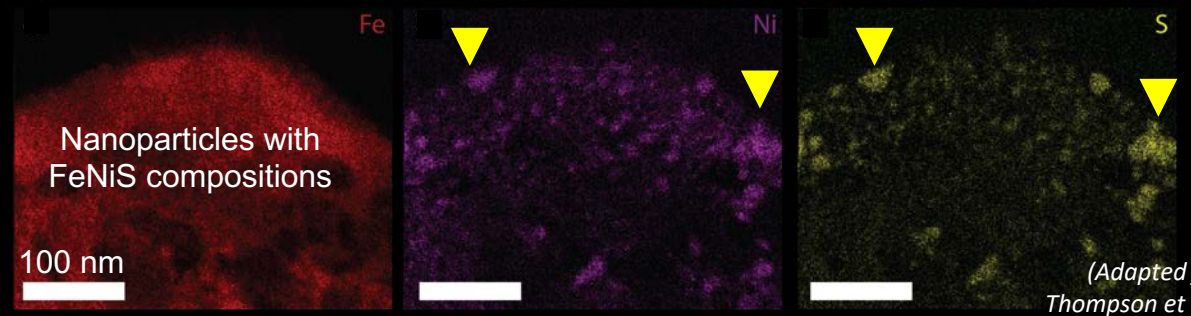
How do carbonaceous meteorites respond to space weathering?

→ Laboratory experiments yield conflicting and diverging spectral trends
→ Mineralogical complexity of the targets yields compositionally diverse nanophases
→ Effects of these nanophases on spectral properties is unpredictable

The Moon experiences only one 'style' of space weathering



(Adapted from Lantz et al. 2017)

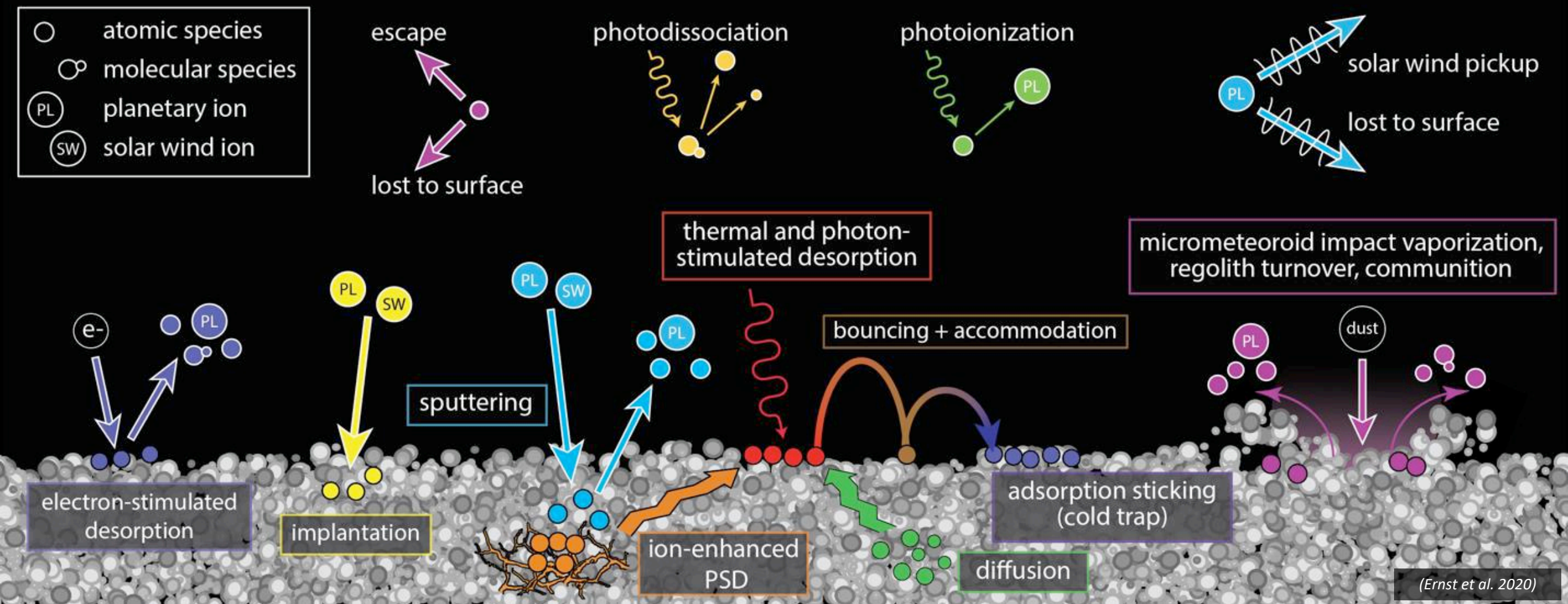


(Adapted from Thompson et al. 2020)

Recommendation: *Prioritize understanding the space weathering environment at the Moon as a natural laboratory for other airless bodies*

Space weathering effects on materials with exotic compositions or in end-member environments are largely unknown.

Mercury: low-Fe, high-C composition and an extreme space weathering environment



(Ernst et al. 2020)

Where do we go from here?

Over the next decade prioritize:

- Funding landed and orbital missions which better characterize the space weathering environment as relevant to exploration hazards
- Funding correlative R&A investigations leveraging laboratory experiments, remote sensing datasets and returned samples (where available)
- Understanding the relationship between space weathering and volatile cycling
- Using the Moon as a natural laboratory for understanding space weathering, including studies of lunar swirls
- Studies which further our model of space weathering to include Mercury and other airless surfaces

This will ensure:

- Maximizing science return from past, ongoing, and future missions to airless surfaces with orbital, robotic, and human exploration
- Preparedness for human exploration, hazards, and *in situ* resource utilization
- A robust understanding of the evolution of airless surfaces
- Improved linkages between meteorites and parent body asteroids

We must treat space weathering as a universal process that is critically important to our understanding of the solar system and the science return from all future missions to airless bodies.