



Space Exploration and the Lunar Surface Environment

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Hope College Seminar

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Artemis: A Foundation for Deep Space Exploration



Space Launch System



Orion Spacecraft



Human Landing System



Surface Operations



Gateway



Exploration Ground Systems



Space Communications
& Navigation



Surface Mobility



Spacesuits



Surface Infrastructure

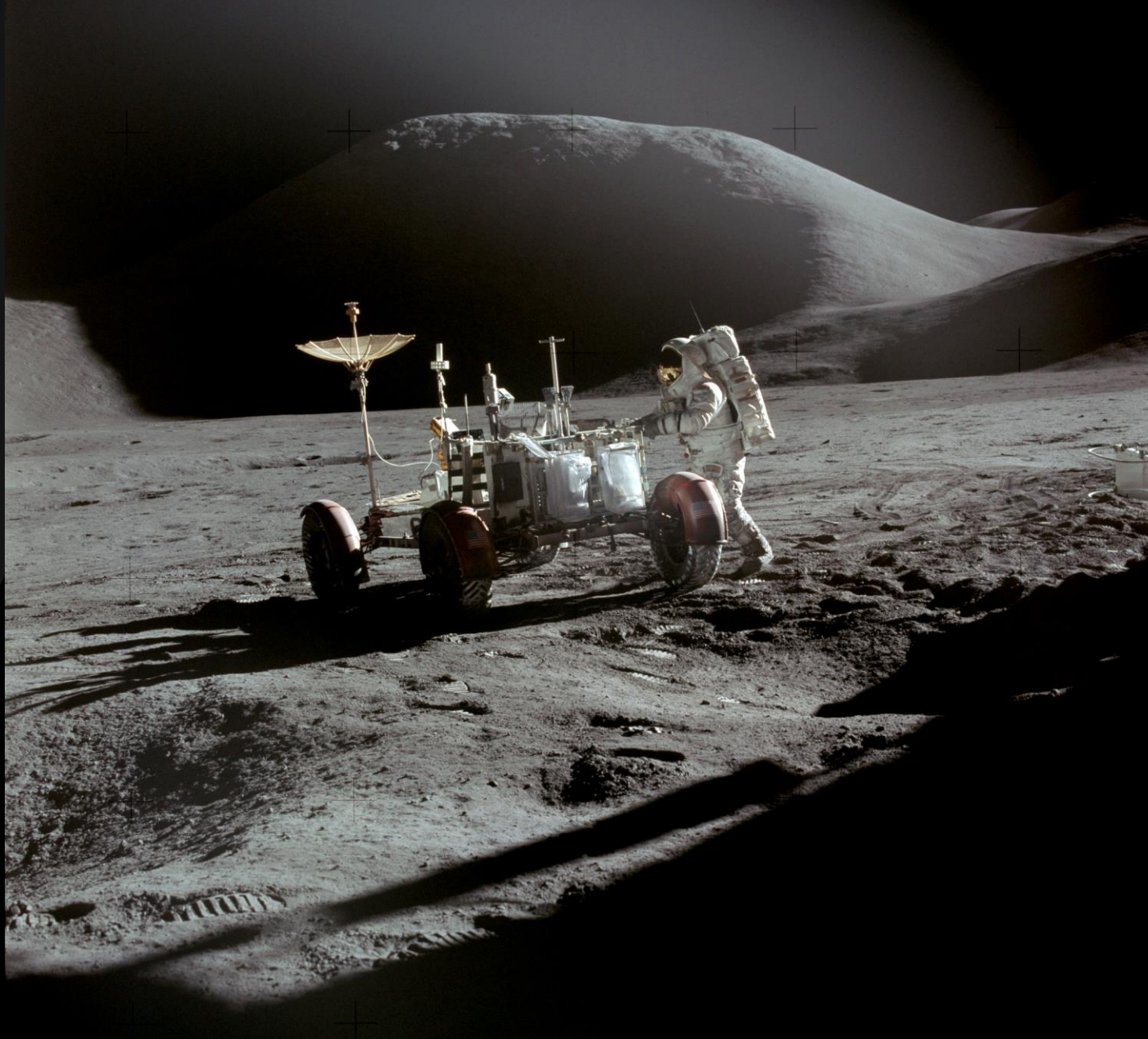


No atmosphere

Fine, abrasive
lunar regolith

Craters caused
by meteoroid
bombardment

AS15-86-11603
NASA/scanned by Kipp Teague



Incident
radiation

Unintuitive
lighting
environment

Extreme thermal
conditions

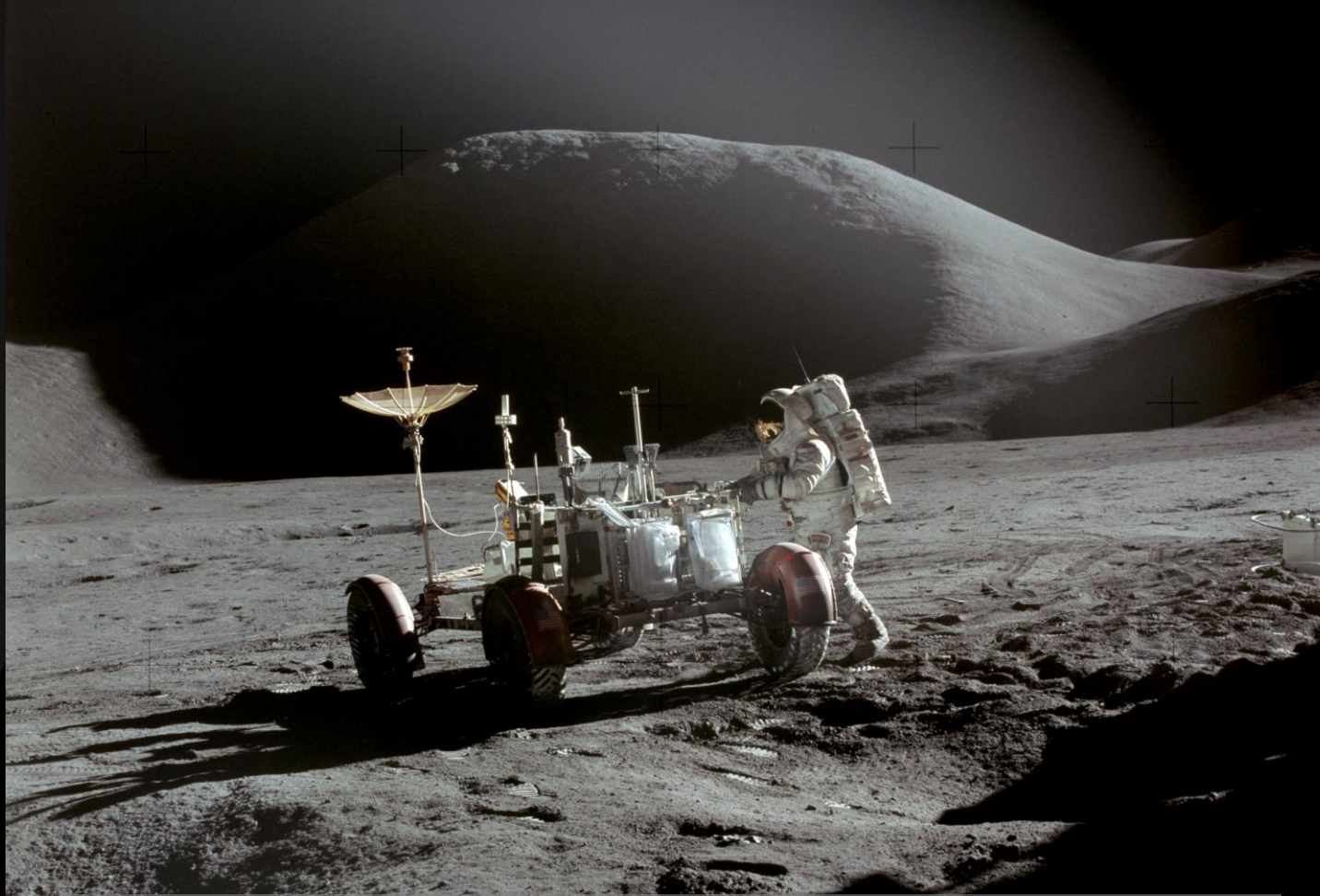


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Natural Environments

*The stuff that's there
before you get there*



The Natural Environments group at Marshall Space Flight Center compiles relevant natural environments research into a design specification for engineers to use while designing flight hardware

Experiments and Measurements

Flight Data

Science
Publications



SLS-SPEC-159
REVISION I

EFFECTIVE DATE: OCTOBER 27, 2021

**CROSS-PROGRAM
DESIGN SPECIFICATION FOR
NATURAL ENVIRONMENTS (DSNE)**

The Lunar Regolith



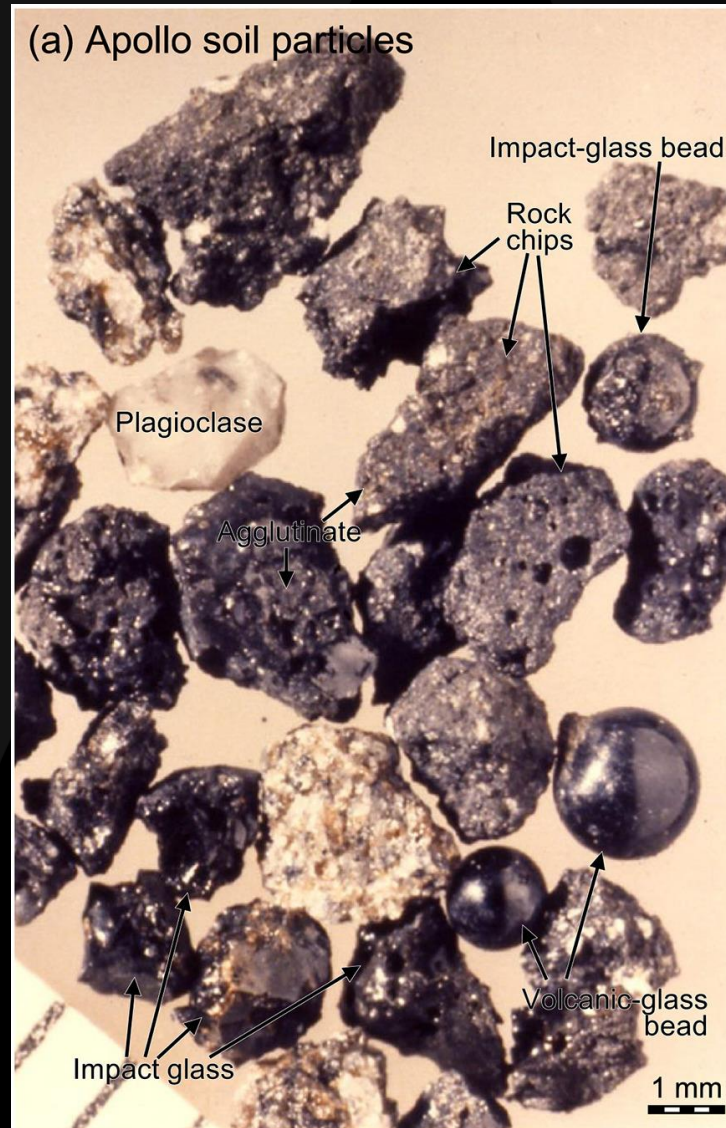
NASA/JSC/AS11-40-5877

“The lunar regolith is the surficial layer of fragmented material (rocks, soil, and dust) that covers virtually the entire surface of the Moon.”

–DSNE Section 3.4.2.1, General Description of the Lunar Regolith

Median Regolith Depth	
Mare	3 – 5 <i>m</i>
Highlands	10 – 15 <i>m</i>

Lunar Regolith Particle Shapes



Lunar regolith particles have angular, irregular shapes due to impact processes

Figure from Zeng et al. 2019.

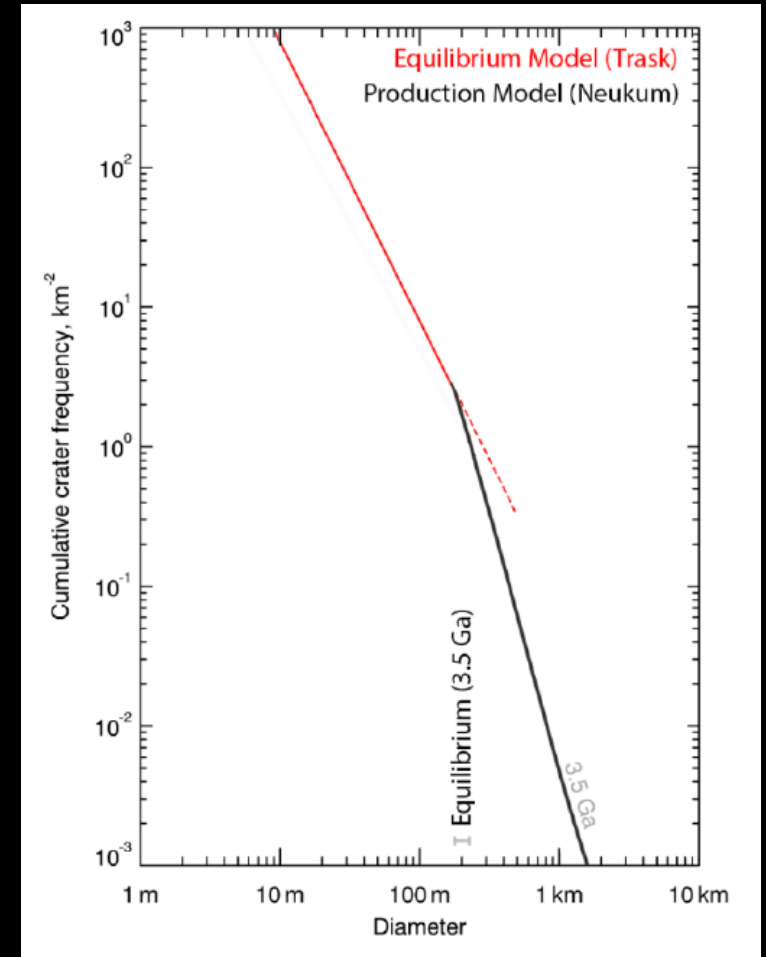
<https://doi.org/10.1029/2019JE006237>

Craters on the Lunar Surface



Craters are produced by meteoroid impacts into the lunar surface; their sizes follow a logarithmic distribution

Craters degrade over geologic time, which changes characteristics like their depth-to diameter ratio



DSNE Figure 3.4.1.1-1

Rocks on the Lunar Surface

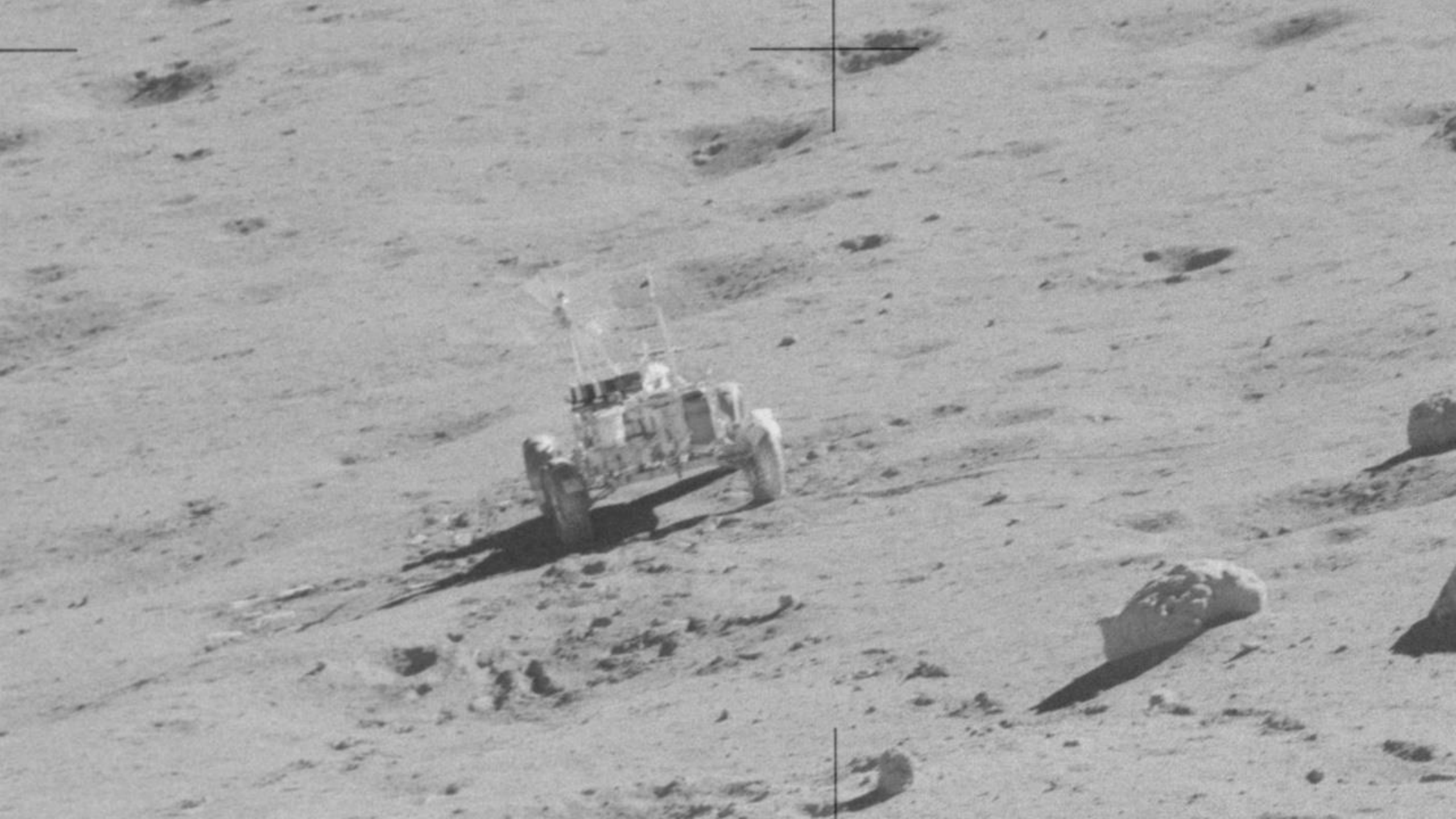
Rocks are relatively rare on lunar surface; fractional area of rocks $\geq 1\text{ m}$ typically $< 1\%$

Rocks are not randomly distributed; fractional area can be high (10% – 20%) in certain regions

DSNE 3.4.1.4





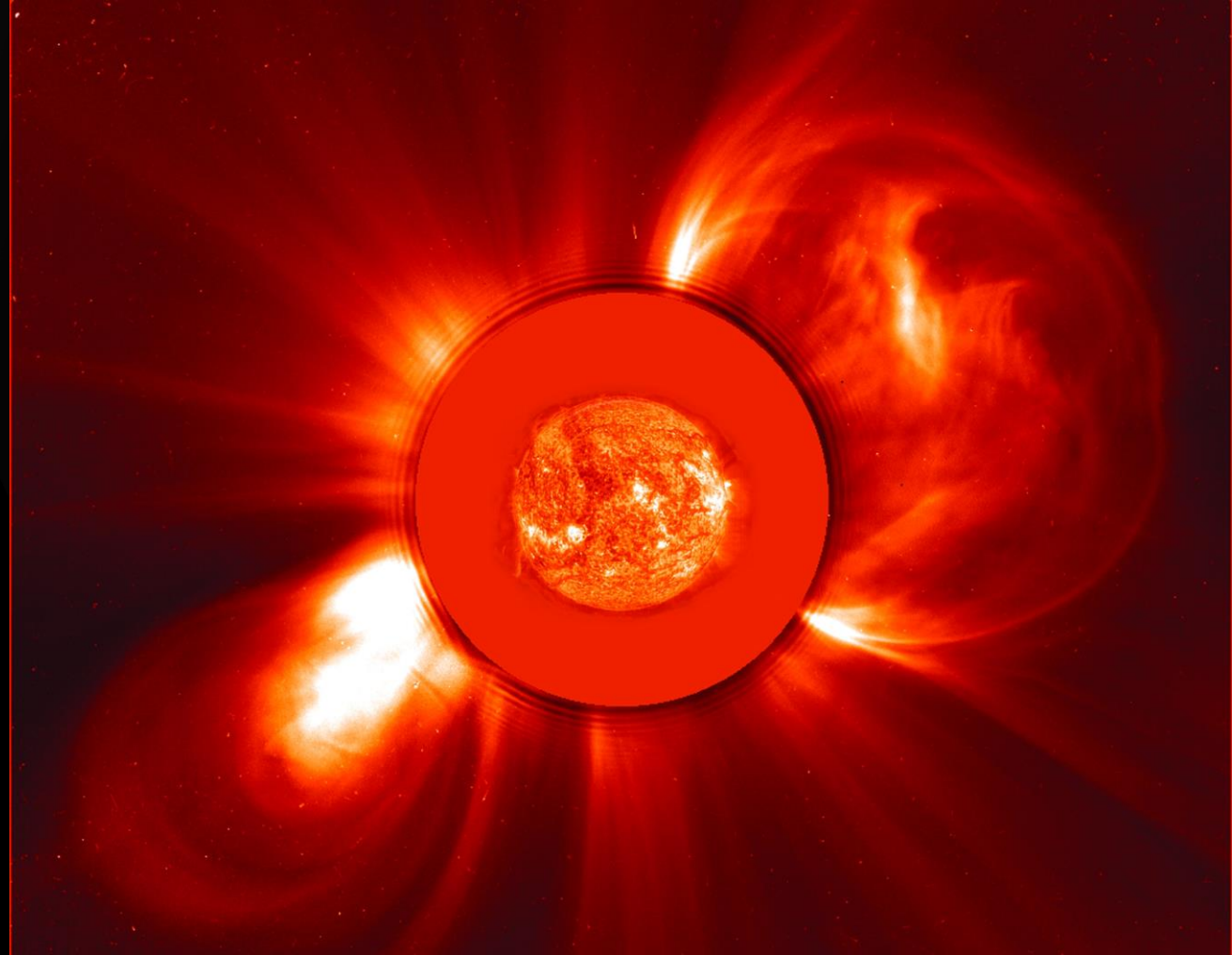


Radiation Environments



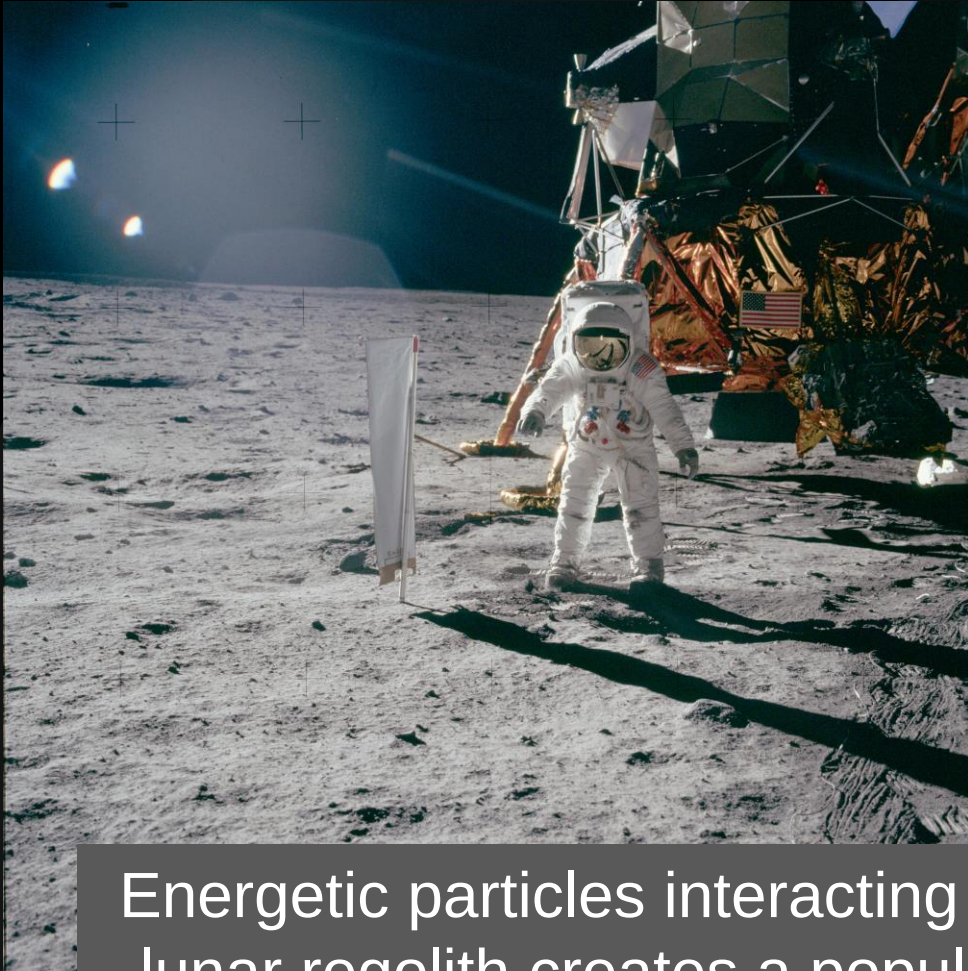
The solar wind consists of ions originating from the Sun

Radiation can disrupt electronics, causing *single event effects*, and cause long-term damage from exposure

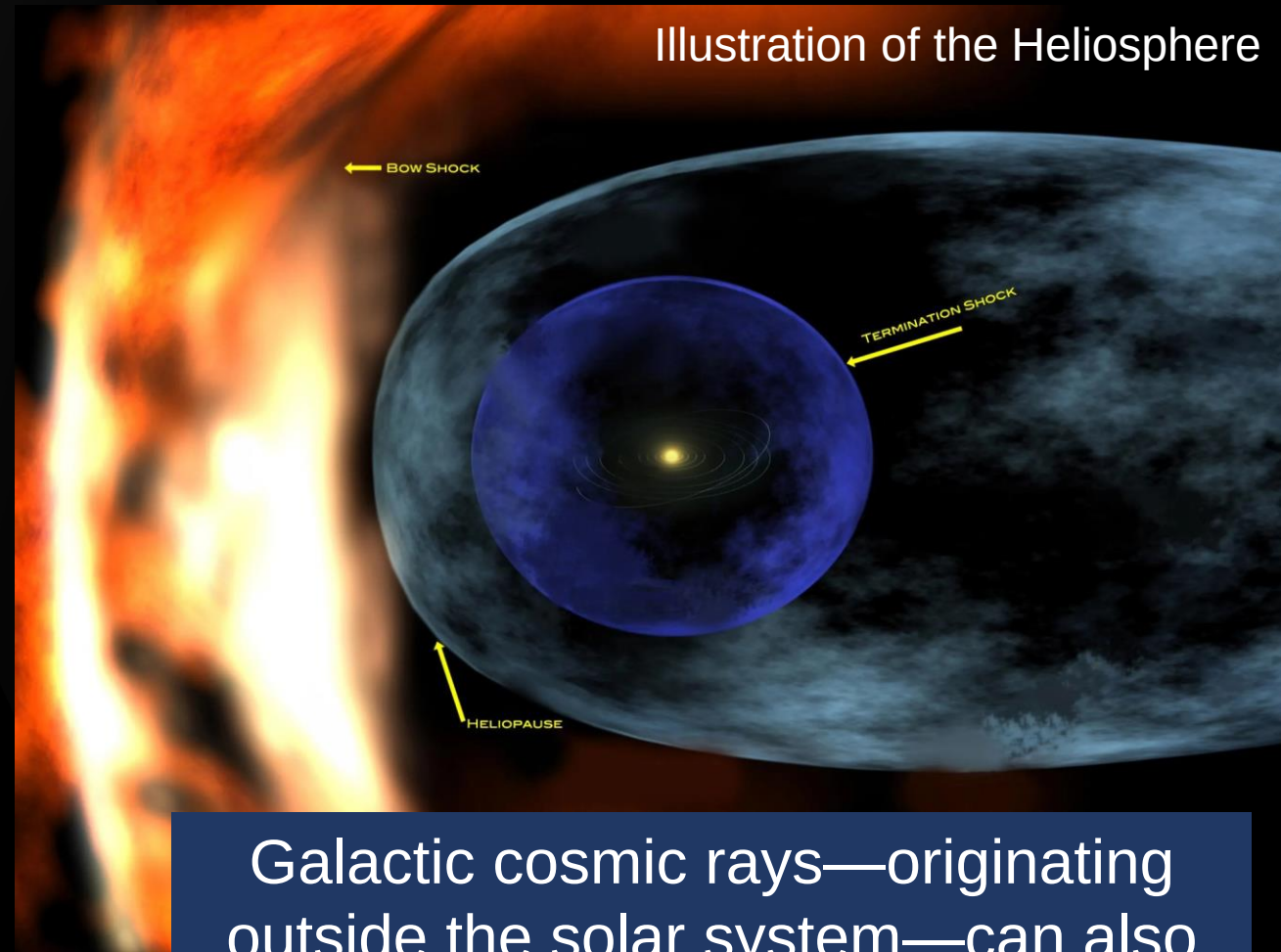


SOHO/LASCO C2 Coronagraph
[SOHO-Gallery: Best Of SOHO \(nasa.gov\)](http://soho-gallery.nasa.gov)

Radiation Environments



Energetic particles interacting with the lunar regolith creates a population of neutrons radiating from the surface



Galactic cosmic rays—originating outside the solar system—can also cause single event effects and contribute to the total radiation dose



Natural light sources

- Solar illumination
 - Average solar flux at Moon same as that at Earth
 - Maximum and minimum affected by lunar orbit
 - Incident light nearly collimated (angular diameter $\approx 0.5^\circ$)
 - Lunar day, or synodic period, is 29.5 Earth days

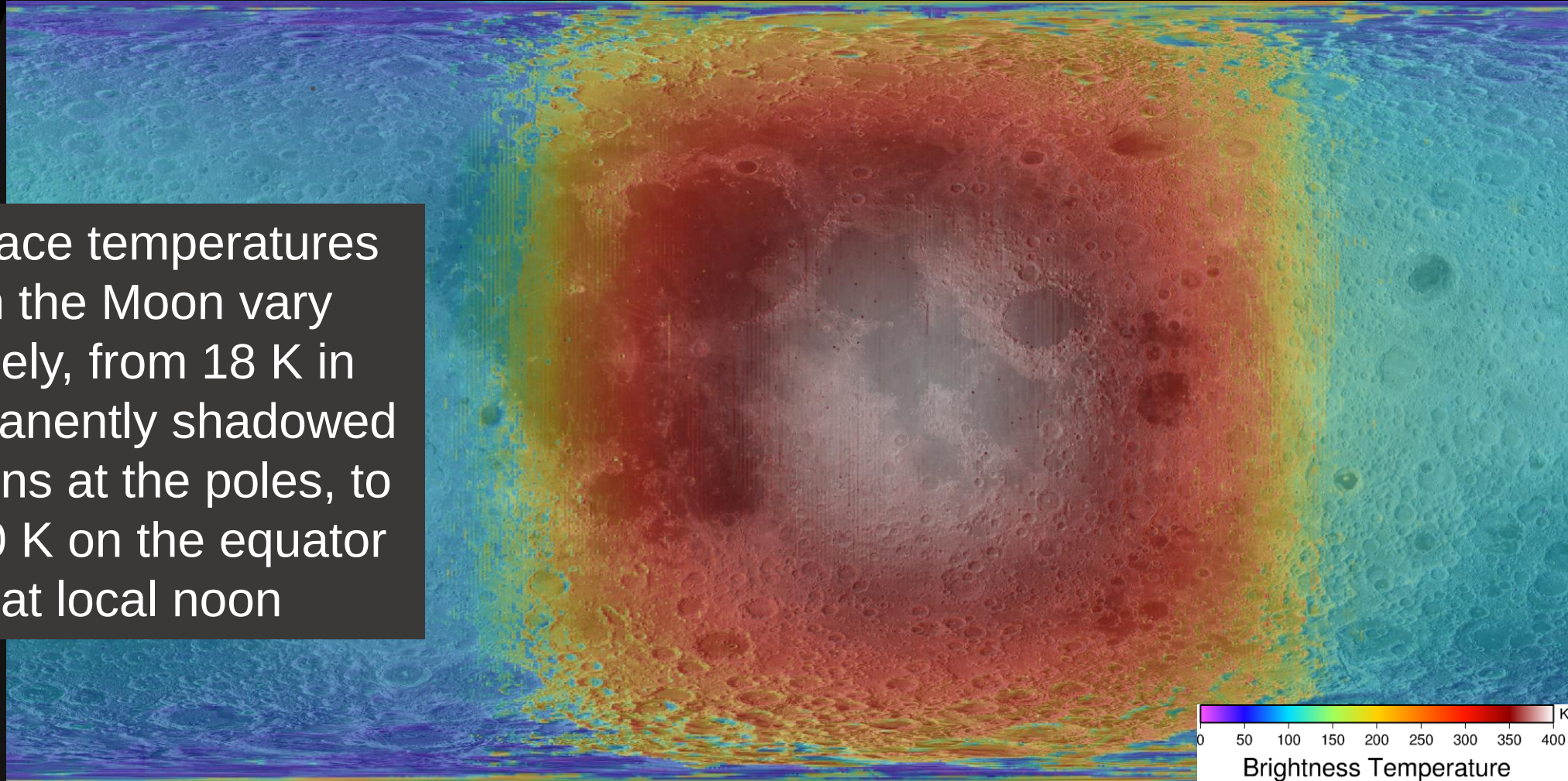
Solar Flux at Lunar Orbit	
Maximum	$1421 \pm 5 \frac{W}{m^2}$
Mean	$1367 \pm 5 \frac{W}{m^2}$
Minimum	$1315 \pm 5 \frac{W}{m^2}$

DSNE Section 3.3.9.1.1

Lunar Surface Thermal Environment

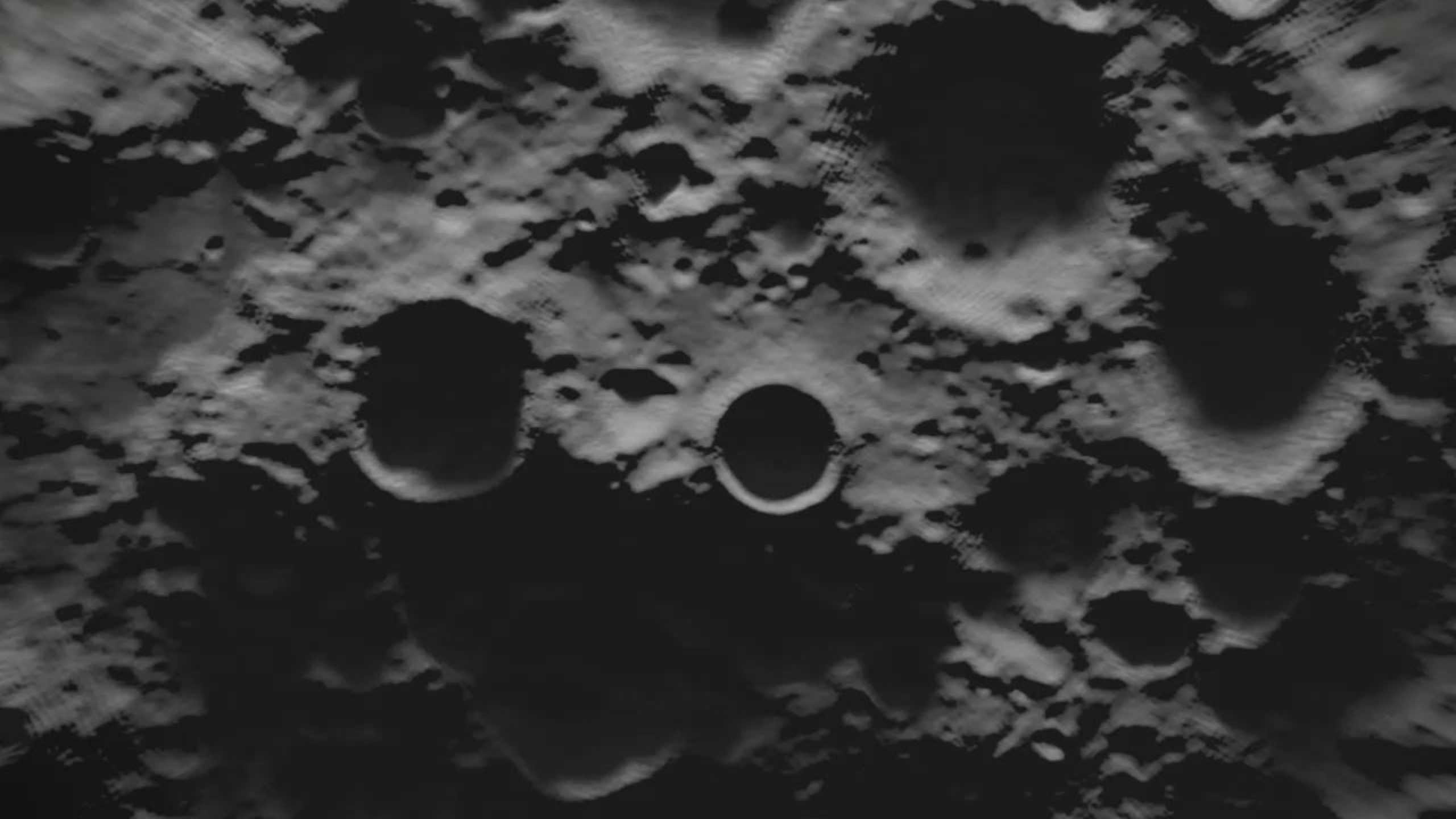


Surface temperatures on the Moon vary widely, from 18 K in permanently shadowed regions at the poles, to ~400 K on the equator at local noon

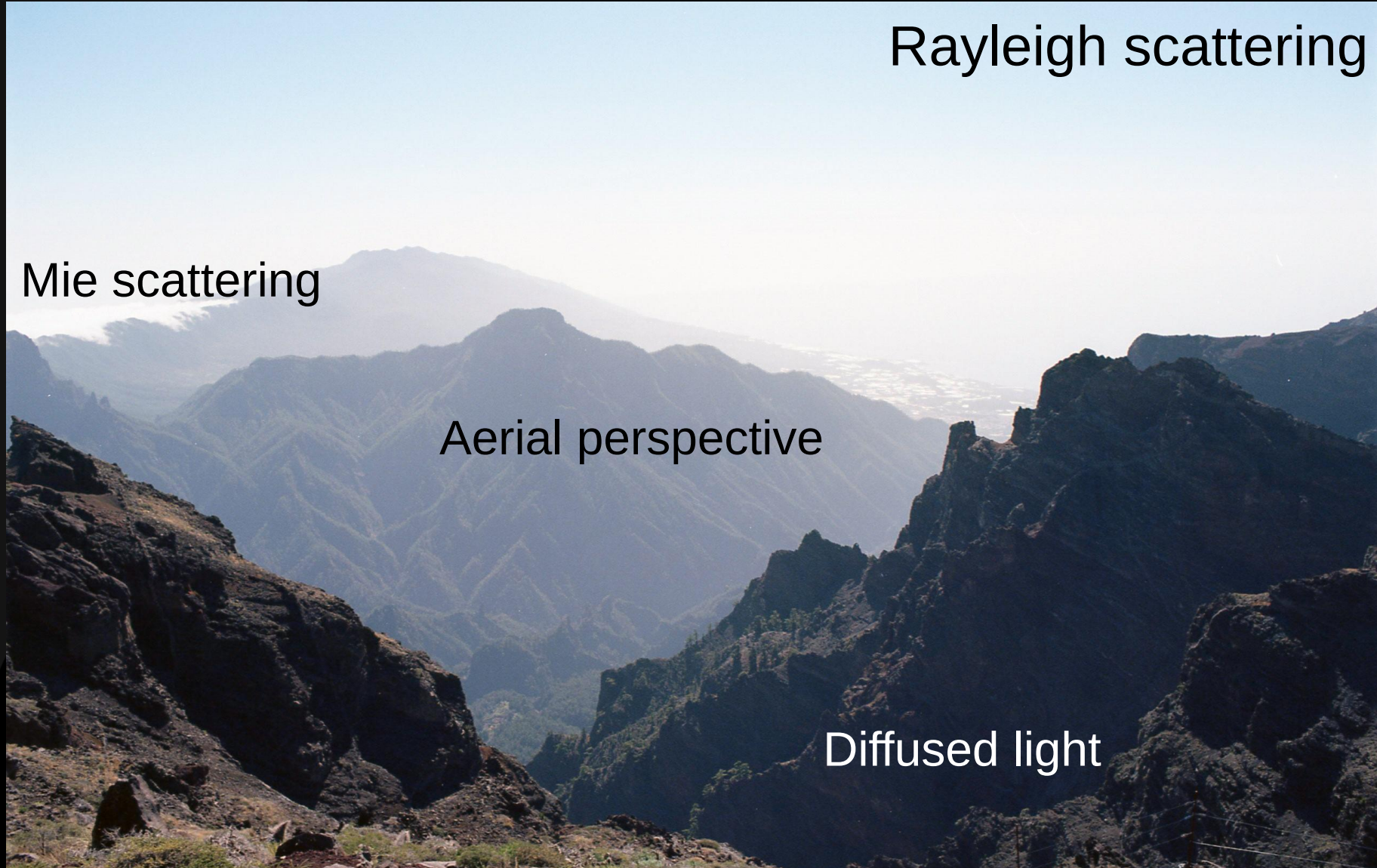


LRO/DIVINER/GSFC





Earth's lighting environment



Rayleigh scattering

Mie scattering

Aerial perspective

Diffused light

Earth's lighting environment



1807 m (5928 ft) elevation
17 km (11 mi) distant

1844 m (6050 ft) elevation
6.6 km (4.1 m) distant

W.A. Chambers



(distances/elevations measured with Google Earth)



AS15-87-11793
NASA/scanned by Kipp Teague



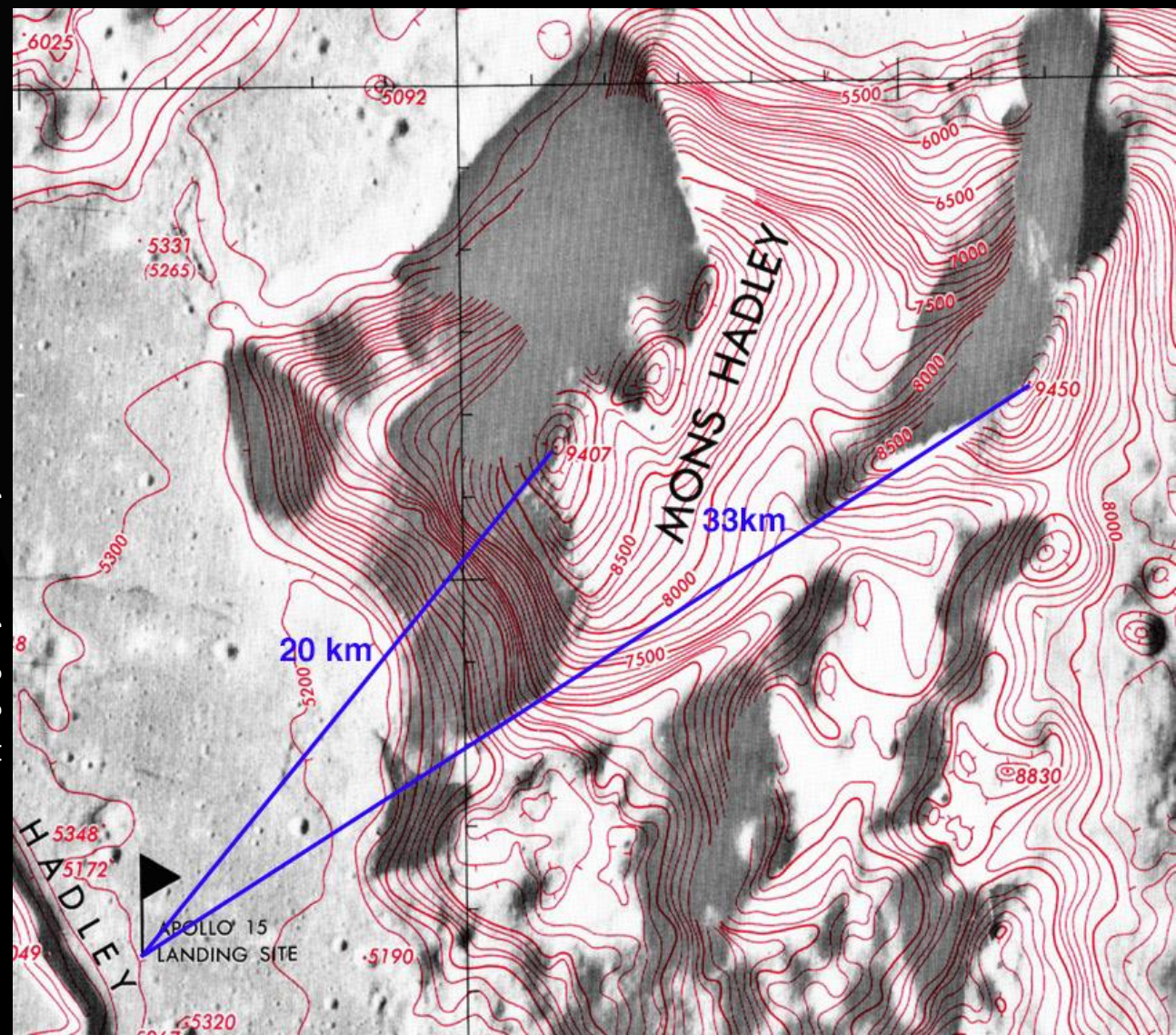


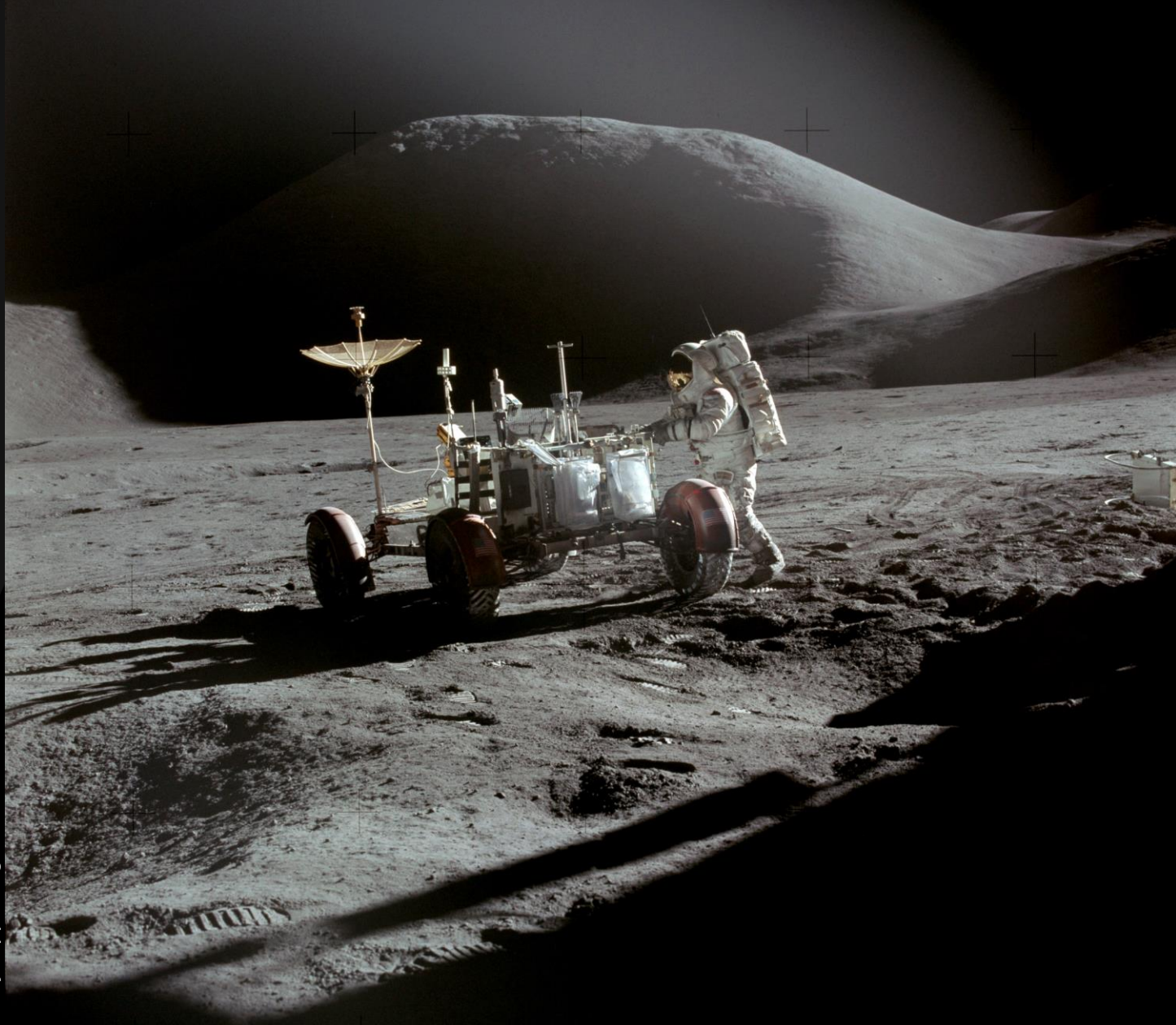
Mons Hadley

4100 m (13,000 ft) elevation change
20 km (12 mi) distant



Labeled detail from LTO41B4
NASA/U.S. Defense Mapping Agency/scanned by LPI





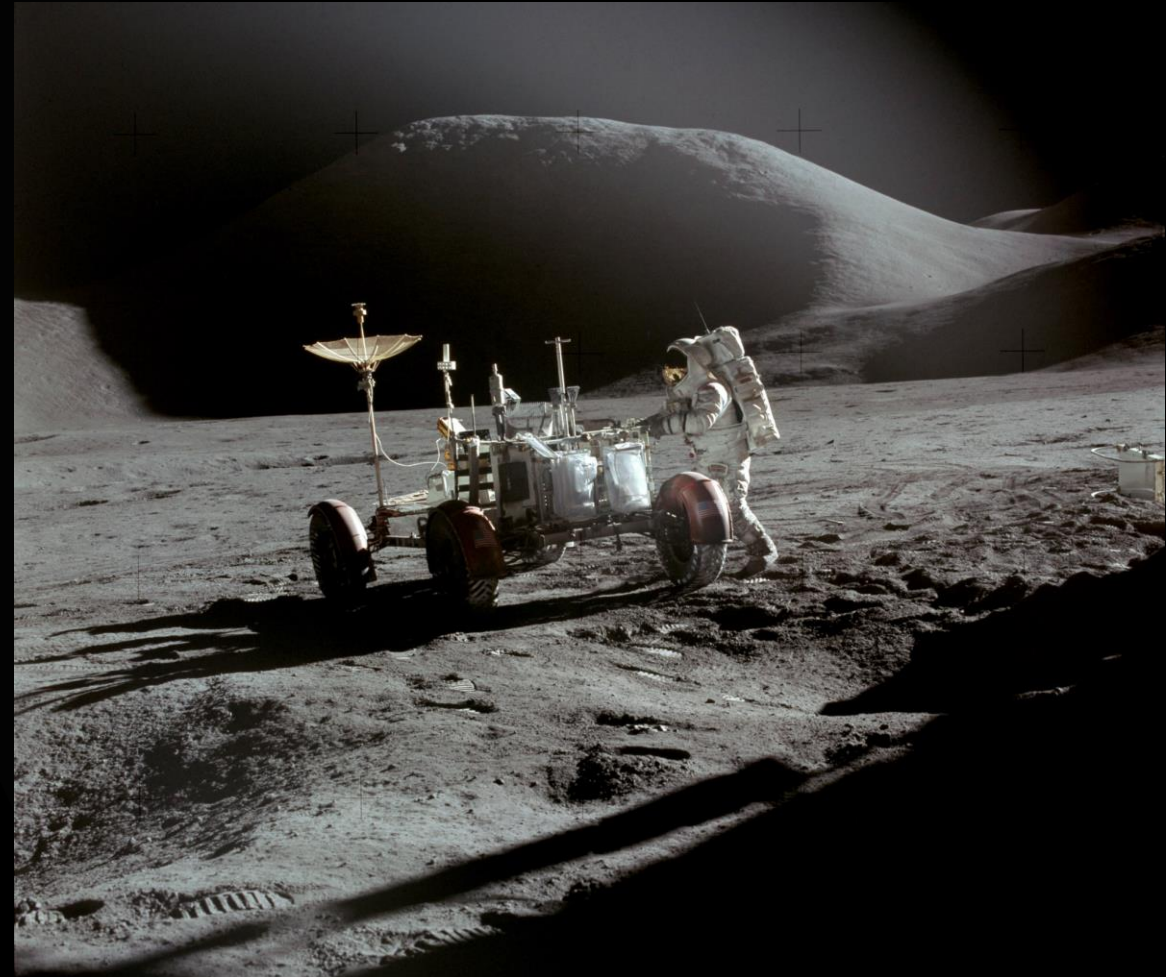
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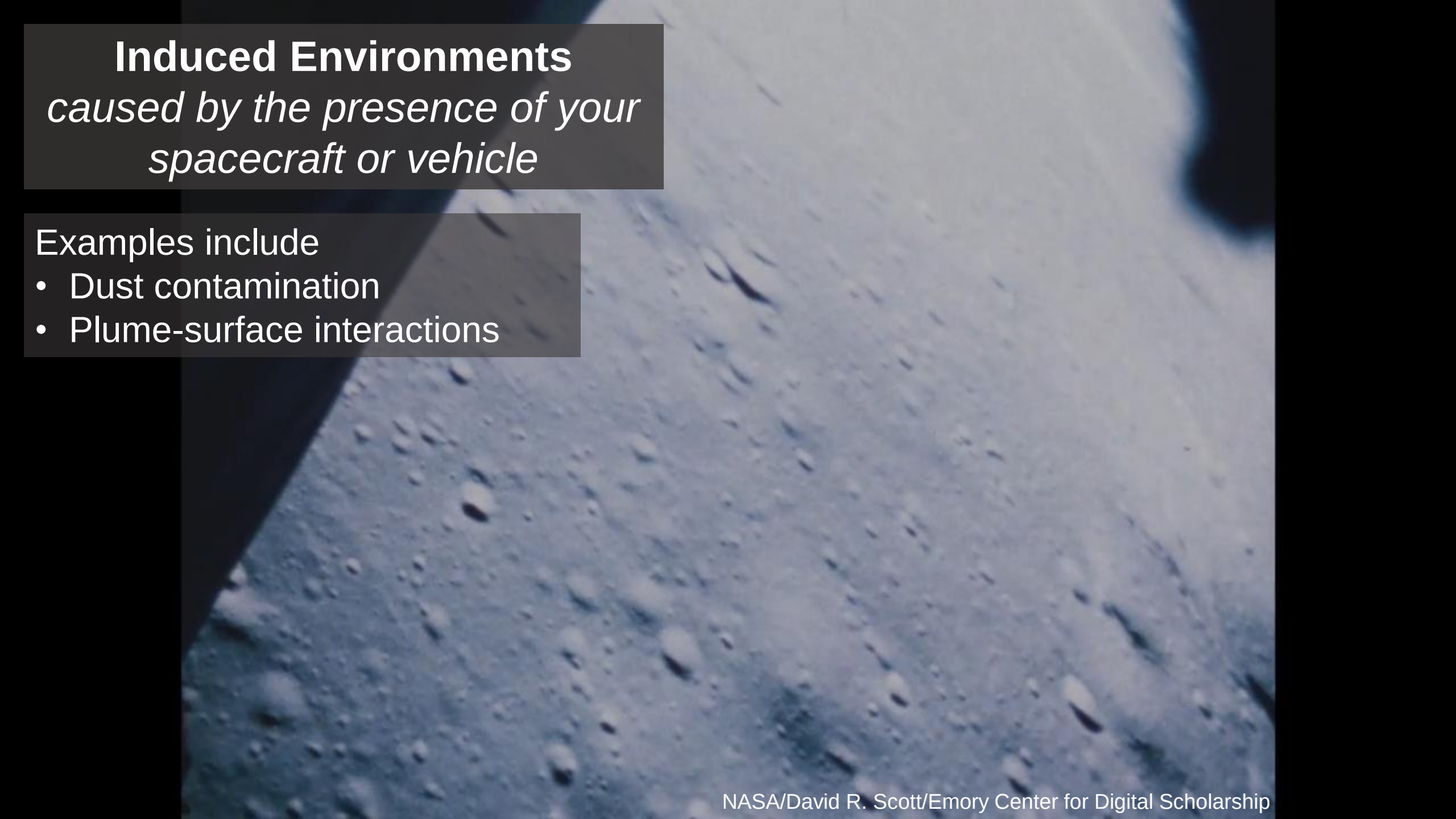
Lunar lighting environment



Lack of lunar atmosphere has a significant effect on lighting environment, and therefore on human perception

No atmospheric scattering, distortion, and no familiar visual cues (e.g., trees, clouds)



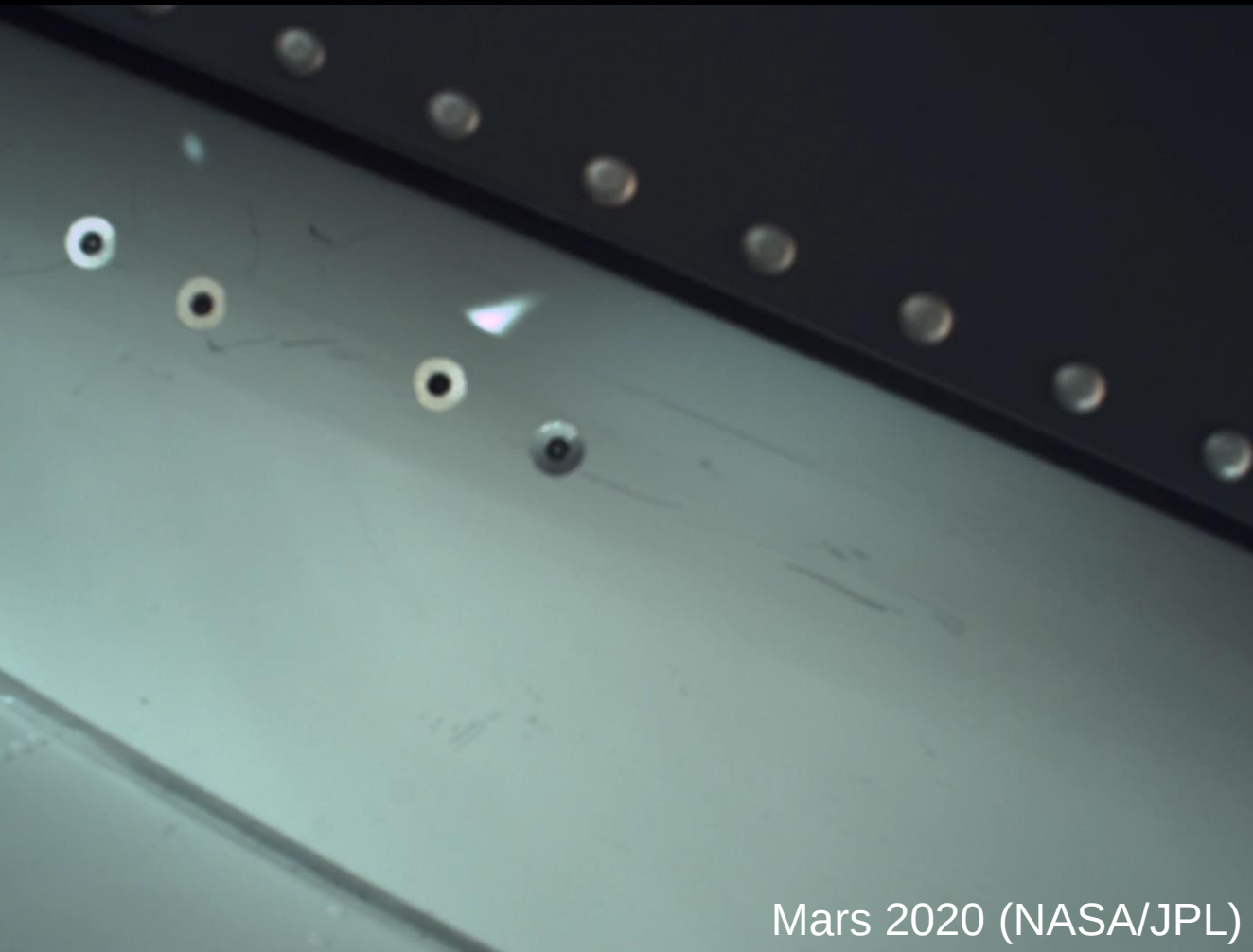


Induced Environments *caused by the presence of your spacecraft or vehicle*

Examples include

- Dust contamination
- Plume-surface interactions

**Plume-surface interactions
occur during retropropulsive
landing on an unimproved
planetary surface**



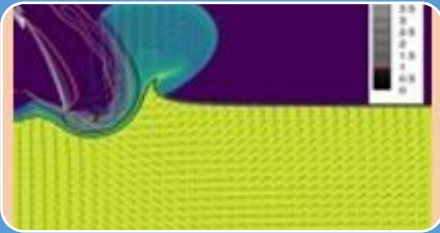
Mars 2020 (NASA/JPL)

**Rocket exhaust erodes and
ejects material, posing potential
hazards to landing spacecraft
or surrounding assets**



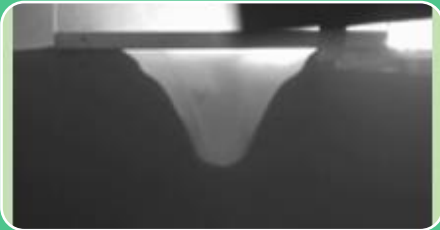
Apollo 11 (NASA)

Approaches to Studying Plume-Surface Interactions



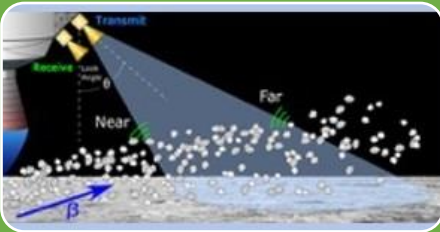
Modeling & Simulation

- Fills in testing and data gaps; predict new environments
- Large uncertainty, current tools need quantitative validation



Experimental Data

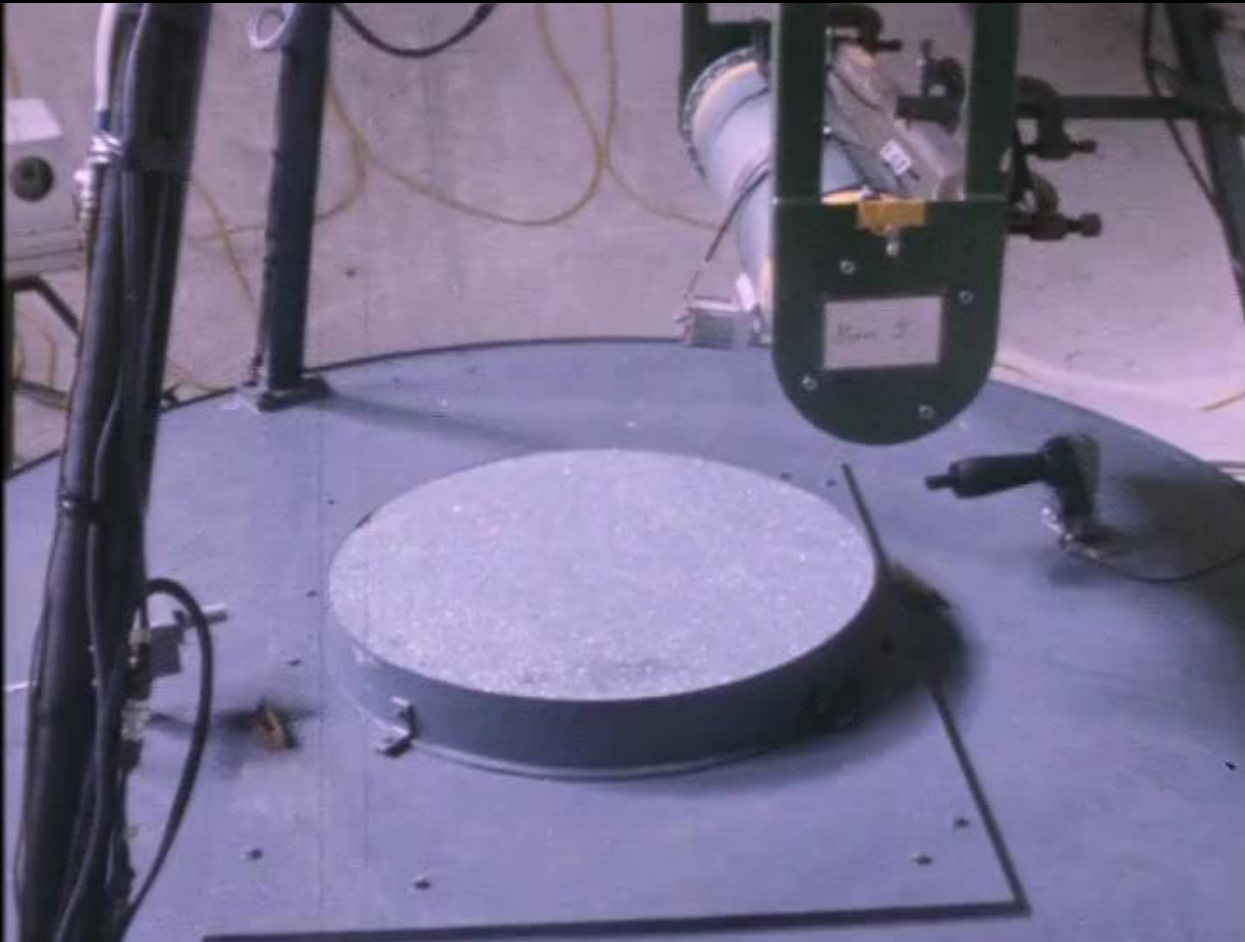
- Varying levels of fidelity
- Better control, instrumentation



Flight Data

- Ground truth
- Limited opportunities, data

Apollo-Era Testing



Land and Scholl (1969) Video Supplement

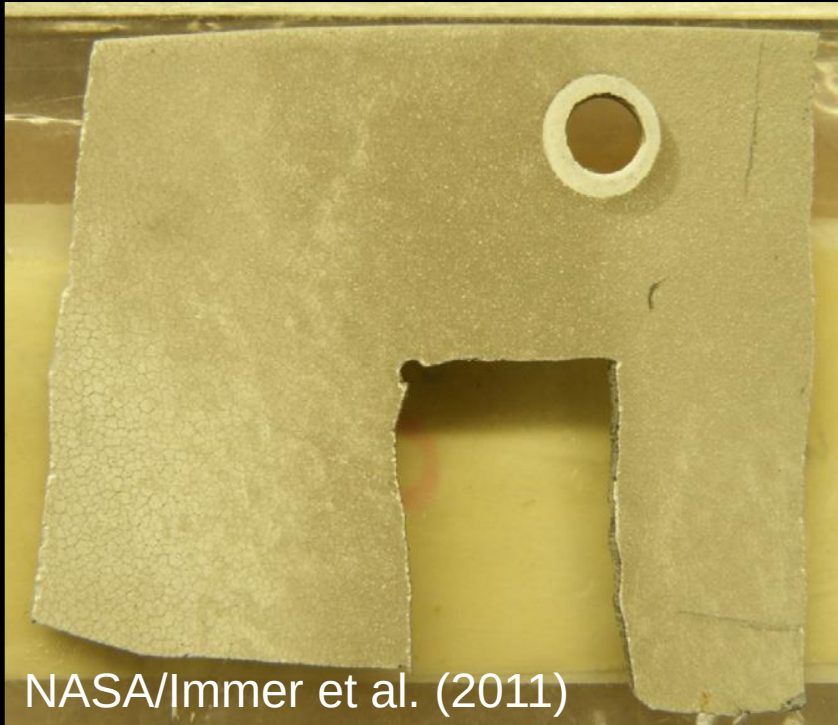
Historical testing at NASA Langley Research Center



Land and Scholl (1969)

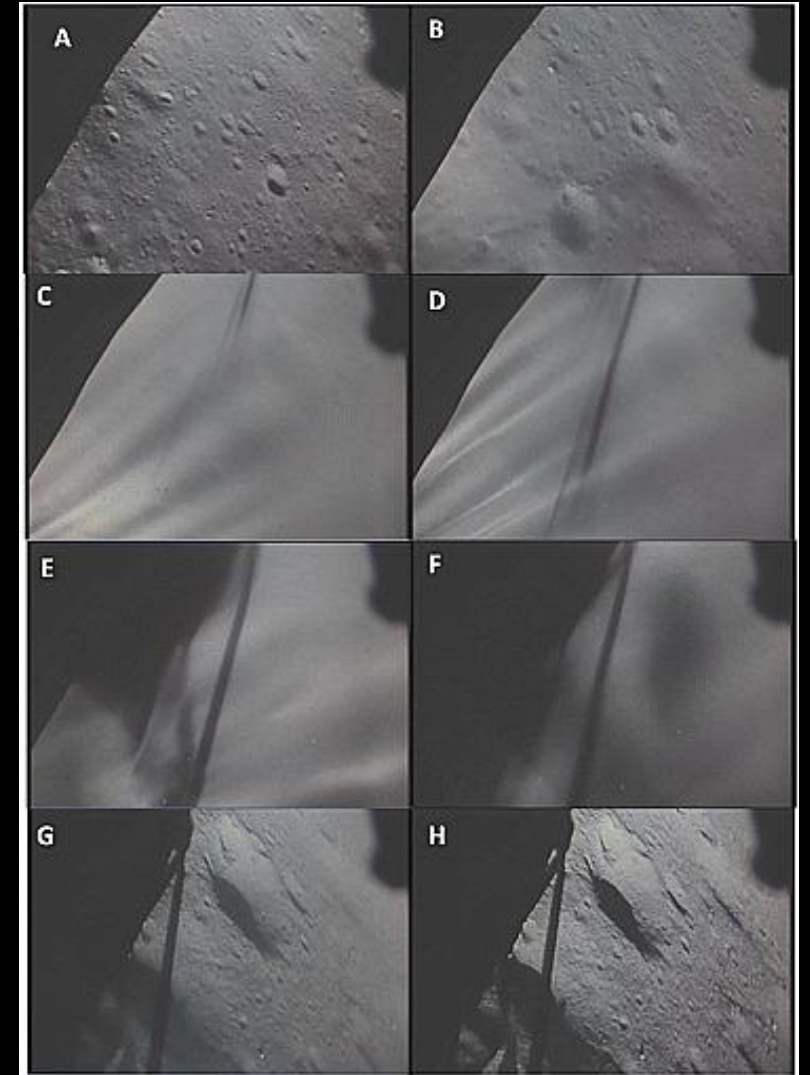
Apollo Flight Data

Apollo landing videos show erosion, visual obscuration



NASA/Immer et al. (2011)

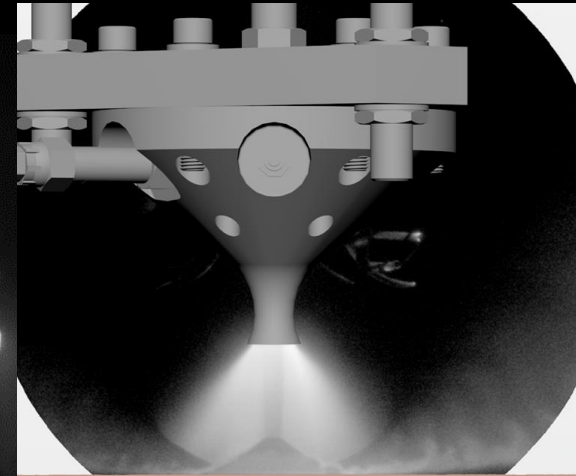
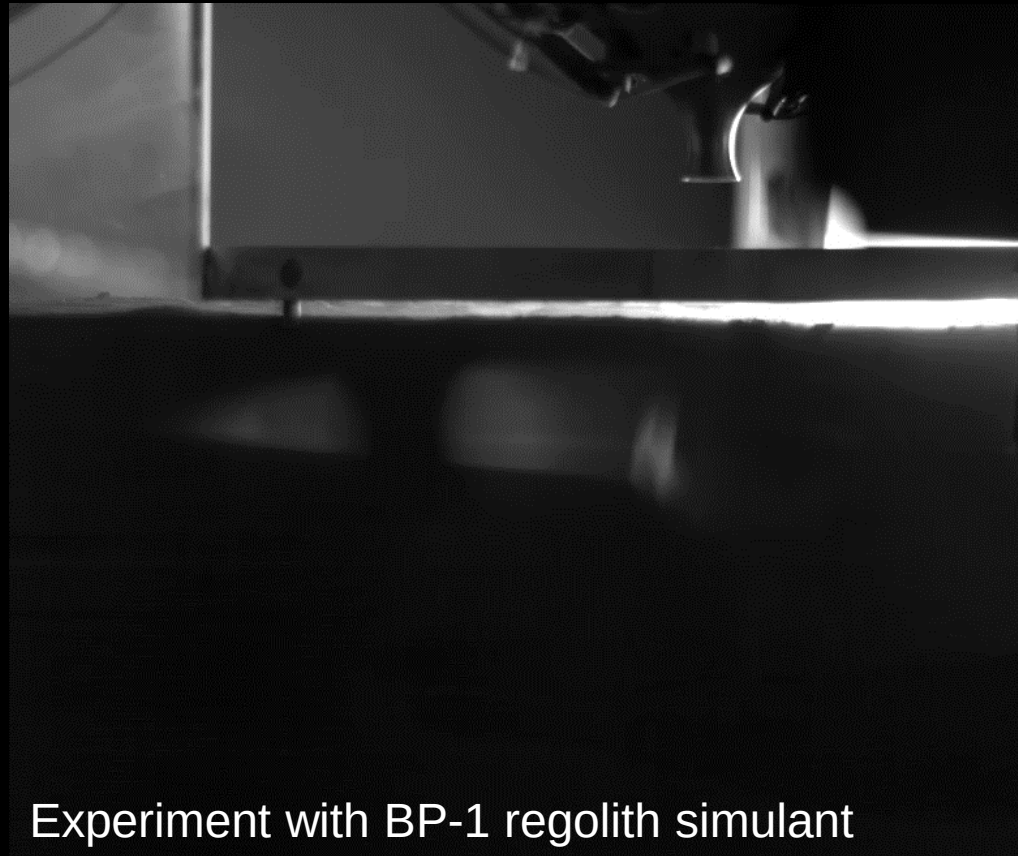
Apollo 12 astronauts recovered damaged samples from Surveyor III



Images from Apollo 15; figure from Metzger et al. (2011)

NASA Plume-Surface Interaction Testing

- Subscale, half-space, supersonic plume-surface interaction test
- Six regolith simulants, variable mass flow rate, variable vacuum pressure
- Variations in behavior observed across parameter space



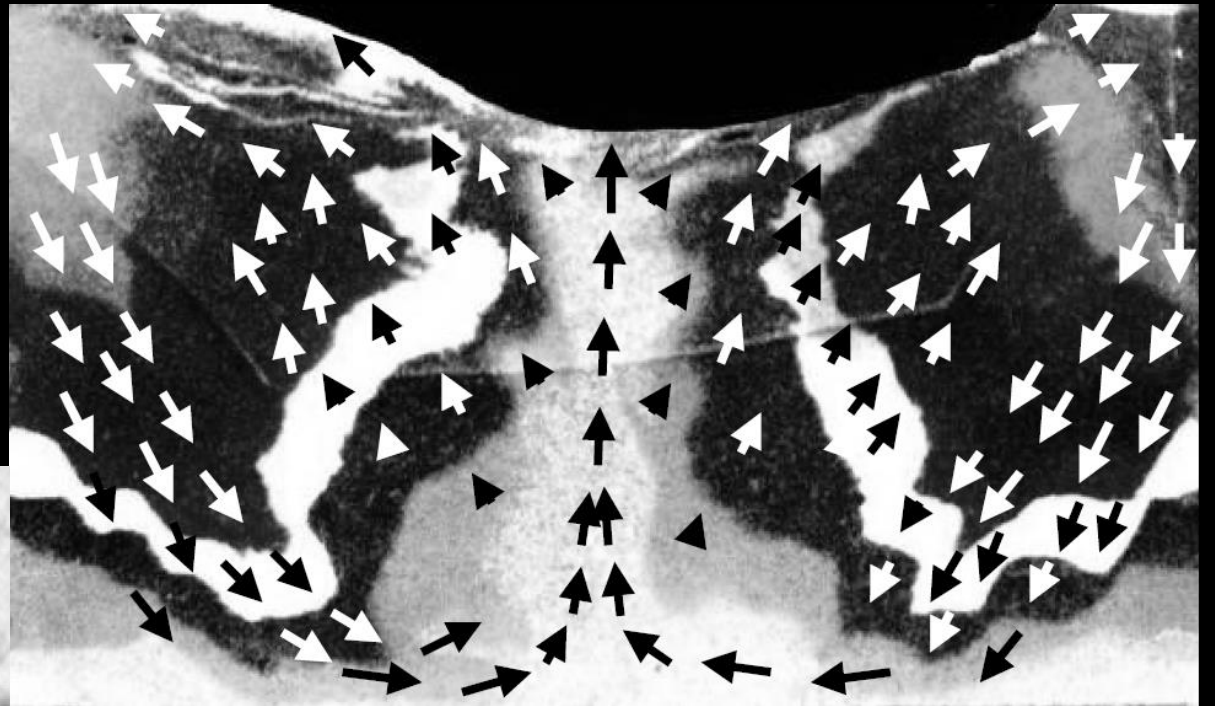
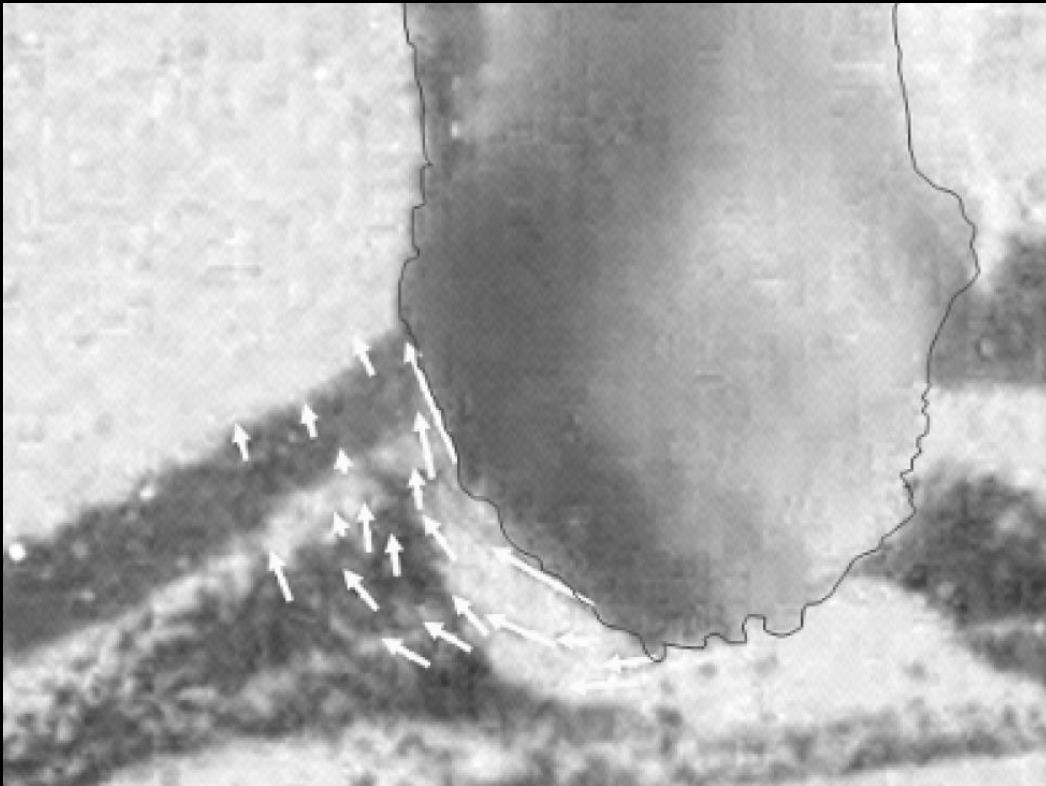
Plume flow visualization
Rodrigues *et al.* (2023)

Experiment with BP-1 regolith simulant

Test overview: <https://doi.org/10.2514/6.2022-1811>

Testing to Understand Phenomena

Images from Metzger et al. 2009.



Layers of sand modified by PSI;  arrows show direction of motion

Diffusion-driven flow parallel to the developing crater's surface 

Effects of Reduced Gravity

UCF/CLASS/Chambers





quartz sand



glass beads



CI Orgueil

50 ms jet
25 cm nozzle height
side view

Computational Modeling

- Generalized PSI modeling remains a challenge due to complex physics
- Range of methods applied
 - Simplified/semi-empirical
 - One-way coupled CFD
 - Two-way coupled CFD
- Approaches
 - Eulerian-Eulerian
 - Eulerian-Lagrangian

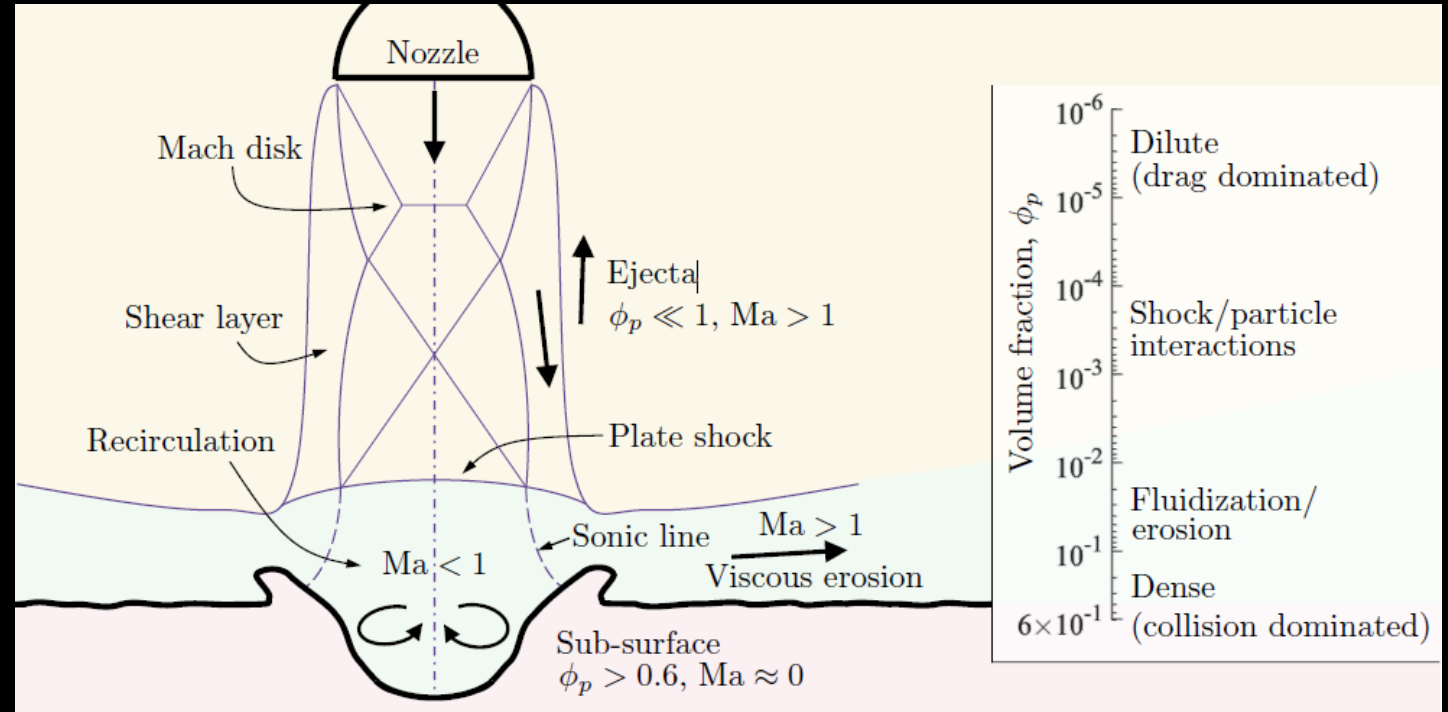
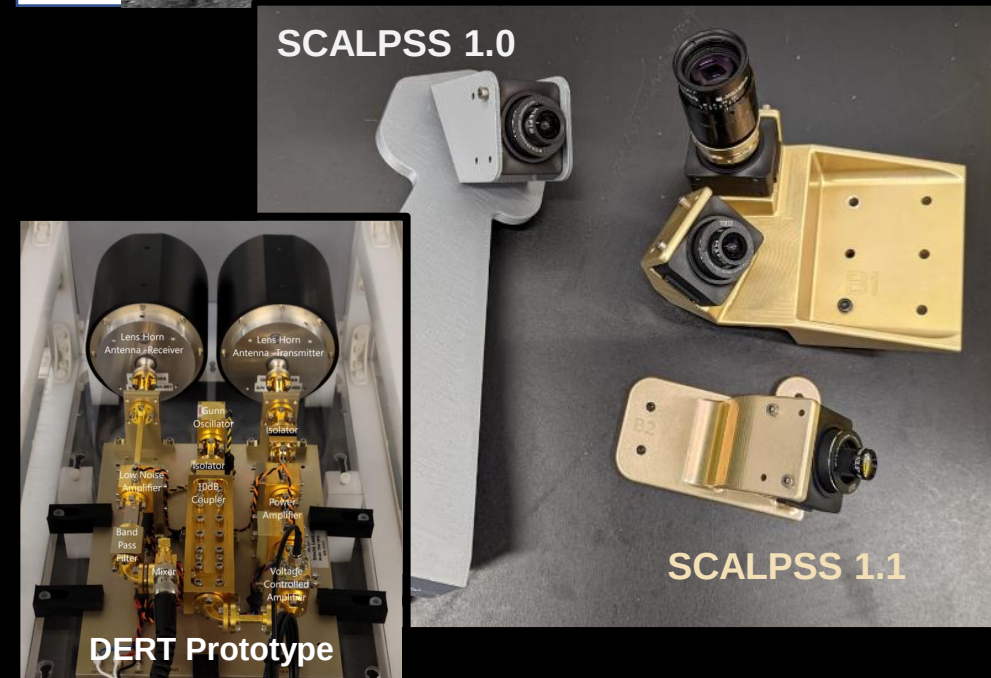
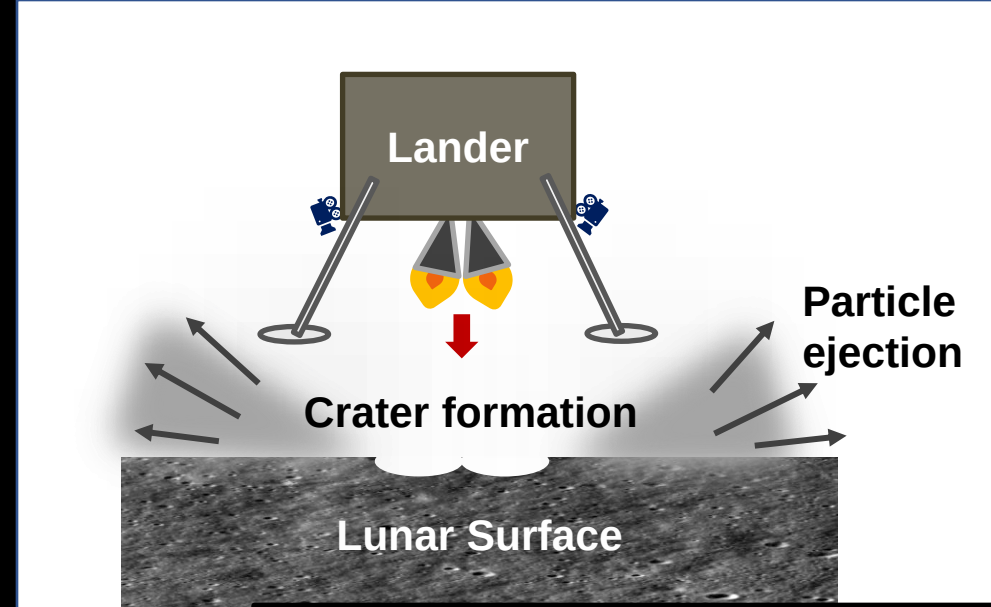


Illustration of flow regime variation, which results in challenges for PSI modeling. Figure from Capecelatro (2022), (CC BY 4.0).

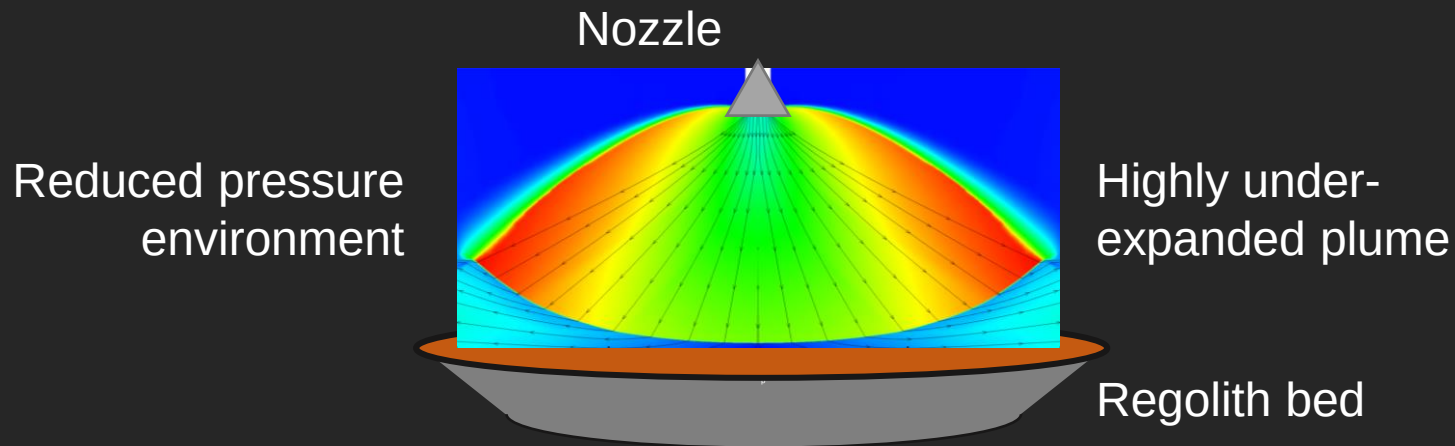
NASA Flight Instrumentation

- Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS)
 - Stereo imaging for PSI
- Lunar Lander Base Instrumentation (LLBI)
 - Measurement of environment induced below lander by thrusters and PSI, MEDLI-heritage
- Particle Impact Event Sensor (PIE)
 - Measurement of ejecta energy
- Dust Ejecta Radar Technology (DERT)
 - Millimeter-wave doppler radar measurement ejecta particle velocities
- Mini-Suite Electronics (MSE)
 - Centralized payload commanding



The Human Landing System PSI Ground Test

As we return to the Moon with larger spacecraft and different operating concepts, we need to better understand plume-surface interactions to reduce risk to missions and crew



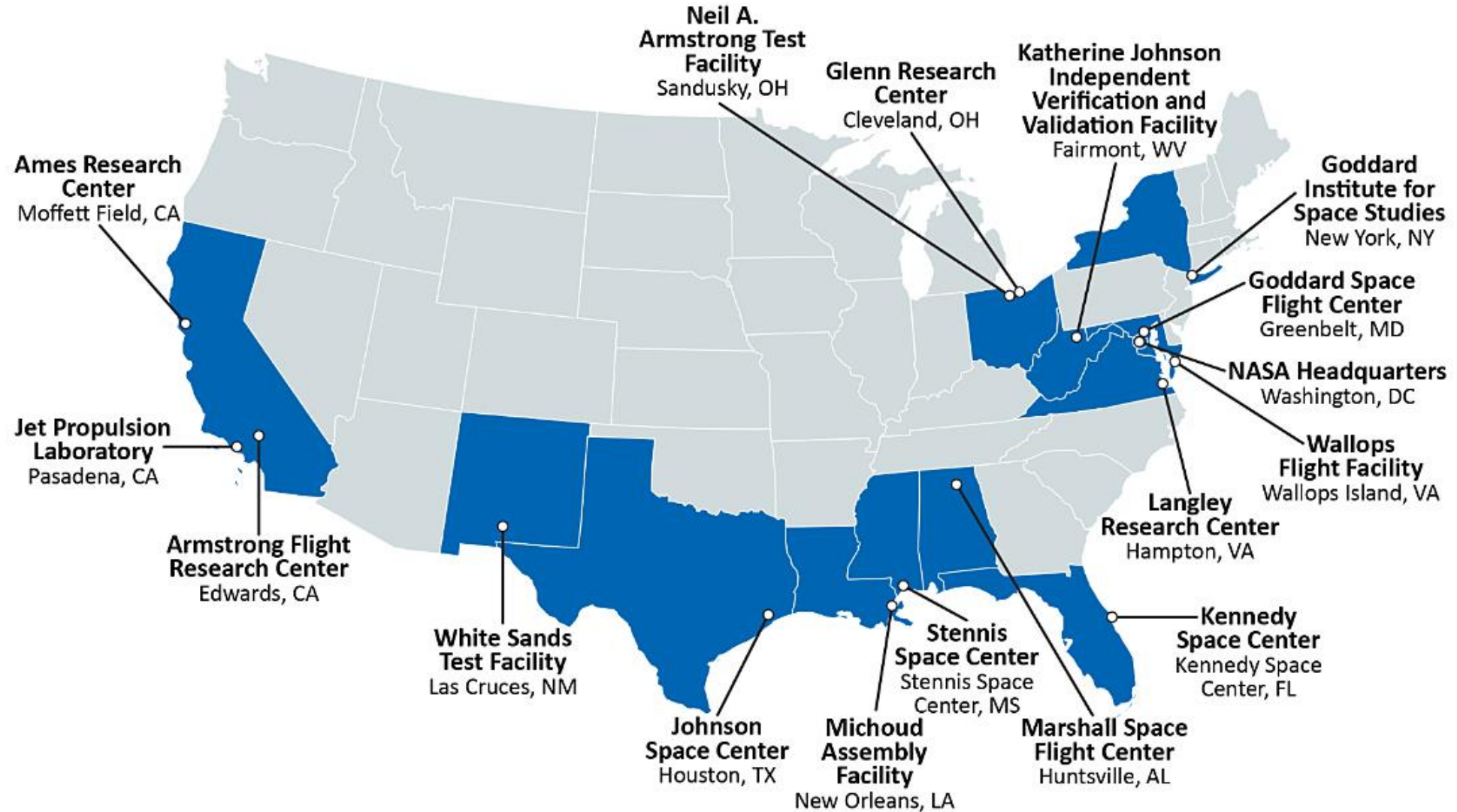
60-ft Vacuum Sphere (NASA LaRC)



Conclusions

- NASA missions to the Moon will rely on understanding the lunar surface environment
- Experts at NASA and our partners in the US and around the world are working to better understand these environments to enable mission success

NASA Centers and Facilities



NASA Internship Programs

At NASA, we explore the extraordinary every day and our work is more than just a profession — it's a lifelong pursuit and a passion. NASA offers several opportunities for students to undertake meaningful and challenging projects that truly make an impact on humanity.

QUICK FACTS

NASA's Office of STEM Engagement provides, annually, more than 2,000 students the opportunity to impact the agency's mission through a hands-on internship.

A wide background image showing a view from a spacecraft window, looking out at Earth's blue and white clouds. In the foreground, parts of the spacecraft's interior and a person's arm are visible.

<https://www.nasa.gov/learning-resources/internship-programs/>

Questions?

