Understanding the Impact of Exploration on the Lunar Volatile System

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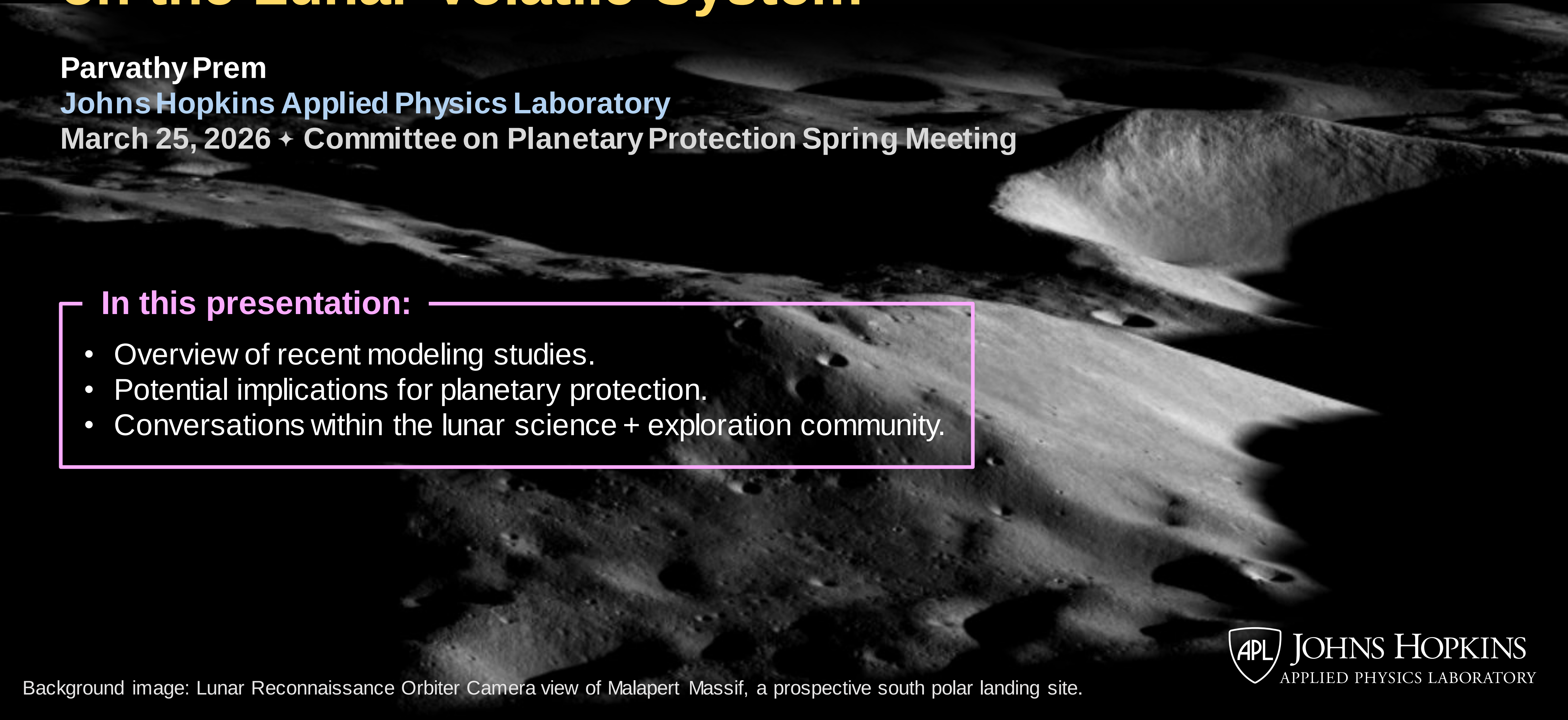
In this presentation:

- Overview of recent modeling studies.
- Potential implications for planetary protection.
- Conversations within the lunar science + exploration community.

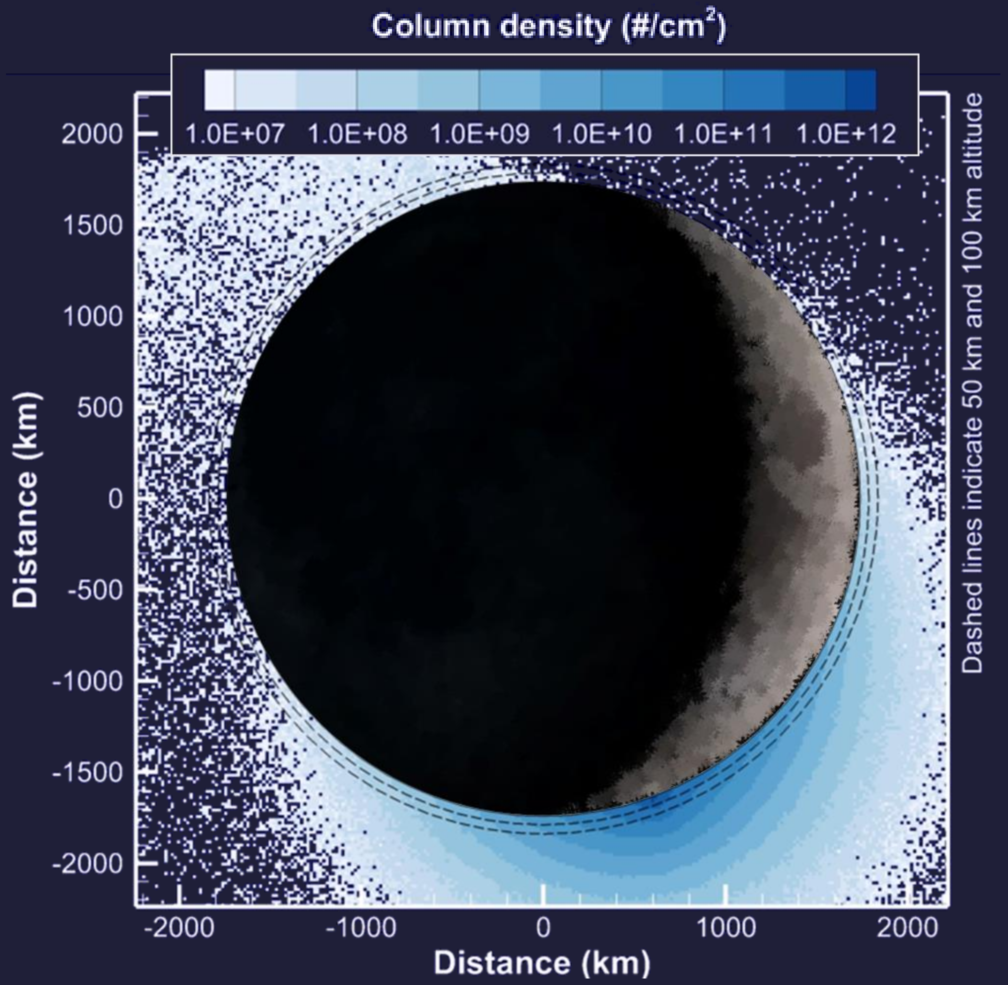


Background image: Lunar Reconnaissance Orbiter Camera view of Malapert Massif, a prospective south polar landing site.

Recent Studies of Spacecraft Exhaust Propagation

- The persistence of exhaust gases was observed during the Apollo era (e.g., Freeman et al., 1973) and has been revisited through models of volatile transport, loss and deposition on the Moon.

- While all models have uncertainties, recent studies find:
  - Anthropogenic volatiles may be **globally** transported (Prem et al., 2020; Paiva and Sinibaldi, 2025).
  - Changes to the **lunar exosphere** are significant but likely temporary for a single landing (e.g., Prem et al., 2020).



Simulated exospheric column density of water released by a mid-sized lander, 1 hour after landing at 70° S.

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Recent Studies of Spacecraft Exhaust Propagation

PSR = Permanently Shadowed Region

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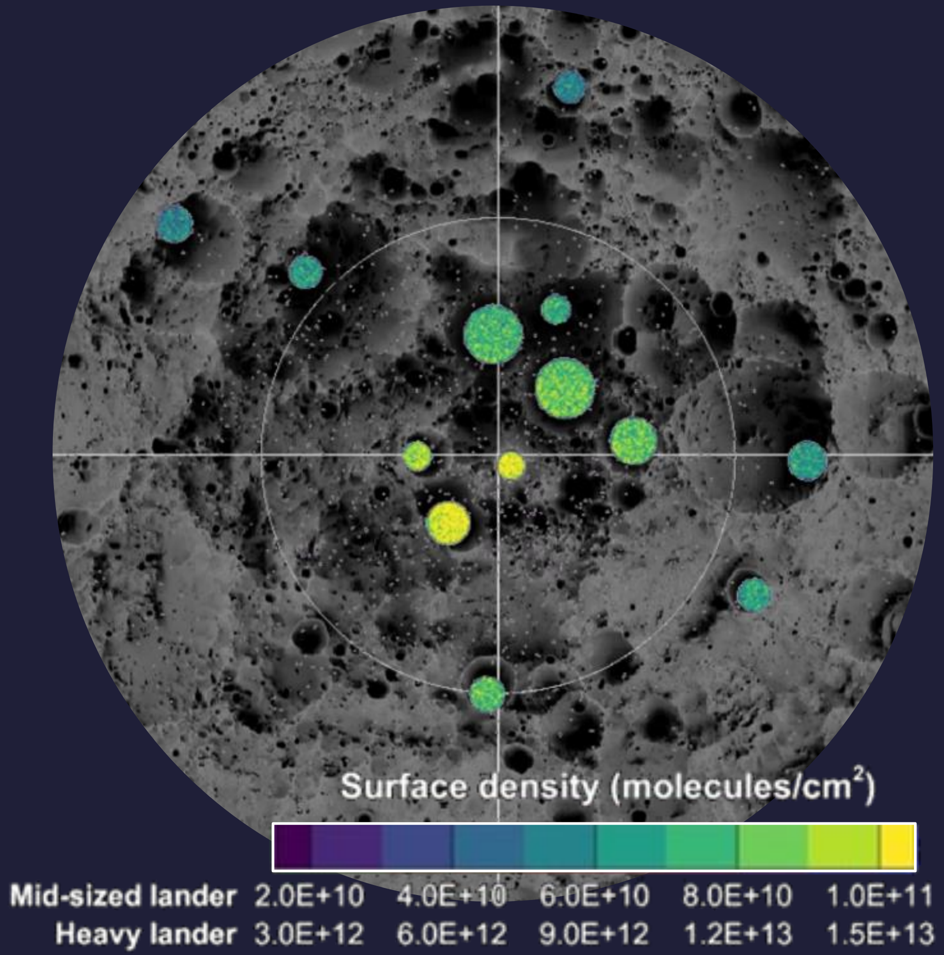
  - Changes to the **lunar exosphere** are significant but likely temporary for a single landing (e.g., Prem et al., 2020).
  - Heavy polar landings may observably alter the distribution of cold-trapped **surface frosts** (Farrell et al., 2024).

- Exhaust gases are only one of several possible sources of anthropogenic volatiles (e.g., Killen et al., 2024, Boccelli et al., 2026), and water is only one of several possible species.



Modeled deposition of water in south polar PSRs, two lunar days after a landing close to the rim of Shackleton crater.

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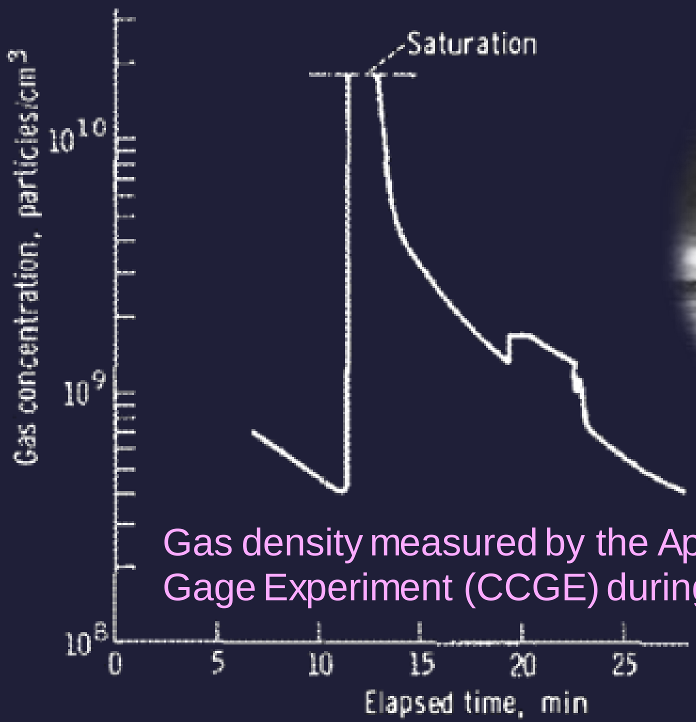
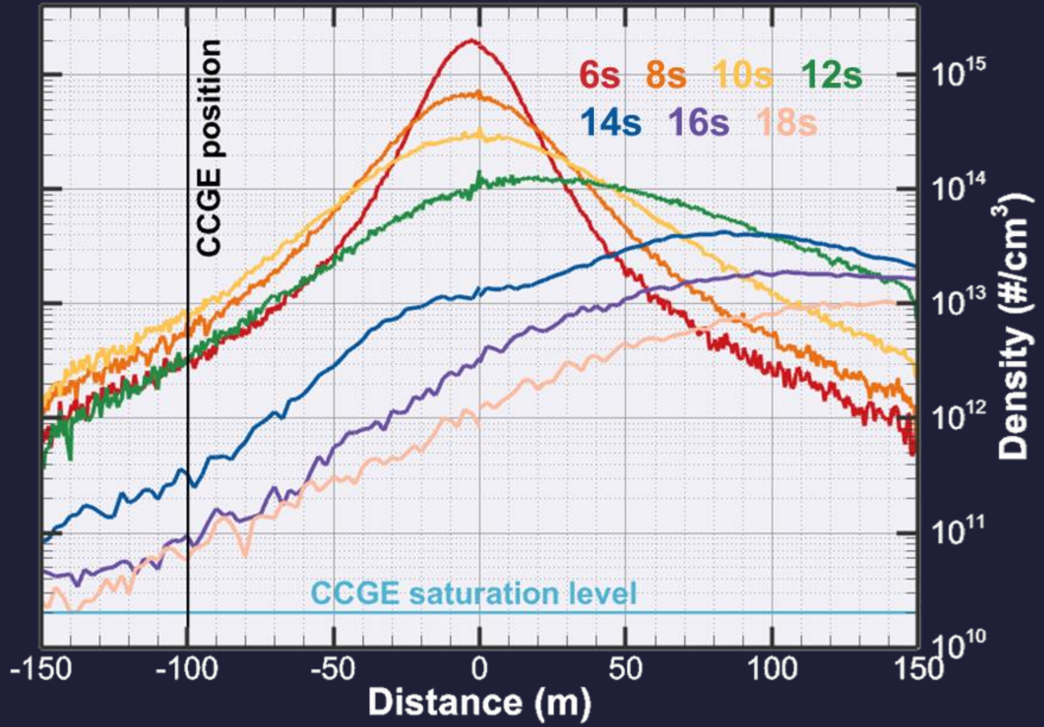
Outlook for Characterizing Anthropogenic Volatiles

- Measurements of **surface and exospheric volatiles over time** (many ways to do this!) can constrain model parameters and improve predictions to support mission planning.
- **Information on landing + surface operations** is critical input to models, and enhances the science return from these active volatile release experiments.



Gas density measured by the Apollo 15 Cold Cathode Gage Experiment (CCGE) during Lunar Module ascent.
[Johnson et al., 1972]

Modeled gas density during Lunar Module ascent.



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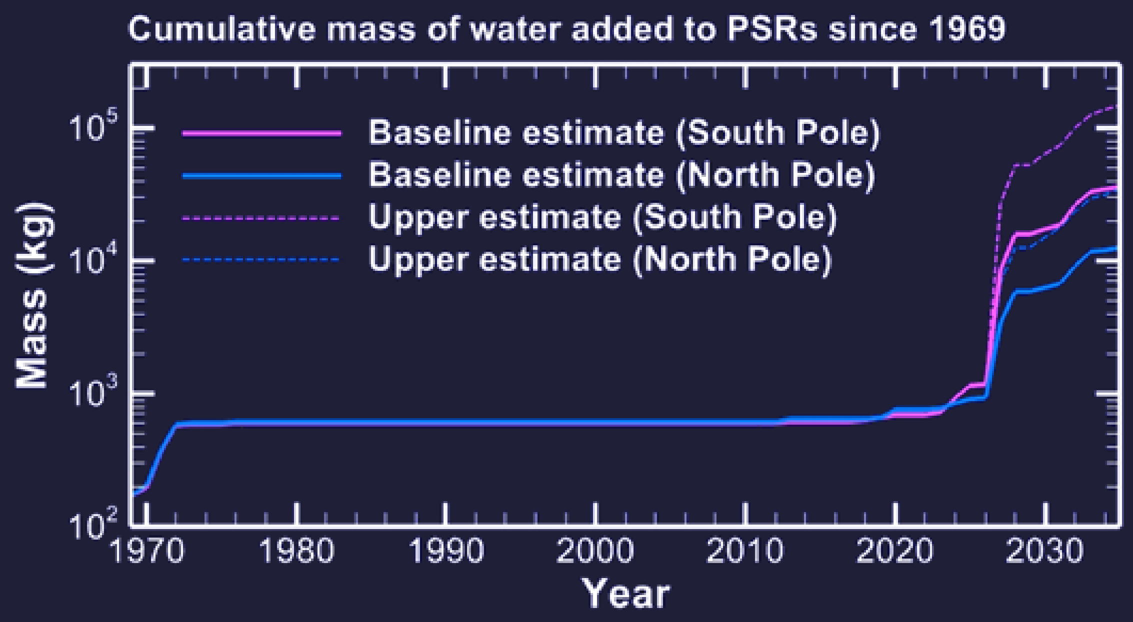
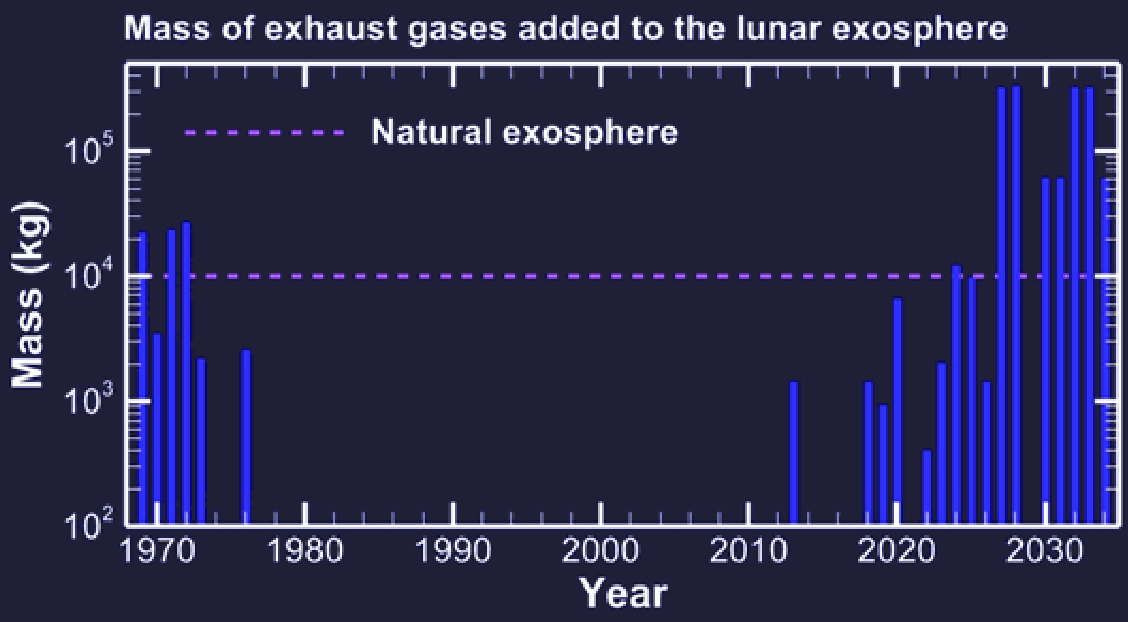
Examining Environmental Impact Over Time

- Estimates like those below (Prem et al., 2025) involve assumptions: timeline of future missions, how much exhaust landers release, and what fraction migrates to the poles –these **should be updated over time**.
- Estimated **water accumulation in PSRs** near South Pole (~36–148 metric tons) is comparable to estimated naturally-occurring surface frost (~60 metric tons; Brown et al., 2022).
- Longevity of **exospheric changes** depends on gas composition and frequency of missions.



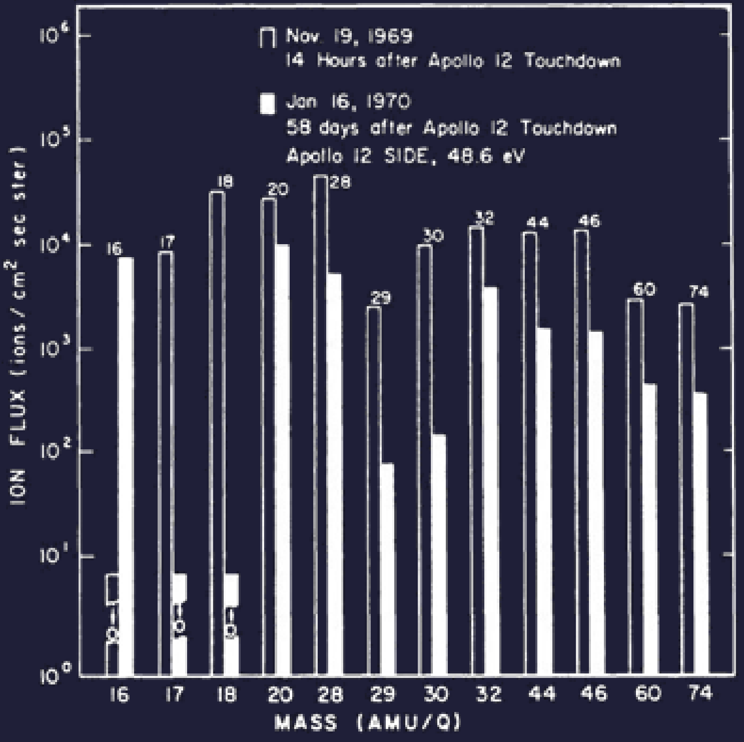


Reflections on Planetary Protection

> **Category IIa.** All missions to the surface of the Moon whose nominal mission profile does not access areas defined in Category IIb should provide the planetary protection documentation and an organic inventory limited to organic products that may be released into the lunar environment by the propulsion system,

- In addition to spacecraft position, thruster pointing direction (in the case of exhaust gases) is important in **defining access to PSRs**.
- **Non-organic products** can serve as important tracers of exhaust migration, and influence the transport of organic products – knowing **source properties** (e.g., composition, mass flow rate) is important.
- **Non-propulsion systems** (e.g., Vondrak, 1992; Killen et al., 2024) can also interact with the lunar volatile system.

Exhaust gases from Apollo 12, 14 hours and 58 days after landing (Freeman et al., 1973). ▶



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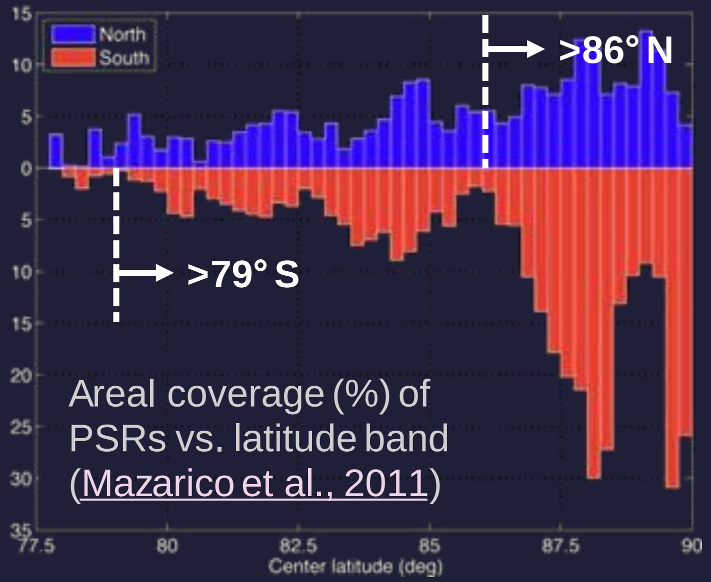
Reflections on Planetary Protection

> **Category IIb.** All missions to the surface of the Moon whose nominal profile accesses Permanently Shadowed Regions (PSRs) and/or the lunar poles, in particular latitudes south of 79°S and north of 86°N should provide the planetary protection documentation and an organic inventory in line with Section 7 [Ref. National Academies of Science, Engineering and Medicine 2020 and COSPAR 2021].
>
> **Note:** Category IIb applies to all PSRs, irrespective of latitude, and non-PSR regions within the latitude limits south of 79°S and north of 86°N.

- Rationale for asymmetric requirements between North/South is not entirely clear; also of note that not all PSRs are cold traps for volatiles.
- **Non-organic volatiles** inform interpretations of the **geological and astrobiological record in PSRs**, and are important for determining origins (e.g., Mandt et al., 2026), inferring organogenic origin (e.g., Flory et al., 1972), and understanding potential in situ synthesis of organics from simpler precursors (Crites et al., 2013).



Areal coverage (%) of PSRs vs. latitude band (Mazarico et al., 2011)

Community Conversations

LSSW = Lunar Surface Science Workshop
ANGSA = Apollo Next Generation Sample Analysis

- Issues highlighted at Sep 2020 LSSW on Planetary Protection and PSR Classification (some of these topics are also discussed in Planetary Protection for the Study for Lunar Volatiles):
  - **What is the level of contamination that is detrimental to science?**
    - Depends on the nature of the science question, and the **answer may change** as analytical tools advance and science questions evolve (e.g., ANGSA investigations of unopened Apollo samples, 50 years later).
    - Related Questions: How do anthropogenic processes compare in magnitude to natural processes? (e.g., Siddiqi et al., 2026). Are environmental changes temporary or permanent?
  - **PSR environments are not all the same**, and may fall into different categories (e.g., Schörghofer and Williams, 2024; Ahrens et al., 2025).
  - There is a need to advance models of **vertical and lateral migration** of contaminants, and a **need for measurements** to test model parameters and predictions.
  - Also a need to advance understanding of **volatile transport and distribution at the exploration scale** (e.g., how/if geologic features can mitigate contamination).

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Concluding Thoughts

- **Documentation enables science.**
  - Operational information (e.g., landing trajectories, lander exhaust/outgassing characteristics), when collected and shared, can be vital input for scientific studies – from modeling to sample analysis.
  - This was practiced during the Apollo era (e.g., Simoneit et al., 1969), and should be in the future.
- **Monitoring environmental impact should be an ongoing process.**
  - Long-term observations of the dynamic, evolving lunar surface and exosphere are scientifically valuable and operationally useful (e.g., LEAG CLOC-SAT Report, 2022; also surface-based observations).
  - Reframing the question from preventing environmental impact towards understanding (and adapting to) it.
- **Understanding environmental impact is a compelling and motivating science question.**

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