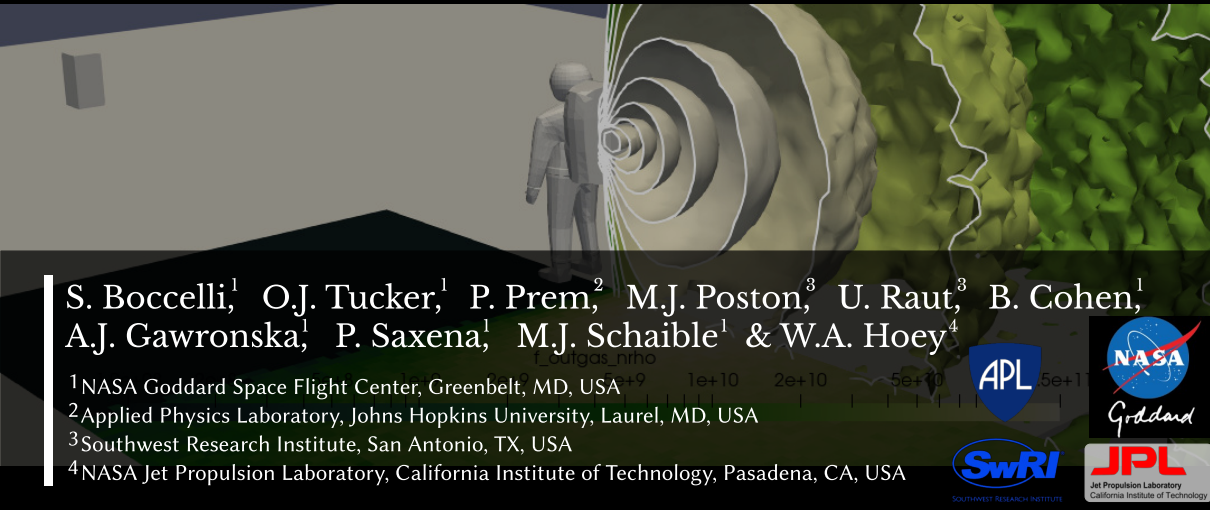
Rarefied Gas-dynamic Simulations for Lunar Exploration

NASA Postdoctoral Program

TFAWS 2025, San Jose, California



S. Boccelli,[1] O.J. Tucker,[1] P. Prem,[2] M.J. Poston,[3] U. Raut,[3] B. Cohen,[1] A.J. Gawronska,[1] P. Saxena,[1] M.J. Schaible[1] & W.A. Hoey[4]

[1] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA
[3] Southwest Research Institute, San Antonio, TX, USA
[4] NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

APL

NASA Goddard

SwRI Southwest Research Institute

JPL Jet Propulsion Laboratory California Institute of Technology

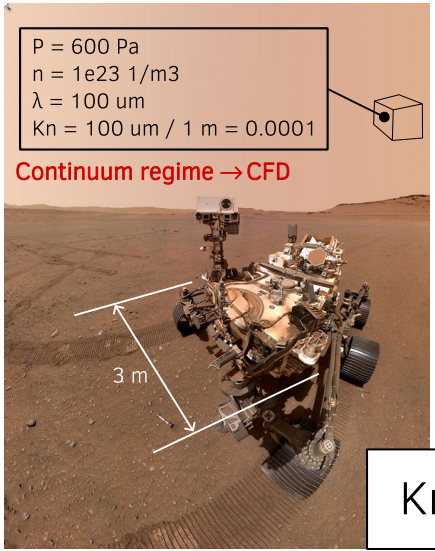
Overview

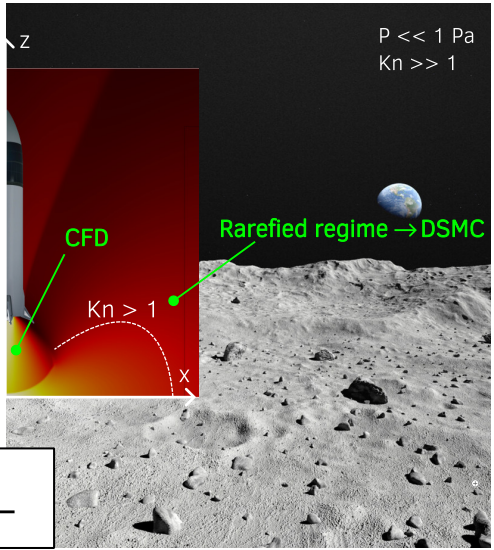
1. Intro: rarefaction regimes
2. Application: Lunar lander plumes
3. Application: PITMS measurements on the Peregrine-1 mission
4. Application: lander and astronaut contamination (outgassing)

Overview

1. Intro: rarefaction regimes
2. Application: Lunar lander plumes
3. Application: PITMS measurements on the Peregrine-1 mission
4. Application: lander and astronaut contamination (outgassing)

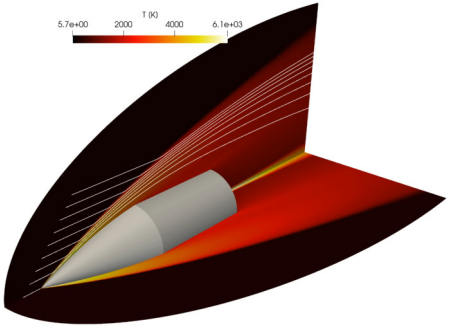
Two fluid-dynamic regimes $\Longrightarrow$ two numerical methods





$$Kn = \lambda / L$$

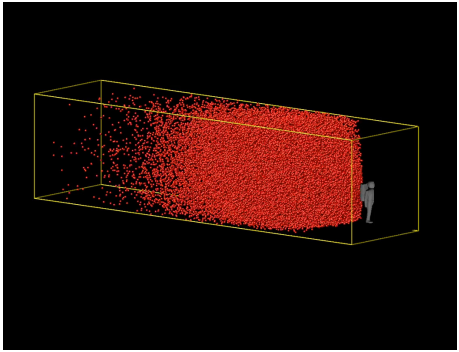
Continuum regime: Computational Fluid Dynamics (CFD)



Fluid dyn. PDEs: $\frac{\partial}{\partial t}\vec{U} + \vec{\nabla} \cdot \vec{F} = \vec{S}$

Hyper2D (Open Source $\Longrightarrow$ GitHub)

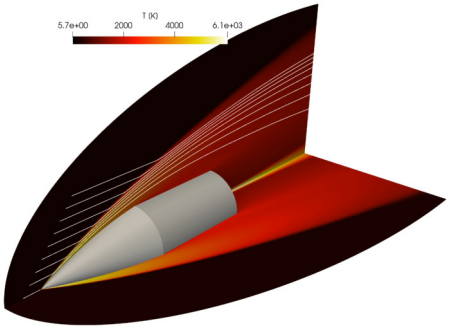
Rarefied regime: Direct Simulation Monte Carlo (DSMC)



Individual particles

SPARTA (Open Source $\Longrightarrow$ GitHub)

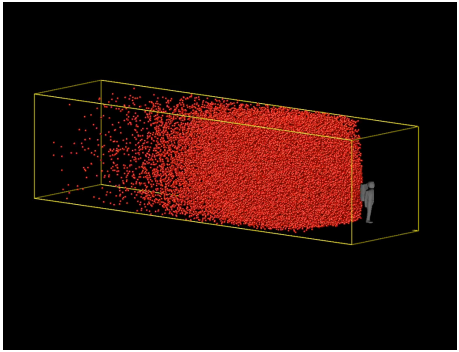
Continuum regime: Computational Fluid Dynamics (CFD)



Fluid dyn. PDEs: $\frac{\partial}{\partial t}\vec{U} + \vec{\nabla} \cdot \vec{F} = \vec{S}$

Hyper2D (Open Source $\Longrightarrow$ GitHub)

Rarefied regime: Direct Simulation Monte Carlo (DSMC)



Individual particles

SPARTA (Open Source $\Longrightarrow$ GitHub)

MOMENT METHODS →

[Presentation: Ethan Rice et al.]

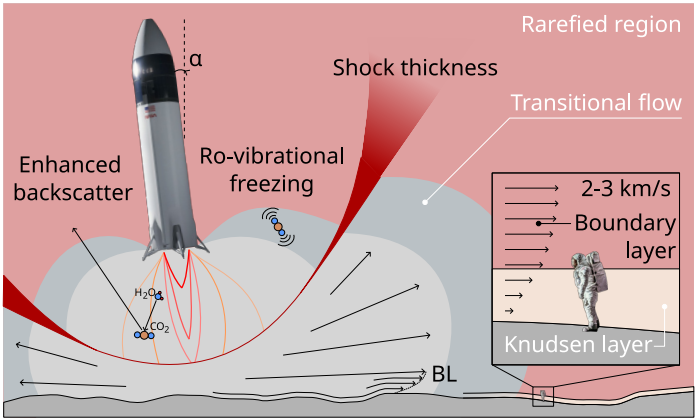
Overview

Lunar lander plumes

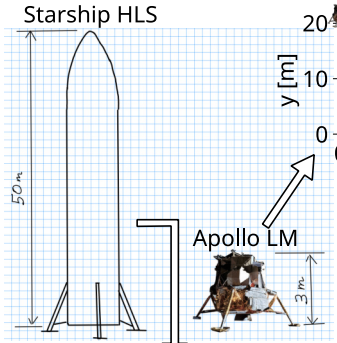
Important considerations:
- Safe distance (effect on astronauts & structures)
- Regolith contamination (affects scientific goals)
- Plumes: active scientific experiments (H_2O retention/desorption)

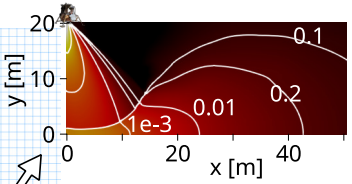
Lunar lander plumes

Important considerations:
- Safe distance (effect on astronauts & structures)
- Regolith contamination (affects scientific goals)
- Plumes: active scientific experiments (H2O retention/desorption)



Apollo vs Starship-size landers



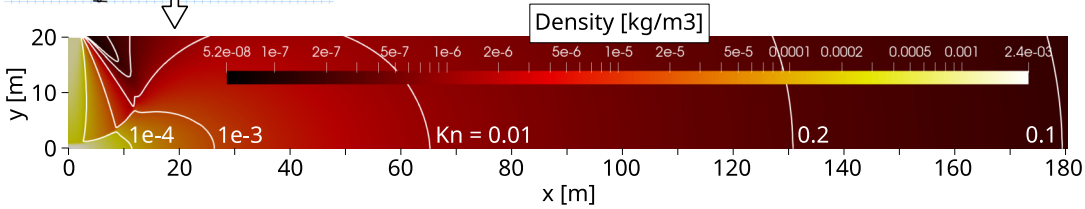


Continuum: Kn < 0.0001

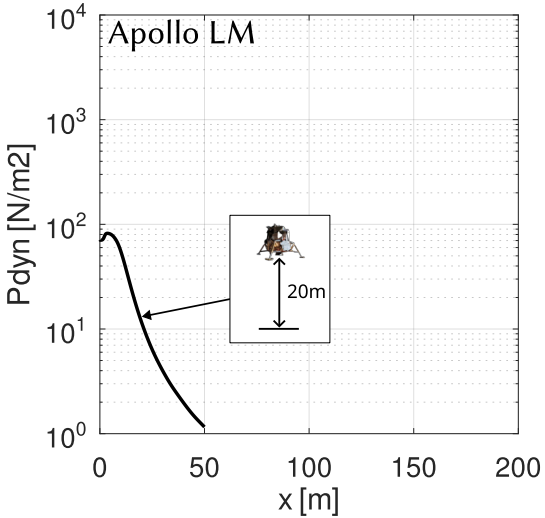
Transition: 0.001 < Kn < 0.1

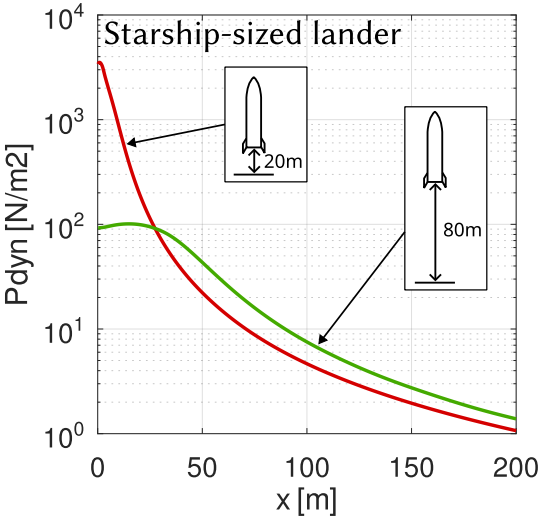
Strongly rarefied: Kn > 0.1

Free-molecular: Kn > 10



Apollo vs Starship-size landers: dynamic pressure





Overview

1. Intro: rarefaction regimes
2. Application: Lunar lander plumes
3. Application: PITMS measurements on the Peregrine-1 mission
4. Application: lander and astronaut contamination (outgassing)

PITMS lunar mass spectrometer

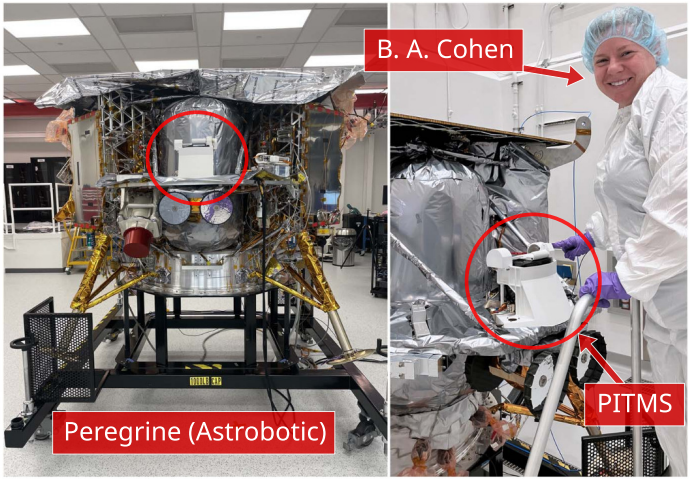


Figure 4. PITMS mounted to the Peregrine lander Deck D (left) in the Astrobotic clean room and (right) during remove-before-flight activities (with B.A.C. for scale). The Iris cover (N. Potter 2023) is mounted to the underside of Deck D. The PITMS aperture opens to the $+X$ direction of the spacecraft.

PITMS mass spectrometer:

Developed and flown by NASA Goddard Space Flight Center, in partnership with the European Space Agency (ESA) and its prime contractor The Open University and subcontractor RAL Space

Launch: Jan 8th, 2024

- Propulsion sys. anomaly while pressurizing tank

- PITMS activated and detected H_2O, oxydizer and combustion products

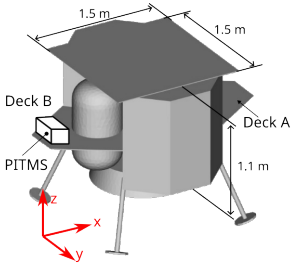
We run DSMC simulations to interpret the measurements:

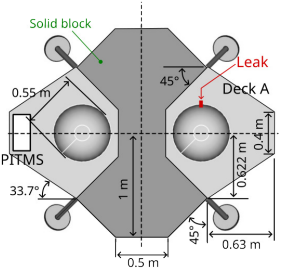
- Could a leak reach PITMS?
- What are the main phenomena?
- What diffusion paths? Compare to Rosetta
- Outlook on outgassing

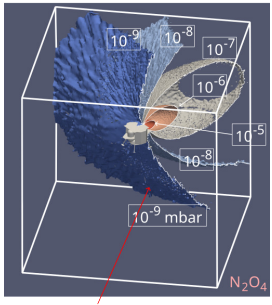
[Cohen et al., The Peregrine Ion Trap Mass Spectrometer (PITMS): Results from [...], The Planetary Science Journal, 2025

Peregrine: external transport or internal diffusion paths?

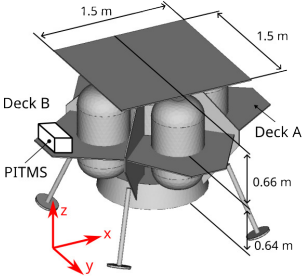
Geometry 1

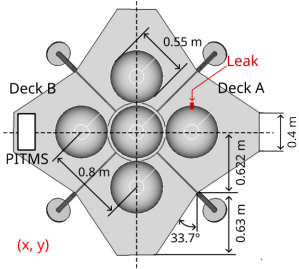


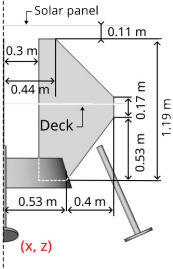


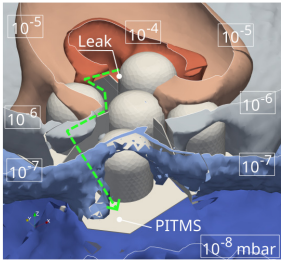


Geometries 2 & 3

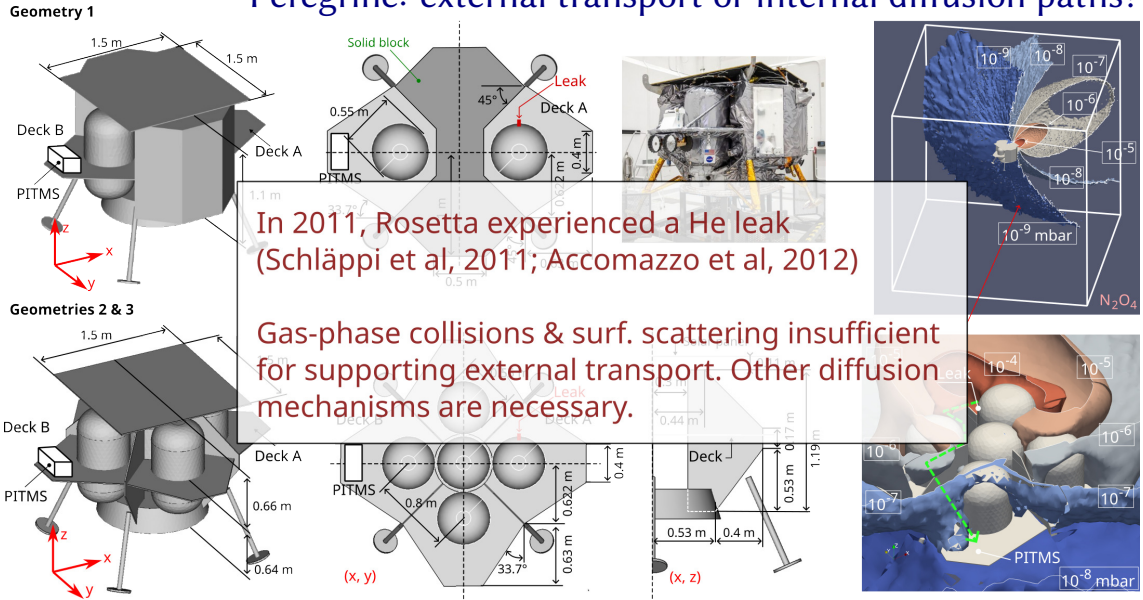








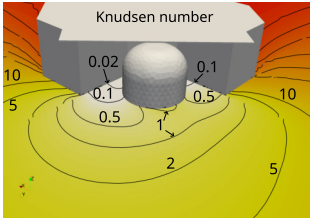
Peregrine: external transport or internal diffusion paths?



In 2011, Rosetta experienced a He leak (Schläppi et al, 2011; Accomazzo et al, 2012)

Gas-phase collisions & surf. scattering insufficient for supporting external transport. Other diffusion mechanisms are necessary.

Peregrine: Kn and inter-species collisions

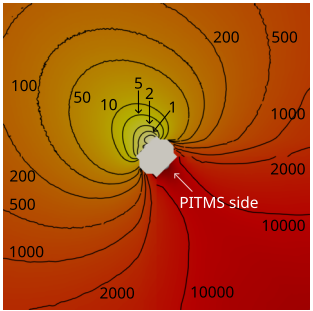


Observations

> Continuum near vent

> Free-molecular at PITMS side

> Species-dependent Kn number not sufficient



Observations

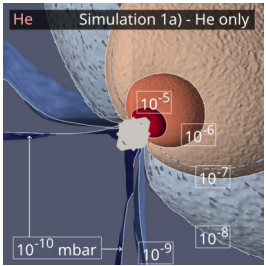
Our simulations: He, NO, N2O4

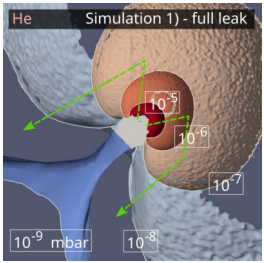
Large mass ratio increases He mobility around the spacecraft

Also see:

> Conte et al., Europa lander plume-induced contamination: DSMC modeling of mono-propellant plume testing, 2021

> Clout et al., Numerical study and semi-analytical model of rocket motor exhaust backflow in rarefied atmosphere, Physics of Fluids, 2025.





S. Boccelli et al, *DSMC analysis of Astrobotic's Peregrine Mission-1* [Under Review]

Overview

Mass-spectrometer measurements on the lunar surface

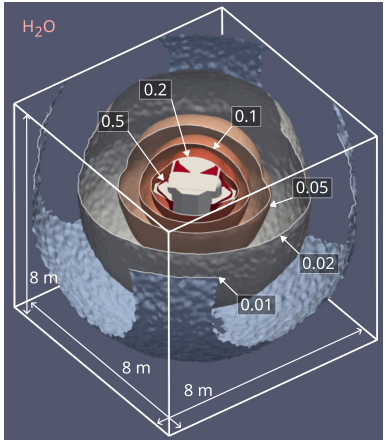
PITMS was intended to measure lunar volatile species, including H_2O.

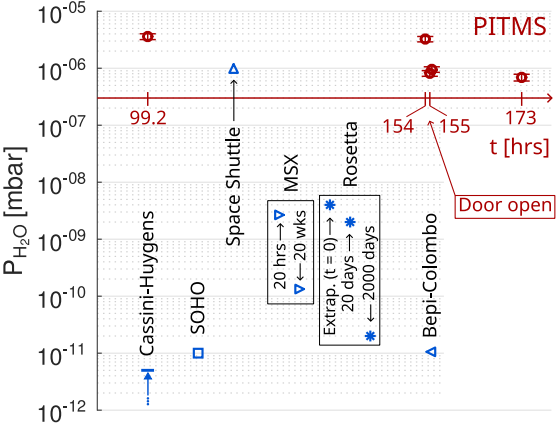
- The lander plume deposits contaminants on the lunar surface (H_2O and other species) $\rightarrow$ measurable by mass specs
- Landers execute scheduled venting operations to expell excess fuel
- The lander is a water-vapor source because of outgassing $\implies$ to be quantified

Also see:

- Killen et al, *Moon: Handle With Care*, 2024
- Killen et al, *Temporary atmospheres produced by human activities on the Moon*, 2025

Quantifying Peregrine's outgassing rate





Outgassing:

Collisionless simulation -> easy (ballistic traj)
Material properties & temp -> difficult

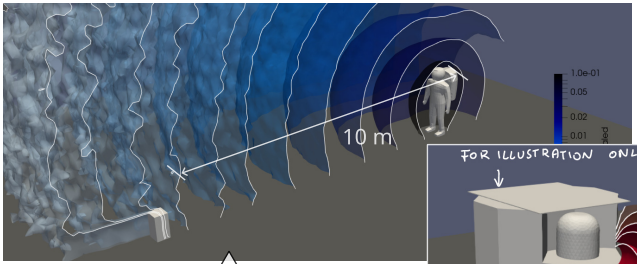
PITMS measured P{H2O} = 1E-6 mbar
From the particle sim & geo model we estimate
N{H2O} = 1E15 particles/cm2/s
m{H2O} = 2.8E-8 g/cm2/s

→ S. Boccelli et al, *DSMC analysis of Astrobotic's Peregrine Mission-1* [Under Review]

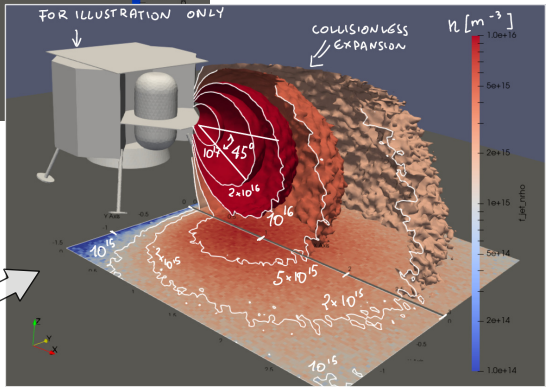
Astronauts might also contaminate scientific measurements

Astronauts deploy instruments!

[WORK IN PROGRESS]



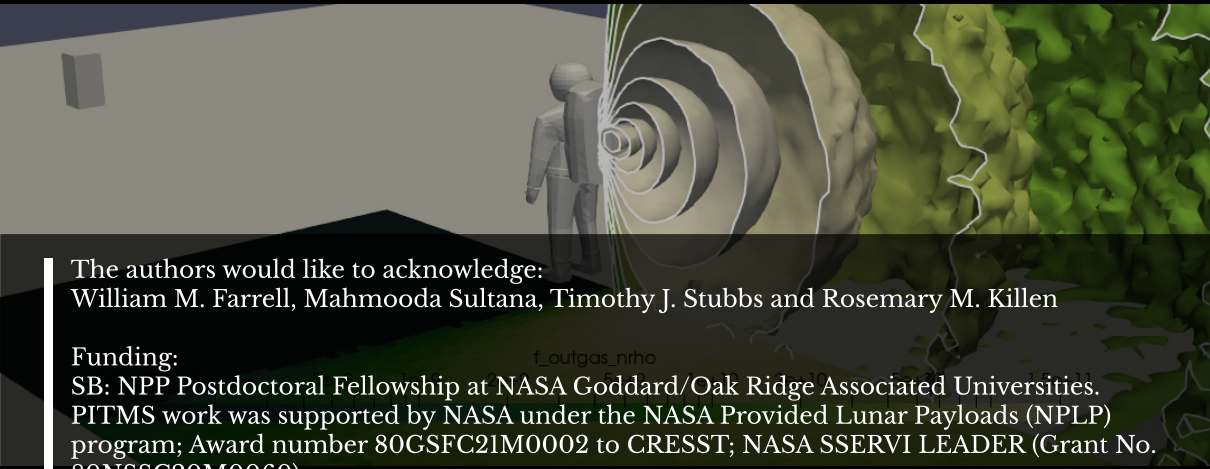
Impact of space suit outgassing on astronaut-delivered instrument



Scheduled fuel venting operations from lunar lander

Rarefied Gas-dynamic Simulations for Lunar Exploration

TFAWS 2025, San Jose, California



The authors would like to acknowledge:
William M. Farrell, Mahmooda Sultana, Timothy J. Stubbs and Rosemary M. Killen

Funding:
SB: NPP Postdoctoral Fellowship at NASA Goddard/Oak Ridge Associated Universities.
PITMS work was supported by NASA under the NASA Provided Lunar Payloads (NPLP) program; Award number 80GSFC21M0002 to CRESST; NASA SSERVI LEADER (Grant No. 80NSSC20M0060).