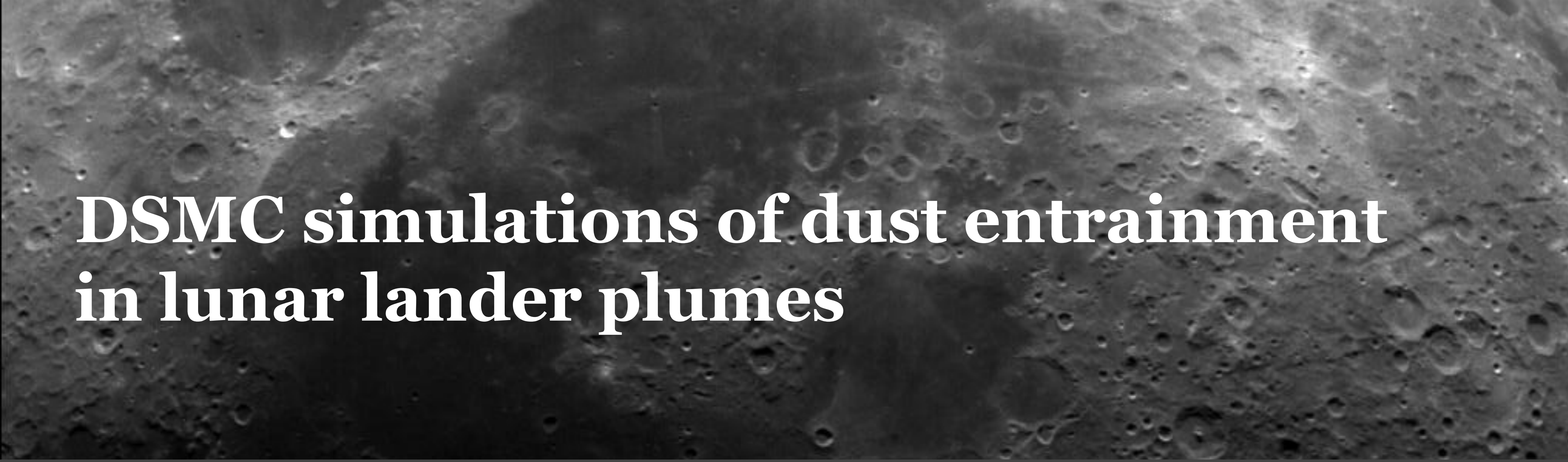

DSMC simulations of dust entrainment in lunar lander plumes

Dust, Atmosphere, and Plasma Environment of the Moon and Small Bodies
June 6, 2023

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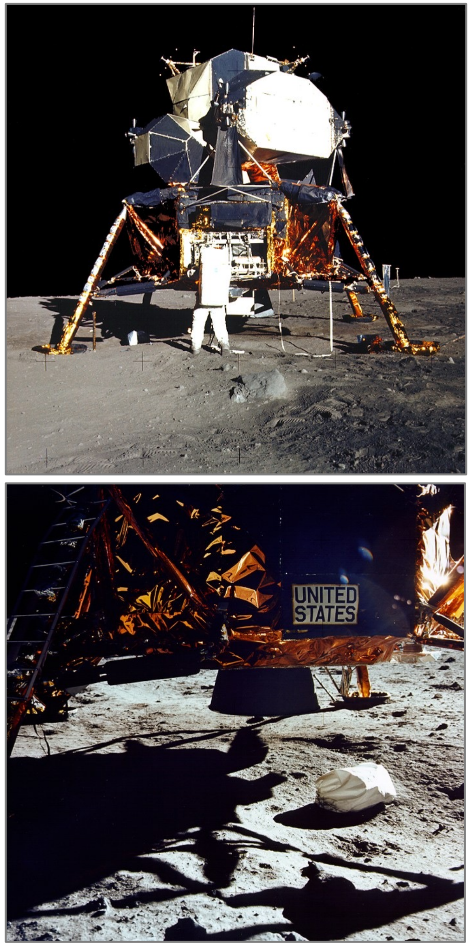
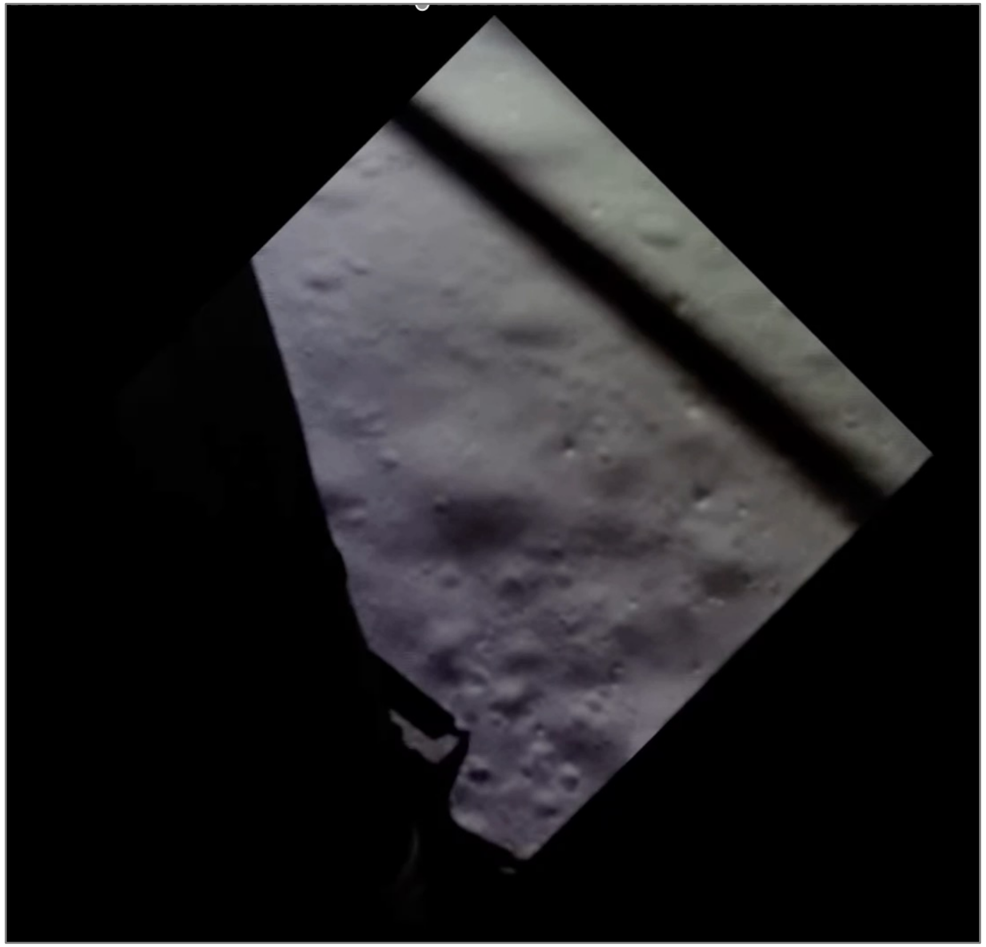
Motivation



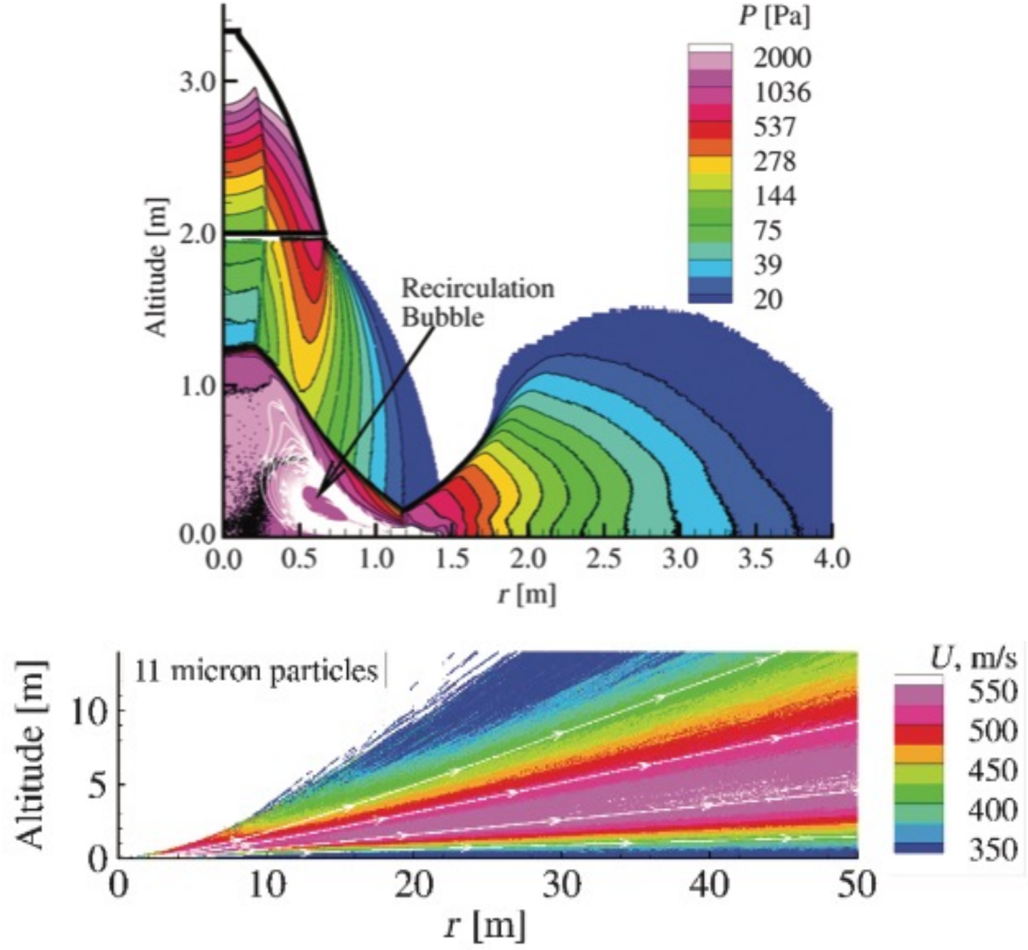


Credit: NASA (left), https://www.firstmenonthemoon.com (right)

- Apollo 11 astronauts began observing dust spray at an altitude of about 40 ft
- Saw little evidence of excavation/cratering beneath the lander
- Reported issues with dust sticking to spacesuits, interfering with instruments, and blocking up mechanisms, etc.

Objectives

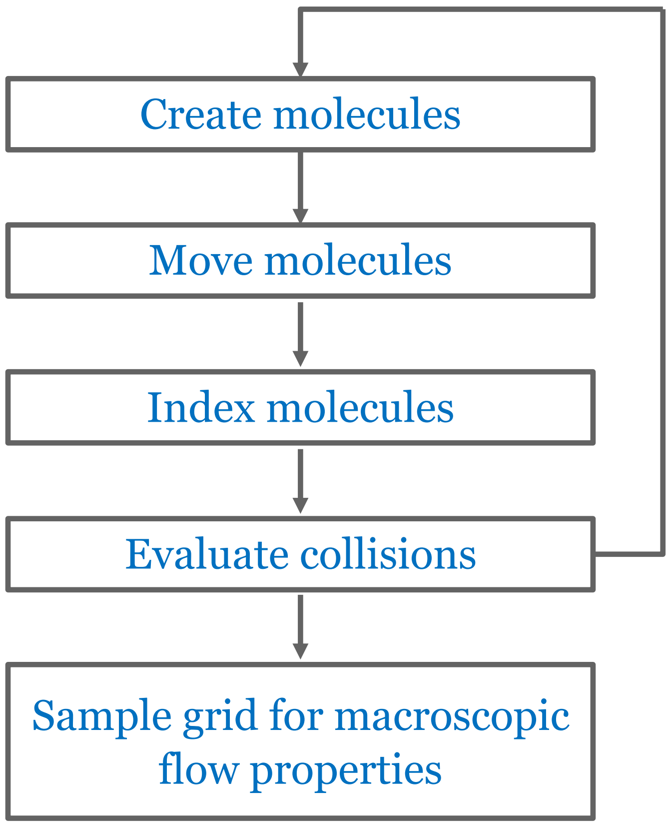
- Use the Direct Simulation Monte Carlo (DSMC) method to study dust behavior during lunar landings
- Continuation of work started by Morris (2012)
- Compare erosion profile, ejecta velocity, ejecta angle, spray density, and settling time for
  - ➢ Different lander classes
  - ➢ Different landing sites
  - ➢ Full lander descent path



Example gas plume and dust spray (Morris et al. 2012)

Direct Simulation Monte Carlo (DSMC)

- DSMC method based on Bird (2004)
- Code previously used to model comet impacts (Stewart et al. 2011), volcanic plumes on Io (Zhang et al. 2003), plumes on Enceladus (Yeoh et al. 2015), and lunar lander descents (Prem et al. 2020)
- Gas molecules and dust particles are created and moved within a meshed grid
- Each simulated molecule represents a larger number of real molecules
- Motion is based on the probability of collisions between particles in the same grid cell



Plume creation

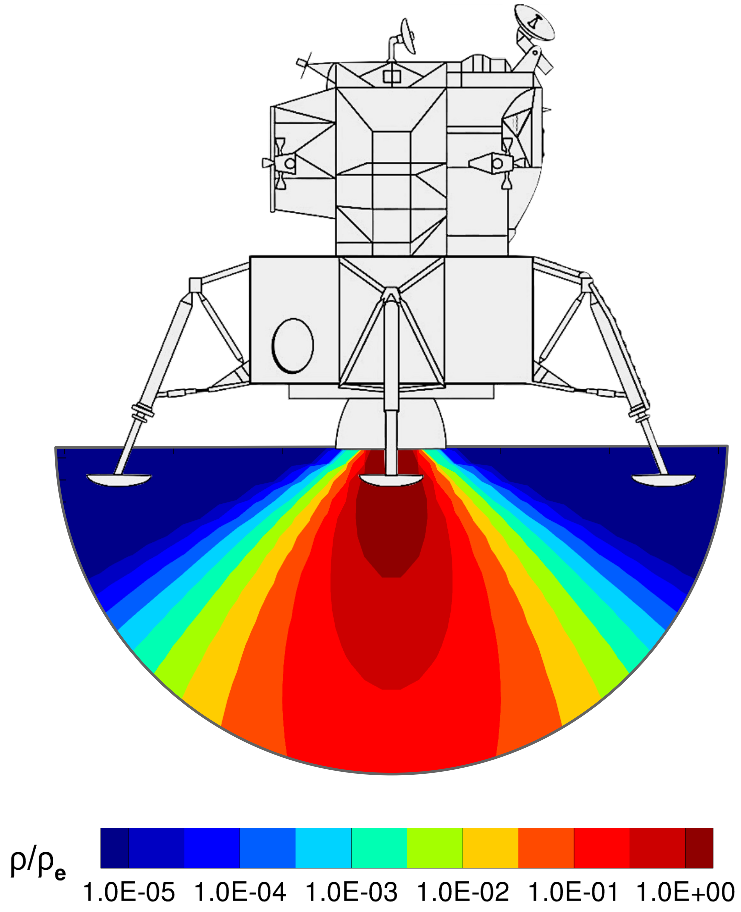
- Plume molecules are created within a spherical source region using an analytical expression from Roberts (1966) (see also Prem et. al 2020)

$$\frac{\rho}{\rho_e} = \frac{\gamma(\gamma-1)M_e^2}{2}\left(\frac{r_e}{h}\right)^2 (cos\theta)^{\gamma(\gamma-1)M_e^2}$$

$$\frac{T_o}{T} = \left(\frac{\rho_o}{\rho}\right)^{\gamma-1} = \left(1+\frac{\gamma-1}{2}M^2\right)$$

ρ is gas density, M is the Mach number, γ is the ratio of specific heats, r_e is the exit radius, and h and θ are the distance and angle from the nozzle exit

- Molecules that remain in the source region are destroyed before new molecules are created



Dust creation

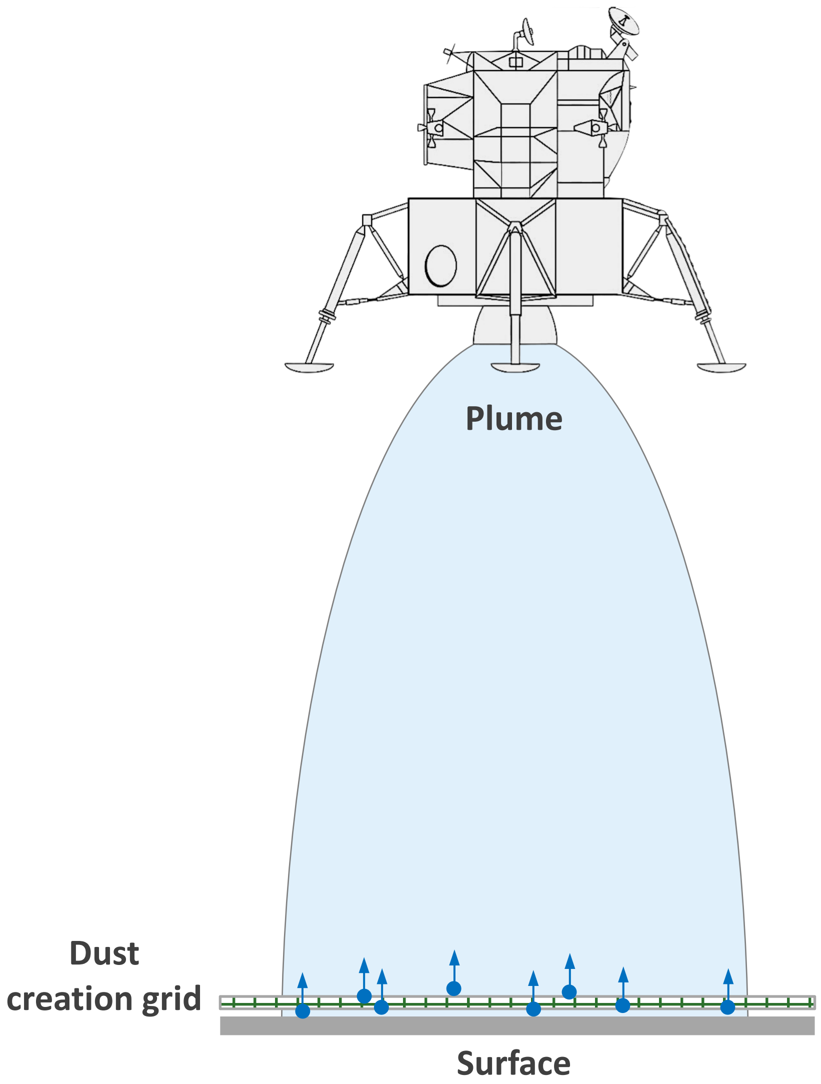
- Dust is created using an **empirical scaling** relationship based on Metzger et al. (2009, 2010)

$$\phi_e \propto \frac{\rho_g U_g^2}{2 g \rho_d D_d} \equiv Fr^2$$

$$\phi_e = 0.0025 \text{ x } \frac{1}{2} \rho_g U_g^2$$

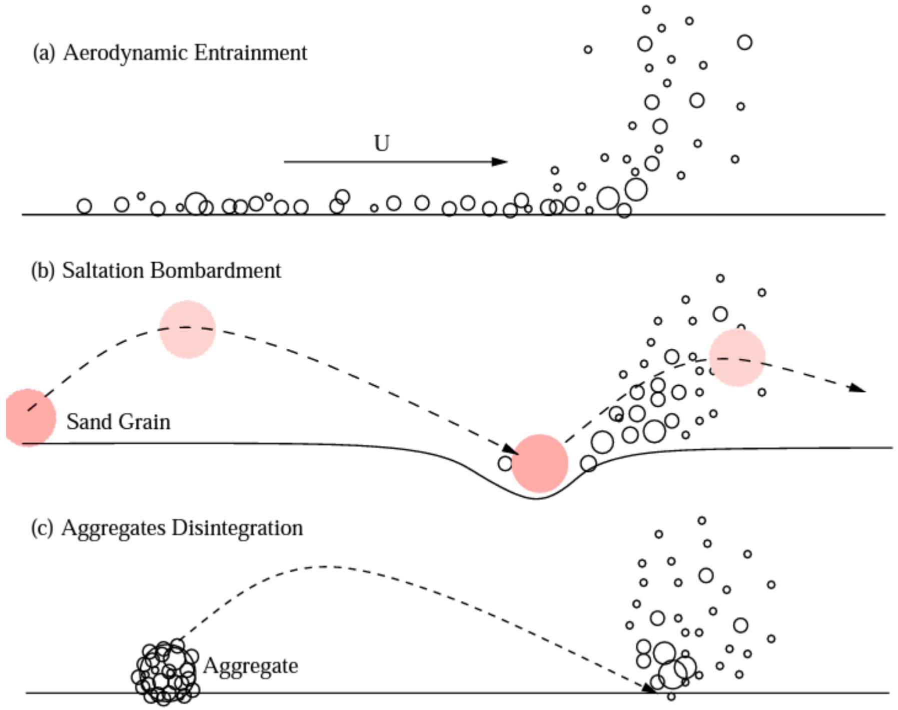
ϕ_e is the eroded particle mass flux, $\rho_g U_g^2/2$ is the dynamic pressure of the gas, and ρ_d and D_d are the density and diameter of the dust

- Dust is added to the system by sampling the dynamic pressure of the gas at a height of 5 cm above the surface
- Dust is given an initial upward velocity of 0.1 m/s



Dust-gas interactions

- Only consider viscous dust erosion due to aerodynamic entrainment
- Dust grains stick to ground after contacting the surface
- Gas-dust interactions follow a modified version of the coupling method proposed by Burt and Boyd (2004)
- Momentum and energy are transferred through
  - Gas-gas collisions
  - Gas-dust and dust-gas interactions
  - Dust-dust collisions



Mechanisms for viscous dust erosion (Shao 2008, Morris 2012)

Dust-gas coupling

- Interactions are evaluated by summing the **drag and thermal energy** transfer to each dust particle **from all gas molecules** in the same computational cell

$$Drag\ force = \sum_{i}^{N_g}\left[\frac{\pi R_d^2 N_{g,i} m_g}{V_c}\left(c_{r,i} + \frac{\tau_d}{3}\sqrt{\frac{2\pi k_b T_d}{m_g}}\right)\boldsymbol{u_{r,i}}\right]$$

$$Heat\ transfer = \sum_{i}^{N_g}\left[\frac{\tau_d \pi R_d^2 N_{g,i} m_g}{V_c}\left(\frac{1}{2}c_{r,i}^2 + \frac{e_{rot,i}}{m_g} - \left(1+\frac{\Lambda}{4}\right)\frac{2k_b T_d}{m_g}\right)\right]$$

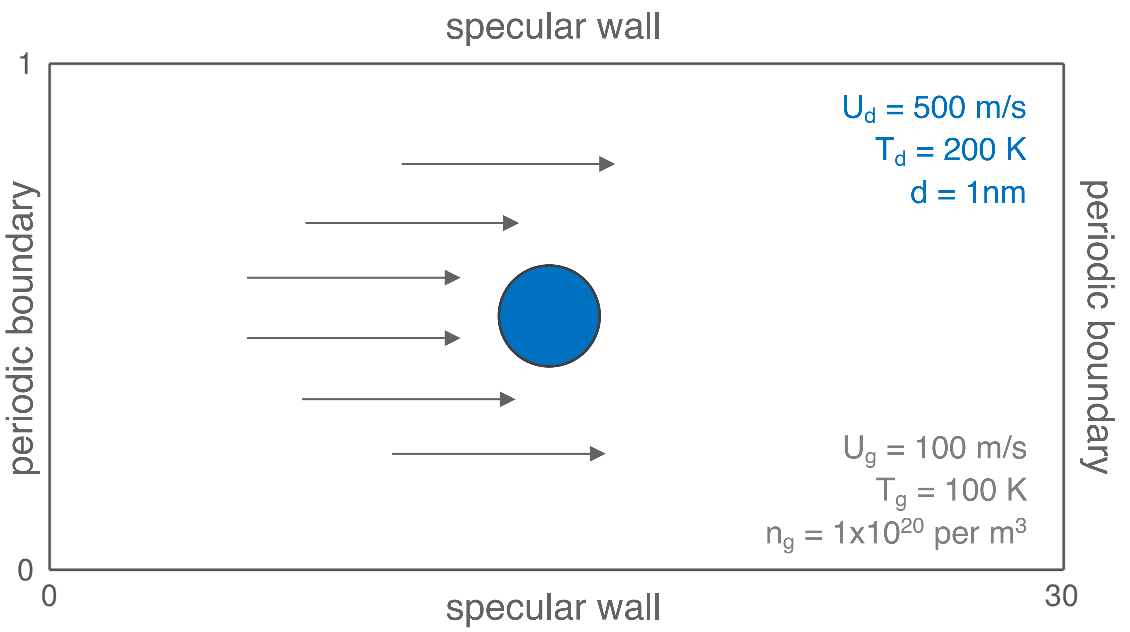
N_g is the number of gas molecules, m_g is the gas molecular mass, R_d and T_d are the radius and thermal temperature of the dust, V_c is cell volume, c_r and u_r are relative speed and velocity, e_{rot} and Λ are the rotational energy and degree of freedom of the gas

- The velocity and temperature of the dust is updated accordingly (see Morris et al. 2015)

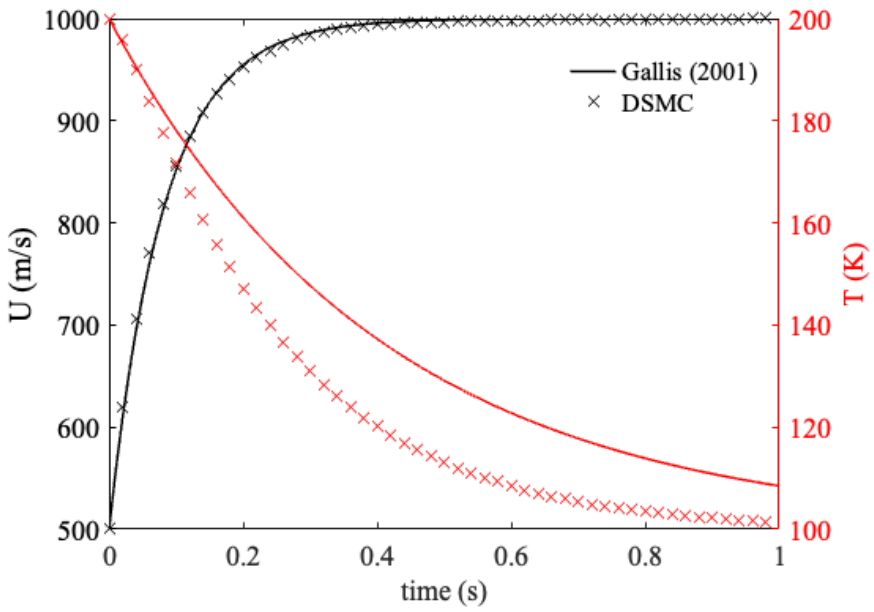
Initial validation

Inject a dust particle into a gas stream and verify that the velocity and temperature of the particle relax to that of the gas

Simulation setup

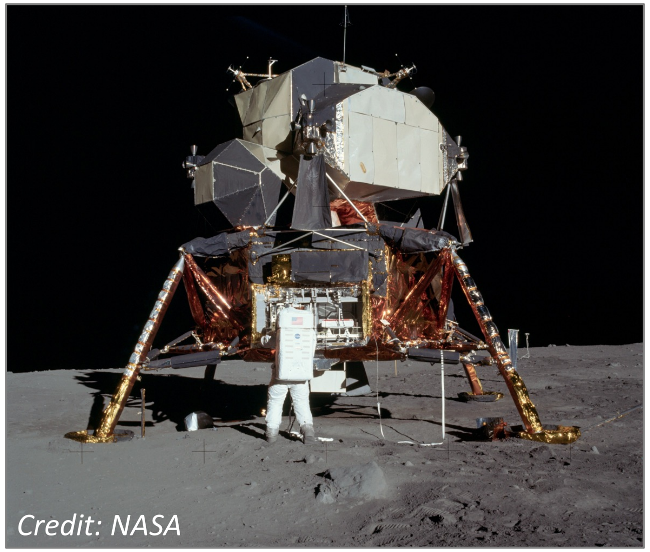


Results for a 1 nm dust particle

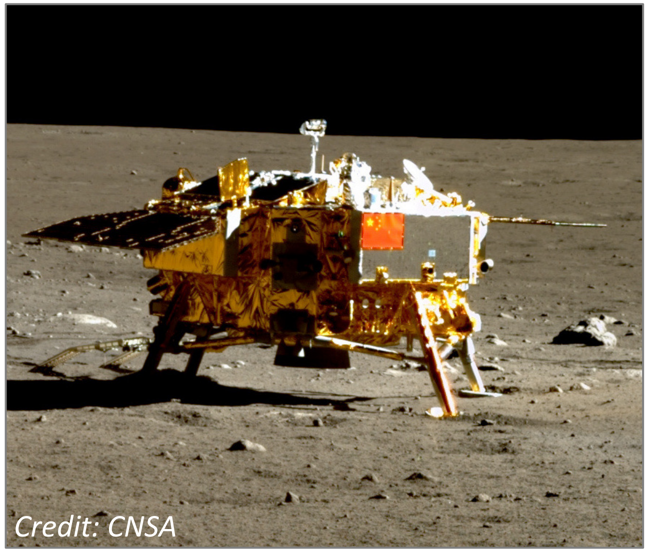


Preliminary analysis

Apollo Lander



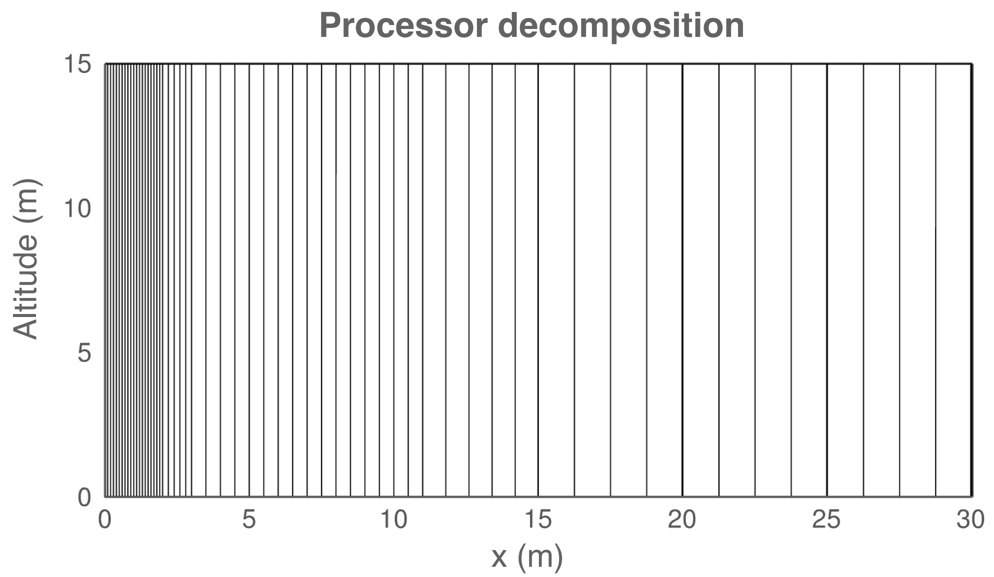
Chang'e 3 Lander

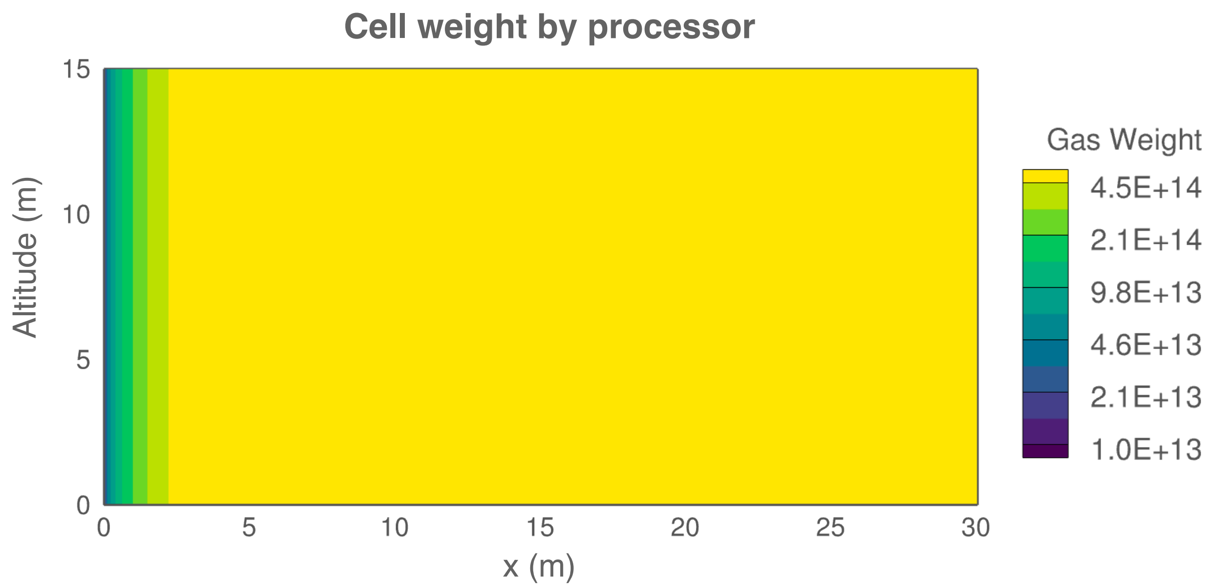


Simulated properties at nozzle exit

	Diameter (m)	Thrust (kN)	M	ρ (kg m^{-3})	P (Pa)	T (K)	V (m/s)
Apollo	1.62	13.3	5.03	1.09×10^{-3}	190	496	2,430
Chang'e	0.6	2.5	5.0	1.02×10^{-3}	252	514	2,705

Simulation setup





Grid height: 15 m

Grid horizontal distance: 30 m

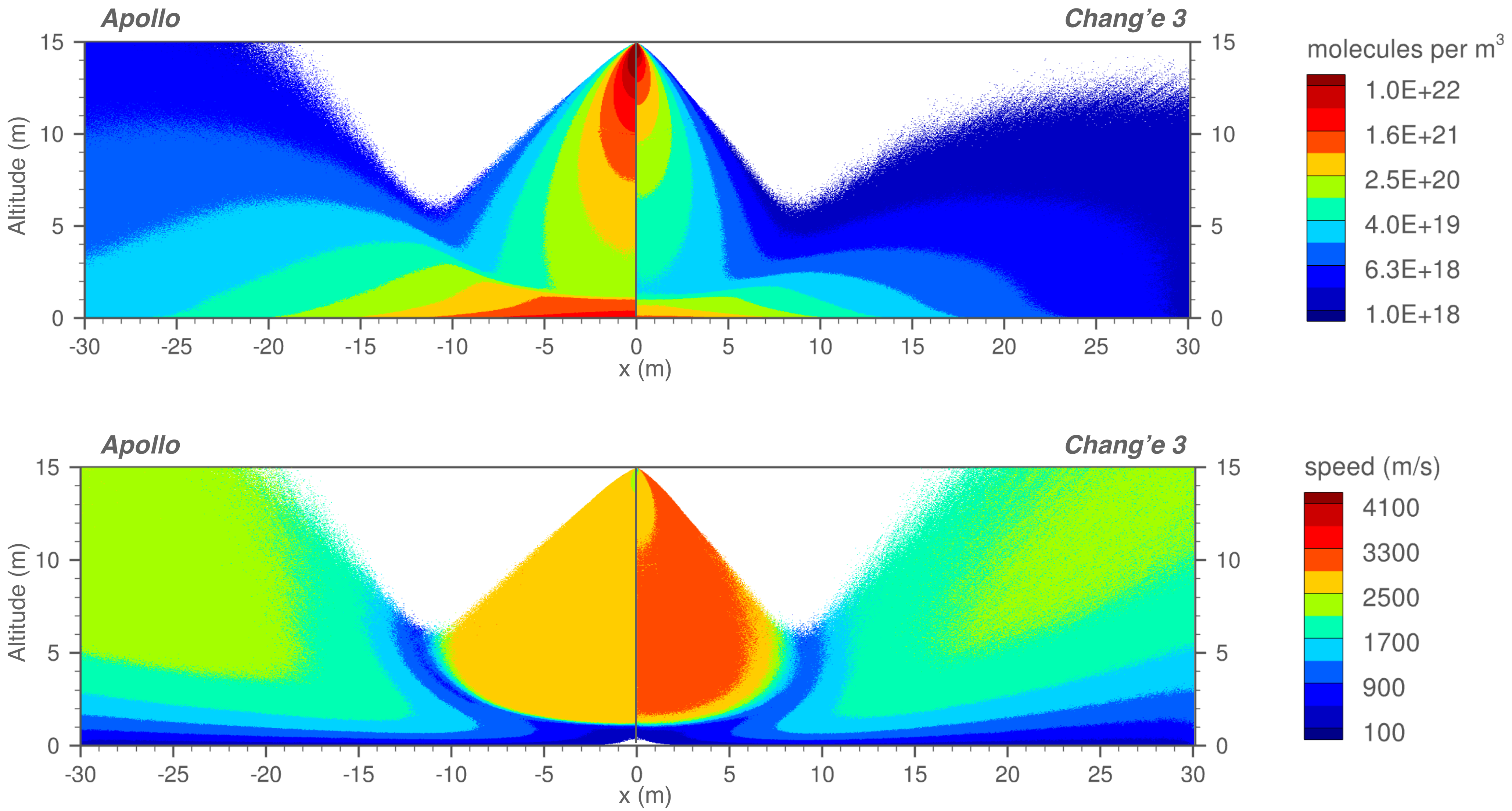
Grid resolution: 0.05 m x 0.025 m x 0.5°

Simulation time step: 0.15 ms

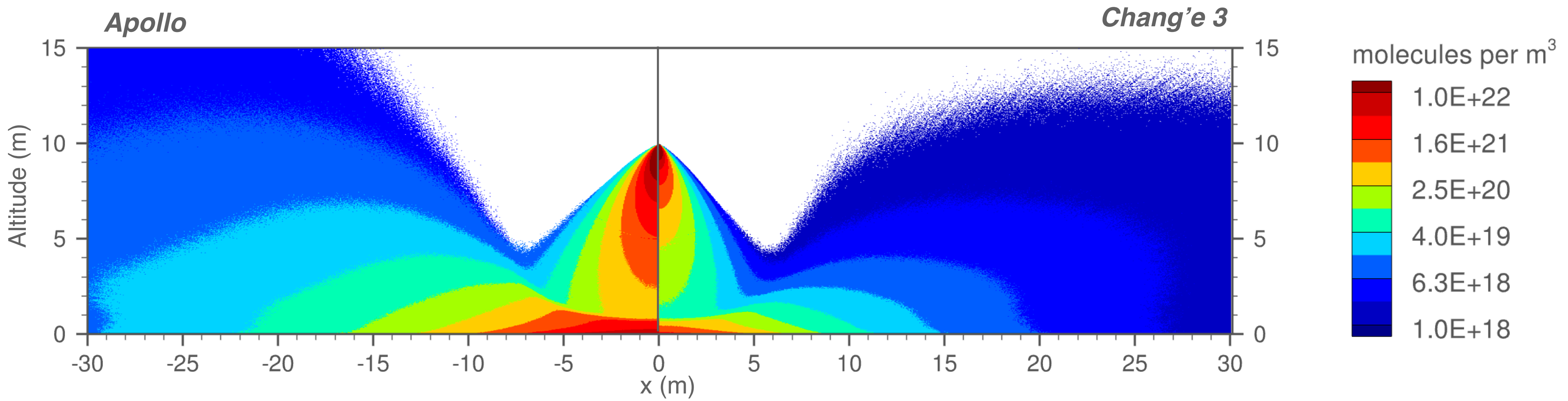
Dust diameter: 1 μm

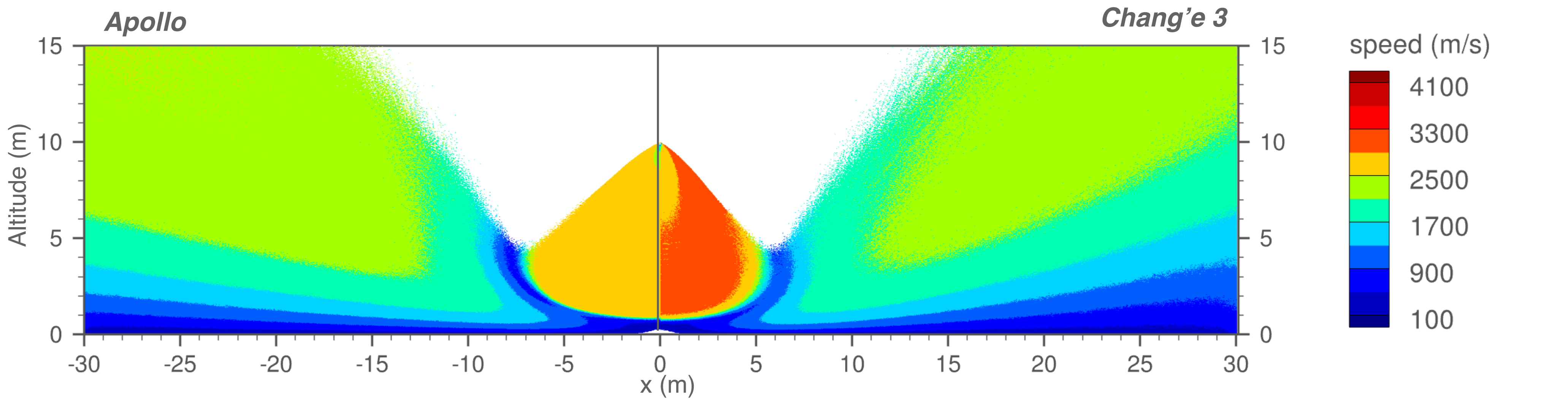
Dust weight: ~1x10^4 real molecules per simulated molecule

Plume characteristics – 15 m hover

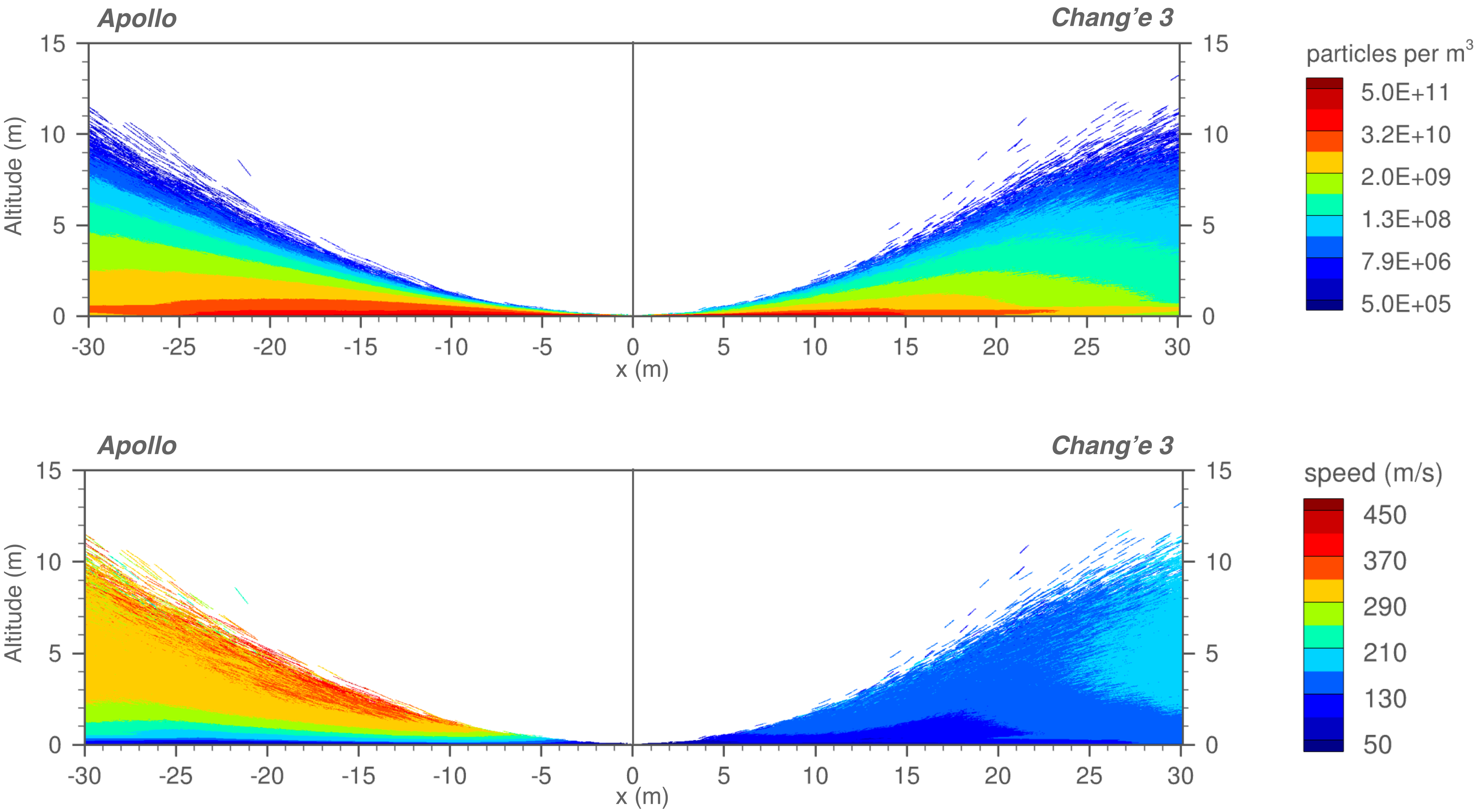


Plume characteristics – 10 m hover

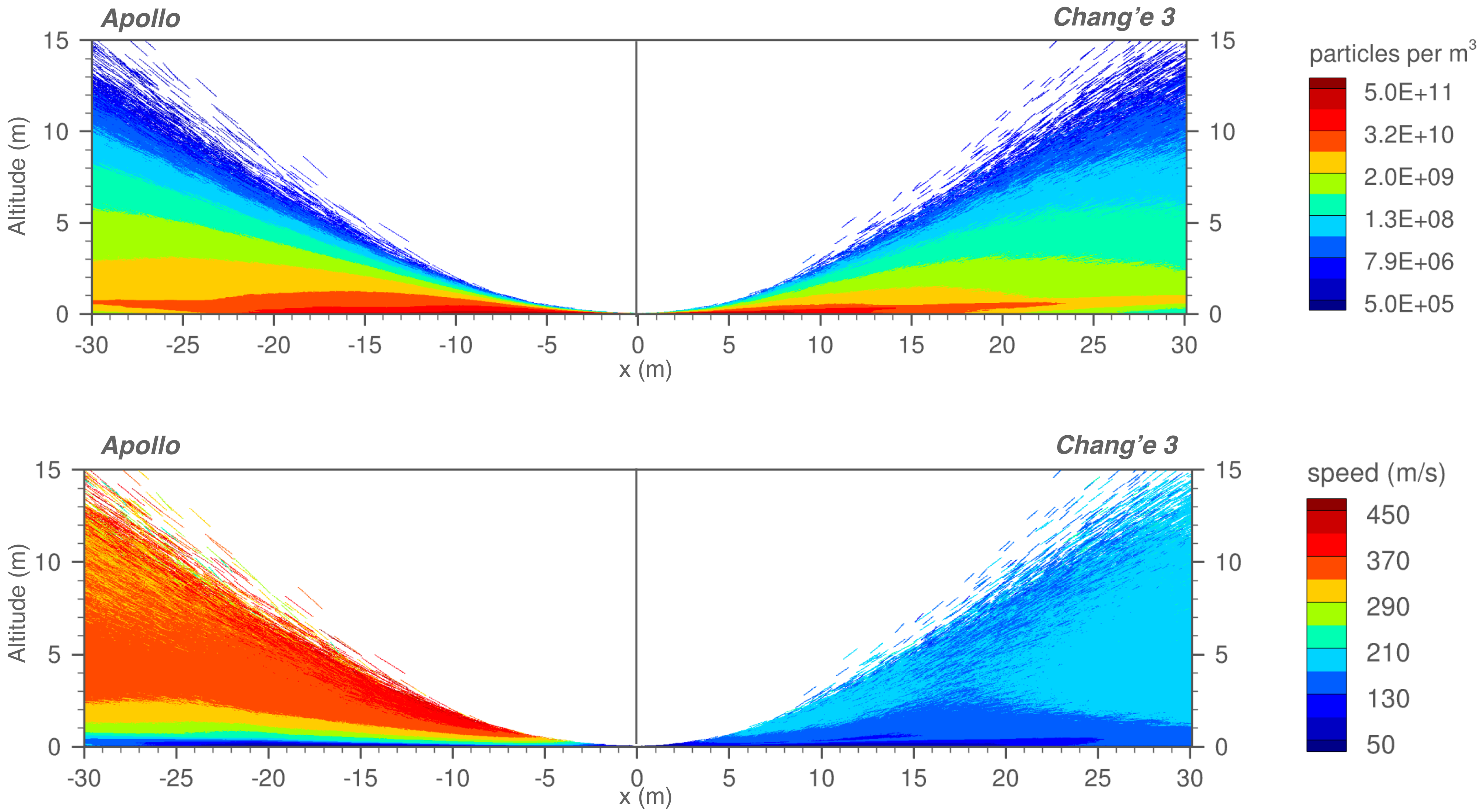




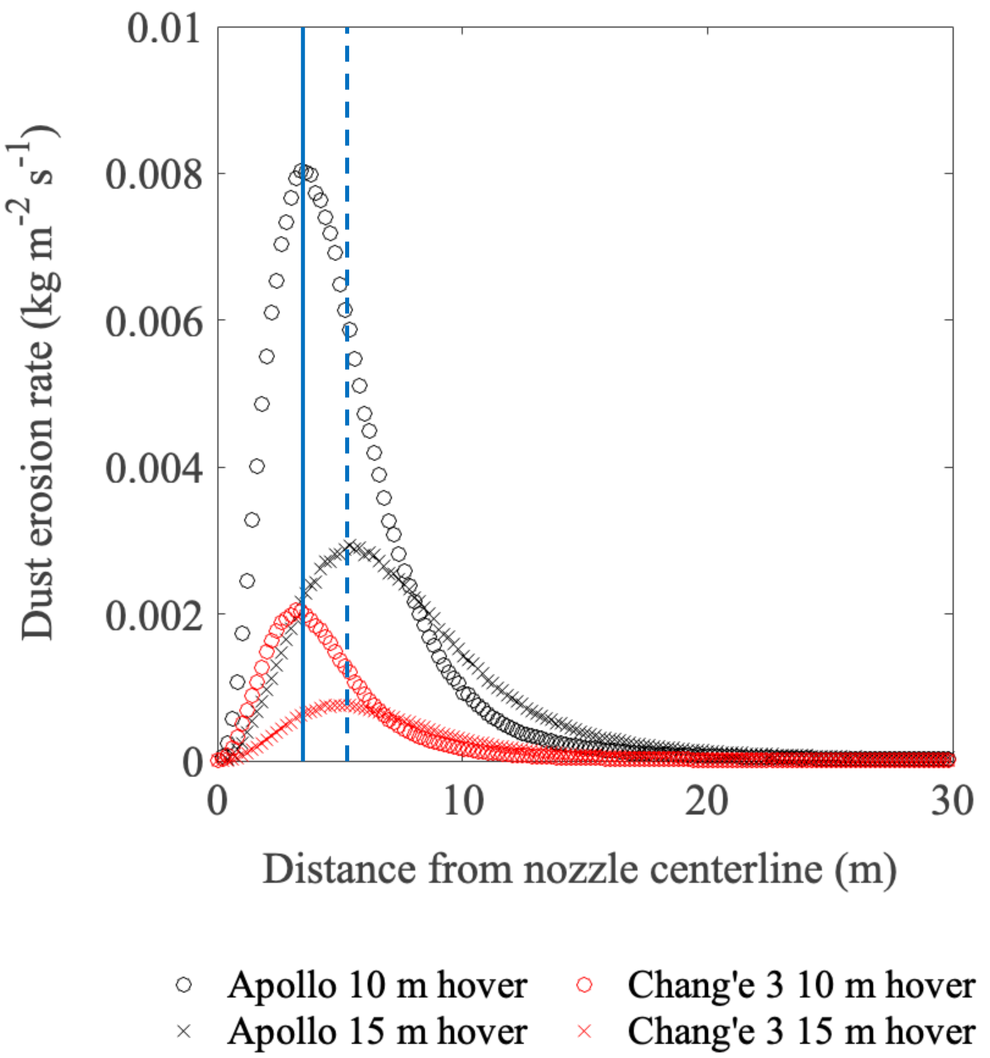
Dust spray – 15 m hover



Dust spray – 10 m hover



Erosion rate



Future work

Possible code modifications

1. Revise method for introducing plume molecules
2. Add alternative dust erosion models
3. Allow dust to rebound off of surfaces and walls

Planned analysis

4. Validate the code against experimental data
5. Vary lander type and landing location
6. Quantify dust erosion, particle trajectory and dust settling time for full lander descents

Thank you!

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