Transport of Water in a Transient Impact-Generated Lunar Atmosphere

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Microsymposium 57
March 19th, 2016

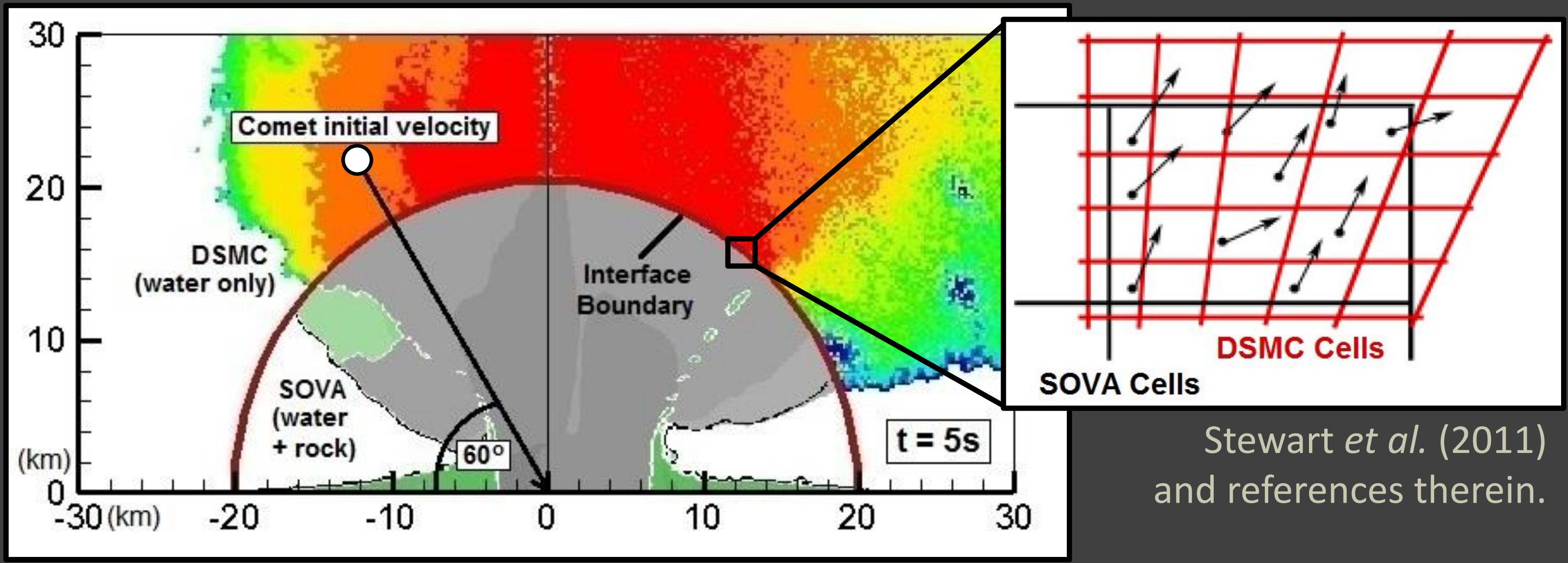
Computations performed at the Texas Advanced Computing Center.
Supported by NASA's Lunar Advanced Science and Exploration Research program.

Motivation

- Comets as a source of lunar polar volatiles: understanding **what happens between delivery and cold-trap deposition** plays a key role in interpreting observations.
- Volatile **transport/loss processes** are different after an impact – this **affects abundance** and **distribution** of volatile deposits:
  - How much vapor remains gravitationally bound for various impact parameters[1] is important – but there is more to the problem.
  - Collisionless exosphere transforms into a **collisional atmosphere**.[2,3]
  - **Cold-trapping may be non-uniform**.[3,4,5]
  - Photochemistry[6] and other interactions between **multiple species**.
  - Radiative heat transfer and shielding from photodestruction[3] in an **optically thick** atmosphere.

[1]Ong *et al.* (2010); [2]Stewart *et al.* (2011); [3]Prem *et al.* (2015); [4]Schorghofer (2014); [5]Moores (2016); [6]Berezhnoi and Klumov (2002).

The Hybrid SOVA-DSMC Method



Stewart *et al.* (2011)
and references therein.

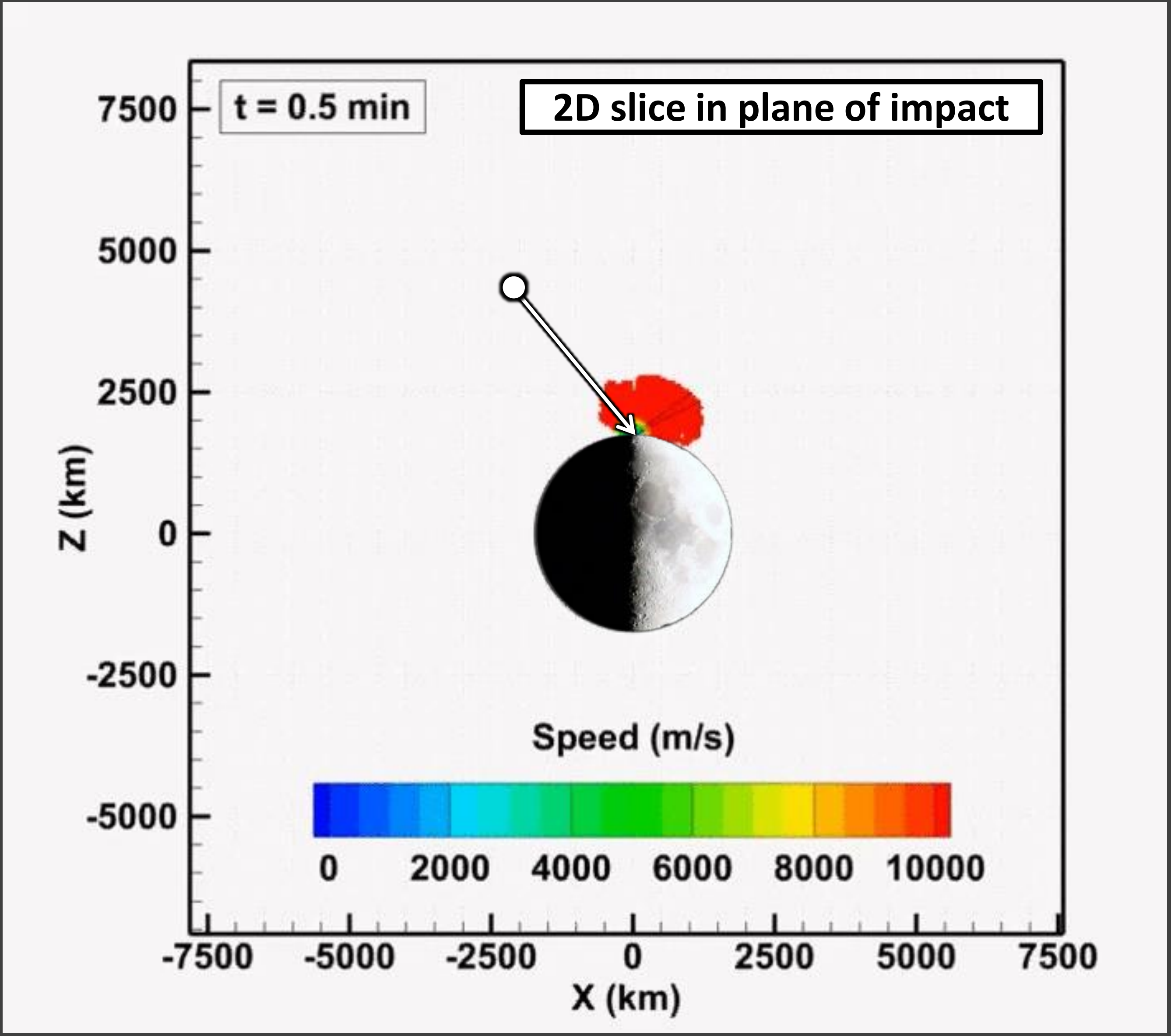
- **SOVA hydrocode** models impact and **hydrodynamic flow** of comet and target melt/vapor, out to 20 km from point of impact.
- **DSMC method** tracks **representative water molecules** until escape, photodestruction or cold-trap deposition.
- Results shown here are for impact of an H_2O ice sphere, 1 km in radius. Impact at North Pole, 30 km/s, 60° impact angle (from horizontal).

Model Parameters & Simplifications

- **Tracking water from impact to permanent shadows:**
  - Molecules move under **variable gravity**, interacting through **collisions**.[1]
  - Temperature-dependent surface **residence times**.[2]
  - **Diurnally varying** lunar surface temperature.[3]
- **Loss and capture mechanisms:**
  - Vapor moving with > escape velocity at 30 s after impact is neglected; remaining vapor tracked out to 40,000 km from lunar surface.
  - **Photodestruction** and **self-shielding**[4] of vapor from solar ultraviolet.
  - **Cold traps**: 1 at North Pole (1257 km^2), 6 at South Pole (4575 km^2). [5]
- **Simplifications:**
  - **Only H_2O in the vapor phase** is modeled i.e. photodissociation products, chemical reactions and atmospheric condensation are not modeled.
  - Results shown here treated vapor as **transparent to infrared radiation**.

[1]Bird (1994); [2]Sandford and Allamandola (1993); [3]Crider and Vondrak (2000), Hurley *et al.* (2015); [4]Prem *et al.* (2015) + references therein; [5]Elphic et al., 2007, Noda et al., 2008.

An Impact-Generated Atmosphere



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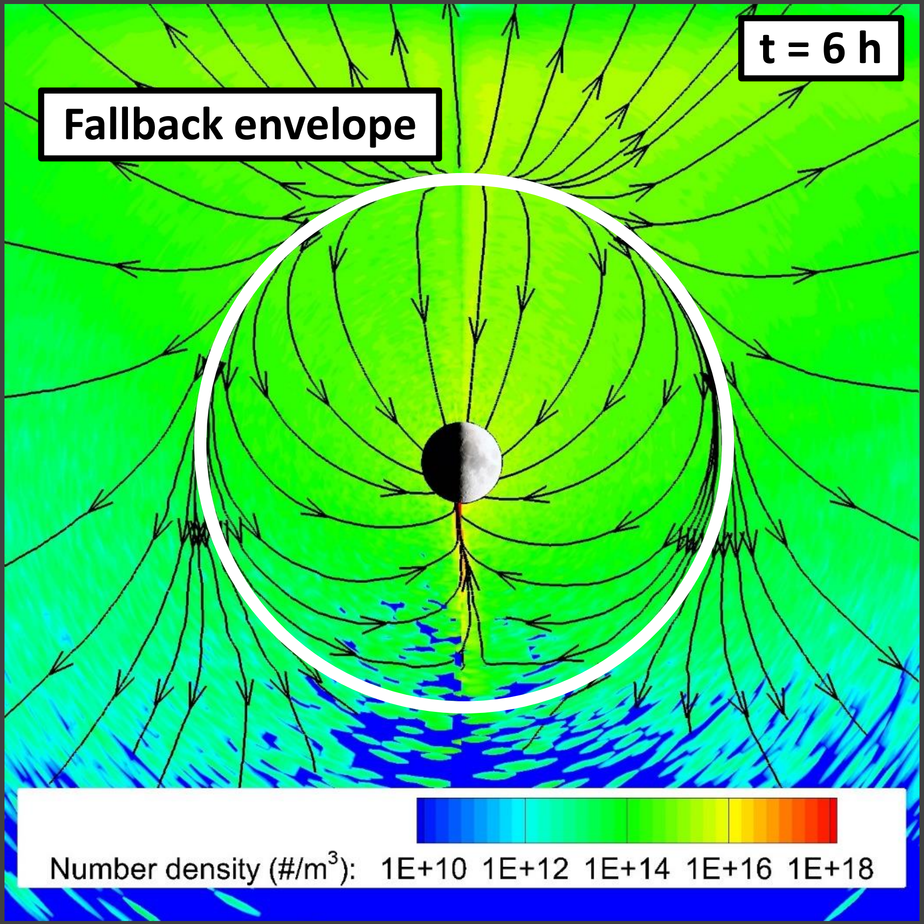

Collisional features slowly dissipate as atmosphere approaches the collisionless limit (few lunar days).

- Initial rapid outward expansion; growth of **expanding, near-spherical "fallback envelope"** can be described analytically.
- **Antipodal shock** channels vapor to surface at impact antipode.
- Low-altitude shock over **day side** hemisphere → vapor is **turned, slowed, compressed** and **heated.**
- Day-side **pressure-driven winds** travel from day to night and out from impact site – directional streaming vs. random walk.
- Dense **day side atmosphere shields low-altitude molecules** from photodestruction.

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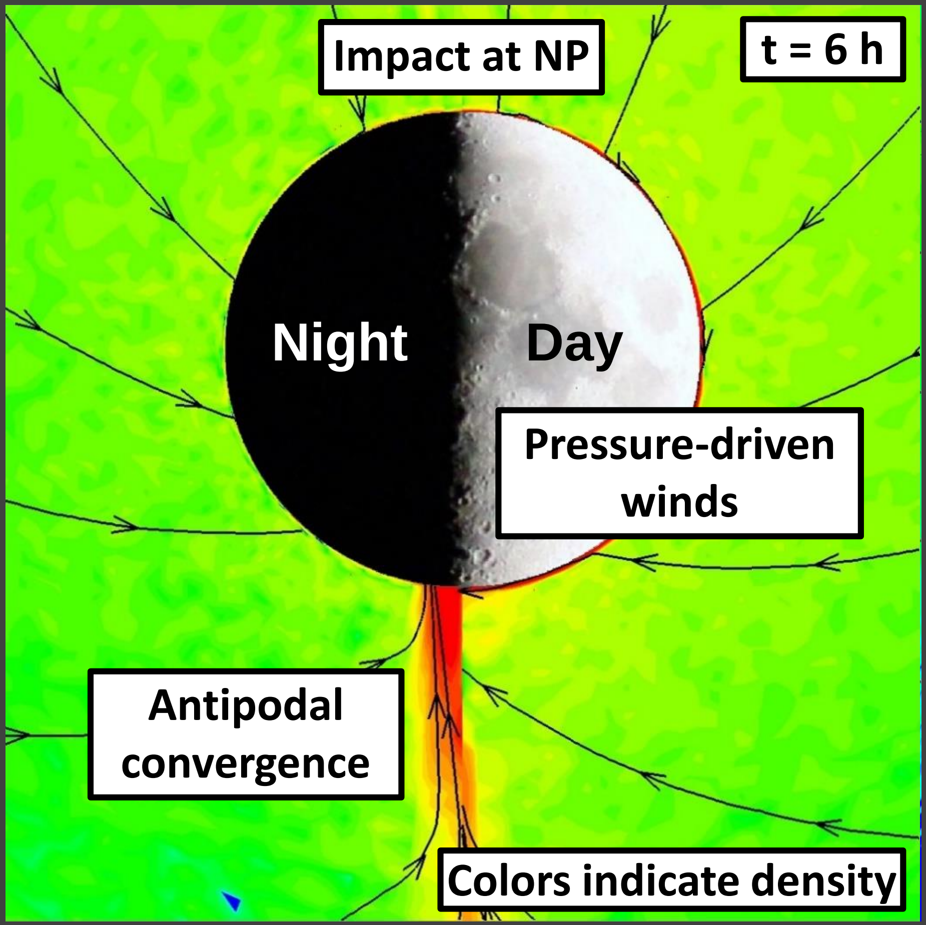

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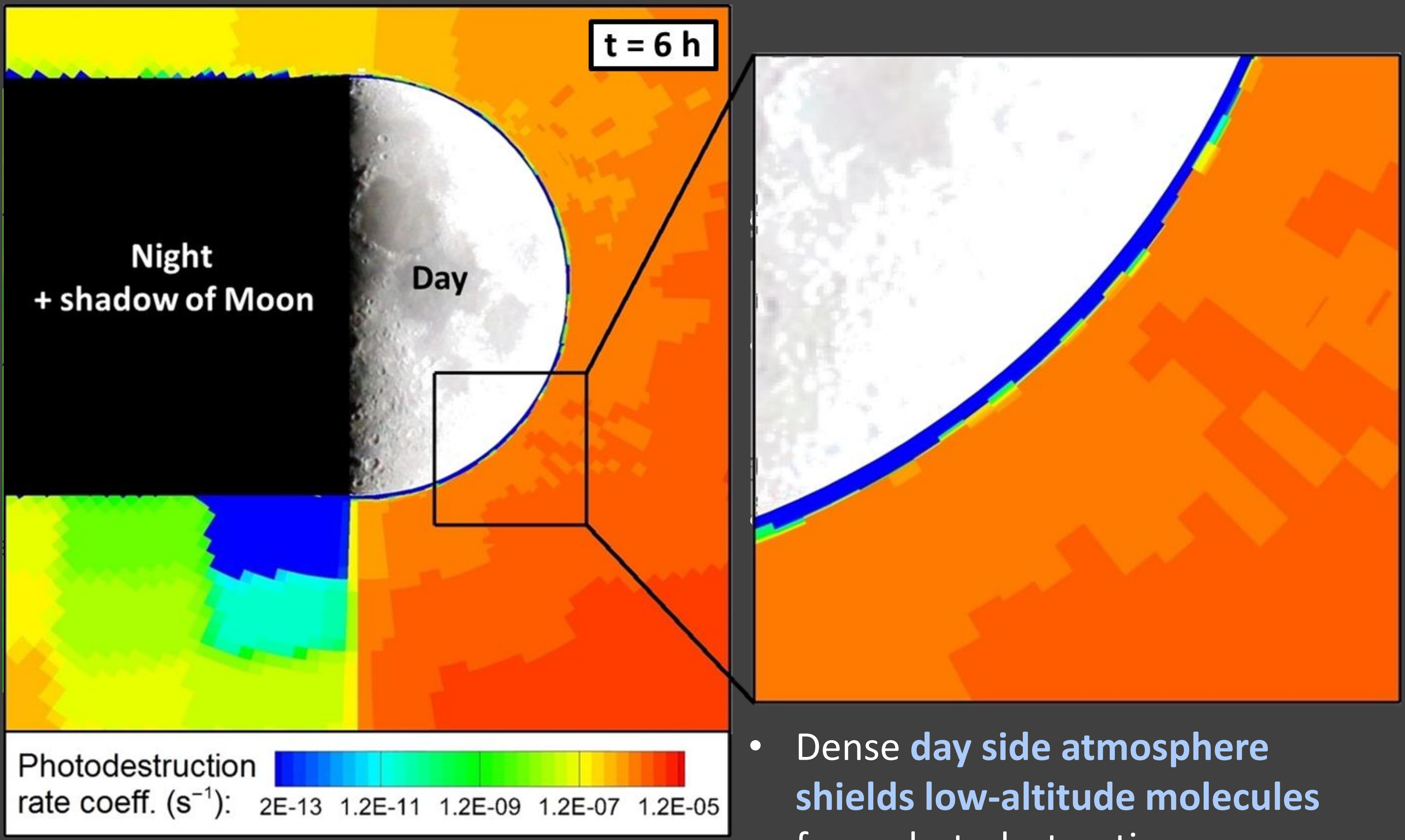

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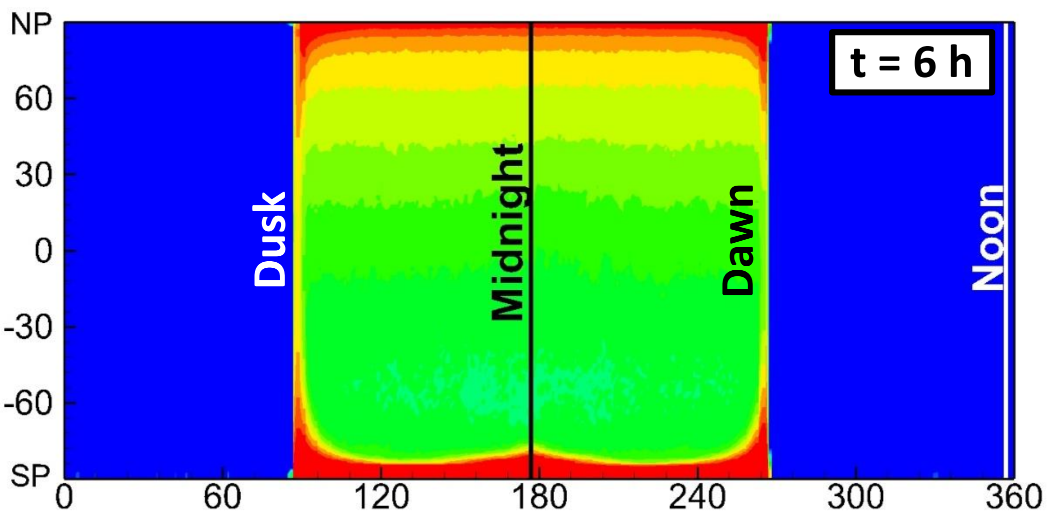
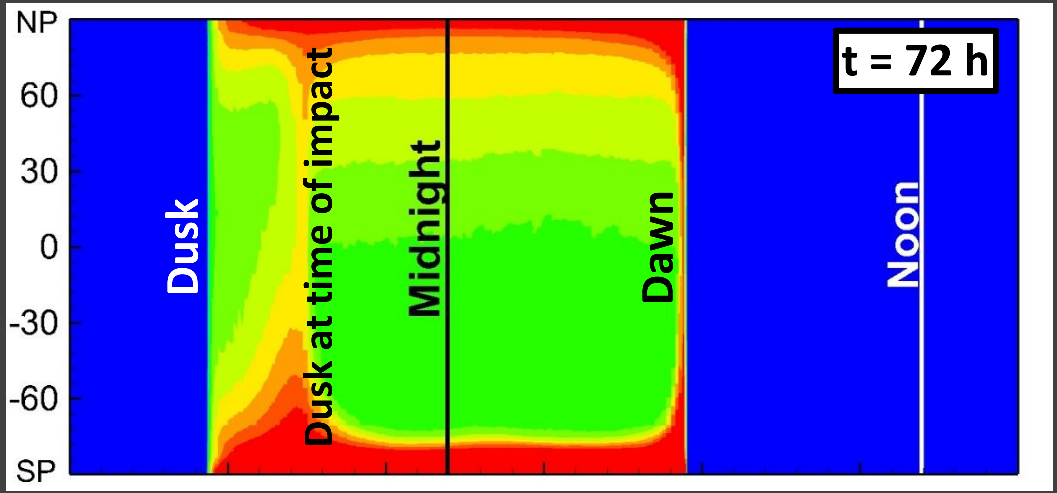
Transient Night-Side Frost Deposits



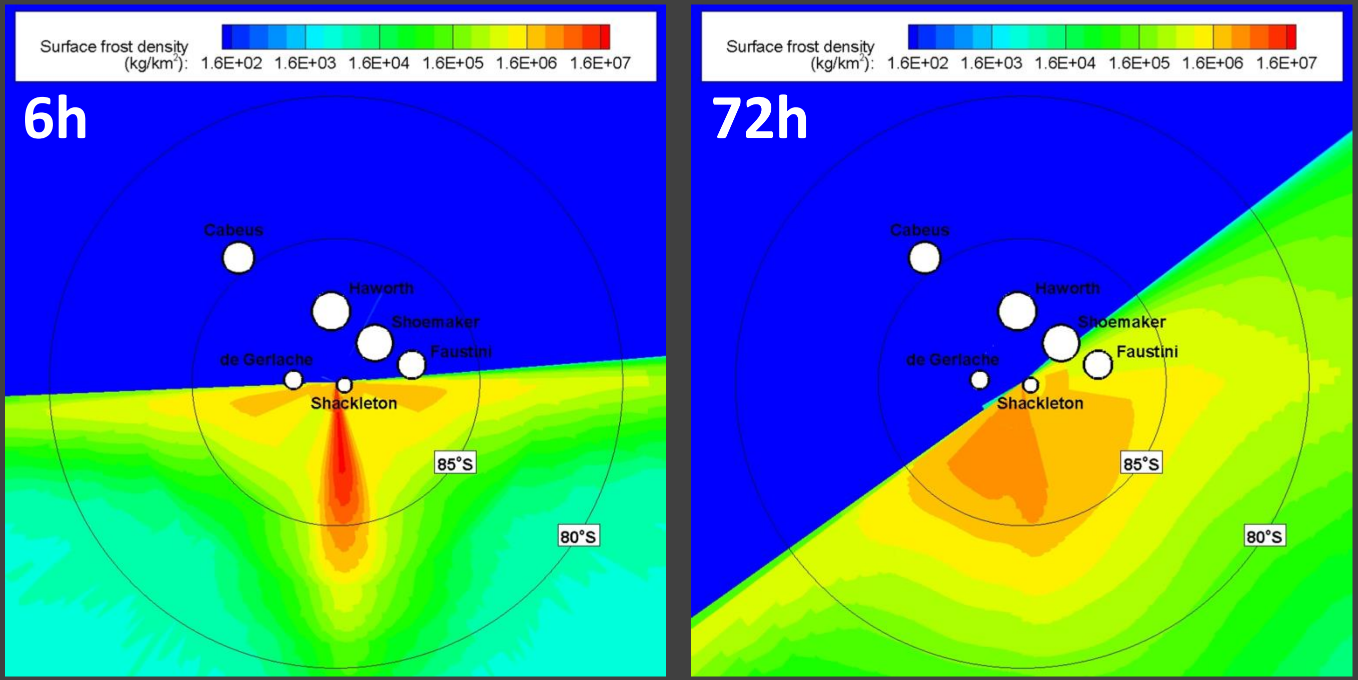


Antipode at South Pole
Colors (this slide + next) indicate surface frost density

- Frost density is highest around the point of impact and the antipode. Suggests **in general, an impact may not result in more cold-trapping at the closer pole** as in Schorghofer (2014).
- **Persistent band of frost at dawn terminator**; temporary band of frost at time-of-impact dusk longitude.
- Antipodal shock dissipates (~48h) as fallback diminishes, but **surface footprint and higher atmospheric density around antipode persist**.

Non-Uniform Cold Trapping

Prem *et al.*



- **Contrast in water abundance** between cold traps **decreases over time**; nature of non-uniformities ***depends on impact location***.
- **Are non-uniformities preserved in the late-term collisionless limit?** Moores (2016) finds preferential cold-trapping at lower latitude cold traps in the collisionless limit (for equatorial impacts).
- Probably depends on longevity of collisional structures + transport.

Non-Uniform Cold Trapping

Cold trap	**Area (km^2)**	**6 hours**		**72 hours**	
		Water captured (kg/km^2)	*Relative magnitude*	*Water captured (kg/km^2)*	*Relative magnitude*
Cabeus	897	4.65×10^5	**<u>1.00</u>**	2.80×10^6	1.17
Faustini	697	6.09×10^5	1.31	2.86×10^6	1.20
de Gerlache	314	8.31×10^5	1.79	3.85×10^6	1.61
Haworth	1295	5.75×10^5	1.24	3.01×10^6	1.26
Shackleton	201	2.20×10^6	**<u>4.73</u>**	6.49×10^6	**<u>2.72</u>**
Shoemaker	1170	6.84×10^5	1.47	2.39×10^6	**<u>1.00</u>**

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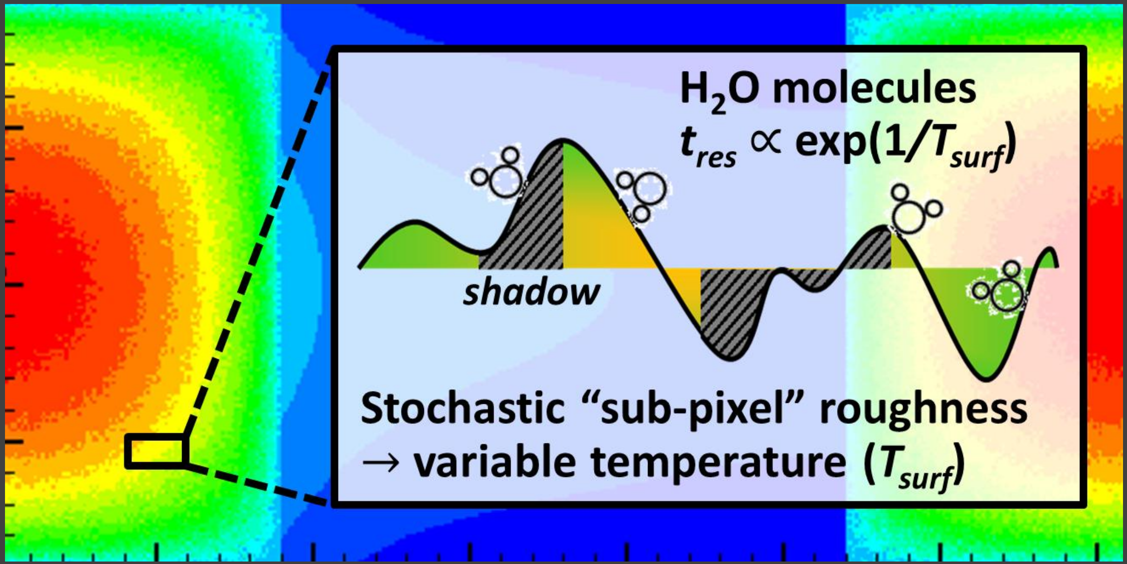
Inferences & Further Questions

- **What can we say about the volatile fallout from a *specific* impact?**
  - **Impact parameters** (angle, velocity etc.) determine amount of vapor that is gravitationally bound – this affects **longevity of atmosphere, degree of shielding from photodestruction, strength of shock structures**.
  - **Change in location of antipode** may cause **different deposition patterns**; interaction of antipodal shock with the day side atmosphere could result in **complex wind patterns**.
- **How do multiple species interact in a collisional atmosphere?**
  - **Non-condensables** (impact-delivered or produced via reactions) could inhibit condensation of water frost, but also strengthen shielding effect.
- **Does the optical depth of the atmosphere affect volatile transport?**
  - **Trapping of thermal radiation** changes **strength of shock structures** – this could affect migration/deposition rates. ***Photon Monte Carlo method recently implemented to model this.***

The Influence of Surface Roughness

- Surface roughness on the Moon → **large temperature variations over very small scales** (Bandfield *et al.*, 2015; Hayne *et al.*, 2013).
- **Surface residence time of volatiles depends strongly on temperature** – even small-scale variations influence volatile transport and cold-trapping at the global scale.



- Recently implemented a **stochastic model for global "sub-pixel" roughness** – slope/time of day used to compute temperature, includes shadowing.
- Strongest influence at low solar incidence angles i.e. at **terminators** (affects late-term migration after impacts and other volatile delivery scenarios) and **near poles** (affects cold-trapping rate).

Summary & Outstanding Questions

Volatile transport in an impact-generated atmosphere is governed by:

- **Gas-gas interactions:**
  - ➡ **Pressure-driven winds vs. random walk** in a collisional atmosphere.
  - ➡ Characteristic shock structures could lead to **non-uniform cold trap deposition and increased antipodal deposition**. **Do short-term non-uniformities in post-impact volatile fallout persist?**
  - ➡ **Impact parameters, location and time of day** affect details of fallout.
  - Photochemistry and interactions between multiple species: **do cold trap deposits mirror impactor in composition?**

➡ **Dissertation research (in progress)**

- **Gas-surface interactions:**
  - ➡ How do **temperature variations due to large-scale topography and small-scale roughness** affect volatile transport?
  - **Quantitative description of volatile-regolith interactions** (e.g. Poston *et al.*, 2015) is important.

- **Gas-radiation interactions:**
  - ➡ **Self-shielding** from solar UV can mitigate photodestruction.
  - ➡ How much does **trapping of thermal radiation** affect volatile transport?