Comets as a source of lunar volatiles: tracking water from impact to permanent shadows

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Background & Motivation

- Several missions, from Clementine (1994) to LRO/LCROSS (2009 - present), have observed signs of lunar water, **particularly in regions of permanent shadow (cold traps) near the poles.**
- The Moon's orientation relative to the Sun, low thermal conductivity of the regolith and the absence of atmosphere → temperatures cold enough to trap a range of species.
- Origins of cold-trapped water?
  - Primordial water in the lunar interior.
  - Interaction between solar wind protons and surface.
  - **Volatile-rich comet/meteorite impacts.**

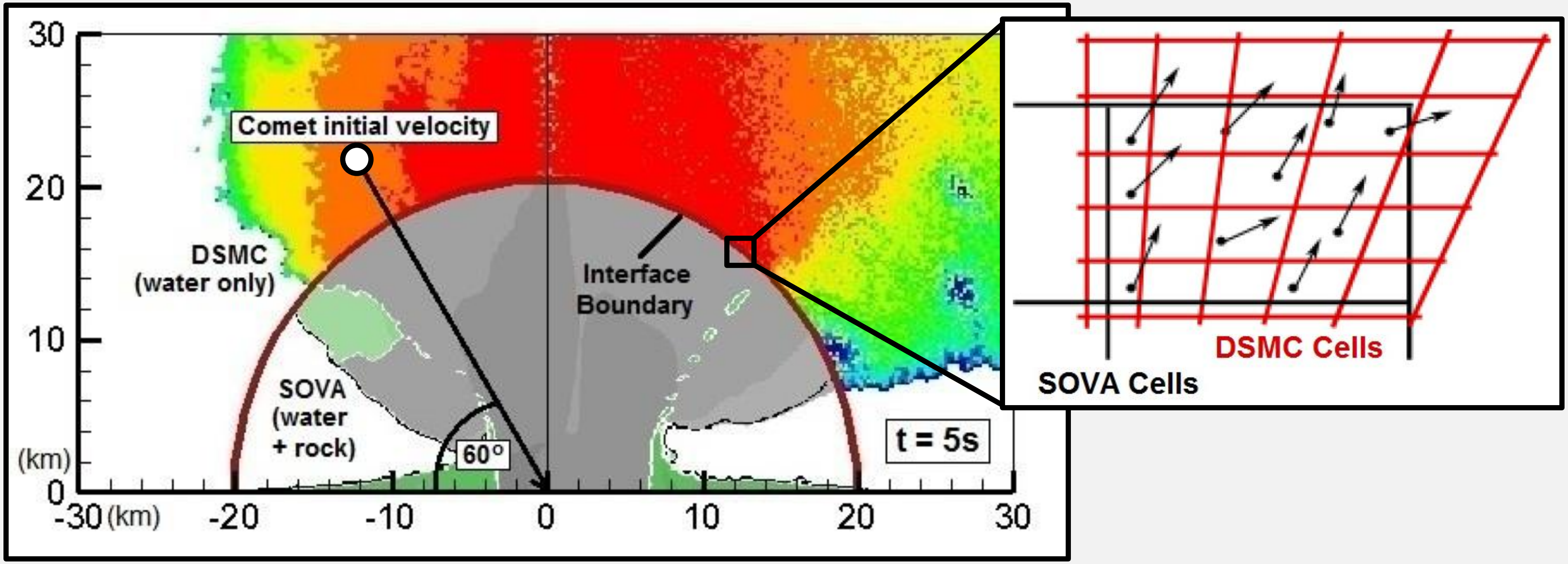
Background & Motivation

- Why study comets?
  - Volatiles appear to be heterogeneously distributed[1] between cold traps - is this a consequence of delivery, as well as post-deposition, mechanisms?
  - Detection of CH_4, NH_3 and other compounds[2] besides H_2O at Cabeus.
  - Isolated sub-surface H signatures[3] at some PSR's ⇒ episodic sources?

- Challenges to modeling the impact-delivery process:
  - Relatively dense (collisional) post-impact atmosphere ⇒ **volatile transport no longer only through collisionless ballistic hops**. What does this mean for the magnitude and spatial distribution of the volatile fallout?
  - Collisional transport ⇒ certain physical processes (e.g. photochemistry, radiation) are affected. How does this affect ice deposition?

[1] Gladstone *et al.*, 2012 (JGR) and Mitrofanov *et al.*, 2010 (Science); [2] Colaprete *et al.*, 2010 (Science); [3] Miller *et al.*, 2014 (Icarus).

Computational Method



- **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, out to 40,000 km from lunar surface, until escape, destruction or capture.
- Comet: 1 km radius, pure H_2O ice. Impact at 60°, 30 km/s.

See Stewart *et al*., 2011 (Icarus), Prem *et al*., 2014 (Icarus, under revision) and ref.s therein.

Computational Method

- Tracking water from impact to permanent shadows:
    - Molecules move under variable gravity, interacting through collisions.
    - Diurnally varying surface temperature (basic map).
    - Temperature-dependent surface residence times for H_2O molecules.
- Loss and capture:
    - UV light is attenuated as it passes through atmosphere ∴ sunward regions are preferentially photo-destroyed, lower layers are shielded.
    - Seven cold traps: 1 at North Pole (1257 km^2), 6 at South Pole (4575 km^2).
- Current simplifications:
    - Only H_2O, in the vapor phase, is modeled.
    - Photo-products (e.g. H, OH) and chemical reactions are not modeled.
    - Simplified treatment of radiative heat transfer - spontaneously emitted radiation escapes, solar infrared absorbed unattenuated, heating of vapor by lunar surface not modeled.

See Stewart *et al*., 2011 (Icarus), Prem *et al*., 2014 (Icarus, under revision) and ref.s therein.

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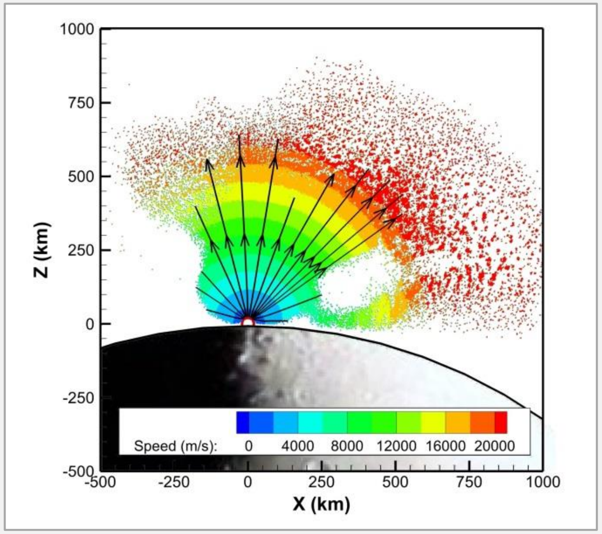
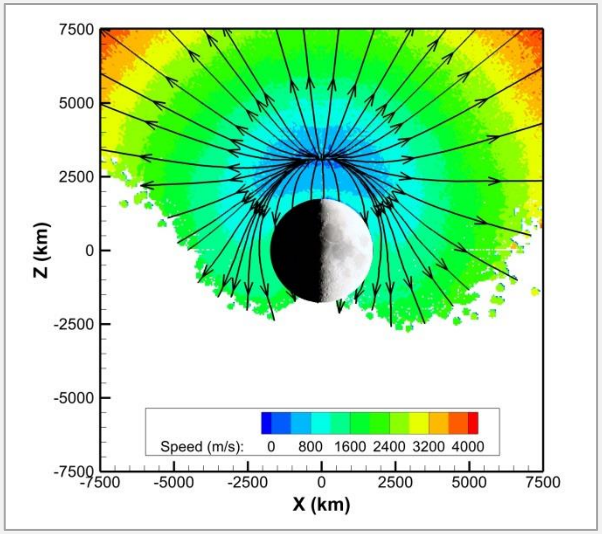
Atmospheric Structure & Evolution

Water vapor cloud (DSMC) at 30 s; x_{max} = 1,000 km



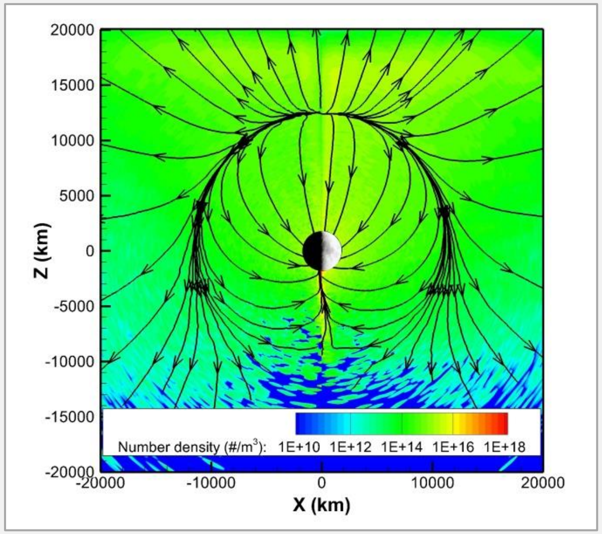
Speed (0 to 20,000 m/s)
Arrows mark flow direction
Viewed in plane of impact

Water vapor cloud (DSMC) at 40 min; x_{max} = 7,500 km



Speed (0 to 4,000 m/s)
Arrows mark flow direction
Viewed in plane of impact

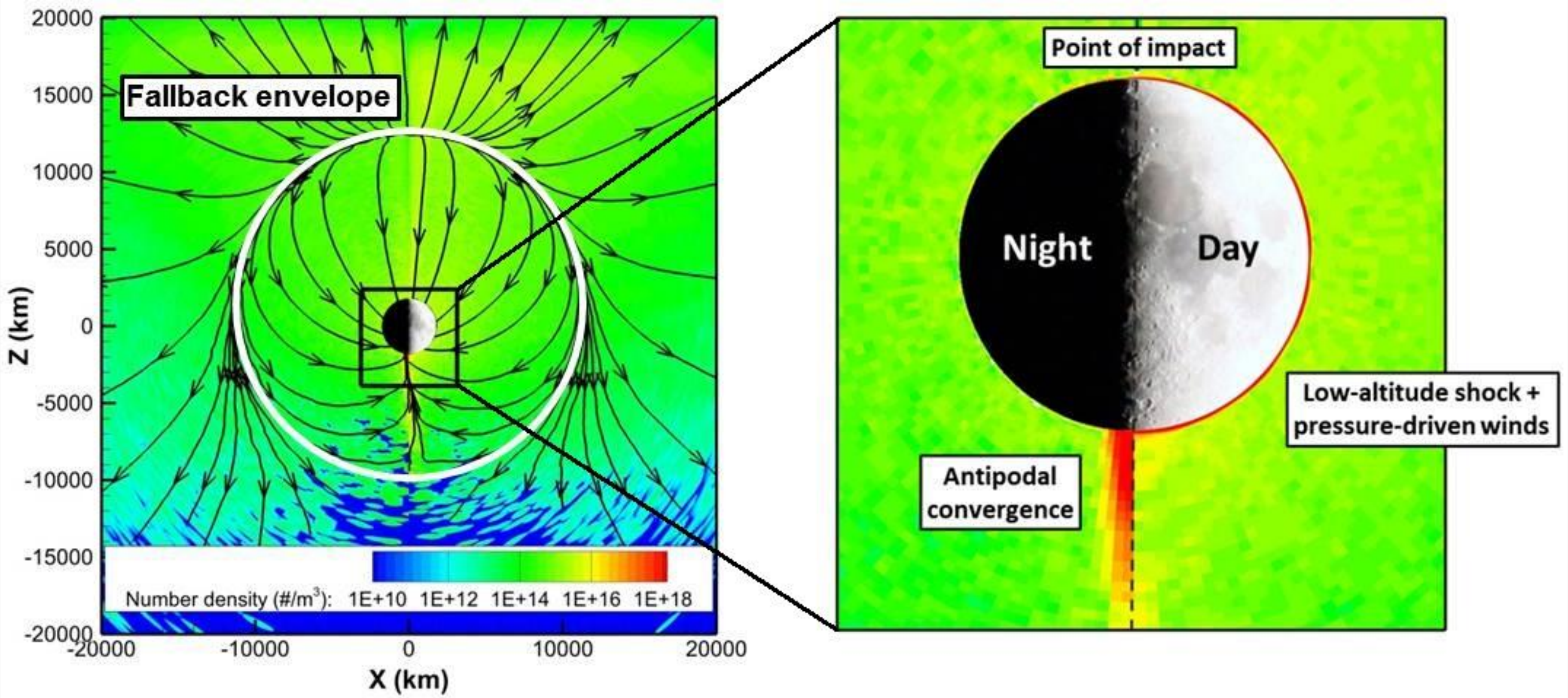
Water vapor cloud (DSMC) at 6 h; x_{max} = 20,000 km



Density (10^{12} to 10^{18} m^{-3})
Arrows mark flow direction
Viewed in plane of impact

- Rapid ($v \geq v_{esc}$) initial outward expansion; within 1 h after impact, gravitationally bound vapor begins to fall back to lunar surface.
- Fallback is bounded by an expanding, ~ spherical fallback envelope.

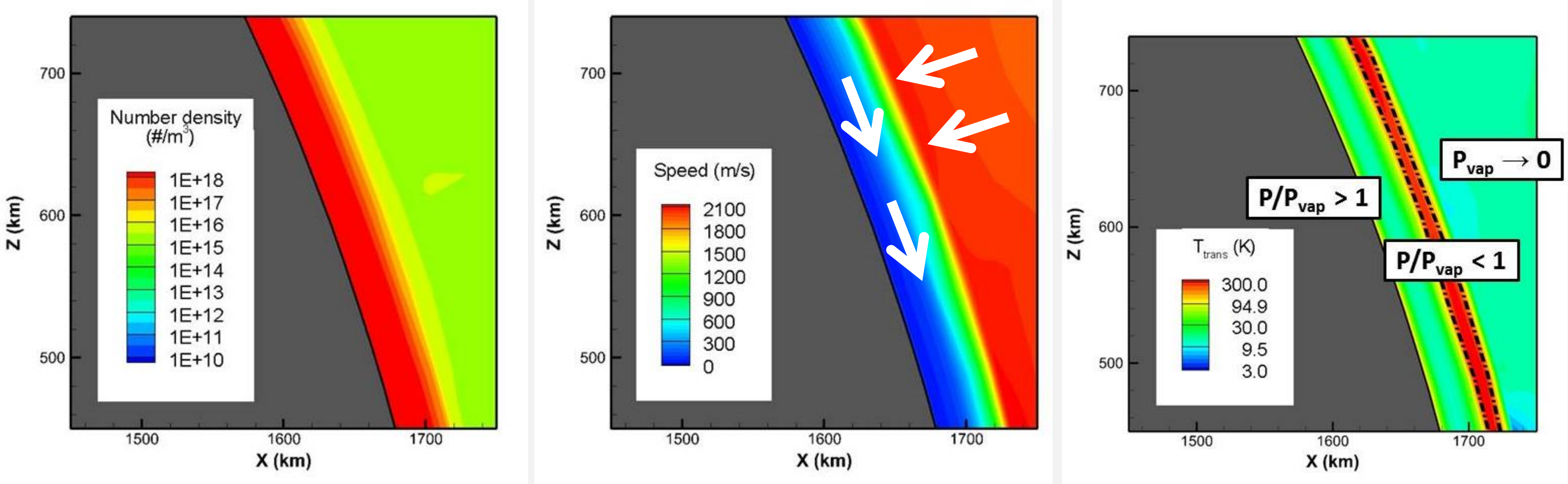
Atmospheric Structure & Evolution



- Collisional nature of the atmosphere gives rise to:
  - **Antipodal shock** - drives a concentrated jet of water vapor down to surface.
  - **Pressure driven day-side winds** → directional streaming vs. random walk; winds travel from day-side to night-side, and north to south.

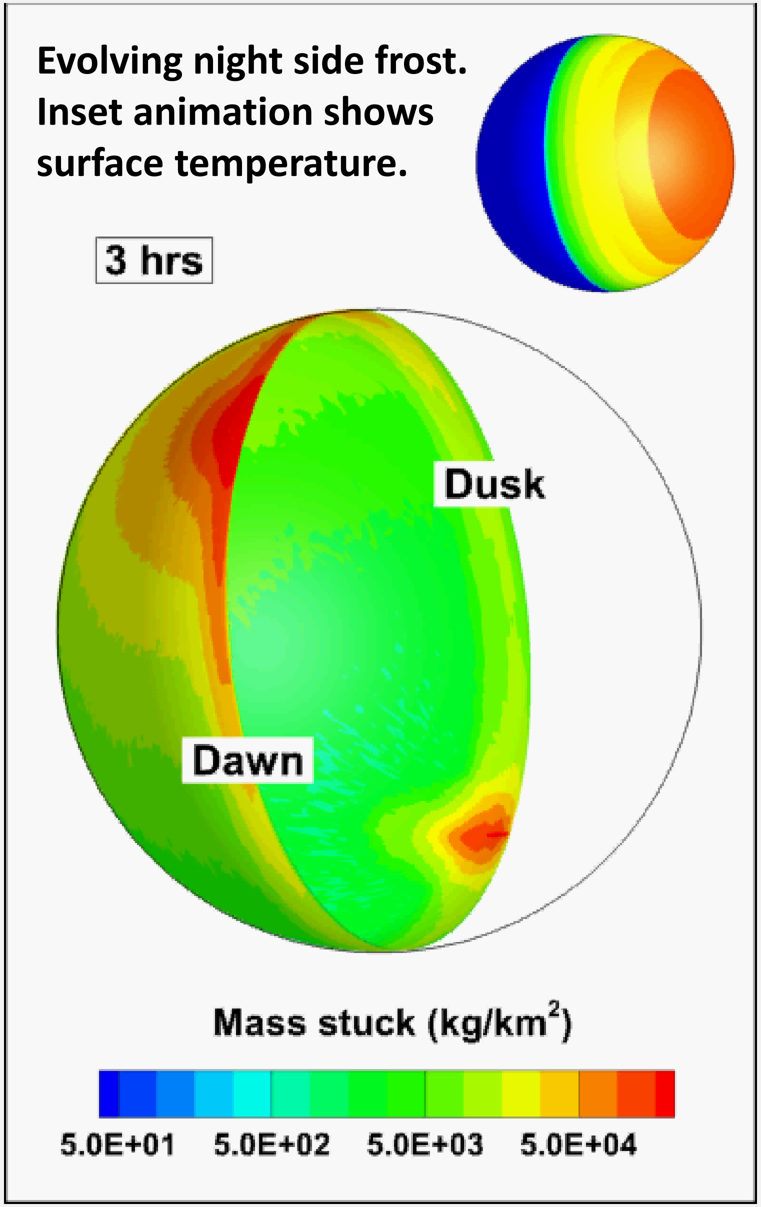
These slowly dissipate as atmosphere approaches the collisionless limit.

Cometary Rainfall?



- Day-side residence times O(1 μs) ⇒ molecules remain aloft. Infalling vapor travels at supersonic speeds, causing a low-altitude surface shock → vapor is **compressed, slowed, turned** and **heated**.
- Cold, dense, supersaturated layer sandwiched between shock- and surface-heated vapor ⇒ **condensation could occur in the presence of dust → day-side mist or precipitation.** *Requires more detailed treatment of radiative heat transfer, gas-dust interactions.*

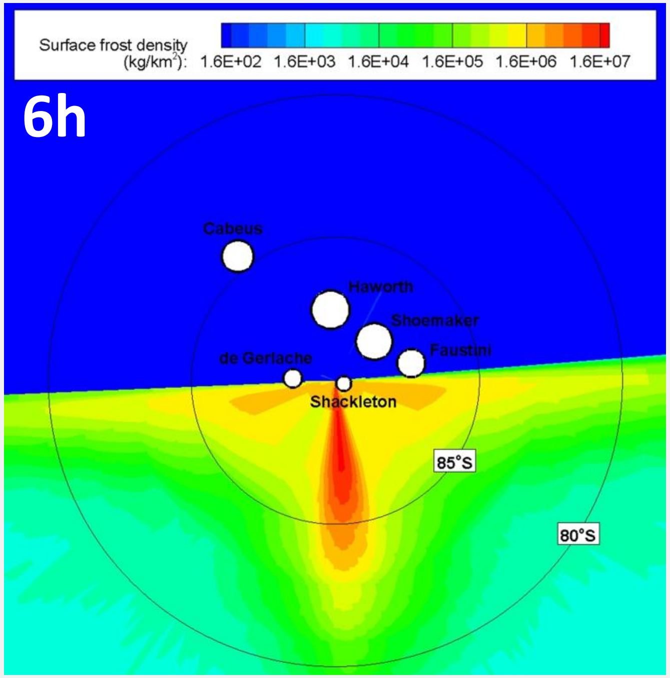
Transient Night-side Frosts

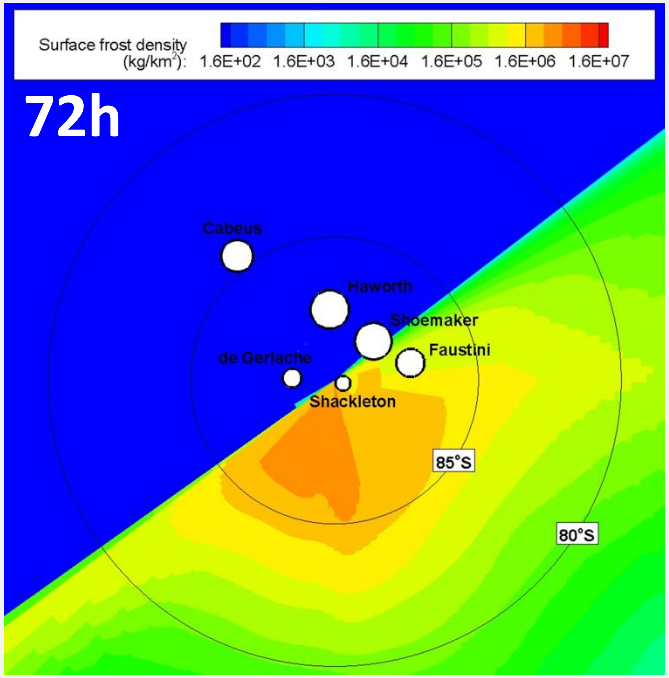


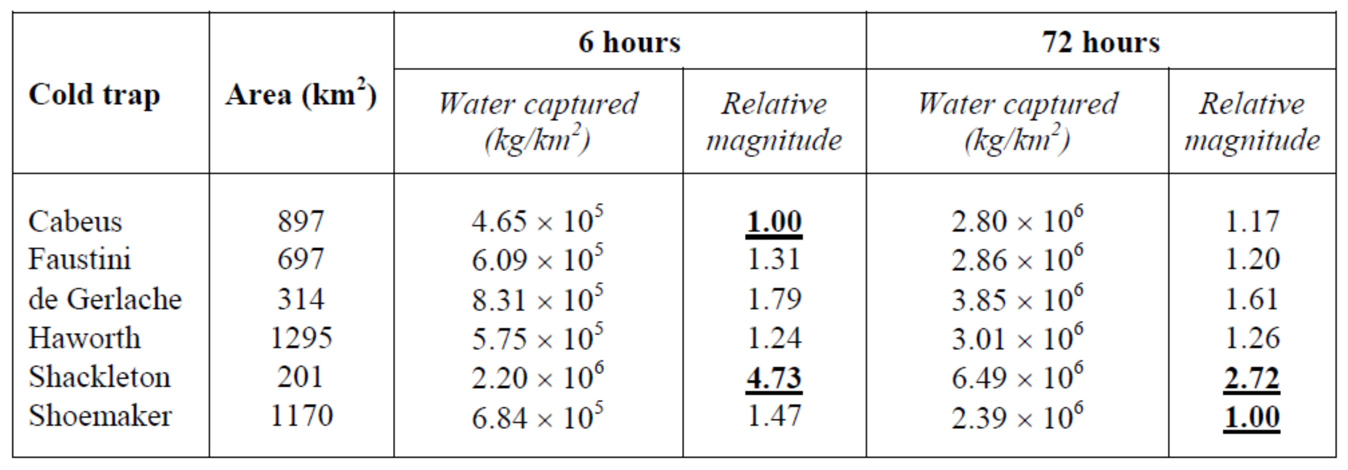
Evolving night side frost. Inset animation shows surface temperature.

- Frost density is highest around the point of impact and the antipode. O(10^5 kg/km^2) ≡ ~0.1 mm water ice.
- Impact at North Pole → **thicker deposits at south polar cold traps**.
- Antipodal shock **footprint remains after shock has dissipated**.
- Dawn terminator: frost sublimating at sunrise pushed back across to the night-side by day-side winds.
- Dusk terminator: band along initial dusk terminator records diminishing intensity of fallback with time.

Non-Uniform Cold Trapping







Cold trap	**Area (km²)**	**6 hours**		**72 hours**	
		Water captured (kg/km²)	*Relative magnitude*	*Water captured (kg/km²)*	*Relative magnitude*
Cabeus	897	4.65×10^5	1.00	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	4.73	6.49×10^6	2.72
Shoemaker	1170	6.84×10^5	1.47	2.39×10^6	1.00

- **Contrast between cold traps ↓ in time** as antipodal shock vanishes and night-side frost migrates.
- Nature of non-uniformities **depends on impact location**.
- **Are non-uniformities preserved** as atmosphere becomes collisionless?

Concluding Thoughts

- Volatile transport in a transient atmosphere is qualitatively different (from collisionless hopping), characterized by **shocks**, **pressure-driven winds** and **markedly non-uniform cold-trapping** - at least in the short term (~ days after impact).
- Other influences and questions:
  - **Impact parameters** determine quantity of gravitationally bound vapor, and thereby shock strengths, atmospheric structure and deposition patterns.
  - **Other species** (impact-delivered or arising from photochemical processes) and **dust** could significantly affect heat transfer, degree of shielding and other aspects of the transport/trapping process e.g. **non-condensable species** could inhibit the condensation of water.
  - How does **surface roughness**, which causes large variations in temperature over small scales, affect volatile migration?
  - How do winds interact with **topography** at specific craters?