Transport of Water in a Transient Impact-generated Lunar Atmosphere

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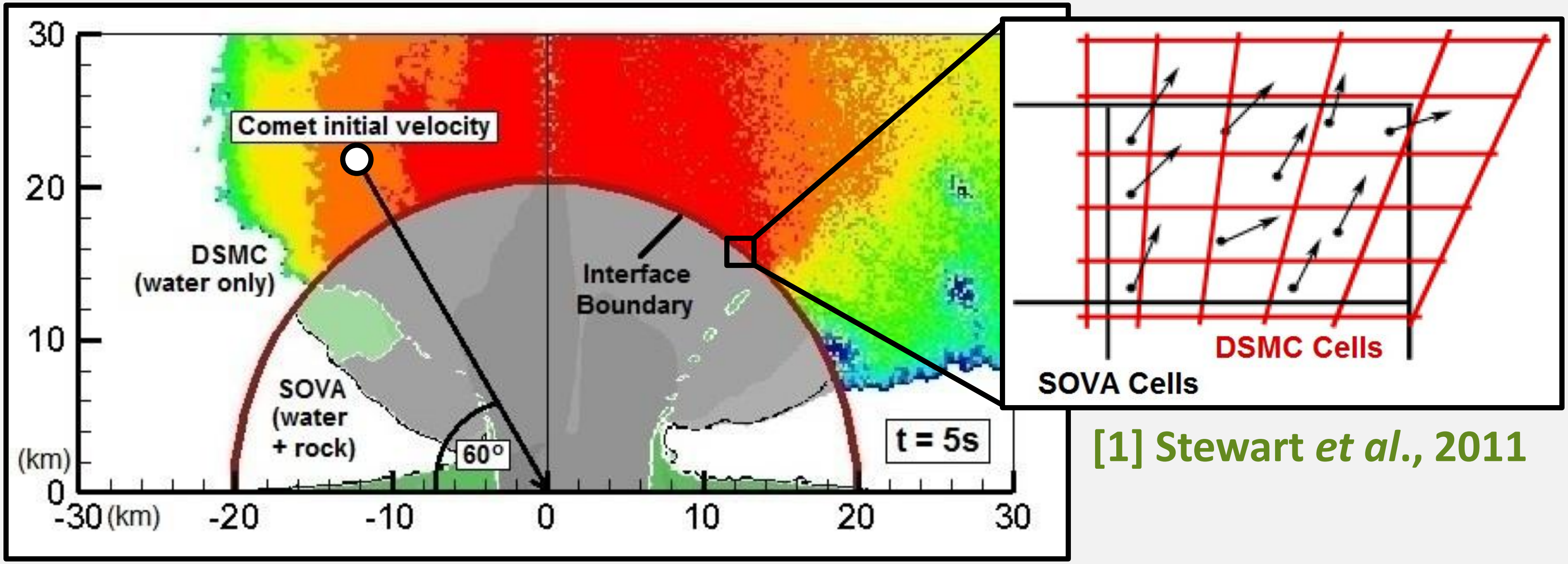
Motivation

- **Lunar ice - why study comet impacts as a source of water in permanently shadowed regions (cold traps)?**
  - 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.
  - *Only* sub-surface signatures[3] at some cold traps ⇒ episodic sources.
- **Challenges to modeling the impact-delivery process:**
  - Relatively dense (collisional) post-impact atmosphere ⇒ **volatile transport no longer through only 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) become more important. 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).

Numerical Method



[1] Stewart *et al.*, 2011

- **SOVA hydrocode** models impact/vaporization of a comet (r = 1 km) composed of pure water ice. **DSMC, a particle-based technique,** then tracks water vapor until escape, destruction or capture[1].
- Simplifications in baseline simulations:
  - Optically thin ⇒ no attenuation of sunlight or re-absorption of radiation.
  - Photo-products (e.g. H, OH) and chemical reactions are not modeled.
  - Radiative heating of gas by lunar surface is neglected.

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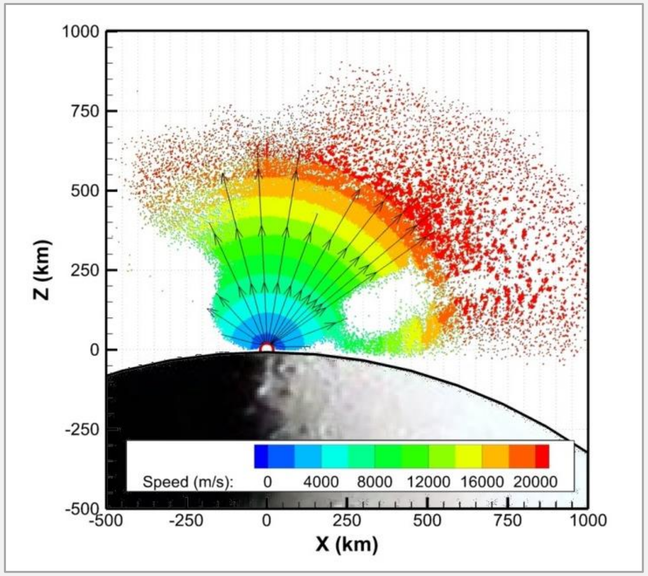
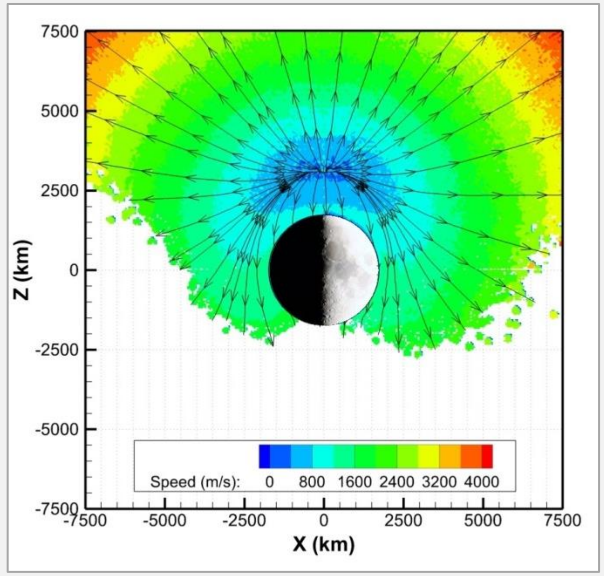
Gas Dynamics in a Transient Atmosphere

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



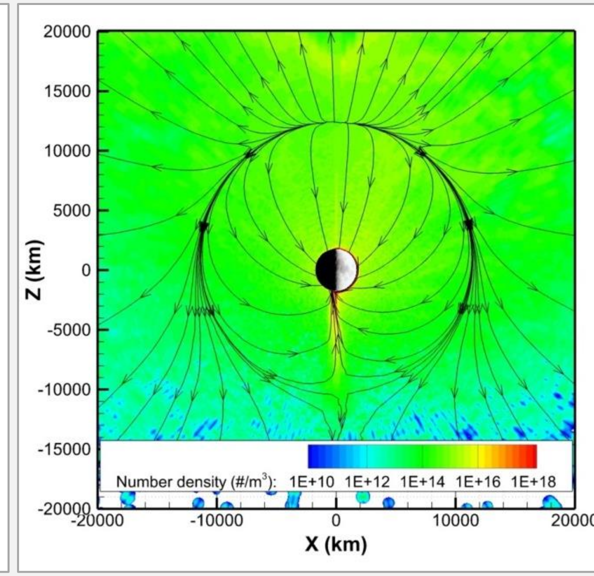
Colors represent speed; Scale: 0 to 20,000 m/s; Streamlines superimposed.

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



Colors represent speed; Scale: 0 to 4,000 m/s; Streamlines superimposed.

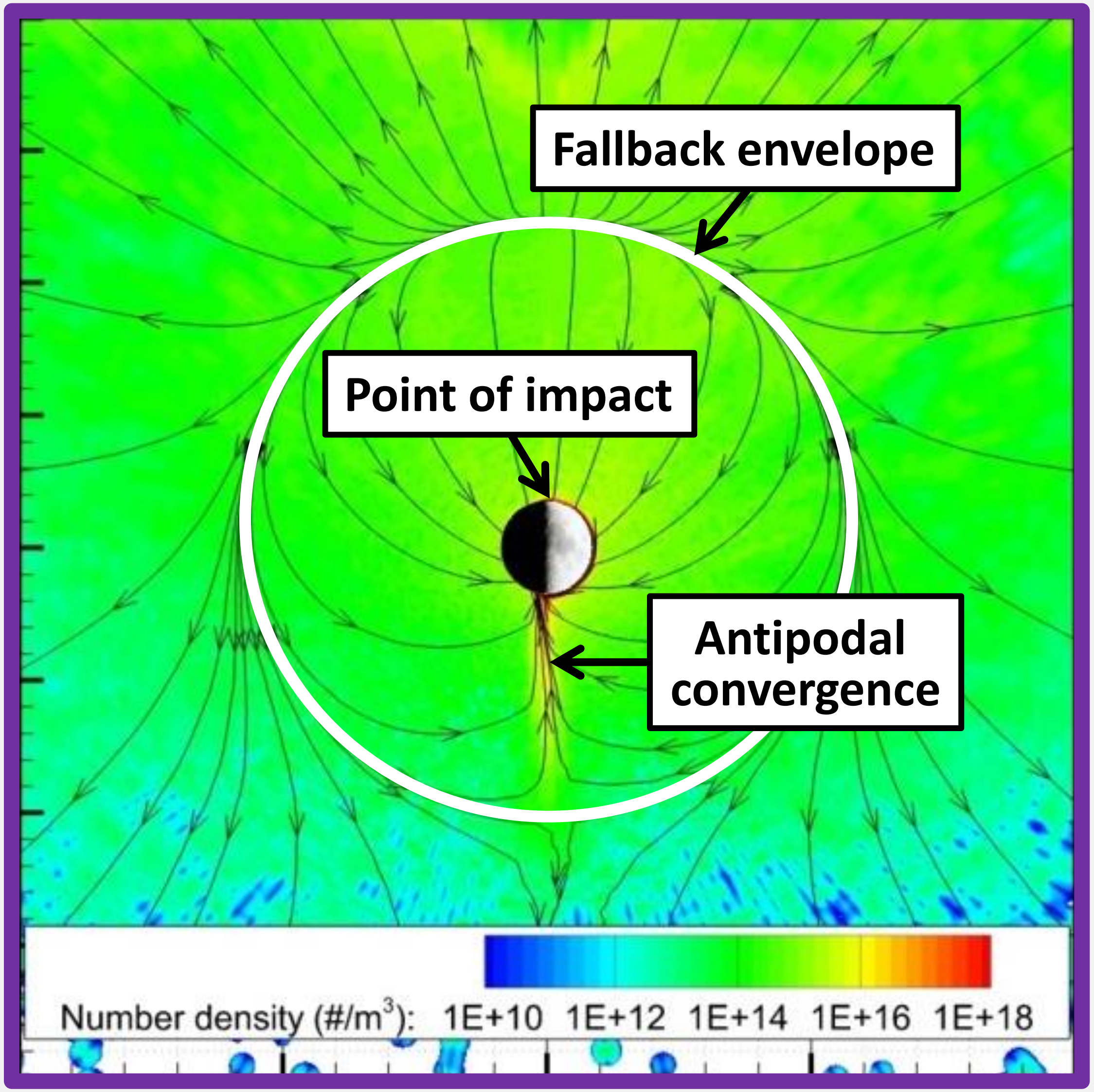
Water vapor cloud (DSMC) at 6 h; x_{max} = 20,000 km



Colors represent density; Scale: 10^{12} to 10^{18} m^{-3}; Streamlines superimposed.

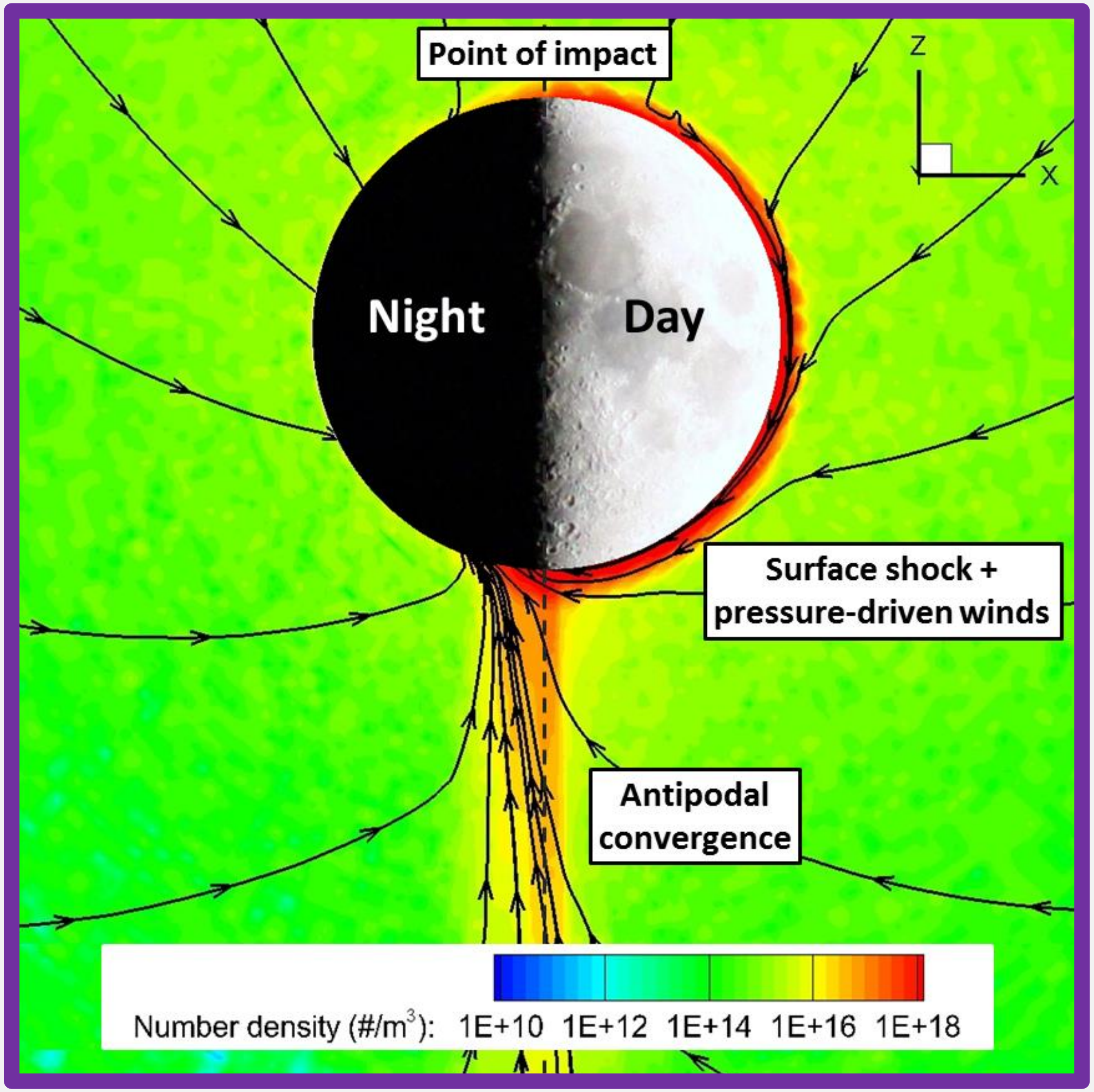
- Rapid ($v \geq v_{esc}$) initial outward expansion; within 1 h after impact, gravitationally bound vapor begins to fall back to lunar surface.
- Fallback is bounded by an expanding, ~ spherical fallback envelope.

Gas Dynamics in a Transient Atmosphere



- Antipodal convergence leaves a surface footprint on the night side surface (for this impact location) where frost density ↓ by 10 x across ~200 km.
- Pressure-driven day side winds lead to directional streaming (vs. molecular random walk) to night side and/or cold traps.
- As atmosphere gradually approaches collisionless limit, shock structures and winds dissipate.

Gas Dynamics in a Transient Atmosphere



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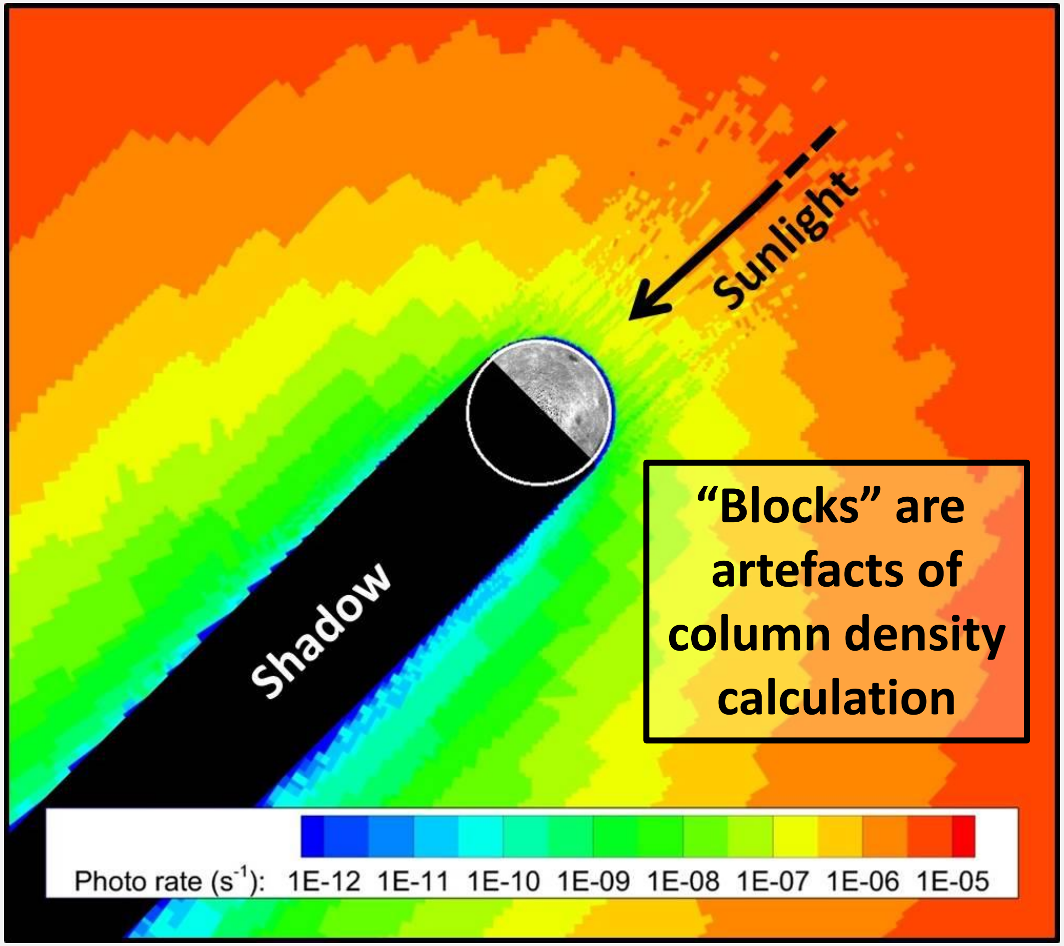
Shielding from Photodestruction

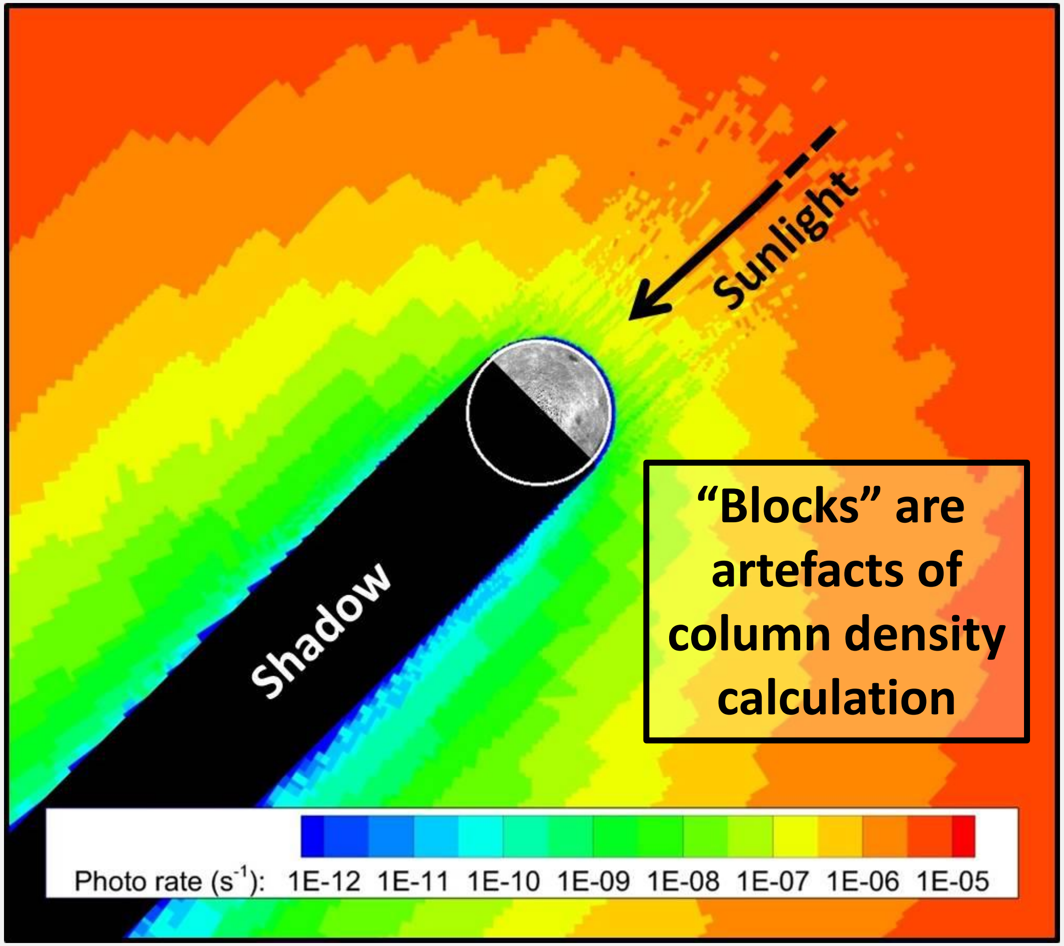


Cross-section of vapor cloud in equatorial plane, 6 h after impact, illuminated as marked. Unattenuated photo rate $\simeq 1.2 \times 10^{-5}$ s^{-1}

- Photodestruction is the primary loss process.
- In an optically thin case, shielding is negligible - not the case after an impact.
- Implementation:

- Column density in direction of sunlight is calculated (on a coarser grid) at regular intervals, thus accounting for motion of Sun and changes in atmospheric structure.
- Photodestruction rate (from Crovisier, 1989) is attenuated accordingly.

Shielding from Photodestruction



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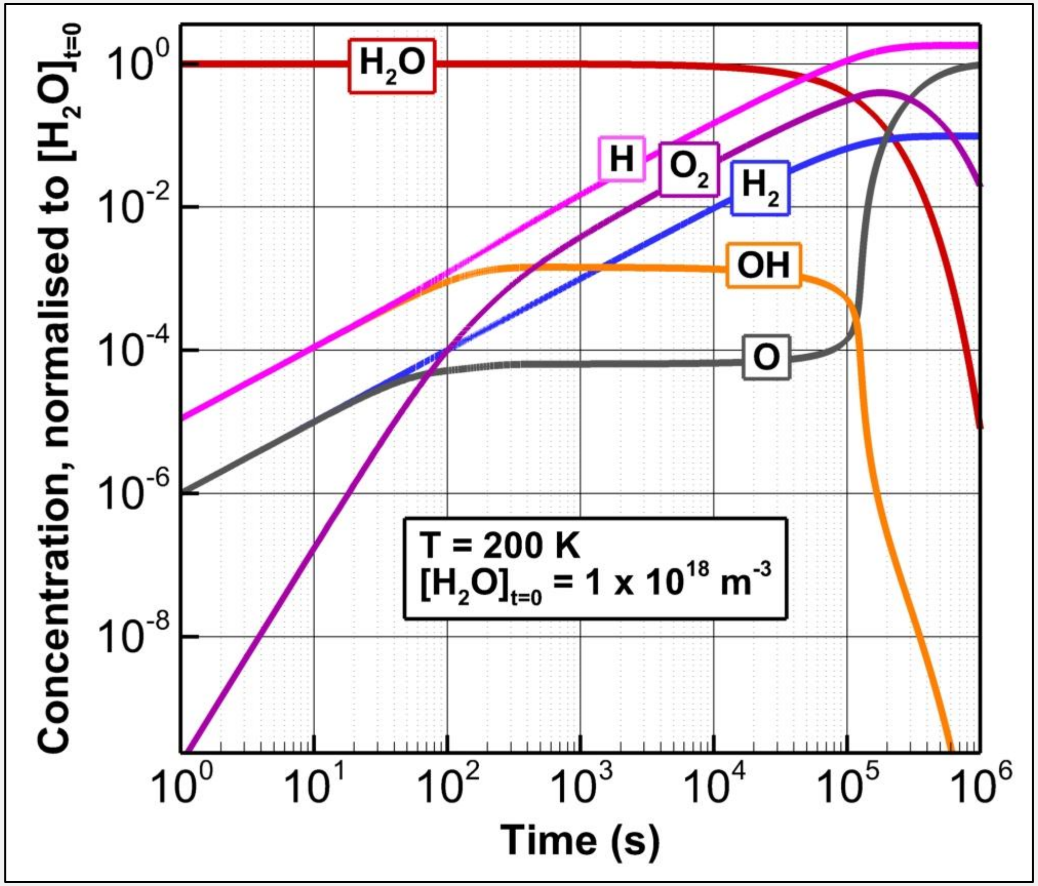
- Taking shielding into consideration, the overall destruction rate ↓ ~30 x over the time interval 1 to 3 h after impact.
- Long-term influence of shielding on ice deposition (from impact till vapor cloud becomes optically thin) - to be studied.

Photo-products and Chemistry



- Do photo-products matter? Simple 0D model can offer insights (similar approach to that of Berezhnoi & Klumov, 2002).
- Actual post-impact scenario: 3D, non-equilibrium rates, lighter species may escape - calls for detailed modeling.

$H_2O + h\nu \rightarrow H_2 + O$; $H_2O + h\nu \rightarrow H + OH$;

$OH + OH \rightarrow H_2O + O$; $OH + h\nu \rightarrow O + H$;

$O_2 + h\nu \rightarrow O + O$; $OH + O \rightarrow H + O_2$

Rate expressions from Huebner (1992), Tsang & Hampson (1986) and Giguere & Huebner (1978).

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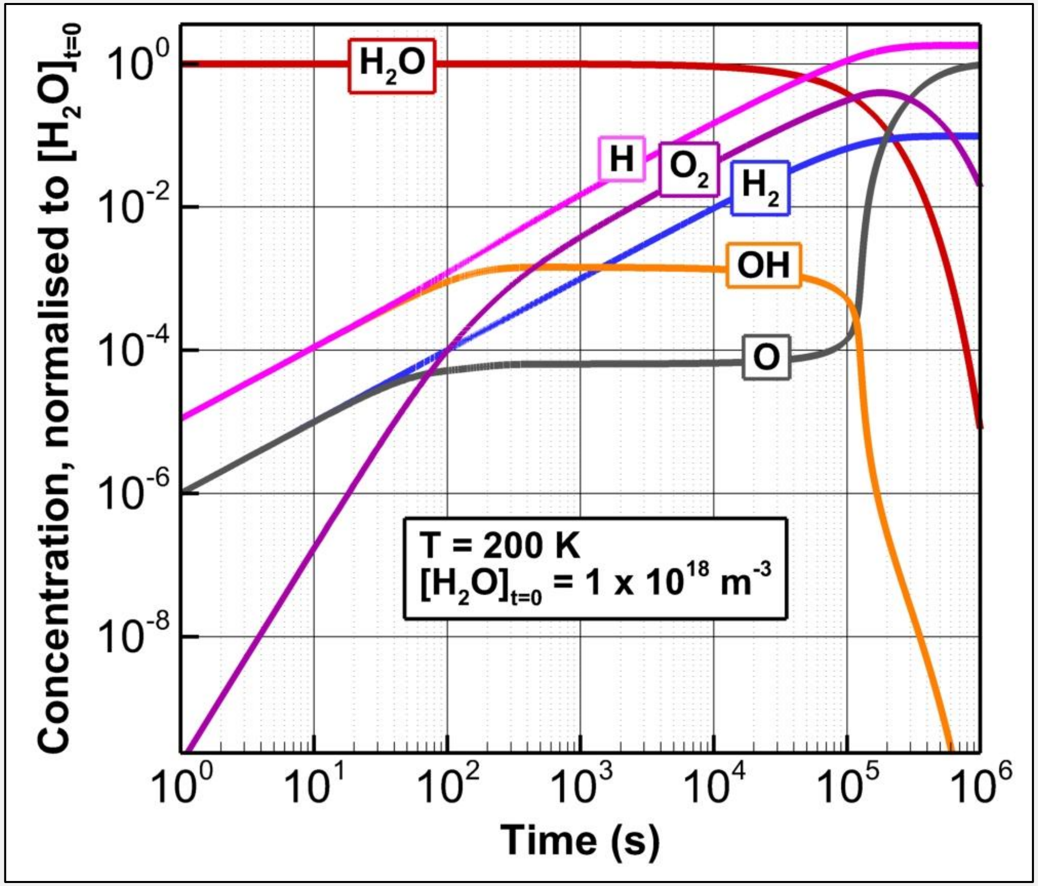

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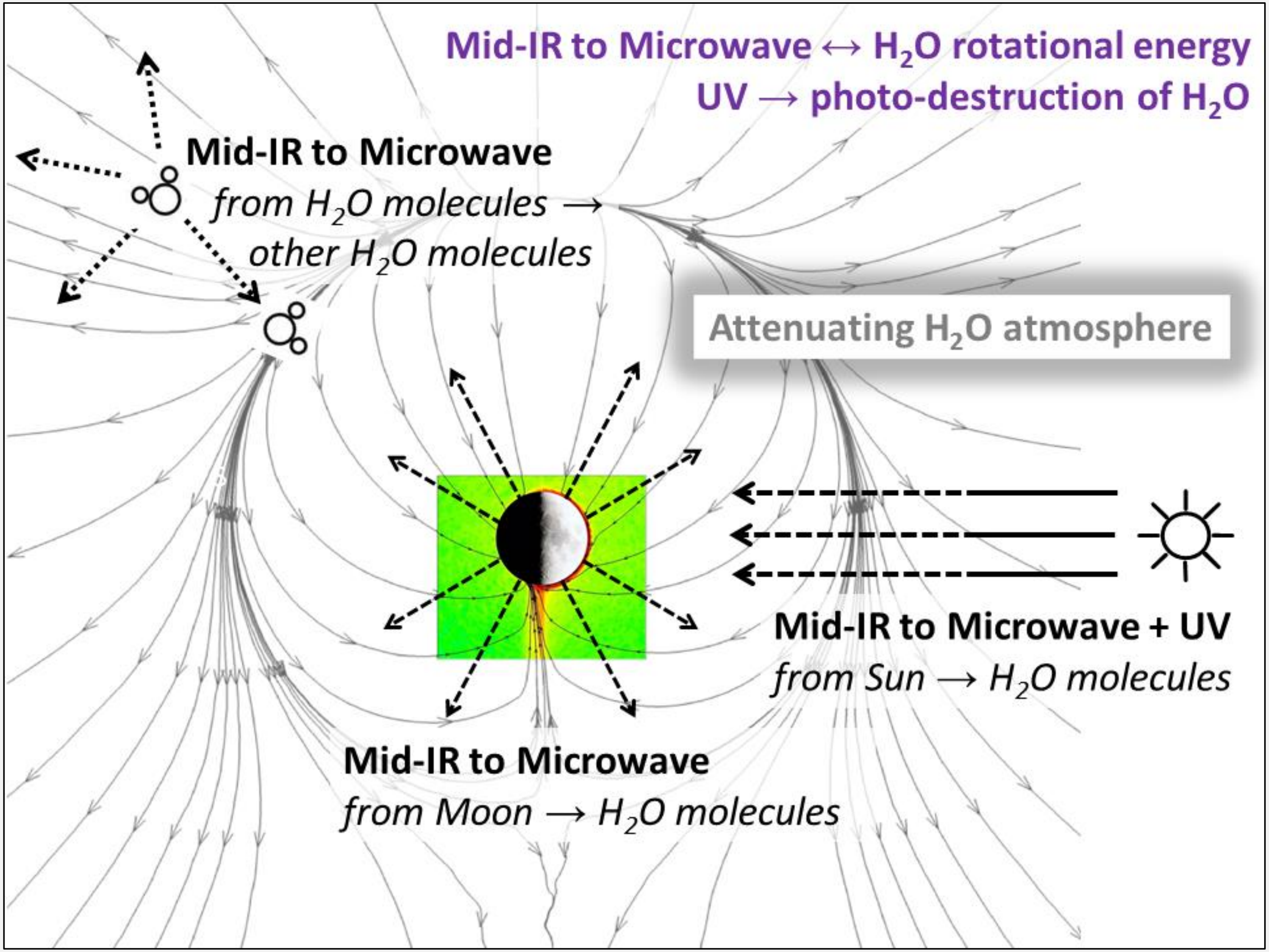
- **Key implications:**
  - Recombination reactions can slow the H_2O loss rate.
  - Non-condensables (like O_2) can inhibit condensation (as seen in Moore *et* al., 2009; mentioned by Arnold, 1979).

Radiative Energy Transfer



Radiative Energy Transfer

- **Implementation:**

- Solar IR: Attenuation handled by extending shielding algorithm.
- Radiation within vapor cloud: Amount of energy spontaneously emitted as molecules within a cell cool can be calculated analytically (Crovisier, 1984). Monte Carlo method (e.g. Sohn *et* al., 2012) used to propagate "bundles" of energy through gas until complete absorption. **(Validation in progress.)**
- IR radiation from lunar surface: Monte Carlo method can be extended to handle surface emission. **(Work in progress.)**

- **Preliminary observations:**

- Reabsorption of radiation originating within vapor cloud increases gas temperature at all altitudes → affects strength of shock structures.
- This in turn can change day-side wind speeds/patterns and the surface footprint of the antipodal shock.

Summary and Future Work

- **Volatile-rich impactors can generate a relatively thick transient lunar atmosphere. While this atmosphere is collisional:**
  - Volatile transport occurs through pressure-driven winds.
  - Antipodal convergence of vapor can leave a discernable surface footprint.
- **Physical processes that are usually negligible in the collisionless lunar exosphere, become important after an impact:**
  - Shielding allows a greater fraction of water to migrate to cold traps.
  - Photochemistry → competing effects (recombination vs. non-condensables).
  - Radiative energy transfer influences atmospheric structure, and thereby, deposition patterns.
- **Future work and further questions:**
  - Complete implementation of DSMC radiation and chemistry models.
  - How do the radiation field and chemistry change when we consider a comet composed of dust, and volatile species other than H_2O?
  - Modeling surface roughness and topography could provide further insight into deposition at individual cold traps.