PDF version of talk presented at the DPS Annual Meeting, Oct 2012.

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Cometary Delivery of Lunar Water:
Transient Atmosphere Dynamics and Deposition Patterns

Parvathy Prem[1], N. A. Artemieva[3], E. Pierazzo[3], B. D. Stewart[1], D. B. Goldstein[1], P. L. Varghese[1], L. M. Trafton[2]

[1]The University of Texas at Austin (Department of Aerospace Engineering)
[2]The University of Texas at Austin (Department of Astronomy)
[3]Planetary Science Institute

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Introduction

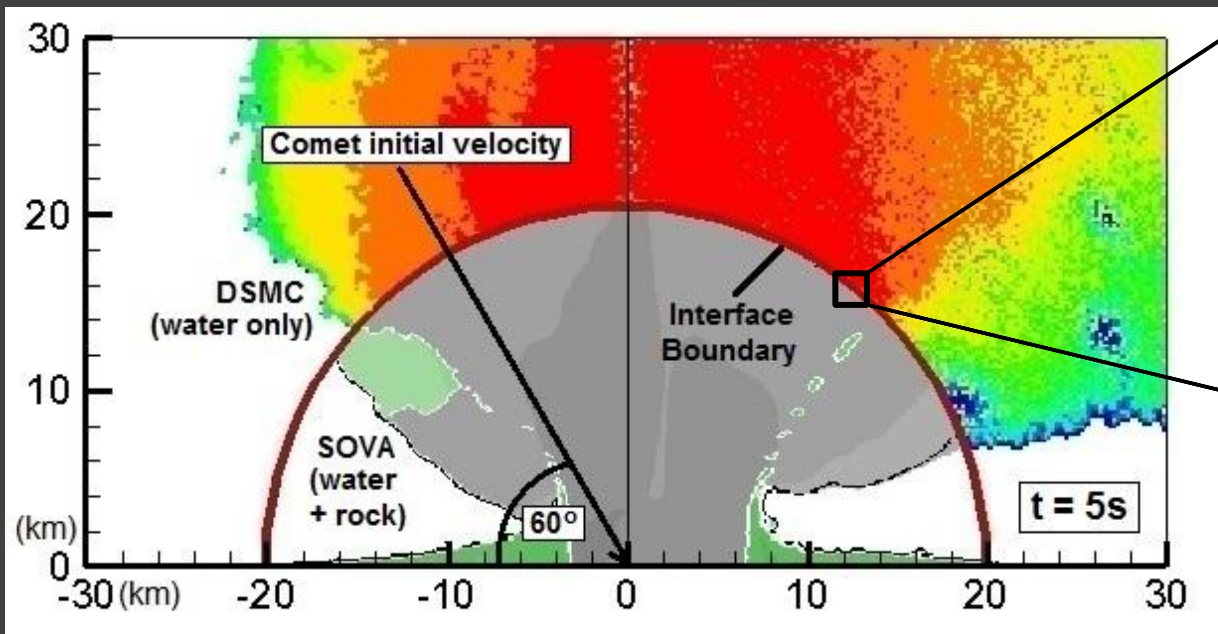
- Observations by several missions- from Clementine (1994) and Lunar Prospector (1998) to LCROSS (2010) and others- suggest presence of lunar water, particularly in craters with regions of permanent shadow (cold traps) at the poles.
- Origins of lunar water?
  - Primordial water in the lunar interior.
  - Interaction of surface minerals with solar wind protons.
  - Volatile-rich comet/meteorite impacts.
- Questions:
  - How much water could comets have contributed to the lunar volatile inventory and deposited at cold traps?
  - How do impact parameters (angle, speed, location etc.) influence the quantity of cometary water retained?
  - Given a site indicative of a comet impact, what can we say about the associated volatile fallout?

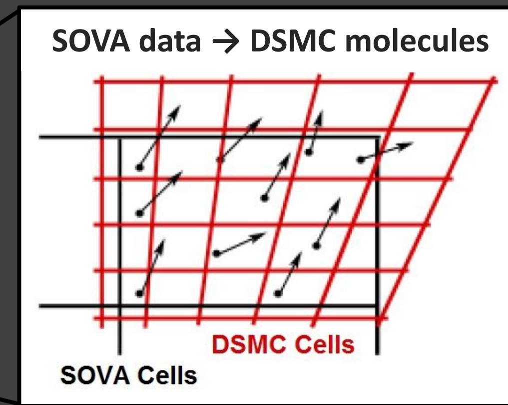
Approach & Computational Method

- Comet: pure H_2O ice, 1 km radius; target: dunite.
- Varying impact angle (45^o, 60^o), speed (30 km/s, 20 km/s).
- Hybrid SOVA-DSMC method. DSMC code includes:
  - Surface temperature, dependent on distance from sub-solar point[1] and Moon's rotation.
  - 7 cold traps[2]: 1 NP (1257 km^2) + 6 SP (4575 km^2).
  - Temperature-dependent residence times[3] for H_2O on H_2O ice matrix[4].
  - Variable gravity.
  - Photodestruction probability[5].

[1]Butler, 1997; [2]Elphic *et al.*, 2007 and Noda *et al.*, 2008; [3]Langmuir (1916) and Frenkel (1924); [4]Sandford and Allamandola, 1993; [5]Huebner, 1992

Approach & Computational Method

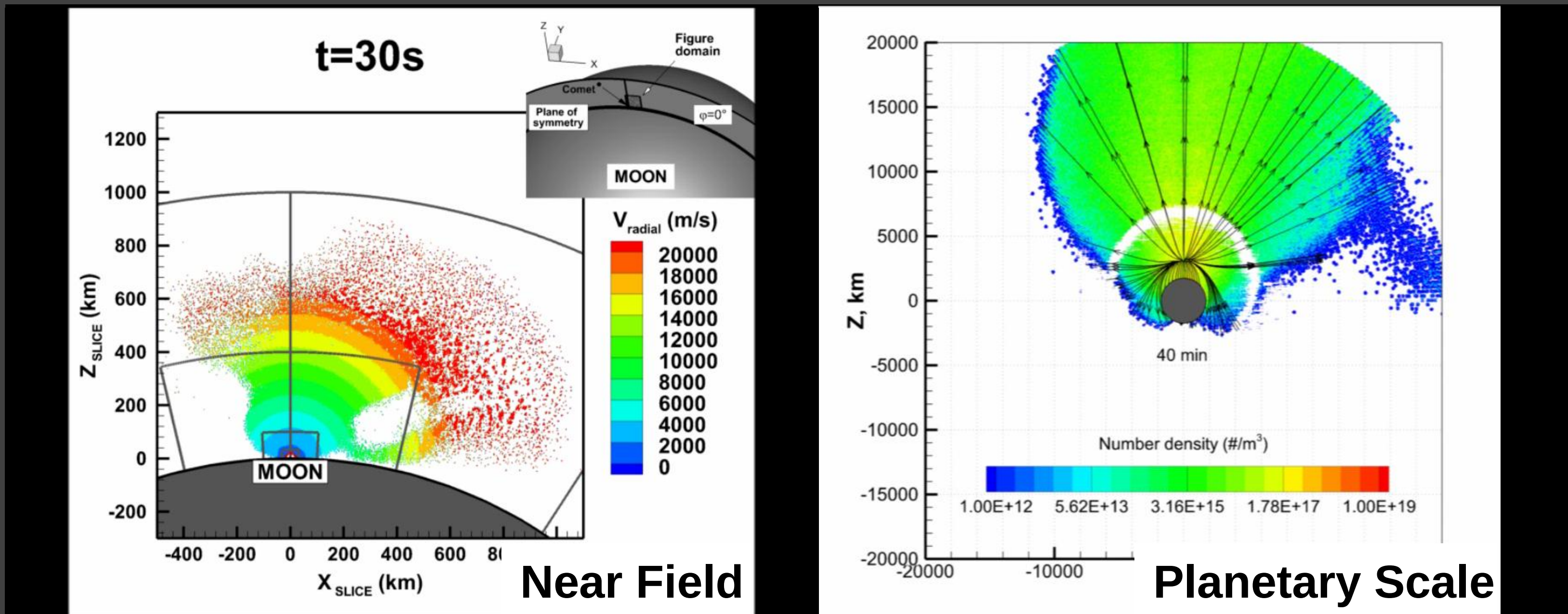




Supersonic speeds ∴ only SOVA → DSMC coupling, none vice versa.

- **SOVA**: Simulates impact and hydrodynamic flow of relatively dense vaporized/molten comet and target material.
- **DSMC** (Direct Simulation Monte Carlo):
  - Simulates water vapor only. Particle based method- create, move, index, collide and sample ‘molecules’ (Bird, 1994).
  - Transition to rarefied but collisional expansion into vacuum.
  - DSMC is highly parallelizable.

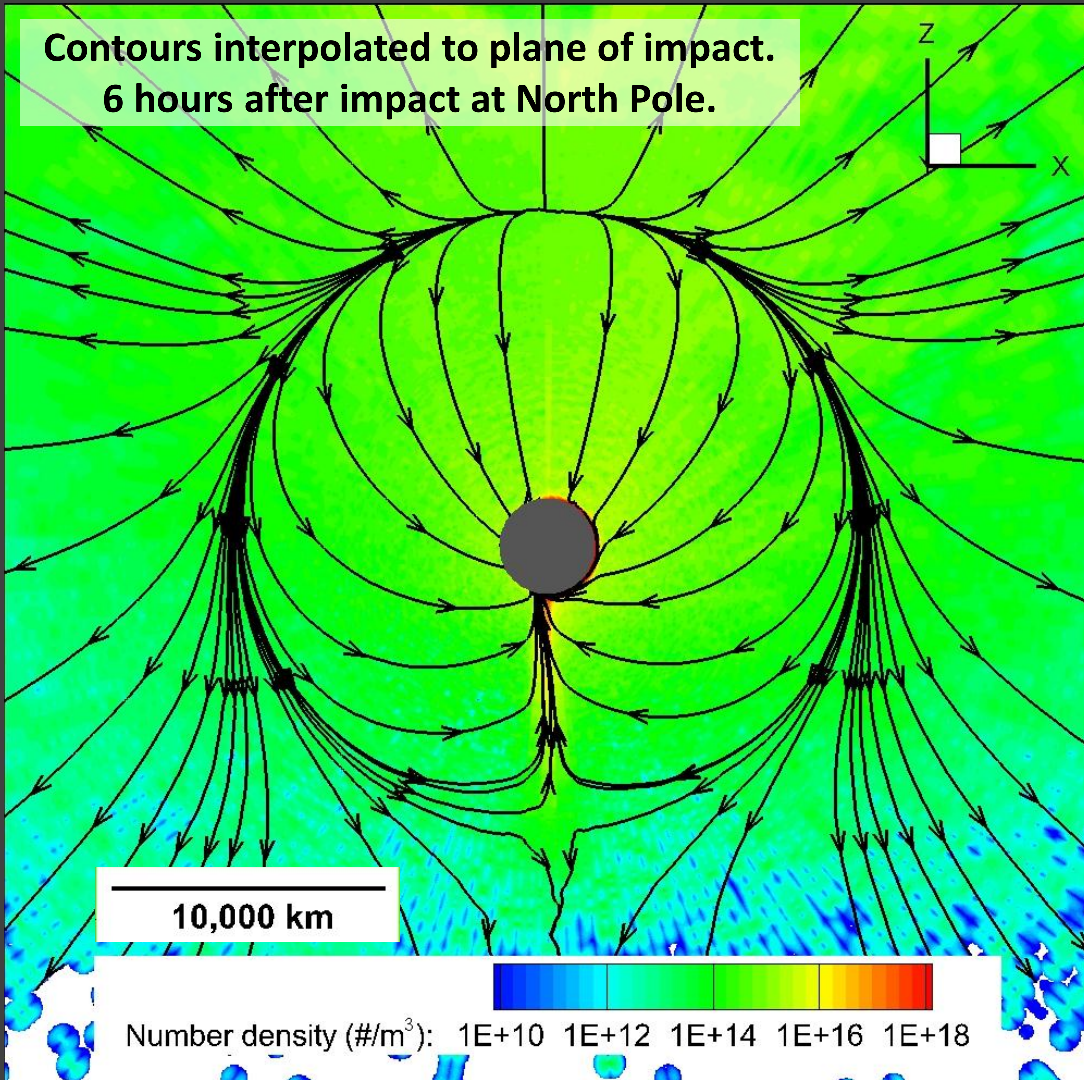
Initial Flow Field



60°, 30 km/s impact. Contours interpolated to plane of impact.

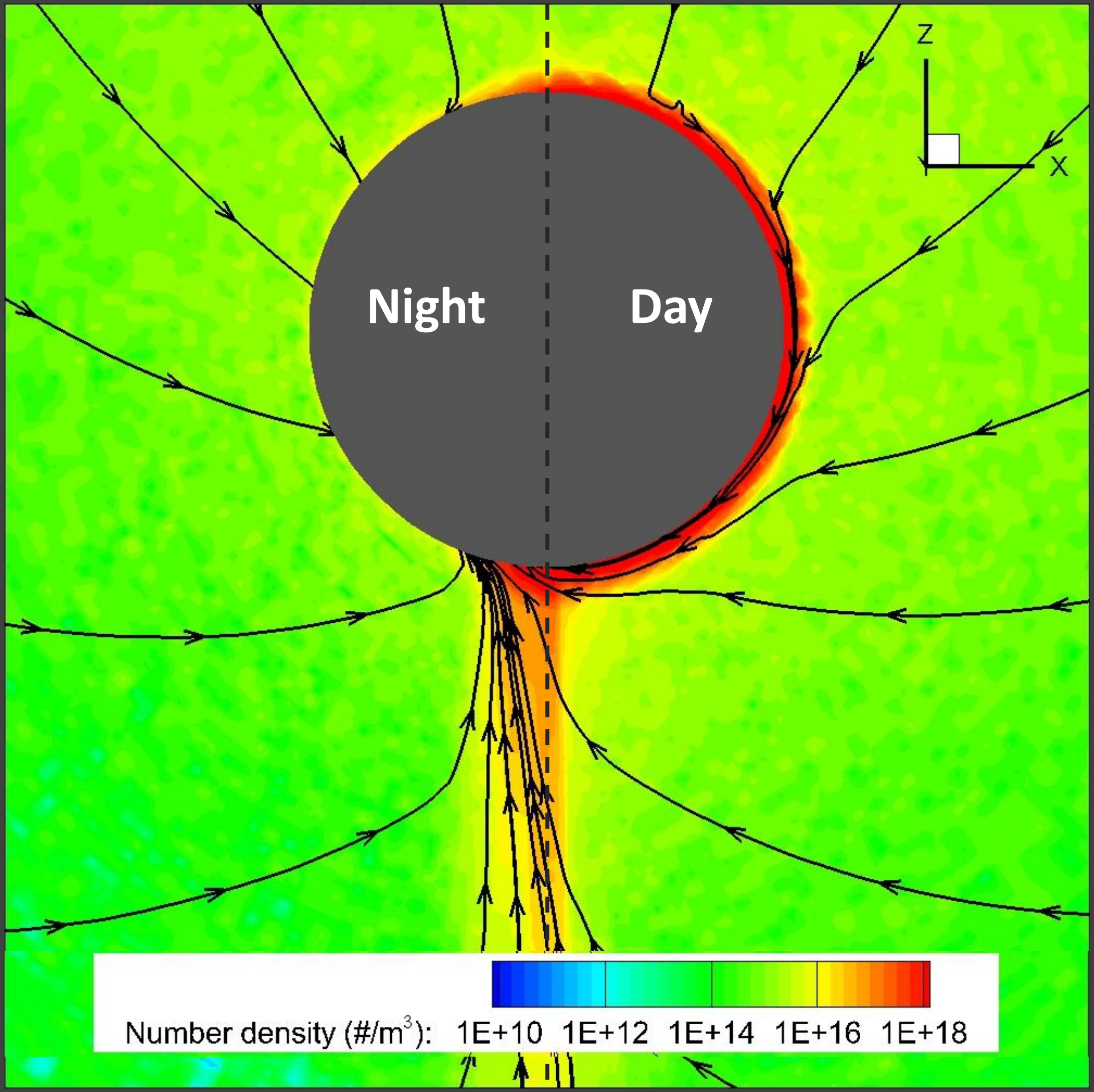
- Initial rapid radial expansion at velocities in excess of lunar escape velocity (2380 m/s).
- At later times, material enclosed by the white line travels below escape velocity, begins to fall back to surface.
- Later simulations neglect escaping vapor.

Transient Atmosphere Features



- Antipodal deposition. (Also seen in simulations of basin-forming impacts- Hood & Artemieva, 2008.)
- Ground-hugging day-side wind. driven by North-South pressure gradient. Reaches SP within 1-3 hours.

Transient Atmosphere Features



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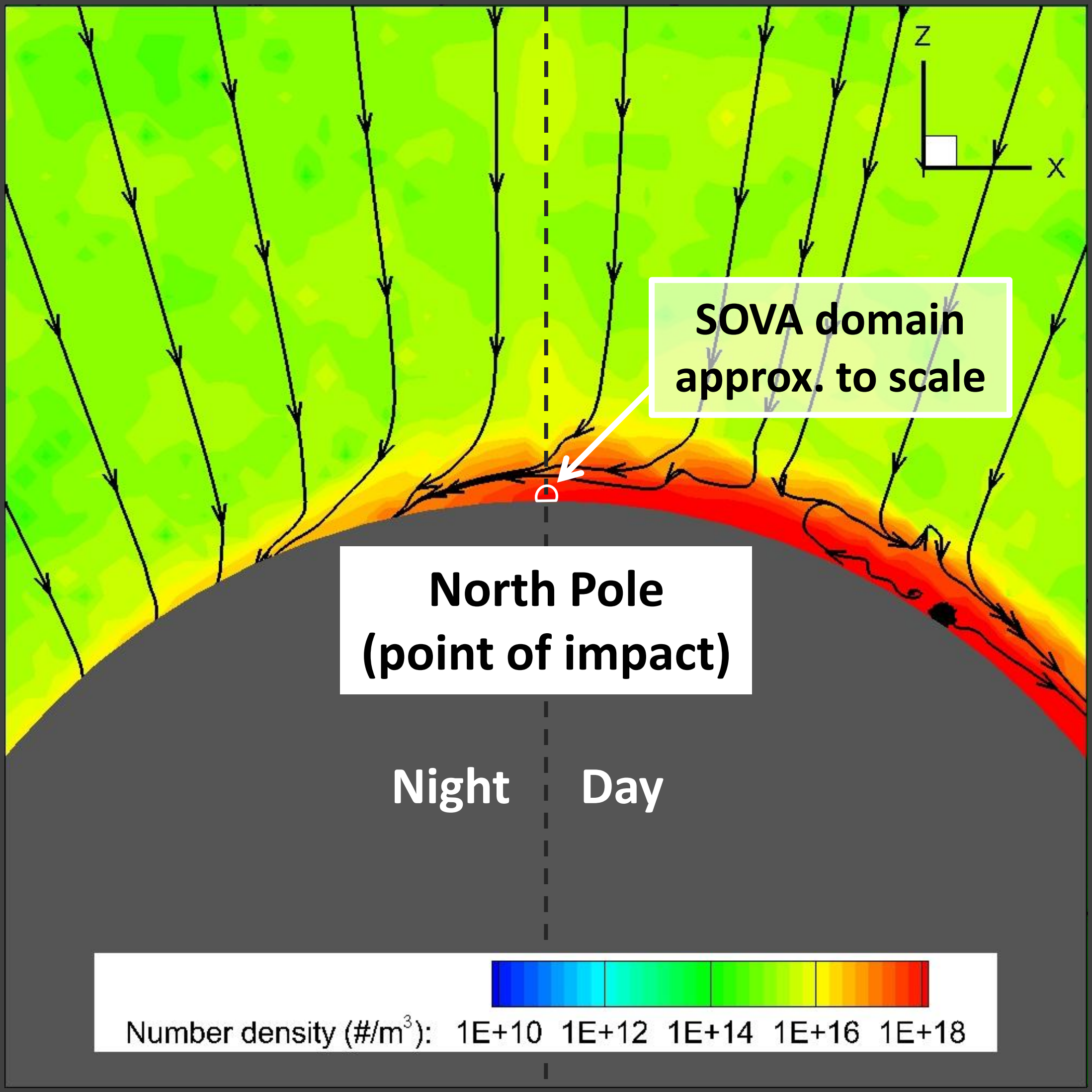
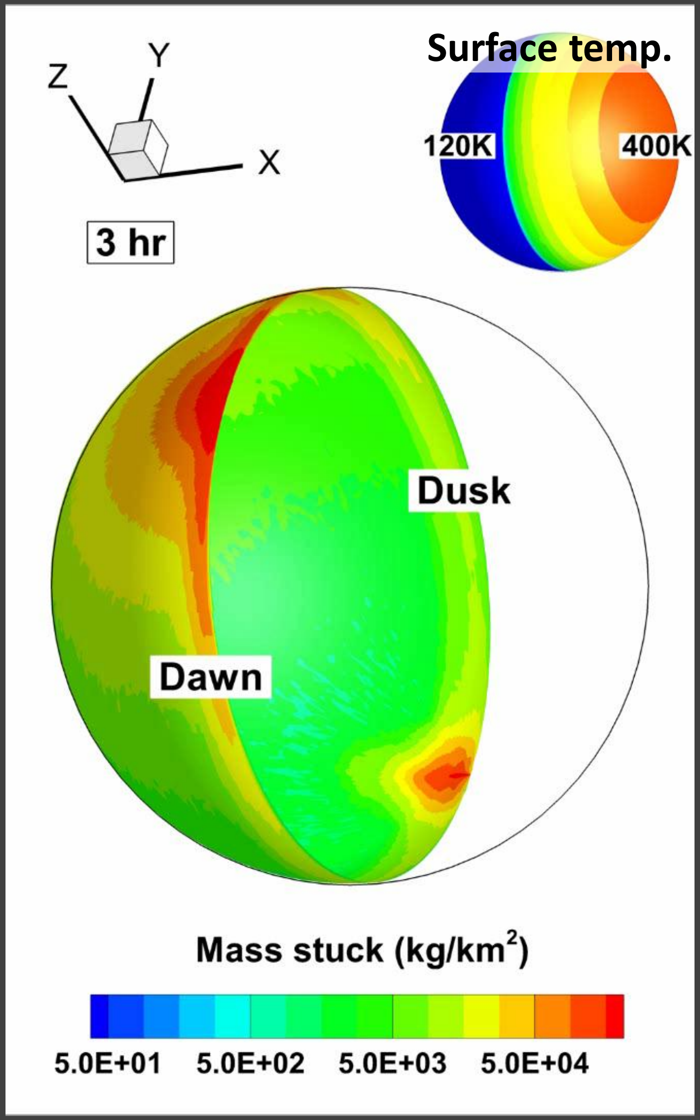


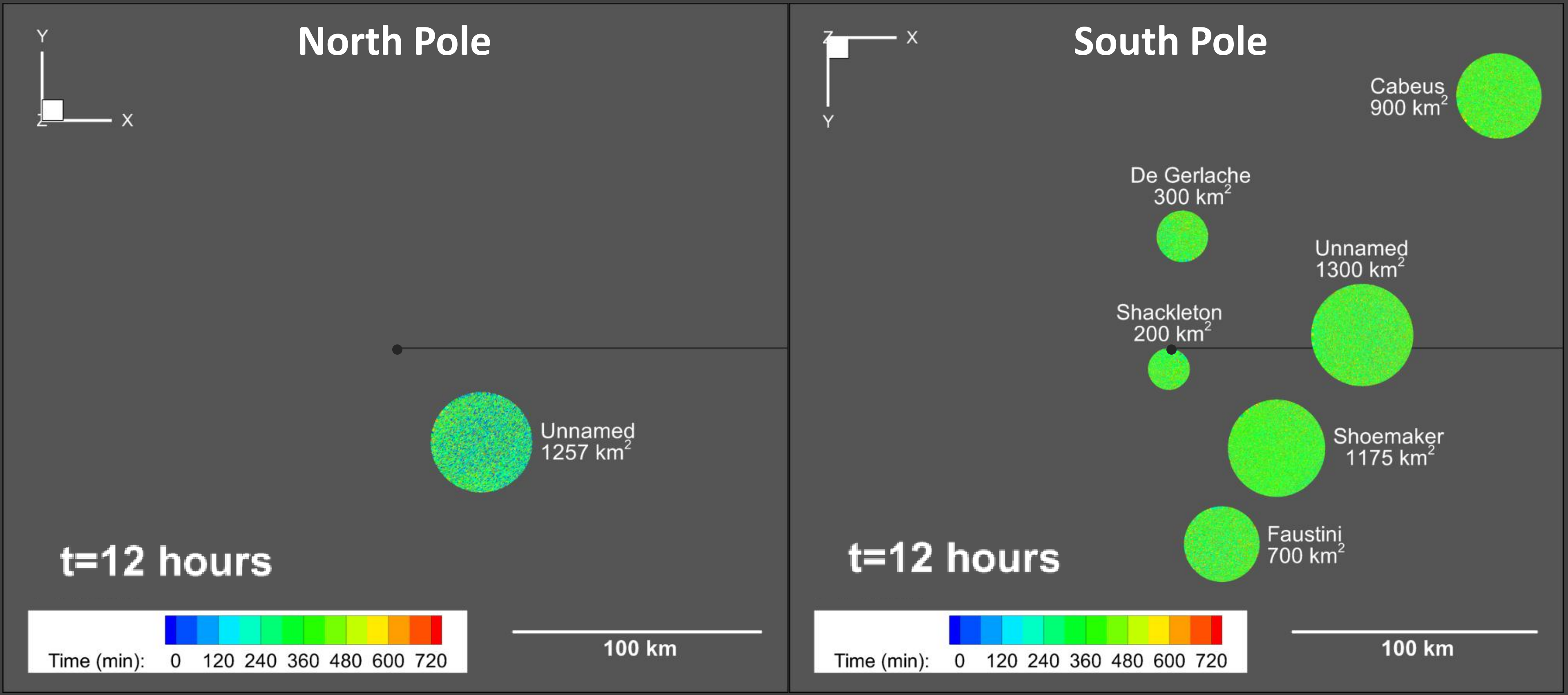
- Antipodal deposition. (Also seen in simulations of basin-forming impacts- Hood & Artemieva, 2008.)
- Ground-hugging day-side wind. driven by North-South pressure gradient. Reaches SP within 1-3 hours.
- Day-night pressure gradient → region of reversed flow near point of impact (NP).

Surface Deposition Features



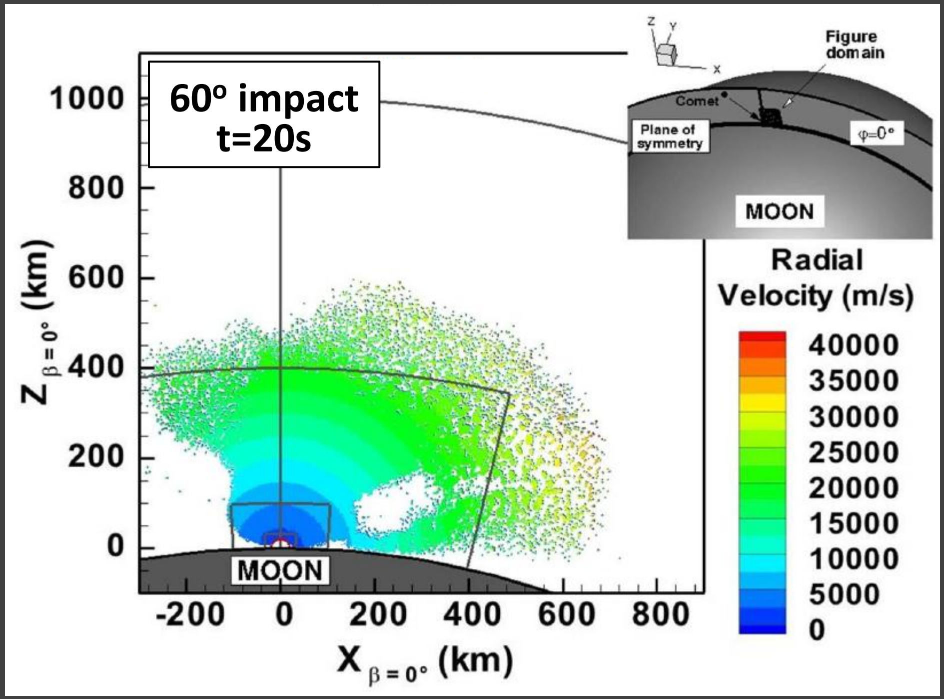
- Instantaneous snapshots of deposition patterns at 3 hour intervals. Cold traps not shown.
- Concentration of mass at poles due to day-side wind and antipodal convergence. $O(10^5)$ kg/km^2 $\equiv$ ~0.1 mm ice.
- Concentration of mass at terminators due to day-night pressure gradient.
- Difference between dusk/dawn deposits due to fallback on to regolith with/without ice cover.

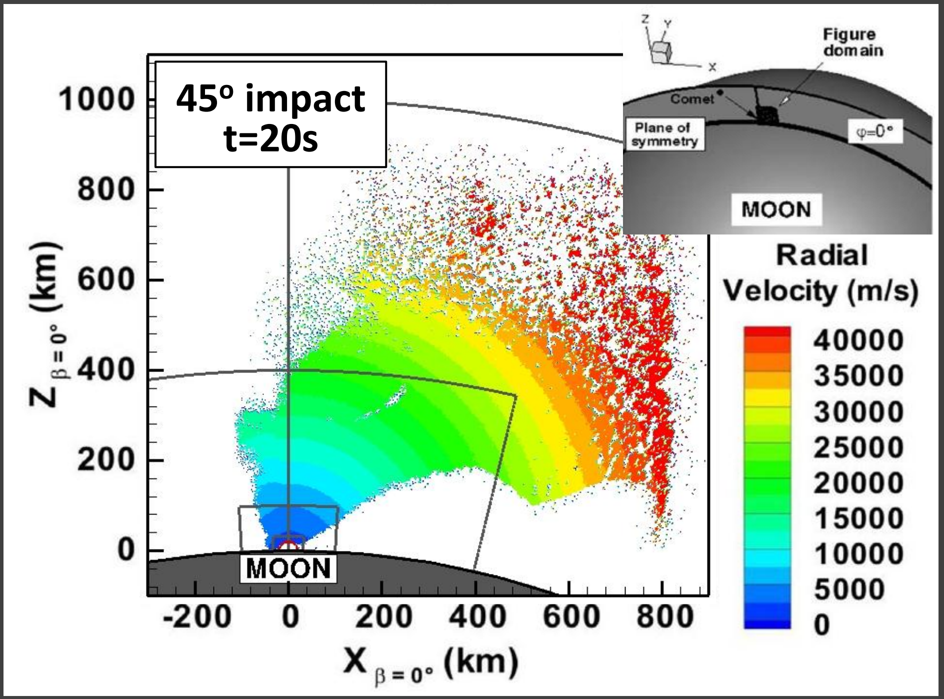
Deposition at Cold Traps



- Impact at North Pole → earlier deposits at North Pole cold trap.
- Antipodal convergence + day-side wind → later deposits at South Pole cold traps.
- Deposits colored by time of deposition.

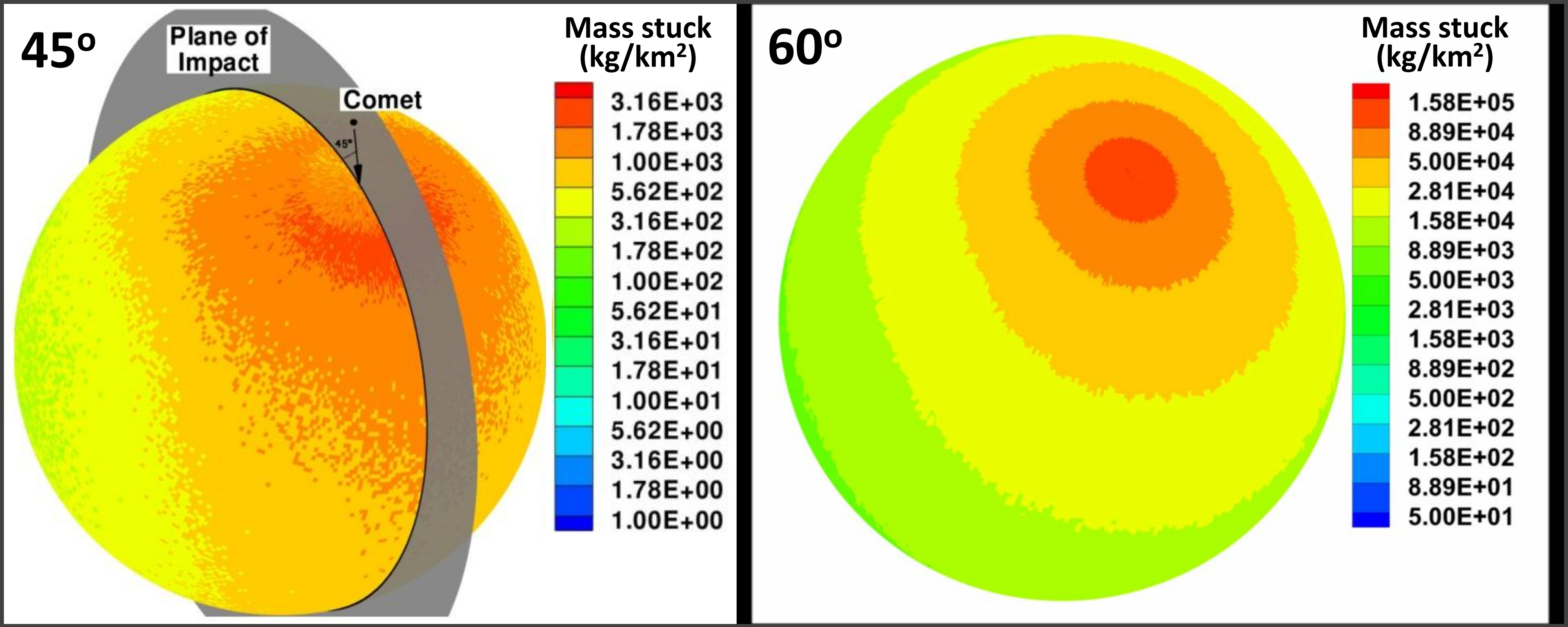
Influence of Impact Angle





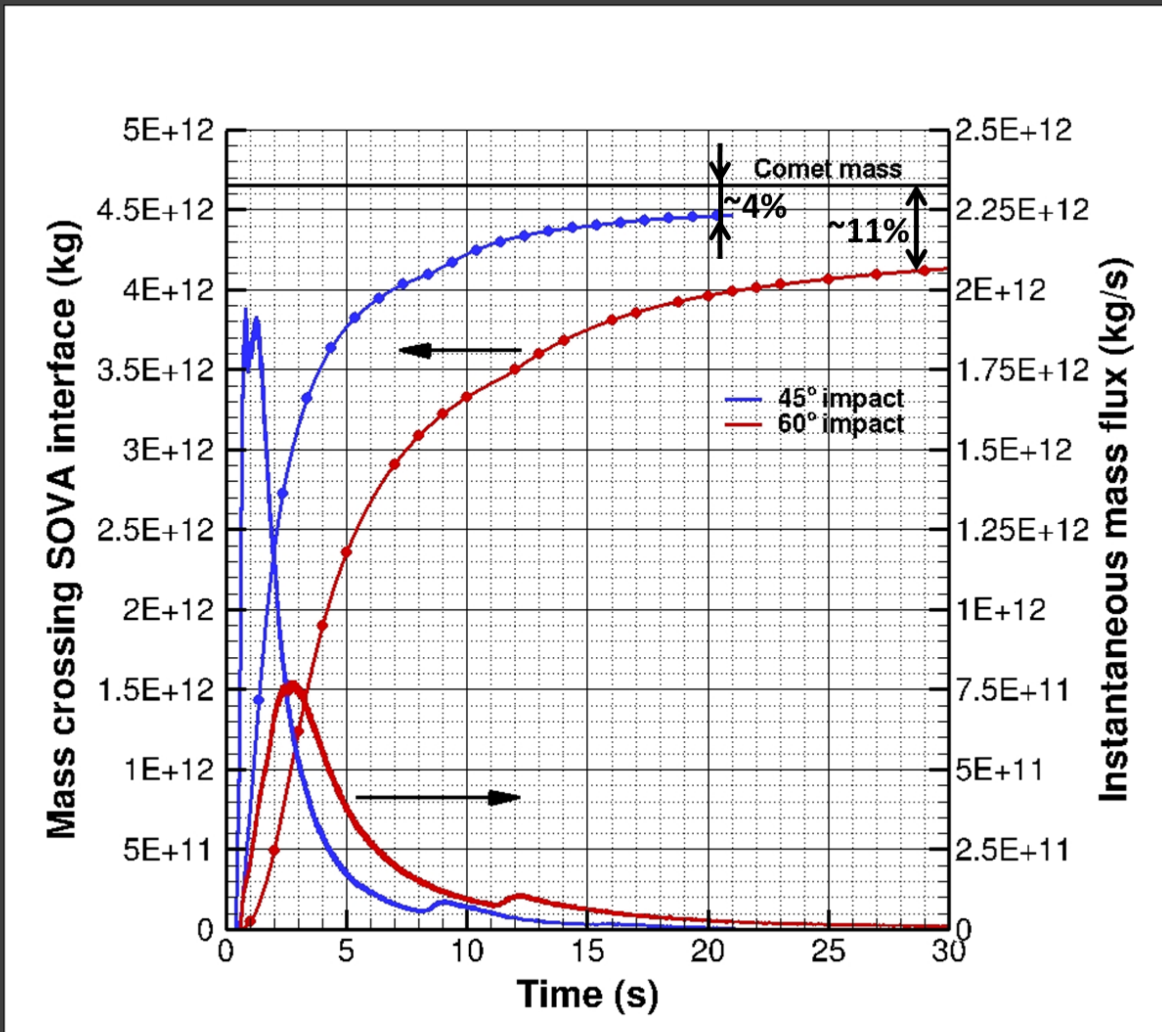
- Less downrange focusing in the more vertical (60º) case → more symmetric (about point of impact) fallback.
- Lower plume kinetic energy in the more vertical case → less water escapes. (Consistent with findings of Pierazzo & Melosh, 2000 and Gisler *et al.*, 2006)

Comparison of Fallback Trends



- Surface temperature fixed at 120K ∴ all water falling back sticks, no migration due to temperature variations. After 7 (Earth) days, most water has escaped or fallen back.
- Thicker (~50x) and more symmetric deposits in 60° case.

Simulations of Remaining Water



Small amounts of water mixed with rock are neglected: ~1% comet mass for 60° run; ~3% for 45° run.

- SOVA simulations stopped when:
  - Outflow → subsonic.
  - Flux asymptotes → 0.
- Remaining water independently sublimated from a 'crater' centered at point of impact.
- ~10% of comet mass remains at the end of 60° SOVA run. ~1% for 45° run.

Conclusions

- **Stewart *et al.*, 2011 (Icarus 215, 1-16)** – long term (~6m) evolution and final results for a 45º, 30 km/s impact:
  - Similar retention rates for different impact locations - 0.14% of the comet mass is trapped ≡ 1.12 kg/m^2 ≡ ~1 mm ice over all cold traps.
- 60º @ 30 km/s & 45º @ 20 km/s runs in progress.
  - Preliminary results suggest greater ultimate retention of water.
  - Dynamic transient atmosphere: day-side wind, antipodal deposition.
- Further considerations (not currently incorporated):
  - Radiative cooling of vapor.
  - Condensation (nucleation by dust/rock fragments?).
  - Optical shielding from photodestruction.
  - More complex treatment of "remaining water".
  - Detailed topography/temperature maps.
  - Mechanisms acting after deposition in cold traps, for instance- space weathering (Crider & Vondrak, 2003), sub-surface migration of water molecules (Schorghofer & Taylor, 2007).