Modeling the Influence of Small-Scale Surface Roughness on the Lunar Exosphere

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Background and Motivation:

The behavior of volatiles on the Moon and other nominally airless bodies is a subject of ongoing interest, intimately linked to the interaction of exospheric species with the bounding surface. Several recent works (e.g. Bandfield et al., 2015; Hayne et al., 2013) show that the lunar surface can sustain dramatic variations in surface temperature over very small scales. **How does the distinctive surface thermal environment influence volatile transport on the Moon and other similar bodies?**

Method:

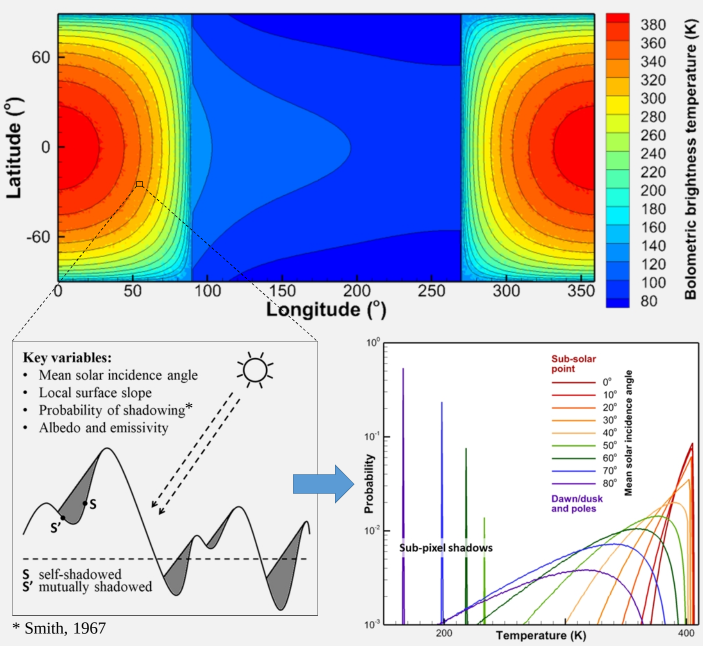
1. We develop a thermal model to account for "sub-pixel" surface temperature variations due to small-scale, stochastic roughness.

   Model constraints:

   i. LRO Diviner data indicate sub-pixel anisothermality closely matched by stochastic roughness of RMS slope angle = 20° (Bandfield et al., 2015).

   ii. Modeled pixel-integrated brightness temperature should be consistent with observations (Williams et al., 2016; Hurley et al., 2015).

What do we mean when we talk about lunar surface temperature?



* Smith, 1967

- Each 1° × 1° pixel has a distribution of surface temperatures, determined by the degree of roughness and the mean solar incidence angle.
- Migrating exospheric **molecules sample the surface down to the smallest scales** over which temperature variations occur.

  Gas-surface residence time, $t_{res} \propto \exp(-E_a/k_B T_{surf})$ [E_a = activation energy]

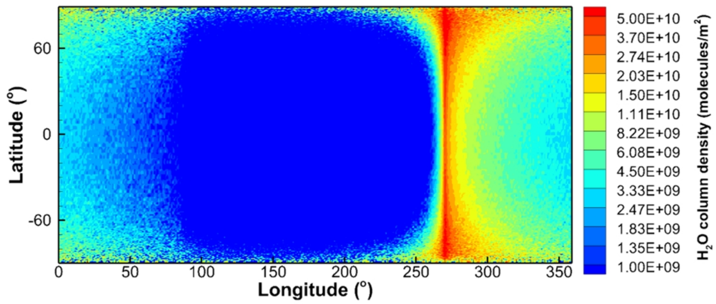
2. Rough surface temperature model is coupled to Monte Carlo simulations of exospheric water vapor transport.
   - Global, uniformly distributed source (impulsive release).
   - Molecules travel along ballistic trajectories, with temperature dependent surface residence times. *Adsorbed molecules experience time-varying surface temperature and shadowing.*
   - Loss mechanisms – gravitational escape, photodestruction, cold-trapping.

Key parameters explored:

- ***Shadow temperature.*** Do non-equilibrium effects change the distribution of shadow temperatures? What role do small-scale cold-traps play?
- ***Desorption activation energy.*** How 'sticky' is the lunar surface? How would the same rough surface interact with different species?

Results:

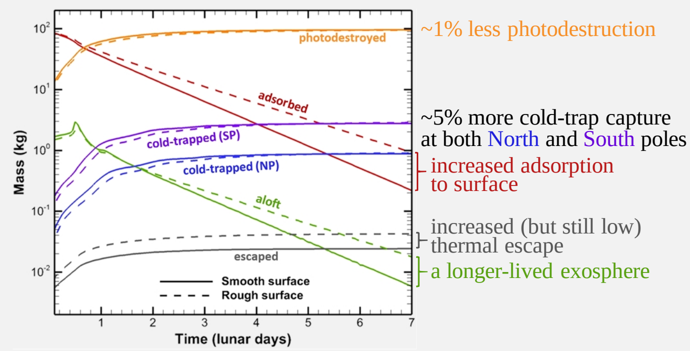
Representative snapshot of exospheric column density:



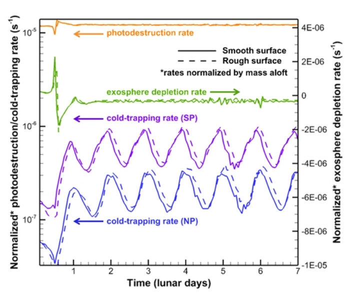
- *Note:* Enhanced column density at the dawn terminator (270° longitude) at sunrise due to mobilization of water adsorbed to the night-side.

Comparing water vapor transport over rough and smooth surfaces:

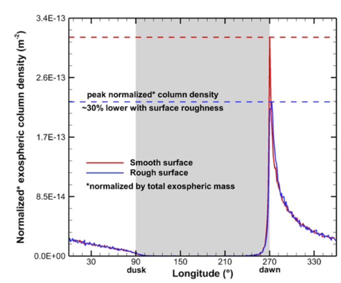
The introduction of surface roughness leads to:



- Preferential depletion of the exosphere through cold-trap capture vs. photodestruction due to the temporary capture and concentration of exospheric molecules by cool/shadowed surfaces near the poles.
- Slower migration to the poles due to cool/shadowed day-side surfaces



Comparative **rates** for rough/smooth surface cases. (*Note:* Diurnal cycling of cold-trapping rates is due to transit of the dawn terminator.)



Change in **exospheric structure** due to surface roughness largely confined to "blurring" of the dawn terminator, most noticeable at low latitudes.

Summary:

- Accounting for 'sub-pixel' variations in lunar surface temperature has a modest but noticeable influence on volatile transport, leading to increased cold-trap capture, decreased photodestruction, increased thermal escape, and an overall increase in longevity (for an impulsively released water vapor exosphere). Effects on exospheric structure are minimal.
- Results are sensitive to how the coldest surfaces (e.g. shadows) are modeled, as well as the energetics of gas-surface interactions – different for other volatile species and on other bodies.

References: Bandfield et al., 2015 (*Icarus* #248); Hayne et al., 2013 (*DPS* #45); Hurley et al., 2015 (*Icarus* #255); Smith, 1967 (*JGR* #72); Williams et al., 2016 (*Icarus*, in press). **Acknowledgements:** Computational support for this work was provided by the Texas Advanced Computing Center.