Drill Don't Dig: Subterranean Lakes on the Moon as an Economic Resource

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Agenda

- Overview: Why there **will** be liquid water under the lunar surface.
- The Lunar Thermal Modeling: The Surface versus the Interior.
- A Near Surface Radiative Thermal Model
- Thermal Model for the Lunar Crust
  - Two Initial Conditions
- Where We Might Find Water
- Drill Don't Dig: Daylight Water as a Resource.
- Quick Reconnaissance Missions to Look for Water
- Thoughts on Astrobiology (and Protecting It)
- Conclusions

Overview

- The Moon has a hot interior and a relatively cold surface, with a cooler crust on top of a warmer mantle (at $\sim$800 K).
- The crust thus **must** get warmer with depth.
  - There is thus always a depth range where liquid water **could** exist.
  - Whether it **does** exist depends on if it was ever available, and whether what was available has been was prevented from escaping into space.
- This talk deals with zonally averaged thermal models for the Moon's crust.
- These depend on
  - The immediate subsurface temperature, which result from a radiative balance.
  - And the thermal gradient in the interior, which can be estimated from the Fourier equation.
- Just as for petroleum or natural gas, survival of liquid water at depth requires
  - the deposition of water in the past and
  - a protective cap over the liquid water layer.
- Simply put, anywhere there is ice, there may be liquid water underneath it.
- The existence of liquid water at depth provides a new way of thinking about water as an economic resource for the Moon.

Thermal Models for the Lunar Crust

The Fourier Thermal Equation For The Lunar Crust

- The 1-D Fourier Thermal Equation is [Jiménez-Díaz et al., 2021, Lingam and Loeb, 2020]

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = -\mathrm{k}\,\frac{\partial \mathrm{T}^2}{\partial \mathrm{z}^2} \tag{1}$$

  where T is the temperature, t the time, k the thermal conductivity, and z the depth (here increasing downwards).

- We are seeking a static solution, so the initial condition is irrelevant, and the left hand side is thus zero.
  - This implies that, if k is $\approx$ constant (which seems reasonable below the regolith gardening zone, i.e., for z $\gtrsim$ 20 m), the crust will have an $\approx$ linear thermal gradient.

- The lunar crust here extends between the Immediate SubSurface (ISS) and the Crust-Mantle Boundary (CrMB) and so has a thickness (the CrMB depth), a net (or bulk) temperature gradient and thermal fluxes at the top (from the Sun and the CMB) and the bottom (from the Mantle).

- The thermal flux from above varies with latitude.

- It is therefore **not** possible to have all of the other quantities be independent of latitude.

Boundary Conditions for the Crustal Fourier Thermal Equation

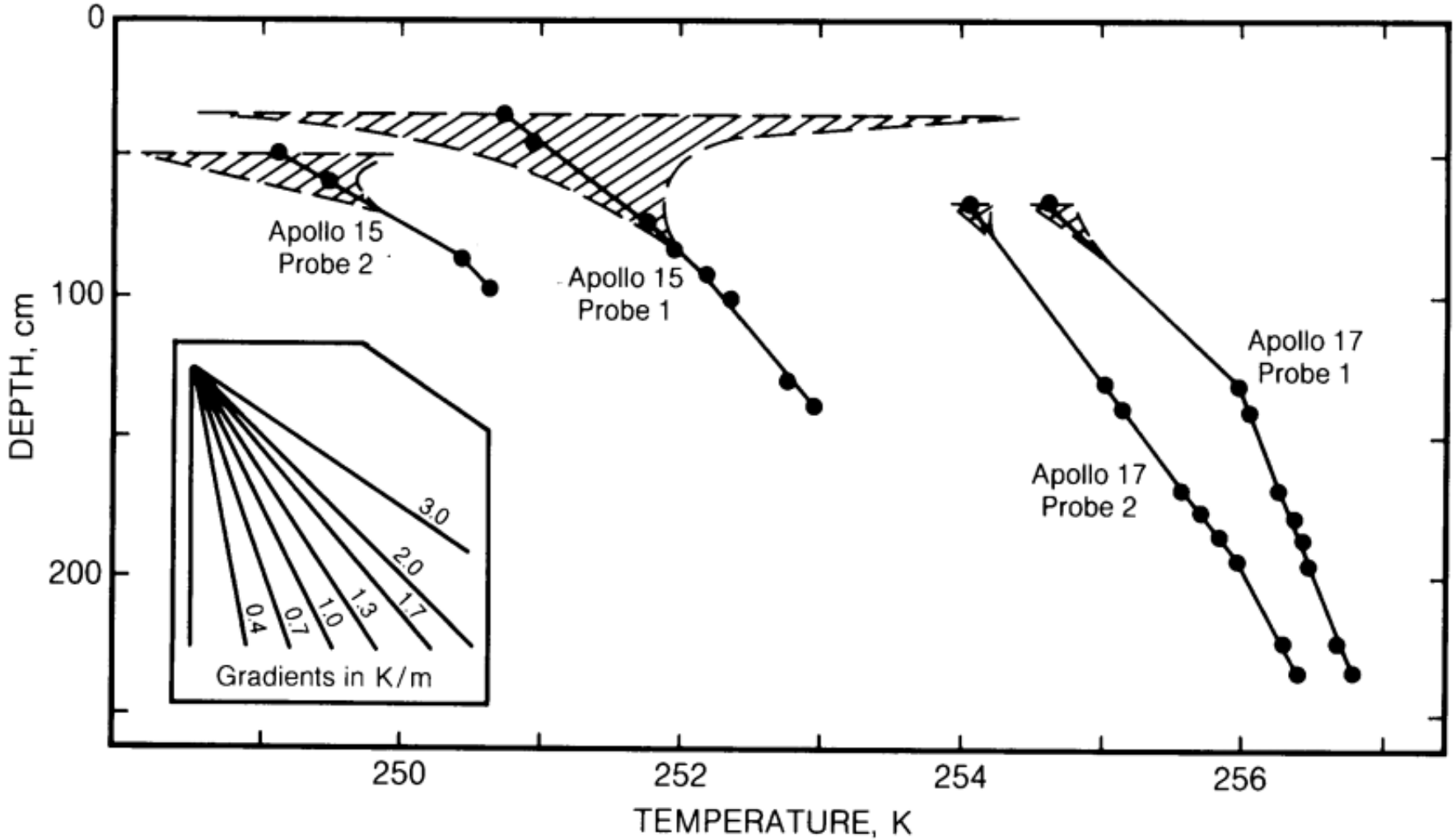
- The thermal gradient is estimated from the static Fourier equation [Jiménez-Díaz et al., 2021, Lingam and Loeb, 2020]

$$\mathrm{F_z} \;=\; -\mathrm{k}\,\frac{d\mathrm{T}}{d\mathrm{z}} \tag{2}$$

  where F is the internal heat flux.

- We considered two types of lower boundary conditions in our modeling:
- Dirichlet boundary conditions, where the CrMB **temperature** is fixed, and
- mixed Dirichlet-Neumann boundary conditions, where the CrMB **heat flux** is fixed.
- We assume that the **depth** of the CrMB is constant. If this is true, then
  - an isothermal crust-mantle boundary implies the heat flux varies with latitude, and
  - a uniform crust-mantle boundary heat-flux means the CrMB temperature varies with latitude.

The Lunar Surface "Thermal Trumpet"

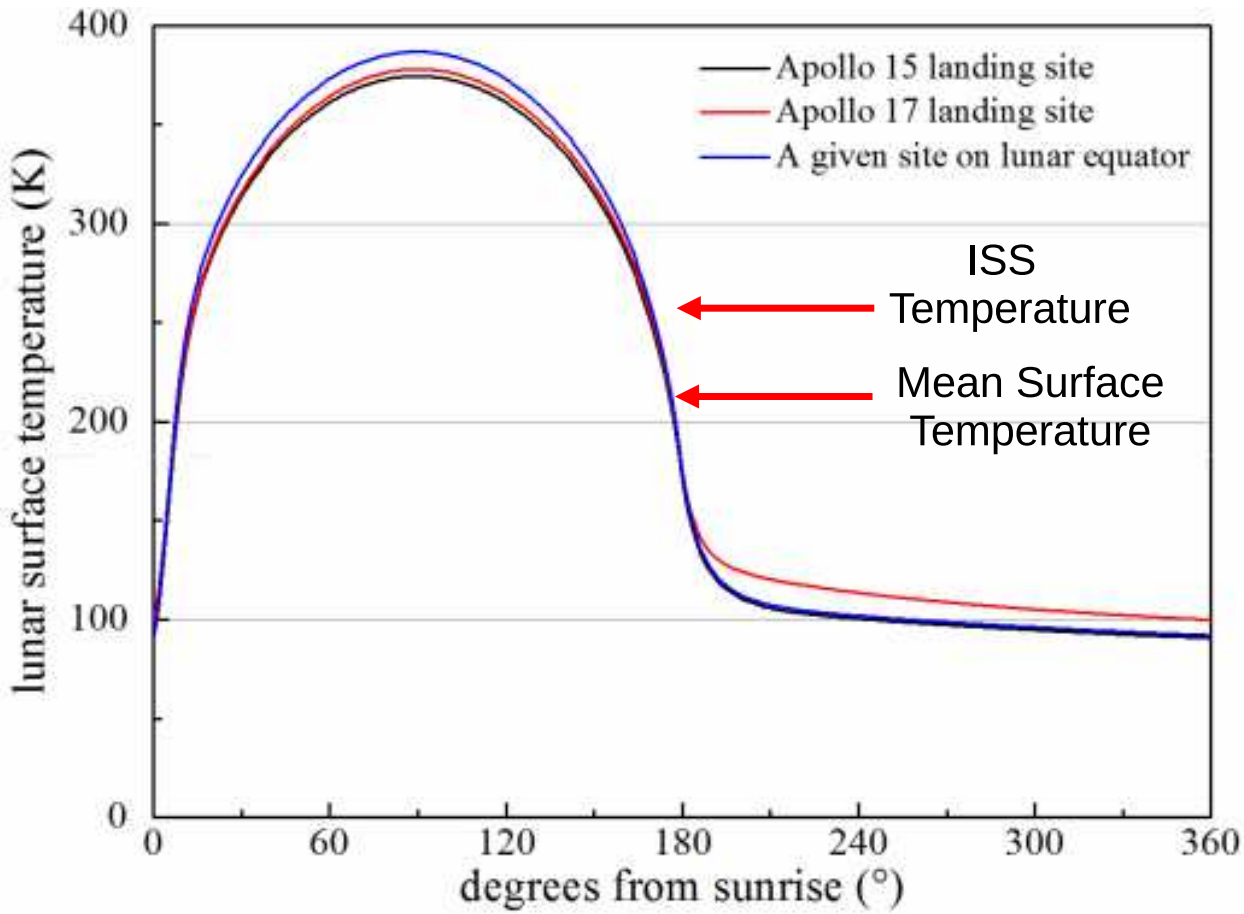


The near-equatorial diurnal surface temperature as measured by the various Apollo 15 and 17 ALSEP probes [Heiken et al., 1991]. The large thermal variations of the immediate surface are largely gone by a depth of ~75 cm to 1 m, but below that depth there is still a relatively large thermal gradient (of order 1 K / m).

A Three Layer Thermal Model for the Lunar Crust

- The large thermal gradients shown in the Apollo data at a depths $\gtrsim$75 cm **cannot** apply to the entire crust.
  - That gradient would imply a Mantle depth of < 1 km!
- We thus extend on the work of Vasavada et al. [1999] and use a **3** layer crustal model.
  - Layer 1 extends from 0 to 2 cm and has k $\sim 10^{-3}$ W m^{-1} K^{-1} (the temperature dependent "top" model of Vasavada et al. [1999]).
  - Layer 2 extends from 2 cm to 20 m and has k $\sim 10^{-2}$ W m^{-1} K^{-1} (the temperature dependent "bottom" model of Vasavada et al. [1999]).
  - Layer 3 is for crustal depths > 20 m and has k = 1.875 W m^{-1} K^{-1}, based on measured values for plagioclase feldspars at temperatures between 100 and 1000 K [Linvill et al., 1984].
- Layer 1 is the low density, low conductivity layer immediately at the surface.
- Layer 2 is apparently appropriate for gardened regolith.
- Layer 3 represents deeper, unfractured, highlands terrain.
- We developed an empirical radiative model for the ISS temperature (at 75 cm depth) based on the two-layer model TWO of Vasavada et al. [1999].

The Diurnal Thermal Cycle on the Lunar Surface



The near-equatorial diurnal surface temperature as measured by Apollo 15 and 17 and modeled by Song et al. [2017]. On Earth, surface temperatures are dominated by atmospheric conduction, which is predominately a linear effect, and so the immediate subsurface temperature is equal to the mean temperature on the surface above it. (This reasonably predicts most terrestrial cave temperatures.) Lunar surface temperatures are dominated by radiative effects and so the ISS temperature is **not** close to the mean surface temperature.

The ISS Temperature Model

- The Moon has a small obliquity and thus a small seasonal variation in insolation, and so below the surface skin depth the near surface can be modeled by a static thermal equilibrium.

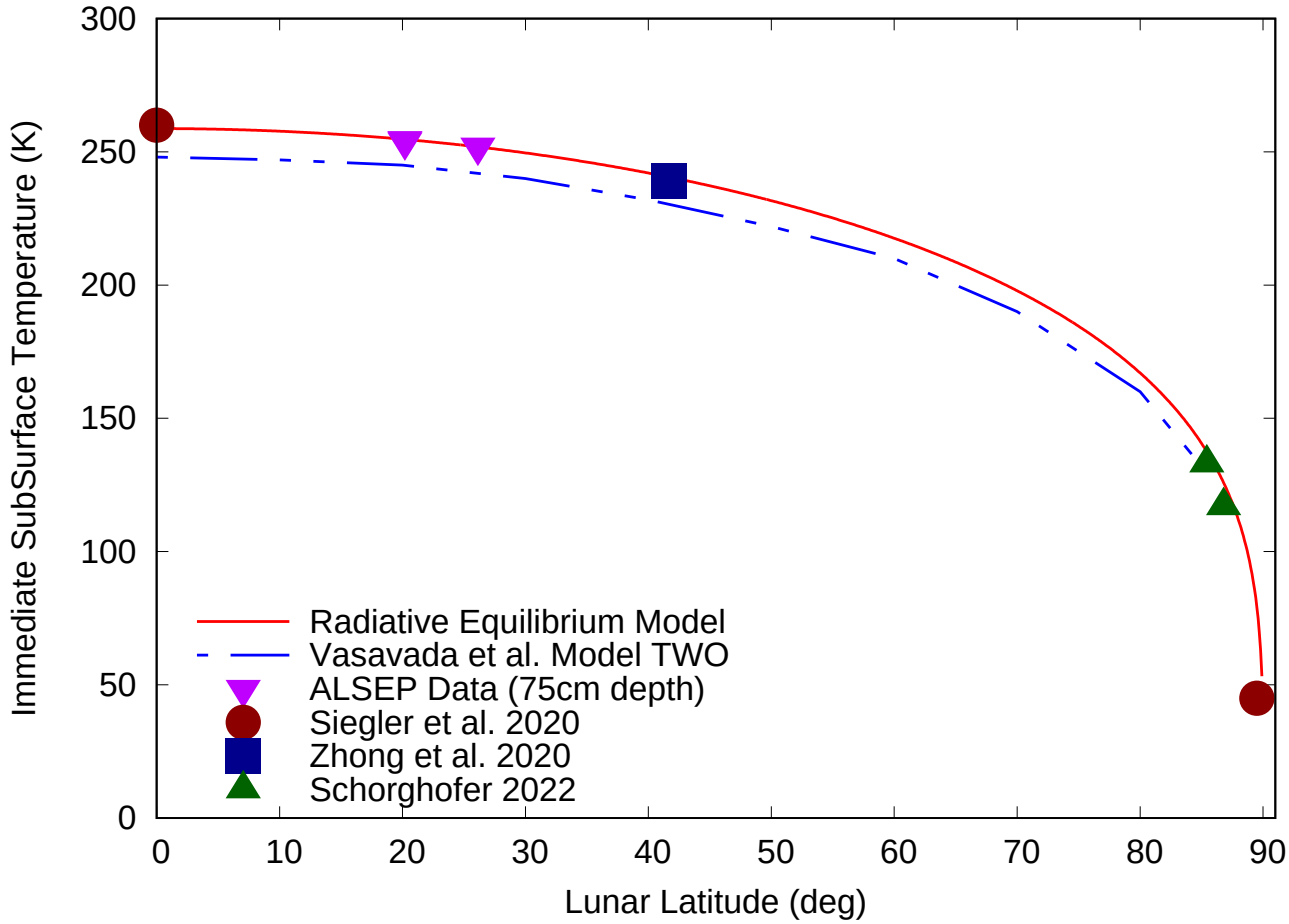
- A simple model of the near-surface mean temperature below the skin depth based on a radiative equilibrium between heating from below, from the diurnally averaged solar insolation and the temperature loss to space.
  - This modeling badly needs sub-surface temperature measurements at the ISS layer or below at a range of latitudes, which could be performed by even rapid reconnaissance CLIPS missions.

- Our model is based on a 1 parameter scale fit to the Apollo 15 and 17 data, and seems to fit the available data and modeling to $\sim$5 K.

- ISS temperatures in this model range from 258.7 K at the equator to 237.3 K at 45° and 53.2 K at the poles.

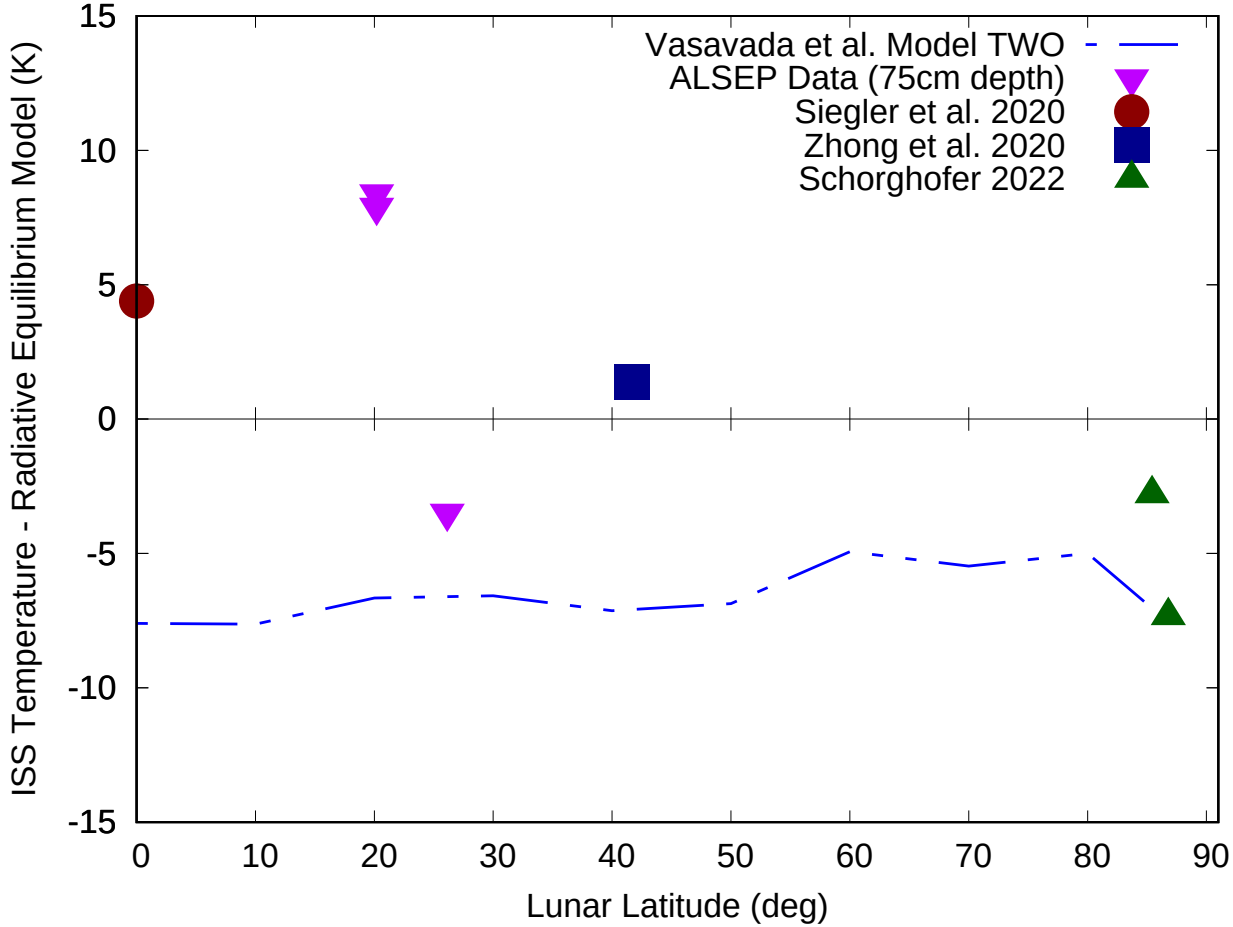
- This implies that interior temperatures of lunar caves (far from skylights) should always below freezing, but not cold enough to preserve water except at the poles.

The ISS Temperature Model



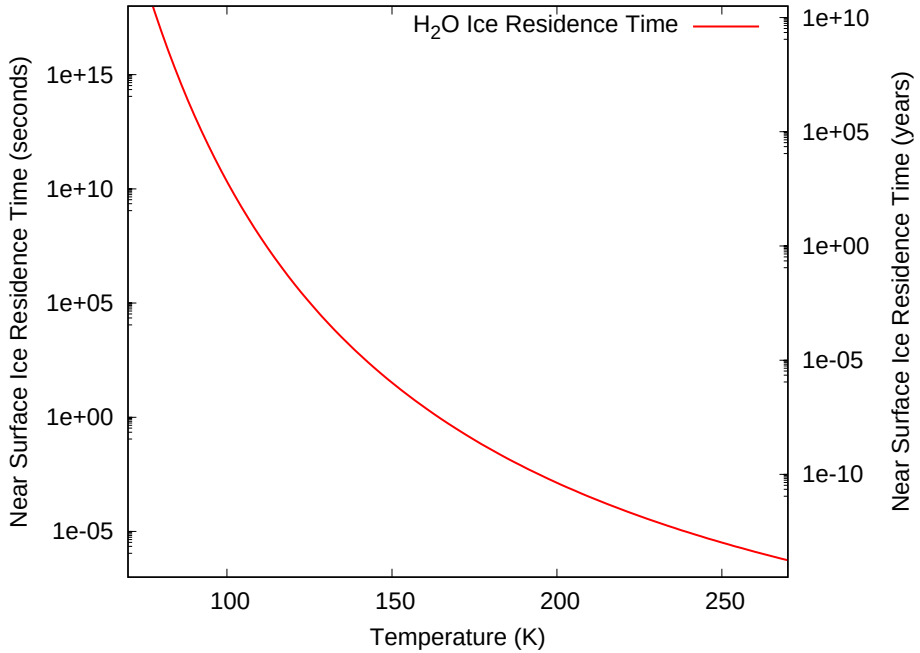
Zonally averaged models for the ISS temperature (the temperature at a depth of ∼0.75 m, just beneath the diurnally varying surface layer). The Vasavada Model TWO is from Vasavada et al. [1999]; our model (the solid red line) is similar but is fit to the Apollo heat flow measurements [Langseth et al., 1976] (triangles). Also shown are modeled temperatures from Siegler et al. [2020], Zhong et al. [2020], Schorghofer [2022]. Note that the ISS temperature is everywhere below the freezing point of water.

ISS Temperature Residuals



The residuals of the zonally averaged ISS temperature model shown in the previous figure. The triangles are Apollo heat flow measurements [Langseth et al., 1976]; also shown are predicted subsurface temperatures from Siegler et al. [2020],Zhong et al. [2020] and Schorghofer [2022]. The Vasavada et al. [1999] model TWO is biased about 5-7 K low and the $\sqrt{\text{residuals}}$ of the other points is $\sim$5 K.

Ice Retention Times in Vacuum



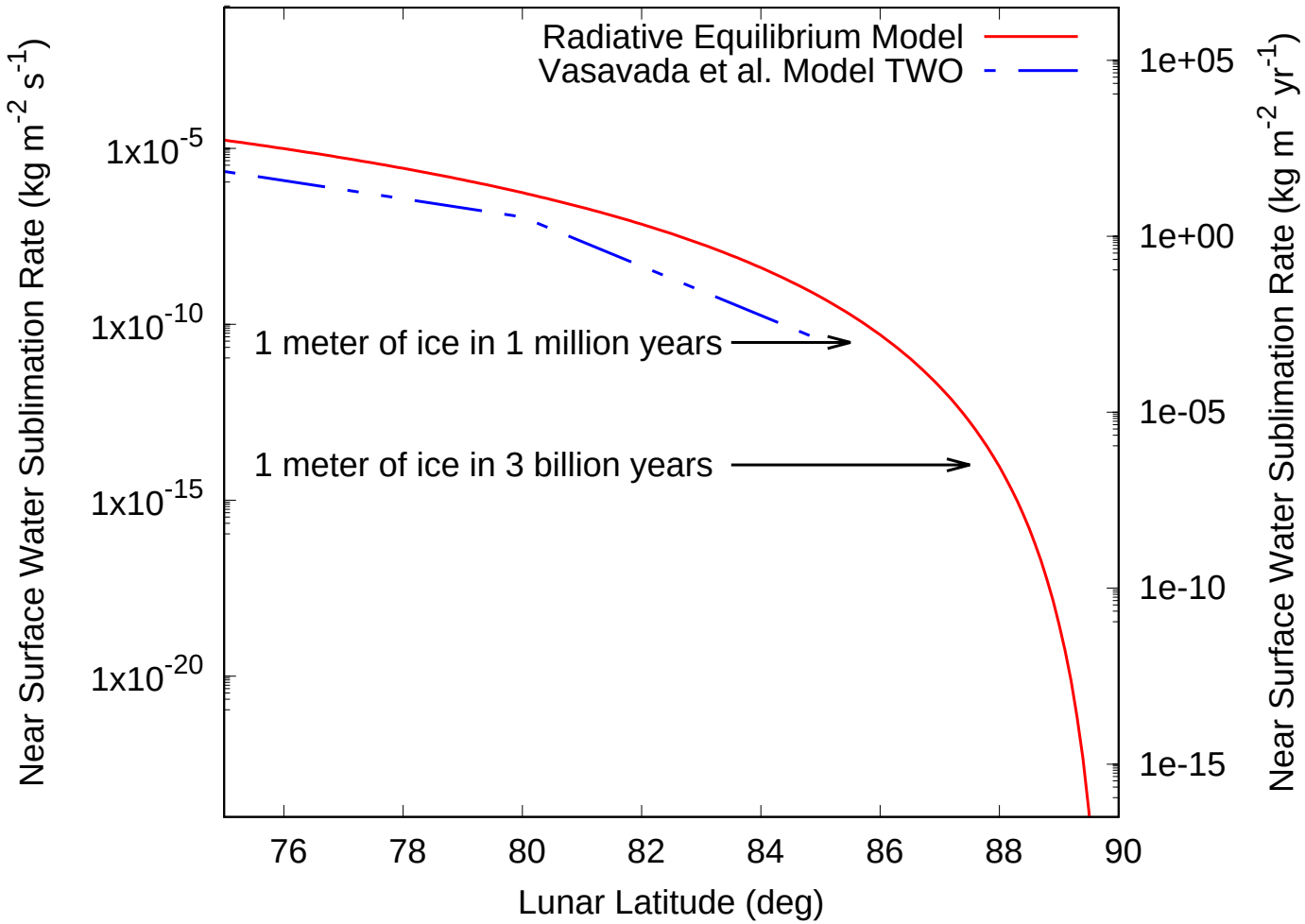
Residence times of water molecules on the surface of ice exposed to vacuum, from Schorghofer and Taylor [2007]. Note that lava tubes and other caves exposed to vacuum are highly unlikely to retain water ice for geologic times except at high latitudes.

Temperature and Water at Depth

Water At Depth

- Liquid water cannot survive exposure to vacuum.
- A cap of water ice would undoubtedly be an effective means of preventing the water in a subterranean lake from escaping.
- In our spherical model water ice would need to be poleward of $\sim 87^\circ$ to be sufficiently cold to survive for geologically long periods at or near the surface.
  - However, PSR are found at latitudes as low as 58° in both hemisphere, indicating that it might be possible for surface ice to exist in places over a much wider range of latitudes.
- What about below the surface?
- ISS temperatures in this model range from 258.7 K at the equator to 237.3 K at 45° and 53.2 K at the poles.
- This implies that interior temperatures of lunar caves (far from skylights) should always below freezing, but not cold enough to preserve water except near the poles.
- The same is true of surface regolith. The regions of heavily fractures and gardened rock in the top 10 - 30 meters are not cold enough to preserve water except near the poles - an overburden of 50 meters of regolith might preserve ice down to about 80° latitude.
- Water at lower latitudes will be at depth.

Surface Ice Retention Times

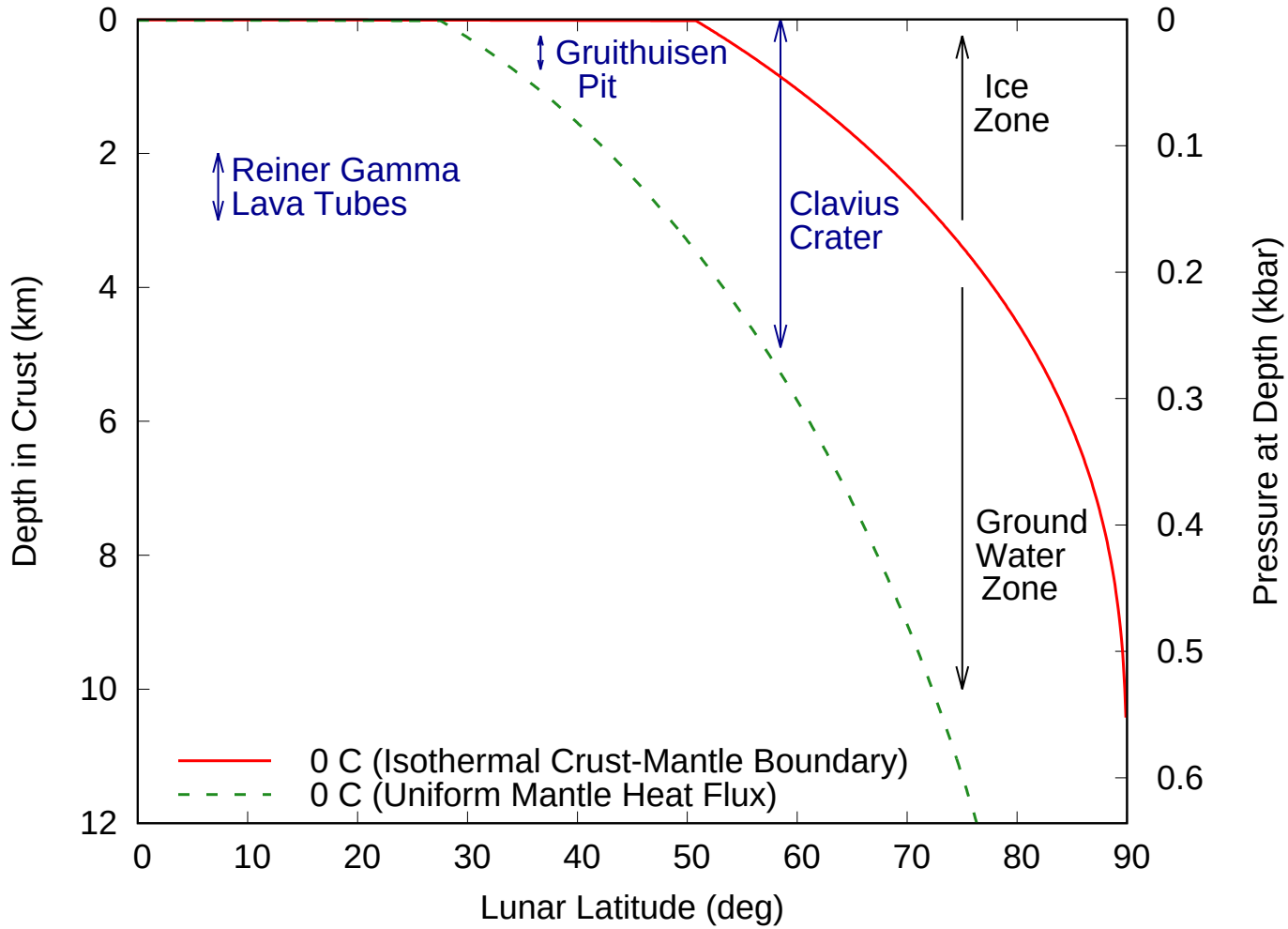


The lifetime and sublimation rate of water ice at ISS (just below the diurnal layer), using the steady state mean temperature estimates shown earlier.

Liquid Water At Depth

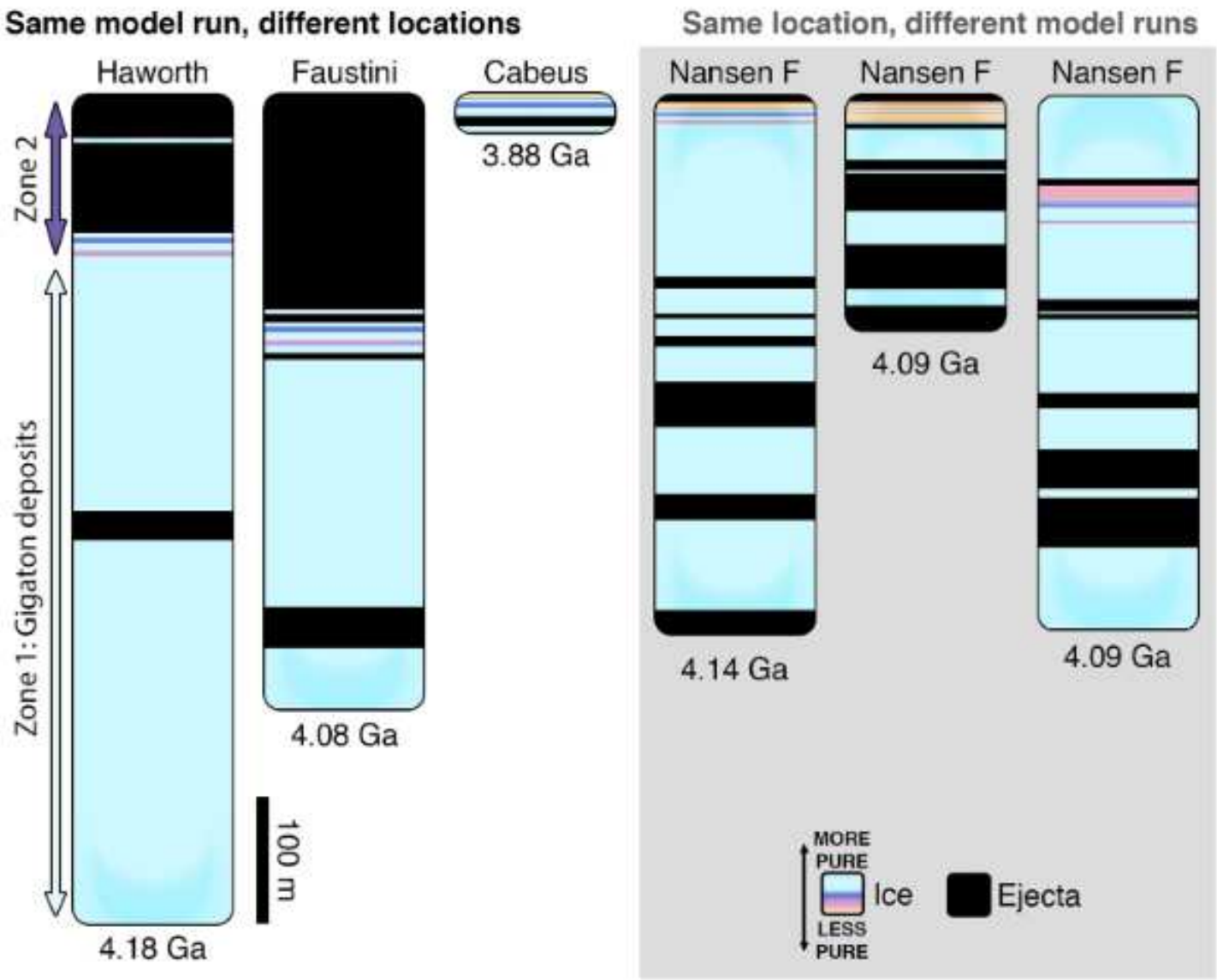
- I am not satisfied with either of the lower boundary conditions.
  - The iso-thermal CrMB means that mantle fluxes have to **increase** at the poles, which seems unlikely.
  - However, the uniform mantle heat flux B.C. means that the freezing depth is depressed to 33.6 km at the poles, and the CrMB temperature itself is quite depressed.
  - Could the polar cold depress the CrMB depth? A lower CrMB depth and a 36.2 heat flux would act (near the surface) like the uniform mantle heat flux B.C., but this needs to be explored further.
- What about water below the surface?
- Suppose we are interested at liquid water at a depth $\gtrsim$ 1 km.
- For an isothermal CrMB a 1 km freezing point depth is at 59.7° while for the fixed heat flux B.C. it occurs at 36.2°.
- If we assume a NaCl saturated brine, the 1 km melting point would be at 71.6° for the isothermal CrMB B.C. while for the fixed heat flux it occurs at 55.9°.

The ice / water transition depth for pure water.



The depth at which pure liquid water would freeze assuming a 1-D heat equation and two types of boundary conditions: Dirichlet boundary conditions (the solid red line, with an isothermal crust-mantle boundary) and mixed Dirichlet-Neumann boundary conditions (the dashed green line,with a uniform crust-mantle boundary heat-flux). With these subsurface temperatures, liquid water (under a protective cap) may be found even at mid-latitudes. Note that Clavius Crater, which has a detectable amount of surface water [Pugacheva et al., 2021], is deep enough that it subsurface water might be seeping into it.

Stratjgraphy of Lunar Ice.



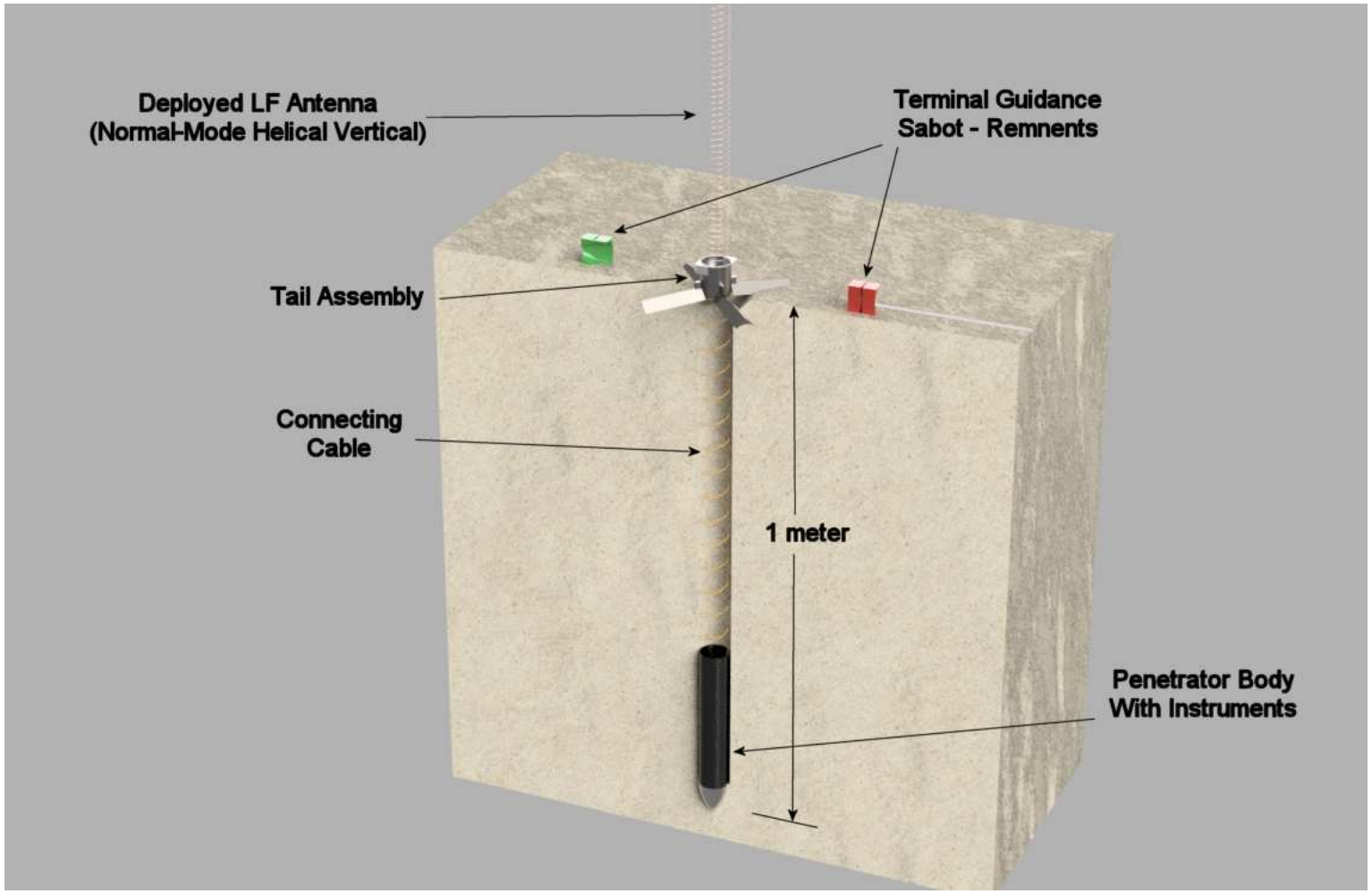
Models of the ice / regolith stratigraphy for several polar craters, from Cannon et al. [2020]. At least in this model, there could be substantial amounts of water ice in the polar regions, possibly with liquid water deep underneath. These events would also deliver water to sub-polar regions, possibly to be trapped there until the present day.

Finding and Extracting Deep Lunar Water: A Temporary Conclusion

- There are many difficulties inherent in extracting water from Permanently Shadowed Regions (PSR) of the Moon.
- From our work it seems likely that there could be liquid water on the Moon at shallow depths poleward of $\sim 70^\circ$ latitude, and at considerable depths (many km) near the poles.
  - The same events that could have delivered and then buried km thick strata of ice at the poles [Cannon et al., 2020] could have delivered substantial amounts of water to sub-polar latitudes, and buried them too.
- How could this water be found?
  - Liquid water - or brines - will strongly reflect low frequency ground penetrating radar
  - This has been done for Mars [Orosei and et al., 2018].
  - Electrical properties experiments can be very sensitive at detecting water (ice or liquid).
  - Both of these techniques could be rapidly deployed into candidate areas with short duration precursor missions (i.e., in conjunction with a CLPS landing).
- Deep drilling is going to be hard on the Moon - much harder than on Earth.
- However, there is deep technology for the movement and processing of liquid water, and I feel sure that, if it is found, it will be drilled.

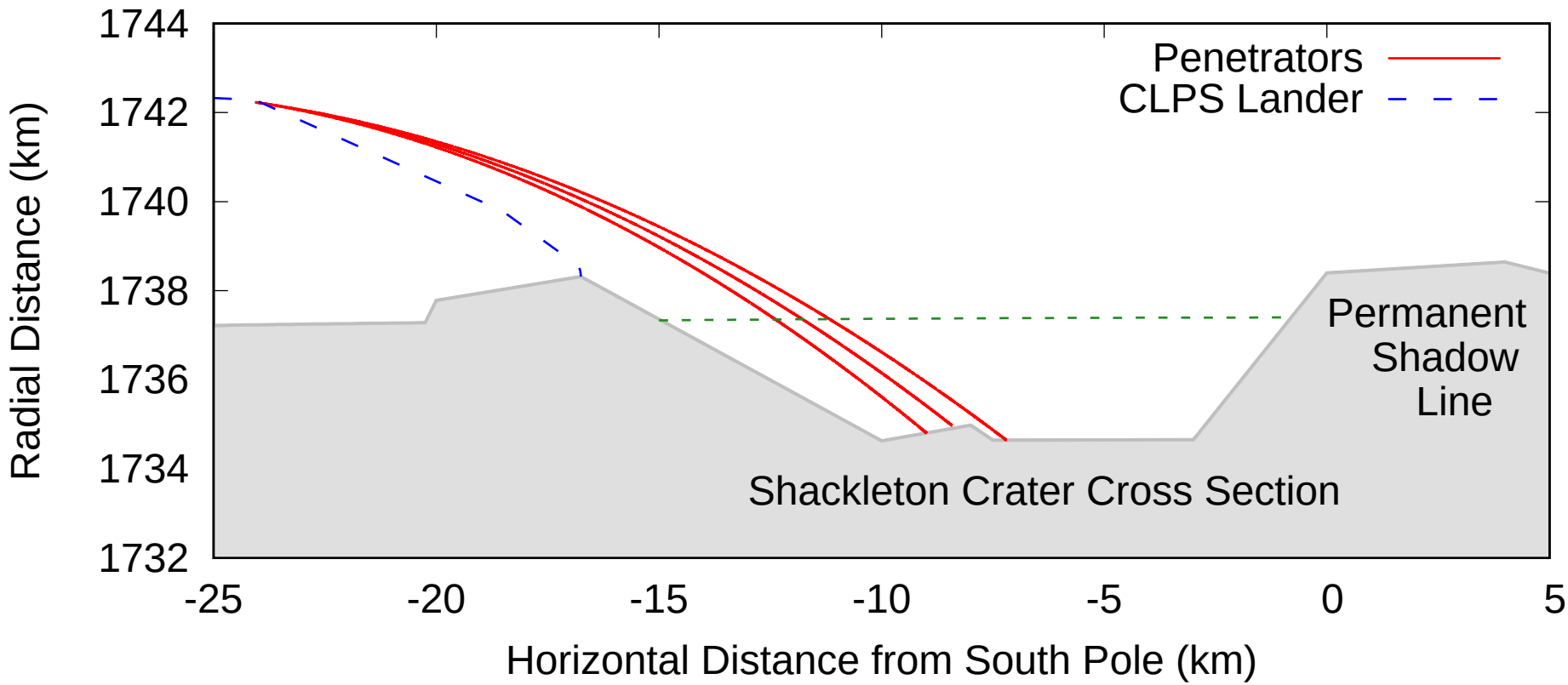
Quick Reconnaissance Missions to Look for Water

Ballistic delivery of Soil Properties Experiments using Mote Penetrators.



A Mote penetrator after deployment with a nominal 1 meter penetration into the lunar regolith. The electronics and most of the scientific payload would be carried in the penetrator itself and would be automatically embedded below the lunar surface. Cameras, other instruments, and communication antennas are carried in the tail section left on the surface.

Ballistic delivery of An Array of Geodetic Instruments using Mote Penetrators.



Deployment of Mote Penetrators into the Shackleton Crater PSR. The Motes are assumed to be deployed in flight from a CLPS Lander. The Motes then deploy into the center of the PSR, while the CLPS lander proceeds to soft land at the crater rim.

Mote Penetrator Before a Ballistic Test

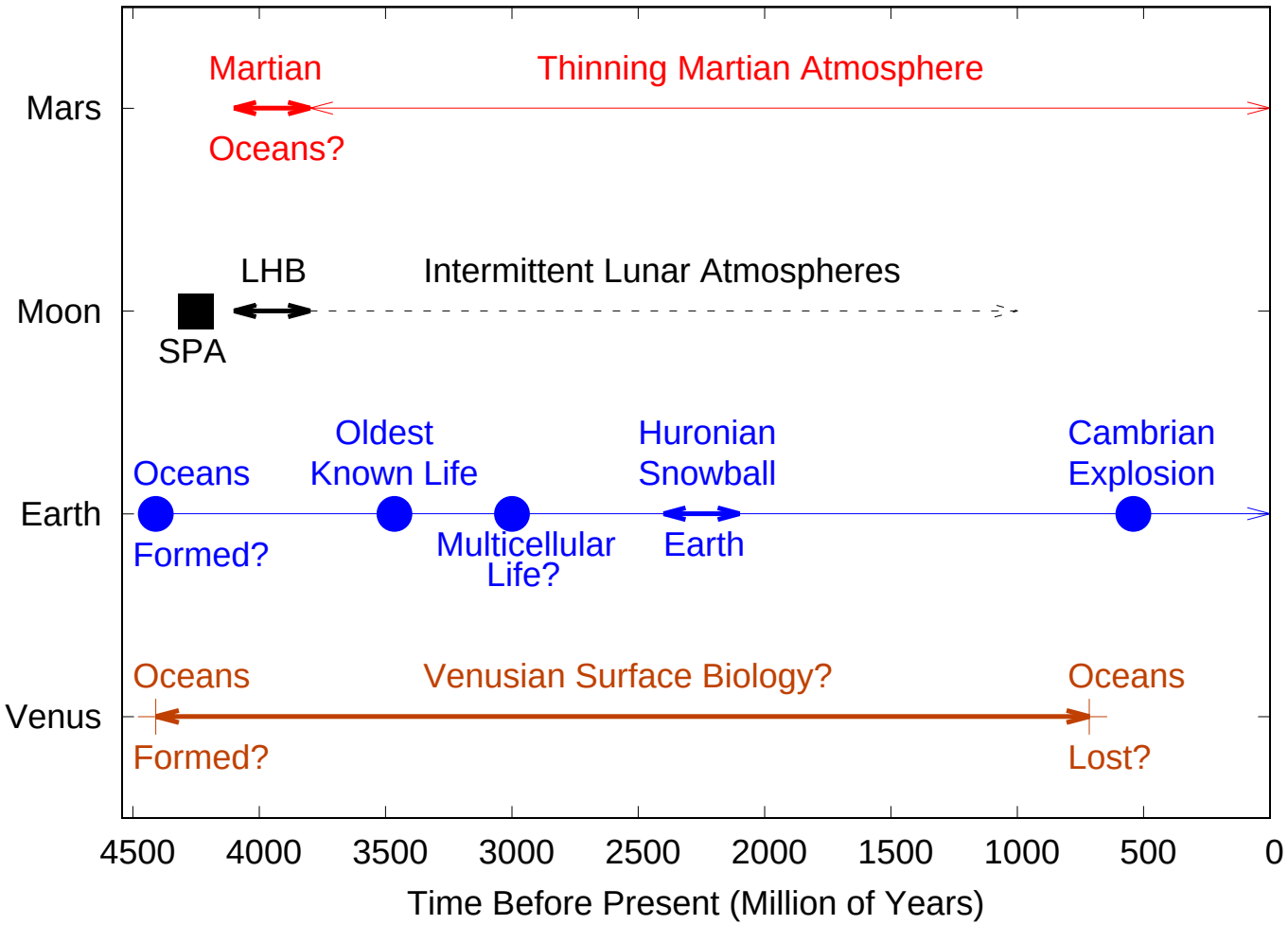
A Mote penetrator (held by SII Chief Engineer Paul Blase) before a ballistic flight using our penetrator cannon.

Water, Astrobiology and Science

Fossil Lunar Water Could be of Astrobiological Interest

- Life on Earth apparently began shortly after the formation of the oceans [Dodd et al., 2017, Lingam and Loeb, 2021].
- At that time,both Venus [Way et al., 2016] and Mars [Dickeson and Davis, 2020] may have possessed oceans and been habitable themselves, raising the question whether all three planets possessed early biospheres.
- The Earth and Mars have likely always been able to exchange biological material through the ejection of surface material after large meteorite impacts.
- A habitable Venus would also possibly been able to both send and receive biomaterial in the same fashion.
- Solar system panspermia may be possible after large meteorite impacts on biologically active bodies
- It however appears unlikely that living organisms or spores could survive vacuum impacts even at the 2.4 km s^{-1} lunar escape velocity [Jerling et al., 2008, Lingam and Loeb, 2021], and it is generally assumed that this sort of panspermia would not include the Moon.
- However, the Moon likely possessed temporary atmospheres after meteorite impacts or volcanic activity in its early history [Needham and Kring, 2017].
  - The same events that brought water to the Moon might have also caused an temporary atmosphere to form, thus enabling the Moon to receive biological material.
- The lunar interior, and especially buried lunar water, cannot be ignored as a possible repository for fossils of ancient life.

The Moon Could Store the Astrobiological History of the Solar System.



Periods in the history of the solar system when Venus, the Earth, the Moon and Mars could have supported mutual lithopanspermia, with atmospheres thick enough to slow down incoming meteorites but not (as for Venus today) too thick to allow for the ejection of debris after large impacts. Various geological and biological periods are indicated; SPA denotes the formation of the South Pole Aitken basin, from Garrick-Bethell and Miljković [2018], and LHB the Late Heavy Bombardment period. The period from the LHB to roughly 1 Gyr ago had numerous large lunar impacts, and thus recurrent periods of transient atmospheres. There was thus a period extending over roughly 3 Gyr when the Moon could have at times received biological material from other planets without the material being sterilized by hypervelocity impacts on the Moon.

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