Modeling Near-Surface Temperature Gradients and Thermal Emission from the Lunar Regolith

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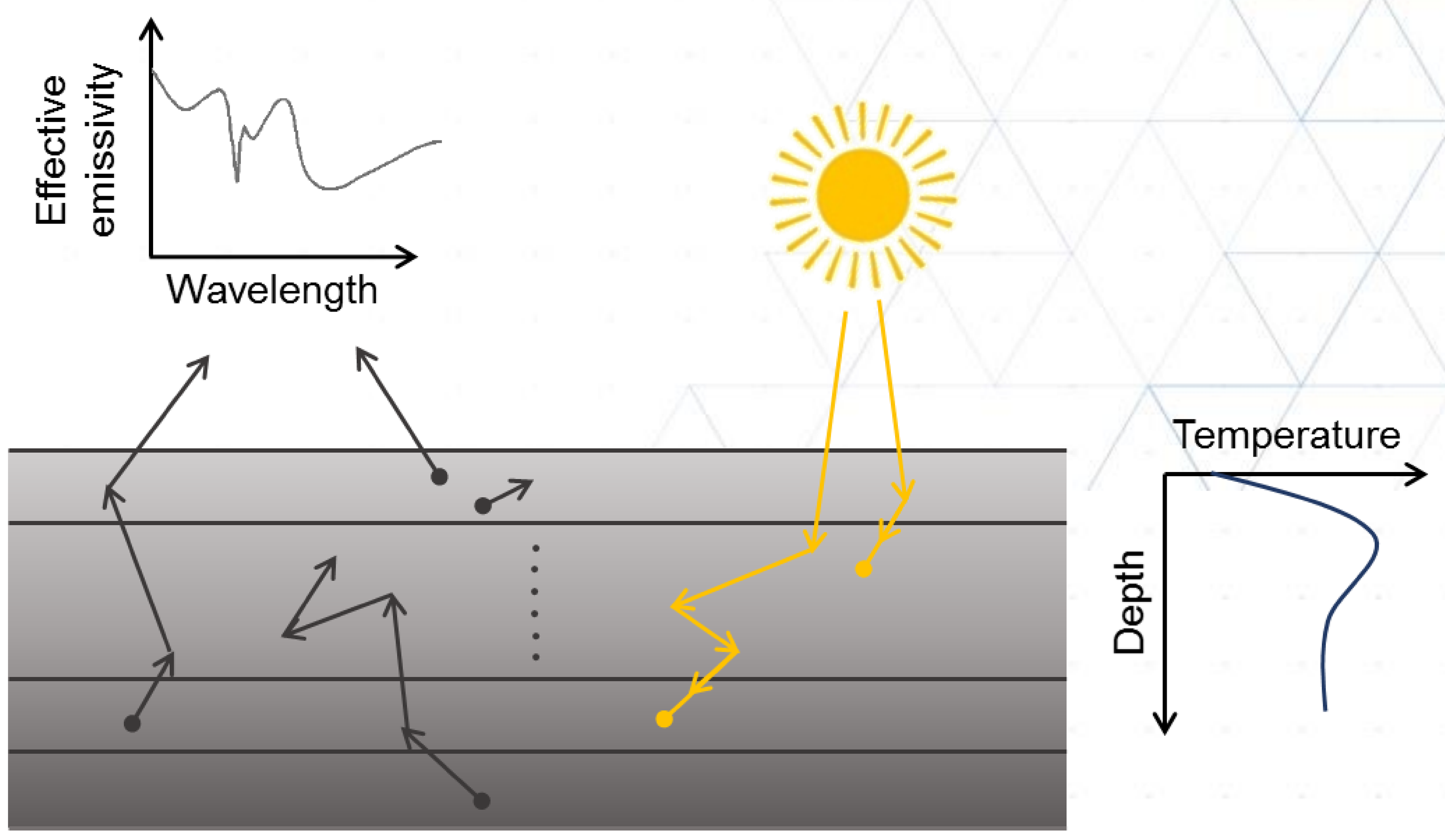
Motivation

Thermal emission measurements can provide a powerful means of determining the composition and texture of planetary surfaces. However, **in order to accurately interpret an emission spectrum, it is important to understand how temperature varies within the region of the subsurface from which 'surface' thermal emission originates.** This is particularly important on the Moon and other airless bodies, where low regolith thermal conductivity under near-vacuum conditions can give rise to steep near-surface temperature gradients, which in turn can influence the shape of emission spectra [1-4].

This work focuses primarily on two questions: What is the **magnitude and shape of near-surface temperature gradients under lunar-like conditions**? What is the relationship between **regolith properties**, the **near-surface thermal environment**, and **infrared spectral characteristics**?

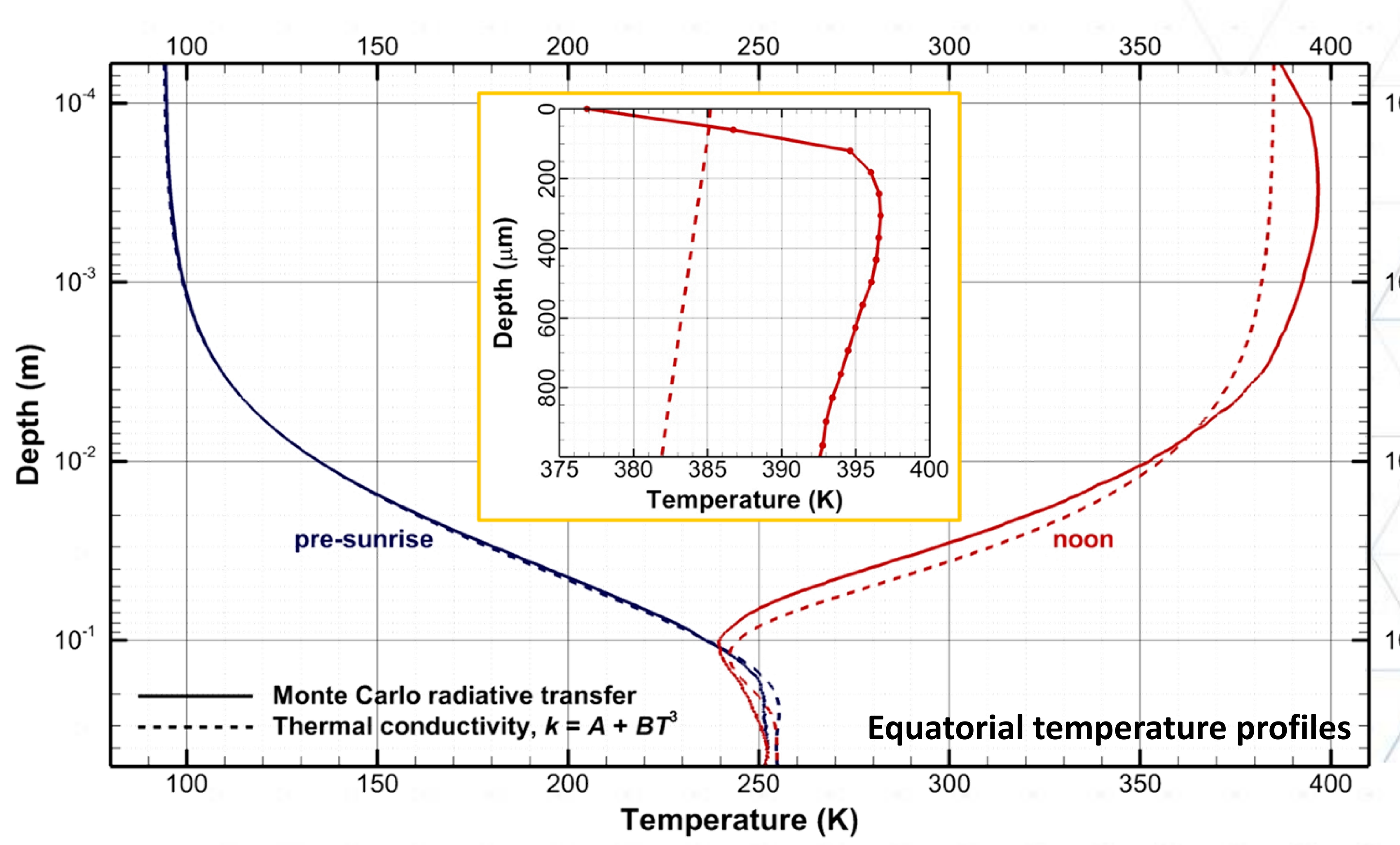
Numerical approach

ReBL: the Regolith Boundary Layer model



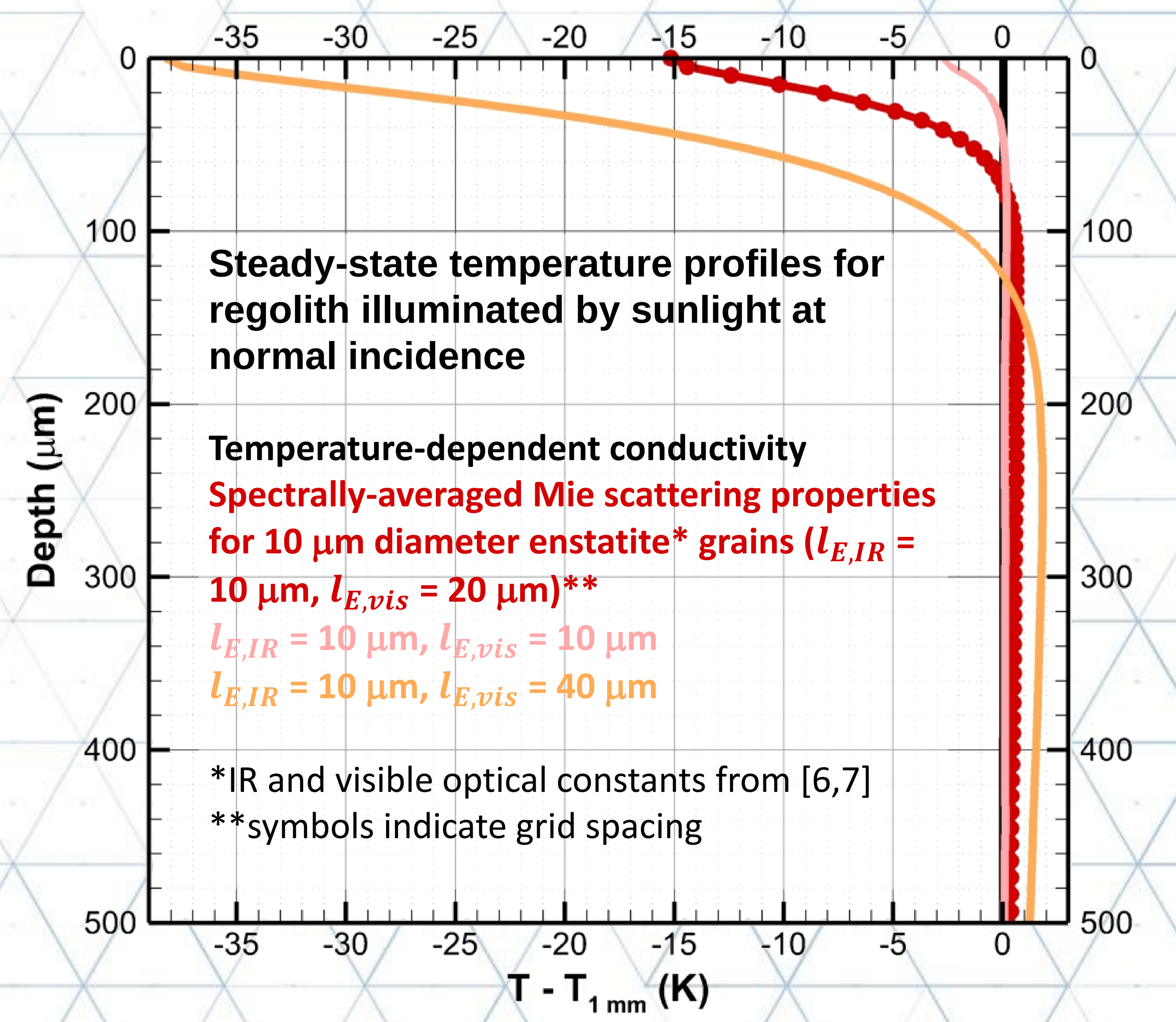
- Temperature, T at time t and depth z is governed by the 1-D heat equation, $\rho c(\partial T/\partial t) = \partial(k\partial T/\partial z - q_R)/\partial z$, controlled by **conductive** and **radiative** heat transfer.
- Radiative flux (q_R) is computed using a Monte Carlo approach, i.e. by tracking the propagation of a large number of representative bundles of **infrared (emitted)** and **visible (solar)** energy through a modeled plane-parallel regolith, accounting for scattering and absorption.
- **Extinction length** (l_E) and **single-scattering albedo** (w) are calculated separately and provided as input to the Monte Carlo code.
- Discretized governing equation is solved on a linearly stretched grid ($\Delta z_{i+1} = \alpha \Delta z_i$). Increasing cell size with depth (from **<10 μm** to ~10 mm over 0.5 m); time-step size limited by smallest cell size.

Radiative heat transfer vs. 'radiative conductivity'

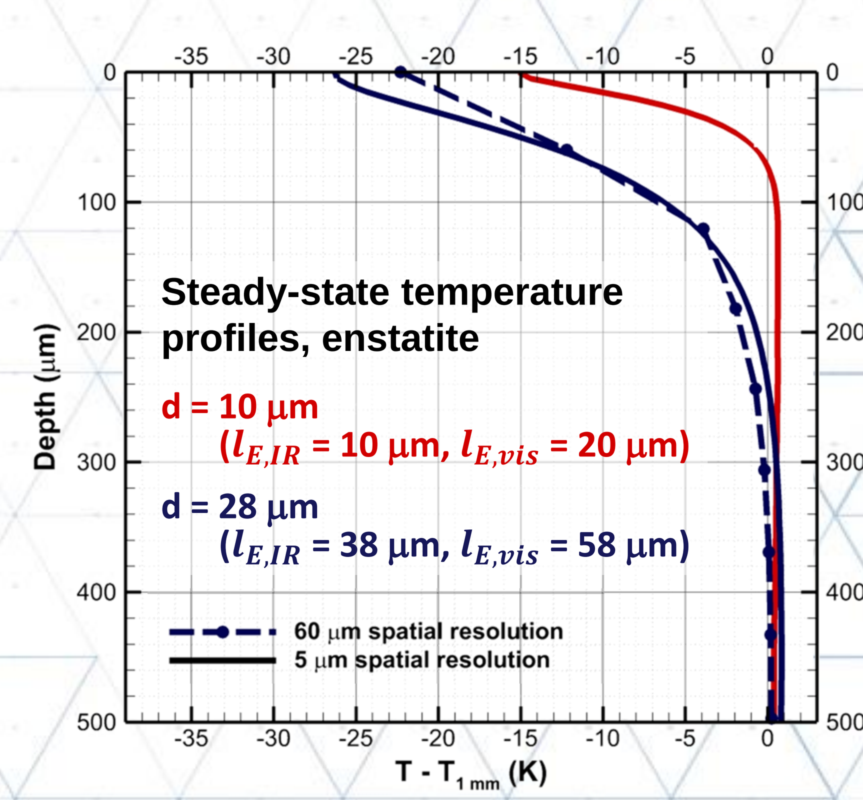


- A temperature-dependent conductivity cannot capture thermal gradients over length scales at which the medium is optically thin.
- Monte Carlo calculation uses $l_{E,IR}$ = 38 μm, $l_{E,vis}$ = 58 μm. Other thermophysical properties in both cases from [5]. Spatial resolution is 60 μm at the surface.
- Magnitude of near-surface gradient is maximum at noon, shape controlled by the balance between solar heating and infrared emission in the sub-surface.

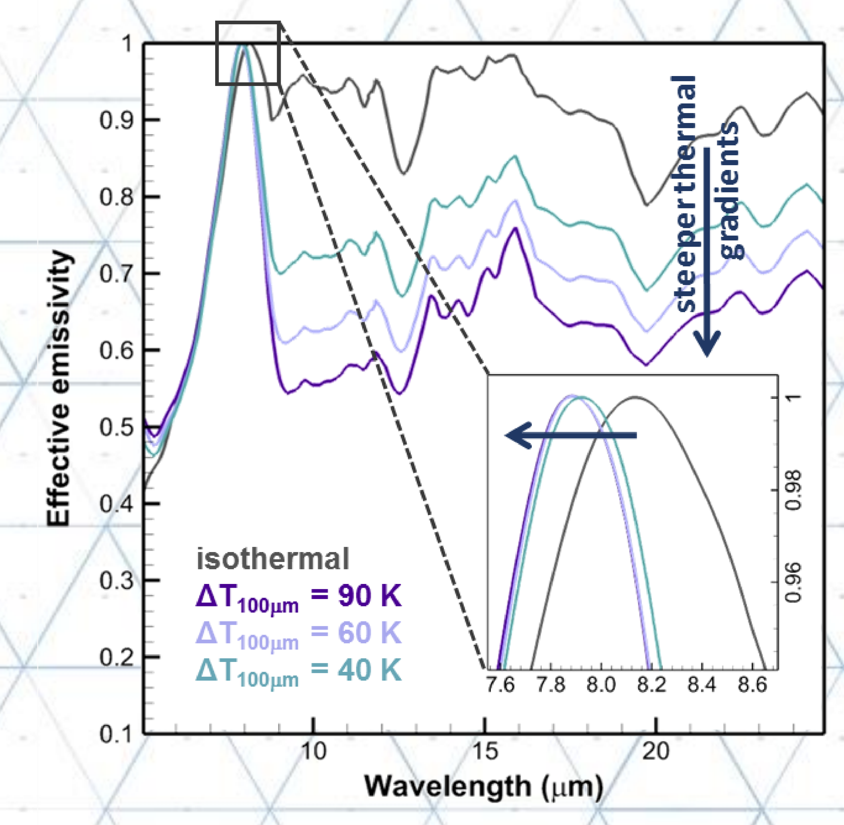
Regolith properties and the thermal environment



- **Greater contrast** between visible and infrared extinction lengths → **steeper** near-surface thermal gradient [1].
- Extinction length varies considerably across the IR spectrum, from ~8-10 μm in reststrahlen band regions to ~50 μm in the vicinity of the Christiansen frequency.



Grain size affects scattering/absorption properties, and thereby thermal gradients.



In turn, thermal gradients lead to changes in **spectral contrast** and a shift of the **emissivity maximum**.

Summary

Lunar 'surface' thermal emission originates within a thin, non-isothermal region of the sub-surface (the 'epiregolith' [8]). The magnitude and shape of epiregolith thermal gradients depends strongly on regolith properties such as composition and grain size, all of which in turn influence the characteristics of measured emission spectra.

Future investigations

- Model thermal gradients at various latitudes/times of day on the Moon, as well as under simulated lunar environmental conditions in the lab, and characterize the resultant changes in spectral characteristics.
- How strongly do spectral variations in optical properties influence sub-surface thermal gradients?
- What scattering/absorption properties are representative of the lunar regolith? How do we account for roughness, space weathering and other factors?

References: [1] Henderson & Jakosky (1997), *JGR;* [2] Hale & Hapke (2002), *Icarus*; [3] Millán et al. (2011), *JGR*; [4] Donaldson Hanna et al. (2012), *JGR*; [5] Hayne et al. (2017), *JGR*; [6] Zeidler et al. (2015), *ApJ*; [7] Huffman & Stapp (1971), *Nature Phys. Sci.*; [8] Mendell & Noble (2010), *LPSC*.

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