THERMAL SPECTRA OF SIMULATED METER-SCALE PURE-ICE PENITENTES, WITH RELEVANCE TO EUROPA CLIPPER SPECTROSCOPY.

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Introduction: Penitentes are thin, blade-like ice structures that naturally form on Earth. Found in locations with high solar flux and low humidity, their formation is driven by incident sunlight focused towards the troughs, light penetration and heat conduction within the snow surface, and nonuniform sublimation and melting where the troughs sublimate faster than the peaks [1]. Penitente formation on the Jovian moon of Europa is debated, as Europa's near-vacuum atmosphere and negligible vapor layer present a regime different than Earth's and whose physics are not well encapsulated in any preexisting model [2]. Resolving this question of Europan penitente formation is paramount to the success of any future lander mission, as meter-scale penitentes would pose a serious issue for a successful landing.

To help settle this question, we have developed and validated a computational radiative and conductive heat transfer (RHT) model that simulates solar and black body radiation through rough snow and ice surfaces [3]. This model accounts for wavelength-dependent multi-scattering of photon bundles to output the internal heat sources within the snow surface (Figure 1). These internal heat sources, combined with the radiative cooling of the surface, are then used to solve heat conduction for an adaptive mesh, outputting the temperature of the snow surface and within the snowpack. These two processes, photon scattering and heat transfer, are iteratively repeated until the temperatures of the snowpack have reached a steady, diurnally periodic cycle.

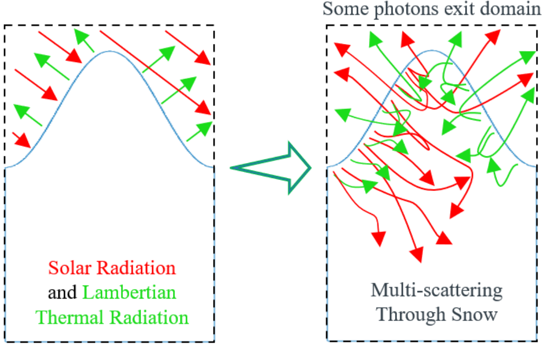

Figure 1: Photon scattering and absorption within the simulated snow surface. A periodic boundary condition is imposed on the left and right sides of the domain to simulate an infinitely long penitente field. Crucially, some photon bundles exit the domain through the top.

The post-heat transfer surface temperatures can be used to simulate sublimation in an airless, free molecular regime, providing insight into penitente growth or erosion on Europa. This is currently being investigated by our team [4].

However, another path of research lies exclusively within the RHT model. As Figure 1 shows, during the photon scattering process, there are some photon bundles that backscatter and exit the domain after partial absorption within the snow. Some black body photons emitted directly from the free surface may not re-strike the surface at all, instead exiting the domain with the same characteristics as when they were emitted. Together, these so-called "exitance" photons provide a spectral signature of the European surface that spacecraft such as the upcoming *Europa Clipper* can detect (Figure 2), potentially allowing scientists to help answer the question of penitente formation from a remote sensing perspective. Consequently, we explored the *thermal* spectra of meter-scale pure-ice penitentes compared to a flat snow surface. Although the reflected solar spectra is of equal importance, that will be the subject of a future investigation.

Methods: Using our RHT model, we simulated solar exposure, black body self-radiation, light absorption, and heat conduction of meter-scale sinusoidal penitentes with various height-to-width ratios. A height-to-width ratio of 0 corresponds to a flat surface. The sun's spectral emission is approximated as a black body at Jupiter's average distance to the Sun (5.2 AU), and its path is simulated as moving parallel to the penitente's ridges.

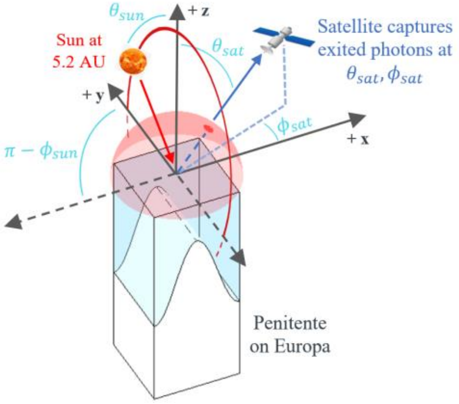

Figure 2: Diagram of the simulated domain. The Sun's path was simulated to be in the yz-plane.

The RHT model is run until the temperatures of the simulated penitentes have reached a steady, diurnally periodic cycle. Using these diurnal temperature fluctuations, the black body emission of the penitentes is simulated again. As a subset of photons exit the domain, their wavelength, energy, zenith angle, and azimuth angle are recorded. The zenith and azimuth angles are then used to bin the exited photons into a hemispherical angular grid, representing the various locations that a spacecraft may be located relative to the penitente. Finally, the spectra of each angular bin can be produced with the wavelength and energy values.

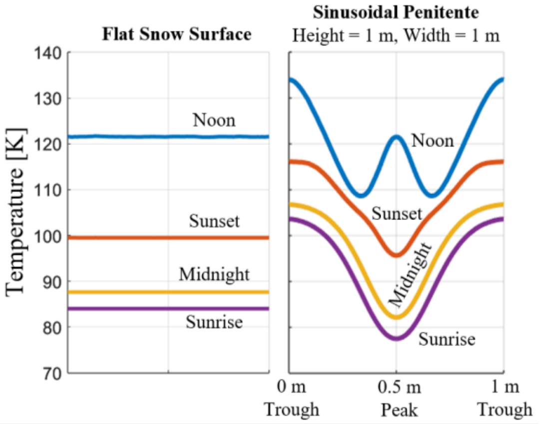

Figure 3: Diurnal temperatures of a flat snow surface and sinusoidal penitente on Europa. Both of these periodic swings are close to *Galileo* readings, which observed diurnal temperature fluctuations between 86 and 132 K at low European latitudes [5].

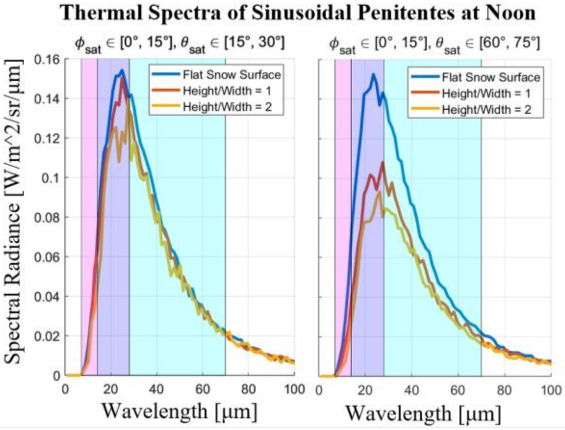

Figure 4: Thermal spectra of meter-scale penitentes from two angular perspectives at noon (see Figure 2 for angle definitions). The three differently shaded wavelength bands correspond to the spectral bands of E-THEMIS, an infrared imager onboard *Europa Clipper*.

Results: For a penitente's thermal spectral signature, the temperatures of the sides and peak are more relevant, as photons emitted from a lower height, especially from the troughs, have a high likelihood of being reabsorbed back into an adjacent penitente instead of exiting the domain.

At noon, the temperature of the penitente's peak is very close to the temperature of a flat snow surface (Figure 3). In addition, black body photons emitted from the penitente's peak are almost guaranteed to exit the domain (Figure 1). Combined, this causes the thermal spectra of a sinusoidal penitente and a flat snow surface to be nearly identical from a nadir perspective (Figure 4).

However, from a more oblique viewing angle, the thermal spectra noticeably differ (Figure 4). This is from two effects. Due to the nature of Lambertian scattering, where near-normal trajectories are biased, oblique viewing angles receive a higher number of photons from the side of the penitente compared to the peak. As the sides of the penitente are cooler than a flat surface at noon (Figure 3), we should expect the oblique angle spectra to shift rightward. However, as the temperature difference is minimal (at most 15 K), this shift is not obvious. The more prominent effect at play, and the reason for the clear downward shift, is that photons emitted from the sides have a chance to be reabsorbed back into an adjacent penitente. In other words, due to a higher possibility of reabsorption, the exitance "power" of the sides is weaker than the peaks, resulting in weaker oblique spectra for penitentes compared to a flat surface.

Conclusion: The thermal spectra of pure-ice, sinusoidal penitentes on Europa was investigated. Using a radiative heat transfer model, the steady, diurnal temperatures of various height-to-width ratio penitentes was found, and the thermal spectra at noon was produced. Due to the potential redeposition of black body photons emitted from the sides of the penitente, the penitente spectra at oblique angles is shifted downward compared to the spectra of a flat snow surface, while the spectra from nadir perspectives is roughly equivalent. Future investigation will examine the spectra of different times of day, the spectra of reflected and backscattered solar radiation, and the effect of varying parameters such as density, heat conductivity, and snow grain radii.

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References: [1] Claudin, P. et al. (2015), *Physical Review E*, *92*(3), 033015. [2] Hand, K.P. et al. (2020). *Nat. Geosci.*, *13*(1), 17-19. [3] Carreon, A. et. al. (2023) *JGR.* [4] Macias, A. et. al. (2023) *JGR.* [5] Spencer, J. R. et. Al (1999), *Science*, *284*(5419), 1514-1516.