# Reflectance and Emission Modelling of Airless Exoplanets

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## Introduction

**Rocky airless bodies** in the solar system, e.g., Mercury, the Moon, and many asteroids, host a rough silicate **regolith** layer. The surface roughness influences their reflectance and emission phase curves. At small phase angles, the **opposition effect** increases the reflected radiation, and **thermal beaming** leads to higher emitted radiation compared to smooth surfaces (see Figure 1). At higher phase angles, surface roughness leads to **shadowing**, i.e., the measured thermal emission is smaller than predicted by the equilibrium model for a smooth surface.

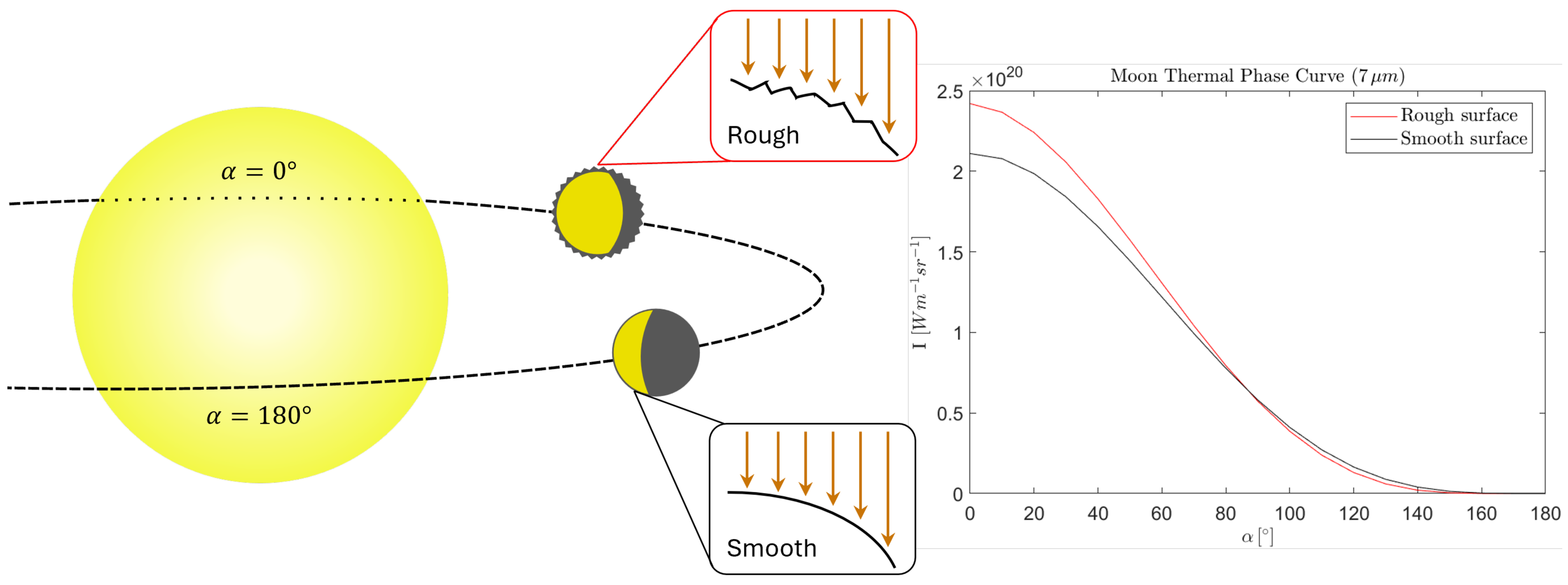


Figure 1: Simulated phase curves for a rough and a smooth surface. Adopted from [6]

The rocky exoplanets **LHS 3844 b** [1], **GJ 1252 b** [2], **TRAPPIST-1 b** [3], and **TRAPPIST-1 c** [4] are roughly Earth-sized, likely have no atmospheres, and their surfaces largely remain mysterious. In this work, we model the reflectance and emission of airless exoplanets and analyze how surface roughness and albedo affect the infrared phase curves. The resulting model can then impose constraints on the surface structure of the exoplanets.

## Methods

We model the reflectance component of the radiation with the **Hapke model** [7] and fix all parameters except for the spectral **single-scattering albedo**. We derive two example sets of albedo values from lunar satellite and returned sample data (arbitrary single-scattering albedos are possible):

- **Mare** albedo: darker surface, basaltic composition
- **Highland** albedo: brighter surface, feldspathic composition

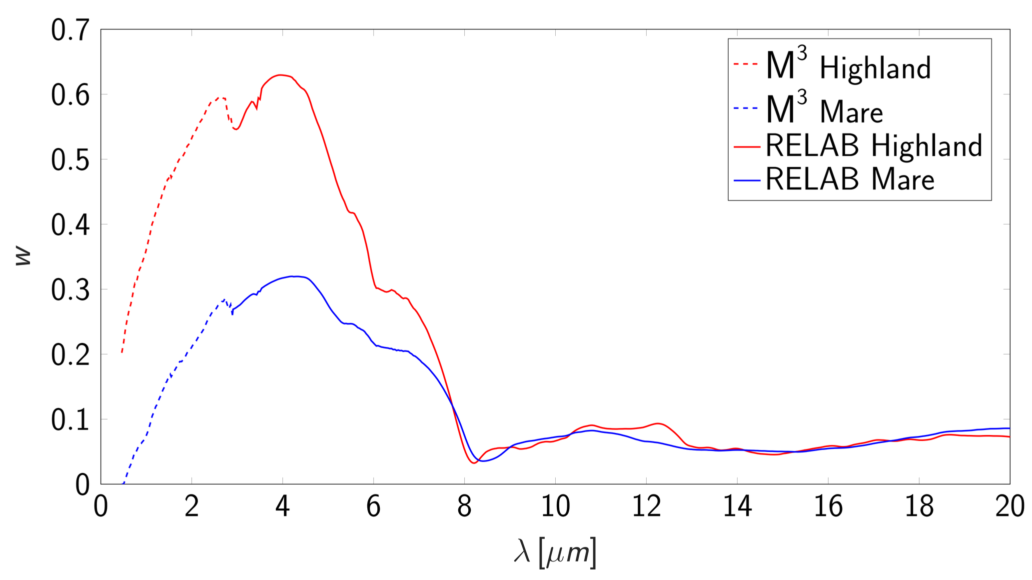


Figure 2: Single-scattering albedos used for the exoplanet phase curve computation.

We use the **thermal roughness model** from [5] for the emission component, which is mainly controlled by the albedo and the roughness parameter (**average roughness angle**). We simulate disk-resolved radiances of the planets for different phase angles and integrate them over the disk to retrieve the phase curves. We focus on the wavelength region of the JWST NIRSpec G395H/F290LP disperser/filter combination (2.7 μm – 5.2 μm).

## Partially molten surface

The high surface temperature may lead to **partial melting** and prohibit the formation of a rough regolith layer. However, the thermal beaming effect originates from the edge of the visible disc far from the subsolar point. To demonstrate this, we combine the rough and the smooth model in Figure 3. Where the brightness temperature of the rough model exceeds 1000 K, we assume a smooth surface. The phase curve of the **combined model is almost indistinguishable from the rough model**.

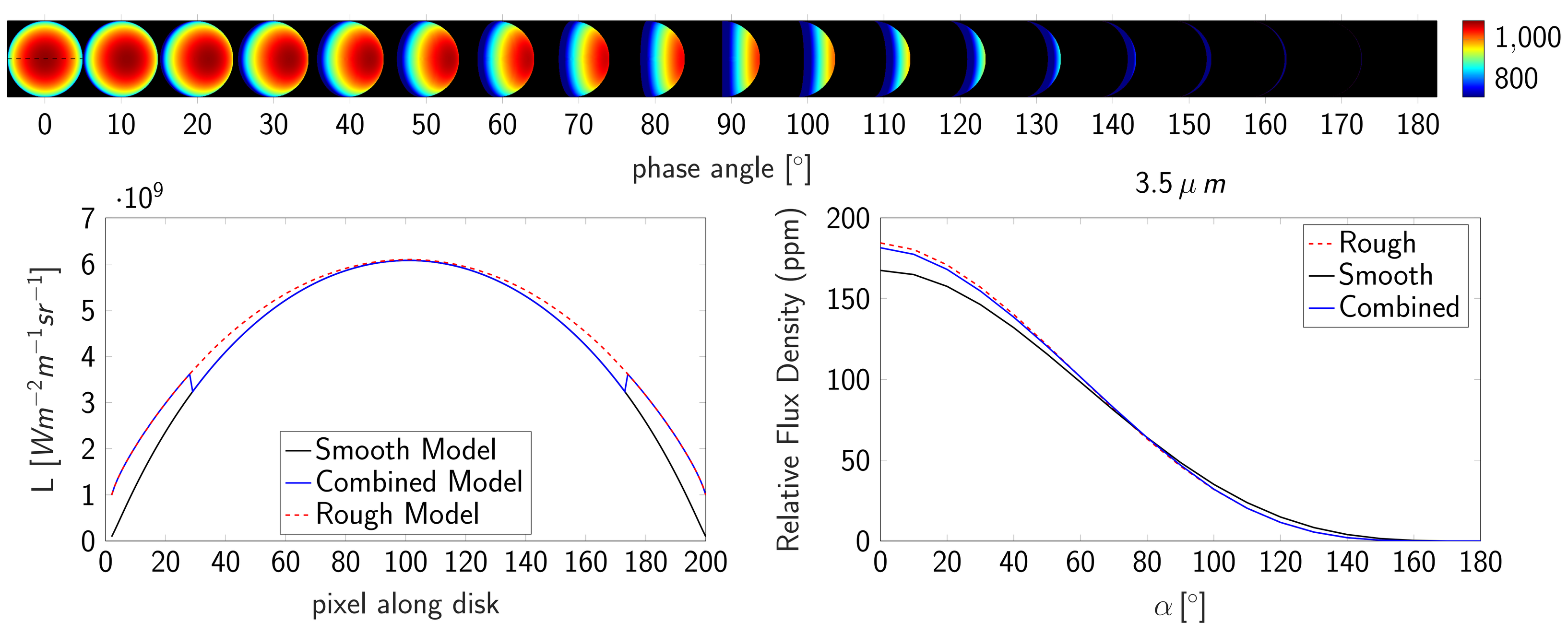


Figure 3: Top: Simulated disk-resolved brightness temperature for LHS 3844 b. Bottom left: Radiance along the marked profile. Bottom right: Thermal emission phase curve for the rough, smooth and the combined model.

## Results

Figure 4 shows the reflectance and emission phase curves for LHS 3844 b for different roughness angles and albedos. The **reflected component** is smaller than the emitted component in the infrared wavelength region but **not negligible**. The **thermal beaming** and shadowing effects are clearly visible. The opposition effect is most likely not detectable due to the occultation of the planet during the secondary eclipse.

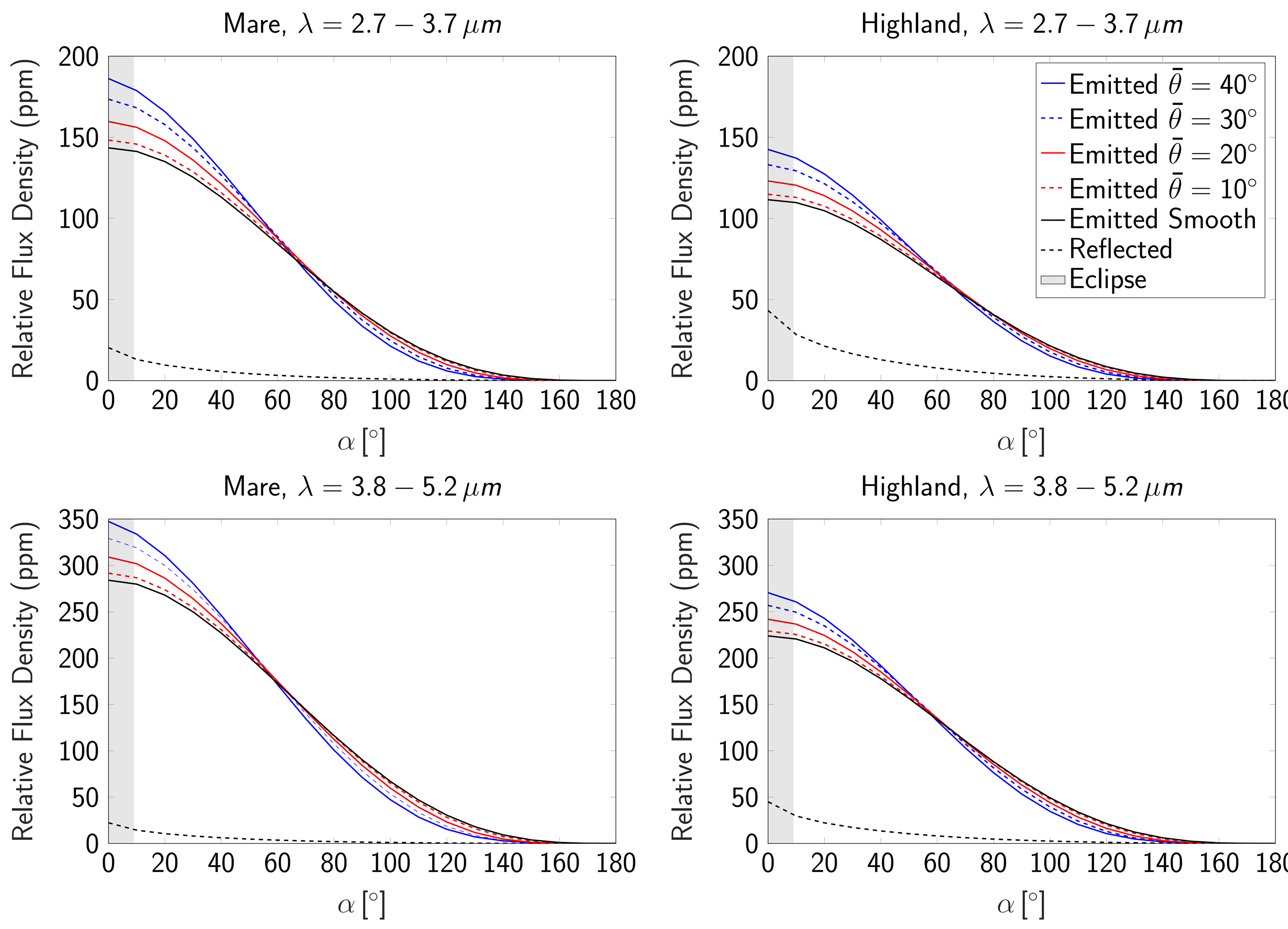


Figure 4: Simulated reflectance and emission phase curves of LHS 3844 b in 2 wavelength regions for different albedos (Mare, Highland) and surface roughness angles.

The simulations of all four exoplanets show that the **albedo influences the amplitude of the phase curve**, and the **surface roughness alters the shape of the phase curve**. Figure 4 shows that the two parameters appear interchangeable at small phase angles (close to the secondary eclipse). However, considering the entire phase curve allows **albedo and surface roughness to be separated**. Figure 5 shows the combined phase curves for the other three exoplanets. The phase curve of GJ 1252 b is like that of LHS 3844 b and the parameter influences can likely be separated. TRAPPIST-1 b and TRAPPIST-1 c have much lower relative flux densities, which makes parameter retrieval difficult.

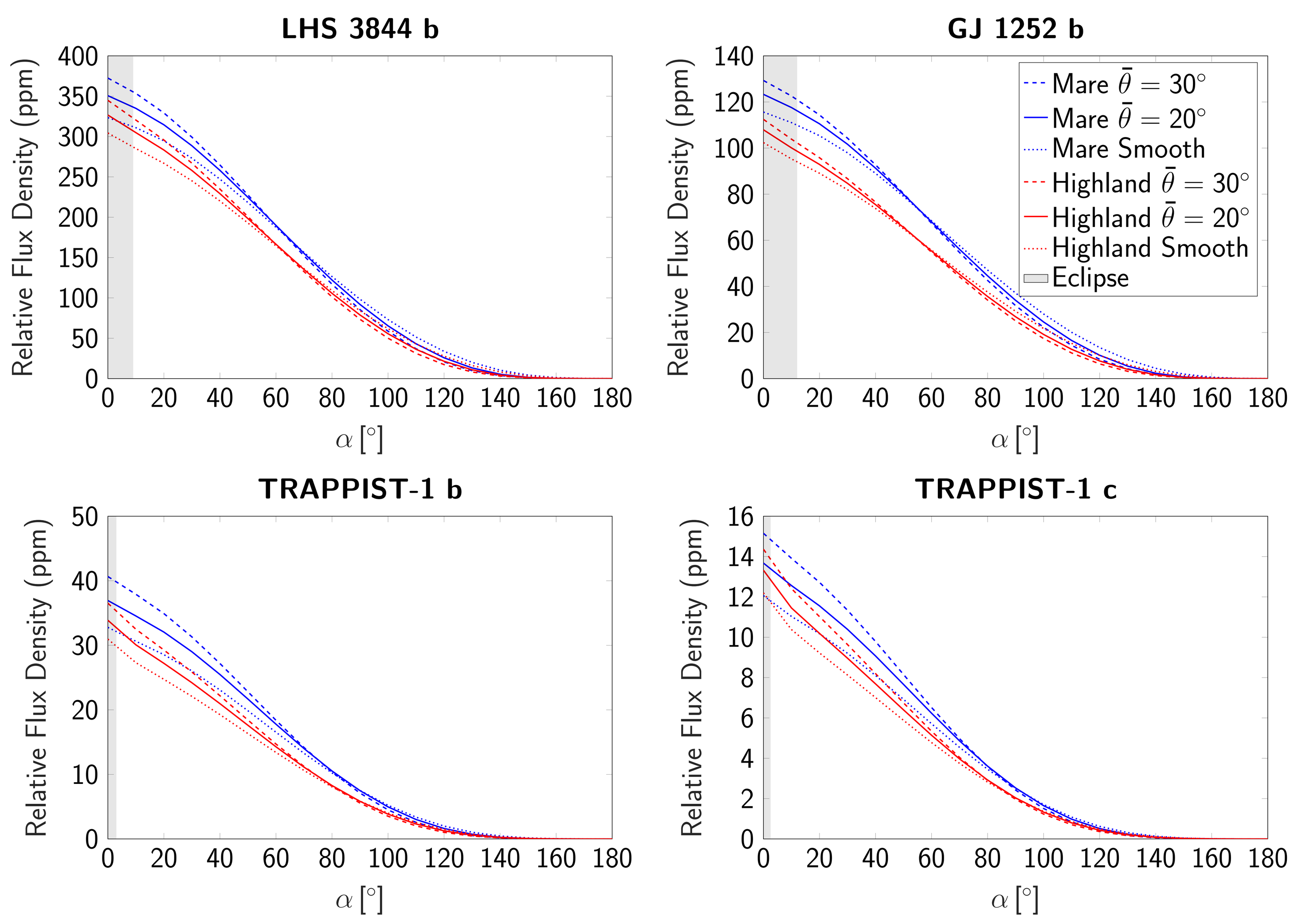


Figure 5: Combined reflectance and emission phase curves for the wavelength 3.8 – 5.2 μm.

## Conclusion

The surface roughness and albedo effects are detectable and most likely separable for LHS 3844 b and GJ 1252 b with NIRSpec on JWST. This would allow the **retrieval of one or both parameters from phase curve measurements**, which can provide information about the nature of extrasolar planetary surfaces (e.g., similarity to solar system objects). Additional albedo constraints can further improve the retrieval scheme. Due to extensive space weathering, the closely orbiting exoplanets likely have a low albedo, similar to Mercury or the maria of the Moon.

Our combined model can easily be adapted to additional targets and allows for a wide range of parameters. This makes it a **powerful tool for the analysis of phase curve measurements** of airless exoplanets. We are currently using the model to investigate NIRSpec measurements of LHS 3844 b (JWST, GO 4008 [6]).

## References

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