THE LUNAR EPI-REGOLITH – A HYPOTHESIS TO EXPLAIN THE LUNAR FLYBY DATA OF MERTIS.

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Introduction: On 10th April 2020, the BepiColombo spacecraft performed a gravity assist maneuver with Earth [1]. During the flyby, the MErcury Radiometer and Thermal Infrared Spectrometer (MERTIS) [2, 3] acquired the first high-resolution space-based thermal infrared measurements of the lunar surface. To obtain emissivity spectra (7-14 µm), we carefully calibrated the radiance data of the spectrometer. We used an advanced fractal thermal roughness model [4] similar to [5, 6]. The resulting spectra are surprising because they do not exhibit a strong Christiansen feature around 8 µm, which was expected based on laboratory measurements of Apollo samples [7] and rare telescopic measurements [8] in the thermal infrared. Instead, the spectra have an emissivity minimum near 8 µm and an emissivity maximum at 9 µm. The comparison with laboratory spectra of common lunar minerals does not yield a clear identification of the mineral phases that are known to occur on the moon [9]. There is no clear silicate mineral composition or other effects such as grain size, temperature, or submicroscopic iron that can account for the spectral shape. Further, no significant spatial variations are found across the lunar disk.

One working hypothesis to explain the spectral shape is the following: The uppermost layer of the regolith underwent extensive space weathering that leads to a very thin but porous layer that is dominated by agglutinates and glassy mineral rims. This layer, also known as the epi-regolith, could not be preserved by any sample return mission so far. Thermal gradients are known to establish in the uppermost layer of the regolith of an airless planetary body and to be responsible for small spectral shifts, as described by [7, 10, 11]. We assume a heterogeneous composition of this layer and assume that the outermost layer is dominated by a glassy component. Strong thermal gradients lead to the effect that thermal emission comes from deeper layers of the regolith (on scales of several tens to one-hundred micrometers) and is modulated by a cold glassy layer on top. Because the uppermost layer is thin and cold, it effectively reflects the thermal emission that comes from several microns below. The resulting spectrum is an intricate combination of mineral emissivity spectra and glassy reflectance spectra. The glassy reflectance spectra account for the maximum around 9 µm and the minimum near 8 µm. There is also an interaction between minerals, causing a shift of the secondary minimum. The more mafic the minerals are, the stronger the shift to higher wavelengths. To test this hypothesis, we performed light scattering simulations of the upper regolith and found that it can successfully reproduce the effects seen by MERTIS on a qualitative level.

Methods: We used the DIScrete Ordinates Radiative Transfer (DISORT) framework [12] to simulate the uppermost layer of the regolith. We assume that this layer consists of a mineral mixture and is covered by a glassy layer. The single-scattering albedos of both materials are retrieved from the emissivity spectra of the Berlin Emissivity Database [13]. A thermal gradient was constructed, comparable to [11]. The optical depth is calculated from the emissivity spectra. We run the model with various numbers of layers and relative optical depths of these layers and try out different mineral compositions.

Results: The results of the DISORT simulations in comparison to MERTIS spectra are shown in Figure 1. The dashed black line shows the mean mare spectrum, and the solid black curve shows the mean highland spectrum. The red curve is a scaled and offset version of the DISORT result. One can see that the most important features of the lunar spectra are well reproduced: (1) There is a local minimum around 8 µm, (2) a global maximum around 9 µm, and (3) a decline towards larger wavelengths. All these features qualitatively agree with the spectral features found in MERTIS data. However, there is a deviation beyond 10 µm.

Discussion: At first glance, the novel dataset and the hypothesis presented seem to contradict previous findings. However, we can put forward several arguments to alleviate the contradictions.

Why do the Apollo return samples don't look like this in the lab? Emission spectra of the Apollo soil samples [14] do not exhibit these effects but behave as a "normal" mixture with a maximum around 8 µm and a decline for larger wavelengths. This may be related to the fact that the upper layer of the regolith is fragile and was not preserved in the Apollo samples. It was either blown away by the landing rocket jet [15] or destroyed while collecting and transporting the samples. Hence, one cannot reproduce these effects in the laboratory even if one uses original Apollo samples.

Does it contradict telescopic observations of the Moon? There are also examples of TIR telescopic measurements of the Moon that show strong Christiansen features that are not present in MERTIS data [8]. However, the telescopic measurements were targeted and some may have captured a young or unusual area. Because the resolution of MERTIS was comparatively low on the Moon, one MERTIS pixel contains the spectral average of larger regions (about 500 km x 500 km) that cannot resolve local spectral characteristics resolved in the telescopic spectra, for example, crater walls. Other spectra in [8] also exhibit a maximum around 9 µm and a minimum at 8 µm.

Does it contradict the Diviner findings? The DIVINER radiometer has three channels in the region around 8 µm, which were used to determine the Christiansen feature wavelength of the lunar regolith [16]. It was found that the Christiansen feature has a mean position of 8.15 µm for feldspathic highlands and 8.3 µm for mafic mare regions [16]. The findings from MERTIS seem to contradict the results from DIVINER because the MERTIS-measurements do not exhibit a clear Christiansen feature around 8 µm. Further investigations are needed to explain these differences.

An independent check of MERTIS with Venus. On 15th October 2020, MERTIS performed a swing-by maneuver with Venus [17]. Infrared spectra were obtained that feature the thick atmosphere of Venus. The radiance spectra were compared to an established atmospheric model showing a good overall agreement [18]. This independent test strongly supports the credibility of the lunar MERTIS spectra.

Summary and conclusion: MERTIS lunar spectra are puzzling and do not confirm what was expected. The new hypothesis helps to explain these spectra given only materials that are already known to be present. Simulations with DISORT radiative transfer modeling yield first results that are consistent with the findings of MERTIS. Further simulations, measurements, laboratory experiments, and ultimately, close-up images of the untouched epi-regolith are necessary to thoroughly test this hypothesis and arrive at a better understanding of MERTIS lunar flyby spectra. Laboratory experiments with thin glassy layers on top of a mineral regolith were carried out at the Planetary Spectroscopy Laboratory in Berlin and are presented in this conference [19]. First evidence is shown that thin glassy layers may be responsible for significant shifts of features in the measured spectra that may explain the spectra seen by MERTIS [19]. Further experiments involve spectral unmixing with glassy endmembers [20].

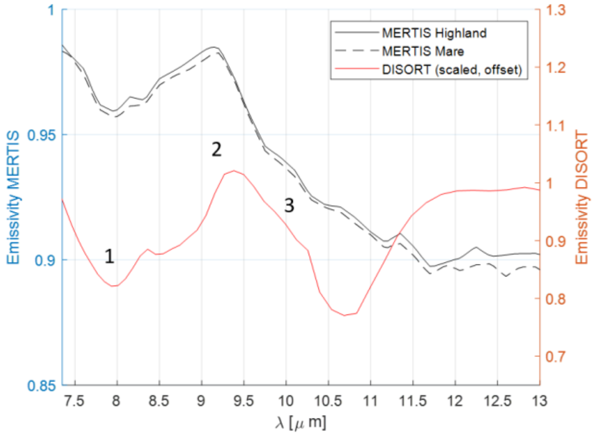

Figure 1. Comparison of DISORT-modeled spectrum (red) with mean mare and highland spectra of MERTIS (black, [4]). The result from DISORT is a glassy layer on top of anorthite (scaled and offset). Note that features 1, 2 and 3 are found in the measured and the modeled spectra. However, there is a deviation beyond 10 µm which is currently unexplained.

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