RESEARCH ARTICLE
10.1029/2019JE006338

Key Points:
• The Lunar Orbiter Laser Altimeter is sensitive to temperature-dependent changes of normal albedo
• At 1,064 nm, the maria show a slightly stronger negative change in surface reflectance with temperature than the highlands
• The measured temperature-dependent changes in normal albedo are consistent with the presence of pyroxene at the lunar surface

Supporting Information:
• Supporting Information SI
• Table SI

Correspondence to:
A. N. Deutsch, ariel_deutsch@brown.edu

Citation:

Received 18 DEC 2019
Accepted 27 MAR 2020

Abstract Over the extreme temperature variations experienced in a single lunar day \((T \approx \pm 300 \, \text{K})\), particular minerals common to the lunar surface show spectral changes at discrete near-infrared wavelengths in laboratory settings (Roush & Singer, 1986, 1987, https://10.1111/10.1029/IB091iB10p10301, https://10.1111/10.1016/0019-1035(87)90026-1; Singer & Roush, 1985, https://10.1111/10.1029/JB090iB14p12434). Variations in temperature can cause variations in the size and shape of crystallographic sites, which control the position, shape, and depth of crystal field absorptions. At an observation wavelength of 1,064 nm, the Lunar Orbiter Laser Altimeter (LOLA) should be highly sensitive to temperature-dependent changes of orthopyroxene. Here we analyze temperature-dependent spectral changes of the lunar surface as measured from orbit by LOLA. We couple LOLA measurements of normal albedo with measurements of surface temperature from the Diviner Lunar Radiometer Experiment, analyzing the maria and highlands between ±50°. We provide the first evidence of temperature-dependent spectral changes on the lunar surface from orbital observations, finding that the majority of the surface between ±50° demonstrates a small, yet measurable, negative change in 1,064-nm albedo with temperature \((-R/T)\). The measurable effect is on the order of a few percent change in reflectance per ~80 K, indicating that temperature changes do not have a large effect on measurements of albedo at the sensitivity of the LOLA instrument. Stronger \(-R/T\) values tend to be associated with regions with elevated orthopyroxene, and the maria typically have higher levels of orthopyroxene and stronger \(-R/T\) values than the highlands. Our results suggest that single-wavelength lasers may be powerful tools for understanding the distribution of particular minerals on the lunar surface.

Plain Language Summary In a single day, the surface temperature of the Moon varies over 300 K (540 °F). This massive swing in temperature can affect the ways in which we measure light that is scattered from the lunar surface. The properties of scattered light are important tools for understanding the color and mineralogy of the Moon’s surface; therefore, understanding the influence of temperature on these properties is particularly important in interpreting the presence of different rock-forming minerals or ices on the Moon. Here we measure the effect that temperature has on measurements of surface reflectance specifically for the Lunar Orbiter Laser Altimeter, which is an instrument onboard the Lunar Reconnaissance Orbiter and currently orbiting the Moon. We find that there is a small yet measurable effect where surfaces tend to appear brighter when the surface is colder. This change is consistent with previous laboratory studies of lunar minerals and soils that detected a temperature-dependent change in reflectance properties.

1. Introduction

The thermal environment of the lunar surface is extreme due to the lack of any appreciable atmosphere, the Moon’s slow rotation, and the highly insulating nature of the surface (Vasavada et al., 2012). As a result, equatorial surface temperatures drop ~300 K between local noon and night (Williams et al., 2017). Interestingly, over this great temperature range, mafic rock-forming minerals common to the lunar surface (pyroxene and olivine) show spectral changes in the near-infrared (IR) wavelengths (e.g., Hinrichs & Lucey, 2002; Roush & Singer, 1986, 1987; Singer & Roush, 1985). Variations in temperature cause variations in the size and shape of crystallographic sites, which control the position, shape, and depth of crystal field absorptions (Singer & Roush, 1985).
Multiple laboratory studies have demonstrated the near-IR spectral changes that pyroxene and olivine show with respect to temperature (Hinrichs & Lucey, 2002; Roush & Singer, 1986, 1987; Singer & Roush, 1985). For a constant mineralogy, higher temperatures (red colors in Figure 1) produce a broader absorption band at near-IR wavelengths. In contrast, lower temperatures (blue colors in Figure 1) result in site contraction, producing a narrower absorption band, an increase in the crystal field splitting energy, and an increase in reflectance (Hinrichs et al., 1999; Roush & Singer, 1986, 1987; Singer & Roush, 1985). The spectral dependence on temperature with wavelength is referred to as the thermo-reflectance spectrum and can be quantified as the change in reflectance with temperature as a function of wavelength, $R/T$, in units of K$^{-1}$ (Hinrichs & Lucey, 2002). Hinrichs and Lucey (2002) demonstrated that the thermo-reflectance spectra of pyroxene and olivine are distinct and the wavelengths that are most sensitive to the $R/T$ of each mineral are unique.

The unique thermo-reflectance spectra of pyroxene and olivine have been used previously to characterize the mineralogy of small airless bodies. For example, the spectral properties of Eros as measured by the NEAR-Shoemaker spacecraft were observed to vary with temperature in the near IR (Lucey et al., 2002). These variations were used to assess the abundance of olivine and to suggest that Eros has a surface composition similar to that of an LL chondrite (Lucey et al., 2002). Temperature-dependent spectral effects have also been used to explain the differences between the spectra of olivine-rich A-asteroids (observed at low temperatures in space) and the laboratory spectra of olivines (measured in ambient conditions); the spectra of A-asteroids were most similar to laboratory measurements of low-Fe olivines acquired at low temperatures reasonable for the heliocentric distance of the main asteroid belt (Lucey et al., 1998).

Temperature-dependent spectral effects of different rock-forming minerals are dependent on wavelength, and one of the largest changes for pyroxene overlaps with the 1,064-nm observation wavelength of the LOLA (Smith et al., 2010, 2017) (Figure 1). Figure 2 demonstrates how temperature has a drastic effect on the measured reflectance of pyroxene specifically at LOLA’s observing wavelength. Over the range of temperatures experienced by the lunar surface during the course of a single day ($T \approx 300$ K), low-calcium
Pyroxene varies in spectral reflectance at 1,064 nm by a factor greater than 1.5. Figure 2 illustrates that at its observation wavelength of 1,064 nm, LOLA should be highly sensitive to temperature-dependent changes of orthopyroxene, although not to olivine. LOLA is also expected to not be sensitive to temperature-dependent changes of most high-Ca pyroxenes, although temperature-dependent spectra have not been collected for such samples. Using Gaussian fits to pure pyroxenes from Denevi et al. (2007), we produce Figure 3 that shows the predicted wavelengths for the maximum temperature effect as a function of pyroxene composition. These wavelengths are calculated assuming that the principal temperature activity of any pyroxene occurs on the long wavelength side of the 1-μm absorption, at the position of the full width-half maximum of the absorption band, as is true for orthopyroxene. LOLA should be sensitive to pyroxenes with maximum temperature-dependent changes between 1.014 and 1.114 μm, given that such changes are within a factor of 2 (50 nm) of the laser’s wavelength (1,064 nm). This includes essentially all orthopyroxenes as well as the most-magnesian, least-calcic clinopyroxenes (magnesian pigeonite) (Figure 3). The sensitivity of LOLA to temperature-dependent changes in all other clinopyroxenes is low.

On the lunar surface, which is a complex mixture of many components, there is naturally a more complicated relationship between temperature and reflectance at this wavelength. The abundance of minerals other than pyroxene and also space weathering effects dilute the strong temperature-dependent spectral effects of the pyroxene content. Hinrichs and Lucey (2002) analyzed 11 Apollo soils and found a measurable temperature-dependent spectral effect for the lunar soils (Figure 2). The change in relative reflectance with temperature was on the order of 1% or less per 100 K, which is substantially less than the 5–10% per 100 K for ordinary chondrites and HEDs or the ~35% per 100 K for pure minerals (Hinrichs & Lucey, 2002). The relative weakness of the R/T measured in these specific Apollo samples is likely to be related to (1) the masking effect of submicroscopic iron present in the highly mature soils, (2) the overall low levels of iron in the analyzed samples, and (3) the low sensitivity of the measurements relative to the low reflectance of the soils analyzed (Hinrichs & Lucey, 2002).

Overall, the few percent variation in reflectance at 1,064 nm measured in the Apollo soils over the 100- to 400-K temperature range is close to the noise level of a single LOLA observation (section 2.1). However, LOLA has been acquiring measurements of the Moon’s surface reflectance for nearly a decade...
and the tens of millions of LOLA observations enable statistically significant analyses of temperature-dependent changes (Table S1).

Understanding how the reflectance of the lunar surface varies in response to the Moon’s drastic thermal environment is important in our interpretations of remotely sensed data, as well as our understanding of the mineralogy of the surface. Specifically, understanding the thermal response of the lunar surface to solar forcing is important in the characterization of regolith structure and thermophysical properties (e.g., Hayne et al., 2017; Vasavada et al., 1999, 2012; Williams et al., 2017), surface roughness (e.g., Bandfield et al., 2015; Lawrence et al., 2013), and surface rock abundance (Bandfield et al., 2011, 2014; Ghent et al., 2014) and the photometric behavior of the lunar surface (e.g., Barker et al., 2016; Domingue et al., 2018), and the optical properties of lunar soils are highly relevant to studies of other airless bodies (e.g., Pieters et al., 2000).

Understanding the temperature-dependent spectral behavior of the lunar surface can also help constrain the distribution of specific minerals important in the crustal evolution of the Moon (e.g., Klima et al., 2008, 2011; Lemelin et al., 2019). Furthermore, as additional payloads (with higher resolution and precision) are being prepared to support lunar science and exploration, future remote sensing measurements of the lunar surface should account for temperature changes experienced during observations. This is of particular interest to the volatiles community, given that enhanced reflectance is often used as observational support for the presence of frost and water on airless bodies (e.g., Deutsch et al., 2017; Ermakov et al., 2017; Fisher et al., 2017; Neumann et al., 2013; Zuber et al., 2012).

Thus, here we are interested in how the surface reflectance of the Moon, as measured from orbit by LOLA, changes over the course of a lunar day during the extreme temperature fluctuations. We couple LOLA measurements of lunar surface reflectance with Diviner measurements of lunar surface temperature in order to analyze temperature-dependent changes in highlands and maria reflectance. We discuss implications for using single-wavelength remote sensing instruments as mineralogical sensors and the importance of accounting for temperature-dependent spectral effects in future exploration of the Moon.

2. Methods and Data
2.1. Diurnal Changes in the Lunar Surface Reflectance at 1,064 nm

LOLA measures the Moon’s surface reflectance via the strength of the returned altimetric laser pulse (Smith et al., 2010). Measurements are acquired from nadir at a wavelength of 1,064 nm, which is coincident with a diagnostic absorption feature of pyroxene (centered near 1 \( \mu \)m) due to the presence of Fe\(^{2+} \) in the M2 site of the crystal (Adams, 1974). The M2 site refers to one of two octahedral sites in the crystallographic structure (the “M” nomenclature is used to designate a “metal” or cation site without specifying the cation that occupies the site) (Morimoto, 1988). At LOLA’s wavelength, this iron absorption feature has been observed in laboratory studies to reveal strong temperature-dependent spectral changes (Figure 1) (e.g., Hinrichs et al., 1999; Roush & Singer, 1987).

We analyze the normal albedo of the lunar surface using LOLA data acquired by Detector 3 on Laser 1 during the nominal mission phase (LRO_NO_01 through LRO_NO_13) and the science mission phase.

---

**Figure 3.** The wavelengths of maximum temperature-dependent reflectance changes are shown with respect to pyroxene composition (Di = diopside; Hd = hedenburgite; Fs = ferrosilite; En = enstatite) on a pyroxene quadrilateral diagram.
The normal albedo is defined as the ratio of brightness of a surface observed at zero phase angle (where the angle between the illumination source, surface, and detector is 0) from an arbitrary direction to the brightness of a perfectly diffuse surface located at the same position but illuminated and observed perpendicularly (Hapke, 2012). The normal albedo is measured independent of illumination conditions and is not influenced by the local surface topography (Hapke, 1993; Lucey et al., 2014; Smith et al., 2010).

Previously, Lemelin, Lucey, Neumann, et al. (2016) produced calibrated LOLA data that were acquired during the first 10 months of the nominal mission phase. These data were corrected for the sensitivity drift of the lasers with time (i.e., the natural degradation of the lasers) and for anomalous data, which were primarily acquired when the received energy was <0.14 fJ, when the spacecraft was pointing off nadir, or when the range was >70 km (Lemelin, Lucey, Neumann, et al., 2016). The data were scaled to the normal albedo presented by Lucey et al. (2014), who calibrated LOLA reflectance measurements to Kaguya Multiband Imager observations acquired at zero phase angle at 1,050 nm.

In order to increase the spatial and temporal data coverage for this analysis, we supplement nominal mission phase (NO) data with science mission phase (SM) data. Including these additional data more than doubles the coverage in local time (Table S1), allowing for a more robust statistical analysis. All of the data we use are calibrated to agree with the Lemelin, Lucey, Neumann, et al. (2016) data, by accounting for the long-term drift of Detector 3 during NO and SM via a cubic polynomial, with a step function offset between the nominal and science mission phases (Figure S1).

In this calibration, we utilize all daytime data (solar incidence <89°) and discard observations that were acquired >3° off nadir or during the few days during NO_01 when the laser gains were not fixed (GAINS=FSW). We correct each observation for drift in each mission month and hour of local time (between 07:00 and 16:00) by the polynomial function and bin the data in 1° × 1° spatial bins in order to minimize intrinsic reflectance variations and to suppress anomalies associated with the laser thermal blanket. The data in each local hour for each mission month are regressed between ±25° latitude against the Gridded Data Record Albedo Map LDAM_4 (https://ode.rsl.wustl.edu/mars/pagehelp/quickstartguide/index.html?lola_grdram.htm) to obtain the best linear fit to the normal albedo map. The regression coefficients are mapped to the fraction of the LOLA mission month (NO or SM) that they represent, and we fit a cubic polynomial to the slope and a linear polynomial to the intercept to remove the long-term drift of Detector 3 during NO and SM via a cubic polynomial, with a step function offset between the nominal and science mission phases (Figure S1).

During the 9 years of still ongoing operations, LOLA has nominally collected data throughout the lunar day, although returns are minimal when the LRO spacecraft crosses the terminator due to an artifact introduced from instrument cooling and contraction (Smith et al., 2010); thus, the bulk of calibrated LOLA reflectance data have been acquired between the local hours of 07:00 and 16:00. Our data analysis is limited to local hours of 08:00 and 15:00 to avoid times where the laser blanket anomalies are strongest. Here we analyze the LOLA data for differences in mean normal albedo during the cycle of the lunar day (between the local hours of 08:00 and 15:00) at 1-hr bins by sorting the data based on the local hour at which the data were acquired. Each local hour represents the beginning time of each hourly bin.

The mean normal albedo at each grid cell (1° × 1°) is computed from several thousand individual observations, and our analysis utilizes more than 33 million LOLA observations to enable statistically significant albedo variations (Table S1). We quantify the systematic error by estimating the standard error of the linear comparison of the gridded data with the Terrain Camera-calibrated data (Lucey et al., 2014) and estimate that the error for our LOLA normal albedo is <3% error. Lemelin, Lucey, Neumann, et al. (2016) found that the greatest absolute errors in normal albedo (3–4%) stem from off-nadir geometries, and so here we exclude off-nadir observations from our analysis.

Our analysis covers the lunar surface between 50°N and 50°S, latitudes between which temperature fluctuations are greatest (Williams et al., 2017). We find that beyond these latitudes, the laser thermal blanket anomalies strongly interfere with the laser’s measurements of normal albedo. The data are binned in 1° × 1° spatial bins, representing surface areas that are ~30 × 30 km². Latitude-dependent reflectance
variations associated with space weathering have been observed with LOLA (Hemingway et al., 2015; Lemelin, Lucey, Neumann, et al., 2016; Lucey et al., 2014; Smith et al., 2017), and thus, we limit the extent of each analyzed spatial cell. We also analyze how diurnal changes differ between the highlands and maria, given that these terrains have intrinsically different reflectance properties (e.g., Lucey et al., 2014; McEwen & Robinson, 1995; Pieters, 1978, 1986). We use the lunar maria boundaries as mapped by Nelson et al. (2014) from a 643-nm monochromatic Lunar Reconnaissance Orbiter Camera Wide-Angle Camera image mosaic, generated from the ratio of Band 1 (321 nm) and Band 3 (415 nm), and a Clementine color ratio product. Note that for simplicity, we use the term “reflectance” to mean the normal albedo of the lunar surface, describing the bidirectional reflectance of the surface at zero phase angle; thus, these measurements are independent of illumination conditions.

2.2. Diurnal Changes in the Lunar Surface Temperature
The Diviner Lunar Radiometer Experiment characterizes the Moon’s thermal environment by mapping the thermal emission from the lunar surface over complete spatial (latitude and longitude) and temporal (diurnal and seasonal) ranges (e.g., Paige et al., 2010; Williams et al., 2017). With the Diviner instrument, we estimate the surface temperature at 1-hr bins between the local hours of 08:00 and 15:00 in order to complement the local time-of-day reflectance measurements from LOLA. We use bolometric temperature data from the Diviner global cumulative product, which provides data at a spatial resolution of 0.5° and a temporal resolution of 0.25-hr local time (http://pds-geosciences.wustl.edu/lro/lro-l-dlre-4-rdr-v1/lrodlr_1001/data/gcp/). The bolometric temperature is derived from the brightness temperatures of the individual Diviner spectral channels that measure the Moon’s radiance and is thus a measure of the spectrally integrated flux of IR radiation emerging from the lunar surface (Paige et al., 2010; Williams et al., 2017).

The surface temperature at each grid cell (1° × 1°) is calculated from a data set composed of more than 10 million Diviner observations to enable statistically significant temperature variations. The greatest standard deviations of the Diviner temperature measurements are associated with higher latitude observations, but here our analysis targets only the latitudes between 50°N and 50°S, where associated errors are smallest (Williams et al., 2017). The one-sigma standard deviation of the mean indicates an error of <1.5%.

3. Results
3.1. Temperature-Dependent Changes in the Lunar Surface Reflectance
Measurements of lunar surface reflectance and temperature for local hours between 08:00 and 15:00 are shown in Figure 4. During this time window, the surface experiences a maximum temperature change of ~80 K, with peak temperatures around local noon. There is an asymmetry around these peaks due to the thermal inertia of the lunar regolith, such that the surface is slightly warmer in the afternoon (Williams et al., 2017).

Between the hours of 08:00 and 15:00, there are subtle yet recognizable changes in the measured surface reflectance as measured by LOLA at 1,064 nm (Figure 4). Specifically, the surface appears to have a relatively lower reflectance when it is warmest at 12:00 and appears to have a higher reflectance when the surface is coldest, around 08:00 or 15:00. The most distinctive changes are easily identifiable in the maria and in the regions immediately adjacent to the maria (Figure 4).

3.2. The Strength of Temperature-Dependent Reflectance Changes
We quantify the mean thermo-reflectance value at each individual degree of latitude between ±50°, separately for the highlands and maria, in order to (1) minimize latitude-dependent reflectance variations associated with space weathering (Hemingway et al., 2015; Lemelin, Lucey, Neumann, et al., 2016; Lucey et al., 2014; Smith et al., 2017) and (2) disentangle intrinsic reflectance differences between the two major geologic terrains (e.g., Lucey et al., 2014). The mean thermo-reflectance value at each degree of latitude is calculated from a few hundred thousand LOLA observations (thousands of individual observations at each local hour between 08:00 and 15:00) (Table S1). The temperature-dependent change in surface reflectance at 1,064 nm is, on average, stronger in the maria ($R/T * 1,000 = -0.36$) than in the highlands ($R/T * 1,000 = -0.20$) (Table S2).
In Figure 5, we show examples of thermo-reflectance spectra for the highlands and maria. For example, the first row in Figure 5 shows the temperature-dependent changes in surface reflectance at 1,064 nm specifically for the latitudinal region between 10°N and 11°S, for both the highland and mare surfaces. The least-squares fit to the slope is plotted in gray, representing the mean thermo-reflectance value ($R/T \times 1,000$). In the subsequent rows of Figure 5, we show the same data but for groups of latitudinal bins. For each degree of latitude between 50°N and 50°S within the highlands and maria, we plot the mean surface reflectance at 1,064 nm for each local hour between 08:00 and 15:00 with respect to the mean surface temperature for each local hour between 08:00 and 15:00. Again, for each degree of latitude, we solve for a least-squares fit to the hourly points (gray lines in Figure 5). The data are displayed in subplots based on latitudinal groups in order to view the $R/T$ with more clarity.
Figure 5. The 1.064-nm surface reflectance of the lunar highlands (left) and maria (right) is shown with respect to the surface temperature during the time of data acquisition. The individual data are plotted as circles and lines of best fit (each derived from a few hundred thousand observations; Table S1) are shown for each degree of latitude between 50°N and 50°S, representing a single thermo-reflectance value (R/T). Different latitude ranges are displayed in subplots for clarity. The annual mean surface temperatures for each terrain type for each degree of latitude are correlated by time of day to the LOLA data.
The average thermo-reflectance value \((R/T \times 1,000)\) reported in each subplot is calculated from the temperature-reflectance relationship of a single degree of latitude, for both the maria and the highlands. As discussed in section 2, the systematic error of these data is estimated to be <2%. From the associated error of the LOLA and Diviner measurements, we estimate that the uncertainties of our derived thermo-reflectance values to be on the order of 2.5%.

We find that the majority of the lunar surface between 50°N and 50°S demonstrates a small, yet measurable, negative change in the surface reflectance at 1,064 nm with temperature, consistent with the presence of pyroxene. For nine of the 10 subplots, the mean \(R/T\) has a negative slope, indicating a general darkening in the surface reflectance with a warming of the surface. The outlier to this trend is the highlands group between 30°N and 50°N. The maria consistently show stronger \(R/T\) values than the highlands, meaning that they show a more drastic temperature-dependent change in the measured surface reflectance at 1,064 nm (Table S2). For the maria, the mean \(R/T \times 1,000\) values are on the order of approximately \(-0.2\) to \(-0.5\) K\(^{-1}\). The lunar highlands also tend to show a negative \(R/T\) trend, although the \(R/T \times 1,000\) values of the highlands are lower (\(-0\) to \(-0.4\) K\(^{-1}\)) than those of the maria. However, for some latitudinal bands, these highland values are nearly equivalent in strength to the \(R/T\) of the lunar maria (Figure 5). Pure orthopyroxene has a \(R/T \times 1,000\) of approximately \(-0.9\) K\(^{-1}\) at 1,064 nm for the temperature range that is experienced by the lunar surface between the local hours of 08:00 and 15:00 (Figure 2).

In Table S2, we document the maximum thermo-reflectance values for the highlands and maria, analyzed at a spatial resolution of one latitudinal degree (see supporting information). We find that, overall, the maria have a stronger (more negative) \(R/T \times 1,000\) value (\(-0.36\)) in comparison to the highlands (\(-0.20\)). Overall, the highlands show the strongest temperature-dependent changes in the equatorial region (15°N–15°S) and southern midlatitudes (15°S–30°S). The maria also show the strongest temperature-dependent changes within these regions, although similarly strong changes were detected for the maria between 30° N and 50°N as well. A coarse spatial correlation between the terrane type (Figure 6b) and the strength of temperature-dependent reflectance changes in reflectance (Figure 6a) can be observed in Figure 6.

This negative relationship between surface reflectance and temperature changes is depicted in Figure 6a, where the mean \(R/T \times 1,000\) values are shown for 1° × 1° spatial bins. These values typically range from \(-0\) to \(-1\) K\(^{-1}\). There are also some anomalous regions on the surface area (shown in white) that experience either a positive or no change in surface reflectance with temperature changes. These regions are typically found along the latitudinal fringes of the study area, where laser thermal blanket anomalies are most prevalent in the data (Figure 4).

4. Discussion

4.1. Temperature-Dependent Spectral Changes in the Highlands and Maria

The results presented here provide the first evidence for temperature-dependent spectral changes of the lunar surface. These results are consistent with laboratory studies that observe a temperature-dependent spectral change for common lunar minerals (Roush & Singer, 1986; Singer & Roush, 1985) and Apollo samples (Hinrichs & Lucey, 2002). Measurements of returned lunar soils revealed a change in relative reflectance with temperature of \(-1%\) or less per 100 K at near-IR wavelengths (Hinrichs & Lucey, 2002). This is similar to the \(R/T\) that we measure (Figure 5). We find that this change may be indicative of the mineralogy of the surface (section 4.2), which suggests important opportunities for understanding surface mineralogy remotely at a single wavelength.

We find that the majority of the lunar surface between 50°N and 50°S demonstrates a small, yet measurable, negative change in the surface reflectance at 1,064 nm with temperature; however, our entire study region does not reveal this measurable \(R/T\) relationship. One factor complicating this analysis is the sensitivity of the LOLA instrument in detecting these extremely small changes in surface reflectance, which are on the order of a few percent change. This change is detected by co-adding the LOLA data that features single shot uncertainty of 12% (Smith et al., 2010) but importantly results from analyzing statistical data sets that include >17 million individual laser shots for each of the local hour groups (Table S1). Thus, we find that our analysis is statistically robust and note that the extremely small changes measured here are comparable.
Figure 6. The temperature-dependent changes in lunar reflectance in panel (a) are compared to the distributions of lunar highlands and maria in panel (b) and of low-calcium pyroxene in panel (c). Specifically, panel (a) expresses the magnitude of temperature-dependent reflectance changes ($R/T \times 1,000$). All colored pixels (1° × 1° in spatial extent) have higher reflectances at lower temperatures, and white pixels either show no change or have lower reflectances at lower temperatures. Black pixels indicate regions with insufficient temporal LOLA coverage for the analysis, and lineations are an artifact from the data coverage. Panel (b) displays the normal albedo of the lunar surface calibrated by Lemelin, Lucey, Neumann, et al. (2016). Boundaries of the maria are outlined in green, as mapped by Nelson et al. (2014). Panel (c) displays the absolute orthopyroxene abundance on the lunar surface, expressed as weight percent (wt.%), as derived from the Kaguya Lunar MI (Lemelin, Lucey, Gaddis, et al., 2016, 2019). Panel (d) shows the temperature-dependent reflectance changes specifically within regions with elevated orthopyroxene abundances. All four maps are in a cylindrical projection centered at 0°E and include latitudes between 50°S and 50°N.
to the change in relative reflectance with temperature measured for Apollo soils, which was on the order of 1% or less per 100 K (Hinrichs & Lucey, 2002).

It is also possible that LOLA does not observe a uniformly strong temperature-dependent reflectance change across all the maria or all the highlands due to differences in optical maturity (Hinrichs & Lucey, 2002). Mature soils show less contrast due to the attenuating effect of submicroscopic iron that has accumulated through time from space weathering processes (e.g., Hapke, 2001; Pieters & Noble, 2016; Pieters et al., 2000). The cumulative amount of submicroscopic iron affects the optical properties of measured and modeled soils, resulting in spectral darkening and reddening and subdued absorption bands in the near IR (e.g., Pieters et al., 2000). Additionally, surfaces that are low in pyroxene will show a weaker temperature-dependent spectral change at LOLA’s wavelength (Hinrichs & Lucey, 2002). Changes in absorption band symmetry at 1,064 nm occur as Fe$^{2+}$ crystal field absorptions become narrower with decreasing temperature, and these changes are due to the intrinsic absorbance properties of the minerals (Hinrichs et al., 1999; Moroz et al., 2000; Roush & Singer, 1986, 1987; Schade & Wäsch, 1999; Singer & Roush, 1985). Finally, the surface reflectance measured by LOLA may also be affected by grain size effects given that varying grain size can cause variations in absolute reflectance at near-IR wavelengths (Adams & Filice, 1967; Clark & Roush, 1984; Hapke, 1993, 2012; Milliken & Mustard, 2007; Mustard & Hays, 1997; Pieters, 1983; Pieters et al., 1993). However, grain size is effectively normalized by the process of regolith formation (Fischer & Pieters, 1994), and Lucey (2006) demonstrated that empirical methods for the derivation of elemental abundances that depend on spectral-elemental correlations (e.g., Lawrence et al., 2002) require a narrow grain size to function and would be ineffective if grain sizes varied significantly at the 100-m scale. Overall, variations in maturity and grain size may affect measurements of surface reflectance at 1,064 nm but are not expected to substantially influence our analysis of the lunar surface between ±50°. Importantly, variations in maturity and grain size are not expected to produce temperature-dependent effects. Absorbing species other than orthopyroxene, however, can limit or even prohibit temperature-dependent changes in the 1,064-nm surface reflectance at the sensitivity of the LOLA data.

4.2. LOLA as a Mineralogical Sensor

As discussed in section 1, different minerals have unique thermo-reflectance spectra that are wavelength dependent, which have been used in the past to characterize the mineralogy of asteroids (Lucey et al., 1998, 2002). The observation wavelength of LOLA is particularly sensitive to temperature-dependent spectral changes of low-calcium pyroxene (Figure 2). While it is not commonly considered to be a mineralogical sensor, our results suggest that future laser altimeters as well as LOLA could be used to map the relative abundance of particular minerals (here, pyroxene) from detections of temperature-dependent reflectance changes. Pyroxenes are the most prevalent mafic mineral on the Moon and are commonly used as a tool for understanding the magmatic source, composition, and cooling history of remotely sensed surfaces (e.g., Adams, 1974; Cloutis & Gaffey, 1991; Greenhagen et al., 2010; Klima et al., 2008, 2011; Sunshine & Pieters, 1993; Yamashita et al., 2012). Understanding the distribution of pyroxene mineralogies is important to our understanding of the crustal evolution on the Moon.

There is substantial heterogeneity in the distribution and absolute abundance of orthopyroxene at the lunar surface (Figure 6c). Analyses of Kaguya Multiband Imager data indicate that low-calcium pyroxene is abundant (up to ~50 wt.%) in the Procellarum KREEP Terrane and in Mare Tranquilitatis and is the dominant mafic mineral in the South Pole-Aitken basin (Figure 6c; Lemelin, Lucey, Gaddis, et al., 2016, 2019). We find that the parts of the surface that do have higher levels of orthopyroxene indeed show a negative $R/T$ relationship (Figure 6), consistent with laboratory studies (Hinrichs & Lucey, 2002; Roush & Singer, 1986; Singer & Roush, 1985). However, we observe temperature-dependent reflectance changes even on parts of the surface that are orthopyroxene-poor.

In Figure 7, we show the correlation between the amount of orthopyroxene (wt.%) and the thermo-reflectance spectra (K$^{-1}$) for the highlands (red) and maria (blue). In general, the maria have higher abundances of orthopyroxene exposed at the surface than do the highlands (Lemelin, Lucey, Gaddis, et al., 2016, 2019). We find that, on average, the maria also have stronger negative $R/T$ values, as indicated by the spread of data shifted to the left in the box plot below Figure 7. This trend suggests that the mare surfaces show a slightly larger change in the surface reflectance at 1,064 nm between the local hours of 08:00 and 15:00 than do the highlands.
We also note that there is considerable overlap between the $R/T$ values calculated for the maria and highlands. Thus, there are likely to be other factors that are influencing how different regions of the surface experience the changes of surface reflectance as measured by LOLA during these different times of day. Figure 6 shows that the greatest temperature-dependent changes in reflectance are concentrated near the boundaries of the maria. There are likely to be some mixing effects between the boundaries of the maria and highlands, given that these contacts are diffuse due to mixing processes through time (Fischer & Pieters, 1995; Li & Mustard, 2000, 2003, 2005). Spectral mixture analyses indicate that large impact craters have resulted in highland contamination of the spectral properties of mare surfaces (Li & Mustard, 2003), as lateral transport is more efficient than vertical transport during mixing along these boundaries (Li & Mustard, 2000).

As discussed in section 4.1, other factors that complicate thermo-reflectance spectra may include differences in iron levels, grain size, or optical maturity. For example, the absorption features of mature surfaces are relatively subdued as a result of space weathering processes (e.g., Lucey et al., 2000; Noble et al., 2001; Pieters et al., 1993, 2000). The optical maturity index derived by Lucey et al. (2000) indicates that lunar surface maturity is partly dependent on geologic setting, given that crater interiors tend to mature more slowly compared to their ejecta and that larger ejecta features tend to mature more slowly than smaller features. Generally, Copernican surfaces are relatively more immature compared to older surfaces (Lucey et al., 2000) and are associated with lower surface porosities (Mandt et al., 2016), higher rock abundances (Ghent et al., 2014; Mazrouei et al., 2019), and rougher surfaces (Neumann et al., 2015). The most immature surface on the lunar surface today includes surfaces near Tycho, Stevinus, Giordano Bruno, and some northern highlands, between De La Rue, Hayn, and Bel'kovich craters. These regions tend to show stronger $R/T$ values (Figure 6), consistent with the understanding that more immature surfaces exhibit stronger contrast in absorption features.

Importantly, variations in maturity and grain size are not expected to result in temperature-dependent variations in surface reflectance. Therefore, while variations in these factors may help explain why particular surfaces exhibit more subdued temperature-dependent spectral changes, variations in these factors are not expected to contribute to the presence of temperature-dependent spectral changes.

We also observe heterogeneity in the strength of $R/T$ values within the mare deposits (Figure 6a), which vary in orthopyroxene abundances (Figure 6c; Lemelin, Lucey, Gaddis, et al., 2016b; Lemelin et al., 2019) as well.
as in age (e.g., Hiesinger et al., 2003, 2010, 2011). The mineralogy of mare basalts shows both temporal and spatial heterogeneity. For example, young Oceanus Procellarum basalts are rich in olivine and show a stratigraphic gradation with underlying units of lower olivine abundance, while young Orientale basalts are olivine poor and rich in high-Ca pyroxene (Varatharajan et al., 2014). This heterogeneity suggests variability in FeO content in younger basalts across the Moon (Varatharajan et al., 2014), and such heterogeneity may affect the strength of the temperature-dependent signal detected here.

5. Conclusions

We have documented the first evidence of temperature-dependent spectral changes on the lunar surface from orbital observations. Our statistical analysis, incorporating more than 53 million individual LOLA shots, indicates that temperature variations do have a measurable effect on the reflectance of the surface at 1,064-nm wavelength. Specifically, measurements of higher reflectance were acquired by LOLA when the surface temperatures of the Moon were lower. The measurable effect discussed here is on the order of a few percent change in reflectance per ~80 K, indicating that temperature changes do not have a large effect on measurements of the lunar surface at the sensitivity of the LOLA instrument.

An ability to understand how the lunar surface varies with temperature will provide important constraints for future remote sensing observations of the Moon. Such observations can help assess the relative abundance of particular rock-forming minerals (here, pyroxene) that exhibit a change in spectral reflectance with temperature, using a single-wavelength laser.

Temperature-dependent spectral changes have important implications for future remotely sensed observations of the Moon, as additional spectrometers and single-wavelength lasers with higher resolution and precisions are designed and operated. These results suggest that additional laser wavelengths targeted at olivine can provide independent data for the distribution of that mineral. For example, a laser with an observation wavelength at 1,460 nm should be sensitive to temperature-dependent spectral changes of olivine, although not pyroxene. However, as discussed in detail in sections 1 and 4, there are various factors that can potentially complicate orbital measurements of temperature-dependent spectral changes, such as iron levels, grain size, or surface maturity. Of particular interest is understanding these effects on interpretations of the presence of surface volatiles. Both the science and exploration communities have strong interests in the presence of surface ice on the Moon (and beyond). Enhanced surface reflectance has been used to characterize the presence of surface ice not only on the Moon (e.g., Fisher et al., 2017; Qiao et al., 2019; Zuber et al., 2012) but also on Mercury (Chabot et al., 2014; Deutsch et al., 2017; Neumann et al., 2013), smaller airless bodies (e.g., Ermakov et al., 2017; Platz et al., 2016), Mars (e.g., Bell et al., 1999; Smith et al., 1998), and beyond. Thus, understanding how temperature affects observations of surface reflectance has widespread importance in the planetary community.

Data Availability Statement

The uncalibrated LOLA normal albedo data used in this study can be accessed from the LOLA PDS Data Node at http://imbrium.mit.edu/DATA/LOLA_LARDER/laser1/. The Diviner temperature data can be accessed at http://pds-geosciences.wustl.edu/lro/iro-l-dire-4-rdr-v1/lrodlr_1001/data/gcp/. The Kaguya Lunar Multiband Imager data of surface orthopyroxene content can be accessed at https://astrogeology.usgs.gov/search/map/Moon/Kaguya/MI/MineralMaps/Lunar_Kaguya_MIMap_MineralDeconv_OrthopyroxenePercent_50N50S. Temperature-dependent reflectance changes of the lunar surface at 1,064 nm and supplementary Tables S1 and S2 have been archived at the Brown Digital Repository and can be accessed at https://10.1111/10.26300/y5ep-4j46.

References


Acknowledgments

We thank Deanne Rogers for her editorial handling of the manuscript, as well as Wenzhe Fa and two anonymous reviewers for providing helpful feedback. This work is supported by NASA issued through the Harriet G. Jenkins Graduate Fellowship to A. N. D. (Number NNX16AT19H), by the NASA Discovery Program to G. A. N, by NASA-Goddard to J. W. H. for participation in the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) Experiment Team (NNX11AK29G, NNX13AO77G, and 80NSSC19K0695), and also by the LRO LOLA Experiment to P. G. L. The time-ordered, globally calibrated normal albedo data used in this study can be accessed from the LOLA PDS Data Node at http://imbrium.mit.edu/DATA/LOLA_LARDER/laser1/. The Diviner temperature data can be accessed at http://pds-geosciences.wustl.edu/lro/iro-l-dire-4-rdr-v1/lrodlr_1001/data/gcp/. The Kaguya Lunar Multiband Imager data of surface orthopyroxene content can be accessed at https://astrogeology.usgs.gov/search/map/Moon/Kaguya/MI/MineralMaps/Lunar_Kaguya_MIMap_MineralDeconv_OrthopyroxenePercent_50N50S.


