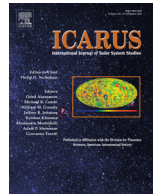




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Effects of varying environmental conditions on emissivity spectra of bulk lunar soils: Application to Diviner thermal infrared observations of the Moon

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ABSTRACT

Currently, few thermal infrared measurements exist of fine particulate ($<63 \mu\text{m}$) analogue samples (e.g. minerals, mineral mixtures, rocks, meteorites, and lunar soils) measured under simulated lunar conditions. Such measurements are fundamental for interpreting thermal infrared (TIR) observations by the Diviner Lunar Radiometer Experiment (Diviner) onboard NASA's Lunar Reconnaissance Orbiter as well as future TIR observations of the Moon and other airless bodies. In this work, we present thermal infrared emissivity measurements of a suite of well-characterized Apollo lunar soils and a fine particulate ($<25 \mu\text{m}$) San Carlos olivine sample as we systematically vary parameters that control the near-surface environment in our vacuum chamber (atmospheric pressure, incident solar-like radiation, and sample cup temperature). The atmospheric pressure is varied between ambient (1000 mbar) and vacuum ($<10^{-3}$ mbar) pressures, the incident solar-like radiation is varied between 52 and 146 mW/cm^2 , and the sample cup temperature is varied between 325 and 405 K. Spectral changes are characterized as each parameter is varied, which highlight the sensitivity of thermal infrared emissivity spectra to the atmospheric pressure and the incident solar-like radiation. Finally spectral measurements of Apollo 15 and 16 bulk lunar soils are compared with Diviner thermal infrared observations of the Apollo 15 and 16 sampling sites. This comparison allows us to constrain the temperature and pressure conditions that best simulate the near-surface environment of the Moon for future laboratory measurements and to better interpret lunar surface compositions as observed by Diviner.

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1. Introduction

Apollo mare and highland soils (e.g. Pieters et al., 1993, 2000, 2006; Noble et al., 2001, 2006; Taylor et al., 2001, 2010) as well as basaltic rocks (Isaacson et al., 2011) and breccias (Noble et al., 2005) have been well-characterized across the visible- to near-infrared (VNIR) wavelengths to constrain the effects of mineralogy, mineral chemistries, ilmenite content, particle size and space weathering on their spectra. These laboratory analyses provided ground truth for remote sensing observations from Earth-based

telescopic observations and spacecraft observations like those from National Aeronautics and Space Administration's (NASA) Clementine, Galileo and Lunar Prospector, European Space Agency's (ESA) Small Missions for Advanced Research in Technology (SMART-1), Japan Aerospace Exploration Agency's (JAXA) SELENE Kaguya, and Indian Space Research Organisation's (ISRO) Chandrayaan-1 as well as key insights into the composition and evolution of the lunar surface. Recently the Diviner Lunar Radiometer Experiment (Diviner), a nine band thermal infrared (TIR) radiometer, was launched onboard NASA's Lunar Reconnaissance Orbiter (LRO) (Paige et al., 2010a), making it necessary for detailed laboratory analysis of lunar samples across TIR wavelengths. Thermal infrared characterization will (1) aid in 'ground-truthing' the bulk thermal properties of the lunar surface (e.g. Bandfield et al., 2011, 2014; Vasavada et al. 2012; Ghent et al., 2014) and lunar surface compositions

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(e.g. Greenhagen et al., 2010; Glotch et al., 2010, 2011; Allen et al., 2012; Donaldson Hanna et al., 2012a, 2015a), (2) estimate the spectral effects due to space weathering (e.g. Glotch et al. 2015; Lucey et al., 2016), (3) better constrain the near surface (upper hundreds of microns) environmental conditions of the Moon (e.g. Thomas et al., 2012; Donaldson Hanna et al., 2012b), and (4) support thermal models of the surface (upper meter), in particular the semi-permanently and permanently shadowed regions at the lunar poles (e.g. Paige et al., 2010b; Foote et al., 2012; Johnson et al., 2013; Warren et al., 2014; Greenhagen et al., 2015).

The fine particulate nature of the regolith and the lack of an appreciable atmosphere complicate the interpretation of thermal infrared emission observations of airless bodies like the Moon and asteroids. On the Moon and other airless bodies there are no interstitial atmospheric gases between regolith grains to transfer heat through conduction; rather heat is transferred through radiation and grain-to-grain contacts. Radiative cooling becomes very efficient at the near-surface (upper hundreds of microns) as it is exposed to the coldness of space, thus setting up a strong thermal gradient between the near-surface and the portions of the upper centimeter of regolith being heated by incident solar radiation (e.g. Logan and Hunt, 1970; Logan et al., 1973; Henderson and Jakosky, 1994). This is unlike planets with atmospheres like the Earth and Mars where the pore space between regolith grains is filled with interstitial gases, which allows heat to transfer efficiently from depth to the surface through conduction. Thus, the upper hundreds of microns of regolith on planets with an atmosphere are nearly isothermal (e.g. Henderson and Jakosky, 1994).

The depth in the lunar regolith from which the measured emission originates depends on the wavelength as well as the composition and physical nature of the regolith materials. As the wavelength varies so does the depth from which the measured thermal emission originates, thus different temperatures are measured owing to the thermal gradient in the near-surface (Logan and Hunt, 1970; Logan et al., 1973; Henderson and Jakosky, 1994, 1997). Across wavelength regions where materials have high absorption coefficients and surface scattering dominates (spectral regions covering the reststrahlen bands) the measured emission comes from the cooler surface (upper tens of microns). Across transparent regions of the spectrum where materials have low absorption coefficients and volume scattering dominates (spectral regions covering the Christiansen feature and transparency feature) the measured emission comes from deeper (upper hundreds of microns), warmer portions of the near-surface. Therefore, a single thermal infrared emission measurement of the lunar surface from orbit is sampling multiple depths and temperatures within the upper hundreds of microns and cannot easily be reconciled with a single Planck function (Logan and Hunt, 1970; Logan et al., 1973; Henderson and Jakosky, 1994, 1997). Thus, thermal infrared spectral measurements represent an effective emissivity of the lunar surface as they include diagnostic features due to composition and particle size that are affected by the thermal gradient.

Previous laboratory emissivity measurements of particulate rocks, minerals, and lunar soils under vacuum and lunar-like conditions (Hunt and Salisbury, 1964; Murcray, 1965; Logan and Hunt, 1970; Logan et al., 1973; Salisbury and Walter, 1989; Henderson et al., 1996; Thomas et al., 2012; Donaldson Hanna et al., 2012a, 2012b, 2015a) observed an enhancement in the spectral contrast of the Christiansen feature (CF) and a shift in the CF position to shorter wavelengths (higher wavenumbers) when compared to spectra measured under isothermal or 'Earth-like' conditions. These observed spectral differences were attributed to the strong thermal gradient generated within the uppermost portion of particulate samples from the vacuum environment and solar-like incident radiation (Logan et al., 1973; Henderson et al., 1996; Henderson and Jakosky, 1997). The observed spectral changes under

vacuum and lunar-like environmental conditions demonstrate the need for making laboratory measurements under comparable near-surface conditions for the interpretation of remote sensing observations of airless bodies like the Moon, Mercury, Mars' moons Phobos and Deimos, and asteroids.

Currently, few measurements have been published of fine particulate ($<63 \mu\text{m}$) samples (e.g. minerals, mineral mixtures, rocks, meteorites, and lunar soils) measured under simulated lunar conditions. These laboratory spectral measurements are fundamental for interpreting thermal infrared observations by Diviner and future TIR lunar observations. In this work, we make thermal infrared spectral measurements of a suite of well-characterized Apollo bulk lunar soils as we systematically vary parameters that control the near-surface environment in our vacuum environment chamber (atmospheric pressure, incident solar-like radiation, and sample cup temperature). The observed spectral changes are characterized as each parameter is varied to constrain which parameters have the largest effect on the spectral measurements. Finally spectral measurements of Apollo 15 and 16 bulk lunar soils are compared with Diviner TIR observations of the Apollo 15 and 16 sampling sites. This comparison allows us to constrain the temperature and pressure conditions that best simulate the near-surface environment of the Moon for future laboratory measurements and to better interpret lunar surface compositions as observed by Diviner.

2. Background

Remote sensing observations provide key insights into the formation and evolution of a planet's surface through the determination of its surface composition. A fundamentally important component to interpreting the composition of a planet's surface is a suite of laboratory measurements of well-characterized analogue materials. Laboratory thermal infrared spectral measurements of analogue samples have been successfully applied to map planetary compositions on Earth and Mars (e.g.; Ramsey and Christensen, 1998; Feeley and Christensen, 1999; Hamilton and Christensen, 2000; Wyatt et al., 2001; Rogers et al., 2007). TIR emissivity spectra are sensitive to the chemistry and structure of all common rock-forming silicates and exhibit unique spectral features that can be used to identify them. These diagnostic features include the Christiansen feature (CF), reststrahlen bands (RB), and transparency features (TF) as seen in Fig. 1. The CF is an emissivity maximum resulting from a rapid change in a material's refractive index at wavelengths shorter than those of the fundamental molecular vibration bands. Conel (1969) found that the CF position in silicates is diagnostic of bulk mineralogy as it changes with the change in bond strength and molecular geometry associated with changing mineralogy. As seen in Fig. 1, plagioclase feldspars (which have little Fe, but high Al and Ca contents) have shorter wavelength CF positions than pyroxenes and olivines (which have high Fe and/or Mg content and low Al). The RB are the fundamental molecular vibration bands due to stretching (Si–O–Si, Si–O–Al, Si–Si, and Si–Al) and bending motions (O–Si–O and O–Al–O). The fundamental vibration bands occur in spectral regions where surface scattering dominates (regions where minerals have high absorption coefficients) for particle sizes and packing states of typical regoliths. The exact frequencies, shapes and intensities, and number of absorptions in the RBs are dependent on atomic masses and bond lengths, geometry, and bond strengths within mineral crystal lattices. Because all minerals consist of unique structures and/or compositions, virtually every mineral has a different set of vibrational characteristics and thus a highly diagnostic set of RB absorptions (e.g. Lyon, 1964; Conel, 1969; Salisbury and Walter, 1989; Hamilton, 2000). The TF is an emissivity minimum caused by volume scattering of fine particulates (typically $< 63 \mu\text{m}$) in a

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