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The global surface temperatures of the moon as measured by the diviner lunar radiometer experiment

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ABSTRACT

The Diviner Lunar Radiometer Experiment onboard the Lunar Reconnaissance Orbiter (LRO) has been acquiring solar reflectance and mid-infrared radiance measurements nearly continuously since July of 2009. Diviner is providing the most comprehensive view of how regoliths on airless bodies store and exchange thermal energy with the space environment. Approximately a quarter trillion calibrated radiance measurements of the Moon, acquired over 5.5 years by Diviner, have been compiled into a 0.5° resolution global dataset with a 0.25 h local time resolution. Maps generated with this dataset provide a global perspective of the surface energy balance of the Moon and reveal the complex and extreme nature of the lunar surface thermal environment. Our achievable map resolution, both spatially and temporally, will continue to improve with further data acquisition.

Daytime maximum temperatures are sensitive to the albedo of the surface and are ~387–397 K at the equator, dropping to ~95 K just before sunrise, though anomalously warm areas characterized by high rock abundances can be > 50 K warmer than the zonal average nighttime temperatures. An asymmetry is observed between the morning and afternoon temperatures due to the thermal inertia of the lunar regolith with the dusk terminator ~30 K warmer than the dawn terminator at the equator. An increase in albedo with incidence angle is required to explain the observed decrease in temperatures with latitude. At incidence angles exceeding ~40°, topography and surface roughness influence temperatures resulting in increasing scatter in temperatures and anisothermality between Diviner channels.

Nighttime temperatures are sensitive to the thermophysical properties of the regolith. High thermal inertia (TI) materials such as large rocks, remain warmer during the long lunar night and result in anomalously warm nighttime temperatures and anisothermality in the Diviner channels. Anomalous maximum and minimum temperatures are highlighted by subtracting the zonal mean temperatures from maps. Terrains can be characterized as low or high reflectance and low or high TI. Low maximum temperatures result from high reflectance surfaces while low minimum temperatures from low-TI material. Conversely, high maximum temperatures result from dark surface, and high minimum temperatures from high-TI materials.

Impact craters are found to modify regolith properties over large distances. The thermal signature of Tycho is asymmetric, consistent with an oblique impact coming from the west. Some prominent crater rays are visible in the thermal data and require material with a higher thermal inertial than nominal regolith. The influence of the formation of the Orientale basin on the regolith properties is observable over a substantial portion of the western hemisphere despite its age (~3.8 Gyr), and may have contributed to mixing of highland and mare material on the southwest margin of Oceanus Procellarum where the gradient in radiative properties at the mare-highland contact is broad (~200 km).

1. Introduction

The Diviner Lunar Radiometer Experiment (Diviner; Paige et al., 2010a) is one of seven instruments aboard NASA's Lunar Reconnaissance Orbiter (LRO) (Chin et al., 2007; Tooley et al., 2010; Vondrak et al., 2010). Diviner has been systematically mapping

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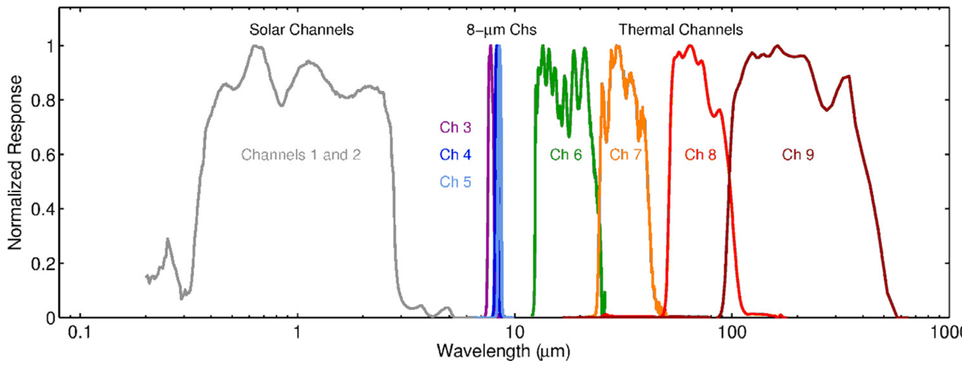

Fig. 1. Diviner's nine spectral passbands.

the Moon since July 5, 2009 acquiring ~250 billion calibrated radiometric measurements (as of April 2015) at solar and infrared wavelengths covering a full range of latitudes, longitudes, local times and seasons. These are the first such comprehensive measurements of the Moon, or any other airless body, providing the ability to characterize the global lunar thermal environment, one of the most extreme of any planetary body in the solar system (Paige et al., 2010b).

The Moon is an important airless body to study not only because of its accessibility, but because it's ancient surface records events that occurred during the earliest phases of the formation of the Earth and the inner solar system. The Moon also exhibits a wide range of important planetary processes, such as impact cratering, volcanism, volatile cold-trapping and space weathering that relate directly to similar processes that are observed on both large and small bodies elsewhere in the solar system.

Early Diviner observations have been used to infer the average radiative and bulk thermophysical properties of the near-surface regolith at the equator (Vasavada et al., 2012). With continued operations, the current density of Diviner observations both spatially and in local time is high enough that diurnal temperatures can be adequately resolved globally at 0.5 deg pix^{-1} spatial resolution to create global gridded map datasets. This provides insight into the radiative and thermophysical properties of the lunar regolith globally. In this paper, we present an empirical view of the Moon as seen from Diviner, utilizing all acquired nadir-pointing observations without the aid of detailed physical models or laboratory data. We first discuss the Diviner instrument and its mapping history followed by the description of the data gridding and map production. We next present the maps in global, cylindrical projection and discuss and characterize the lunar global temperatures. This is followed by a discussion of processes that have resulted in widespread regolith modification that influence surface temperatures as observed by Diviner.

2. The diviner instrument

2.1. Instrument description

Diviner is a 9-channel radiometer that maps solar reflectance and infrared emission over a wavelength range of 0.3 to 400 μm (Paige et al., 2010a). The spectral response of Diviner's channels is shown in Fig. 1. Channels 1 and 2, with identical spectral passbands of 0.35–2.8 μm, measure reflected solar radiation from the lunar surface at two different sensitivities. The remaining channels (3–9) observe emitted infrared radiation from which brightness temperatures of the lunar surface are derived. The three narrow spectral passband filters of channels 3–5 are used to map the wavelength of the mid-infrared thermal emission maximum, a spectral feature called the Christiansen Feature (CF) near 8 μm (Conel, 1996) which is diagnostic of the bulk silicate mineralogy (e.g. Greenhagen et al., 2010; Glotch et al., 2010, 2011). The remaining channels (6–9) are broad channels intended to characterize the surface thermal emission over a wide range of temperatures with separate filters covering ~13–23, ~25–41, ~50–100, and ~100–400 μm (full width half max).

The ground-projected surface footprint of Diviner is dependent on spacecraft altitude which varies between ~40 and 170 km in its current elliptical orbit configuration, but is ~170 m cross-track and ~500 m in-track, accounting for spacecraft motion which results in elongation in the in-track direction, at the nominal altitude of ~50 km during the mapping mission phase (Williams et al., 2016). Each channel consists of an array of 21 detectors that are nominally nadir-pointing collecting data in a pushbroom configuration with an integration period of 0.128 s. The characteristics of the Diviner instrument are described in further detail in Paige et al. (2010a).

2.2. Mapping history

LRO launched on 18 June 2009 and the spacecraft commissioning phase was initiated on 27 June 2009. Diviner began acquiring data eight days later on 5 July 2009 (Fig. 2). The initial commissioning orbits were quasi-frozen ~30 × 200 km polar orbits with periapsis near the lunar south pole. On 15 September 2009, LRO transitioned into a near-circular, 2 h period mapping orbit with an average altitude ~50 km (referenced to a 1737.4 km sphere) to start the Nominal Mission (Mazarico et al., 2011a). After the initial 1 year nominal mission, LRO began its two year Science Mission, during which it transitioned back into an elliptical quasi-frozen orbit on 11 December 2011. LRO is currently conducting its second extended science mission.

The time evolution of the LRO orbit geometry during the mission phases is shown in Fig. 2, encompassing the period of time that data used in the maps was acquired. The LRO orbit plane is inclined approximately 90° from the equator and is nearly fixed in inertial space. The Moon rotates 360° relative to the LRO orbit plane every 27.3 day sidereal rotation period, during which the sub-spacecraft longitude migrates 360° of longitude. This defines the length of one Diviner mapping cycle in the level 2 Global Data Records (GDR), which have been archived at the NASA Planetary Geosciences Node (LRO-L-DLRE-5-GDR-V1.0) (Paige et al., 2011). LRO obtains "daytime" coverage (defined here to be 6 am to 6 pm local solar time) during half of each orbit, and "nighttime" coverage (6 pm to 6 am local time) during the other half. As the Earth/Moon system orbits the sun, the local time of the of the LRO orbit shifts ~1.8 h earlier during each mapping cycle, providing full local time coverage over the course of half of an Earth Year. The lunar spin axis is inclined by 1.54° relative to the ecliptic, which