An analytic function of lunar surface temperature for exospheric modeling

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ABSTRACT

We present an analytic expression to represent the lunar surface temperature as a function of Sun-state latitude and local time. The approximation represents neither topographical features nor compositional effects and therefore does not change as a function of selenographic latitude and longitude. The function reproduces the surface temperature measured by Diviner to within ±10 K at 72% of grid points for dayside solar zenith angles of <80°, and at 98% of grid points for nightside solar zenith angles >100°. The analytic function is least accurate at the terminator, where there is a strong gradient in the temperature, and the polar regions. Topographic features have a larger effect on the actual temperature near the terminator than at other solar zenith angles. For exospheric modeling the effects of topography on the thermal model can be approximated by using an effective longitude for determining the temperature. This effective longitude is randomly redistributed with 1 sigma of 4.5°. The resulting "roughened" analytical model well represents the statistical dispersion in the Diviner data and is expected to be generally useful for future models of lunar surface temperature, especially those implemented within exospheric simulations that address questions of volatile transport.

1. Introduction

The surface temperature is an important input to lunar exosphere models because it can modulate the velocity distribution of exospheric particles and adsorption of particles to the surface. Various approaches have previously been adopted to incorporate temperature variations across the surface in such models. Butler (1997) used a latitude function of temperature. Crider and Vondrak (2000) implemented a function of the solar zenith angle, where the nightside temperature was held constant. However, due to the finite thermal inertia of lunar regolith, a constant night-time temperature is inconsistent with observations (Vasavada et al., 2012). It also fails to reproduce the nightside distribution of exospheric helium. To capture these effects Hodges (1973) used a linearly decreasing temperature on the lunar nightside from dusk to dawn to reproduce Lunar Atmospheric Composition Experiment (LACE) observations of helium. Leblanc and Chaufray (2011) also

reproduce the LACE results using a linear nightside temperature function, and further explore how choice of energy distribution and thermal accommodation factor influence the nightside helium density on the Moon.

More recently, the temperature of the surface of the Moon has been measured by the Diviner Lunar Radiometer Experiment (Diviner) onboard the Lunar Reconnaissance Orbiter (LRO) by mapping the albedo of the Moon through a range of IR wavelengths (Paige et al., 2010a). Diviner measures the albedo with 2 broadband solar channels. A further 7 narrowband channels spanning 7.55–400 μm wavelengths in the infrared provide brightness temperature data. As each channel will be affected by sub-pixel variations in the surface temperature differently, Paige et al. (2010b) defined a bolometric brightness temperature for describing the temperature of the lunar surface. Vasavada et al. (2012) used Diviner equatorial data to constrain a thermal model of the lunar regolith that includes a robust calculation of heat balance using model of regolith conductivity that exponentially increases as a function of depth.

These global data can be deposited in a look-up table for implementation in models that require knowledge of the lunar surface temperature. Alternatively, a robust model such as Vasavada's can be used. However, exospheric models query the surface temperature many times as many test particles recycle on each simulation timestep, making it computationally intensive to use a look-up table for these types of simulations. There is a trade between runtime efficiency and accuracy in the temperature differences caused by composition, rock size, and topography. Thus an analytic function is advantageous in terms of ease of implementation and run-time efficiency. We present an analytic function for the surface temperature of the Moon that is only a function of position in Sun-state coordinates. The deviations of the analytic function from measured lunar temperature are presented for new Moon orientation. The function is a good representation of measured temperature, while neglecting effects tied to selenographic position.

2. Analytic function

The temperature function is an analytic approximation to the temperature observed by Diviner. It comprises two functions, one describing the day and one the night matched at the terminator. The observed dayside temperature is well-reproduced by a cosine function of the solar zenith angle, ψ, defined as the angle between the Moon–Sun line and the vector from the center of the Moon through the point on the lunar surface. Although the Lambertian model of dayside temperature calls for a function of $T_{ss} \cos^{1/4}(\psi)$, where T_{ss} is the subsolar temperature, this function goes to zero at the terminator, which is difficult to match to the nightside. Clementine long wave infrared (LWIR) data are consistent with the $\cos^{1/4}$ shape (Lawson et al., 2000) as are the dayside Diviner data (Vasavada et al., 2012). Leblanc and Chaufray (2011) assumed the dayside function to be in the form of:

$$T(\psi) = T_0 \cos^n(\psi) + T_1 \quad (\psi < 90°) \tag{1}$$

which allows the temperature at the terminator to be defined, making it easier to implement in models. Dayside Diviner observations (Vasavada et al., 2012) are well reproduced using $T_0 = 262$ K, $T_1 = 130$ K, and $n = 1/2$. This function peaks at 392 K at the subsolar point and falls off slowly toward the terminator, where the temperature is 130 K:

$$T(\psi) = 262 \cos^{1/2}(\psi) + 130 \text{ K} \quad (\psi < 90°) \tag{2}$$

An alternative is to use the $\cos^{1/4}(\psi)$ function but include a floor value that the calculated temperature is not allowed to be less than to ensure the value does not go below a preset limit at the terminator. We use:

$$T(\psi) = 392 \cos^{1/4}(\psi) > 130 \text{ K} \quad (\psi < 90°) \tag{3}$$

which is more correct physically, but introduces a plateau within 1° SZA of the terminator that may not be desirable, depending on the application. This is problematic near the pole, where the function gives a constant dayside temperature at latitude within 1° of the pole.

We approximate the cooling of the nightside with a 6-term polynomial fit in longitude, φ. A latitude-dependence is also observed, and is reproduced using a sine function of the colatitude, θ. Using longitude (φ) in radians ranging from ($\pi/2$, $3\pi/2$) with $\varphi = \pi$ at midnight, the nightside temperature is approximated by:

$$T(\theta, \varphi) = \sum_{i=0,\dots,5} (a_i \varphi^i) + 35(\sin(\theta) - 1) \quad (\psi > 90°) \tag{4}$$

where $a = [444.738, -448.937, 239.668, -63.8844, 8.34064, -0.423502]$. At the equator, this function decreases from 130 K post-dusk to 95 K pre-dawn. There is a 35 K difference from the

equator to the pole at all longitudes. At high latitude, the function goes from 95 K at post-dusk to 60 K at pre-dawn. The pre-dawn polar region is the coldest location of the Moon using this analytic function. Fig. 1 (top) shows the temperature function using a $0.5° \times 0.5°$ resolution using Eq. (2) for the dayside and Eq. (4) for the nightside.

For comparison, Diviner data are shown (Fig. 1, middle). The Diviner maps are created from nadir-only Diviner level 1 data. Each data point is geometrically corrected using a Lunar Orbiter Laser Altimeter (LOLA) derived digital elevation map (DEM) defined on an icosahedral geodesic grid comprised of 83,886,080 triangles with sides ~1 km in length. Each data point is ray traced from the detector to the surface to determine the correct latitude and longitude that each observation was made. The data was then binned into 0.5° longitude and latitude bins and 0.25 h of local time. This procedure is done for each of the seven Diviner IR-channels, which are then used to determine the bolometric brightness temperature, the wavelength-integrated radiance expressed as a temperature of an equivalent blackbody (Paige et al., 2010b). This results in a diurnal temperature curve for each 0.5° map pixel with a temporal resolution of 0.25 h of local time. The temperature for each pixel, given a pixel's latitude, longitude, and local time relative to a subsolar point, is then interpolated from the pixel's 0.25 h binned diurnal curve to create maps of instantaneous global temperatures for any given subsolar point. The map in Fig. 1 uses the anti-Earth point as the subsolar point.

The relative difference in the analytic function and the data is shown (Fig. 1, bottom). At this resolution, 74% of the grid points are within ±10 K of the Diviner observations. On the dayside at solar zenith angles <80°, 73% of grid points are within ±10 K of the Diviner observations. The nightside function at solar zenith angles >100° falls within ±10 K for 98% of the gridpoints. The model values for locations within 10° of the lunar terminator deviate from the Diviner observations by less than ±10 K on only 47% of the grid points. Thus, the function fits the Diviner observations well except near the terminator. The disagreement stems from the fact that temperature is an extremely strong function of incidence angle when the latter nears 90° (Vasavada et al., 2012). Topography at the terminator produces local variations in the incidence angle, which translates into large local variations in the temperature. Because the analytic function ignores topography, it cannot account for these effects.

In effect, the terminator is an inhomogeneous region for the lunar exosphere. In exospheric models, residence times of volatiles condensed on the nightside are a sensitive function of temperature in cooler locations and should be expected to vary widely at locations near the terminator. Therefore, the topographical effects will determine how far beyond the terminator the Moon must rotate to reach the release temperature for a given species. In addition, the vertical profile of exospheric density at the terminator may be sensitive to these shadowing effects because particles traversing the terminator were launched from a wide range of local temperatures.

This motivates a technique to implement an effective distribution that resembles the effect of topography without being tied to specific locations on the Moon. The surface temperature felt by a particle on contact with the surface can be calculated at a longitude shifted by a few degrees from the actual longitude of the point of contact. A simple method for this correction is to assign to each particle in the simulation an offset from the actual longitude for the purposes of calculating surface temperature using the analytical function $T(\theta, \varphi)$ defined previously. We suggest choosing an effective longitude from a Gaussian distribution of offset longitudes with a sigma of 4.5°. This distribution of effective longitudes is peaked on the actual longitude and includes small numbers of points with effective longitudes at further than ±10° from the actual longitude, representing thermal effects of sloped