DIURNALLY VARIABLE CONDUCTIVITY IN MARS HIGH-ELEVATION PARTICULATE SURFACES.

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Introduction: Thermal models can accurately represent most surfaces on Mars, but Arsia Mons' caldera floor behaves differently. Thermal models predict temperatures in this region which are up to ~15 K warmer than TES 14:00 h observations, while models of nearby regions closely match observed temperatures. The caldera surface appears to be affected by some physical process that is not incorporated into the thermal model. We investigate several possible causes for the anomalously low observed afternoon temperatures including: diurnally variable thermal inertia, a surface with non-Lambertian photometric properties, underestimated atmospheric dust opacity, and effects from frequent water-ice cloud coverage [1]. Of these possible causes, we suspect that thermal conductivity exhibits a strong temperature dependence in the caldera floor's unusual and dynamic environment, causing thermal inertia to vary diurnally.

Arsia Mons is southernmost in the row of three massive shield volcanoes comprising Tharsis Montes. The caldera floor is an extreme environment on Mars more than 16 km above the planetary geoid [2] where atmospheric pressures range annually between about 0.85 mb and 1.22 mb (calculated for a scale-height of 10 km, and adjusting for the seasonal CO_2 sublimation cycle). Temperatures on this surface drop to the point of CO_2 condensation (<145 K), each night, and then nearly double by noon the next day (exceeding 300 K during the summertime) [1]. This wide temperature range is characteristic of surface materials with extremely low thermal inertia, such as fine-grained dust, which is consistent with the fact that Mars' atmosphere can transport only the finest dust grains (~2 μm) via suspension up to Arsia Mons' elevation [3,4]. With a diameter exceeding 110 km, this caldera is large enough to contain mesoscale weather systems [5] and may be a topographic trap for atmospheric dust. If the caldera floor is covered by trapped atmospheric dust, then this may be among the finest-grained surfaces with some of the lowest thermal inertia found anywhere on Mars.

Thermal Inertia and Thermal Conductivity: Thermal inertia (I) is a measure of how effectively a material resists changes in temperature, and is defined as $I=(k\rho c)^{1/2}$, where k is thermal conductivity, ρ is bulk density and c is specific heat capacity. SI units for I are J m^{-2} $s^{-1/2}$ K^{-1} which we will henceforth refer to as 'tiu' (thermal inertia unit) as proposed by *Putzig* (2006) [6].

Under Mars surface conditions, high-thermal-inertia materials (>1000 tiu, such as bedrock and water-ice) resist changes in temperature and exhibit smaller diurnal and annual temperature variations. Indurated dust, horizontal mixtures of dust and rock, and sandstones have intermediate thermal-inertia values (400-1000 tiu), and unconsolidated granular materials, such as sand and dust, have low thermal inertia (<400 tiu). Low-thermal-inertia materials hold absorbed energy (heat from solar insolation) near the surface where it is quickly and continuously re-emitted into the atmosphere. Accordingly, surface temperatures of low-thermal-inertia materials are warmer during the day and colder at night than those of materials with higher thermal inertia.

In basaltic granular surfaces on Mars (e.g. dust and sand), ρ varies by a factor of <2 and c remains nearly constant, but k varies by several orders of magnitude. Thermal-inertia differences in these materials are therefore ascribed to differences in thermal conductivity [7]. Three components contribute to the bulk thermal conductivity of these materials:

$$k_{Total} = k_{radiative} + k_{gas} + k_{solid}$$

This equation is a reasonable first-order approximation of the true relationship where some interdependence exists between the individual components. $k_{radiative}$ describes the contribution from radiative heat transfer between the surfaces of individual particles, and is proportional to T^3 where T is temperature [8]. $k_{radiative}$ is strong at high temperatures but is not significant below about 300 K [9,10,11], so this term is negligible under most Mars conditions. k_{gas} is the dominant conduction mechanism for particulate materials under Mars conditions [10,12]. This component represents the transfer of heat energy between particles via the kinetic energy of gas molecules colliding from grain to grain within the pore spaces. Gas conductivity is proportional to the mean free path of atmospheric gas molecules, and inversely proportional to the density of the gas [13], and is therefore sensitive to changes in both temperature and pressure. k_{solid} is the contribution to conductivity in particulate materials from heat flowing directly through the contact points between individual grains. The distribution of particle sizes and the packing geometry within the material affects k_{solid} by changing the amount of surface-to-surface contact between individual grains. Heat will build up and remain around these contact points (which are small compared with the grains themselves) and allow only small amounts of energy to pass through the contact area, effectively behaving as an array of thermal capacitors [14].

Observations: We used data collected over the Arsia Mons caldera and two nearby control areas during the first year of TES [15] mapping (February 1999 to

January 2001; TES orbits 1584-9991). The two nearby control areas were selected for their lack of albedo or topographic variations and are assumed to represent the general Tharsis region at different elevations. These regions allow comparison of our results with previous studies and with results from the caldera floor.

Experimental Technique: We use the 'KRC' thermal model [1,16] to calculate lookup tables of surface temperatures which are interpolated to the times and seasons of each TES observation. Best-fit modeled parameters are then determined (via function minimization [1]) for three possible upper-surface conditions: {1} *Homogeneous* (vertically and horizontally consistent in composition and particle size): Case {1-a} returns the best-fit thermal inertia to a homogeneous surface assuming TES-observed albedo, and Case {1-b} treats both thermal inertia and albedo as free parameters. Treating albedo as a free parameter allows a comparison between best-fit values with those derived from TES observations. If this two-parameter case returns albedo values that are consistent with TES observations, then best-fit thermal inertia should be consistent with results from Case {1-a} and are likely to represent the actual surface material. Condition {2}: *Vertically layered thermal-inertia components*: Case {2-a} assumes that the surface layer has lower thermal inertia than a bottom layer fixed to a value of basalt bedrock (2280 tiu). Case {2-b} is a duricrust model where the surface layer has higher thermal inertia than a substrate composed of fine dust (28 tiu, [17]). The free parameters in cases {2-a} and {2-b} are the thickness (in mm) and thermal inertia of the surface layer. Condition {3}: *Horizontal rock mixtures*: Cases {3-a} and {3-b} assume that 10% of the surface area is covered by rocks (2280 tiu, with albedo values of 0.15 and 0.26, respectively), and return the best-fit thermal inertia of the non-rock component [1].

Results and Discussion: In the control areas, modeled temperatures fit consistently with observations in all homogeneous and vertically layered cases, but adding a rock component caused RMS errors to increase substantially [1]. On the caldera floor, our models do not fit nearly as well; the fixed-albedo cases return afternoon temperatures up to 15 K warmer than observations, while the variable-albedo case returns lower errors, but also returns albedo values more than 2 standard deviations higher than the observed mean value. As with the control areas, the rock-mixture cases return much higher errors [1].

The unexpected thermal behavior on the caldera floor may be consistent with thermal inertia that varies over diurnal timescales. If the thermal inertia is higher at midday than at night, then afternoon temperatures would be cooler than those modeled for nighttime thermal inertia values. Absolute temperature and the mean-free-path of atmospheric gas molecules both vary by a factor of two each day, which may induce a change thermal conductivity substantial enough to cause the temperature discrepancy we observe [1]. Laboratory experiments conducted by Fountain and West found that thermal conductivity in fine particulate materials (in vacuum) nearly doubled in the temperature range experienced on Arsia Mons (~145–300 K in TES 02:00 h and 14:00 h measurements) [9]. Even though Martian surfaces do not experience vacuum conditions, these experimental results may indicate the direction and magnitude (to first order) of how [$k_{radiative} + k_{solid}$] may vary with temperature on the caldera floor. k_{gas} also increases with temperature because more kinetic energy is transported by the interstitial gas molecules and the mean-free-path of these molecules can double during the midday on Arsia Mons [18,11].

Bulk conductivity of granular surfaces appears to increase with temperature in low-pressure environments [1]. A 4-fold increase between predawn and midday would mean a 2-fold increase in thermal inertia, allowing heat to penetrate more deeply into the surface and resulting in lower afternoon temperatures. Further laboratory studies and expanded modeling capabilities are necessary to improve our understanding of Martian surfaces under these dynamic conditions. We are unable to determine, at this time, the factor by which bulk conductivity must vary to cause the observed temperature range on Arsia Mons.

To understand how variable thermal conductivity would affect surface temperatures, we have designed a 1-dimensional thermal model where conductivity depends on surface temperature. Results from this model will be presented.

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