**THEMIS / TES STUDY OF THE ARSIA MONS / OTI FOSSAE THERMAL ANOMALY.**

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**Introduction:** Arsia Mons (southernmost of the three massive Tharsis-ridge shield volcanoes on Mars) is an extreme topographical feature that affects both climate and surface properties of the surrounding region. The Tharsis region has been thoroughly examined, and previous studies have determined the region to be mostly covered by a mantle, up to 2 meters thick, of fine (clay or silt-sized) unconsolidated granular material with low thermal inertia of about 70 J $m^{-2}$ $s^{-1/2}$ $K^{-1}$ (henceforth referred to as IU) [1-4].

The Arsia Mons / Oti Fossae thermal anomaly abuts the southeastern flanks of Arsia Mons and exhibits thermal behaviors unique from any other terrain in the Tharsis region. This region is centered at approximately 11° S, 244° E at an elevation of about 6-8 km, and covers an area of more than 15,000 $km^2$ (Figure 1) [5]. The northwestern edge of the anomaly is sharply defined at the topographic boundary where the volcano's flanks are truncated by younger basal flows (Figure 2), though some of the anomalous characteristics appear to creep up the slope in some places (Figure 3). In other directions where there is no topographic boundary, the edges of the anomaly are more diffuse.

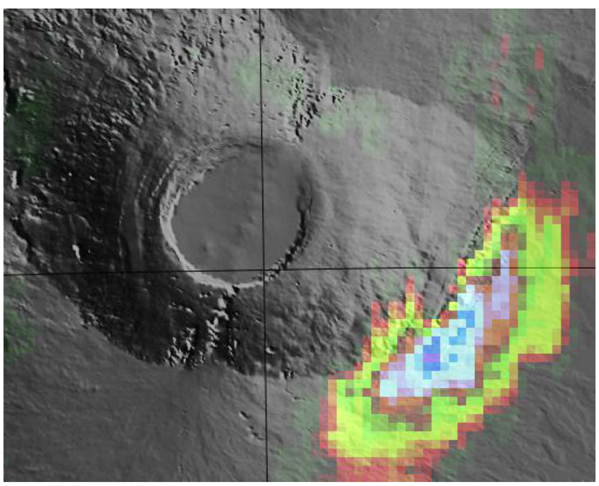

**Figure 1:** Context image showing Arsia Mons and the anomalous region. This is a MOLA shaded relief map overlain with TES-derived global thermal-inertia. Maximum thermal-inertia values for the anomaly are about 336 IU. The surrounding Tharsis region has a fairly consistent thermal-inertia value of about 70 IU.

This anomalous region has a substantially higher thermal inertia than the rest of Tharsis, and stands out strikingly in thermal images. Visible-wavelength observations, however, show only minor differences between it and the surrounding terrain other than a modestly lower albedo that is not always apparent.

Data from the Mars Odyssey Thermal Emission Imaging System (THEMIS) show the anomalous region to be warmer than its surroundings in the predawn hours, but also in late-afternoon observations (Figures 3 & 4). This is unusual because temperatures at thermal-inertia boundaries will cross values twice each day, and day/night IR observations of a single location will usually appear as negatives of each other. This is because materials with lower thermal inertia have larger variations of diurnal temperatures and therefore surpass the higher-thermal-inertia materials in both the warming and cooling portions of each day.

This study uses data observed by THEMIS, and by the Mars Global Surveyor's (MGS) Thermal Emission Spectrometer (TES) and Mars Orbiter Camera (MOC). These are compared with the 'KRC' thermal model to further constrain the thermophysical properties that govern this anomaly.

**Background:** Kieffer et al. (1976) first reported the anomalous nature of this region (cool in the afternoon and warm at night compared with surrounding terrain) by examining early data from the Viking Infrared Thermal Mapper (IRTM), an infrared radiometer sensitive to mid-IR wavelengths in five bands centered between 7 µm and 20 µm. IRTM also had a visible / near-IR band covering the range between 0.3 µm and 3.0 µm [6]. In 1989, the Phobos 2 Thermoscan instrument observed the anomaly, confirming that it exists on the surface, and is not an atmospheric phenomenon. There are no Mariner images of this particular feature [5].

Thermal inertias of the anomaly were first derived from predawn IRTM 20-µm brightness temperatures with a maximum value of about 336 (IU) near the center. This maximum value corresponds to that of unconsolidated sand-sized particles, but could also be indurated dust particles, a thin layer of dust over rock, or a horizontally hetergeneous mixture of rock and dust on the surface.

Zimbelman (1984) proposed this anomaly may be a consequence of the cyclic removal and deposition of dust over million-year timescales with the anomalous region being a 'window' through the present dust layer, and the underlying material may correspond to the current surface of Solis Planum to the southeast [7].

A more recent investigation by Nowicki (2007) also suggests this region may be experiencing erosion rather than deposition, with the anomaly being a 'window' that exposes an older surface [8].

**Observations:** This study uses data obtained from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES), the MGS Mars Orbiter Camera (MOC) narrow-angle camera, and from THEMIS VIS and IR cameras.

TES temperatures are derived from data collected by the TES thermal bolometer, which covers a continuous range of the thermal infrared between 5.1 and 100 microns [9]. MGS followed a constant off-axis polar orbit that forces the spacecraft to maintain equatorial observations at 2 a.m. and 2 p.m. (+/- 45 minutes) throughout the mission.

2 a.m. TES observations over a single Martian year show the anomalous region is usually about 30-35 K warmer than the surrounding terrain, while at 2 p.m. it's about 10 K cooler than the surroundings (Figure 4). TES-derived Lambertian albedo values are ~0.26 in the anomaly and ~0.29 in the surroundings. Furthermore, the TES dust-cover index generated by Ruff and Christensen (2002) shows lower amounts of dust covering the anomalous region with very low values in the center where thermal inertia is the highest [10].

The THEMIS instrument has two cameras: one for visible-wavelengths and one for the thermal infrared. The visible-wavelength (VIS) camera observes in 5 bands at either 18 or 36 meters per pixel. In this study we use only band-3 observations (centered at 0.65 µm) and 18-meter resolution. The infrared (IR) camera observes 10 bands (centered at 6.78 – 15.32 µm) at 100-meter resolution. We use band 9 (~12 µm) to derive surface brightness temperatures.

While 2 p.m. TES temperatures of the anomaly are slightly lower than the surrounding region, THEMIS IR images show the region to be warmer both in the morning and in the pre-dawn hours (Figures 3 & 4). As with TES, the early-morning differences are about 30-35 K, while afternoon temperatures of the anomaly are about 10-15 K warmer than the surroundings. A goal of this investigation is to explain these peculiar temperature differences.

We use visible-wavelength images obtained by both MOC and THEMIS. MOC is a high-resolution narrow-angle camera that observes with a maximum resolution of ~1.5 meters per pixel, while THEMIS gives much broader spatial coverage at 18 or 36 meters per pixel.

THEMIS VIS images clearly show lava-flows both on and around the anomaly. These are basal flows that are younger than Arsia Mons' flanks with the differences between them shown in figure 2. This high-resolution MOC image shows lighter-toned outcrops of a material that could be eroded dune forms [8] that are similar in the anomalous region, but far less numerous.

**Experimental Technique:** We employ a multi-layered thermal-diffusion model called 'KRC' [11], which has been used extensively in the study of Martian thermo-physical properties [11-14]. This model calculates surface temperatures throughout an entire Martian year for a specific set of slope, azimuth, latitude, elevation and albedo for up to ten different thermal-inertia values.

To calculate surface temperatures, KRC uses the Delta-Eddington approximation for radiative flux [11] to solve the subsurface thermal-diffusion equation using finite-difference methods. The upper boundary condition is solar insolation (calculated at each step according to orbital position, orbital inclination and time of day) on top of a single-layer gray atmosphere, and a mean Martian visible dust opacity of 0.2 is used. Though the model adjusts the atmospheric column-density for this opacity to scale-height values, both are held constant throughout the year, which could seasonally affect the model's accuracy during periods of heavy atmospheric dust or frequent water-ice cloud activity.

We ran multiple KRC models, for a range of albedos, thermal inertias and layer depths to create a lookup table of temperatures. Values from this table are then interpolated (bilinear) to match the corresponding dates and times of each TES observation. After this interpolation, we have a working index of temperatures modeled to the time of each TES observation at a logarithmic range of ten thermal inertias between 50 and 1131 IU; a logarithmic range of 15 layer depths between 5 and 640 mm; and a linear range of 17 albedo values between 0.1 and 0.5. The downhill-simplex method of function minimization [15] is then used to compare modeled with observed data to determine best-fit values for thermal inertia (other cases will also determine the best-fit albedo or layer depth).

Afternoon and nighttime data are fit simultaneously to obtain best fit thermal inertias. We examine four specific cases: the first uses homogeneous boundary conditions and albedo values that are fixed to observed values (and +/- 1 standard deviation). Our second case also uses homogeneous boundary conditions, but albedo becomes a free parameter. Comparison of best-fit and observed albedos provides a gauge for our confidence in best-fit thermal-inertia values.

Our third case uses a two-layered model with albedos fixed to observed values. The free parameters in this case are thermal inertia and depth of the surface dust layer. Case 3 is compared with the homogeneous cases to determine whether surface temperatures are influenced by a high-thermal-inertia sub-surface material such as bedrock. We ran KRC models using 2 different values of thermal inertias for the lower material: 1844 and 2280 IU—each of these generated surface temperatures for fifteen upper-layer depths ranging logarithmically between 5 and 640 mm. 2280 IU is the thermal inertia of solid basalt [16], and is the expected upper-limit for this volcano's bedrock because outgassing of the cooling lava at this elevation would have caused some degree of porosity in the material [*17*]. The fourth case tests for a horizontally heterogeneous surface composed of sand or indurated dust with various percentages of exposed basalt covering the surface.

**Discussion:** This anomalous region has a thermal-inertia value corresponding to that of unconsolidated sand, but there are no visible bedforms or other indication of sand deposits within the anomaly (though some bedforms can be found just west of the anomaly on the lower flanks of Arsia Mons). A layer of indurated dust covering the lava flows could also have this thermal-inertia value. However, because we don't have in-situ measurements of Martian indurated dust and cannot know the actual grain sizes or the degree or depth of cementation, we can only mention this as a possibility.

A reasonable possibility is a rock/dust mixture on the surface, and results from our model-fiting technique seem to support this idea. We obtained superior results with case 4 (which assumes a rock/dust mixture). RMS errors for this case were 1.6 K, while best fits for the other cases had errors between 2.1 K and 4.5 K (Figure 5). At the boundary shown in Figure 2, notice how the younger anomalous region is smoother with fewer of the lighter-toned outcrops than Arsia Mons' older flanks. Nowicki (2007) suggests these outcrops may be eroded duneforms with the unmantled appearance, suggesting the region has undergone erosion rather than deposition. This older surface does not have the appearance one would expect for having such a low thermal inertia of ~70 IU, and may therefore be covered by a thin veneer of unconsolidated dust [8].

The center of the anomaly has the highest thermal inertia (~350 IU), and also has the smoothest appearance with the fewest lighter-toned outcrops. This may be the result of a basaltic lava flow that was once covered in dust, and subsequently eroded to expose the upper surface of the flow with dust remaining in cracks and other protected spaces. Our best-fit modeled results seem to support this idea by returning the lowest RMS errors for rock/dust mixtures.

Zimbelman's proposal that the region may be a 'window' exposing an older surface is supported by Nowicki (2007) [8] and by the results from our model-fitting technique. However, more recent high-resolution images from THEMIS and MOC indicate that a correspondence between this unit and the surface of Solis Planum, as discussed previously, is unlikely due to different visible morphologies.

The curious phenomena that THEMIS IR images show the anomaly to be warmer at both times of day is explained in figure 4. This is apparently a consequence of observational times combined with the particular combination of thermal-inertia values that exist at the boundary.

In the future, we will calibrate THEMIS IR data with TES-derived temperatures in order to generate high-resolution thermal-inertia maps at 100 meters per pixel. Mesoscale atmospheric models of the region may also provide insights about local wind patterns, telling us if an erosional environment is reasonable to assume.

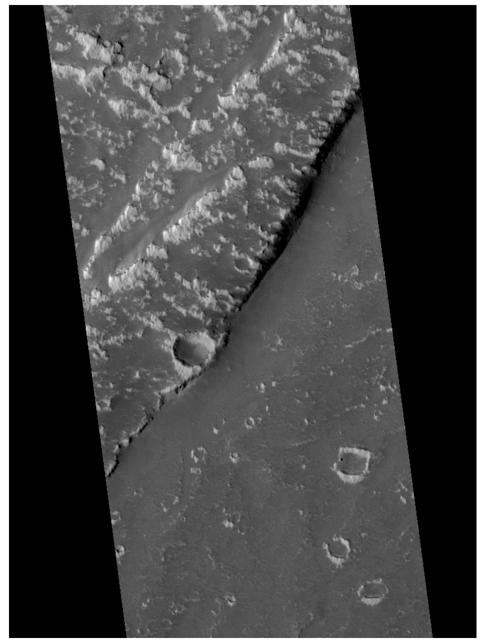

**Figure 2:** MOC image M0804732 (2.84 m/pix) showing the boundary along the northwestern edge of the anomaly. The upper-left surface has a thermal inertia of about 70 IU, and the lower right portion (younger) has a value of about 280-300 IU. Notice how the lower-inertia unit has a greater density of lighter-toned outcrops.

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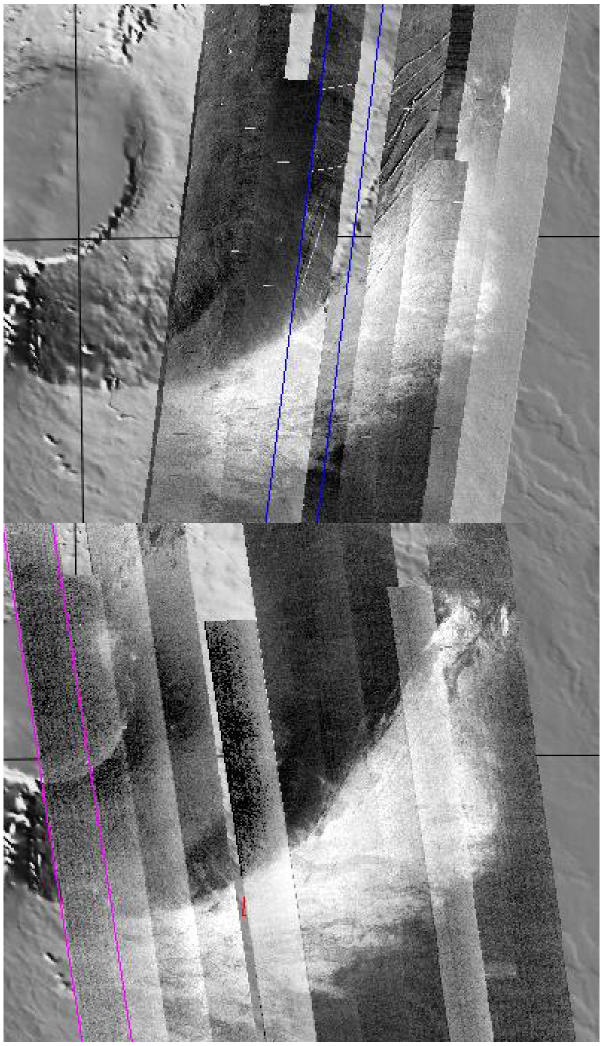

**Figure 3:** Mosaic of afternoon (top) and early morning (bottom) THEMIS IR images with the anomalous region warmer than surroundings at each of these times. Notice how some of the anomalous behavior appears to creep up the volcano's flank in some places – this is most obvious in early-morning observations.

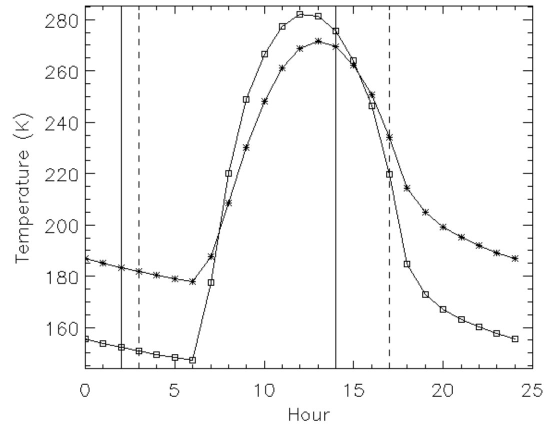


**Figure 4:** KRC diurnal temperatures for thermal-inertia values of 71 IU (boxes) and 283 IU (stars) at $L_s$.= 160° Solid vertical lines show approximate times of MGS observations, dashed lines are for THEMIS. This graph demonstrates why the anomaly is warmer for both times of THEMIS observations (Figure 3).

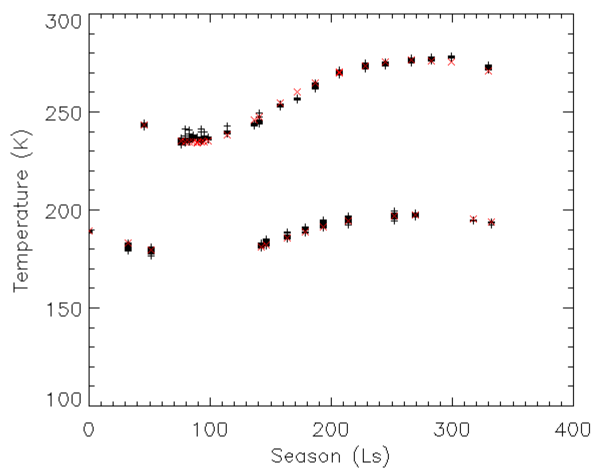


**Figure 5:** Best-fit results for Case 4 using diurnal temperatures derived by TES over one Martian year. This case assumes a rock/dust mixture with 20-40% rock. RMS error is 1.6 K. This modeled case fits observations better than homogeneous or vertically layered cases.