THE OBSERVATIONAL BIAS OF THERMAL SPECTRA DUE TO SUBPIXEL VARIATIONS.

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Introduction: The Dawn mission to Vesta has provided an extensive amount of data that drives our understanding of it and other asteroids. During the encounter, the Dawn mission took numerous spectral cubes of Vesta's surface with the Visual and Infrared Spectrometer (VIR). These data provide spatially resolved spectra of Vesta's surface, out to a wavelength of 5.1 microns [1]. We used this data to measure the surface temperatures of the Vesta around the crater Cornelia [2]. However, when comparing the measured temperatures to both computer models and the theoretical maximum from black body calculations, we noted that the surface appears much hotter than expected.

This discrepancy has been noted by others for other objects and has been explained as beaming [3] and a combination of beaming and self heating [4]. Recent work has focused on using complex modeling to track the effects of beaming, self heating, shadows and subpixel hotspots [5, 6, 7]. On Vesta specifically, [7] has explained the difference in measured temperatures and expected temperatuse to be due to a low effective emissivity. [8] has noted a similar issue in their work.

We have found a more clear method to describe the measured temperatures on Vesta solely based on subpixel variations of the surface.

Vesta Temperature: The irradiance detected by the VIR instrument beyond 4 microns is a function of both reflected solar light and thermal emission. We make the assumption that the surface reflectance does not change between 4.6 and 5.1 microns. By doing so, we can use the observed flux at 4.6 and 5.1 to constrain both the temperature and surface reflectance. We have determined that our values are similar to those calculated by the VIR team [8]. Figure 1 shows the surface temperature of Cornelia as well as a nearby crater to the south. While Cornelia is more scientifically interesting, we used the highly degraded crater to the south to test and calibrate our methodology. The degraded crater has been highly gardened by impacts, it's rim has been highly degraded, and there is no indication of mineralogical or tectonic variations or thermal abnormalities. We assert that the photometric, spectral and thermal properties of this crater are homogenous, and as such, we can use topographic variations to understand the effects of illumination conditions on the measured surface temperature. Figure 2 shows the temperature of the nearby crater plotted as a function of incidence angle, and one can note the expected cooling trend with increasing incidence angle.

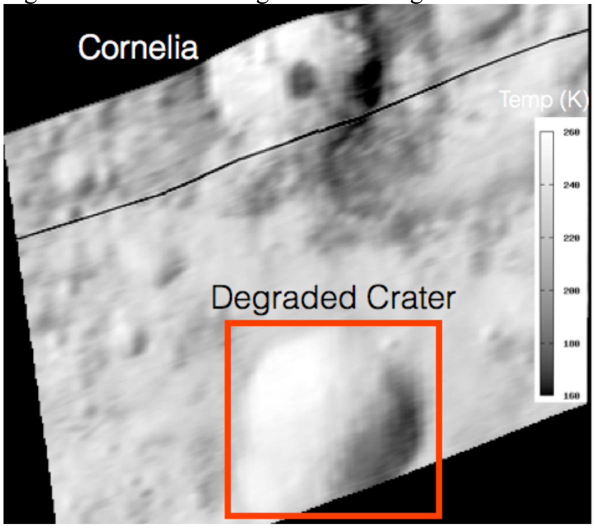

Figure 1 – Temperature of Cornelia and a highly degraded crater to its south. The degraded crater is highly homogeneous and was used to valid the effects of incidence angle. VIR_IR_1B_371813008_1

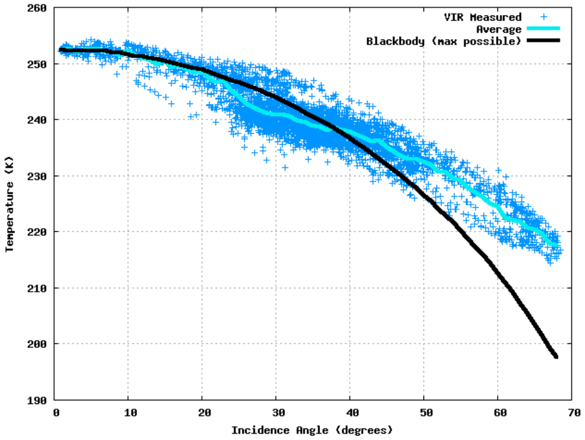

Figure 2 – The blue points are the measured surface temperatures of the highly degraded crater. The light blue line is the mean temperature for each degree of incidence angle. The black line is the maximum temperature that the surface should be assuming emissivity of 1, Bond albedo of 0.19 (the average for that region) and no thermal conduction.

Black Body Temperature: In general, the maximum temperature of a surface will be the black body temperature with a Bond albedo of 0. This assumes no heat flow or other factors. Figure 2 shows the black body temperature as a function of incidence angle. The flux is based on the mean solar flux, the actual distance of Vesta, and an average Bond albedo in this region of 0.18.

What is striking is that the observed surface temperature is higher than the theoretical limit, which has been noted by other researchers [5, 6, 7].

For our analysis we used 2 VIR observations from HAMO and HAMO2: VIR_IR_1B_371813008_1 and VIR_IR_1B_1_393798660. The data presented here are from the first cube, and the second cube's data are similar. The phase for VIR_IR_1B_371813008_1 is 28.5°, the incidence angle ranged from 0 to 68°.

What is important to note is that at low incidence angles, the observed temperatures closely match the expected values; however, as incidence angle increases, there becomes a larger discrepancy between theoretical acceptable temperatures and observed temperatures. Thermal studies of comets have noted a similar trend [6].

Subpixel Model: We have determined that the observed temperature of Vesta can be described by modeling the surface as a rough surface so that every particle grain has a region that is orthogonal to the sun and that the rest of the grain is cool due to minimal illumination, Fig 3.

This can be seen if one assumes the surface if filled with spheres on a slope. Regardless of the sun position, a part of the spheres will be fully illuminated, while edges will be without significant illumination. When incidence angle is near 0, there are no shadows and the tops of the grains are fully illuminated. However, when the incidence angle is large, especially past 60°, there are significant shadows and the portion of the sphere that is illuminated is reduced. Further, the observation geometry will result in a larger fraction of the cold part of the grain being observed.

To simplify calculations, we use square grains that have one face orthogonal to the sun. As such, the projected area for the VIR observations can be approximated as Eq. 1. This results in the observed thermal spectrum being a mixture of thermal flux from both the hot and cold regions of the particles, Eq. 2. It is important to note that this thermal spectrum has a different shape than the thermal spectrum of a homogenous surface. If one solves the Planck function for temperature, one will get different temperatures depending on which wavelength range is used.

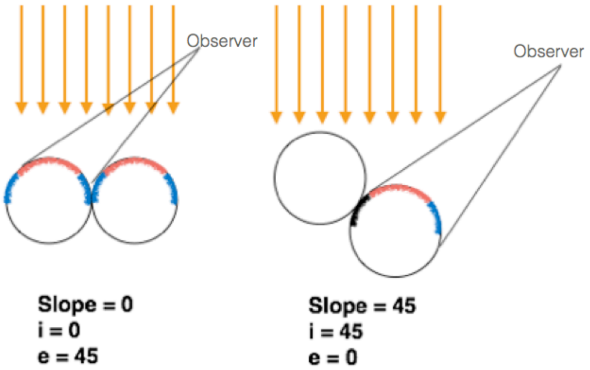

Figure 3 – This shows how a rough surface causes significant subpixel variations. The observed thermal spectrum is a mixture of the thermal spectra from all hot and cold spots. The observed thermal spectrum will have a different shape than the Planck function.

$$A_{hot} = A\cos^2(i) \tag{1}$$

$$\Phi_{observed} = A_{hot}\Phi_{hot} + A_{cold}\Phi_{cold} \tag{2}$$

Conclusion: The effect of subpixel thermal variations is strong and has considerable impact on the shape and magnitude of the observed thermal spectrum. As such, one can not directly use the thermal irradiance at a specific wavelength to determine the temperature. Doing so would result in a temperature in-between the two extreme values and be higher than the average temperature for the surface.

Continued modeling is required in order to understand the effects of subpixel thermal variations; however, it does provide a clear theoretical model to explain the higher than expected measured temperatures and avoids the use of the poorly defined beaming factor.

References: [1] deSanctis M. C. et al. (2011) *Sp. Sci. Rev., 163,* 329-369. [2] Palmer E. E. et al. (2012) *DPS 44,* 207.10. [3] Lebofsky L. A. et al. (1986) *Icarus, 68,* 239-251. [4] Spencer J. R. (1989) *Icarus, 83,* 27-38. [5] Davidsson B. J. R. et al. (2013) *Icarus, 224,* 154–171. [6] Groussin O. et al. (1989) *Icarus, 222,* 580–594. [7] Rozitis B. and Green S. F. (2011) *M. N. Royal Ast. Soc.*, 415, 2042-2062. [8] Tosi F. H. (2012) *DPS 44,* 207.11. [9] Titus T. N. et al. (2013) *LPS XXXIV,* Abstract #1719.

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