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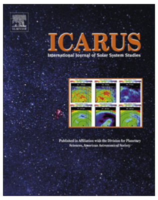

Separation of thermal inertia and roughness effects from Dawn/VIR measurements of Vesta surface temperatures in the vicinity of Marcia Crater

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ABSTRACT

A physical model of small scale roughness has been applied to the analyses of VIR (Visible InfraRed mapping spectrometer) – measured surface temperatures in the Marcia Crater region of asteroid Vesta. Model-generated surface temperatures which include the effects of minicrater-induced flux enhancements and viewing geometry are compared with the measured surface temperature dependence on solar incidence and emission angles. Results indicate that an extremely low thermal inertia ($I = <5\,\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1/2}}$) and high roughness (rms slopes $\sim 35°$) characterizes almost all of the areas in and around Marcia Crater. The one clear exception is the relatively cool pitted terrain region within Marcia Crater which requires either a higher thermal inertia value ($I \sim 10$) or significantly less roughness to match the VIR data. The $I \sim 5$ finding is the lowest value found for the regolith of any airless body in the inner Solar System and is difficult to reproduce in either laboratory measurements or theoretical models of the thermal conductivity of dry granular materials in vacuum.

1. Introduction

Marcia Crater is the largest well-preserved, post-Rheasilvia impact crater on Vesta. The event that formed Marcia Crater disrupted the relatively large region of dark, hydrated material found in this hemisphere of Vesta, exposing both buried dark material and fresh, bright material with its strong pyroxene absorptions consistent with Vesta's eucritic crust (Williams et al., 2014). Several peculiar terrains were mapped as discrete geologic units (Williams et al., 2014): pitted terrains (Denevi et al., 2012), gully-like features (Scully et al., 2015), smooth materials, dark lobate materials, bright lobate material, and bright crater material. The thermal behavior of the Marcia region, as far as dark and bright material units and the pitted terrain are concerned, was already briefly touched in previous works (Tosi et al., 2014; De Sanctis et al., 2015). This work presents for the first time a high resolution thermo-physical modeling of this region, which is a natural complement to previous works relevant to the inference of intrinsic thermal properties of specific Vesta terrains.

Thermal inertia is the key parameter constraining the heat exchange and thermal balance of planetary surfaces. For an airless body such as Vesta it depends primarily on regolith porosity and grain size (Gundlach and Blum, 2013) which in turn can be interpreted in terms of impact/erosion processes, depositional history, and outgassing potential. Diurnal surface temperature variations provide the primary diagnostic for thermal inertia ($I = (k * \rho * c)^{0.5}$) where k = thermal conductivity, ρ = density and c = specific heat in MKS units). For a smooth lambertian surface at known heliocentric distance, with well constrained values for the Bond albedo and infrared emissivity, surface temperatures map almost uniquely to the thermal inertia parameter. However, for real surfaces, departures from smoothness on both large and small scales (topography and roughness) produce shadowing and reradiation effects which alter the surface temperature distributions and resultant thermal flux. The end effect can be an ambiguity in the interpretation of thermal flux measurements in terms of thermal inertia.

For unresolved thermal flux measurements of asteroids and comets from Earth and space-based platforms, the signatures of thermal inertia and surface roughness cannot be separated, and only a range of global thermal inertia values can be estimated. At near- to mid-infrared wavelengths thermal flux measurements of surface temperatures of airless bodies of known size frequently

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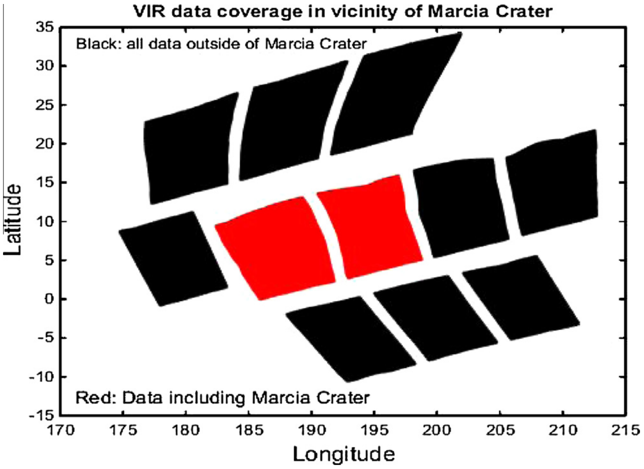

Fig. 1. VIR data coverage in and around Marcia Crater during the HAMO-2 phase of the Dawn Mission at Vesta. Longitude coordinate in the Dawn Claudia System. Red areas include Marcia Crater region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exceed the theoretical values based on radiative equilibrium (zero thermal inertia) models for which the surface radiative flux equals the solar input flux. The thermal effects of small scale roughness have long been considered the likely cause of observed thermal flux enhancements for the infrared observations. The infrared enhancements have traditionally been modeled by adding a beaming parameter to the radiative boundary condition at the surface (see Lebofsky et al., 1986; Lebofsky and Spencer, 1989, and references therein). The beaming parameter has been a useful parameterization for rescaling surface temperatures to match disk-integrated infrared fluxes of unresolved planetary bodies. However, it is both wavelength and solar phase angle dependent and, for disk-resolved observations, cannot reproduce the center-to-limb variations in flux enhancements of statistical or physical roughness models (Rozitis and Green, 2011). In particular, the single beaming parameter approach cannot clearly separate the effects of thermal inertia and roughness: comparable disk-integrated flux measurements can be reproduced both by a smooth low thermal inertia surface and a high thermal inertia surface with significant roughness. (See Section S1 of Supplementary Material.)

Alternative to the beaming parameter, physical models of roughness have been developed to explain thermal infrared enhancements and directional effects seen in observations of airless planetary surfaces. Both statistical models of roughness and, more commonly, fractional surface coverage by “mini-craters” have been presented to reproduce the flux enhancements seen in the infrared observations. The early work of Buhl et al. (1968) and Winter and Krupp (1971) considered the effects of spherical-shaped craters as a source of the thermal flux phase effects observed on the Moon. They found that a lunar surface covered with ~50% near hemispherical craters (Buhl et al., 1968) or ~2/3 coverage of a mixture of hemispherical and shallower craters (Winter and Krupp, 1971) could reproduce the Moon’s center-to-limb emission profile. Computations of crater-induced thermal flux enhancements on asteroids were introduced by Hansen (1977) for the purpose of improving asteroid albedo and diameter estimates based on combined visual and infrared photometry. Subsequent investigators who used crater-added thermal models for the interpretation of asteroid flux measurements included Spencer (1990), Lagerros (1996, 1997, 1998), Muller and Lagerros (1998), Delbo and Tanga (2009), Matter et al. (2011), O’Rourke et al. (2012), and Keihm et al. (2012). The common finding of these investigators was that crater-based models of physical roughness, with varying values of depth/diameter ratios and fractional coverage, could account for the infrared thermal enhancements seen in the larger asteroid observations. However, absent disk-resolved thermal flux data, unique determination of thermal inertia and roughness parameters could not be made.

The large data base of highly resolved Visible InfraRed (VIR) (De Sanctis et al., 2011) mapping spectrometer thermal flux measurements of Vesta from the DAWN spacecraft (Russell et al., 2012) presented an extraordinary opportunity for separating the effects of thermal inertia and roughness on regional scales. By combining shape model information (R. Gaskell, personal communication to the VIR Team, 2013) with VIR pixel locations, the observation geometry could be constrained at sub-km scales, including solar incidence and emission angles and their azimuth separation, parameters required to uniquely compute flux enhancements due to minicrater roughness and thereby separate the effects of roughness from the thermal inertia constraint. In Section 2 the VIR data base of Vesta surface temperatures and observation geometry parameters used in this work are described. Thermal model development and minicrater roughness calculations used for comparisons with the VIR surface temperature data are presented in Section 3. Modeling results in terms of best fit thermal inertia and roughness parameters within Marcia Crater, and for the extended regions surrounding Marcia Crater, are presented in Section 4. Section 5 compares our Vesta thermal inertia results with previous work and presents a discussion of the implications of the derived thermal inertia and roughness constraints as they pertain to regolith porosity and particle size. Section 6 summarizes our results.

2. VIR surface temperature data base

The VIR determinations of surface temperature rely on the radiance measurements in the 4.5–5.1 μm range of the VIR instrument, the range dominated by thermal emission from the surface. For each VIR pixel the measured spectral radiance is used to determine both surface temperatures and a near IR spectral emissivity by means of a Bayesian retrieval algorithm. The assumptions and methodology of the Bayesian algorithm are the same as those described in the Appendix of Tosi et al. (2014). Briefly, within the spectral range 4.5–5.1 μm, a synthetic spectrum is considered, given by the superposition of a reflected solar spectrum, modeled by an appropriate photometric function, and a thermally emitted spectrum, where the emissivity is initially considered equal to 0.95 across the whole range. Subsequently, a best fit is sought between this synthetic spectrum and the VIR measured spectrum, within the in-flight instrumental noise characteristic of each observation. Surface temperature and spectral emissivity, which are the two unknown quantities, are free to float within a given range defined a priori, until convergence around stable values is achieved.

In the Marcia observations considered here, the typical value of emissivity in the 4.5–5.1 μm range used for the retrieval is 0.76–0.99, which embraces the values typical of the categories of bright material units (lower emissivity) and dark material units (higher emissivity) already investigated previously (Tosi et al., 2014). (Note that the near-infrared emissivity differs from the mid-infrared emissivity required for modeling of the radiative flux balance at the surface.) Because the VIR-measured fluxes vary steeply with temperature in the near-infrared, the derived surface temperatures are relatively insensitive to plausible errors in the emissivity constraint, resulting in formal errors <1 K for surface temperatures above 220 K (Tosi et al., 2014). Dynamic range limitations limit the reliable surface temperature determinations to values >180 K, thus precluding night side measurements.

All work reported herein is based on analysis of the VIR measurements of Vesta surface temperatures in the regions including and surrounding Marcia Crater during the second High-Altitude