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Interpretation of combined infrared, submillimeter, and millimeter thermal flux data obtained during the Rosetta fly-by of Asteroid (21) Lutetia

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ABSTRACT

The European Space Agency's Rosetta spacecraft is the first Solar System mission to include instrumentation capable of measuring planetary thermal fluxes at both near-IR (VIRTIS) and submillimeter–millimeter (smm–mm, MIRO) wavelengths. Its primary mission is a 1 year reconnaissance of Comet 67P/Churyumov–Gerasimenko beginning in 2014. During a 2010 close fly-by of Asteroid 21 Lutetia, the VIRTIS and MIRO instruments provided complementary data that have been analyzed to produce a consistent model of Lutetia's surface layer thermal and electrical properties, including a physical model of self-heating. VIRTIS dayside measurements provided highly resolved 1 K accuracy surface temperatures that required a low thermal inertia, $I < 30$ J/(K m^2 s$^{0.5}$). MIRO smm and mm measurements of polar night thermal fluxes produced constraints on Lutetia's subsurface thermal properties to depths comparable to the seasonal thermal wave, yielding a model of $I < 20$ J/(K m^2 s$^{0.5}$) in the upper few centimeters, increasing with depth in a manner very similar to that of Earth's Moon. Subsequent MIRO-based model predictions of the dayside surface temperatures reveal negative offsets of ~5–30 K from the higher VIRTIS-measurements. By adding surface roughness in the form of 50% fractional coverage of hemispherical mini-craters to the MIRO-based thermal model, sufficient self-heating is produced to largely remove the offsets relative to the VIRTIS measurements and also reproduce the thermal limb brightening features (relative to a smooth surface model) seen by VIRTIS. The Lutetia physical property constraints provided by the VIRTIS and MIRO data sets demonstrate the unique diagnostic capabilities of combined infrared and submillimeter/millimeter thermal flux measurements.

1. Introduction

Measurements of thermal fluxes from planetary solid surfaces at infrared (IR), submillimeter (smm), and millimeter (mm) wavelengths provide complementary information relevant to the thermal and electrical properties of regolith materials. At infrared wavelengths shortward of ~50 μm, the surface layer opacities of solid bodies are sufficiently high that the measured thermal radiation can be interpreted directly in terms of surface temperature and thermal inertia. Major uncertainties occur when a non-smooth surface produces "hot spots" related to self-heating. These cases can require an empirical or physical model of surface roughness for interpretation of IR data. The effects are greatest for flux measurements of main belt asteroids in the near infrared (3.5–5 μm) for which the warm areas are disproportionately weighted in the signal due to the non-linear Planck function. It is commonly seen that Earth-based near- and mid-IR measurements of asteroid dayside surface temperatures exceed their theoretical maximum for a black body smooth surface at a given Sun distance. The phenomenon has been commonly accounted for by adding a beaming parameter to the surface radiative flux balance equation (e.g., Jones and Morrison, 1974; Lebofsky et al., 1986; Lebofsky and Spencer, 1989; Harris, 1998), effectively rescaling the temperature distribution across the surface to match the measured disk-integrated fluxes. However, with the advent of increasing use of spacecraft-based IR and radiometric instruments, well-resolved measurements of medium to small body thermal fluxes are becoming available, justifying more sophisticated thermal modeling of regolith surfaces, including physical models of self-heating.

At smm, mm, and longer wavelengths absorption losses decrease sufficiently that subsurface layers contribute significantly to the observable thermal emission, thus providing information on the subsurface temperature regime. Effective emission depths increase with increasing wavelength. Sensitivity to surface hot spots is diminished by conductive effects and the Planck law for thermal emission becoming more linear with temperature so that small hot spots no longer dominate the measurement. For

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particulate regolith material of low thermal inertia, as occurs on the Moon and is believed to commonly occur on larger asteroid surfaces (Spencer et al., 1989; Muller and Lagerros, 1998; Delbò et al., 2007), the dayside subsurface regimes include regions of very large thermal gradients, 50 K/cm or more, related to the downward propagation of large surface temperature excursions which occur during the rotational cycle. When the larger gradients occur at the principal emission depths of the wavelength-dependent fluxes, the interpretation of the thermal flux measurements becomes extremely sensitive to the electrical absorption of the regolith material; i.e., the penetration depth. In order to optimize the interpretation of the thermal flux measurements, multi-frequency observations, including the smm/mm and infrared, are required.

In this paper we describe the synergy of the multi-frequency thermal flux measurements of the Asteroid (21) Lutetia obtained by the MIRO and VIRTIS instruments during the Rosetta spacecraft fly-by of July 10, 2010 (Gulkis et al., 2012; Coradini et al., 2011; Tosi et al., 2012). Lutetia is a large main-belt asteroid (mean diameter ~106 km), located in the inner part of the belt, with a semi-major axis of 2.435 AU, eccentricity of 0.1634, and rotation period of 8.1683 h. The spin axis of Lutetia lies nearly in its orbital plane, similar to the planet Uranus. Its large obliquity, 96.35° (Carry et al., 2010; Sierks et al., 2011), is responsible for strong seasonal effects because its northern and southern poles alternate between being in constant illumination and in constant darkness with the orbital period of ~3.8 years. Prior to the Rosetta fly-by, estimates of Lutetia's surface thermal properties were made based on Earth and space telescope infrared measurements (Mueller et al., 2006; Carvano et al., 2008; Delbo and Tanga, 2009; Lamy et al., 2010). The findings were consistent, indicative of low thermal inertias in the range I = 5–50 J/(K m^2 s$^{0.5}$). The ground based values are consistent with the independent results of the VIRTIS and MIRO fly-by measurements (Coradini et al., 2011; Gulkis et al., 2012).

At the time of the Rosetta encounter with Lutetia, the subsolar latitude was 47°N, high enough for the North Polar regions to be continually illuminated over the diurnal cycle and significantly warmer than the high latitude South Polar regions which were in continual darkness. The Rosetta spacecraft (s/c) approached the sunlit Northern Hemisphere of Lutetia at near zero phase angle on 10 July 2010. Closest approach (CA) occurred at 15:44:57 UTC onboard at a fly-by distance (Rosetta to Lutetia center) of 3168.2 km (Schulz et al., 2012). The fly-by trajectory carried Rosetta over Lutetia's North Pole, shifting the sub-s/c solar phase by ~180°, from local noon to local midnight, over a ~5 min period approximately centered on CA. While viewing sunlit terrain both VIRTIS near-IR and MIRO dual channel thermal flux measurements were obtained. Approximately 30 min after CA, the s/c performed a deliberate slew motion to scan the MIRO beams on and off Lutetia's unlit southern limb for the purpose of measuring the winter night temperatures and the limb position. During the nightside slew, the MIRO channels obtained thermal flux measurements over a 1.5 min period during which the MIRO beams crossed onto the southern limb, migrated to the northern limb, then retreated southward until crossing off of the southern limb. Due to the extremely low levels of Lutetia nightside temperatures, only the MIRO mm and smm channels could obtain thermal flux measurements during the nightside slew. A more detailed description of the Rosetta fly-by geometry of Lutetia can be found in Schulz et al. (2012) and Gulkis et al. (2012).

This paper is organized in the following manner. Section 2 provides background information on the VIRTIS and MIRO instruments needed by the readers. Section 3 describes the observations, modeling, and conclusions reached independently by the VIRTIS and MIRO data analyses. In Section 4 we consider both data sets simultaneously and focus on the additional information that can be derived that was not realized when the two data sets were analyzed independently. The principal addition is a constraint on a physical model of roughness that reconciles the VIRTIS-measured dayside IR fluxes with a thermal inertia constraint provided by the MIRO night side smm flux measurements. Conclusions and summary remarks constitute Section 5.

2. Instrumentation

2.1. VIRTIS

The Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) onboard Rosetta consists of two main channels that provide a double capability: (1) high spatial resolution (instantaneous square field-of-view (IFOV), with angular resolution of 51.6 arcsec) visible and infrared imaging in the 0.25–5.1 μm range at a moderate spectral resolution of $R \sim 70$–380 (VIRTIS-M channel) and (2) high spectral resolution spectroscopy, $R \sim 1300$–3000, in the 2.0–5.0 μm range (VIRTIS-H channel). The two channels observe in tandem the same areas in combined modes to take full advantage of their complementarities (Coradini et al., 2007). During the Lutetia fly-by, VIRTIS-H was operating only during the closest approach phase and its data are not discussed here.

VIRTIS-M is an imaging spectrometer, able to acquire a stack of monochromatic images (up to a 220 × 220 arcmin FOV) combined in a three-dimensional object with two spatial dimensions and one spectral dimension, commonly called a hyperspectral cube. This technique allows the reconstruction of the spectrum for each pixel. Thanks to the flexibility provided by an internal scanning mirror, it is possible to acquire cubes in scanning mode (moving the scan mirror at 1 IFOV (55 arcsec) step) or in pushbroom mode (exploiting the natural drift of the spacecraft with respect to the target without moving the scan mirror). VIRTIS-M operates simultaneously in the visual (0.25–1.1 μm) and infrared (1.0–5.1 μm) domains, with spectral sampling steps of 1.89 and 9.44 nm respectively. In the reflectance-plus-emission spectrum of the dayside of Lutetia as measured by VIRTIS, the thermal emission dominates in the region between 3.5 and 5.1 μm (Fig. 1), from which surface temperatures and the spectral emissivity are computed. A brief description of the surface temperature retrieval algorithm is given in the Appendix. A more comprehensive description of the VIRTIS instrument, performance characteristics, and operating modes can be found in Coradini et al. (2007).

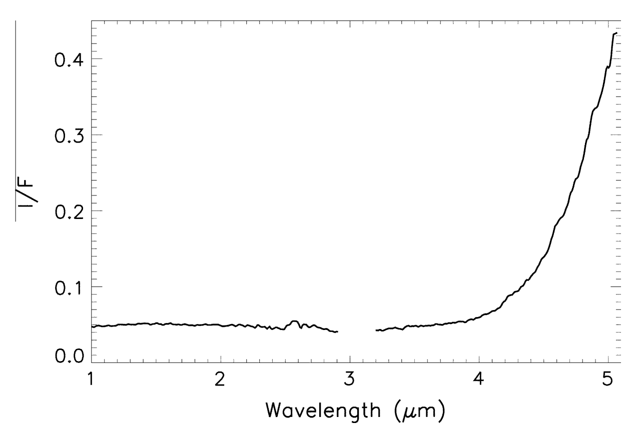

Fig. 1. Spectrum of Lutetia as measured by VIRTIS-M in the infrared range 1.0–5.1 μm during the closest approach phase of the fly-by, in units of calibrated radiance factor I/F defined as specific intensity divided by the incident solar flux scaled for its heliocentric distance. The prominent thermal emission of the asteroid is not removed and is revealed at wavelengths longerward of ~3.5 μm. The spectrum results from the average of all pixels of the target as seen in VIRTIS cube 00237396952. The region centered at 3 μm, not shown, is affected by the counterpart of an instrumental artifact.