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A method to derive surface thermophysical properties of asteroid (162173) Ryugu (1999JU3) from in-situ surface brightness temperature measurements

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ABSTRACT

The MASCOT radiometer MARA on board the Hayabusa2 mission will measure surface brightness temperatures on the surface of asteroid (162173) Ryugu in six wavelength bands. Here we present a method to constrain surface thermophysical properties from MARA measurements. Moreover, uncertainties when determining surface thermal inertia as well as emissivity are estimated. Using data from all filters and assuming constant emissivity, thermal inertia of a homogeneous surface can be determined with an uncertainty range of 250 ±16 $Jm^{-2}K^{-1}s^{-1/2}$, while the emissivity uncertainty is below 6%. Similar results are obtained if emissivity is allowed to vary as a function of wavelength and if the MARA channels with the best signal-to-noise ratio are used to constrain thermal inertia. If the observed surface is heterogeneous and two morphologically different units are present in the instrument's field of view, thermal inertia of the subunits can be retrieved independently if their contrast in terms of thermophysical properties is large enough. If, for example, the surface is covered by equal area fractions of fine-grained and coarse-grained material, then thermal inertia is found to be retrievable with uncertainties of 658 ±78 and 54 ±22 $Jm^{-2}K^{-1}s^{-1/2}$ for the coarse-grained and fine-grained fraction, respectively.

1. Introduction

Surface processes on airless bodies are governed by their surface energy balance, and instruments to measure surface brightness temperatures have been payloads on several orbiter (Chase, 1969; Kieffer et al., 1972; Kührt et al., 1992; Christensen et al., 2001; Fergason et al., 2006a; Paige et al., 2009; Hiesinger et al., 2010; Tosi et al., 2014; Okada et al., 2017) and landed missions (Fergason et al. (2006b); Spohn et al. (2007, 2015); Biele and Ulamec (2008); Gómez-Elvira et al. (2012); Hamilton et al. (2014); Vasavada et al. (2017); Grott et al. (2017)). Thermal emission can change the orbit and spin state of small bodies through the Yarkovsky (Rubincam (1995); Chesley et al. (2003); Bottke et al. (2006)) and YORP (Paddack (1969); Bottke et al. (2006)) effects, and thermal fatigue due to repeated temperature cycling can result in breakup of rocks, adding to the generation of surface regolith (Delbo et al., 2014). While surface thermophysical properties depend on the detailed microphysics of grains and inter-grain contacts (e.g., Piqueux and Christensen (2009a, b); Gundlach and Blum (2013); Sakatani et al. (2017)), the majority of effects can be captured in a single parameter under the assumption that regolith properties are constant. This parameter is the surface thermal inertia, which determines the response of the surface temperature to insolation. While the assumption of constant regolith properties does not generally hold, it is widely applied since it greatly facilitates the analysis and interpretation of the returned thermal data.

Thermal inertia was derived for numerous planetary bodies from observations by telescope, spacecraft, and landed missions. In general, the data is fit by comparing observed temperatures to numerical thermal models, and surface thermophysical properties are then derived from best fits. Thermal models like the Near Earth Asteroid Thermal Model (NEATM, Harris (1998)) are used to fit data from unresolved observations like, e.g., spaceborne infrared telescopes (for example WISE and Spitzer, see, e.g., Landsman et al. (2016), Harris and Drube (2016)). The NEATM assumes a spherical shape and neglects rotation, roughness, as well as thermal conductivity and inertia. Instead, they introduce a fitting parameter η, which incorporates thermal inertia. In contrast, more complex thermophysical models (TPM) include heat conduction and often explicitly consider asteroid shape. They can include radiative transfer in the atmosphere (if present, e.g., Kieffer (2013)), or surface roughness (e.g.,Giese and Kührt (1990), Davidsson and Rickman (2014)). A TPM has also been used to model telescope data and derive thermal

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inertia for near-earth asteroid Itokawa (Müller et al., 2005, 2014).

Ideally, fitting a model to the data should consider the entire diurnal temperature curve. However, remote sensing usually delivers only sections of the diurnal curve due to viewing geometry restrictions (Christensen et al., 2001; Fergason et al., 2006a; Tosi et al., 2014; Okada et al., 2017). To compensate for this shortcoming, the fits are usually restricted to the coldest and hottest temperatures since they show the strongest dependence on regolith properties. These temperatures occur just before sunrise and shortly after local noon, respectively (Fergason et al., 2006a, b; Mellon et al., 2000). Recently, a modified method to derive thermal inertia has been proposed by Takita et al. (2017), who consider the phase shift between the maximum daytime temperature and local noon. This method particularly suits a viewing geometry with the observing spacecraft hovering above the sub-solar point.

The situation is different for landed spacecraft, as those can observe the surface during an entire day-night cycle. This was done on comet 67P/Churyumov-Gerasimenko by the MUPUS radiometer (Spohn et al., 2015), as well as on Mars by the Rover Environmental Station Ground Temperature Sensor REMS-GTS (Hamilton et al., 2014) and the Mars Exploration Rovers' miniTES instruments (Fergason et al., 2006b). Fitting the entire diurnal temperature curve allows for a more precise thermal inertia estimation, since thermal inertia determines the rate of cooling and heating of the surface, and this rate is only fully recorded when the entire diurnal temperature data is available.

Further complications arise if temperatures in the instrument's field of view are heterogeneous below the spatial resolution of the employed sensors. The most common sources for sub-pixel heterogeneity are shadows, surface roughness, and heterogeneous thermal inertia, e.g. boulders and fine grains. The latter was identified as one complication when interpreting temperature data of the REMS-GTS sensor (Hamilton et al., 2014). Yet, surface roughness is known to considerably influence the total flux emitted by a given surface as it causes varying illumination conditions in the field of view (e.g., Kührt et al. (1992), Davidsson and Rickman (2014)). However, if the entire diurnal temperature curve has been observed, a restriction of the analysis to nighttime data removes some of these effects, as temperature equilibration will result in more homogeneous temperatures reducing the effect of former shadowing or surface roughness (Fergason et al., 2006a). Therefore, heterogeneous thermal inertia will be the main source for sub-pixel heterogeneity during night.

In 2014, the Japanese Space Agency (JAXA) launched the Hayabusa2 mission to the near-earth asteroid (NEA) (162173) Ryugu (1999JU3) (Saiki et al., 2013; Tsuda et al., 2013). Hayabusa2 is a sample-return mission that will characterize this Cg-type asteroid (Bus and Binzel, 2002) in great detail upon arrival in 2018, and will return samples to Earth in 2020. Hayabusa2 carries a thermal infrared mapper (TIR) (Okada et al., 2017; Takita et al., 2017) that will globally characterize surface temperatures and surface thermal inertia, as well as the MARA radiometer (Grott et al., 2017) as part of the payload on the MASCOT asteroid lander (Mobile Asteroid SCOuT, Ho et al. (2017)). The MAscot RAdiometer (MARA) will observe a surface spot of approximately 12 cm diameter for a full asteroid rotation (7.631 h, Müller et al. (2017)). Under nominal landing conditions this spot will consist of undisturbed regolith roughly 30 cm in front of the lander. The emission angle will be 50° in average (Grott et al., 2017).

After the first set of data has been acquired, MASCOT relocates to a second site, to continue to operate until its primary batteries run out, which are expected to last up to 16 h. At the same time, the main spacecraft's TIR instrument will observe the asteroid from the Hayabusa2 home position at about 20 km altitude above the sub-solar point. The simultaneous observations will allow a joint interpretation of MARA and TIR data. MARA operates an array of six detectors which will observe the asteroid's surface in six individual infrared wavelength bands. Four of the employed filters are narrow band (width of 1.5–2 μm), while a silicon long pass transmits radiation with wavelength larger than 3 μm and a second broadband filter transmits radiation from 8 to 12 μm (Grott et al., 2017). Table 2 provides an overview of the filters used by MARA, their transmissivity bands, and their designations in this paper.

Table 1
(162173) Ryugu parameters used for calculating surface temperatures in the asteroid TPM.

Parameter	Symbol	Value	Unit
Perihelion Distance	a	0.96315	AU
Eccentricity	e	0.19034	–
Pole Orientation	(λ,β)	(329,-39)	° (ecliptic coordinates)
Rotational Period	P	7.631	h
Bond Albedo	A	0.018	–
Emissivity	ε	0.9	–
Heat capacity	c_p	600	J kg^{-1} K^{-1}
Density	ρ	1270	kg m^{-3}
Thermal Conductivity	k	variable	W m^{-1} K^{-1}

Table 2
Overview of MARA channels giving the filter name along with the corresponding transmission wavelength range. To illustrate the wavelength dependence of thermal inertia retrieval when assuming a single thermal inertia while observing a heterogeneous surface, the best-fitting thermal inertia for each MARA channel is also given. In this calculation, the heterogeneous surface was assumed to be covered to 75% by material with $\Gamma = 650$ Jm^{-2}K^{-1}s$^{-1/2}$ and to 25% by material with $\Gamma = 50$ Jm^{-2}K^{-1}s$^{-1/2}$.

Filter Name	B6	W8	B9	B13	W10	SiLP
Wavelength [μm]	5.5–7	8–9.5	9.5–11.5	13.5–15.5	8–12	>3
Γ[Jm^{-2}K^{-1}s$^{-1/2}$]	405	426	398	367	404	377

In the following, we describe a method to determine surface thermal inertia from MARA data taking instrument errors as well as other sources of uncertainty into account. In particular, the influence of an unknown surface emissivity is discussed. Furthermore, we consider heterogeneous surfaces, and address the feasibility of retrieving multiple thermal inertias. Synthetic MARA data is generated using an asteroid surface thermal model (Pelivan et al., 2017), which is presented in Section. 2.1. Radiation exchanged between the surface and the MARA detectors is calculated using the net radiation method (Howell et al., 2016), from which synthetic MARA signals are derived taking the instrument's calibration function into account (Grott et al., 2017). Finally, surface thermophysical properties are derived from the generated signals, and confidence limits are estimated.

2. Methods

2.1. Asteroid thermal model

To calculate synthetic MARA data, asteroid surface temperatures during the observation period are simulated. To this end, we use a thermophysical model (TPM) of the target asteroid (162173) Ryugu, which generates diurnal surface temperature curves by solving the one-dimensional heat conduction equation subject to the boundary conditions at the surface (Eq. (3)) and a boundary condition of zero heat flux at depth. The model is described in detail by Pelivan et al. (2017). The employed solver is part of the commercial NAG Library. It uses the method of lines to convert the partial differential equation into a system of ordinary differential equations and subsequently applies the backward differentiation formula for time integration.

Asteroid surface and subsurface temperatures T are governed by the heat conduction equation

$$\frac{\partial T}{\partial t} = \frac{\pi}{P}\frac{\partial^2 T}{\partial z'^2} \tag{1}$$

where t is time, P is the asteroid's rotation period, and $z' = z/d$ is depth normalized to the diurnal thermal skin depth