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Physical properties of morphological units on Comet 9P/Tempel 1 derived from near-IR Deep Impact spectra

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ABSTRACT

In this paper we analyze near-infrared thermal emission spectra of the spatially resolved nucleus of Comet 9P/Tempel 1 obtained by the NASA spacecraft *Deep Impact*. Maps of spectral reddening, the product X' between the beaming function and directional emissivity, as well as surface temperature are constructed. Thermophysical modeling is used to estimate the degree of small scale surface roughness and thermal inertia by detailed reproduction of the empirical temperature map. Mie and Hapke theories are used in combination with numerically calculated beaming functions to analyze the X' map and place constraints on composition and grain size of the surface material. We show that it is absolutely mandatory to include small scale surface roughness in thermophysical modeling of this object, since the resulting self heating is vital for reproducing the measured temperatures. A small scale self heating parameter in the range $0.6 \leqslant \xi \leqslant 0.75$ is common, but smoother areas where $0.2 \leqslant \xi \leqslant 0.3$ are also found. Contrary to models neglecting small scale surface roughness, we find that the thermal inertia of Comet 9P/Tempel 1 generally is high ($1000–3000\ \mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$), although it may be substantially lower ($40–380\ \mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$) in specific areas. We obtain a disk-averaged reddening of 3.5% $\mathrm{k\AA^{-1}}$, with statistically significant local variations around that value on a ±1.0% $\mathrm{k\AA^{-1}}$ level. Vast regions appear covered by small (∼0.1 μm) highly absorbing grains such as carbon or iron-rich silicates. Other regions appear dominated by somewhat larger (∼0.5 μm) and/or less absorbing grains such as troilite or magnesium-rich silicates. Surface variations in reddening, roughness, thermal inertia, composition and/or grain size are moderately to strongly correlated to the locations of morphological units on the surface. The existence of morphological units with differing physical properties may be primordial, hence reflecting a diversity in the building block cometesimals, or resulting from evolutionary processes.

1. Introduction

The NASA *Deep Impact* (DI) encounter with Comet 9P/Tempel 1 on July 4, 2005 (A'Hearn et al., 2005) provided a rich and unique collection of data obtained with a range of instruments (Hampton et al., 2005). For example, the InfraRed spectrometer on the High-Resolution Instrument (HRI-IR) produced nucleus spectra in the wavelength range $1.04 \leqslant \lambda \leqslant 4.89$ μm with a resolving power $200 \leqslant \lambda/\Delta\lambda \leqslant 800$. In 2×2 binning mode a data matrix is obtained with 512 wavelength bins for 256 spatial pixels. By exploiting spacecraft rotation and performing repeated imaging, 40×256 pixel scans could be produced, where each pixel represents a full spectrum. A single scan obtained during the flyby (#9000036) contains the entire visible side of the nucleus (resolved by ∼1000 pixels) obtained 15,800 km from the comet, ∼26 min prior to closest approach. This scan was used by Groussin et al. (2007) to produce the first 2D surface temperature map of a comet nucleus. By applying a thermophysical model to produce synthetic temperature maps and comparing these with the empirical data, Groussin et al. (2007) also concluded that the thermal inertia $\mathcal{I}$ of the nucleus must be very low, preferably $\mathcal{I} \leqslant 50\ \mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$.

The analysis by Groussin et al. (2007) is an impressive and important first step towards a deeper understanding of the surface conditions of comets. However, certain assumptions have been made that potentially may bias the results and interpretations in a certain direction. For example, small scale surface roughness (i.e., nucleus topography on subpixel scales) has not been taken into account. Small scale surface roughness affects the properties of thermal emission spectra (hence the procedure used to estimate surface temperatures), as well as the thermophysical model needed to interpret those temperatures (inclusion of self heating). It can therefore not be excluded that conclusions regarding, e.g., the thermal inertia of the nucleus may have to be revised if small scale surface roughness is taken into consideration.

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Table 1
Description of all parameter symbols used in the paper.

Symbol	Description	Symbol	Description
a	Grain radius	s	Noise in I_{th} relative to I_λ
A	Bolometric Bond albedo	s_i	Surface area of element i
A_{mod}	Modeled bolometric Bond albedo	t	Time
A_v	Spectral Bond albedo integrated over V-band	t_0	Time of solar culmination
A_{flat}	Projected flat area of rough terrain	T	Temperature
A_{pit}	Integrated surface area of pit interior	ΔT	Temperature difference
A_{rim}	Pit opening area	T_{emp}	Empirical temperature function
A_{rough}	Surface area of rough terrain	ΔT_{emp}	Empirical temperature function error bar
$\mathcal{A}$	Slope angle distribution function parameter	v_i	Pit interior visibility switch
b	Parameter in incomplete gamma function	w	Parameter in incomplete gamma function
$B_\lambda(T)$	Planck function	x	Depth below comet surface
$\mathcal{B}$	Slope angle distribution function parameter	x_*	Dimensionless depth below comet surface
c	Speed of light in vacuum	x'_*	Dimensionless thickness of modeled surface slab
C	Specific heat capacity	X	Effective integrated emissivity
d	Distance from parabola focus to vertex	X'	Product $\Lambda\varepsilon_d$
d_{co}	Co-declination	$\Delta X'$	Difference in X'
D	Slope angle distribution function	X'_{mod}	Modeled version of X'
e	Emission/incidence angle (depending on context)	$X_\star$	Curve tracing low-χ^2 in $\{X, \mathcal{I}\}$ phase space
f	Fraction of surface covered with pits	y	Silicate iron abundance parameter
F_{ij}	View factor	α	Right ascension
G	Irradiation	γ^2	Volume emissivity factor
h	Planck constant	γ^2_{mod}	Modeled volume emissivity factor
H	Maximum distance (in time) for T_{emp} data points to local noon	δ	Declination
H_i	Global self heating flux reaching facet i	ε_d	Directional emissivity
$\mathcal{H}$	Range of local hours covered by T_{emp}	ε_h	Hemispherical emissivity
i	Index	$\varepsilon_{h,mod}$	Modeled hemispherical emissivity
$\mathcal{I}$	Thermal inertia of porous medium	$\bar{\varepsilon}_h$	Integrated emissivity
$\mathcal{I}_{comp}$	Thermal inertia of compacted medium	$\bar{\varepsilon}_{h,mod}$	Modeled integrated emissivity
I_{DI}	Spectral intensity from DI pipeline	θ	Angle between local surface normal and rough surface average normal
I_{pit}	Spectral intensity emitted by pit	$\bar{\theta}_i$	Input mean slope angle
I_{rim}	Spectral intensity emitted by flat area of size A_{rim}	$\bar{\theta}_o$	Output mean slope angle
I_R	Spectral intensity of reddened sunlight	$\bar{\theta}$	Mean slope angle
I_s	Synthetic spectral intensity	κ	Conductivity of porous material
I_{th}	Spectral intensity of thermal emission	κ_{comp}	Conductivity of compacted material
I_λ	Modeled spectral intensity	λ	Wavelength
j	Index	$\Delta\lambda$	Wavelength bin
J	Radiosity	Λ	Beaming function
k	Boltzmann constant	Λ_*	Beaming function of single pit
l_{co}	Co-latitude	μ	Cosine of incidence angle
M	Number of data points in T_{emp} bin	μ_e	Cosine of emission angle
N_r	Random number	ν	Number of degrees of freedom
N_t	Number of flat surface elements in rough terrain	ξ	Small scale self heating parameter
N_λ	Synthetic noise function	ρ	Density of porous material
p	Parameter in Φ function	ρ_{bulk}	Bulk density of the entire comet nucleus
P	Rotational period	ρ_{comp}	Density of compacted material
Q	Incomplete gamma function	σ	Standard deviation
Q_A	Absorption coefficient	σ_{SB}	Stefan–Boltzmann constant
Q_E	Extinction coefficient	Φ	Ratio κ/κ_{comp}
r	Distance between facets in shape model	χ^2	Temperature chi-square
r_h	Heliocentric distance	χ^2_R	Reddening chi-square proxy
R	Reddening	χ^2_{th}	Near-infrared thermal emission chi-square proxy
S	Pit depth-to-diameter ratio	ψ	Porosity
S_{min}	Smallest S consistent with estimated ξ	ω	Rotational angular frequency
$S_\odot$	Solar constant		

Here, an independent analysis of the scan #9000036 spectra is performed, using an approach suitable for a body with surface roughness. The methods, theories and models necessary for this work are summarized in Section 2 (certain related equation derivations and error investigations are given in Appendices A–D). Specifically, Section 2.1 deals with the extraction of spectral reddening, surface temperature, and the product of the beaming function and directional emissivity[1] from the spectra. Section 2.2 describes the nucleus geometrical model, the thermophysical model, the division of the surface into morphological surface units, as well as the method used to estimate the small scale self heating parameter and the thermal inertia of the nucleus. Section 2.3 summarizes a surface roughness model based on considering circular paraboloid pits, which is used to provide possible interpretations of the small scale self heating parameter. Combined with Hapke theory the model is also used to produce a theoretical beaming function. In Section 2.4, a method used to estimate the volume emissivity factor of the nucleus surface material is described. Furthermore, we explain how Mie theory here is used to place constraints on grain size and composition. Finally, the results are presented in Section 3 and discussed in Section 4.

Table 1 summarizes all parameter symbols used throughout this paper.

2. Methods, theories, and models

2.1. Interpreting the HRI-IR Spectra

The spectra composing scan #9000036 with accompanying spectral registration are available in the NASA Planetary Data Sys-

[1] In this paper we distinguish between directional, hemispherical, and integrated emissivities, see Hapke (1993).