Planetary and Space Science 85 (2013) 214–219

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Model of dust thermal emission of comet 67P/Churyumov–Gerasimenko for the Rosetta/MIRO instrument ☆

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ARTICLE INFO

Article history:
Received 22 March 2013
Received in revised form
12 June 2013
Accepted 16 June 2013
Available online 22 June 2013

Keywords:
Comets
Rosetta
67P/Churyumov–Gerasimenko
Dust
Millimeter–submillimeter

ABSTRACT

The ESA's *Rosetta* spacecraft will arrive at comet 67P/Churyumov–Gerasimenko in 2014. The study of gas and dust emission is primary objective of several instruments on the *Rosetta* spacecraft, including the Microwave Instrument for the Rosetta Orbiter (MIRO). We developed a model of dust thermal emission to estimate the detectability of dust in the vicinity of the nucleus with MIRO. Our model computes the power received by the MIRO antenna in limb viewing as a function of the geometry of the observations and the physical properties of the grains. We show that detection in the millimeter and submillimeter channels can be achieved near perihelion.

1. Introduction

Comet 67P/Churyumov–Gerasimenko (67P) was discovered in May 1969 after its perihelion at 1.28 AU. Because of repeated close encounters with Jupiter in 1840 and 1959, the perihelion distance varied from 2.7 AU prior to 1959 to the current value (1.28 AU) and the activity of the comet increased. This increase of the activity likely facilitated its discovery. Comet 67P was observed during the seven perihelion passages since its discovery and an initial characterization of the activity (Osip et al., 1992; Weiler et al., 2004; Lara et al., 2011), of the nucleus properties (Lamy et al., 2007; Tubiana et al., 2008; Kelley et al., 2009) and of the coma environment (Hansen et al., 2007; Agarwal et al., 2007, 2010), has been drawn.

The ESA (European Space Agency) *Rosetta* spacecraft was launched on 2 March 2004, to reach comet 67P in May 2014. The probe will be inserted into an orbit around the nucleus at a heliocentric distance r_h slightly in excess of 3 AU. The lander *Philae* will be deposited on the nucleus in November 2014 ($r_h \approx 3$ AU). The orbiter will be maintained in the vicinity of the comet until perihelion ($r_h = 1.3$ AU) or even until $r_h \approx 1.8$ AU post-perihelion (December 2015). Thus, nineteen months of uninterrupted, close-up observations of the gas and dust coma will be obtained. The *Rosetta* mission is exceptional because for the first time a spacecraft will place a lander on a comet nucleus and follow the comet during its journey towards the Sun. Scientific instruments on the lander and orbiter will characterize the evolution of comet gas and dust activity during its approach to the Sun.

The goals of the *Rosetta* mission are the global characterization of the nucleus (morphology, surface composition, internal structure) and of the coma (development of the activity, composition and physical properties, dust–gas interaction, interaction with the solar wind) with both *in situ* and remote-sensing instruments. The increase of the nucleus temperature leads to an increase of the production rate accompanied by the development of the coma.

Rosetta carries a wide range of scientific payload (Glassmeier et al., 2007), including the Microwave Instrument for the Rosetta Orbiter (MIRO) (Gulkis et al., 2007) to characterize the nucleus, gas and dust properties of comet 67P.

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0032-0633/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.pss.2013.06.008

In this paper we present a model of dust thermal emission to investigate the detectability of dust with the MIRO instrument as a function of the geometry of the observations and of the physical properties of the grains.

2. MIRO instrument

The MIRO instrument (Gulkis et al., 2007) is a consortium instrument, built and operated at the Jet Propulsion Laboratory, with hardware contributions from the Max-Planck-Institute for Solar System Research, and the Paris Observatory. Basic elements of the instrument are a 30-cm diameter, offset parabolic reflector telescope, and two heterodyne receivers operating at millimeter (190 GHz≈ 1.6 mm) and submillimeter (562 GHz≈0.5 mm) wavelengths. The half power beam widths (HPBW) of the MIRO beams are 23.8 ± 1.5 arcmin and 7.5 ± 0.25 arcmin at millimeter and submillimeter wavelengths, respectively. For a typical comet–*Rosetta* spacecraft (S/C) distance $\Delta = 20$ km, the spatial resolutions at the nucleus are 0.138 and 0.044 km at millimeter and submillimeter wavelengths, respectively.

The primary goals of the MIRO instrument are to measure the sub-surface temperatures of the nucleus, the gas production rate, the relative abundances, the velocity and the excitation temperature of gas species, along with their spatial and temporal variability. In particular, MIRO has a very high sensitivity to measure direct outgassing of three volatile species from the nucleus: CO, CH_3OH, NH_3, and three oxygen-related isotopologues of water: $H_2{}^{16}O$, $H_2{}^{17}O$ and $H_2{}^{18}O$ to obtain the fundamental isotope ratios $^{17}O/^{16}O$ and $^{18}O/^{16}O$. We refer the reader to Gulkis et al. (2007) for a detailed presentation of the MIRO instrument.

The millimeter receiver is configured with a single, broad-band continuum detector. The submillimeter radiometer is configured with both a broadband continuum detector and a very-high spectral resolution (44 kHz) spectrometer. Both continuum channels operate in total power mode. The 1 to 5-s Allan deviation noise is estimated to be, respectively, 0.11 K and 0.31 K at millimeter and submillimeter wavelengths (Gulkis et al., 2007). These $1-\sigma$ receiver noises will allow us to estimate the detectability of dust thermal emission with MIRO. The signal-to-noise ratio of the measurement must be $>3\sigma$ for a statistically reliable detection.

3. Model of dust thermal emission

Observations at submillimeter and millimeter wavelengths are most sensitive to large particles in the cometary grain size distribution and complement optical and infrared observations, which probe micrometer-sized grains. By measuring the radiation from large particles, we can obtain information on the dust production rate. Jewitt and Luu (1990) showed that a substantial fraction of the total dust mass in comets is contained within the largest grain sizes.

Our model computes the thermal emission of the dust coma measured in the MIRO beam, expressed in antenna temperature scale, which can be compared to the sensitivity of the continuum receivers. We assume that the dust coma contains grains with radii in the range from $a_{min} = 0.1$ μm to the maximum liftable size a_{max}. The antenna temperature T_A is obtained from numerical integration along lines of sight in the field of view

$$T_A = \frac{\lambda^2}{2k_B}\frac{1}{\Omega_A}\oiint_{\Omega_{MB}} B_d(\theta,\varphi,\nu)P_N(\theta,\varphi)\,d\Omega, \tag{1}$$

where k_B is the Boltzmann constant, λ is the wavelength, and ν is the frequency. $P_N(\theta,\varphi)$ is the normalized MIRO beam pattern (i.e., equal to 1 at maximum) approximated by a Gaussian. Ω is the main beam solid angle and Ω_A is the beam solid angle equal to 5.4×10^{-6} and 5.4×10^{-5} sr at $\lambda = 0.5$ and 1.6 mm, respectively. $B_d(\theta,\varphi,\nu)$ is the spectral brightness (in units of [W m^{-2} sr^{-1} Hz^{-1}]) of the dust grains. We define the spherical coordinate system (z, θ, φ) centered at the *Rosetta* S/C, where z is the radial distance from the S/C along the ray defined by (θ, φ), and $\theta = 0$ corresponds to the center of the beam ($P_N = 1$).

The spectral brightness $B_d(\theta,\varphi,\nu)$ is obtained by numerical integration along z and grain size a:

$$B_d(\theta,\varphi,\nu) = \int_0^\infty \int_{a_{min}}^{a_{max}} F_d(a,z,\theta,\varphi,\nu)\,da\,dz, \tag{2}$$

where $F_d(a,z,\theta,\varphi,\nu)$ describes the contribution of particles of size a to the emission. In the case of an isotropic coma, $F_d(a,z,\theta,\varphi,\nu)$ is only dependent on the distance r of the point (z,θ,φ) to the center of the nucleus. For thermal emission, the term $F_d(a,z,\theta,\varphi,\nu)$ can be written as

$$F_d(a,z,\theta,\varphi,\nu) = n_d(a,r)\pi a^2 Q_{abs}(a,\nu)B_\nu(T_d), \tag{3}$$

where $n_d(a,r)$ is the density distribution of grains of size a, T_d is the equilibrium temperature of the grains, and $B_\nu(T_d)$ is the Planck function. T_d can be assumed in first approximation to be independent of the grain size and taken equal to the equilibrium temperature (Jewitt and Luu, 1990). For example we obtained $T_d = 244$ K and 149 K at the heliocentric distances $r_h = 1.3$ AU and 3.5 AU, respectively. The absorption efficiency Q_{abs} is a function of grain size, shape, composition and porosity of the grain.

We used the Mie theory (Bohren and Huffman, 1983; Van de Hulst, 1957), which is the most common technique used throughout the literature (Lisse et al., 1998; Hanner et al., 1996, 1994; Harker et al., 2002), to compute Q_{abs} for spherical grains of given radius and optical constants $m_\lambda = n - ik$, where n and k are the wavelength-dependent indices of refraction. Three grain compositions are considered: organics, olivine, and two-layer grains. The two-layer composition is based on the structure of cometary grains outlined by Greenberg and Hage (1990). The basic building block consists of a silicate core surrounded by an organic component. The indices of refraction that we used to calculate Q_{abs} for the amorphous olivine and organics are from Pollack et al. (1994).

The Maxwell Garnett effective medium theory was used to calculate the effective refractive index for the two-layer grains (Greenberg and Hage, 1990). We considered two-layer grains with a fractional mass of the mantle component equal to 50%. We adopt a density of $\rho_{Org} = 1.5$ g cm^{-3} for organics grains and of $\rho_{Ol} = 3.5$ g cm^{-3} for olivine grains (Pollack et al., 1994).

In order to simplify the analysis we assume that grains of the same size have the same mass $m_d(a)$ irrespective of their actual composition. We assume that the density of grains is $\tilde{\rho} = 1$ g cm^{-3} which corresponds to a porosity of ≈33%, 71% and 60% for organics, olivine and two-layer grains, respectively. We used a form of the Maxwell Garnett formula, which is described by Hage and Greenberg (1990), to calculate the refractive indices for porous grains. The indices of refraction at the wavelengths $\lambda = 0.5$ mm and $\lambda = 1.6$ mm used in this study are given in Table 1.

The density distribution of dust grains in the size range $(a, a + da)$, which is a term of Eq. (3), is derived from the continuity

Table 1
Optical constants.

Composition	$\lambda = 0.5$ mm		$\lambda = 1.6$ mm		Reference
	n	k	n	k	
Olivine	2.08	4.00×10^{-2}	2.08	3.00×10^{-2}	Pollack et al. (1994)
Organics	2.28	1.90×10^{-2}	2.28	2.80×10^{-3}	Pollack et al. (1994)
Two-layer	2.19	2.82×10^{-2}	2.19	1.46×10^{-2}	This work