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67P/Churyumov–Gerasimenko nucleus model: Portrayal of the Rosetta target ☆

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Abstract

Rosetta is a cornerstone ESA mission dedicated to the detailed study of a comet nucleus before and after the onset of activity. Comet 67P/Churyumov–Gerasimenko is the new Rosetta target. At the moment, little is known about this comet, but the successful design of the ROSETTA mission requires some preliminary knowledge of the comet's physical parameters. In fact, surface and interior temperature, day–night variations, onset of activity, percentage of active surface, intensity of different gas and dust fluxes are needed to select safe orbits around the comet and to optimize the scientific return. These quantities cannot be determined only through ground-based observations, so predictive models of the thermal evolution and differentiation of a cometary nucleus are necessary. We have developed a comet nucleus thermal evolution model that helps in the estimations of the above quantities. The ideal nucleus is an initially homogeneous and porous sphere, composed by a mixture of different ices and dust particles. The results have been computed with a numerical code solving simultaneously the heat conduction and gas diffusion equations through an idealized spherical comet nucleus. We show the results obtained applying this model to a comet nucleus with the characteristics of Churyumov–Gerasimenko. The results indicate that the peculiar dynamical history has a strong effect on the comet with the formation of a dust mantle before the 1959 close encounter. After that event, the perihelion distance was reduced and the comet was probably "reactivated". In our model, we see a slight increase of the activity passage after passage. We found a good agreement between the model results and the few data available.

Keywords: Comets; Rosetta mission; Thermal evolution models; Comet nuclei models

1. Introduction

Rosetta's launch had been originally scheduled for January 2003 on board an Ariane-5 rocket. Rosetta's target then was comet 46P/Wirtanen. Due to the failure of the Ariane Flight 157 in December 2002, the Rosetta launch was postponed. Rosetta was launched in March 2004 and will meet its new target, Comet 67P/Churyumov–Gerasimenko, in 2014. Comet nuclei are very difficult to observe and no direct data of the interior are currently available. Theoretical models of the chemical differentiation and thermal evolution of a nucleus can be used to link coma observations with real nuclei characteristics and properties. The successful design of space missions, and in particular of the onboard scientific instruments, requires some preliminary knowledge of the comet's physical parameters during the different missions phases. Surface and interior temperature, the diurnal-nocturnal variations, the onset of activity, percentage of active surface, intensity of different gas and dust fluxes are needed to select safe orbits around the comet and to optimize the scientific return. Predictive models of the thermal evolution and differentiation of a cometary nucleus are needed to understand the nature of the comet nuclei in terms of composition, structure, and physical properties; to understand the physical phenomena that can occur in comet nuclei; and to foresee comet activity behavior.

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2. Comet 67P/Churyumov–Gerasimenko: what we know

Comet 67P/Churyumov–Gerasimenko, discovered in 1969, has been observed during 6 apparitions; the latest was in 2002–2003. The comet is a Jupiter family comet with a perihelion distance of 1.29 AU and a period of 6.57 years. We currently have few data on the gas and dust activity (Weiler et al., 2004). The comet radius has been derived from different techniques. From HST observations (Lamy et al., 2003), the radius seems to be about 2 km in agreement with the radius estimated by ground-based observations (Mueller, 1992; Kamoun et al., 1998; Tancredi et al., 2000). Radar observations (Kamoun et al., 1998) show an upper limit of 3.7 km for the radius of the nucleus. Similarly, the observations by Mueller (1992) give a radius of 3.2 km using an albedo of 0.03. The rotation period is 12.3 h (Lamy et al., 2003). The comet's lightcurves show outbursts at perihelion with strong similarities in the 1982–1983, 1996–1997, and 2002–2003 apparitions, suggesting that the comet's behavior is similar over several returns or with a slight increase in activity with successive passages. The comet shows a pre/post-perihelion asymmetry with a peak water production of 1×10^{28} mol/s (Kidger, 2003, and reference therein). With the available data, it is difficult to say if minor species production rates are constant or peaked around the perihelion. 67P/Churyumov–Gerasimenko is considered to be a dusty comet (Kiselev and Velichko, 1998) and a peak value of $Af\rho = 450$ cm was recorded.

Beliaev et al. (1986) and Carusi et al. (1985) found that the comet had close encounters with Jupiter in 1840 and 1959, changing the perihelion distance significantly. The comet remained at quite large perihelion distance between 1840 and 1959 ($q = 2.75$ AU). The encounter with Jupiter in 1959 reduced the perihelion distance from 2.75 AU to the present value 1.29 AU.

3. Comet model

The results have been computed with a numerical code solving simultaneously the heat conduction and gas diffusion equations through an idealized spherical comet nucleus (De Sanctis et al., 1999, 2000; Capria et al., 2000). The nucleus is initially homogeneous and composed of ices of water, CO_2, and CO. The dust particles are embedded in an icy matrix. Initially, the water ice is considered to be in the amorphous phase, due to the very low temperatures at which comets are thought to be formed (Rickman and Huebner, 1990). The dust grains are distributed in different size classes and can have different characteristics (mass, density, size, and conductivity). The numerical code computes the heat diffusion in the porous cometary material, leading to water ice phase transition and the sublimation of the volatile ices. When the temperature rises, ices start to sublimate, beginning with the more volatile ones, and the initially homogeneous nucleus differentiates giving rise to a layered structure in which the boundary between different layers is a sublimation front. The model takes into account the amorphous–crystalline phase transition with the release of gases trapped in the amorphous ice. The gases diffuse inside the pore system, either recondensing or escaping into space. Surface erosion due to ice sublimation, particle ejection, and crust formation and compaction are computed at each step. When the ices begin to sublimate, the refractory particles become free and are subject to the drag exerted by the escaping gas, so that they can either be blown off or accumulate on the surface to form a crust. To determine how many particles can be blown off and how many can be accumulated on the surface, the different forces acting on a single grain are compared, obtaining for each distribution a critical radius that represents the radius of the largest particle that can leave the comet. At each time step, we compute the number of free dust particles and the value of the critical radius. Grains with radius smaller than the critical one are ejected. The existence of different dust grain size classes allows for differential deposition and differential dust emission. The model is able to describe the nucleus rotation (day/night effects) and the effects of the nucleus obliquity. For further details, see previous articles (Coradini et al., 1997a,b; De Sanctis et al., 1999; Capria et al., 2000).

The heat diffusion through the porous cometary material is described by the following equation, expressing the conservation of energy:

$$\rho c \frac{\partial T}{\partial t} = \nabla[K \cdot \nabla T] + Q_{H_2O} + Q_{CO_2} + Q_{CO} + Q_{tr}, \qquad (1)$$

where T is the temperature, t the time, K the heat conduction coefficient, ρ the density and c the specific heat of the comet material; Q_{H_2O}, Q_{CO_2}, and Q_{CO} are the specific energies gained or lost by the solid matrix due to sublimation and recondensation of the ices; Q_{tr} is the heat released by the water ice phase transition from amorphous to crystalline form.

The gas flow through the pore system is described by the mass conservation equation:

$$\frac{\partial \rho}{\partial t} = -\nabla \Phi + Q^*, \qquad (2)$$

where ρ is the gas density, Φ its flux, and Q^* the gas source term due to sublimation and recondensation processes. We assume that the gas density can be related to its pressure through the ideal gas law, and that the flows of different gases do not influence each other and the equations can be solved separately for each gas. The temperature on the surface is obtained by a balance between the solar input and the energy re-emitted in the infrared, conducted in the interior and used to sublimate surface ices. At the center of the comet the condition is

$$\frac{\partial T}{\partial r} = 0. \qquad (3)$$

The center boundary condition for the diffusion equation is obtained by assuming that the ice is in equilibrium with its