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67P/Churyumov-Gerasimenko, the new Rosetta target: thermal evolution model

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Abstract. The ESA mission Rosetta will arrive at comet 67P/Churyumov-Gerasimenko in 2014. At the moment, little is known about this comet but the successful design of the mission requires some preliminary knowledge of the comet physical parameters. Predictive models of the thermal evolution and differentiation of the cometary nucleus are necessary. In this paper we show the results of a comet nucleus thermal evolution model applied to the nucleus of 67P/Churyumov-Gerasimenko. The results have been computed with a numerical code solving simultaneously the heat conduction and gas diffusion equations through an idealized spherical comet nucleus made by dust and ices. The models indicate that the peculiar dynamical history has a strong effect on the comet: during the orbital stage at large heliocentric distance the comet was covered by a dust crust that is removed when the comet arrives at the present orbit. The computed gas fluxes are in general agreement with those estimated from the observations.

Key words. Comets: general–Comets:67P/Churyumov-Gerasimenko

1. Introduction

Rosetta's main objective is comet 67P/Churyumov-Gerasimenko. The mission will study the nucleus of the comet and its environment in great detail for a period of nearly two years with an orbiter and a probe on its surface. Comet nuclei are very difficult to observe and no direct data of the interior are at present 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. 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 foresee comet activity behavior.

2. 67P/Churyumov-Gerasimenko

Comet 67P/Churyumov-Gerasimenko belongs to the Jupiter family (q=1.29 AU and period of 6.57 years). Unfortunately, only few data on the gas and dust activity have been recorded. The comet radius has been estimated with different techniques resulting between 3.7 km and 2 km (Kamoun et al.,1998; Tancredi et al., 2000; Mueller,1992). The data indicate that 67P/Churyumov-Gerasimenko is one of the largest Jupiter family comets. The esti-

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Send offprint requests to: M.C. De Sanctis mated rotation period is ~ 12.3 hr. A limited data set on the production rates is available in the literature. This comet was found to be depleted in carbon-bearing molecules by Osip et al. (1992) and A'Hearn et al. (1995). Schulz et al., (2004) reported a very rapid decrease in Afρ between 2.5 AU and 2.9 AU post-perihelion. The comet lightcurves show outbursts at perihelion with strong similarities in the 1982-83, 1996-97 and 2002-2003 apparitions. A pre/post-perihelion asymmetry with a peak water production of 1 x 10^{28} mol/s has been reported. 67P/Churyumov-Gerasimenko is considered to be a dusty comet and a peak value of $Af\rho$ = 450 cm was recorded. The dust coma morphology shows two jet structures in the coma and Chesley and Yeomans (2005) estimated the pole of 67P/Churyumov-Gerasimenko, using the nongravitational acceleration method. They found a pole position R.A.=90^o and Decl.= 75^o with an obliquity of about 43^o. The dynamical history of the comet has been studied by Beliaev et al. (1986) and Carusi et al. (1985). They found that the comet had close encounters with Jupiter in 1840 and 1959 that changed the perihelion distance significantly. The comet remained at a quite large perihelion distance between 1840 and 1959 (q=2.75 AU). The encounter with Jupiter in 1959 reduced the perihelion distance from q = 2.75 AU to the present value q= 1.29 AU.

3. Comet model

The thermal evolution of a comet nucleus resembling that of 67P/Churyumov-Gerasimenko has been computed with a numerical code solving simultaneously the heat conduction and gas diffusion equations through an idealised spherical comet nucleus (De Sanctis et al., 1999, 2000, 2005, Capria et al., 2000). The comet nucleus is considered initially homogeneous and composed of ices of water, CO_2 and CO. The dust component is included as dust particles embedded in an icy matrix. The dust grains are distributed in different size classes and can have different physical and thermal characteristics (mass, density, size, composition, 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 from the more volatile ones: 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 amorphous-crystalline transition with the release of gases trapped in the amorphous ice. The gases diffuse inside the pore system, either re-condensing in the colder layers or escaping in space. 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. Surface erosion due to ice sublimation, particles ejection, crust formation and compaction are computed at each step. The model is able to describe the nucleus rotation (day/night effects) and the effects of the nucleus obliquity. For further details and for the equations see previous articles (Capria et al.,2000, De Sanctis et al., 1999, 2005, Coradini et al., 1997).

4. Model parameters

The composition and structure of comet nuclei are poorly known, and cannot be easily determined from ground observations. Parameters used in these simulations are derived from the observations when available, or chosen among those that are considered typical for comets. We developed different models to test different parameters and hypotheses (dynamical history, presence of trapped CO).

To understand the influence of the particular dynamical history of this comet a multistage capture process from the Kuiper belt to the final Jupiter family orbit of 67P/Churyumov-Gerasimenko is simulated. We used as input the dynamical evolution calculated by Carusi et al. (1985). In one case (Case B)we used a generic multistage process from the Kuiper belt to the present orbit (Table 3). In the first set of models, we considered the comet rotation axis perpendicular to the orbital plane and we computed our model follow-

Table 1. Initial parameters

dust/ice	1
CO_2/H_2O	0.01
CO/H_2O	0.01
radius	2 km
porosity	0.6
rotation period	12.3 h
obliquity	0^o, 43^o
initial temperature	30 K
dust grain density	1000 kg/m3

Table 2. Model parameters

Model	Dynamic	Trap. CO	Obl.
A	Carusi	yes	0^o
B	Generic	yes	0^o
N	Carusi	no	0^o
J	Carusi	yes	43^o

Table 3. Dynamical parameters

Orbit	*a (AU)*	*e*	models
m-stage I	50	0.5	A,B,N,J
m-stage II	25	0.4	A,B,N,J
m-stage III	8	0.5	A,B,N,J
67P/C-G (a)	3.84	0.43	A,N,J
67P/C-G (b)	4.30	0.36	A,N,J
67P/C-G (c)	3.51	0.63	A,B,N,J

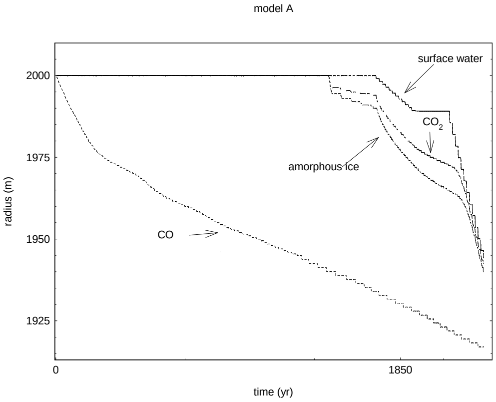

Fig. 1. Model A: nucleus internal stratigraphic evolution during the multistage capture process from the Kuiper belt to the present orbit.

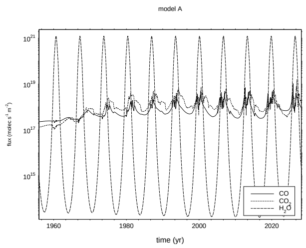

Fig. 2. Model A (present orbit). Water, CO and CO_2 flux versus time.

ing four points on the comet surface: 0^o, 30^o, 60^o and 85^o of latitude. The effect of the kind of volatiles in the nucleus has been evaluated including or excluding the presence of CO as trapped gas in the amorphous ice. The models have CO in both forms: CO ice and CO trapped in the amorphous ice , but model N has only CO ice. In the second set of models (model J) we have simulated the effects of the obliquity of the pole in the comet evolution. We used the pole position by Chesley and Yeomas (2005) that determined an obliquity of the spin axis of about 43^o.

5. Model results

Following the Dynamical parameters by calculated by Carusi et al., (1985) we see that the comet remained at quite large perihelion distance for over 100 years (q=2.75 AU) before the close encounter with Jupiter in 1959. When the nucleus reaches the present orbit the internal structure is affected by the previous thermal history and the upper layers are already differentiated. The CO, CO_2, and the amorphous ice are well below the surface (fig. 1) and the nucleus is covered by a dust mantle.

During the orbital phase at large perihelion distance the comet develops a dust crust that is removed after the 1959 close encounter. In the case B, where a generic multistage evolution is considered, the nucleus does not develop a dust mantle on the surface. When the Carusi et al.(1985) dynamical path is considered, the developed models show similar behavior: a long period (1840-1959) of low activity with the formation of a thin dust mantle and a slow re-activation after the 1959 change of the orbital parameters. The water flux shows a large pre/post perihelion asymmetry and steep perihelion distance dependence, similar to that reported by observers. At the perihelion, the water flux obtained is 2-3 x 10^{28} molec/sec (fig.2). Observers report a peak water production of 1 x 10^{28} molec/sec. Minor species productions have less steep perihelion dependence, due to the depth of the volatile sublimation front. The gas activity is progressively diminished at high latitude due to the minor solar input. CO activity follows the perihelion even if shifted due to the delay of the thermal wave in reaching the deeper layers where volatiles are stored. In model N (only CO ice) the CO activity is quite constant along the orbit.

In model J we used the same physical parameters as model A but adopted the obliquity of 43^0. The results obtained indicate that different zones of the comet contribute to the overall flux in different ways with respect to model A: the northern hemisphere at perihelion is the main contributor to the comet activity in term of water flux and dust, while the southern hemisphere contributes to the water and dust flux only during a small period peaked at the perihelion. Also this model develops a dust crust in equatorial zones during the orbital stage at larger perihelion distance. The crust is removed when the comet passes to the present orbit. Dust production show asymmetry pre/post perihelion. The maximum flux is of the order of 1700 kg/s. Dust production rate is in agreement with the estimation by Weiler et al., (2004), that determined a peak of dust of 2000 kg/s in 1982 at 1.36 AU.

6. Conclusions

Our models indicates that the particular dynamical history has a strong effect on the comet. The model foresees the formation of a dust mantle during the previous orbital stage. When the perihelion distance reduction occurred the comet was probably "reactivated": the nucleus is progressively ablated and this leads to the reduction of the depth of the sublimation fronts and a slow increase of the activity. The volatiles asymmetry is due to the delay of the thermal wave that reaches the deep sublimation fronts. The water and dust flux asymmetry is due to the heat stored in the nucleus. The comparison between the models results and the few observations seems to indicate an agreement between them, but more detailed studies from an observational and a theoretical point of view are needed.

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