Available online at www.sciencedirect.com
SCIENCE DIRECT

Planetary and Space Science 54 (2006) 15–27

Planetary and Space Science

www.elsevier.com/locate/pss

Comet 67P/Churyumov–Gerasimenko: Modeling of orientation and structure

Konrad J. Kossacki[a,b,*], Sławomira Szutowicz[c]

[a]Institute Geophysics, Warsaw University, Pasteura 7, 02-093 Warsaw, Poland
[b]Max-Planck-Institut for Solar System Research, Max-Planck-Str 2, D-37191 Katlenburg-Lindau, Germany
[c]Space Research Center of Polish Academy of Sciences, Bartycka 18a, Warsaw, Poland

Received 9 July 2004; received in revised form 2 September 2005; accepted 30 September 2005
Available online 1 December 2005

Abstract

The comet 67P/Churyumov–Gerasimenko is the current target of the mission Rosetta, initially planned to investigate comet 46P/Wirtanen. These two comets have similar orbits, except the distance to the Sun at perihelion, but different orbital histories and different masses. Thus, structures of the nuclei can be significantly different. The evolution of comet Wirtanen was simulated by several authors, while comet Churyumov–Gerasimenko became an object of high interest only recently and is not well investigated. In the present work we simulate the evolution of the nucleus, down to tens of meters below the surface, using an extended version of the model previously applied for comet Wirtanen [Kossacki et al., 1999. Comet 46P/Wirtanen: evolution of the subsurface layer. Icarus 142, 202–218.]. The model includes strengthening of the nucleus due to sintering of the ice grains. Simulations are performed for different latitudes, accounting for the evolution of the orbit and for changes of the nucleus orientation, as well as diurnal and seasonal changes of insolation. The calculated loss of water vapor from the comet is integrated over the nucleus surface and is compared with the observational data. We have found, that the sublimation through the dust mantle can be large enough to reproduce the profile of the total water production as a function of time from perihelion. The required dependence of thickness of the dust layer on latitude qualitatively matches present distribution of the absorbed solar flux. The non-gravitational acceleration in the comet motion together with the simulated sublimation flux are used in order to estimate the mass and the bulk density of the nucleus.

Keywords: Comet composition; Comet dynamics; Ices; Production rate

1. Introduction

The mission Rosetta was planned to investigate comet 46P/Wirtanen. However, the unexpected delay of launch beyond the starting window made impossible reaching the planned trajectory. This resulted in the change of the mission target which is now 67P/Churyumov–Gerasimenko (hereafter called 67P/C–G). This comet is larger than 46P/Wirtanen and it underwent a different dynamical evolution of the orbit. Thus, the nuclei of those two comets may have different internal structures. The estimated radius of comet 46P/Wirtanen is only 0.6 km (Lamy et al., 1998), while that of comet 67P/C–G is about 2 km. According to Lamy et al. (2003) it is 1.98 ± 0.02 km, but the estimate based on absolute magnitude, presented by Tancredi et al. (2000), results in an even higher value for the radius of about 2.5 km. The rotational period determined according to the HST observations is 12.3 ± 0.27 h (Lamy et al., 2003). Both comets belong to the Jupiter family comets and their orbital changes are mostly under Jupiter's control. The present value of the orbital period of 67P/C–G equals to 6.55 years and is larger than the orbital period of 5.44 years for 46P/Wirtanen. The latter comet comes closer to the Sun than 67P/C–G. Their perihelion distances are equal to 1.06 and 1.28 AU, respectively.

The comet 67P/C–G was observed during six returns to the Sun since its discovery in 1969. Last time it passed the perihelion on August 18, 2002. The dynamical history of

*Corresponding author. Institute of Geophysics, Warsaw University, Pasteura 7, 02-093 Warsaw, Poland. Tel.: +49 5556 979289.
E-mail address: kjkossac@fuw.edu.pl (K.J. Kossacki).

0032-0633/$ - see front matter
doi:10.1016/j.pss.2005.09.001

the comet is well defined only to about 300 years backwards and 220 years forwards in time (Królikowska, 2003). Close approach to Jupiter in 1959 shifted the orbit inwards reducing the orbital period from 8.97 years to the present value and leading to the discovery of the comet. The drop in the perihelion distance resulted in increase of the comet's activity. Studies of the comet light curve indicate numerous outbursts of amplitude of about 2 magnitudes when close to perihelion passage during the last three apparitions (Kidger, 2003). The visual light curve and the profile of the production rate exhibit a strong asymmetry with post-perihelion maximum which implies a seasonal effect probably related to the high obliquity and non-uniform activity (Weiler et al., 2004). This can be explained also by variable concentration of dust molecules in the coma, increasing after perihelion due to splitting of larger dust grains blown out of the nucleus. According to our model of the comet's motion the inclination of the orbital plane to the cometary equator is about 90°. This is a reason for large differences in the assumed thicknesses of the dust cover over the nucleus.

In this work we investigate how comet 67P/C–G evolves, including both changes of its activity and the structure of its nucleus. We are mainly interested in the latitudinal dependence of the nucleus properties and in the differences between the nuclei of this comet and of comet 47P/Wirtanen. Thus, in the current work we do not explore the full space of the material parameters describing the nucleus. We simulate thermal and structural evolution of the near-surface layers of the nucleus down to tens of meters below the surface, i.e. to the depth where the seasonal changes of temperature are small. The calculations cover 400 years long period of the comet's orbital motion. For the simulations we use the extended version of the model we have previously developed to investigate surface hardening of comet 47P/Wirtanen due to the vapor diffusion in pores and to the sintering of ice grains. Current version of the model includes the previously omitted diurnal changes of insolation and takes into account the role of latitude, as well as the orientation of the spin axis. We have also improved the procedure used to simulate the orbital motion of the comet, by including the orientation of the nucleus. The calculated profile of the vapor emission versus time from perihelion is compared with the curves derived from observations. The result is used to select the best model describing changes of the orbital elements and the nucleus orientation, as well as to adjust the latitudinal distribution of the dust mantle thickness. The calculated sublimation flux and the non-gravitational perturbations of the orbital motion of the comet are used to derive the mass and bulk density of the nucleus.

2. Description of the model

2.1. Basic features

The model used in this work is based on that presented in our paper (Kossacki et al., 1999) for comet 46P/Wirtanen. The surface of the nucleus is covered by a very porous dust layer. Below the dust layer the nucleus is composed of ice, and mineral dust. In fact, the nucleus contains some amount of more volatile ices, like carbon monoxide. However, the surface layer at least some meters thick should be depleted of very volatile species. For this reason, in the current paper we do not consider minor volatile components. The sublimation of ice proceeds mostly at the bottom of the dust mantle where, at day hours, the temperature can exceed 200 K. Some fraction of vapor escapes to space through the dust mantle, and the rest diffuses downwards and recondenses. High temperature can be encountered also at the sublimation front of the amorphous water ice. Thus, we have decided to account for the presence of ice in both phases, amorphous and crystalline. However, we present also the results obtained when we assumed that the nucleus contains only crystalline ice.

In the previous work (Kossacki et al., 1999) we calculated surface temperature assuming that the nucleus is fast rotating and uniformly insolated. Now, the surface is considered as a set of latitudinal belts of equal areas. The surface temperatures, rates of vapor emission, cohesiveness and the thermal conductivity of the subsurface layer of the nucleus are assumed constant across the width of each latitudinal belt. However, they can significantly vary from belt to belt. The number of the belts needed is determined from the scatter of points composing the observational water production profiles. Increasing the number of considered belts smoothes the synthetic water production curve, but already four belts are sufficient to obtain agreement with the observations. For each of the belts we calculate insolation at the latitude corresponding to the middle of the area. We consider four belts, two in each hemisphere, the latitudes corresponding to the middles of the belt areas are 14.24° and 48.59°. They are positive to the north of the equator and negative to the south. The resulting flux of water emitted from each belt is averaged over the rotational period of the nucleus.

The important feature of the model is the added mechanism of sintering of grains earlier developed for technical applications (see e.g. Swinkels and Ashby, 1980). This theory predicts continuous growth of the grain–to–-grain contact area (Hertz factor) independent of the temperature gradient. The initial value of the Hertz factor characterizes a pristine material of the nucleus, before it could sinter due to warming of the surface. In the warmest layer immediately below the ice-free dust mantle the sintering processes increase the Hertz factor to the values about 0.3. Various sintering mechanisms are known, some of them are non-densifying and some affect both the contact area between grains and the density of the medium. The so called Kelvin effect, which dominates in water ice grains under temperatures typical for the cometary surface layer, affects only the strength of the medium but not its density. By combining the thermal evolution model with the description of the structural evolution of the material