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The change of the comet's shape by sublimation

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Abstract

The excellent imagery of the Rosetta mission revealed that 67P/Churyumov-Gerasimenko features a bi-lobed nucleus [1]. In fact, five out of the seven comets that have been imaged so far are bi-lobed [2], i.e. they consist of two lobes connected by a 'neck'. It has long been surmised that sublimation of the cometary material caused by incident sunlight is capable of changing the nucleus shape over the course of its existence [4].

Our hypothesis suggests that the peculiar shape of those comets is indeed caused by the interplay between an inhomogenous nucleus and the consequent differential sublimation of material exposed to sunlight.

We show that even initially spherical comets with a symmetric density distribution that decreases towards the center of the nucleus can end up having non-convex shapes. The timescale on which this shape transformation occurs is a function of the comets orbit. However, apart from its orbit, a comet's spin evolution greatly affects local sublimation rates leading to the broad range of both convex and non-convex shapes that were observe in cometary nuclei today.

1. Introduction

Short period comets that venture into the inner Solar System are known to experience significant mass loss by sublimation and outgassing. Such a loss of material can make up a significant fraction of the nucleus mass. It is, therefore, not surprising that sublimation caused by solar irradiation has been proposed as a mechanaism to modify the shape of the nucleus itself over time [4]. In this work we address how sublimation modifies the shape of cometary nuclei.

2. A simple model

In order to investigate how the shape of cometary nuclei evolve under sublimation we considered the following model.

- Comets are considered to be roughly spherical initially.
- All comets investigated in this work spin rapidly enough so that changes in the shape of the nucleus can be averaged over one spin period.
- All orbit pericenters are at a large enough distance from the Sun so that the changes in nucleus shapes can be safely averaged over one orbital period.
- The density distribution in the nucleus, $\rho(R)$, is spherically symmetric and given by:

$$\rho(r) = \begin{cases} 1, & R \in [0.6, 1] \\ -5R + 3.5 & R \in [0.5, 0.6] \\ 0.5, & R < 0.5 \end{cases} \quad (1)$$

  where R is a distance from the center of the comet in terms of comet radius.

The rate of material sublimating from a unit area perpendicular to the incident sunlight per unit time at a distance of r from the Sun is described by a sublimation function. In this work we consider the sublimation function of water ice derived in Marsden et al. [3]:

$$g(r) = \alpha \left(\frac{2.808}{r} \right)^m \left(1 + \left[\frac{r}{2.808} \right]^n \right)^k$$

where $\alpha = 0.111262$, $m = 2.15$, $n = 5.093$, $k = -4.6142$.

Changes in the shape of the comet are then calculated by numerically solving the corresponding set of nonlinear partial differential equations.

2.1. Spin history of the nucleus

As the spin history affects the shape of a nucleus in a significant way, we consider it in our model. We divide the evolution of the rotation of the comet's nucleus into two phases. In phase 1 the nucleus spin axis is tilted with respect to the orbital plane by an angle α_1. Over time, sublimation in this configuration deforms the comet's nucleus into a more elongated shape. This, in turn, reduces the moment of inertia around the spin axis. Perturbations such as close approaches with planets, collisions with interplanetary debris, or the sudden onset of jets, would then lead to a destabilization of the rotation state. In our model we define the rotation state after such a perturbation as phase 2. In this phase the comet attains a second spin axis (axis of precession) and it is perpendicular to the former spin axis. The angle between the second spin axis and the orbital plane is named α_2.

3. Results

Sampling the angles α_1 and α_2 we see a variety of shapes. In this work

$$\alpha_1, \alpha_2 \in \{0^\circ, 30^\circ, 60^\circ, 90^\circ\}.$$

Some of the resulting nuclei are displayed in Fig. 1. All the resulting shapes are axially symmetric (as it follows from the model). We can see that some of them are elongated and/or bi-lobed, but some are convex.

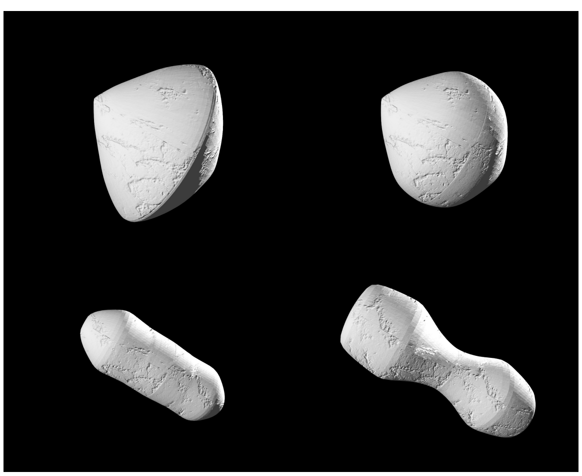

Figure 1: The resulting comets shapes for pairs of α_1 and α_2 $(30^\circ, 30^\circ)$, $(30^\circ, 90^\circ)$, $(60^\circ, 30^\circ)$, $(90^\circ, 90^\circ)$

4. Summary

We have shown that continous sublimation can cause initially spherical, rotating comet nuclei to evolve into more complex shapes. This process occurs very naturally as a consequence of the exposure of a rotating nucleus with non-uniform density to sunlight. Depending on the spin history of the nucleus, both convex and non-convex shapes can evolve. The here proposed mechanism can explain both, the bi-lobed structure of the majority of imaged comets and the convex shape of the remaining nuclei.

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