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A numerical study of the dusty-gas atmosphere of comet 67P/Churyumov-Gerasimenko

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Abstract

We apply out 3D+t model to study the influence of H_2O and CO production and its nonuniformity on the gas and dust dynamics in the vicinity of a rotating three-dimensional nucleus. The parameters of simulations correspond to the conditions of the rendezvous of the Rosetta probe with the comet 67P/Churyumov-Gerasimenko. We assume various models of gas and dust production of the nucleus taking into account available VLT observations. We present also the estimations of aerodynamic forces and dust contamination of the Rosetta orbiter and the lander.

1. Introduction

The Rosetta probe of the European Space Agency was launched 2 March 2004, to reach the vicinity of comet 67P/Churyumov-Gerasimenko (67P/C-G) in May 2014. It is aimed (1) to insert the probe into an orbit around the nucleus at a heliocentric distance r_h slightly in excess of 3 AU, (2) to land a descent module (called Philae) on the nucleus in November 2014, i.e. at $r_h \approx 3$ AU; (3) to maintain the probe in orbit if possible until beyond perihelion (r_h=1.24 AU), i.e. until $r_h \approx 1.8$ AU post-perihelion (December 2015).

It was found that the comet is quite active at 3 AU and this may creates a serious challenge to the two preceding objectives, as an aerodynamic force of a priori unknown magnitude will add itself to the very small gravity (due to the km-size nucleus). It thus appears absolutely necessary to achieve the construction of the gas coma model as soon as possible after the start of the comet observations by the probe, in any case surely before the release of the descent module, which requires a prediction of the aerodynamic force during the descent. Thus, one must have at hand adequate software to process the observations in terms of coma model within six months.

2. Modeling methods

The numerical simulation of the inner atmosphere of an active cometary nucleus offers severe challenges to fluid dynamics because of a juxtaposition of regions with widely differing conditions from fluid to free-molecular. As a consequence, a fully satisfactory treatment of the whole nearnucleus coma calls for a wide set of fluid dynamics methods. In principle, gasdynamic methods are appropriate to those regions where the gas velocity distribution is either a strict Maxwellian or a moderately distorted Maxwellian. Gaskinetic methods, for example the direct simulation Monte–Carlo (DSMC) method, are appropriate at any level of distribution function distortion. The main drawback of the DSMC is its high computational demands. The computational efficiency of this method is decreasing with the increase of density of the flow. We use both approaches (fluid and kinetic) in order to get (1) the best efficiency (minimal execution time) on all phases; (2) maximal precision of simulation and (3) mutual validation of the simulation results.

A multi-species (H_2O, CO) 3D+t gas model is based on: (1) gas-dynamic approach – the numerical integration of the Navier–Stokes equations combined with a locally plane-parallel solution of the collisional Boltzmann equation for the nonequilibrium near-surface Knudsen layer (BE-NSE) [3]; and (2) kinetic approach - the direct simulation Monte–Carlo (DSMC) method. In the region close to the nucleus we use quasi-steady approximation.

For the dust coma two approaches are used as well. (1) Fluid approach - the Dust Multi Fluid method (DMF); and (2) stochastic approach - the Dust Monte-Carlo (DMC). The DMC method allows not only to obtain the spatial distributions of dust but also to trace the individual trajectories of grains. The present 3D+t model is the extension of our model described in [1]. We assume that dust grains are spherical moving under influence of three forces: the nucleus gravitational force, gas coma aerodynamic force, and solar radiation pressure force, and consider the full mass range of ejectable grains.

3. Nucleus model

We use a rotating three-dimensional shape of 67P/C-G derived in [2]. The nucleus is ice-dust mixture characterized by the icy area fraction *f*: *f*=const - "*homogeneous*" nucleus, *f*≠const - "*inhomogeneous*" nucleus. The surface flux of CO consists of a fraction a_0 distributed uniformly over the surface, and a fraction $(1-a_0)$ distributed over the sunlit surface in proportion to its illumination. The upward flux of H_2O at each point is computed from sublimation energy budget equation. A nightside (and shadow) an internal heat transfer free parameter is introduced to simulate a heat flux from the nucleus interior at points in shadow. At each point and each size, the dust mass flux is proportional to the gas mass flux.

The largest part of our simulations are made in a range of probable conditions at the time of rendezvous with Rosetta spacecraft i.e. $r_h \approx 3$ AU and gas production rates $Q \approx 10^{26} \div 10^{27}$ s^{-1} and various proportions of CO distribution a_0 (0.1÷0.9).

4. Conclusions

The results illustrate the complex structure of gas and dust coma (see examples on Fig.1 and 2). Though there are vast regions of rarefied flow the BE-NSE results agree well with the DSMC results. In the case of non-rotating nucleus for the dust there is a broad range of dust sizes for which the spatial distribution could be obtained by simple scaling of the distribution for the smallest size. In the case of rotating nucleus this range is rather narrow.

The estimations of aerodynamic forces were made for a free molecular flow. It was found that the aerodynamic force on the orbiter and lander could be comparable with the gravitational force of the nucleus in a large part of a coma. It was found that the dust deposition on the orbiter and lander also could be important.

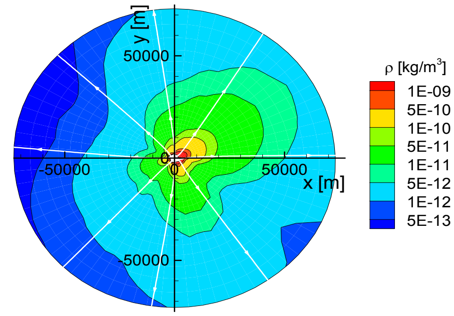

Figure 1: Distribution of gas density and flow lines in the equatorial plane for the case r_h=3 AU, $Q=10^{27}$ s^{-1} and $a_0=0.2$.

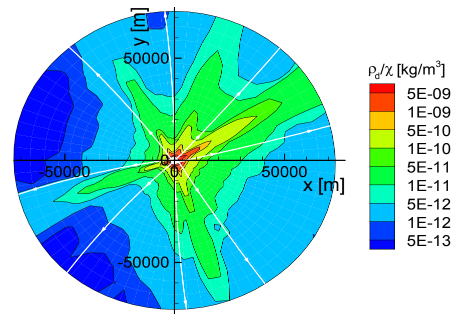

Figure 2: Distribution of dust ($a_d=10^{-7}$ m) density normalized to gas-to-dust ratio χ and flow lines in the equatorial plane for the case r_h=3 AU, $Q=10^{27}$ s^{-1} and $a_0=0.2$.

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