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3-D Simulations of the inner Gas and Dust Coma of Comet 67P/Churyumov-Gerasimenko

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1 Introduction

The physics of the outflow above the surface of comets is somewhat complex. Ice sublimating into vacuum forms a non-equilibrium boundary layer, the "Knudsen layer" (Kn-layer), with a scale height of ∼20 mean free paths. If the production rate is low, the Kn-layer becomes infinitely thick and the velocity distribution function (VDF) remains strongly non-Maxwellian.
The state-of-the-art method to study gas flows inside non-equilibrium regions is Direct Simulation Monte Carlo (DSMC). We have already studied a case with comet 9P/Tempel 1 where the Deep Impact observations were used to define the shape of the nucleus and the outflow was modelled in an attempt to fit the observations of water emissions at 2.66 μm [1]. Here we report on some preparatory models of the outflow from the Rosetta target, comet 67P/Churyumov-Gerasimenko (C-G).
Our aims are to (1) determine the gas flow-field in the innermost coma, (2) determine the surface outgassing properties from analysis of the flow-field, (3) determine initial velocity, bulk composition, and surface fluxes, (4) investigate dust distribution and acceleration by gas drag, (5) studying the scattering properties of the dust and (6) compare with observations over a range of heliocentric distances.

2 Boundary Conditions

The calculations have been performed using the nucleus shape model of [2]. Surface temperatures have been defined using a simple 1-D thermal model (including insolation, thermal emission, sublimation and conduction) computed for each facet of the shape model allowing a consistent and known description of

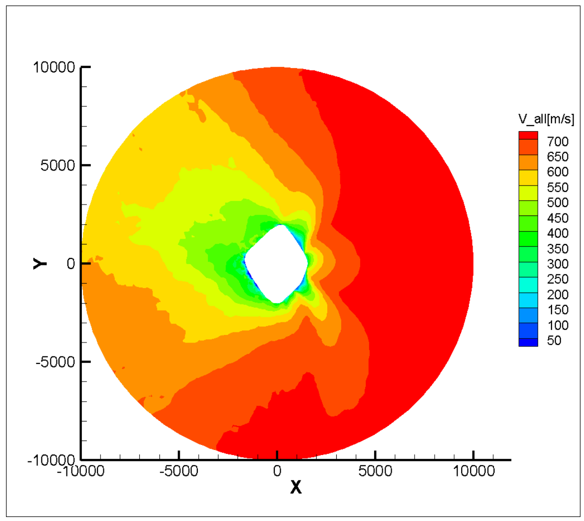

Figure 1: The gas velocity in the x-y plane of the 3D model of outflow from C-G at 2 AU. The sun is in the $+x$ direction and a half Maxwellian VDF was used on the comet surface. The axes are given in metres.

the gas flux and its initial temperature. The DSMC program used is PDSC^{++} [3] which is a 3-D implementation based on work by Wu and co-workers. The typical cell dimension is 3.8 m on the night side and 2.8 m for the day side (comparable to the Rosetta camera resolution from 150 km). The unstructured grid is made up of tetrahedron cells allowing a better description of the surface when compared to a Cartesian grid. The simulation domain extends out to 10 km from the centre of the nucleus. A half-Maxwellian or a cosine VDF at the surface can be used to initialize the gas outflow. Dust particles are assumed to be spherical and at rest on the surface of the nucleus.
The procedure is then (1) calculation of a steady state

solution for the gas field, (2) dust particle tracking in the gas field to get a dust particle distribution function, (3) scattering of the sun light on the dust particles and (4) line of sight integration of the dust brightness to create artificial images.

3 Gas Simulations

Figure 1 shows the velocity of the outflow from C-G simulated at a heliocentric distance of 2 AU with a gas production rate of 69.9 kg s^{-1}. An inhomogeneous case is shown here providing an equivalent active fraction of $\sim$ 7% [2]. Although different species have been simulated the results here are for water vapour and use standard values for the collision model.

4 Dust Tracking

To calculate the dust distribution in the coma we assume test particles in the gas field without any back coupling. The motion of the dust is driven by the drag force resulting from the gas flow. We assume a quadratic drag force with a velocity and temperature-dependent drag coefficient. We also take into account the gravitational force of the nucleus on the dust which will e.g. determine the maximal liftable size of the dust. Using the irregular grid from the gas simulation makes the tracking of the particles slightly more challenging but preserves the advantage of having a better description of the nucleus surface and thus of the physics involved.

5 Scattering

For the scattering of light by the dust we are using Mishchenko's [4] implementation of the T-matrix approach which can calculate (amongst others) the scattering phase function of spheroids, finite cylinders and Chebyshev particles of even order.
A key issue with Rosetta is that it will not be able to view the near-nucleus dust in the forward scattering geometry. This is a major limitation as forward scattering provides knowledge of the particle size. However, the back-scattering geometry is not without use (Figure 2). The figure shows an increase in the slope in the back scattering regime ($150° < \alpha < 180°$) for decreasing values of x which could help constrain our parameter space even with observations restricted to back-scattering geometry.

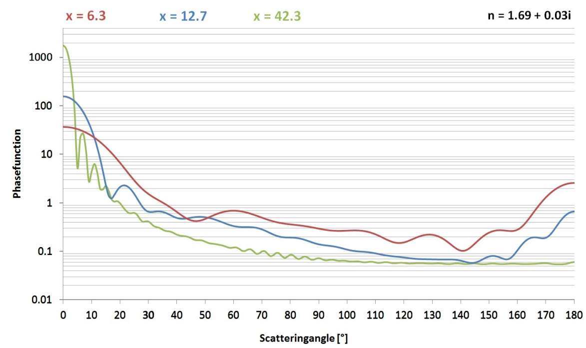

Figure 2: The scattering phase function for refractive index $n = 1.69 + 0.03i$ and three different values of the size parameter $x = \frac{2\pi a}{\lambda}$ with a being the dust grain radius and λ the wavelength. The phase functions were averaged over a size range of $\pm 10\%$ of the respective x.

6 Conclusions

Our DSMC code has been used to study a variety of simple models of the gas outflow from comet C-G. The code uses an unstructured grid and can provide global values for gas density, velocity and temperature out to 10 km from the nucleus at resolutions better than 10 m. Predictions for the flow velocity at 2 AU under simplified boundary conditions have been presented. We are also in the process of combining the gas field solutions with our dust drag and scattering calculations to produce artificial images. The importance of observations in backscattering geometries has been illustrated.

Acknowledgements

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