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Acceleration of ions and nano dust at a comet in the solar wind

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ABSTRACT

A quasi-neutral hybrid simulation of the interaction of the solar wind with the atmosphere of a comet is used together with a test particle simulation of cometary ions and dust to compute trajectories and velocity distribution functions of charged particles, starting outside the diamagnetic cavity at 150 km cometocentric distance. The simulations are run with parameters suited to make predictions for comet 67P/Churyumov–Gerasimenko when it is at a heliocentric distance of 1.45 AU. It is found that the shape of the ion trajectories depends on the location of the source, and that a velocity distribution that is observed at a given point in space is influenced by the spatial structure of the source. Charged dust grains with radii in the 1–10 nm range are accelerated from the nucleus to a distance of 2.9×10^4 km in between 15 min and 2 h approximately. Dust particles smaller than 10 nm in radius are accelerated to speeds over 10 km/s.

1. Introduction

As a comet approaches perihelion and comes closer to the sun, the sublimation of volatiles leads to ejection of gas, ice, and dust. When the water sublimation temperature is reached, it releases a huge amount of water that is ionised by ultraviolet photons from the sun and through charge exchange with the solar wind protons. Observations at comet Giacobini–Zinner showed water-group ion distribution functions that followed a power law at high energies and were flattened at low energies (Richardson et al., 1987). Recent observations by the Rosetta spacecraft at comet 67P/Churyumov–Gerasimenko (Nilsson et al., 2015a) showed how the newly created H_2O^+ ions are picked up by the solar wind and accelerated away from the cometary nucleus in the direction of the solar wind electric field. These observations took place in the early stages of the formation of a cometary magnetosphere when a diamagnetic cavity had not yet been established, while the comet was at heliocentric distances between 3.3 and 3.6 astronomical units (AU), and with the spacecraft between 28 and 100 km from the cometary nucleus.

The cometary pickup ions have been seen to undergo pitch angle scattering into shell-like distributions at comets Halley (Coates et al., 1989) and Grigg–Skjellerup (Coates et al., 1993). These observations were made at distances on the order of 10^5 and 10^6 km from the comet at Grigg–Skjellerup and Halley respectively, when each comet had developed its diamagnetic cavity. This means that the length scales involved in the scattering are those of Alfvén waves and MHD. Fluctuations at smaller scales may also occur in the cometary environment as a result of various different plasma instabilities, such as the Kelvin–Helmholtz instability (Chandrasekar, 1961) or the modified two-stream instability (McBride et al., 1972; Raadu, 1978). In the vicinity of Mars, where the solar wind interacts with the ionosphere of the planet as well as with its neutral exosphere, oscillations in the millihertz range have been observed (Winningham et al., 2006; Gunell et al., 2008). Also mirror mode waves have been suggested as a source of fluctuations at comets (Schmid et al., 2014).

The constituent of comets that most easily can be seen from the ground is a large dust grain population, in the micro-metre size range. These grains move under the influence of the sun's radiation pressure (Eddington, 1910). Schulz et al. (2015) observed dust grains up to a size of 500 μm using the COSIMA instrument on the Rosetta spacecraft. Rotundi et al. (2015) found dust grains in the 100 μm to millimetre range to be more effective optical scatterers than those in the micrometre range when 67P/Churyumov–Gerasimenko was between 3.7 and 3.4 AU from the sun, but they expected that to change as the distance from comet to sun decreases. The reason for this expectation is an asymmetry in the

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grain size distribution between the northern and southern halves of the nucleus, leading to an increase of the emission of small grains from the southern side starting at about 2 AU (Fulle et al., 2010). For dust particles in the size range of tens of nanometres or smaller – that is to say, the nano dust – the scattering cross sections are small and these dust particles do not contribute much to visual observations. As a result the radiation pressure force is also small and instead electrostatic forces become increasingly important. The drag force from the neutral gas is also an important force on the dust grains, but only within a few kilometres from the nucleus.

Snios et al. (2014) compared observations of hard X-rays from five comets with models of scattering and fluorescence of X-rays originating at the sun. They found that scattering by cometary gas was insufficient to explain the observed intensities and suggested that the observations could be explained by scattering from dust particles, both large, in the micro-metre range, and small nanometre sized particles. Szego et al. (2014) predicted that nano dust at comet 67P/Churyumov–Gerasimenko could be observed by the ion and electron sensor (IES) on board the Rosetta spacecraft. Dust particles, down to 2 nm in size, from Saturn's E-ring can be accelerated and ejected from Saturn's magnetosphere and are observed as "Saturnian stream particles" (Hsu et al., 2011). Dust composition and dynamics at both Saturn and Jupiter were reviewed by Hsu et al. (2012). It is not clear how nanometre-sized dust can be lifted from the surface of the comet, but some evidence for the existence for nano dust was already observed with Giotto near comet Halley (Utterback and Kissel, 1990, 1995). In contrast to the nano dust near planets, mentioned above, that possibly originates from a condensation process, the dust near the comet is possibly due to fragmentation, see discussion by Mann and Czechowski (2012). Several observations suggest that dust fragmentation events occur near the comet – discussed by Mann et al. (2006) – so that small dust particles can be produced independent from the conditions of leaving the nucleus. And for instance Clark et al. (2004) discuss fragmentation in order to explain the unpredicted heterogeneity in particle number density that they observed in the coma of Wild 2.

In this paper we present results from a simulation meant to model comet 67P/Churyumov–Gerasimenko when it is at a solar distance of 1.45 AU. We compute distribution functions for cometary water ions. We study the effect the size of the ion source region has on these distributions, and we examine the effects of electric field fluctuations in a region along the ion trajectory. We use the same approach to compute trajectories of dust grains in the size range from 1 to 10 nm, and analyse how the acceleration depends on the dust grain size. The simulation model is described in Section 2; ion distribution functions are presented in Section 3; trajectories of nano dust are computed in Section 4; and the conclusions are discussed in Section 5.

2. Model

The simulations are performed in two steps. First, a global quasi-neutral hybrid model is used to produce electric and magnetic fields. Second, test particle simulations are run, using the calculated fields to compute trajectories for ions and dust particles.

2.1. Quasi-neutral hybrid model

The 3-D self-consistent global plasma simulations were performed using a model based on the hybrid modelling platform HYB, now developed at Aalto University (Finland) and applied to a cometary environment. The model describes the plasma using the quasi-neutral hybrid approach, treating ions as kinetic particles and electrons as a charge-neutralising massless fluid so that $\sum_i q_i n_i + q_e n_e = 0$ where q_i, n_i and q_e, n_e are the ion charge and density and electron charge and density, respectively. The model has been tested for more than 15 years and has been used to study the interaction between the solar wind and planetary objects, such as Mars and Venus (e.g., Jarvinen et al., 2014), the Moon (Kallio, 2005) or, more recently, comets such as comet C/2013 A1 "Siding Spring" for which solar wind mass-loading simulations were performed (Gronoff et al., 2014). The model was described in detail in, e.g., Kallio and Janhunen (2003), Kallio et al. (2006), Kallio and Jarvinen (2012); only specifics related to the electromagnetic fields and inputs for the simulation are provided here. The ion dynamics is governed by the Lorentz force in the expression of Newton's second law, while the electrodynamics fields ($\mathbf{E}, \mathbf{B}$) are solved by Ampère's and Faraday's laws. Ions are accelerated by the Lorenz force where the electric field is derived from $\mathbf{E} + \mathbf{U}_e \times \mathbf{B} = 0$, where $\mathbf{U}_e$ is the electron bulk velocity. Finite ion gyromotion effects and Hall term are naturally included, giving rise to kinetic effects and plasma asymmetries. In the hybrid model, electron resistivity is included in the propagation of the magnetic field in time by Faraday's law $\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E} = -\nabla \times (-\mathbf{U}_e \times \mathbf{B} + \eta \mathbf{j})$; after several values were tested, a conservative value of $\eta = 0.02\ \Omega$m was found to yield more stable results and sharper boundaries than in the case of $\eta = 0$. Moreover, the electron pressure term was ignored since our tests showed that it did not significantly affect the final calculated electromagnetic fields at the spatial scales considered. Grid refinement techniques can be used to target a specific area of the object's environment.

To perform the 3-D global hybrid plasma simulations, a neutral model of the cometary coma is first needed. We used the classical spherically symmetric expansion model of Haser (1957)

$$n_n(r) = \frac{Q}{4\pi r^2 V} e^{-r/\lambda_{H_2O}} \qquad (1)$$

where Q is the production rate of neutral species ejected from the comet under the action of the Solar radiation (in our case H_2O), r the cometocentric distance, V the velocity of the escaping neutrals and λ_{H_2O} the photodestruction scale length (estimated from the photo-rates given by Huebner et al., 1992 for H_2O). Parameters for the Haser neutral model are collected in Table 1. Photodissociation of H_2O into H is negligible below 3×10^4 km from the nucleus, where charge exchange processes between the solar wind and the cometary neutrals may become dominant.

The parameters of the upstream solar wind as well as the photo-ion production rate are summarised in Table 2. The upstream parameters correspond to the conditions recommended by Hansen et al. (2007) propagated at 1.45 AU, i.e., close to perihelion, and hence representing common values expected by Rosetta at comet 67P/Churyumov–Gerasimenko. The solar wind is composed of protons H^+ and alpha particles He^{2+}, the latter amounting to 4% of the proton density. Charge transfer reactions between the solar wind particles and H_2O cometary molecules significantly affect the mass loading and the magnetic field morphology upstream and downstream of the nucleus. A simple analytic model (see Nilsson et al., 2015a, Appendix) shows that, when compared to charge transfer with He^{2+}, charge transfer with H^+ plays the major role at the resolution used in the hybrid

Table 1
Neutral parameters for the Haser model of comet 67P/Churyumov–Gerasimenko at 1.45 AU. $Q(H_2O)$ is the neutral H_2O outgassing rate from the comet, V the velocity of the expanding neutral cloud, λ_{H_2O} the total photodestruction scale length at 1.45 AU heliocentric distance, including ionisation and dissociation and at low solar activity.

$Q(H_2O)$ (s^{-1})	V (km s^{-1})	λ_{H_2O} (km)
2.36×10^{27}	0.70	1.22×10^5