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Physics at sub-ion-gyroradius scales near low-activity comets

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Abstract

The morphology of induced comet magnetospheres varies greatly over a comet's orbit. Far away from the Sun, the cometary activity, quantified by the outgassing rate, is very low and the cometary ion density is smaller than the solar wind ion density. In this case the interaction between the cometary plasma and the solar wind is characterised by a simple deflection of the solar wind as it gets mass-loaded by the cometary plasma. In contrast, near perihelion the cometary activity and outgassing rate increase by several orders of magnitude. A fully developed bow shock forms as part of the interaction between the cometary plasma and the solar wind, and extends tens of thousands to millions of km from the comet nucleus into the upstream solar wind. At low-to-intermediate cometary activity the spatial scales of the induced comet magnetosphere are similar to the gyroradii of the ions and no fully developed bow shock is formed. The comet–solar wind interaction in this transition period is strongly influenced by kinetic effects acting on both cometary and solar wind ions. The physical processes in the plasma environment near such low-activity comets are the subject of this thesis. Its main focus is on the shape, origin, and evolution of the ion velocity distributions (VDFs), as well as the energy transfer between the solar wind and the cometary magnetosphere. Furthermore, a combined approach utilising both in-situ measurements as well as numerical modelling provides a complete 3D picture of the interaction. We use observations from the Rosetta mission and 3D global kinetic hybrid modelling to study the interaction.

The European Space Agency mission Rosetta to comet 67P/Churyumov-Gerasimenko was equipped with a broad spectrum of scientific payloads, including two ion spectrometers: the Ion Composition Analyzer (ICA), and the Ion and Electron Spectrometer (IES) as part of the Rosetta Plasma Consortium (RPC). On 19 April 2016, at a heliocentric distance of 2.8 au, ICA and IES detected partial ring-like VDFs of solar wind protons along with approximately isotropic distributions of the solar wind alpha particles. These observations stand in contrast to the expected and previously observed Maxwellian distributions of deflected solar wind ions usually associated with low cometary activity. The fitted velocity components of the partial rings show a significant deceleration of the proton bulk velocity, potentially connected to the initial stages of bow shock formation. The lack of partial ring formation for alpha particles is attributed to their larger gyroradii compared to protons. The observed cometary pickup ions during this time period also show the initial stages of partial ring formation. The fitted velocities in the case of the cometary ions are much lower compared to those of the solar wind ions, which suggests a strong shielding of the inner coma from the undisturbed solar wind electric field.

The formation of non-Maxwellian ion VDFs as a result of comet–solar wind interaction is subsequently studied using the kinetic hybrid model code Amitis. Partial ring distributions are found to form in large parts of the comet magnetosphere, including close to the nucleus where they have been observed by Rosetta. The shapes of solar wind proton VDFs continuously evolve as the solar wind traverses the cometary plasma environment and are non-Maxwellian throughout most of the magnetosphere. As a result of the solar wind interaction with the cometary ions, the plasma forms a magnetic pile-up layer in the -E-hemisphere, the hemisphere which the solar wind is deflected towards. In this magnetic pile-up layer the magnetic field strength is stronger compared to the interplanetary magnetic field, and the solar wind proton density is increased. Upstream of and in the magnetic pile-up layer, secondary populations of protons resemble reflected ions found at planetary bow shocks. The solar wind alpha particles show a different spatial evolution of their VDFs due to the larger gyroradii. Additional simulations show that the composition of the solar wind affects the size and shape of the induced comet magnetosphere. The large inertia of alpha particles makes them less efficient in transferring energy to the cometary ions and electromagnetic fields upstream of the nucleus. Therefore, a larger proportion of alpha particles at a given solar wind dynamic pressure and cometary activity leads to a relatively larger mass loading of the solar wind protons. This in turn results in an expansion of the magnetic pile-up layer, along with a decrease in magnetic field strength.

Keywords
Comets, solar wind, plasma physics, space plasmas

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