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Modelling of the plasma environment surrounding 67P: the effect of the convective electric field on ion density profiles

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Abstract

By following comet 67P/Churyumov-Gerasimenko along its orbit, Rosetta during its cruise is offering us the unique opportunity to understand the complex evolution of the comet with its environment. Although the coma is not bound at the surface, its photo-ionisation by solar extreme ultraviolet radiation creates a complex plasma environment which interacts with and is influenced by the solar wind. We consider the critical role played by collisionless processes (e.g. the effect of external electric and magnetic fields) in shaping the resulting ionospheric density profiles.

In particular, the photo-ionisation of sublimated water molecules leads to the production of H_2O^+. These new ions are subjected to the electromagnetic environment of the solar wind in which they are born. In particular, the convective electric field $\vec{E}_{conv}$ associated with the component of the solar wind flow perpendicular to the interplanetary magnetic field (i.e. $\vec{E}_{conv} \approx \vec{v}_{SW} \wedge \vec{B}$) strongly influences the dynamics of new ions and electrons and thus their density profiles around the comet. To lowest order that field can be described by the generalized Ohm's law of MHD. However, the small scales associated with 67P must be taken into consideration.

We show that the convective electric field plays a key-role in the distribution of ions in the vicinity of the comet and in their transport. In particular, the comet should not be reduced to a point source in the model; its physical size should be considered. Finally, we discuss the establishment of an induced ambipolar electric field on the ionospheric plasma to counteract the effect of $\vec{E}_{conv}$.

Approach

Neglecting the collisions within the coma of 67P between neutrals, ions and electrons and assuming stationnarity, the Boltzmann equation is reduced to:

$$v_s \frac{\mathrm{d}f(\vec{r}(s),\vec{v}(s))}{\mathrm{d}s} = P - L$$

where s is the curvilinear abscissa, the coordinate along the ion's path (a parabola), v_s, the velocity of the particles along the trajectory, P the ion production rate under solar illumination here.

We assume that the velocity distribution function for the newborn ions $f_M(\vec{v})$ is a Maxwellian, centred around the ion outflow $U_n \approx 650$ m.s^{-1}, propagating radially with some dispersion in both magnitude and direction. On the other hand, the total density for H_2O is assumed to be:

$$n_{H_2O}(r) = \frac{Q}{4\pi U_n r^2}$$

where Q is the outgassing rate in molecules.s^{-1} and r is the cometocentric distance, $P = \nu n_{H_2O} f_M$ where ν is the photo-ionisation rate.

Based on the Liouville theorem, we fixed the velocity at a given location and we track back all the ions with this final configuration during their motion (a parabola):

$$f(\vec{r}(s_0),\vec{v}(s_0)) = \int_{-\infty}^{s_0} P\frac{\mathrm{d}s}{v_s} = \int_{-\infty}^{t_0} P\,\mathrm{d}t$$

Because the trajectory of any ion is a parabola, we decide to not parametrise according the travel time or the curvilinear position but as a function of the true anomaly. Indeed, the trajectory of the ion follows:

$$\rho(\Omega) = \frac{p}{1+\cos\Omega}$$

where $\rho(\Omega)$ is the distance from the focus of the parabola (not the comet) and p, the semi latus rectum. Here, $p = mv_\perp^2/(qE_{conv})$.

Finally, the velocities are wisely sampled for the density evaluation, integration of the distribution function overall the velocity phase space, according to the Gauss-Hermite quadrature.

Results

The comet is assumed to be spheric. The simulations are only extended up to 20 km. As this is a collisionless model, the density and higher moments of the distribution function are determined at a given location, without performing a global simulation.

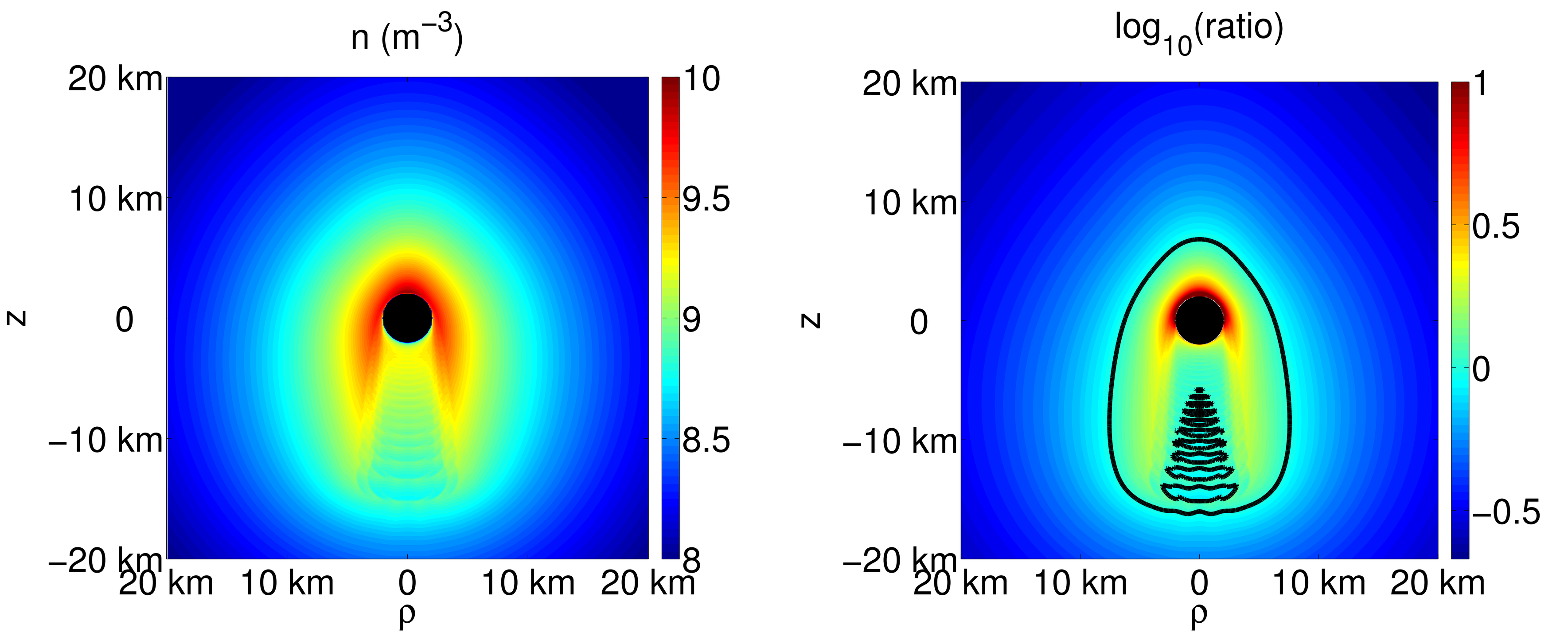

Figure 1: Plots of the ion density (left panel) and ratio of this ion density with the analytical density calculated without electric field (right panel) for $Q = 10^{27}$ s^{-1}, a photoionisation frequency $\nu = 6.10^{-8}$ s^{-1} (at 3.3 A.U.) and $E_{conv} = 5.10^{-4}$ V.m^{-1} along (-z). The black disk represents the comet with a radius of 2 km. The black line in the right panel corresponds to a ratio of 1: our model provides larger density values than the field-free model inside this boundary.

$\vec{E}_{conv}$ deflects strongly the ions downward as expected without strongly affecting the densities: the difference with the model assuming no electric field is smaller than one order of magnitude.

The tail of the comet presents numerical features: in the velocity phase space, the distribution function is not continuous due to the comet itself. Indeed, there is a virtual loss: any ion crossing the comet is lost before reaching the expected location. Moreover, the velocity phase space is open: there is a priori no upper boundary for the ion velocity which makes tricky for the numerical evaluation of the density or other moments.

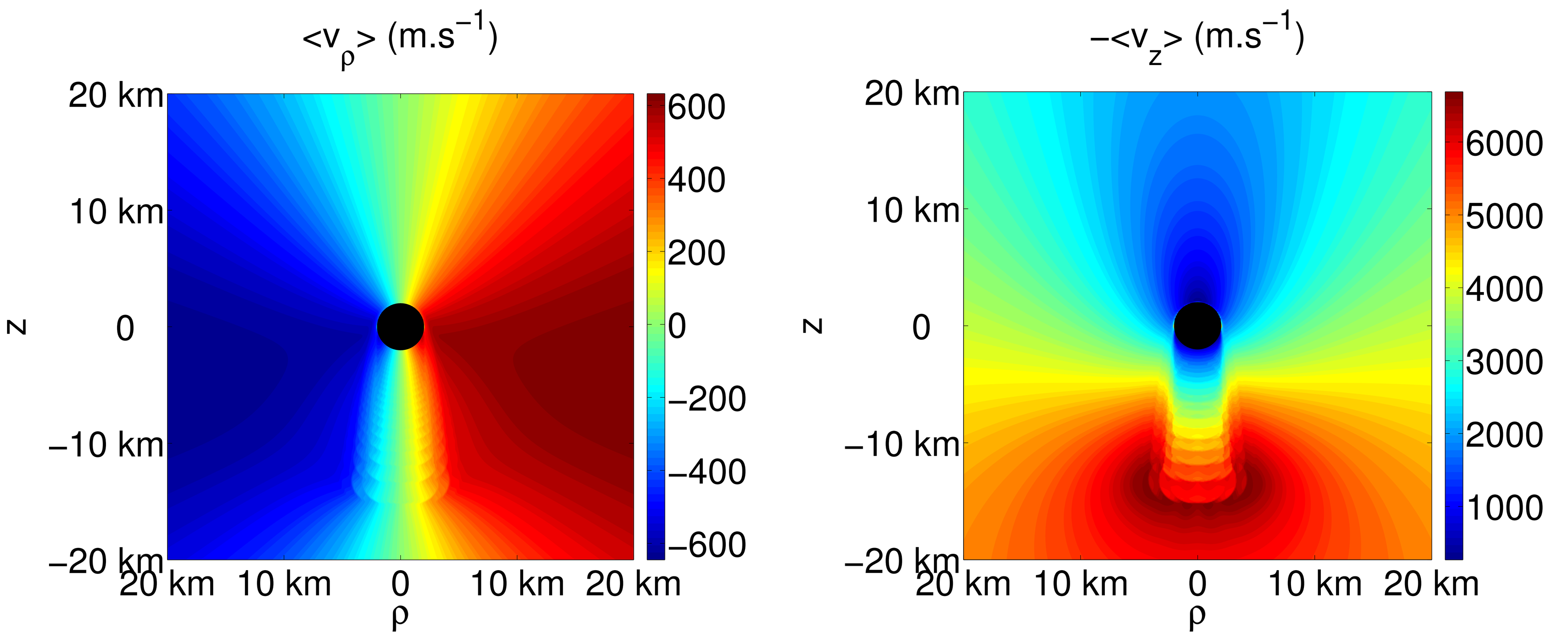

Figure 2: Plots of mean velocity of ions in the perpendicular direction (left panel, $< v_\rho >$) and in the parallel direction of the electric field (right panel, $< v_z >$). The opposite value is taken for $< v_z >$ to underline strong downward velocities.

The electric field is along the z-direction. Therefore the transport of ions in the perpendicular plane is not too much modified, except in the tail, while in the z-direction, the ions are strongly accelerated. Indeed, the mechanical energy provided by $\vec{E}_{conv}$ to ions after a few kilometers is the same order of magnitude than their initial kinetic energy.

Conclusions and Perspectives

We present the first results about the effect of the convective electric field with a colisionless kinetic approach.

- The ion density has no longer a spherical symmetry.
- The comet size and shape affect strongly the structure of the ion coma.
- E_{conv} accelerates the ions significantly, increasing their speed from U_n (typically 400–800 m.s^{-1}) up to 10 U_n at cometocentric distances of ~ 20 km.
- We plan to compare with the recent work by Vigren et al. (2015).
- The electrons are expected to be affected in the same way but in the opposite direction with respecto the z-axis
- An ambipolar electric should set up to ensure the quasi-neutrality between ions and electrons and its effect will be investigated next.