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A comet's tale: Role of charge exchange in the plasma environment of comet 67P/Churyumov-Gerasimenko

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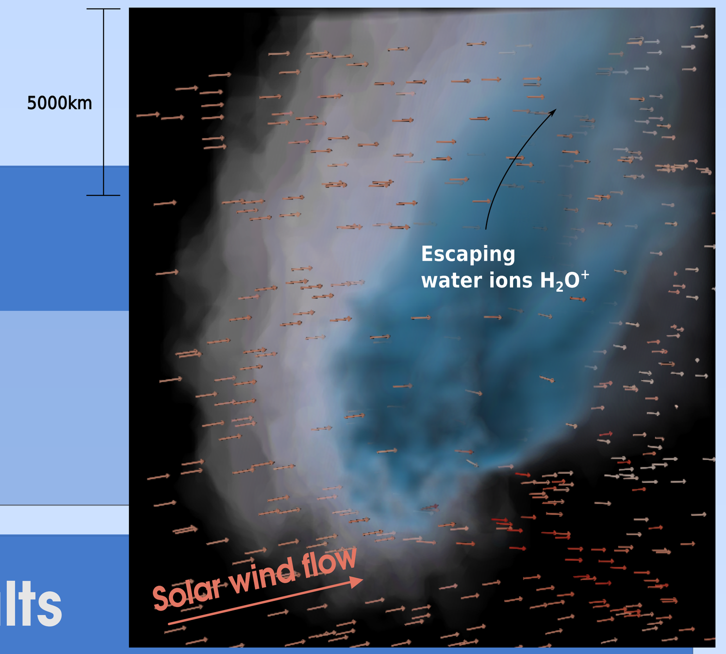
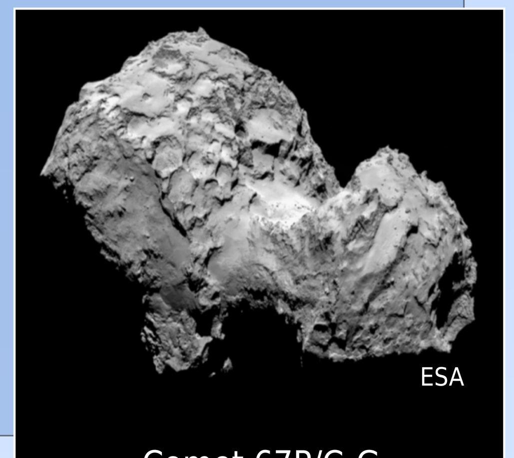


Abstract

http://rosetta.esa.int

On 6 Aug. 2014, the **ESA/Rosetta mission** arrived in the vicinity of comet 67P/Churyumov-Gerasimenko (C-G) and started measuring its complex plasma environment, using notably the **RPC-ICA ion spectrometer** (Rosetta Plasma Consortium Ion Composition Analyser). A simple model of charge-exchange processes is first presented for He^{2+} and H^+ solar wind ions that efficiently convert them into He^+ ions (measured by RPC-ICA) and H energetic neutral atoms, respectively. In a second step, we present a new cometary hybrid plasma model, taking into account photoionisation, charge-exchange, electron impact ionisation and electron recombination, dedicated to the interpretation of RPC-ICA measurements.



Comet 67P/C-G

Charge-exchange in the environment of comets

Charge-exchange at comets (CX) plays an important role in the composition and dynamics of the plasma in the environment of comets (e.g., Gombosi, 1987, Dennerl, 2010). Solar wind charge exchange is for example responsible for cometary X-ray emissions (Cravens et al., 1997) and for the formation of a cometopause. Besides multiply-charged heavy atoms (O^{7+}, O^{6+}), the solar wind (SW) also embeds protons and alpha particles which can be detected by instruments onboard Rosetta.

Formation of He^+ ions and H-ENAs

He^+ ions are created when SW ions charge exchange with cometary neutrals:

$He^{2+} + H \rightarrow He^+ + H^+$ (1)

$He^{2+} + O \rightarrow He^+ + O^+$ (2)

$He^{2+} + H_2O \rightarrow He^+ + H_2O^+$ (3)

Reaction	Cross section at 0.83 keV (cm²)	Reference
(1) He^{2+} + H	1.85×10^{-16}	Barnett et al. (1990)
(2) He^{2+} + O	4.00×10^{-16}	Chanteur et al. (2009)
(3) He^{2+} + H_2O	8.40×10^{-16}	Lindsay et al. (1997); Vavrukh et al. (2008)

Fast hydrogen energetic neutral atoms (H-ENAs) undergo:

$H^+ + H_2O \rightarrow H_{ENA} + H_2O^+$ (4)

Since H_2O is the most prominent neutral species at distances < 1000 km (Haser model in **Fig. 1**), and owing to cross section values, the most efficient mechanisms are reaction (3) and reaction (4).

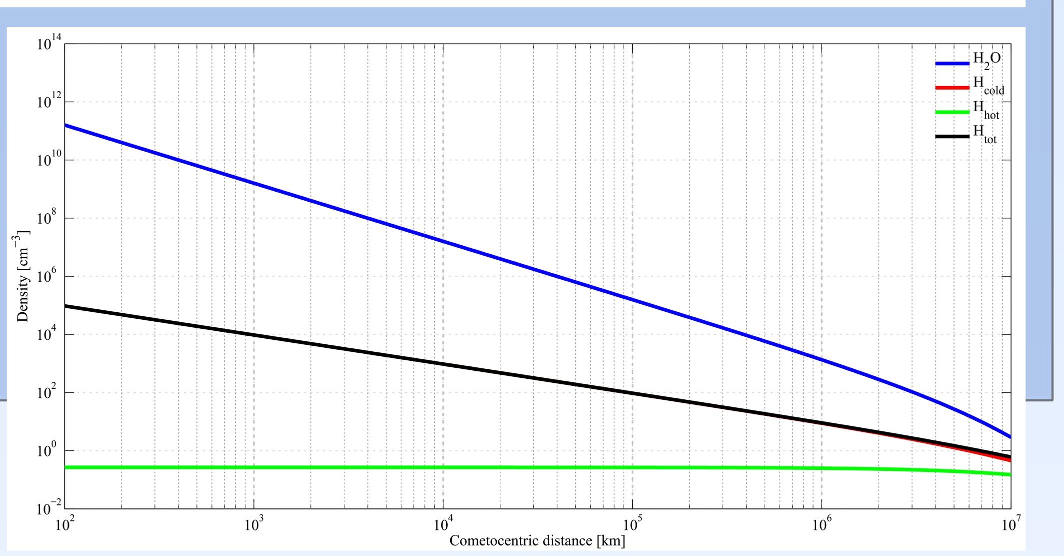
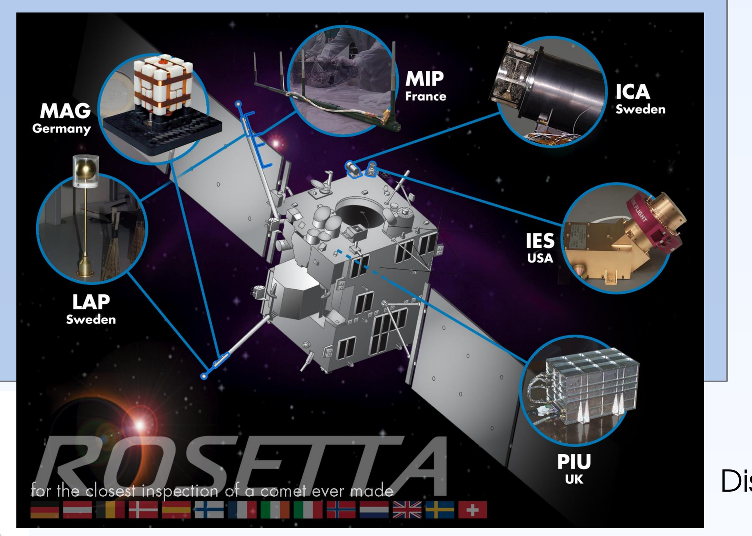


Fig. 1: Haser model with H_2O, and H as main components of the comet's neutral atmosphere

Observations of He^+ ions at 67P/C-G

Onboard ESA/Rosetta, the Rosetta Plasma Consortium (RPC) includes one ion spectrometer, ICA (Ion Composition Analyser), which determines the in-situ energy spectrum and nature of ions.

Fig. 2 shows is a time-energy spectrum by RPC-ICA on 21-09-2014. Charge-exchange reactions between solar wind He^{2+} ions and cometary H_2O molecules led to the creation of fast He^+ ions. First measurements shown in Nilsson et al. (2015) give an average He^+/He^{2+} flux ratio of about 2% at 20 km cometocentric distance.



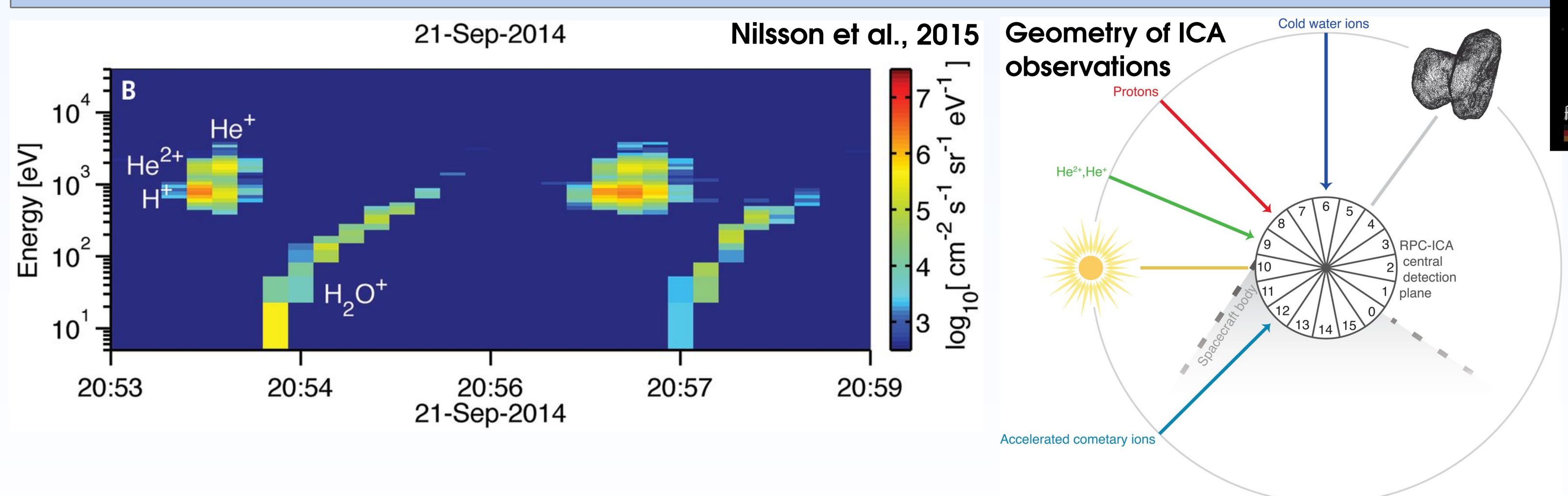


Fig. 2: Example of a typical observation of fluxes performed by ICA on 21 Sept. 2014 (*left*). Angular deflection of ions is observed as sketched (*right*).

Modelling the comet-solar wind interactions

To describe CX processes, two approaches are considered:
1. Simple line-of-sight model with He^+ ions and HENA atoms and impact of outgassing rate on CX efficiency.
2. Newly-developed global 3-D hybrid model of the comet's plasma environment with CX processes.

A simple CX model

If we assume He^+ ions are produced exclusively by CX with H_2O, and have the same velocity, the flux ratio He^+/He^{2+} simply becomes:

$$R = \frac{N_{He^+}(x)}{N_\alpha(x)} = \frac{1-e^{-\sigma_{CX} I(x)}}{e^{-\sigma_{CX} I(x)}}$$

Here $\int_x^\infty N_n(x)dx$ is the column density of neutral H_2O from $x = +\infty$ (sunward direction) and σ_{cx} is the CX cross section for solar wind He^{2+} with H_2O. The column density can also be expressed as:

$$I(x) = \frac{\ln(R+1)}{\sigma_{CX}}$$

Since at the location of Rosetta on 30-09-2014 ($x \sim 20$ km), $R = 0.021$, we deduce a column density $\boldsymbol{I(x_0) = 2.5 \times 10^{17}}$ **m²**.

If we assume in turn a neutral Haser profile and integrate it:

$$I(x_0) = \frac{Q}{4\pi v_0 \int_{x_0}^{\infty} r'^2 dx'}$$

We can deduce an equivalent outgassing rate $\boldsymbol{Q \sim 1.4 \times 10^{25}}$ **s⁻¹** with $v_0 = 400$ m s⁻¹ in good agreement with ROSINA-COPS measurements.

Deduced He^+/He^{2+} and H_{ENA}/H^+ ratios are shown in **Fig. 3** and **4** in the 2-D symmetric plane. Typical values near the surface are 10-30%.

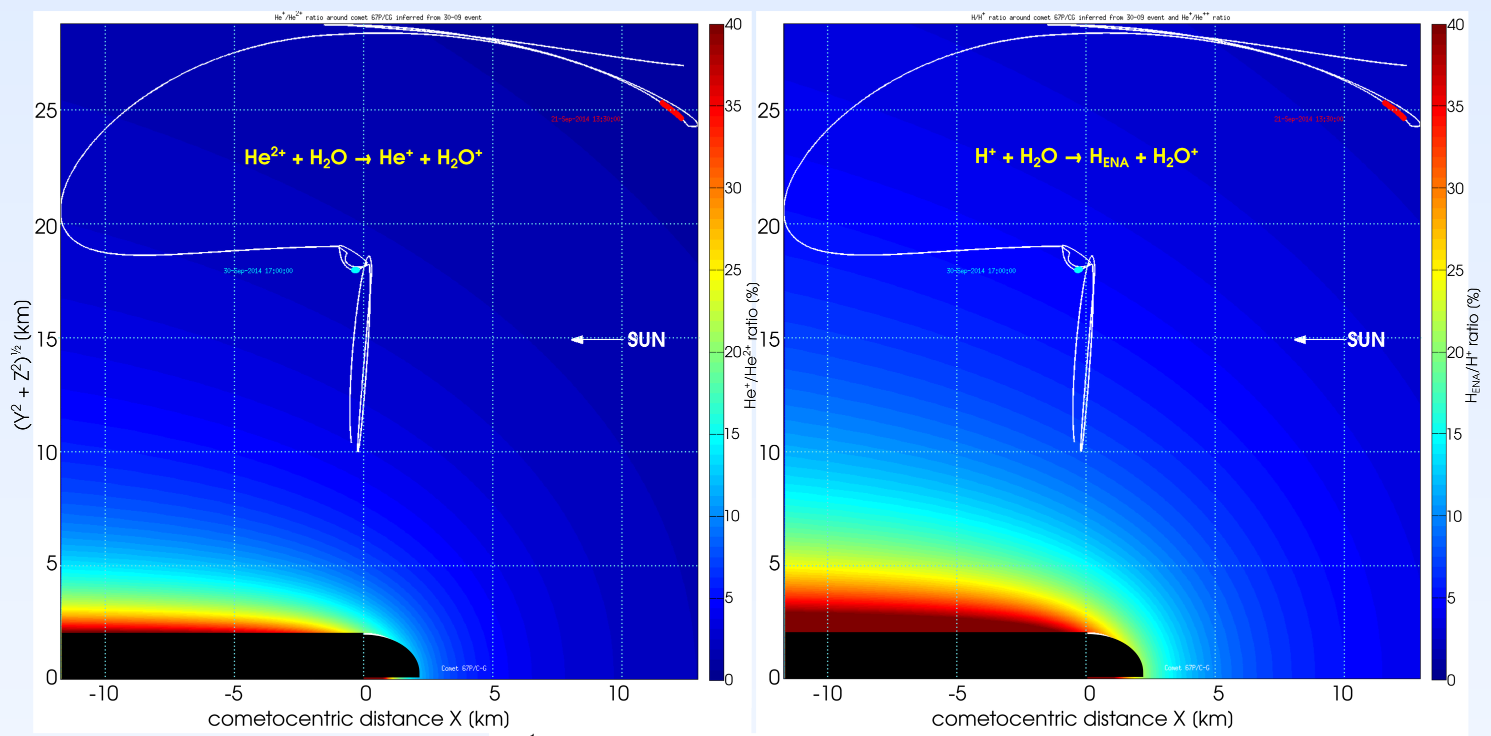


Fig. 3: He^+-to-He^{2+} ratio (*left*) and H-to-H^+ ratio (*right*) in the 2-D symmetric plane. The comet and its shadow along the line of sight are shown in black. ESA/Rosetta's orbit in Sept. 2014 is drawn in white.

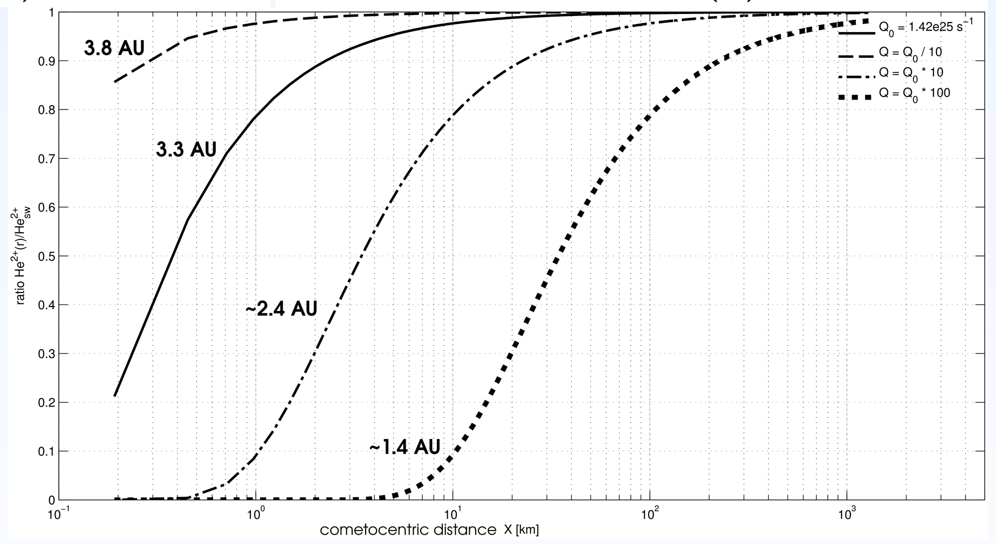


Fig. 4: Efficiency of CX. Distribution of He^{2+} ions normalised to the He^{2+} solar wind density with varying outgassing rates Q.

3-D hybrid model results

A 3-D hybrid model including photoionisation, charge-exchange, electron impact ionisation and electron recombination is developed at Aalto University, based on a new hybrid platform (e.g., Kallio & Jarvinen, 2012 for Mars and www.space.aalto.fi).

The solar wind can interact directly with the cometary outgassing H_2O atmosphere. At perihelion (picture above), a magnetic barrier forms around the comet due to the solar wind being "mass-loaded". Newly-formed Ions are "picked up" by the solar wind flow, i.e., accelerated by the solar wind convection electric field, forming the typical cometary plasma tail.

Fig. 5: Ratio He^+/He^{++} calculated by the hybrid model at 3.3 AU. The box size is ±200 km. We used a grid refinement technique to reach 1.25 km resolution near the comet. Ratios reach about 12% close to the nucleus and in the tail where H_2O densities are highest. $\boldsymbol{B}$ = (0, 10, 0) nT, $n_{H+,sw} = 0.9$ cm⁻³, $Q = 8 \times 10^{26}$ s⁻¹

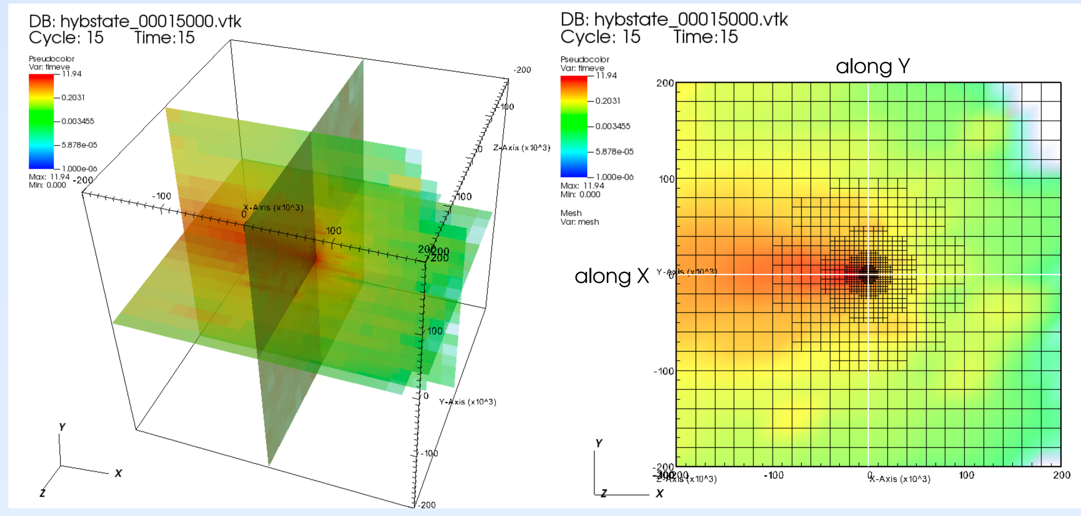
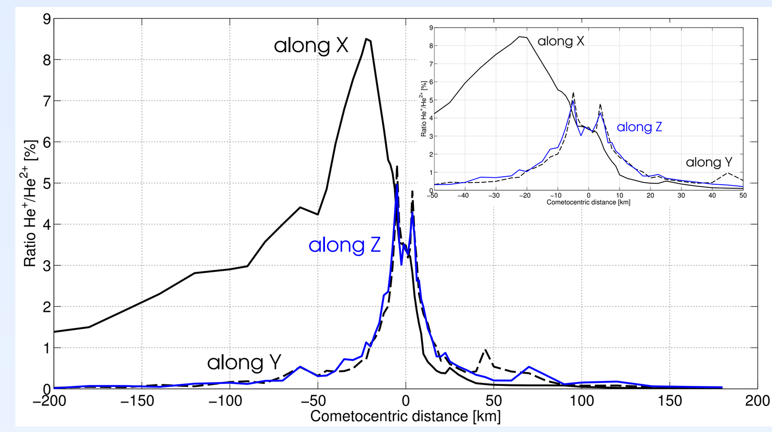


Fig. 6: Ratio He^+/He^{++} calculated along the 3 axes X, Y and Z. The maximum is found along the X axis, while the Y/Z curves exhibit similar features (expected due to spherical symmetry). Ratios within 20 km cometocentric distance are found to be above 1% on average along Y and Z, and above 7% in the tail along X.



Summary and perspectives

Charge-exchange plays a significant role in the environment of 67P/C-G, reaching values of the order of 10% efficiency for the creation of He^+ fast ions and new H_2O^+ ions (**Fig. 5** and **6**).

Our simple CX model yields results comparable to those calculated by the hybrid model, validating our approach. Efficiency of charge-exchange is found to be depending on the distance to the comet and on the overall outgassing rate.

Several points are currently investigated with our global cometary hybrid model:
 * **role of the water production rate and charge-exchange processes** in the formation of plasma regions at comet 67P/C-G and for **various heliocentric distances**
 * **Formation of a cometopause**

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