Charge Exchange and Ion Chemistry in the Gas Coma of Enceladus

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Abstract

Enceladus, the small inner icy moon of Saturn, has been discovered by Cassini observations to be emitting a large quantity of water molecules ($Q \sim 10^{28}$ H_2O/s) from its south pole. Because of the low surface gravity, the expanding gas will move away from Enceladus forming a toroidal-shaped gas cloud around Saturn. In the dense region of the neutral atmosphere, the incoming magnetospheric plasma flow has strong interaction via charge exchange and collisional process. Because of the large amount of gaseous material surrounding Enceladus, the magnetospheric flow could be slowed down substantially in analogy to the comet-solar wind interaction. The new pickup ions and the fast neutrals generated by charge exchange process have long-ranging effects in the local and global structures and dynamics of the Saturnian magnetosphere. By using a simple flow model with a heritage from cometary study, we investigate the production of new water-group ions and fast neutral atoms and molecules in the vicinity of Enceladus. Some preliminary results will be reported here.

1. Introduction

Before *Cassini-Huygens* mission, Enceladus is always an intriguing icy satellite in the Saturnian system. Part areas on Enceladus' surface show no craters indicating major resurfacing events in the geologically recent past (Smith et al. 1981; Squyres et al. 1983). In addition, Showalter *et al.* (1991) found that, using the combined spectrophotometric data of the E ring from ground-based measurements with those from the Pioneer 11 and Voyager encounters, its optical depth profile peaks sharply near the orbit of Enceladus. This moon was thought to be the source of the ring of micron-sized grains.

From HST observations Shemansky et al. (1993) detected large magnetospheric OH densities. The most obvious source of OH is dissociation of sputtered H_2O molecules from the small icy satellites' surface and Saturn's rings (e.g. Johnson et al. 1983; Shi et al. 1995). The model of Richardson (1998) demonstrated that that the required source strength of OH radicals is at least an order of magnitude larger than can be supplied by sputtering. Possibly other supply mechanisms exist.

In 2005 July, the Cassini spacecraft instruments made the exciting discovery that Enceladus is actively venting both gas and grains (Porco et al, 2006; Waite et al, 2006; Spahn et al, 2006). In Fig1, it is seen that clear plume ejected from the Enceladus' south pole. The gas plume from the south pole of Enceladus has now been considered to be the main source of the neutral gas of mainly water composition and dust cloud of micron-sized icy grains in the magnetosphere between 3 and 10 radii. However, in spite of the small size of Enceladus, how the heat generated in the interior is still an open question.

During these Enceladus encounters in 2007, Dougherty et al. (2006) detected the disturbances in the local field using the Cassini magnetometer. This indicates the interaction of the magnetospheric plasma of Saturn with Enceladus' plume. Also, it is seen by the disturbance in the plasma flow (Tokar et al. 2006).

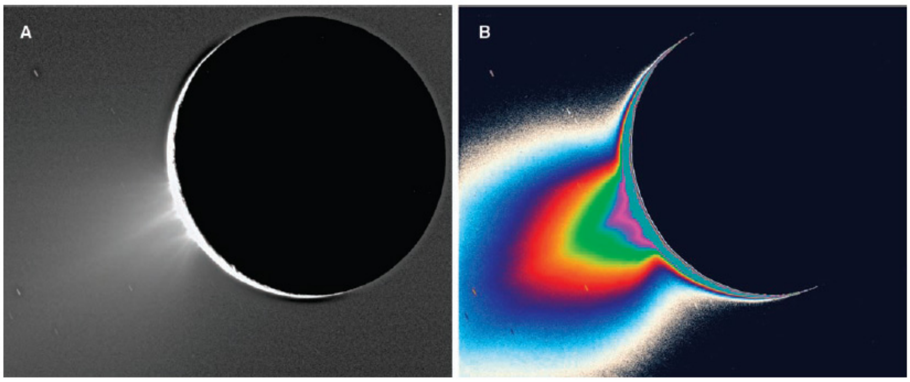

Figure 1: (A) ISS (Imaging Science Subsystem) images of Enceladus' plume. The south pole is pointing toward the lower left. (B) A color-coded version of (A). (Porco et al. 2006)

In this paper, we investigate the plasma interaction of Enceladus gas coma with Saturn's magnetosphere. We will develop a cometary-like interaction model to simulate the local interaction of the magnetospheric olasma with the expanding gas cloud from Enceladus. The ionizing and charge-exchange process will lead to the generation of ion cyclotron waves and plasma turbulence. Such wave-particle interaction might result in ion acceleration in the vicinity of Enceladus' orbit which signature might be seen in the Cassini instruments.

2. Model Descriptions

2.1 Neutral Atmosphere Model

Our neutral atmosphere model is based on the discovery of Ion and Neutral Mass Spectrometer (INMS) on the Cassini spacecraft. It investigated the composition and spatial distribution of gases in the Enceladus' plume (Waite et al. 2006). The atmospheric composition shows the primary constituents with H_2O (91%), CO_2 (3.2%), N_2 or CO (4%), and CH_4 (1.6%). It is shown in the average mass spectrum (Fig. 2). They also found that the radial density distribution was asymmetric in the inbound and outbound data (Fig. 3). To simplify our calculations, we assume the density distribution law as $\boldsymbol{N(r) = N0 * (1 / r^2)}$ with the distance from the center of Enceladus, *r*.

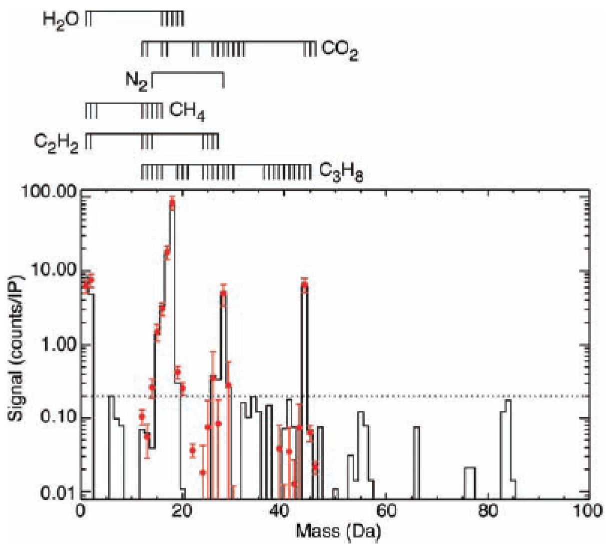

Figure 2: Average mass spectrum for altitudes below 500 km. (Waite et al. 2006)

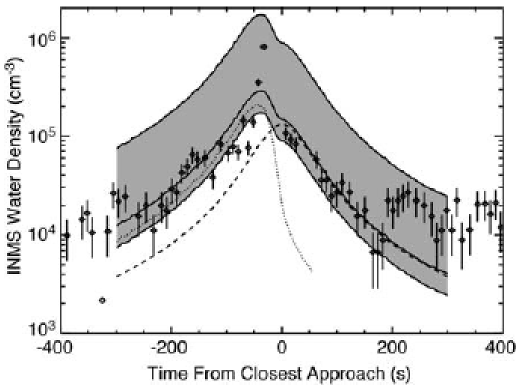

Figure 3: Comparison of model results to INMS density data near its closet approach to Encledus. The INMS-measured water densities show in the diamonds. (Waite et al. 2006)

2.2 MHD model: Plasma Environment

Using the Cassini Plasma Spectrometer (CAPS), Tokar et al. (2006) detected strong deflections in the corotation ion flow, starting at ~27 Enceladus radii from Enceladus. It is a result of the interaction of the magnetospheric corotation plasma with Enceladus' expanding gas coma. Because the slowed and deflected plasma flow extended more than 30 Enceladus radii from Enceladus, as shown in Fig. 4, and the neutral density distribution is that *N(r)* is proportional to *r*, we think it is a comet-like interaction model rather than Io-like. We adopt a 2D cometary plasma flow field model (Ip, 1989), which is based on 3D MHD simulations of Fedder et al.. Fig. 5 shows our plasma interaction model, the flow streamlines and the flow velocity near Encelaus at (0,0).

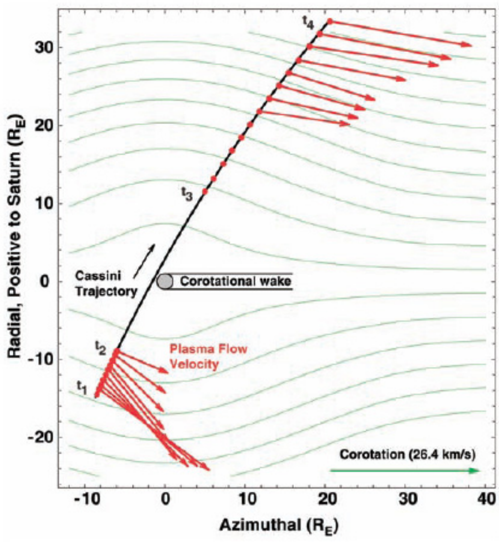

Figure 4: Plot of the Cassini trajectory and ion flow velocities obtained from CAPS. (Tokar et al. 2006)

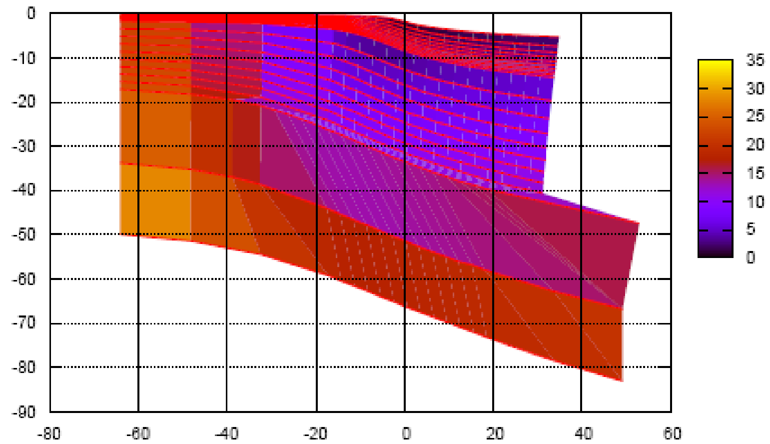

Figure 5: The plasma flow field near Enceladus. The corotation direction is toward to +X axis. X and Y axis are both in unit of Enceladus' radii. The flow velocities (km/s) show in color-scale.

2.3 Chemical Model and Test Particle Model

Our work is to study the chemical reations (e.g. photoionization and charge exchange processes) of Enceladus' gas coma in the plasma interaction field. We adopt a set of flow field models and then integrate the continuity equation,

$$\frac{1}{A}\frac{d}{ds}(njvjA) = qj - sj$$

for *j*th ion species. In above equation, *vj* is the flow velocity along the streamline, *nj* the number density, *qj* the production rate, *sj* the loss rate and A is the cross section of the streamline. To compute the *jth* production rate and loss rates, we have to include the effects of photoionization, electron impact ionization and charge exchange processes. Here we use the summary tables of chemical reactions in Sittler et al. (2005).

Table 1: Photoionization rates

Reaction	Enceladus-Dione	References
$H + h\nu \rightarrow H^+ + e$	8.0E-10	*Huebner and Giguere* [1980]
$H_2 + h\nu \rightarrow H^+ + H + e$	1.0E-10	*Huebner and Giguere* [1980]
$H_2O + h\nu \rightarrow H^+ + OH + e$	1.4E-10	*Huebner and Giguere* [1980]
$NH_3 + h\nu \rightarrow H^+ + NH_2 + e$	3.7E-11	*Huebner et al.* [1992]
$H_2 + h\nu \rightarrow H_2^+ + e$	5.9E-10	*Huebner and Giguere* [1980]
$H_2O + h\nu \rightarrow H_2O^+ + e$	3.7E-9	*Huebner and Giguere* [1980]
$O + h\nu \rightarrow O^+ + e$	2.3E-9	*Huebner and Giguere* [1980]
$H_2O + h\nu \rightarrow O^+ + H_2 + e$	6.4E-11	*Huebner and Giguere* [1980]
$O_2 + h\nu \rightarrow O^+ + O + e$	5.8E-10	*Huebner and Giguere* [1980]
$CO_2 + h\nu \rightarrow O^+ + CO + e$	2.8E-10	*Huebner et al.* [1992]
$O_2 + h\nu \rightarrow O_2^+ + e$	5.6E-9	*Huebner and Giguere* [1980]
$OH + h\nu \rightarrow OH^+ + e$	3.7E-9	*Huebner and Giguere* [1980]
$CO_2 + h\nu \rightarrow CO_2^+ + e$	2.6E-9	*Huebner et al.* [1992]
$CO_2 + h\nu \rightarrow CO^+ + O + e$	1.68E-10	*Huebner et al.* [1992]
$CO_2 + h\nu \rightarrow C^+ + O_2 + e$	1.2E-10	*Huebner et al.* [1992]
$NH_3 + h\nu \rightarrow NH_3^+ + e$	6.8E-9	*Huebner et al.* [1992]
$NH_3 + h\nu \rightarrow NH_2^+ + H + z$	1.96E-9	*Huebner et al.* [1992]
$NH_3 + h\nu \rightarrow NH^+ + H_2 + e$	7.66E-11	*Huebner et al.* [1992]
$NH_3 + h\nu \rightarrow N^+ + H_2 + H + e$	3.6E-11	*Huebner et al.* [1992]

Table 2. Charge exchange Rates in cm^3/s

Reaction	Enceladus	Dione	Reference
$H^+ + H \rightarrow H + H^+$	1.5E-8	1.5E-8	*Newman et al.* [1982]
$O^+ + H \rightarrow O + H^+$	6.2E-9	6.3E-9	*Stebbings and Rutherford* [1968]
$O^+ + OH \rightarrow O_2 + H^+$	1.2E-10	1.2E-10	*Giguere and Huebner* [1978]
$H^+ + H_2 \rightarrow H + H_2^+$	1.7E-10	1.7E-10	*Tawara* [1978]
$H_2^+ + H_2 \rightarrow H_2 + H_2^+$	6.6E-9	6.6E-9	*Massey and Gilbody* [1974]
$H^+ + H_2O \rightarrow H + H_2O^+$	5.0E-8	5.0E-8	*Tawara* [1978]
$H^+ + H_2O \rightarrow H + H_2O^+$	8.2e-9	8.2e-9	*Ip* [1997]
$O^+ + H_2O \rightarrow O + H_2O^+$	2.3E-9	2.3E-9	*Albritton* [1978]
$OH^+ + H_2O \rightarrow OH + H_2O^+$	1.6E-9	1.6E-9	*Huntress* [1977], *Kim et al.* [1975]
$OH^+ + H_2 \rightarrow H + H_2O^+$	1.1E-9	1.1E-9	*Huntress* [1977]
$H_2^+ + H_2O \rightarrow H_2 + H_2O^+$	3.9E-9	3.9E-9	*Huntress* [1977]
$OH^+ + OH \rightarrow H_2O^+ + O$	7.0e-10	7.0e-10	*Ip* [1997]
$H_2^+ + OH \rightarrow H_2O^+ + H$	7.6e-10	7.6e-10	*Ip* [1997]
$H^+ + O \rightarrow H + O^+$	5.5E-9	5.5E-9	*Stebbings et al.* [1964]
$O^+ + O \rightarrow O + O^+$	9.9E-9	9.9E-9	*Stebbings et al.* [1964]
$O_2^+ + O_2 \rightarrow O_2 + O_2^+$	6.4E-9	6.4E-9	*Banks and Kockarts* [1973]
$H_2^+ + O_2 \rightarrow H_2 + O_2^+$	9.4E-9	9.4E-9	*Tawara* [1978]
$O^+ + O_2 \rightarrow O + O_2^+$	2.1E-9	2.1E-9	*Albritton et al.* [1977]
$OH^+ + O_2 \rightarrow OH + O_2^+$	2.0E-10	2.0E-10	*Bortner et al.* [1972]
$H_2O^+ + O_2 \rightarrow H_2O + O_2^+$	5.0E-9	5.0E-9	*Fehsenfeld et al.* [1967]
$H^+ + O_2 \rightarrow H + O_2^+$	1.17E-9	1.17E-9	*Rudd et al.* [1985]
$O^+ + CO_2 \rightarrow CO + O_2^+$	1.1E-9	1.1E-9	*Giguere and Huebner* [1978]
$H^+ + OH \rightarrow H + OH^+$	3.0E-10	3.0E-10	*Giguere and Huebner* [1978]
$H^+ + OH \rightarrow H + OH^+$	2.1e-9	2.1e-9	*Ip* [1997]
$H_2^+ + O \rightarrow H + OH^+$	1.0E-9	1.0E-9	*Giguere and Huebner* [1978]
$O^+ + H_2 \rightarrow H + OH^+$	1.6E-9	1.6E-9	*Huntress* [1977], *Kim et al.* [1975]
$H_2^+ + OH \rightarrow OH^+ + H_2$	7.6e-10	7.6e-10	*Ip* [1997]
$O^+ + OH \rightarrow O + OH^+$	3.0E-10	3.0E-10	*Giguere and Huebner* [1978]
$O^+ + OH \rightarrow O + OH^+$	3.6e-10	3.6e-10	*Ip* [1997]
$O^+ + NH_3 \rightarrow NH_2 + OH^+$	2.2E-9	2.2E-9	*Huntress* [1977], *Oppenheimer* [1975][a]
$O^+ + CO_2 \rightarrow O + CO_2^+$	1.1E-10	1.1E-10	*Rudd et al.* [1985][a]
$H^+ + CO_2 \rightarrow H + CO_2^+$	1.1E-9	1.1E-9	*Rudd et al.* [1985]
$H^+ + NH_3 \rightarrow H + NH_3^+$	5.2E-9	5.2E-9	*Huntress* [1977]
$H_2^+ + NH_3 \rightarrow H_2 + NH_3^+$	5.7E-9	5.7E-9	*Huntress* [1977]
$OH^+ + NH_3 \rightarrow OH + NH_3^+$	1.2E-9	1.2E-9	*Huntress* [1977]
$H_2O^+ + NH_3 \rightarrow H_2O + NH_3^+$	2.2E-9	2.2E-9	*Huntress* [1977]
$H_2^+ + H_2O \rightarrow H_2 + H_3O^+$	3.4E-9	3.4E-9	*Huntress* [1977]
$OH^+ + H_2O \rightarrow O + H_3O^+$	1.3E-9	1.3E-9	*Huntress* [1977]
$H_2O^+ + H_2 \rightarrow H + H_3O^+$	6.1E-10	6.1E-10	*Huntress* [1977], *Kim et al.* [1975]
$H_2O^+ + H_2O \rightarrow OH + H_3O^+$	2.1E-9	2.1E-9	*Huntress* [1977]

[a]Estimated.

Table 3. Electron Impact ionization rates in cm^3/s

Reaction	Enceladus	Dione	References
$H + e \rightarrow H^+ + 2e$	1.3E-10	2.45E-9	*Lotz* [1967]
$H + e^a \rightarrow H^+ + 2e$	3.1E-8	3.1E-8	*Lotz* [1967]
$H_2 + e \rightarrow H^+ + H + 2e$	7.3E-14	3.3E-11	*Ip* [1997]
$H_2 + e^a \rightarrow H^+ + H + 2e$	1.01E-8	1.92E-8	*Ip* [1997]
$H_2O + e \rightarrow H^+ + OH + 2e$	1.66E-12	7.4E-11	*Orient and Srivastava* [1987]
$H_2O + e^a \rightarrow H^+ + OH + 2e$	4.06E-8	4.35E-8	*Orient and Srivastava* [1987]
$NH_3 + e \rightarrow H^+ + NH_2 + 2e$	2.58E-14	1.79E-12	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow H^+ + NH_2 + 2e$	5.28E-10	5.44E-10	*Mark et al.* [1977]
$H_2 + e \rightarrow H_2^+ + 2e$	2.26E-10	2.2E-9	*Kieffer* [1969]
$H_2 + e^a \rightarrow H_2^+ + 2e$	5.5E-8	5.5E-8	*Kieffer* [1969]
$NH_3 + e \rightarrow NH + H_2^+ + 2e$	1.35E-13	1.86E-12	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow NH + H_2^+ + 2e$	9.51E-11	9.63E-11	*Mark et al.* [1977]
$H_2O + e \rightarrow H_2O^+ + 2e$	8.6E-11	8.88E-10	*Orient and Srivastava* [1987]
$H_2O + e^a \rightarrow H_2O^+ + 2e$	9.32E-8	9.3E-8	*Orient and Srivastava* [1987]
$O + e \rightarrow O^+ + 2e$	2.01E-10	2.0E-9	*Lotz* [1967]
$O + e^a \rightarrow O^+ + 2e$	8.2E-8	8.2E-8	*Lotz* [1967]
$H_2O + e \rightarrow O^+ + OH + 2e$	1.26E-13	9.72E-12	*Orient and Srivastava* [1987]
$H_2O + e^a \rightarrow O^+ + OH + 2e$	1.06E-8	1.16E-8	*Orient and Srivastava* [1987]
$CO_2 + e \rightarrow O^+ + CO + 2e$	2.17E-12	7.4E-11	*Orient and Srivastava* [1987]
$CO_2 + e^a \rightarrow O^+ + CO + 2e$	1.22E-8	1.45E-8	*Orient and Srivastava* [1987]
$O_2 + e \rightarrow O_2^+ + 2e$	2.1E-10	1.98E-9	*Banks and Kockarts* [1973]
$O_2 + e^a \rightarrow O_2^+ + 2e$	1.5E-7	1.72E-7	*Banks and Kockarts* [1973]
$OH + e \rightarrow OH^+ + 2e$	3.7E-10	3.16E-9	*Richardson et al.* [1986]
$H_2O + e \rightarrow OH^+ + 2e$	1.7E-11	3.7E-10	*Orient and Srivastava* [1987]
$H_2O + e^a \rightarrow OH^+ + 2e$	4.61E-8	4.6E-8	*Orient and Srivastava* [1987]
$CO_2 + e \rightarrow CO_2^+ + 2e$	1.73E-10	2.36E-9	*Orient and Srivastava* [1987]
$CO_2 + e^a \rightarrow CO_2^+ + 2e$	1.63E-7	1.9E-7	*Orient and Srivastava* [1987]
$CO_2 + e \rightarrow CO^+ + 2e$	4.45E-12	7.05E-11	*Orient and Srivastava* [1987]
$CO_2 + e^a \rightarrow CO^+ + 2e$	6.04E-9	6.99E-9	*Orient and Srivastava* [1987]
$CO_2 + e \rightarrow C^+ + O_2 + 2e$	9.5E-14	5.92E-12	*Orient and Srivastava* [1987]
$CO_2 + e^a \rightarrow C^+ + O_2 + 2e$	3.33E-9	3.86E-9	*Orient and Srivastava* [1987]
$NH_3 + e \rightarrow NH_3^+ + 2e$	2.66E-10	2.03E-9	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow NH_3^+ + 2e$	5.23E-8	5.26E-8	*Mark et al.* [1977]
$NH_3 + e \rightarrow NH_2^+ + H + 2e$	3.85E-11	6.6E-10	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow NH_2^+ + H + 2e$	4.2E-8	4.32E-8	*Mark et al.* [1977]
$NH_3 + e \rightarrow NH^+ + H_2 + 2e$	1.71E-13	9.21E-12	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow NH^+ + H_2 + 2e$	1.49E-9	1.52E-9	*Mark et al.* [1977]
$NH_3 + e \rightarrow N^+ + H_2 + H + 2e$	1.33E-14	1.26E-12	*Mark et al.* [1977]
$NH_3 + e^a \rightarrow N^+ + H_2 + H + 2e$	5.44E-10	5.67E-10	*Mark et al.* [1977]

[a]Hot Electron Component.

2.4 Preliminary Results and Discussions

The new pickup ions and the fast neutrals generated by charge exchange process have long-ranging effects in the local and global structures and dynamics of the Saturnian magnetosphere. By using a simple flow model with a heritage from cometary study, we investigate the production of new water-group ions and fast neutral atoms and molecules in the vicinity of Enceladus. Some preliminary results will be reported here.

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