Proton-Oxygen Differences in Energization During Dipolarization in Saturn's Magnetotail: A Case Study of Cassini Observations

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Abstract

We examine the evolution of energy spectra of protons (H^+) and singly-charged oxygen ions (O^+) with energies greater than 1 keV during the course of a dipolarization event in the Saturn's magnetotail that occurred around 0200 UT on 2 July 2004. Observations made by Cassini/MIMI/CHEMS showed that the energy spectrum after the event was harder for O^+ than H^+ particularly at >50 keV. The >50 keV energetic O^+ dominated O^+ energy density, while the H^+ energy density was contributed from a wide energy range. The spectral characteristics indicate that O^+ were energized more effectively than H^+ during the dipolarization and that the energized O^+ made a significant contribution to plasma pressure. As this O^+ response to magnetic field reconfiguration is similar to that observed in the Earth's magnetotail, it is likely that effective and/or selective energization of heavy ions is universal to the magnetotails of magnetized planets.

Introduction

It is believed that radial transport with sharp, localized filamentary structures due to inter-change instabilities is the main transport process in the Saturn's inner magnetosphere [e.g., *Hill et al.*, 2005; *Paranicas et al.*, 2016; *Azari et al.*, 2018]. Global injections of energetic (non-thermal) particles with energies greater than 10 keV were also observed in the magnetotail, associated with large-scale reconfigurations of the magnetotail magnetic field probably caused by magnetic reconnection [c.f., *Mitchell et al.*, 2005, 2015]. The pressure of the non-thermal plasma becomes comparable to thermal pressure outside 9 Rs, where Rs is the Saturn's radius, and dominates over it outside 12 Rs [e.g., *Sergis et al.*, 2009, 2010]. The large-scale injections therefore play an important role in the plasma dynamics in the Saturn's magnetotail such as transport and acceleration. Observations made in-situ by Cassini showed different plasma characteristics between the two

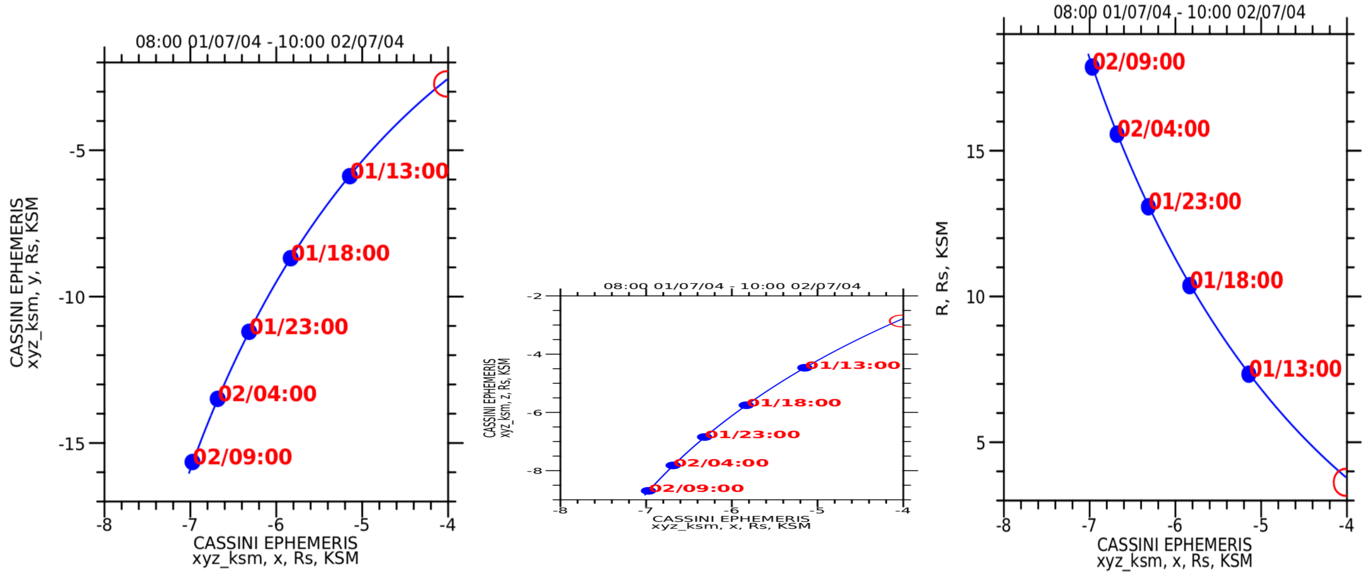

Figure 1: *Orbit of Cassini on (left) X-Y, (middle) X-Z, and (right) X-R planes in KSM coordinates, where R is the radial distance from the center of Saturn, from 0800 UT on 1 July 2004 to 1000 UT on 2 July 2004.*

major species, H^+ and O^+ (e.g., relatively higher temperature for O^+ than H^+) [e.g., *Dialynas et al.*, 2009]. Our study aims at understanding generation and transport of non-thermal H^+ and O^+ during the large-scale reconfiguration and associated injections. In this paper, we report H+ to O+ differences in energy spectra during the course of the magnetic field dipolarization that occurred on 2 July 2004.

Dataset and Results

Figure 1 shows the trajectory of Cassini during the injection event of interest (~0200 UT on 2 July 2004). Cassini was located on the post-midnight to dawn side near the magnetic equator, [X, Y, Z] ~ [-6, -12, -7] Rs in the Kronocentric Solar Magnetospheric (KSM) Coordinates.

We used energetic ion observations made by Charge Energy Mass Spectrometer (CHEMS) of the Magnetospheric Imaging Instrument (MIMI) on board Cassini [*Krimigis et al.*, 2004]. Figure 2 shows energy-time spectrograms of omni-directional fluxes for H^+ and singly-charged water-group ion, W^+ (O^+, OH^+, H_2O^+, and H_3O^+) on 1 and 2 July 2004. The energy ranges used in this study are ~3 to ~200 keV for H^+ and ~10 to ~200 keV for W^+. *DiFabio* [2012] reported that, for 96 keV W^+, the composition abundance is ~53% for O^+, ~22% for OH^+, ~22% for H_2O^+, and ~3% for H_3O^+. Observations of OI 1304Å emissions by the ultraviolet imaging spectrograph (UVIS) on board Cassini [*Melin et al.*, 2009] suggested that the spatial distribution of neutral oxygen in the magnetosphere is broader than that of OH. The broader distribution was reproduced by a simulation model [*Cassidy and Johnson*, 2010; *Smith et al.*, 2010].

As reported by *Achilleos et al.*

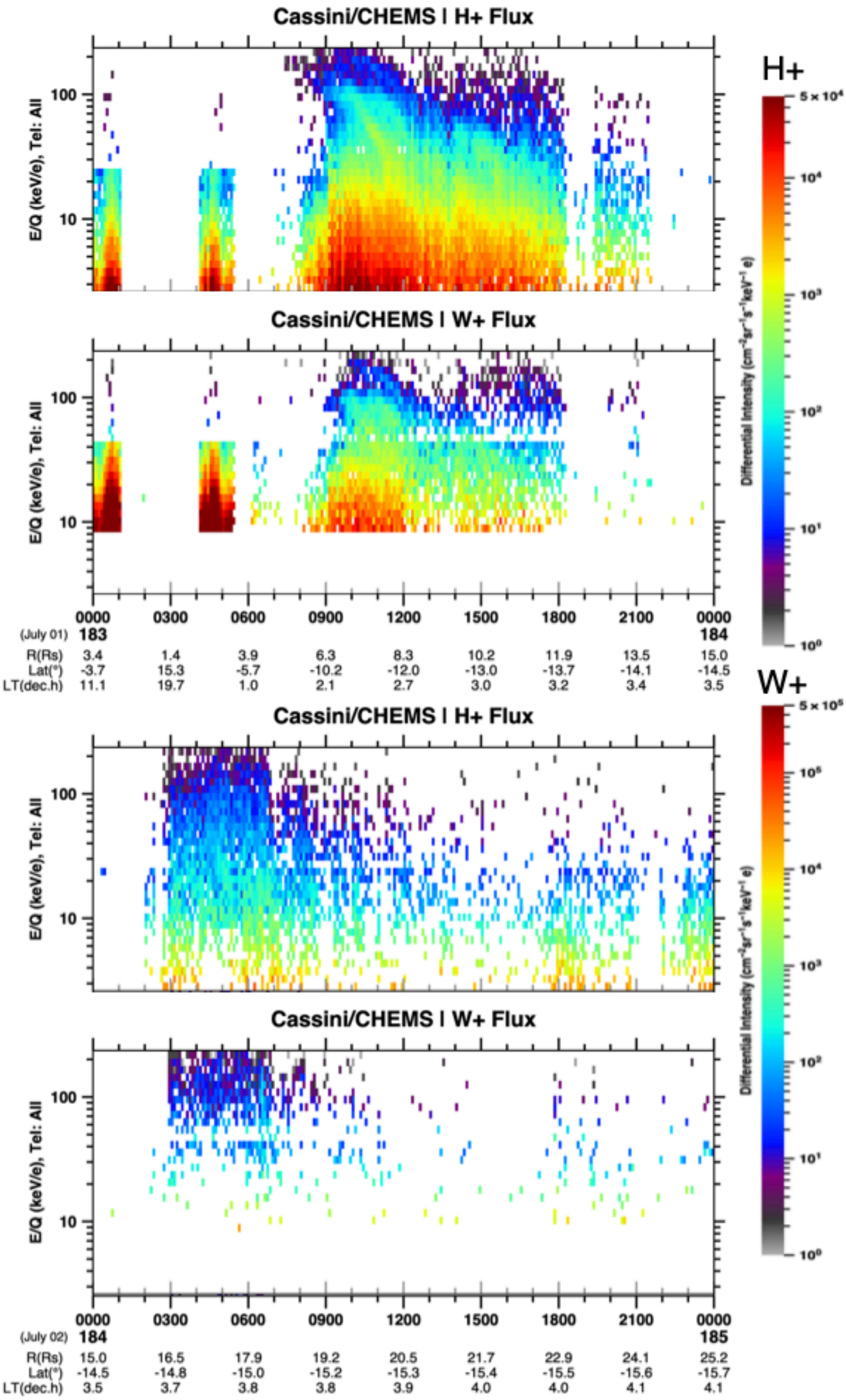

Figure 2: *Energy-time spectrograms of proton (H^+) and singly-charged water-group ion (W^+) omni-direcitonal fluxes for (bottom) 2 July 2014 and (bottom) 2 July 2014.*

[2015] and *Mitchell et al.* [2015], sudden enhancements of energetic ion and electron fluxes were observed at ~0200 UT on 2 July 2004, associated with a decrease in the Z component of the magnetic field. It is interpreted that the event occurred in response to a large-scale magnetic field dipolarization followed by injections of energetic particles.

We first compared energy spectra of the differential flux between before and after the injection event. For the pre- and post-event spectra, we used omni-directional differential flux data averaged over the periods of 0600-1200 UT on 1 July 2004 and 0300-0600 UT on 2 July 2004, respectively. The post-event energy spectra were harder than the pre-event ones for both H^+ and O^+. We then examined energy density contributed from each of the energy bins in order to determine energy ranges that make the significant contribution to total energy density, which we term "contributing energies". H^+ energy density was contributed from a wide energy range, 10-100 keV, while the contributing energies for O^+ were shifted toward higher energies, >50 keV, with the dominant contribution from 100 keV or higher.

Discussion

This case study showed clear differences in energy spectra of keV-range energetic ions between H^+ and O^+. The O^+ spectrum became harder than H^+ after a dipolarization event, although both spectra show a similar slope before the event. The contributing energies (i.e., energy ranges that make a significant contribution to total energy density) were higher for O^+ than H^+ after the event. The O^+ to H^+ differences indicate that O^+ is effectively or selectively energized during the magnetic field reconfiguration in the magnetotail.

We believe that kinetic motions of energetic ions during the reconfiguration play an important role in producing specie-dependent features of energy spectra. Important factors responsible for the kinetic effects are likely spatially localized and/or temporally impulsive electric field induced by the magnetic reconnection or associated fast flows and magnetic field pile-up in the near-planet magnetotail.

These spectral characteristics are similar to those observed in-situ and remotely (with observations of energetic neutral atoms) in the Earth's magnetotail [*Keika et al.*, 2013 and references therein]. *Keika et al.* [2018] reported that the contributing energies are higher for O^+ than H^+ in the outer part of the Earth's inner magnetosphere, that is, in the transition region between dipole-like and tail-like magnetic field configurations. The close similarity between Saturn and Earth suggests that effective or selective energization of heavy ions during the magnetic field reconfiguration is universal to the magnetotails of magnetized planets. The significance of the effective cooling due to the collisions with neutral gas needs to be further investigated.

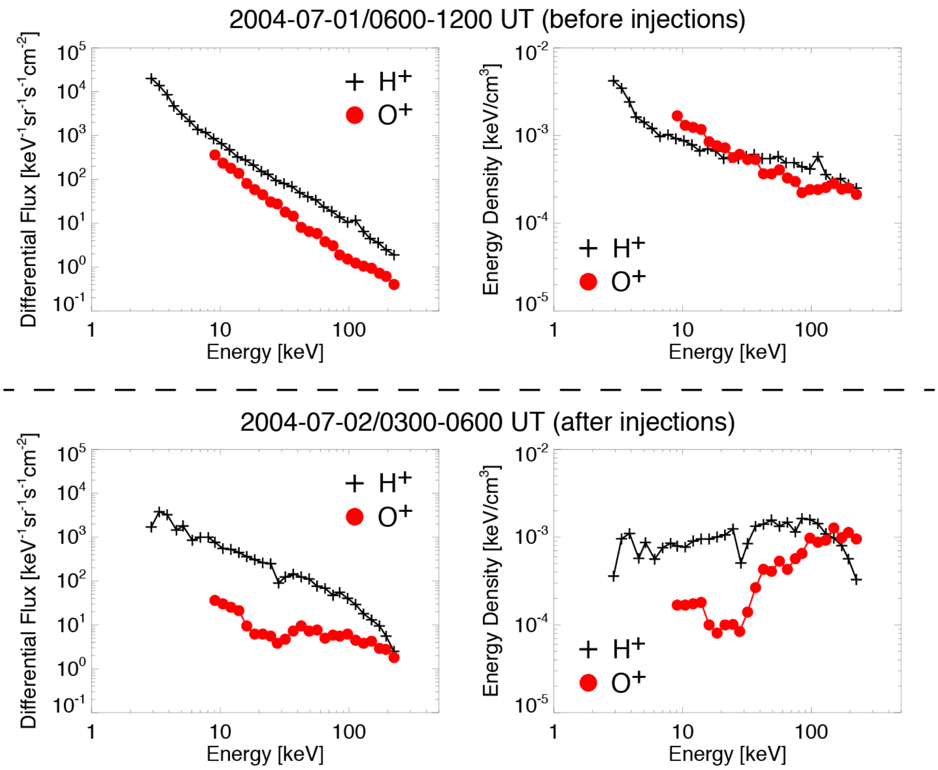

Figure 3: *The left panels are energy spectra of differential fluxes for protons (H^+) and oxygen ions (O^+, dominating over the other water-group ions) (top) before and (bottom) after the injection event on ~0200 UT on 2 July 2004. The right panels show energy spectra of energy density, indicating energy ranges that significantly contribute to ion pressure.*

Acknowledgments

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