A brief review of plasma transport and energization in the magnetosphere of magnetized planets

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Abstract

This paper provides a brief introduction of plasma transport and energization in the magnetospheres of magnetized planets, particularly Earth, Jupiter, and Saturn. Two compelling science questions are introduced: the relative abundance of solar wind-origin plasma and planet/moon-origin plasma, and the preferential energization of heavy ions of planet/moon atmospheric origin. Addressing the science questions will yield substantial clues in identifying how universal the underlying physical processes are in the magnetospheres and what determines diversity among different magnetized planets.

Introduction

The interaction of a planet with the solar wind is an important science topic that has been investigated with theory, modeling, and in-situ and remote-sensing observations. A large number of previous studies have advanced our understanding of the complex interaction such as the structure of boundaries between different plasma and field characteristics, the electromagnetic coupling between different regions, and plasma kinetic behaviors in the dynamic system. It is well known that the solar wind-magnetosphere interaction is primarily determined by the characteristics of atmosphere (neutral particles), the strength of the intrinsic magnetic field, and the planet rotation. This paper provides a brief introduction of science questions that can be addressed by future comparative studies of plasma transport and energization in the magnetospheres of magnetized planets.

Plasma transport in the Earth's magnetosphere on the meridional plane is initiated by the magnetic reconnection at the dayside magnetopause (**Figure 1**, top panel). The reconnected field lines, which contain solar wind plasma such as electrons, protons, and high-charge-state heavy ions, are convected anti-sunward and then accumulated in the magnetotail. The transported plasma are concentrated and heated to form the sheet-like region called the plasma sheet. The hot plasma is further transported toward Earth due to large-scale magnetospheric convection or small-scale, impulsive magnetic field reconfiguration, called dipolarization, triggered by magnetic reconnection in the plasma sheet. The reconnection results in plasma transport tailward as well (called a plasmoid). The earthward-transported plasma gain energy on the way to the inner magnetosphere to become the dominant contributor to enhanced plasma pressure in the inner magnetosphere. The hot plasma is eventually lost through the dayside magnetopause, into the ionosphere, or due to neutralization through charge-exchange collisions with cold hydrogen called geocorona. In addition to this transport and energization sequence, called the Dungey cycle [*Dungey*, 1961], plasma escaping from the upper atmosphere is transported predominantly along the field lines and then supplied to the plasma sheet and the inner magnetosphere. The supplied plasma is composed of electrons, protons, and low-charge-state heavy and molecular ions.

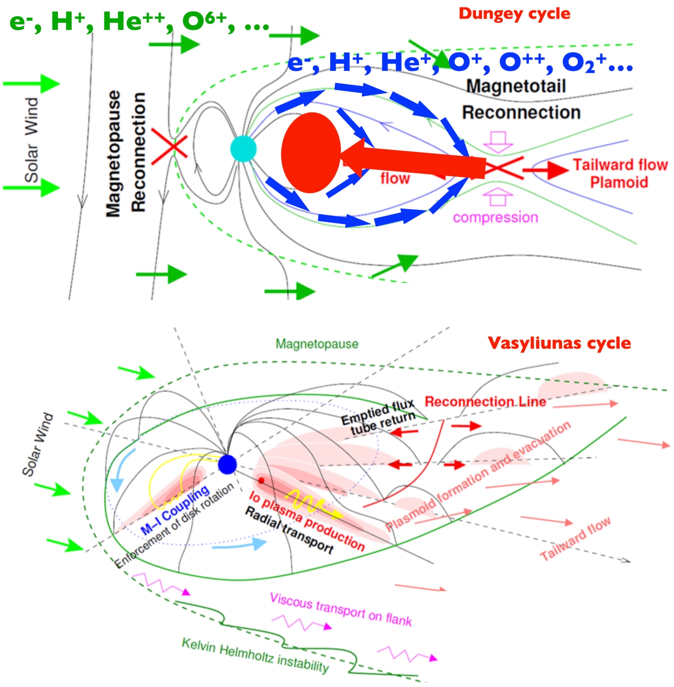

Figure 1: *Illustrations of plasma transport in (top) Earth's magnetosphere and (bottom) Jovian magnetosphere [Modified from Louarn et al., 2015].*

Plasma transport is predominantly determined by the planet rotation for the magnetosphere of fast rotating planets such as Jupiter and Saturn (**Figure 1**, bottom panel). Although the Dungey cycle occurs in the outer magnetosphere, the inner magnetosphere is governed by the fast rotation. The majority of plasma corotate with the planet, and the resultant centrifugal force acting on plasma plays an important role in the force balance and dynamics. The outward transport of the corotating plasma, primarily due to inter-change interactions,

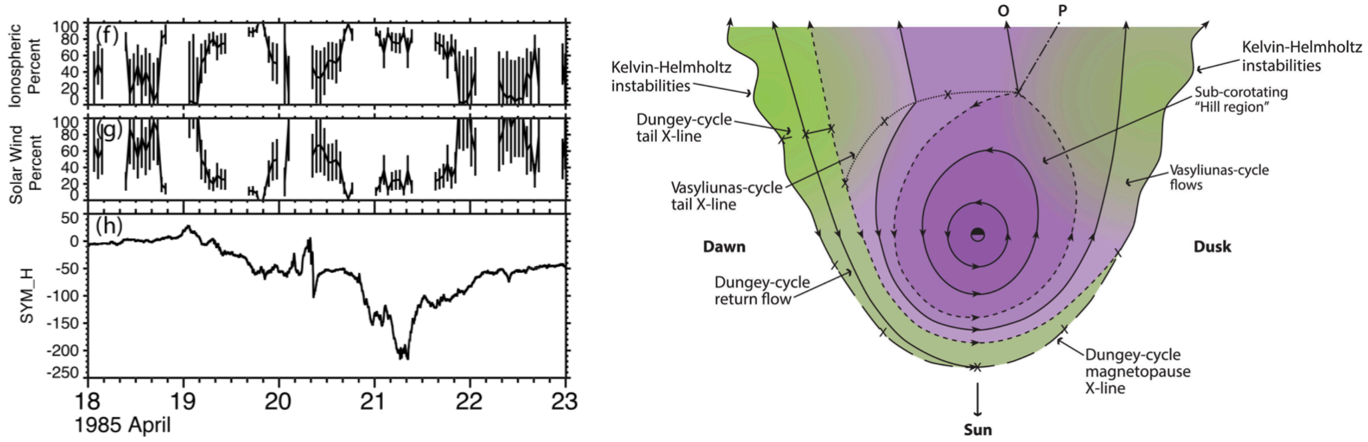

Figure 2: *(left) Temporal variations of the relative abundance of solar wind-origin and ionospheric plasma [modified from Lynn, 2020] in the Earth's magnetosphere. (Right) Illustration of the relative contribution from solar wind- and moon-origin plasma to the Saturn's magnetosphere [Allen et al., 2018].*

stretches the magnetic field lines to form the plasma sheet. The magnetic reconnection occurs in the plasma sheet, and the associated magnetic field reconfiguration transports the heated/accelerated plasma back to the inner magnetosphere. This rotation-driven plasma transport is called the Vasyliunas cycle [*Hill et al.*, 1974; *Vasyliunas*, 1983]. The magnetospheric plasma of Jupiter and Saturn predominantly originate from the upper atmosphere and the moons. Io of Jupiter and Enceladus of Saturn supply low-charge-state Sulfur ions and water-group ions, respectively.

Open science questions

One of the interesting topics in terms of plasma transport is the relative abundance of solar wind-origin plasma and planet/moon-origin plasma. As mentioned above, the transport in the Earth's magnetosphere is mainly driven by the solar wind, and that in the Jovian and Kronian magnetospheres is by the planet rotation. The composition abundance is accordingly determined; solar wind plasma is dominant in the Earth's magnetosphere, and the Jovian and Kronian magnetospheres are occupied mainly by plasma of planet/moon origin. However, it is also reported that the other origin can make a significant contribution to density and/or pressure. For example, *Kistler* [2020] observationally showed that ionospheric protons dominate over solar wind protons in the near-Earth magnetosphere during magnetic storms (**Figure 2**, left panel). *Allen et al.* [2018] performed a statistical study using Cassini data, suggesting that solar wind plasma penetrate deeper into the Kronian magnetosphere than previously expected, particularly in near-Saturn magnetotail (**Figure 2**, right panel). It remains an open question how the relative abundance and its spatio-temporal variations depend on the conditions of the solar wind and the ionosphere, and for Jupiter and Saturn, the internal activity of moons that supply a large amount of cold heavy ions.

Another unresolved issue is energization in the near-planet magnetotail and its dependence on ion species. It

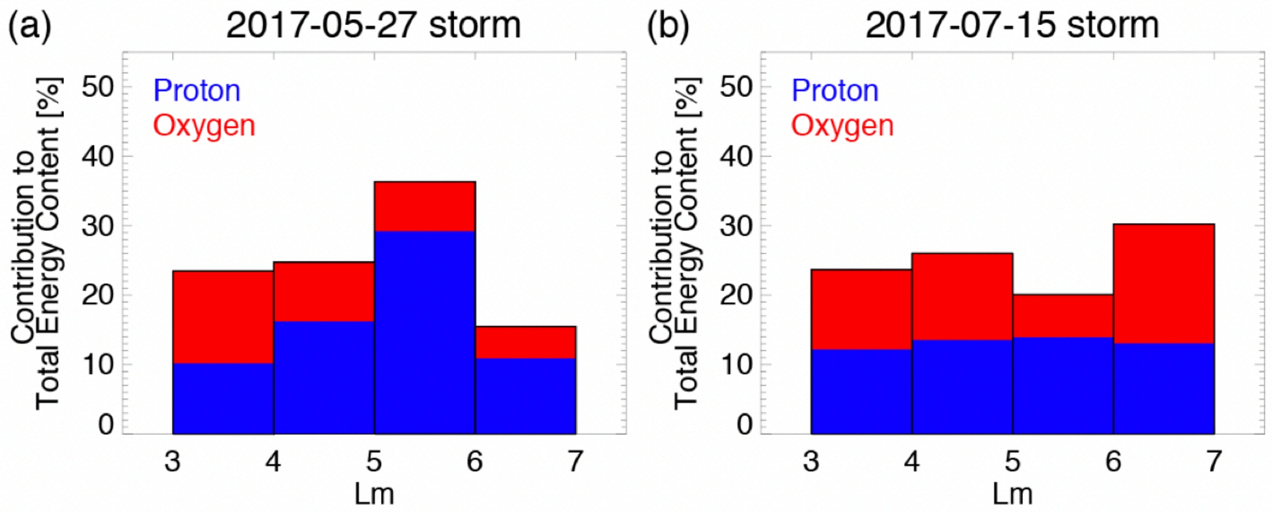

Figure 3: *Contribution from protons and oxygen ions to the total energy content stored in the inner magnetosphere, as a function of the McIlwain's L parameter [modified from Keika et al., 2019].*

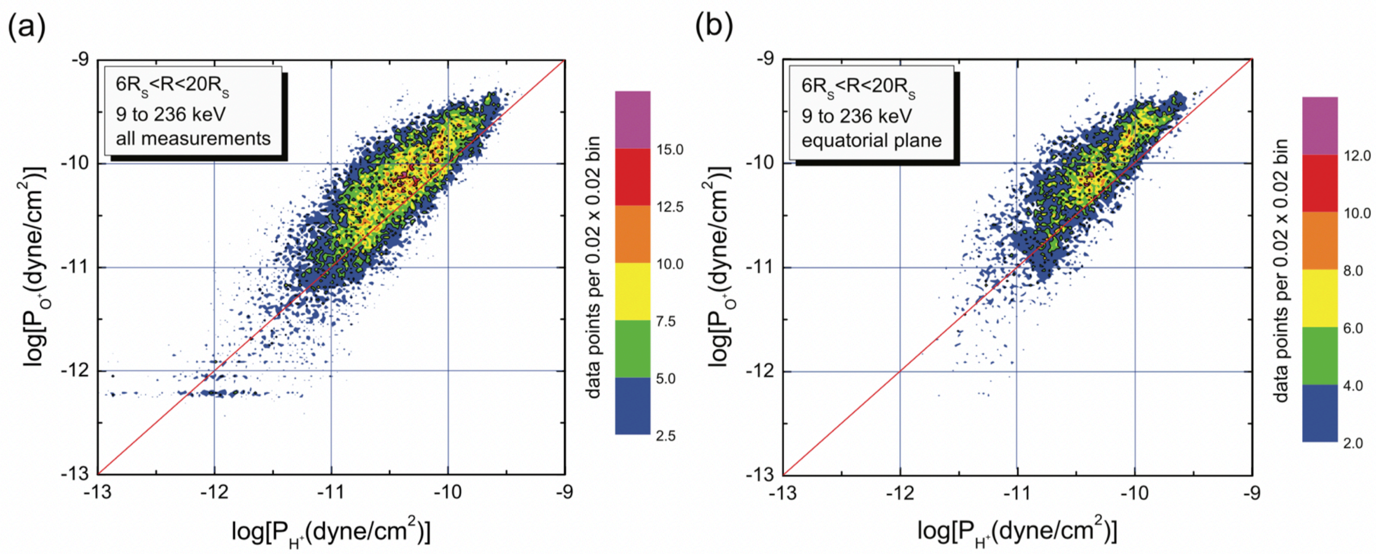

***Figure 4:** Relative significance of water-group heavy ion (mainly O+) pressure and proton pressure for (left) all events observed by Cassini and (right) events observed near the equatorial plane [Dialynas et al., 2009].*

is well known that, in the Earth's magnetosphere, singly-charged oxygen ions (O+) make a significant contribution to plasma pressure in the inner magnetosphere during magnetic storms [e.g., *Nosé et al.*, 2005; *Keika et al.*, 2013, 2019], in other words, when the total pressure increases. The O+ contribution can be comparable to the proton contribution (**Figure 3**). Plasma pressure in the Jovian magnetosphere is dominated by heavy ions such as sulfur and oxygen ions [e.g., *Mauk et al.*, 2004]. In the Kronian magnetosphere, pressure from water-group ions (e.g., O+, HO+) is comparable to that from protons [e.g., *Dialynas et al.*, 2009]. The water-group ion contribution increases as increasing total pressure (**Figure 4**). The pressure enhancements of heavy ions can be interpreted as a consequent of enhanced supply of heavy ions to the magnetosphere. However, the evolution of energy spectra suggest preferential energization of heavy ions in the near-planet magnetotail. Observations made by Arase showed that O+ is more energized than H+ in the near-Earth magnetotail (**Figure 5**, left panel) [*Keika et al.*, 2018]. In-situ ion observations made by Cassini indicated similar preferential energization of water-group ions after a dipolarization event (**Figure 5**, right panel) [*Keika et al.*, 2020].

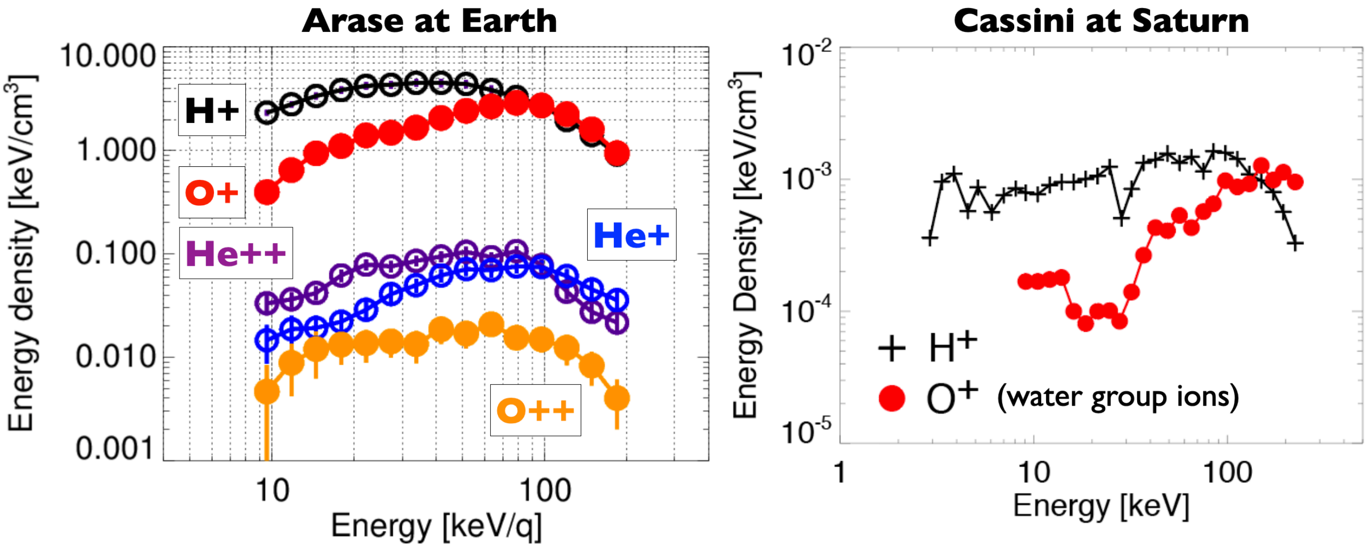

***Figure 5:** Comparison of energy spectra between different ion species. (left) Arase observations in the near-Earth magnetotail and (right) Cassini observations in the Kronian magnetotail [modified from Keika et al., 2019, 2020].*

Summary

It is yet to be identified how the relative abundance of solar wind and ionospheric/moon-origin plasma changes and how heavy ions of ionosphere/moon origin (mostly low-charge-state) are preferentially energized. These are compelling science questions particularly for comparative studies that are aimed at identifying what physical processes are universal and what determines diversity among planetary magnetospheres. These unresolved issues will be addressed by ongoing missions such as Arase for Earth and JUNO for Jupiter, and future in-situ measurements at Mercury by BepiColombo and comprehensive imaging by STORM (https://stormmission.com).

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