論文の内容の要旨

Dynamics in Jupiter’s inner magnetosphere revealed by EUV spectroscopic observations
（極端紫外域の分光観測から明らかにする木星の内部磁気圏におけるダイナミクス）

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Jupiter rotates with a period of ~10 hours and has the strongest intrinsic magnetic field in the solar system. Furthermore, the magnetic field and dynamic pressure of solar wind at Jupiter are weaker than they are at Earth. Therefore, plasma flow in Jupiter’s magnetosphere is predominantly in the direction of its rotation, confirmed up to the greatest distance covered by the Galileo spacecraft (~150 R_J [R_J: the radius of Jupiter]). In the inner magnetosphere of Jupiter (< ~10 R_J), the satellite Io orbits with a period of 42 hours and has active volcanoes that have been monitored via infrared observations with ground-based telescopes. Io’s atmosphere mainly contains sulfur dioxide and is sustained by a set of volcanic outgassing and sublimation. The sulfur dioxide is dissociated into sulfur and oxygen atoms via electron impact or photodissociation. The atoms which obtain sufficient energy to escape form a neutral cloud around Io. They are ionized by electron impact, charge exchange, or recombination and picked up by Jupiter’s magnetic field. The ions are then accelerated to a nearly corotational flow of ambient plasma and form a torus-like structure called the Io plasma torus (IPT). The plasma in the torus is transported outward in the radial direction by centrifugal force on a timescale of several tens of days. The ions are excited by electron impacts and emit radiation mainly in the ultraviolet (UV) wavelength range.

The electron environment in Jupiter’s magnetosphere was surveyed by past missions. An in-situ observation between 6 to 13 R_J was made by the Voyager spacecraft within an energy range of 10 to 5950 eV. The Galileo spacecraft provided further information between 6 to 8 R_J in an energy range of 0.9 to 5200 eV. These observations showed that the electron velocity distribution in the above region had a hot tail. There is a trend that at larger distances from Jupiter, there is a greater fraction of hot electrons to the total electron density. The Cassini spacecraft was able to detect temporal variation in the hot electron density. Cassini observed IPT radiation from several tens of days after a volcanic eruption on Io in 2000 and recorded a trend in which luminosity decreased with time. The Cassini observation indicated that temporal variation in the observed UV radiation can be reproduced assuming an increase in the density of hot electrons after the volcanic eruption in addition to an increase in the plasma supply rate to the IPT.

There is controversy over whether the hot electrons in the IPT are transported from outside the torus or generated locally in the torus. The interchange motion of magnetic flux tube and an Earth-like injection whose signatures were captured by the Galileo spacecraft have been proposed as candidate carriers of hot electrons from outside the torus. However, from the viewpoint of magnetohydrodynamics, it is difficult to transport plasma inward in the radial direction to the inner magnetosphere, where the intrinsic magnetic field is strong, and it has not been clarified whether inward transport contributes to the presence of the hot electrons in the IPT. Meanwhile, three possible mechanisms of heating inside the IPT have been proposed. The first is the interaction with Alfvén waves generated by the radial motion of the magnetic flux tubes. The other two, which are heating mechanisms near Io, are the interaction with Alfvén waves generated by Io's passage through Jupiter's magnetosphere or the interaction with ion cyclotron waves excited by pickup molecular ions. No conclusion has been reached as to which mechanism is the dominant reason for the temporal variation in the hot electron density. This is mainly because there has been no observation that includes a time series from a volcanic activation to a return to initial state. One of the purposes of this study is to explore the mechanism behind the temporal variation in the hot electron density.

By clarifying the mechanism of the temporal variation in the hot electron density, how plasma transport or heating changes occur during a volcanically active period can be understood; therefore, there is a possibility that the response of Jupiter's magnetospheric dynamics to volcanic activation can be explored. It can be expected that volcanic activation would cause the following changes in Jupiter's magnetospheric dynamics: (1) increases in the plasma density in the IPT; (2) enhanced mass loading; and (3) increases in the efficiency of radial transport due to increases in the magnetic flux tube content. The other purpose of this study is to validate this hypothesis on the response of Jupiter's magnetospheric dynamics to volcanic activation.

To clarify the temporal variation in the plasma density and temperature in the IPT associated with volcanic activation using the spectral data from the Hisaki satellite is an effective way to tackle the above topics. Hisaki has been observing IPT radiation intermittently from its launch at the end of 2013 to the present day. It has been performing imaging spectroscopy of planetary atmosphere/plasma in the extreme UV wavelength range from Earth orbit. Spectroscopic remote sensing is a powerful tool for deriving the density and temperature of plasma. The method of exploring the condition of plasma in emission regions using spectral data is called plasma diagnosis and has been used mainly in the fields of astronomy and nuclear fusion. In this study, the method was applied to data from Hisaki.

This study investigated the temporal variation in the density and temperature of plasma in the IPT associated with volcanic activation for the longest period to date. The periods of observation used in this study are December 2013 to April 2014, November 2014 to May 2015, and January 2016 to December 2016. From the observations of Io by ground-based telescopes, five volcanic events are indicated to occur before and during these periods. The temporal variation in radiation from the IPT showed that, of the five volcanic events, the one that occurred in 2015 had the greatest impact on the IPT. The findings of this study are described below.

The temporal variation in the hot electron density in the IPT was researched for the longest period. The dawn-dusk asymmetries of the hot electron density were found for the first time. After two volcanic events, including the one in 2015, the increases in the hot electron density were confirmed only on the dusk side. After two other volcanic events, the hot electron density increased on both the dusk and the dawn sides. After the other event, no increase was confirmed on either the dusk or the dawn side, though this might be due to the insufficiency of the observation period.

The temporal variation in the radial distribution of mass density in the IPT, whose radial gradient can be considered an indicator of the amount of plasma transported outward, was clarified in this study. As a result, in the period after the greatest volcanic event in 2015, the time taken from volcanic activation to a decrease in the mass density gradient was found to be ~30 days. In comparison, the time taken to increase the hot electron density on the dusk side was found to be ~40 days during the same period. This meant that it took approximately ten days from the increase in the amount of plasma transported outward, that is to say, from the enhancement of the radial motion of flux tubes, to increase the density of hot electrons. Based on the estimation that the growth time of the interchange instability is approximately one hour, local heating associated with the radial motion of the flux tubes was revealed not to be the dominant mechanism by which the hot electron density increased and its dawn-dusk asymmetry occurred during this specific period that involved the greatest volcanic event.

The dependence of the hot electron density on the Io phase angle was also investigated. It was clarified that when the hot electron density near Io increased, the hot electron density far from Io also increased. Moreover, it was revealed that the dawn-dusk asymmetries of the hot electron density occurred regardless of the location of Io. These results indicate that heating near Io is not the mechanism responsible for the increases in the hot electron density and the dawn-dusk asymmetries.

The local heating was revealed not to be the dominant mechanism responsible for the increase in the hot electron density and its dawn-dusk asymmetry for a period involving the greatest volcanic event, as indicated above. Therefore, it can be concluded that transport is the cause of the increase in the hot electron density after the greatest volcanic event. As for the periods involving other volcanic events, though they could not be fully verified due to data discontinuities, there is no contradiction in considering that the transport is responsible for the increase in the hot electron density. As the cause of the dawn-dusk asymmetry of the hot electron density, both loss and transport can be listed, and future direct observations would be useful to identify it.

As mentioned above, as for the period involving the greatest volcanic event, it was revealed that inward plasma transport developed after the increase in the plasma supply rate to the inner magnetosphere. This suggests that increased mass loading increased the efficiency of radial transport. Based on the lengths of the periods from the occurrence of volcanic eruptions to the increases in hot electron density, the timescale of plasma transport associated with volcanic activation was suggested to be 20–80 days.