Three-year of observations of Jupiter’s aurora and Io plasma torus variabilities by earth orbiting extreme-ultraviolet spectroscope HISAKI

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Abstract. Extreme Ultraviolet spectrograph, EXCEED, on-board the HISAKI satellite is designed for observing tenuous gas and plasma around planets in the solar system. It enables us to obtain continuous and long-term data set and find time variability in the planetary magnetosphere and ionosphere with time scales of several hours to months. Here, we introduce new findings of Jupiter’s UV aurora and plasma emissions from the Io plasma torus obtained from the HISAKI observation.

1. Overview of the HISAKI satellite
HISAKI was launched on 14 Sep. 2013 from the Japan Aerospace Exploration Agency’s (JAXA) Uchinoura Space Center. After the initial operation of the EUV spectrograph (extreme ultraviolet spectroscope for exospheric dynamics, EXCEED), regular operation of Jupiter observation began from Dec. 2013. One of the main purposes of the mission is observation of the Io plasma torus (IPT) and Jovian aurora to investigate energy transport in the rotation-dominated magnetosphere [1-4]. The spectral range covered by EXCEED is 55 to 145 nm. The typical spectral resolution with the 140-arcsec slit was about 0.6 nm and the spatial resolution was evaluated to be 17 arcsec. The orbital period of the satellite is about 106 minutes and the inclination is 31 degrees. While observation of the planet is interrupted during Earth’s eclipse of the planet and when the satellite passes over the South Atlantic Anomaly region, the data set still has enough continuity to find dynamical behaviour in the planetary magnetosphere and ionosphere. Detailed descriptions of scientific instruments are found in literatures [5-7]. Based on HISAKI’s monitoring capability, coordinated observation of HISAKI with Hubble Space Telescope (HST) [8], x-ray space telescopes (Chandra, XMM/Newton, and SUZAKU) [9], and many ground-based optical/radio facilities has been conducted.
2. **Hot plasma injection into the Io plasma torus**

Jupiter’s magnetosphere is known as a strong particle accelerator that contains ultra-relativistic electrons in its inner part. They are thought to be accelerated by whistler-mode waves excited by anisotropic hot electrons injected from the outer magnetosphere. In this context, electron transportation in the inner magnetosphere has key roles for transporting both free energy to excite the plasma wave and seed populations of the relativistic electron. However, it is still not well understood. From spectral diagnosis analysis, HISAKI show evidence for global inward transport of flux tubes containing hot plasma. High-spectral-resolution observations of the IPT enable us to obtain radial profiles of the hot electron density (figure 1). It gradually decreases with decreasing radial distance, despite the collisional time scale between hot and thermal ambient electrons is short and the hot electrons should lose their energy rapidly. This indicates a fast and continuous resupply of hot electrons responsible for keeping the hot electron population [10].

In addition to the global steady inward flow of the hot electron, simultaneous monitoring of the aurora and the IPT enables us to find definitive relationship between an explosive energy release in the magnetosphere which is manifested as an aurora transient and its connection to the inner magnetosphere. During a period from Dec. 2013 to Feb. 2014, nine pairs of brightenings of the aurora and IPT were found and showed the aurora preceded the IPT by 11.7 hours on average [11]. Physical mechanism responsible for this rapid response of the inner magnetosphere is an open question.

![Figure 1. Plasma parameters in IPT as a function of radial distance for dawn (left) and dusk (right). (top) thermal electron density [cc]. (bottom) hot electron density [cc]. The hot electron density increasing with radial distance on both portions is taken as evidence of energy transport into the IPT via centrifugally driven interchange motion.](image)

3. **The solar wind impact on the inner magnetosphere of Jupiter**

Because of significant rotationally-dominated plasma flow in Jupiter’s magnetosphere, solar wind influence on its inner-part has been thought to be negligible. HISAKI’s continuous observation enabled to find the solar wind influence on the inner magnetosphere for the first time. HISAKI found enhancements of the dusk/dawn brightness ratio of the IPT in response to rapid increase of the solar wind dynamic pressure (figure 2) [12]. The dawn-dusk asymmetry in the IPT has been reported from the Voyager observation and dawn-to-dusk electric field is one of the leading explanations. The HISAKI observation indicates that dawn-to-dusk electric field in the inner magnetosphere is modulated by the change of dynamic pressure of the solar wind and enhanced under compressed conditions.

4. **Jupiter’s aurora driven by internal magnetospheric process and the solar wind**

Jupiter’s auroral emissions reveal energy transport and dissipation through the planet’s giant magnetosphere and upper atmosphere. While the main auroral emission is internally driven by planetary rotation in the steady state, transient brightening is generally thought to be triggered by compression by the external solar wind. The HISAKI and HST campaign observation in Jan. 2014
provides the first evidence that short-lived transient brightening of aurora can be internally driven (Three arrows in figure 3) [8]. These aurorae appeared under the quiet solar wind condition and HST shows the intense emissions appearing from the polar cap down to latitudes around Io’s footprint, suggesting a rapid energy input into the polar region by the internal plasma circulation process. HST itself also obtained unique data set to study time variability in Jupiter’s auroral structure [13, 14]. New characteristic of auroral response to the solar wind is also found. The auroral total power increases when an enhanced solar wind dynamic pressure hits the magnetosphere and the auroral total power shows a positive correlation with the duration of a quiescent interval of the solar wind that is present before a rise in the dynamic pressure, more than with the amplitude of dynamic pressure increase [15].

Figure 2. (a) The IPT brightness ratio in the spectral range of 64-77 nm. Arrows present the timings when the ratio exceeds 2.5. (b) Dynamic pressure of the solar wind extrapolated from Earth. Grey areas show arrival timings of abrupt increases (>0.1 nPa) with the error of the arrival times. The arrows which fall within the temporal errors of solar wind events are presented in red color.

Figure 3. Total power of Jupiter’s northern EUV aurora and solar wind parameters from 21 Dec. 2013 to 30 Jan. 2014. (top) The auroral total power as a function of day 2014. Vertical black arrows indicate days when the sudden brightening occurred on 4, 11, and 14. The times when northern auroral images were taken by HST/STIS are indicated by green ticks. (bottom) Solar wind variations extrapolated from those observed at Earth to Jupiter. [8]

Wide spectral coverage of the EXCEED instrument enable to include H\textsubscript{2} Lyman and Werner band emissions in aurora spectra and provide us aurora electron energy and total emission power [16-17]. Auroral electron energy is estimated using a hydrocarbon color ratio and emission intensity in the long wavelength range (138.5–144.8nm) provides indicator for emission power and auroral electron energy flux. HISAKI provides auroral electron parameters and their relation under different auroral activity
levels. Relations between the auroral electron energy and flux estimated from the observation are distributed well along the theoretical field-aligned theory with a probable range of the magnetospheric parameters. Short- (within <1 rotation) and long-term (>1 rotation) enhancements of auroral intensity accompany increases of the electron number flux rather than the electron energy variations. The short- and long-term enhancements could be related to drivers of magnetospheric disturbances (internal and the solar wind, respectively. See also figure 3). Aurora power enhancements are mainly due to increased electron flux, not increase in electron energy, independent of drivers of aurora.

5. Plasma heating through satellite-planetary magnetic field interaction
Electromagnetic interaction between satellite and planetary magnetic field is a unique subject for Jupiter’s magnetosphere. HISAKI observation found ion brightness maxima just downstream of Io. Spectral analyses show that it is caused by the increase in the hot electron population downstream of Io and 140 GW of energy is efficiently converted to hot electron production in the IPT [18].

6. Summary and future direction
The HISAKI satellite completed three-year observations of solar system planets since Dec. 2013. Advantage of EUV spectroscopy and long-term monitoring provide us many new findings on global and dynamic features of Jovian magnetosphere and reveal mass and energy transport process in the magnetosphere. In addition, HISAKI is also a unique platform to sense exosphere and ionosphere of Venus, Mars, Mercury and Earth.

In the spring of 2015, enhancement of neutral sodium cloud around Jupiter is reported [22]. The cloud enhancement directly reflects increase in Io’s volcanic activity. Observation of IPT with HISAKI during this period also showed dramatic change in the sulfur and oxygen ion emissions and indicated significant plasma mass input to the inner magnetosphere. This is an unrepeatable chance to investigate response of mass and energy flows in the magnetosphere and aurora signature to the mass input. The studies are now on going. JAXA’s AKATSUKI and NASA’s JUNO spacecraft inserted orbits around Venus and Jupiter, respectively, and stated observation of atmosphere and magnetosphere of each planet. Collaboration between HISAKI and these orbiters must provide unique opportunities to investigate dynamic feature of upper atmosphere and magnetosphere of plants.

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