The Astrophysical Journal Letters, 872:L24 (5pp), 2019 February 20 https://doi.org/10.3847/2041-8213/ab0427

© 2019. The American Astronomical Society. All rights reserved.

Short-term Variation in the Dawn–Dusk Asymmetry of the Jovian Radiation Belt Obtained from GMRT and *Hisaki* EXCEED Observations

H. Kita[1], H. Misawa[2], A. Bhardwaj[3], F. Tsuchiya[2], G. Murakami[1], C. Tao[4], T. Kimura[5], K. Yoshioka[6], A. Yamazaki[1], Y. Kasaba[2], I. Yoshikawa[6], and M. Fujimoto[1,7]

[1] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 2525210, Japan; kita@stp.isas.jaxa.jp
[2] Planetary Plasma and Atmospheric Research Center, Tohoku University, Sendai, Miyagi 9808578, Japan
[3] Physical Research Laboratory, Ahmedabad 380009, India
[4] Space Environment Laboratory, National Institute of Information and Communications Technology, Koganei, Tokyo 1848795, Japan
[5] Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Miyagi 9808578, Japan
[6] Department of Complexity Science and Engineering, University of Tokyo, Kashiwa, Chiba 2778561, Japan
[7] Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo 1528550, Japan

Received 2018 December 17; revised 2019 January 29; accepted 2019 February 3; published 2019 February 19

Abstract

In order to reveal variations of days to weeks in the brightness distribution of Jovian Synchrotron Radiation (JSR), we made simultaneous radio and ultraviolet observations using the Giant Metrewave Radio Telescope (GMRT) and the *Hisaki* EXtreme ultraviolet spectrosCope for ExosphEric Dynamics (EXCEED). It is known from visible and ultraviolet observations that Io plasma torus (IPT) has dawn–dusk asymmetry, and that this asymmetry is believed to be due to the dawn-dusk electric field. Continuous ultraviolet observation by *Hisaki* reveals that dawn–dusk asymmetry of IPT changes in days to weeks, therefore, if this global electric field around Io's orbit (5.9 Jovian radii) could penetrate the radiation belt region (<2 Jovian radii), the variations in brightness distribution of JSR and IPT are expected to be correlated. The GMRT observations were made from 2013 December 31 to 2014 January 16 at 610 MHz and 2016 March 14–June 23 at 1390 MHz, while *Hisaki* continuously monitored IPT. The statistical analysis indicates that JSR and IPT do not have a significant correlation. Although these results do not support our hypothesis, we cannot rule out the possibility that the dawn-dusk electric field was masked by some other process, including the conductivity variation and/or the time-variable longitudinal asymmetry of JSR.

Key words: planets and satellites: individual (Jupiter) – radio continuum: planetary systems – ultraviolet: planetary systems

1. Introduction

The Jovian radiation belt is located in a strong intrinsic magnetic field region, and there are relativistic electrons ranging from a few hundred kilo-electron volts up to 50 mega-electron volts. Jovian synchrotron radiation (JSR) from these relativistic electrons has been used as a probe for remote sensing of the Jovian radiation belt (Berge 1966). Variations in the intensity of JSR over days to weeks have been investigated in many studies (e.g., Klein et al. 1972; Miyoshi et al. 1999; Misawa & Morioka 2000; Bolton et al. 2002; Bhardwaj et al. 2009; Tsuchiya et al. 2010, 2011; Kita et al. 2013, 2015). On the other hand, short-term variations in the brightness distribution were first reported by Santos-Costa et al. (2009), showing that the dawn-to-dusk peak emission ratio of the radio image changed on a timescale of a few days. Brice & McDonough (1973) predicted the solar ultraviolet (UV)/extreme ultraviolet (EUV) heating effect on the short-term variation in the brightness distribution of JSR. The diurnal wind system produces a difference in the dawn-dusk electric potential, and how this potential difference could produce a dusk-to-dawn electric field in the radiation belt. The dawn–dusk asymmetry would also change with the solar UV/EUV because the solar UV/EUV heating induces the diurnal wind system. However, the daily variations in the dawn-to-dusk ratio of JSR cannot be explained by only solar UV/EUV heating (Kita et al. 2013). Hence, Kita et al. (2013) proposed the following hypothesis for the daily variations in the dawn–dusk asymmetry of JSR. The Io plasma torus (IPT) exhibits dawn–dusk asymmetry in its brightness distribution as well, which can be explained by a dawn-to-dusk electric field in the Jovian inner magnetosphere (Barbosa & Kivelson 1983; Ip & Goertz 1983; Goertz & Ip 1984). As the dawn-to-dusk electric field shifts the drift orbit of the energetic electrons around Jupiter, the electron energy exhibits a dawn–dusk asymmetry; i.e., electrons accelerate at the dusk side and decelerate at the dawn side, which would cause the dawn–dusk asymmetry of JSR.

The generation mechanism for the dawn-dusk electric field is proposed as follows (Goertz & Ip 1984). The plasma disk is compressed in the noon side and is expanded tailward by the solar wind in the night side. The azimuthal current flowing in the plasma disk is also distorted, causing day–night asymmetry. The azimuthal current flowing along the edge of the plasma disk is closed by a field-aligned current from the dawn-side plasma disk and through the ionosphere to the dusk side. The dawn-to-dusk Pedersen current generates a dawn-to-dusk electric field in the ionosphere, and this electric field is also projected into the magnetosphere. The dawn-to-dusk electric field can change the drift orbit of electrons in both the radiation belt and IPT. Therefore, the electron energy may change adiabatically. The dawn-to-dusk electric field in Io's orbit is expected to be several $\mathrm{mV\,m^{-1}}$ (Schneider & Trauger 1995; Smyth et al. 2011). Because day–night asymmetry of the azimuthal current is caused by solar wind compression, the strength of the field-aligned current is expected to vary with the solar wind dynamic pressure. Long-term monitoring of IPT from Earth-orbiting satellite *Hisaki* EXtreme ultraviolet spectrosCope for ExosphEric Dynamics (EXCEED) showed that the dusk-to-dawn brightness ratio of IPT enhanced near the rise of the solar wind dynamic pressure (Murakami et al. 2016). Han et al. (2018) also showed that the dawn-dusk electric field could drive the radial diffusion of the energetic electrons, which is one of the candidates to explain yearly variation in the total flux density of JSR. If such a large-scale electric field also affects the inner radiation belt region (L value is less than 2), then it would tend to cancel out the reverse dusk-dawn asymmetry from diurnal winds, and thus a correlation between the two parameters could appear (Kita et al. 2013). However, there has been no observational evidence to evaluate this hypothesis.

In this study, we investigate the hypothesis that the dawn–dusk asymmetry of JSR and IPT vary in the same trend, in order to reveal short-term variations in the spatial distribution of the Jovian radiation belt. We made coordinated observations using a radio interferometer (Giant Metrewave Radio Telescope (GMRT)) and an EUV spectroscopy satellite (*Hisaki* EXCEED). From the radio interferometer observations, we measured the dusk-to-dawn peak emission ratio of JSR. From the UV spectroscopic observations, we measured the dusk-to-dawn emission ratio of IPT, which was used as a proxy for the dawn-to-dusk electric field. As the dawn-to-dusk electric field is expected to change with the dynamic pressure of the solar wind, we also compared a solar wind dynamic pressure model with the dusk-to-dawn ratio of JSR and IPT.

2. GMRT—*Hisaki* EXCEED Observation Campaign

2.1. Radio Observations and Analysis of Jupiter's Radiation Belt

The GMRT observations were conducted in 2014 at 610 MHz and in 2016 at 1390 MHz. Peak electron energies corresponding to these frequencies are 10 and 16 MeV around 1.5 Rj, where JSR is the most intense. The observation time was 2 hr per day, including flux and phase calibrations. The radio observations are summarized in Figure 1. We observed JSR at two central meridian longitudes (CMLs), 0°–160° and 210°–360°, which roughly correspond to the local peak of JSR total flux (Klein et al. 1989). The black bars indicate each of Jupiter's scans.

The observed data were calibrated, flagged, and imaged using the National Radio Astronomy Observatory Astronomical Image Processing System. We produced reconstructed radio images for each scan and adjusted all synthesized beams to 24.26 arcsec and 10 arcsec for 2014 and 2016, respectively. Because the Jovian magnetic axis is tilted from the rotational axis, the apparent dusk-to-dawn ratio modulates at ~10 hr with respect to the CML. We applied the reference cubic sine function to remove this longitudinal dependence of the dusk-to-dawn ratio, as the same procedure as Kita et al. (2013). The reference cubic function is different for 2014 and 2016, because the longitudinal dependence varies from frequency and spatial resolution.

2.2. UV Observations and Analysis of IPT

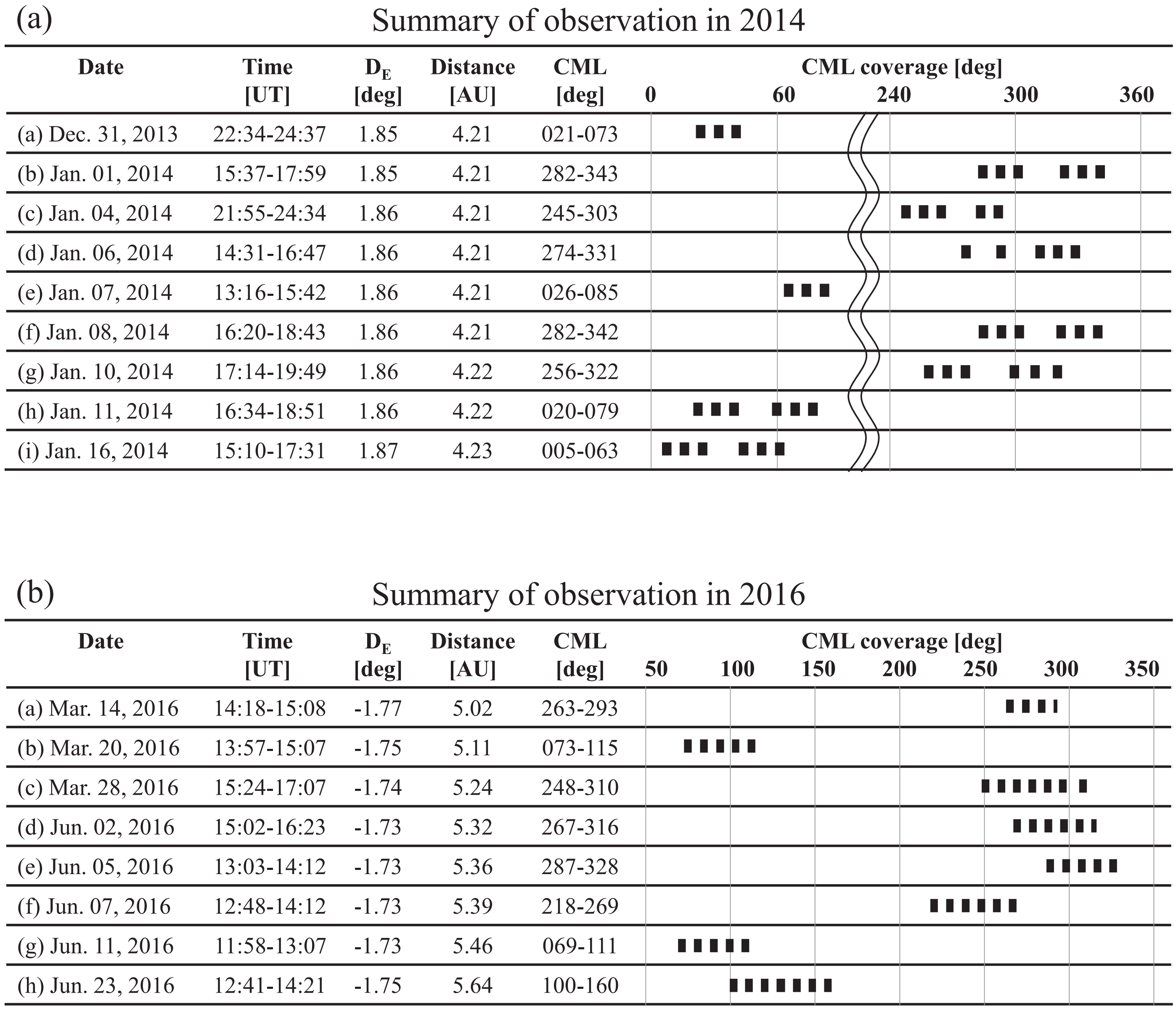
The *Hisaki* satellite is an Earth-orbiting EUV spectroscope, and one of the purposes of this mission is to observe UV emissions from the Jovian aurora and IPT. Its detectable wavelength ranges from 55 to 145 nm, and its spatial resolution is 17 arcsec (Yoshioka et al. 2013; Yamazaki et al. 2014; Yoshikawa et al. 2014). *Hisaki* EXCEED continuously monitored Jupiter using a 140 arcsec "dumbbell"-like shape slit, which is designed to observe IPT and the aurora simultaneously.

We used the *Hisaki* EXCEED L2 data, a 1 minute time resolution of the spectrograph image in the FITS format. We averaged all of the sulfur lines within 70.5 ± 6.5 nm, integrated for ~50 minutes, spatially averaged them over ~1 Rj around 5.9Rj, and derived the intensity ratio between the dawn and dusk area. This wavelength range covers multiple sulfur lines of S II (76.5 nm), S III (68.0, 70.2 and 72.9 nm), and S IV (65.7 and 74.9 nm), which is the same as Murakami et al. (2016). The dusk-to-dawn intensity ratio exhibits longitudinal variations due to the Jovian rotation and the Io phase. As we are interested in the days-to-weeks variation in the dusk-to-dawn ratio, we smoothed the data by averaging over 2 days in order to reduce the modulation of Io's orbital period (Tsuchiya et al. 2015).

3. Results and Discussions

The variations in the dawn–dusk asymmetry of JSR and IPT are shown in Figure 2. The top panel shows the dusk-to-dawn intensity ratio of IPT. The large points with a solid line indicate the smoothed profile of the original data. The second panel shows the dusk-to-dawn ratio of JSR. Each symbol indicates CML range (CML1: 0°–160°, CML2: 210°–360°). The smoothed profile of the dusk-dawn ratio of IPT is overplotted. The third panel shows the solar EUV variation obtained from the solar EUV monitor (SEM) on board the *Solar and Heliospheric Observatory* (*SOHO*) satellite. The *SOHO*-SEM observed the integrated flux over wavelengths ranging from 0.1 to 50 nm. We shifted the solar UV/EUV flux by about 2–5 days, taking into account the equatorial rotation period of the Sun and Sun–Earth–Jupiter angle (Miyoshi et al. 1999). We excluded the data observed on 2014 January 8–9, because the solar energetic particle penetrated the SEM housing and the particle-related signals were observed. The bottom panel shows the solar wind dynamic pressure around Jupiter, which is estimated by propagation of solar wind variation observed around Earth using a 1D MagnetoHydroDynamic (MHD) model (Tao et al. 2005) (Figure 2(a)) and Juno solar wind measurement (Wilson et al. 2018; Figure 2(b)). The ambiguity of the arrival time of solar wind shock in Figure 2(a) during this period was approximately ±20 hr. The dusk-to-dawn ratio of IPT was larger than one on average, which was also reported in previous observations (Murakami et al. 2016). On the other hand, the dusk-to-dawn ratio of JSR was less than one on average; i.e., the dawn side was brighter than the dusk side. The reversed dawn–dusk asymmetry can be explained by the different source of the electric field. The averaged dawn–dusk asymmetry of IPT is caused by the dawn-to-dusk electric field, which is thought to be generated by the field-aligned current system around the auroral latitude (Khurana 2001; Murakami et al. 2016), while the dynamo electric field generated by the diurnal wind system at mid-low latitude is dominant in the radiation belt region (Kita et al. 2013). The magnetic footprint of the radiation belt is lower in latitude than the Io footprint, therefore, the dawn–dusk asymmetry in JSR is strongly affected by the diurnal wind system, and that of IPT is affected by the field-aligned current system.

The time series of the dawn-to-dusk ratios of IPT and JSR indicated that they sometimes varied in the same trend. For example, at first glance, both dusk-dawn ratios around DOY 150–165 in 2016 varied in the same trend. The energy dependence would be one of the possible reasons for the difference between 2014 and 2016. Because the energetic electrons drift slower than the corotation and they spent more



(a) Summary of observation in 2014

Date	Time [UT]	D_E [deg]	Distance [AU]	CML [deg]
(a) Dec. 31, 2013	22:34-24:37	1.85	4.21	021-073
(b) Jan. 01, 2014	15:37-17:59	1.85	4.21	282-343
(c) Jan. 04, 2014	21:55-24:34	1.86	4.21	245-303
(d) Jan. 06, 2014	14:31-16:47	1.86	4.21	274-331
(e) Jan. 07, 2014	13:16-15:42	1.86	4.21	026-085
(f) Jan. 08, 2014	16:20-18:43	1.86	4.21	282-342
(g) Jan. 10, 2014	17:14-19:49	1.86	4.22	256-322
(h) Jan. 11, 2014	16:34-18:51	1.86	4.22	020-079
(i) Jan. 16, 2014	15:10-17:31	1.87	4.23	005-063

(b) Summary of observation in 2016

Date	Time [UT]	D_E [deg]	Distance [AU]	CML [deg]
(a) Mar. 14, 2016	14:18-15:08	-1.77	5.02	263-293
(b) Mar. 20, 2016	13:57-15:07	-1.75	5.11	073-115
(c) Mar. 28, 2016	15:24-17:07	-1.74	5.24	248-310
(d) Jun. 02, 2016	15:02-16:23	-1.73	5.32	267-316
(e) Jun. 05, 2016	13:03-14:12	-1.73	5.36	287-328
(f) Jun. 07, 2016	12:48-14:12	-1.73	5.39	218-269
(g) Jun. 11, 2016	11:58-13:07	-1.73	5.46	069-111
(h) Jun. 23, 2016	12:41-14:21	-1.75	5.64	100-160

Figure 1. Radio observation time coverage and geometries (D_E (Jovicentric decl. of the Earth), the distance between the Earth and Jupiter, and CMLs) over observation sequence on each day in (a) 2014 and (b) 2016. The black bars represent the CML observational range for 0°–160° and 200°–360°.

time in the inflow/outflow sectors, the drift orbit of higher-energy electron displaces more than that of the lower energy electron. However, statistical analysis indicated that the IPT and JSR did not have a strong positive correlation as expected from the hypothesis. Figure 3 indicates the scatter plot of the dusk-to-dawn ratio of JSR and IPT. Spearman's rank correlation coefficient is −0.22 for 2014 and 0.048 for 2016. A correlation t-test at 10% significance level shows that JSR and IPT are regarded as having no correlation. The correlation between JSR and the solar wind dynamic pressure is not significant either. The energetic electrons drift slower than the corotation, which means that they may take longer to organize over all longitudes when a change in the dawn-dusk electric field occurs. The rotation period (corotation + magnetic gradient drift) of 10 MeV and 16 MeV electron are ~10.5 hr and ~11.0 hr at 1.5 *Rj*, respectively. In this study, response delays can be negligible comparing to the observation cadence. We do not consider any time lag between IPT and JSR, because the dawn-dusk electric field affects JSR and IPT at the same time. Hence, the short-term variation in the dawn-dusk asymmetry of JSR cannot be explained only by the dawn-dusk electric field.

Although these results did not support our hypothesis, we cannot rule out the possibility that the dawn-dusk electric field was masked by some other processes that could control the short-term variations in the dawn-to-dusk ratio of JSR. Here, we discuss the possible causalities of why the correlation is weak. Because the ionospheric potential difference induced by the field-aligned current depends on the ionospheric conductivities, the solar UV/EUV effect might appear in the dawn–dusk asymmetries of JSR. The stronger the solar UV/EUV, the weaker the dawn-dusk electric field because of higher conductivity. The third panel of Figure 2 indicates the solar UV/EUV. We cannot find a strong correlation between both dusk-to-dawn ratios and the solar UV/EUV; however, the conductivity variation should be taken into account. Because

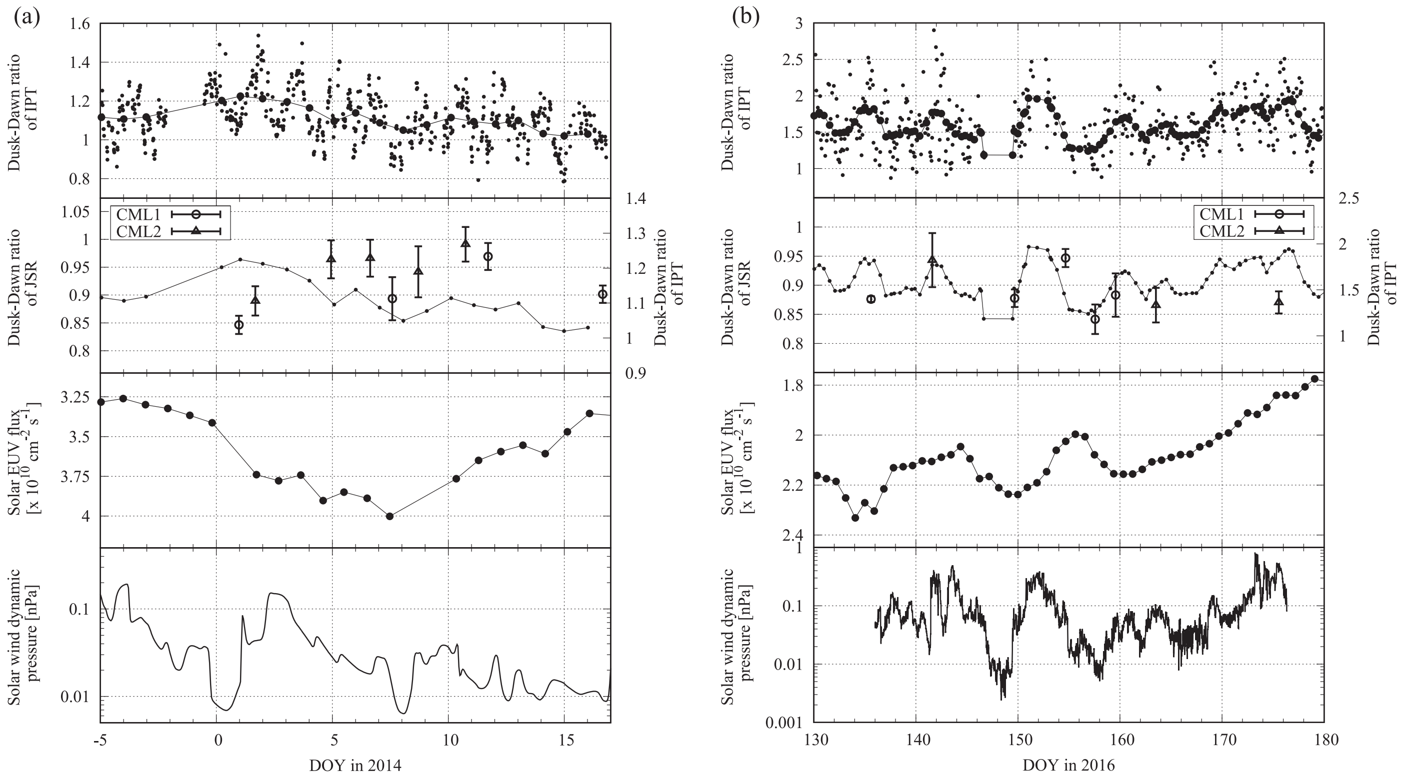


Figure 2. Comparison results of the dawn–dusk asymmetry of IPT and JSR for (a) 2014 and (b) 2016. The top panels show the dusk-to-dawn ratio of IPT. The large points with solid lines are smoothed profiles of the dusk-to-dawn ratio of IPT. The second panels show the dusk-to-dawn ratio of JSR. The open circles and triangles indicate the observed longitude of CML1 (0°–160°) and CML2 (200°–360°), respectively. The smoothed profile of the dusk-dawn ratio of IPT is overplotted. The third panels are solar UV/EUV flux observed by *SOHO*-SEM. The bottom panels show the solar wind dynamic pressure around Jupiter (a) estimated from a 1D MHD model (Tao et al. 2005) and (b) in situ measurement by Juno (Wilson et al. 2018).

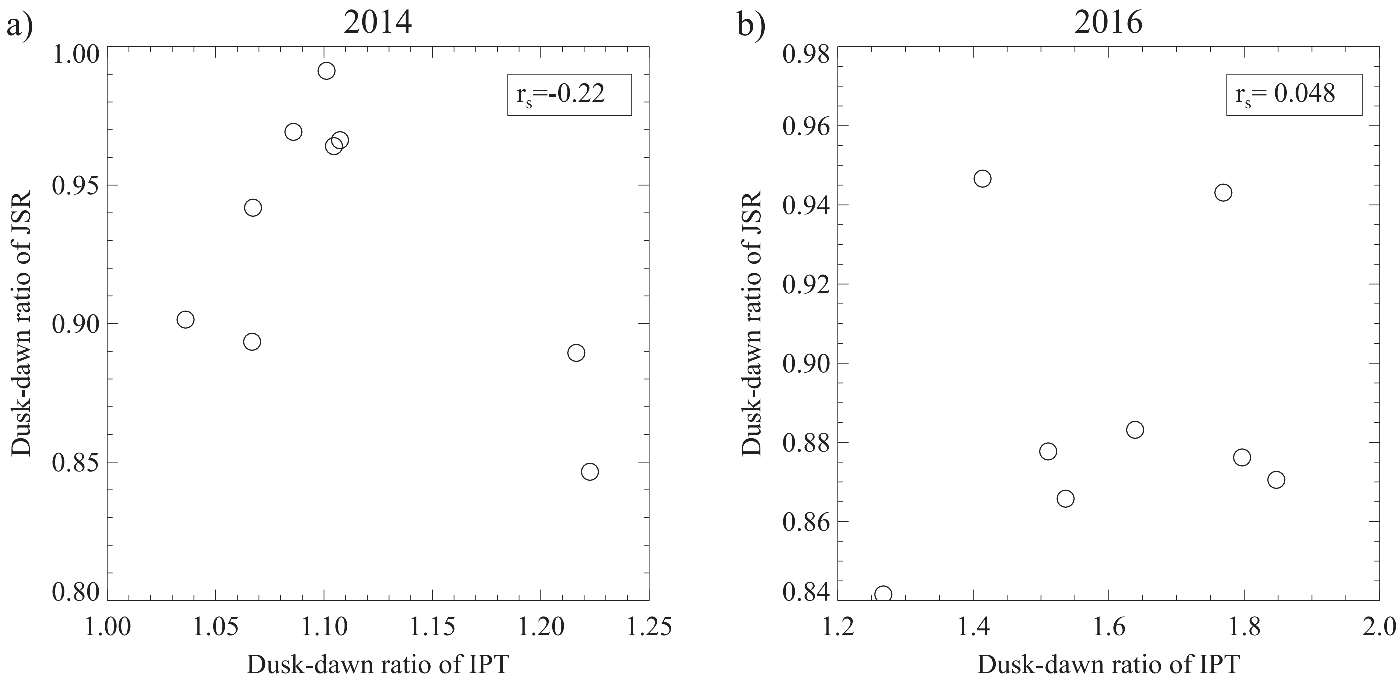


Figure 3. Scatter plot of the dusk-dawn ratio of IPT and JSR for 2014 and 2016. r_s indicates Spearman's correlation coefficient.

the ionospheric potential difference is the source of the electric field, the ionospheric potential map should also be taken into consideration. Dawn-dusk electric field is mapped from the ionospheric potential difference induced by the field-aligned current. As the potential difference becomes smaller at the lower latitude, the effect of the dawn-dusk electric field would be smaller in the innermost magnetosphere. The study with an ionospheric potential solver (e.g., Nakamizo et al. 2012) for Jovian ionosphere would give us a clue to estimate these effects quantitatively.

Another possible causality is longitudinal asymmetry. Figure 5 of Santos-Costa et al. (2014) shows that equatorial emissivity of JSR has several hot spots. *P*-band data is more asymmetric than *L*-band data, and it could change over time. Such a hotspot effect can be reduced by fitting a cubic sine function to the data for a whole Jovian rotation, however, the CML range is restricted in this study. This effect will lead to an apparent variation in the dusk-to-dawn ratio of JSR. For example, if we observed the JSR when the hotspot located on the dusk side and it somehow disappeared in the next observation, the dusk-dawn ratio of JSR seemed to decrease. In order to solve this problem, we have to observe Jupiter for 10 hr, if the hotspot is steady over 10 hr. More continuous observations with longer duration are essential to confirm the effect of the dawn-dusk electric field and find other causalities of the short-term variation in the dawn-dusk asymmetry of JSR. Previously observed data is effective to confirm these scenarios, and the solar wind dynamic pressure could be used as an index of the dawn-dusk electric field if the observation of the dawn–dusk asymmetry of IPT is not available.

We thank the staff of the GMRT that made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. The GMRT data are available from GMRT Online Archive (https://naps.ncra.tifr.res.in/goa/mt/search/basicSearch). The data of *Hisaki* spacecraft are in the Data Archives and Transmission System (DARTS) of JAXA (http://darts.isas.jaxa.jp). The Solar Wind data used in this study may be found in the supporting information section of Wilson et al. (2018). H.K. was supported by Institute for International Advanced Research and Education, Tohoku University and Grant-in-Aid for JSPS Research Fellow. F.T. was supported by JSPS KAKENHI grant No. JP26400476 and JP17H02965, and by JSPS and MAEDI under the Japan-France Integral Action Program (SAKURA). This work was supported by Grant-in-Aid for Scientific Research (15H05209) from the Japan Society for the Promotion of Science. The work at PRL is supported by Department of Space, Govt. of India.

ORCID iDs

H. Kita https://orcid.org/0000-0001-9948-5316
A. Bhardwaj https://orcid.org/0000-0003-1693-453X
F. Tsuchiya https://orcid.org/0000-0003-3386-6794

References

Barbosa, D. D., & Kivelson, M. G. 1983, GeoRL, 10, 210
Berge, G. L. 1966, ApJ, 146, 767
Bhardwaj, A., Ishwara-Chandra, C. H., Shankar, N. U., et al. 2009, ASPC, 407, 369
Bolton, S. J., Janssen, M., Thorne, R., et al. 2002, Natur, 415, 987
Brice, N. M., & McDonough, T. R. 1973, Icar, 18, 206
Goertz, C. K., & Ip, W. H. 1984, P&SS, 32, 179
Han, S., Murakami, G., Kita, H., et al. 2018, JGRA, 123, 9508
Ip, W.-H., & Goertz, C. K. 1983, Natur, 302, 232
Khurana, K. K. 2001, JGRA, 106, 25999
Kita, H., Misawa, H., Bhardwaj, A., et al. 2015, JGRA, 120, 6614
Kita, H., Misawa, H., Tsuchiya, F., et al. 2013, JGRA, 118, 6106
Klein, M. J., Gulkis, S., & Stelzried, C. T. 1972, ApJL, 176, L85
Klein, M. J., Thompson, T. J., & Bolton, S. J. 1989, NASSP, 494, 151
Misawa, H., & Morioka, A. 2000, AdSpR, 26, 1537
Miyoshi, Y., Misawa, H., Morioka, A., et al. 1999, GeoRL, 26, 9
Murakami, G., Yoshioka, K., Yamazaki, A., et al. 2016, GeoRL, 43, 12308
Nakamizo, A., Hiraki, Y., Ebihara, Y., et al. 2012, JGRA, 117, A09231
Santos-Costa, D., Bolton, S. J., & Sault, R. J. 2009, A&A, 508, 1001
Santos-Costa, D., de Pater, I., Sault, R. J., et al. 2014, A&A, 568, A61
Schneider, N. M., & Trauger, J. T. 1995, ApJ, 450, 450
Smyth, W. H., Peterson, C. A., & Marconi, L. 2011, JGRA, 116, A07205
Tao, C., Kataoka, R., Fukunishi, H., et al. 2005, JGRA, 110, A11208
Tsuchiya, F., Kagitani, M., Yoshioka, K., et al. 2015, JGRA, 120, 10317
Tsuchiya, F., Misawa, H., Imai, K., et al. 2010, AdG, 19, 601
Tsuchiya, F., Misawa, H., Imai, K., et al. 2011, JGRA, 116, A09202
Wilson, R. J., Bagenal, F., Valek, P. W., et al. 2018, JGRA, 123, 2772
Yamazaki, A., Tsuchiya, F., Sakanoi, T., et al. 2014, SSRv, 184, 259
Yoshikawa, I., Yoshioka, K., Murakami, G., et al. 2014, SSRv, 184, 237
Yoshioka, K., Murakami, G., Yamazaki, A., et al. 2013, P&SS, 85, 250