Io's volcanism controls Jupiter's radio emissions

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[1] Jupiter's sodium nebula showed an enhancement in late May through the beginning of June 2007. This means Io's volcanic activity and the magnetosphere's plasma content increased during this period. On the other hand, Jupiter's radio emission called HOM became quiet after the sodium nebula enhancement. The HOM emission is considered to be related to the activity of aurorae on Jupiter. These observation results therefore suggest that the increase in plasma supply from Io into Jupiter's magnetosphere weakens its field-aligned current, which generates the radio emissions and aurorae on Jupiter. By comparing our observation results to recent model and observation results, we add supporting evidence to the possibility that Io's volcanism controls Jupiter's magnetospheric activity. **Citation:** Yoneda, M., F. Tsuchiya, H. Misawa, Bonfond B., Tao C., M. Kagitani and S. Okano (2013), Io's volcanism controls Jupiter's radio emissions, *Geophys. Res. Lett.*, *40*, 671–675, doi:10.1002/grl.50095.

1. Introduction

[2] Io, one of the Galilean moons, is well known for its volcanic activity. Io's atmosphere consists of volcanic gas whose main constituent is SO_2 [e.g., *Lellouch et al*., 2007]. This volcanic atmosphere is continuously escaping from Io. Particularly, Io's atmosphere becomes magnetospheric plasma through photo-ionization or particle impacts and forms a structure called Io plasma torus. Jupiter's inner magnetosphere is therefore populated with heavy ions of iogenic origin. Neutral particles are produced through the Io plasma torus. For example, $NaCl^+$ ions picked up by Jupiter's corotating magnetic fields from Io's ionosphere and their subsequent destruction by recombination with ambient electrons in the Io plasma torus produce a flow of fast neutral sodium atoms called a "stream" [e.g., *Schneider et al*., 1991; *Wilson et al*., 2002]. These fast neutral sodium atoms also form a great nebula [e.g., *Mendillo et al*., 1990]. [*Lellouch et al*., 2003] suggested that the most likely source of the NaCl atmosphere seems to be direct volcanic output. This volcanically supplied NaCl gas is immediately ionized in Io's day-side ionosphere, and it goes to the Io plasma torus afterward. The average lifetime of $NaCl^+$ in the torus is 10 hours [*Schneider and Wilson*, 1994]. This means the supply rate of Na atoms forming the sodium nebula reflects the volcanic output on Io with a time scale of ~ 10 hours. Although Jupiter's inner magnetosphere is populated by iogenic plasma, influence from the solar wind is not negligible. [*Desch and Barrow* 1984], [*Gurnett et al*., 2002], and [*Nakagawa et al*., 2000] showed that Jupiter's hectometric radio emission, called HOM, depends on the solar wind dynamic pressure. The source regions of HOM are located in Jupiter's inner/middle magnetosphere [*Ladreiter et al*., 1993; *Zarka et al*., 2001], and HOM activity seems to reflect Jupiter's auroral activity. In fact, [*Gurnett et al*., 2002] showed that strong HOM emissions and Jupiter's UV aurorae are triggered by shocks in the solar wind. They concluded that HOM is an index of Jupiter's auroral activity and corresponds to Auroral kilometric radiation (AKR) on the earth. While Jupiter's inner magnetosphere is dominated by the planetary rotation as an energy source and Io as a plasma and neutral source, its variability seems, at least partially, controlled by the solar wind. The following question arises: "How does Io's volcanic activity contribute to Jupiter's magnetosphere?" Several studies aimed at observing Jupiter's sodium nebula or sulfur ion emissions from Io plasma torus have shown that Io's volcanic supply varies [*Brown and Bouchez, 1997; Mendillo et al*., 2004; *Nozawa et al*., 2005; *Yoneda et al*., 2009; *oneda et al*., 2010]. However, with exception of [*Bonfond et al*., 2012], no previous study has shown a dependence of Jupiter's magnetospheric activity, such as aurora, on Io's volcanic supply yet. In this study, we resolve this question by focusing on the D-line brightness from Jupiter's sodium nebula and HOM activity. Although there are other radio emissions that are also thought to be related to aurora activity on Jupiter, direct relations with the aurora have been seen only in HOM [*Gurnett et al*., 2002]. Particularly, [*Zarka et al*., 2001] suggested that the HOM emission comes from regions in L-shell of 7–30 R_j. This includes the source regions of the main oval aurora. Therefore, HOM is the most reliable index to infer the aurora activity, especially the main oval aurora.

2. Observations

2.1. Jupiter's Sodium Nebula

[3] Our observation was carried out at Mt. Haleakala, Maui, Hawaii, from 19 May through 21 June 2007. The optical instrument used for this observation consists of a small refractor (10 cm aperture) and an interference filter for the Na D-line emissions. Details of this observation system and its results are described in [*Yoneda et al*., 2009].

2.2. HOM Emissions

[4] The Radio and Plasma Wave experiment (WAVES) onboard the WIND spacecraft has two receivers: RAD1 for frequencies of 20 through 1040 *kHz* and RAD2 for

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frequencies of 1.075 through 13.825 *MHz*. Typical frequency of DAM (Decametric radio emission from Jupiter) is higher than 10 *MHz*, but they sometimes appear around a few *MHz* as seen in Figure 1. On the other hand, AKR usually occurs below 500 KHz. To avoid these contaminations, frequencies of 700 through 1000 titkHz were chosen for analyzing the HOM signals in this study. As shown in the frequency–time spectrogram of Figure 1, data from WAVES includes signals from the Sun, Earth, and the other celestial sources in addition to that from Jupiter because the WIND spacecraft was cruising around the Earth's Lagrange 1 point in the period we discuss. In this study, signals from the Sun and the Earth were subtracted by means of checking the frequency–time diagrams visually.

3. Results

[5] The D-line brightness of the sodium nebula showed a distinct enhancement at the end of May through beginning of June 2007 (the top panel in Figure 2). While the average lifetime of $NaCl^+$ in the plasma torus is only 10 hours [*Wilson et al.*, 2002], typical average lifetime of major ions of sulphur or oxygen is 10 days or longer [*Delamere et al.*, 2005]. Once the destructive recombination between $NaCl^+$ and electron occurs, then fast neutral sodium atoms whose speed is the same as the corotation speed (74 *km/s*) are produced. Travel time of these sodium atoms for a distance of 50 R_j is 12 hours. Therefore, the sodium nebula brightness follows the supply from Io with a time delay of ~ 1 day. It can be said that the brightness of the sodium nebula is a faithful indication of the supply rate of the torus plasma. Based on this logic, [*Yoneda et al.*, 2010] suggested that the D-line brightness is a representative of the supply rate of plasma from Io to the Io plasma torus. The flux tube content or abundance of Jupiter's inner magnetosphere can be described as follows:

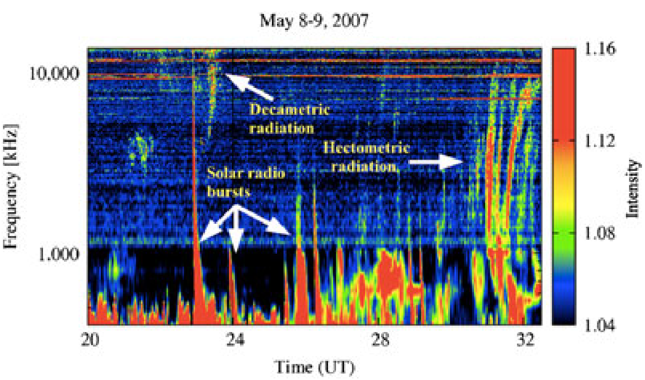

Figure 1. Typical frequency–time spectrogram of hectometoric and decametoric radio emissions from Jupiter and Type III solar radio bursts observed by the WIND spacecraft. The color bars shows the radio intensities as ratio of signals to background noise level in units of potential voltage. Emissions from Jupiter have drift tendencies in both positive and negative, while those from Sun show negative drifts. In addition, lowest frequencies of the most Type III radio bursts are less than 100 *kHz*. Signals from Jupiter and Sun can be separated easily because of these differences in their emission characteristics.

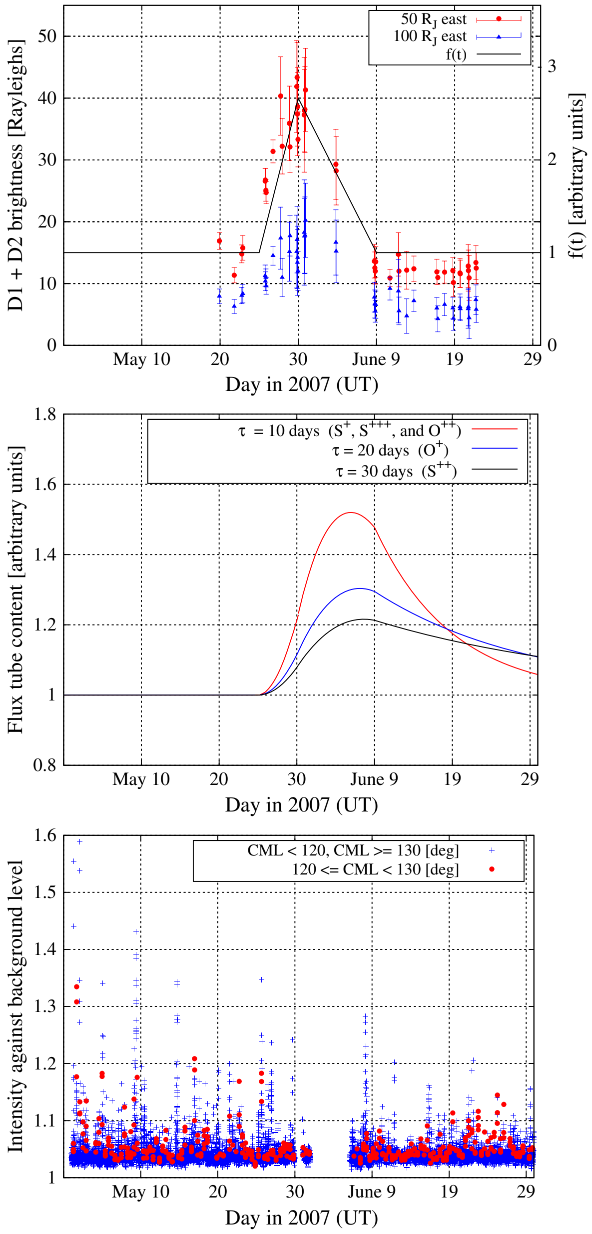

Figure 2. D-line brightness of Jupiter's sodium nebula on the eastern side of Jupiter and a function of *f(t)* derived from the D-line brightness (top), flux tube contents described as *F (t)*in equation 1 reproduced for four ions from the function of *f(t)* in the top panel (middle), and intensity of signals obtained by the WIND spacecraft normalized with background power voltage (bottom). The profile of *f(t)*, which consists of three straight lines, is not based on anymathematical fitting technique. The lifetime of each ion is from the study by [*Delamere et al.*, 2005]. Signals from the Sun and the Earth were removed; therefore, the bottoms panel purely shows time variation in HOM with the offset due to background intensity. The red plots in the bottom panel are HOM intensity obtained only with a central System III longitudes of 120–130 deg. Each plot in the bottom panel is averaged value over 5 *min*. Data at the beginning of June could not be obtained because of contamination from the continuous solar radio bursts.

$$F(t) = \int_{-\infty}^{t} f(t') \exp\left(-\frac{t-t'}{\tau}\right) dt', \qquad (1)$$

where $F(t)$ is the flux tube content at time t, $f(t)$ is the source rate of ions, and τ is the lifetime of an ion. The lifetimes of the ions in this calculation are taken from the study by [*Delamere et al.*, 2005]. For the sake of simplicity, the profile of $f(t)$ is defined as shown in the top panel of Figure 2 based on the D-line brightness. Accordingly, the flux tube content for each species is reproduced as in the middle panel of Figure 2. based on equation 1. The simple calculations shown in the middle panel suggest that the enhancement in flux tube content lasted until the end of June, whereas the enhancement in the D-line brightness disappeared at the beginning of June. The influence of interchange instability is not taken into account in this estimation, but [*Delamere et al.*, 2005] estimated it takes 100–200 days to move the torus plasma from the L-shell of 6 to 9. This time scale is significantly longer than lifetimes of major torus ions and a timescale of the enhancement in the D-line brightness. For example, average lifetimes of sulfur and oxygen ions due to reneutralization or electron impacts are a few tens days [*Delamere et al.*, 2005], and the duration time of the sodium nebula enhancement shown in Figure 2 is 20 days. In fact, [*Yoneda et al.*, 2010] successfully reproduced the time variation of the flux tube content of S^+ ions based on the short-duration enhancement in the D-line brightness of the sodium nebula without taking the interchange instability into account.

[6] The bottom panel in Figure 2 plots the intensity of HOM, as measured by the WIND spacecraft. The HOM intensity was weak in June compared with that in May. The nonactive period seems to almost correspond roughly to the plasma-abundant period. Although the moment at which the HOM intensity first becomes weak cannot be seen in the bottom panel in Figure 2 because of contaminations due to solar radio bursts; the bursts of HOM with spike-like structures are less often after the enhancement in the sodium nebula (or in the plasma-abundant period) than before the event. In addition, the intensities of the HOM bursts in the plasma-abundant period are smaller than those before the event.

[7] Figure 3 plots the intensities of HOM for periods before and after the sodium nebula enhancement as functions of Jupiter's System III longitude. A distinct gap between these two plots occurs around 120 degrees but not around 270 degrees. Red plots in the bottom panel of Figure 2 show the HOM intensity with the System III longitudes of 120 through 130 degrees. At these longitudes, HOM is quite around 9 June while the flux tube contents are abundant in the same period as seen in Figure 2.

[8] Histogram to see relations between the HOM intensity and observed length of time is shown in Figure 4. Data are chosen from the System III longitudes of 120 through 130 degrees as well as the red plots in the bottom panel of Figure 2. The HOM emissions are seen with a wide intensity range before the sodium nebula enhancement. On the other hand, strong emissions seem to be less often after the enhancement while weak emissions are often. Increase in plasma density seems to decrease the occurrence of intense HOM.

4. Discussion

[9] Although it is yet unknown whether an increase in plasma density increases the magnetospheric activity or decreases, several models and observation results in the past gave some insights into this relationship. Hill (1979) found theoretically that the a region in which peaks of the field aligned current is seen moves inward if the plasma sheet increases in density. This means the main aurora oval on Jupiter moves equatorward with increased plasma supply from Io. Although Hill (1979) and Hill (2001) did not show any influence of this effect on Jupiter's magnetospheric activity, [*Nichols and Cowley* 2003] and [*Tao et al.*, 2009] showed that the peak intensity of Jupiter's field-aligned current in regions of the main aurora oval decreases with an enhanced plasma density following the motion of the main aurora oval. It may be said that the decay in the HOM intensity seen in our observation corresponds to that of the field-aligned current shown by [*Nichols and Cowley* 2003] and [*Tao et al.*, 2009]. While Nichols (2011) showed that the increase in the plasma density causes that of the field-aligned current if the density of cold plasma is

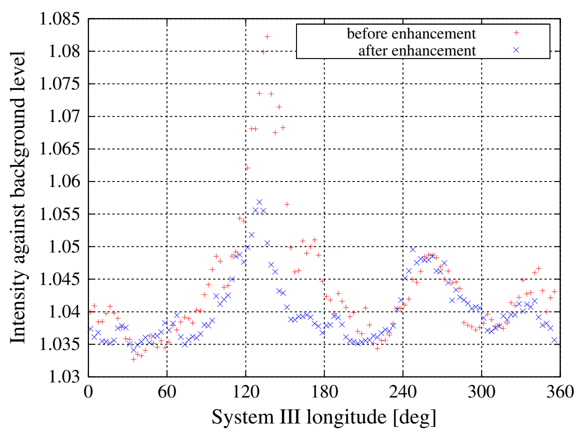

Figure 3. Intensity of HOM obtained by the WIND spacecraft as a function of Jupiter's system III longitude for periods before (red, 1–23 May 2007) and after (blue, 7–29 June 2007) and enhancement in Jupiter's sodium nebula. Each plot is averaged value in a bin whose size is 3 degrees.

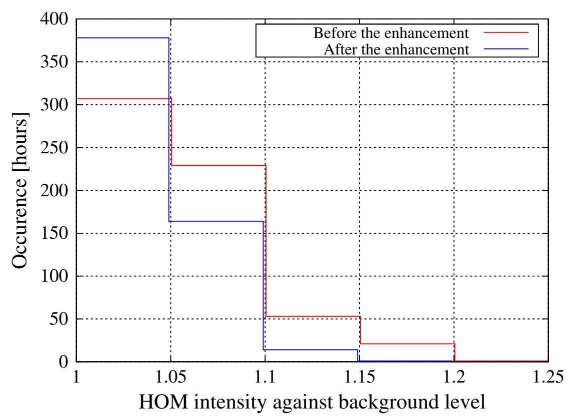

Figure 4. Histogram to show occurrences of HOM as a function of HOM intensity before (red, 1–23 May 2007) and after (blue, 7–29 June 2007) the enhancement in Jupiter's sodium nebula. The data are from the System III longitudes of 120–130 degrees.

proportional to the total plasma supply, they also showed that it works in the opposite way if the cold plasma is independent on the total plasma supply. This may indicate that the population of the cold plasma takes a certain length of time to follow changes in total plasma supply from Io.

[10] [*Bonfond et al*., 2012] observed that the main oval continuous expanded from February to June in 2007 while the occurrence rate of intense patches of emissions equatorward of the main oval increased. While [*Nichols et al*., 2009] attributed this motion of the main oval to the current sheet configuration, [*Bonfond et al*., 2012] concluded that these changes had been caused by an increase of volcanic activity at Io. However, [*Bonfond et al*., 2012] did not find any significant decreasing trend in the UV power from the main aurora oval. Although [*Nichols et al*., 2009] showed decay in the UV aurora emission from the main aurora oval by ~ 100 GW at the end of May in 2007, variations whose amplitudes were ~ 100 GW were seen several times in their observation. Therefore, it cannot be said that the decrease in the aurora emission was found as well as the HOM emission. In our observation, the decay in HOM can be seen around the System III longitude of 120 degrees. This may indicate that the decay in the field-aligned current intensity or the UV power from the main aurora oval occurred only at specific longitudes as well.

[11] Although we are uncertain what mechanism makes the gap clear only at specific longitudes as seen in Figure 3, [*Nakagawa et al*., 2000] showed that solar wind–driven HOM can also be observed at specific longitudes, and HOM observed at around CML of 120 degrees is independent on the solar wind. Furthermore, the dynamic pressure in the solar wind at Jupiter reproduced based on a model of [*Tao et al*., 2005] showed no significant change in our observation period. Although a certain increase in the solar wind dynamic pressure is seen in the model results by [*Clarke et al*., 2009], the correlation between the solar wind and HOM known is positive. We can fairly say that the increase in the HOM activity seen in our study was not due to a change in the solar wind. Although this observation was made during a solar quiet period, solar radio bursts still caused huge contamination in the signal. Unfortunately, HOM activity could not be obtained from data for 27 May through 5 June in 2007 because the HOM signal was contaminated by the solar type III radio bursts. This period was precisely after the beginning of the enhancement of the sodium nebula. We therefore cannot see how sensitively the HOM emission reacted to Io's volcanic activity.

5. Summary and Conclusions

[12] Decay in HOM intensity was found after Io's volcanic enhancement based on data from ground-based observations of Jupiter's sodium nebula and the WIND spacecraft. Past model studies by [*Nichols and Cowley* 2003] and [*Tao et al*., 2009] showed that an enhancement in the plasma supply from Io decreases the field-aligned current between Jupiter's magnetosphere and ionosphere. The decrease in the field aligned current seems to correspond to the decay in the HOM emission seen in this study. In addition, the motion of the main oval that had been expected by [*Nichols and Cowley* 2003] and [*Tao et al*., 2012] was actually detected by [*Bonfond et al*., 2012]. Results of these works are consistent with each other. However, [*Bonfond et al*., 2012] did not find any significant decay in the UV power from the main aurora oval, although decay in the field aligned current intensity was expected by [*Nichols and Cowley* 2003] and [*Tao et al*., 2009]. The decay in HOM was seen only at System III longitudes around 120 degrees as shown in Figure 3. This may indicate that the decrease in the field-aligned current intensity (or the UV power from the main aurora oval) due to increase in the plasma supply from Io occurs only at specific longitudes and also in specific hemisphere. A similar decreasing tendency in Jupiter's radio emission occurred in the wavelength range of 4–5 MHz as well as the HOM intensity. Although it is unclear where this emission comes from since these wavelengths are on the boundary of the HOM and Jupiter's decametric (DAM) emissions, our study suggests that the area in which magnetospheric activity is weakened is not limited to typical HOM source regions but rather covers a vast region in the magnetosphere. In addition to observations of the HOM emissions and Io's volcanism, observations of the DAM emission may help reveal this issue. More events are needed to see the detailed relations between Jupiter's magnetospheric activity and Io's volcanism. However, enhancements in the sodium nebula were found only in 2003 and 2009 as shown by [*Yoneda et al*., 2009] and [*Yoneda et al*., 2010]. Unfortunately, the signal obtained by the WIND spacecraft in 2003 was contaminated by the solar radio bursts, and it was impossible to find the HOM signal from that data. Therefore, direct comparisons between Io's volcanism (or the sodium nebula) and the UV aurora on Jupiter may be able to improve this study.

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