# Effect of the solar UV/EUV heating on the intensity and spatial distribution of Jupiter‘s synchrotron radiation

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Jupiter's synchrotron radiation (JSR) is the emission from relativistic electrons, and it is the most effective probe for remote sensing of Jupiter's radiation belt from the Earth. Recent observations reveal short term variations of JSR with the time scale of days to weeks. Brice and McDonough (1973) proposed that the solar UV/EUV heating for Jupiter's upper atmosphere causes enhancement of total flux density. If such a process occurs at Jupiter, it is also expected that diurnal wind system produce dawn-dusk asymmetry of the JSR brightness distribution.

Preceding studies confirmed that the short term variations in total flux density correspond to the solar UV/EUV. However, the effect of solar UV/EUV heating on the brightness distribution has not been confirmed. Hence, the purpose of this study is to confirm the solar UV/EUV heating effect on total flux density and brightness distribution. We made radio imaging analysis using the National Radio Astronomy Observatory (NRAO) archived data of the Very Large Array (VLA) obtained in 2000, and following results were shown.

1. Total flux density varied corresponding to the solar UV/EUV.
2. Dawn side emission was brighter than dusk side emission almost every day.
3. Variations of the dawn-dusk asymmetry did not correspond to the solar UV/EUV.

In order to explain the second result, we estimate the diurnal wind velocity from the observed dawn-dusk ratio by using the model brightness distribution of JSR. Estimated neutral wind velocity is 46+/-11 m/s, which reasonably corresponds to the numerical simulation of Jupiter's upper atmosphere. In order to explain the third result, we examined the effect of the global convection electric field driven by tailward outflow of plasma in Jupiter's magnetosphere. As the result, it is suggested that typical fluctuation of the convection electric field strength was enough to cause the observed variations of the dawn-dusk asymmetry.

## 1. Introduction

Jupiter's Synchrotron Radiation (JSR) is the emission from relativistic electrons trapped in the strong magnetic field of the inner magnetosphere. Intensity and frequency of synchrotron radiation depend on electron energy, number density and magnetic field strength, so it is the most effective prove for remotely sensing of the Jupiter’s Radiation Belt (JRB) from the Earth and we can obtain information on the dynamics of it. The characteristic frequency of JSR is several tens MHz to several GHz and the relativistic electrons in JRB with several MeV to several tens MeV generate JSR. JSR has been thought to be stable for a long time, because JRB is located in the intense magnetic field region around Jupiter and external forces such as solar wind disturbances is difficult to reach the JRB region.

After the collision of comet P/SL-9 to Jupiter in 1994, observations for JSR have been intensively made and short term variations of JSR have been confirmed by several groups. The time scale of the short term variation is about days to weeks and total flux varies more than 10% (Bolton et al. 2002, Tsuchiya et al. 2010). This variation indicates that the electron density and/or energy change by certain physical processes such as acceleration, transportation and loss of relativistic electrons. Although mechanisms which cause the short term variations have not been revealed well yet, Brice and McDonough (1973) proposed a following scenario (hereafter "the BM scenario") for the short term variations:

i. Solar UV/EUV heating drives neutral wind perturbation in Jupiter's upper atmosphere.
ii. The neutral wind induces both quasi-static and perturbed dynamo electric fields in the ionosphere.
iii. The electric fields are mapped to JRB through the Jupiter's magnetic field line and lead to enhancement of inward radial diffusion of the relativistic electrons trapped in JRB and dawn-dusk electric potential differences produce dawn-dusk asymmetry in the electron spatial distribution.
iv. Finally intensity of JSR enhances and dawn-dusk asymmetry of the emission distribution is produced.

Based on this scenario, it is expected that total flux density and dawn-dusk peak emission ratio are correlated with the solar UV/EUV flux. So far only the total flux observations have shown the verification of the scenario of short term variations. Miyoshi et al. (1999) showed that a short term variation event at 2.3GHz is well correlate to the solar UV/EUV flux index. Tsuchiya et al. (2011) showed that total flux variation of JSR at 325MHz and solar UV/EUV index have positive correlations, and examined the BM scenario using radial diffusion model. However, the effect of solar UV/EUV heating on the brightness distribution has not been confirmed. If the scenario is completely true, dawn side is always brighter than the dusk side due to the steady state diurnal wind, and total flux density and dawn-dusk ratio change corresponding to the solar UV/EUV variations. Existence of such asymmetries in JSR brightness distribution has never been confirmed yet. Therefore, we need to confirm total flux density and brightness distribution simultaneously in order to confirm the B-M scenario more precisely.

The purpose of this study is to confirm the relation between the solar UV/EUV flux and total flux density of JSR, and try to find asymmetries in the brightness distribution expected by the B-M scenario. We have made radio image analysis using the VLA archived data which was made by continuous observation for several days while solar UV/EUV had variation. We derived the total flux density and dawn-dusk ratio of the JSR and evaluate how these parameters vary in relation to solar UV/EUV.

## 2. Observations and data reduction

From 28th January to 5th February 2000, Jupiter was observed at 74MHz and 327MHz simultaneously with the VLA. During this period, the VLA was B configuration with a maximum and a minimum separation between antennas of around 11.4 kilometers and 0.21 kilometers. The observation time range was about 8 hours per day. Jovicentric declination of the Earth (De) is about 2.8 degree and distance between the Earth and Jupiter varied from 5.06 to 5.18 AU. CML (Central Meridian system III Longitude) coverage of each day is summarized in Table.1.

We have selected the data observed at 327MHz because JSR is unresolved at 74MHz, so the data

Table 1 Time schedule and CML coverage for each observation day of the VLA 2000 campaign

| Date | Time [UT] | De | Distance [AU] | CML [degree] |
|---|---|---|---|---|
| 01/28 | 20:51-4:40 | 2.80 | 5.06 | 132-375 |
| 01/29 | 20:39-4:35 | 2.80 | 5.07 | 273-163 |
| 01/30 | 20:31-4:28 | 2.79 | 5.10 | 209-163 |
| 02/01 | 21:27-5:23 | 2.79 | 5.12 | 33-283 |
| 02/04 | 20:17-4:12 | 2.79 | 5.17 | 81-331 |
| 02/05 | 20:12-4:08 | 2.79 | 5.18 | 229-119 |

observed at 74MHz is not suitable for this study. The data were calibrated, flagged and imaged with NRAO AIPS (Astronomical Image Processing Software). Flux calibrator was 3C48 and its flux density was 43.2Jy at 327MHz. 3C49 was used as a phase calibrator and its flux density was about 8Jy. After the calibration procedure, the data was split into 16.5minuets, that is, 10 degrees in Jupiter's rotation.

The technique of imaging at 327MHz is different from ordinary ways. Because full width at half maximum intensity (FWHM) of primary beam is large at low frequency, non-coplanar problem will appear (Perley, 1999). AIPS avoids this problem by making a number of small tangent planes ("facets") and make CLEAN image in each facet using the 2D approximation. This technique also enables us to remove the effects of distant interfering radio sources. Radius of imaging field was 2.5 degree and it was large enough to cover the FWHM of primary beam (2.1 degree). Number of facets was about 130-140 which were set around NRAO VLA Sky Survey (NVSS) source location. Then the UV data was self-calibrated using the clean components from the CLEANed images. After the iteration of imaging and self-calibration procedure, we adjusted the synthesized beam to 27.5 arcsec.

The total flux density of the JSR was determined from integration of final image above the 3 times background rms level. Although this integrated flux density is not equal to total flux density due to the short spacing issue, we can assume the integrated flux

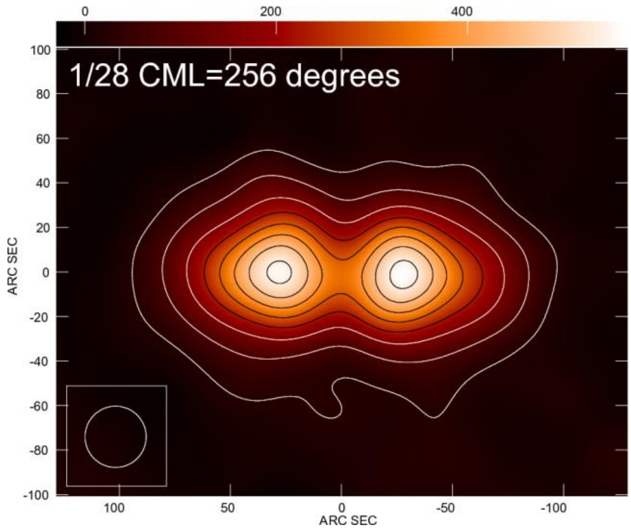


Fig 1 Radio image observed in 28th Jan. Color bar indicates the emission intensity in the unit of [Jy/beam]. We can see the bright spot at the dawn and the dusk side.

density as the total flux density because missing flux at this frequency is very small. Considering the distance between the Earth and Jupiter, the total flux densities were standardized at 4.04 AU. We also need to consider the thermal emission from Jupiter. We are interested in non-thermal emission only, so we need to subtract thermal emission from total flux density. The brightness temperature of Jupiter's thermal emission at 327MHz is 700K (de Pater et al., 2003). We made images and total flux measurement at different CMLs, and fit the beaming curve equation (Klein et al. 1989) in order to remove CML dependence of each day. The beaming curve equation is expressed as cubic sine function,

$$S = A_0\{1 + \sum_{i=1}^{3} A_i(i \times \mathrm{CML} + \phi_i)\},$$

where $S$ is flux density at each CML, $A_0$ is averaged flux density of JSR, $A_i$ and $\phi_i$ are coefficients as a function of De. We use $A_0$ as the total flux density on a certain day.

Dawn-dusk ratio is the peak emission intensity ratio of the dawn side peak divided by the dusk side peak of the final image. If the dusk side peak intensity

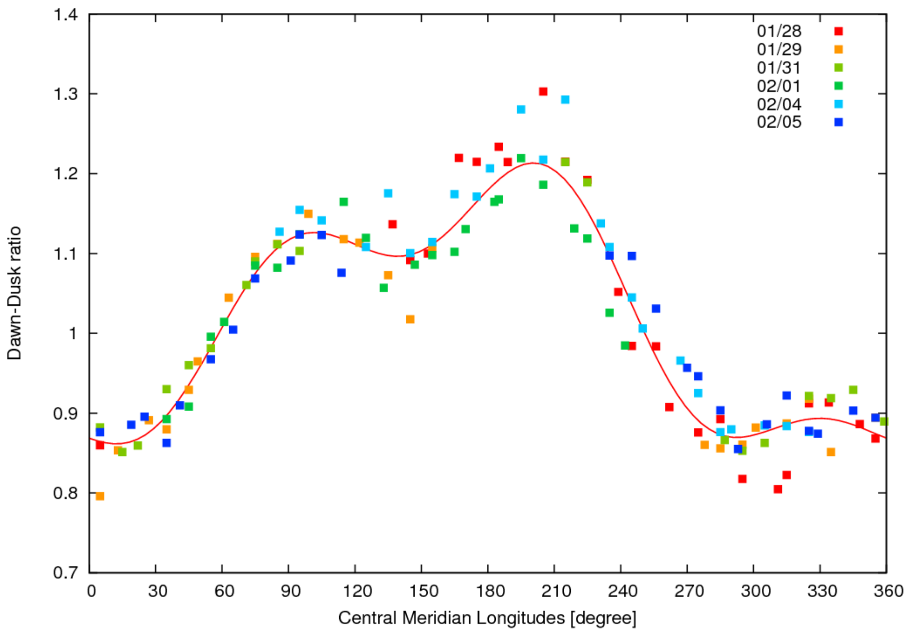


Fig 2 Dawn-Dusk emission ratio variations versus CML. Averaged dawn-dusk ratio is 1.02 +/- 0.0135, larger than unity and this result supports the B-M scenario.

become larger, dawn-dusk ratio become larger. In order to remove CML dependence, we also fit the cubic sine function and we assumed zeroth order coefficient as averaged Dawn-dusk ratio on a certain day. This is the same way as the total flux density derivation.

## 3. Results

Fig.1 shows the example of observed radio image. This image was observed in 28th Jan. We can see the bright spot at the dawn and dusk side region. Color bar indicates the intensity in the unit of Jy/beam.

Fig.2 shows the CML dependence of the observed dawn-dusk ratio on each day. Color squares show the observed data and red line indicates the averaged variation feature of the dawn-dusk ratio using the cubic sine function. Variation feature is almost same for all observation dates and we can see the clear CML dependence of the dawn-dusk ratio. Averaged dawn-dusk ratio is 1.02 +/- 0.0135, larger than unity. This result suggests that some physical processes such as the diurnal wind generated the dawn-dusk asymmetries in the brightness distribution of JSR. This result supports the B-M scenario.

Fig.3 shows the observation result of the averaged total flux density and dawn-dusk ratio. Total flux density of JSR increased from 28th Jan. to 4th Feb by 10%. This variation feature is well correlated with the solar UV/EUV flux with the lag time of 3-4 days. Relation between the solar UV/EUV flux and JSR total flux density showed that the variations of JSR were well correlated with those of the solar UV/EUV flux. Time delay of JSR enhancement to the solar UV/EUV flux variations is almost the same value as observed by IPRT at 325 MHz (Tsuchiya et al. [2011]). Tsuchiya et al. [2011] interpreted that variations of total flux at 325MHz were consistent with a prediction of the B-M scenario, the total flux variations could be caused by the enhancement of radial diffusion associated with the solar UV/EUV heating. The enhancement of the total flux density shown in this study is consistent with their result. Hence this result also supports the B-M scenario.

However, variations of the dawn-dusk ratio did not correspond to those of the solar UV/EUV flux. The

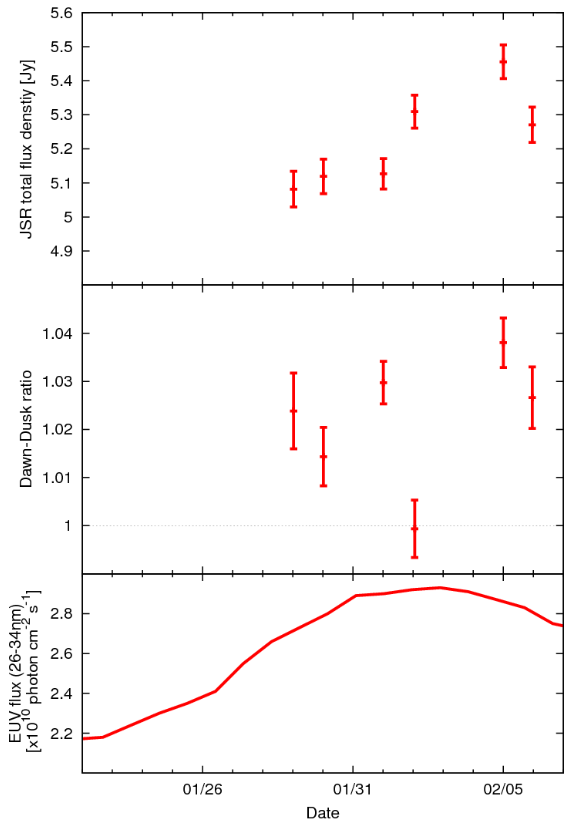


Fig 3 Total flux density and Dawn-Dusk emission ratio of JSR on the 2000 observation.

middle panel of Fig.3 shows the variation of averaged dawn-dusk ratio. We cannot find a simple trend in variations of the dawn-dusk ratio. There was a relatively large depression in the fourth day of the observation. Therefore, the variations feature cannot be explained simply by the solar UV/EUV heating. This result seemed not to be corresponding to the B-M scenario. However, one cannot rule out the possibility that the solar UV/EUV related variations were masked by other processes which were dominated in the variations of dawn-dusk ratio at the day order time scale.

## 4. Discussions

### 4.1 Estimation of diurnal wind velocity

From VLA data analysis, it is found that the dawn-dusk ratio is always larger than unity, that is, the dawn side is always brighter than the dusk side. This result supports the existence of dawn-dusk potential difference induced by diurnal wind system. In order to verify this scenario, we estimated a neutral wind velocity from the observed dawn-dusk ratio and compare with a numerical simulation study relating to Jupiter's upper atmosphere. From the comparison, we can examine weather estimated wind velocity is reasonable or not.

First, we calculated the shifted drift orbit of relativistic electrons by dawn-dusk electric potential difference. This shift changes the magnetic field strength along the orbit, and energy will change due to the first adiabatic invariant conservation. Then, variations of energy and magnetic field also change the emission power of synchrotron radiation, with leading to the dawn-dusk asymmetry. We calculated this dawn-dusk asymmetry of JSR at the magnetic equator using particle distribution model (Divine and Garrett, [1983]).

Second, we calculated the relation between diurnal wind velocity and dawn-dusk ratio. If calculated distribution model of JSR. The dawn-dusk electric potential difference is directly connected to the neutral diurnal wind velocity, so we can obtain the relation between the dawn-dusk ratio and neutral wind velocity. Fig.4 shows the relation between dawn-dusk ratio and wind velocity derived from the model calculation. From the VLA data analyzing results of dawn-dusk ratio, the averaged dawn-dusk ratio is 1.02 +/- 0.0135. Using the linear fitting function in Fig.4, neutral diurnal wind velocity is estimated to be about 46 +/- 11 m/s.

Third, we compared the estimated wind velocity with a simulation study of Jupiter's upper atmosphere made by Tao et al. [2009]. Tao et al. [2009] developed a numerical model of the Jovian magnetosphere, ionosphere and thermosphere coupling system. We can obtain two dimensional wind velocity and temperature distribution in the meridional plane. From this model, maximum conductivity region is expected to be located

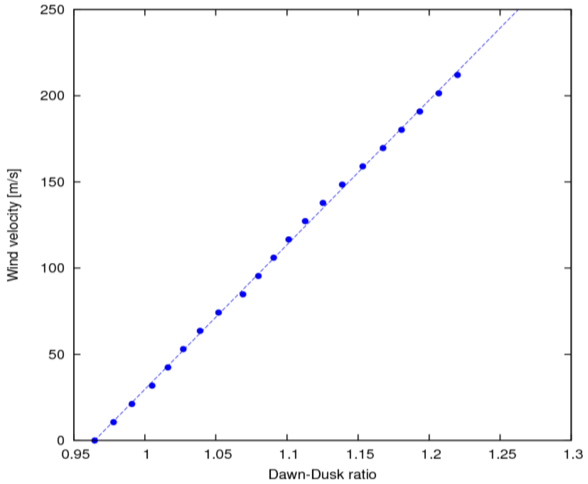


Fig 5 Relation between dawn-dusk ratio and wind velocity derived from the model calculation.

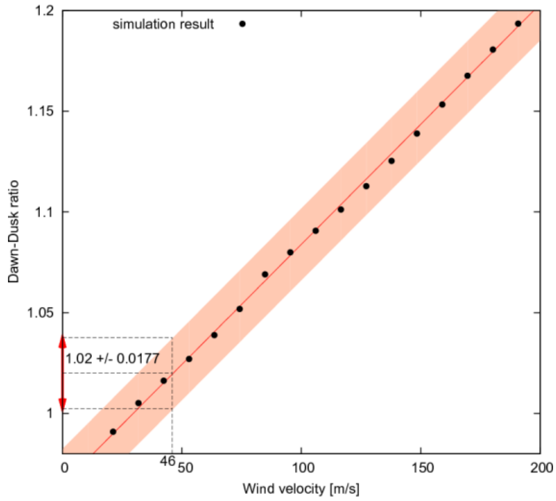


Fig 4 Effect of fluctuating convection electric field on dawn-dusk ratio. Dots indicate model calculation results and hatched region indicates fluctuating convection electric field with +/- 2mV/m.

around 300km from the 1 bar altitude. When F10.7 solar radio flux is 160 sfu, average velocity weighted by conductivity is 27.1 m/s. On the other hand, neutral wind velocity derived from the observed dawn-dusk ratio and the model calculation of this study is about 46 +/- 11 m/s. Although there is a factor difference between the simulated and estimated neutral wind velocities, we can obtain reasonable wind velocity compare to the simulation study.

Hence, we conclude that the diurnal wind system is possible to cause the dawn-dusk asymmetry and the wind velocity of upper atmosphere is expected to be several tens m/s.

4.2 Effect of convection electric field on the daily variations of dawn-dusk ratio

It is known by ground based and space craft observations that the position of the Io plasma torus is shifted to the dawn side (Ip and Goertz [1982], Barbosa and Kivelson [1983]). This shift is thought to be caused by the convection electric field. The convection electric field on Jupiter is driven by the outward flow of plasma, contradictory to the Earth. Such a large scale electric field would affect the radiation belt electrons of Jupiter. In addition to that, some observations show the time variability of Io torus. Schneider and Trauger [1995] reported that the ribbon position showed small but measurable changes shorter than one Jovian rotation. Smith et al. [2011] reported that spatially nonuniform and variable convection electric field should be expected to control the plasma torus structure. They also showed that variations of the ribbon position could be explained by fluctuating convection electric filed. The magnitude of the convection electric field is about 4 +/- 2 mV/m. Fig.5 shows the relation between wind velocity and dawn-dusk ratio. Width of hatched region corresponds the convection electric field variation of 4 +/- 2 mV/m. When neutral wind velocity is 46m/s, the variations of convection electric field cause variations of dawn-dusk ratio by 1.02 +/- 0.0177, comparable to the observed value. Thus time variable convection electric field is possible to explain the observed variations of dawn-dusk ratio.

We propose the following hypothesis for the variations of convection electric field. When tailward plasma outflow increases, convection electric field

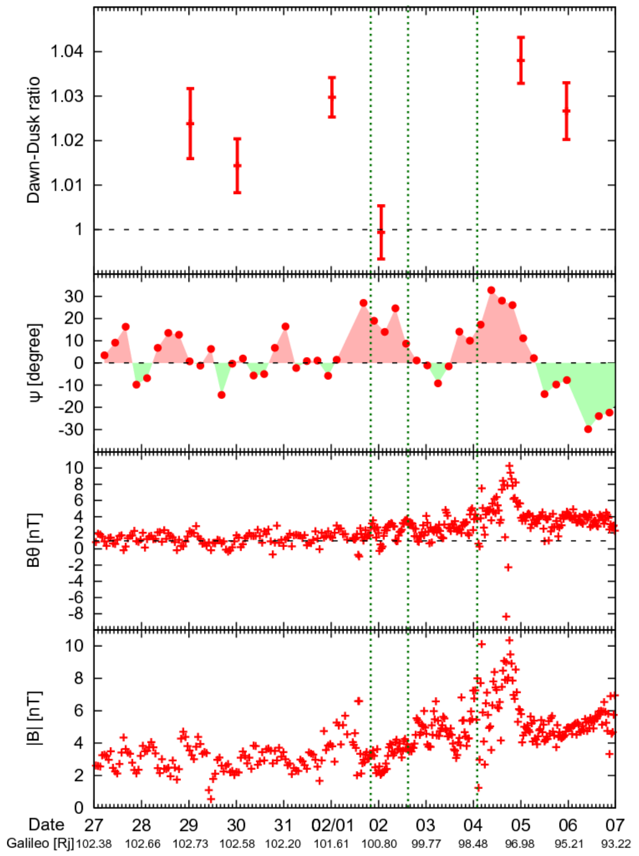


Fig 6 One of the explanations of the short term variations of the dawn-dusk ratio by fluctuating convection electric field.

causes decrease of the dawn-dusk ratio. Corresponding to this enhancement, tailward flow expands the magnetosphere toward the tail and Jupiter's magnetosphere become active.

In order to confirm the above effect on observed dawn-dusk ratio, we checked the existence of tailward magnetic field extension and substorm like event by Galileo Magnetometer and HOM (HectO Metric emission) as an index of magnetospheric activity from WIND satellite data. One of the main results of Galileo mission is that Jupiter has ion flow bursts associated with variations of the north-south component of the magnetic field. In addition to that, it is identified that variations of the energy spectral of the particle distribution is associated with the stretching and depolarization of the magnetic field. This leads to a global magnetotail reconfiguration of the Jovian magnetosphere. Such phenomena are closely resembled to the Earth's substorm, so it is called substorm like event (Kronberg et al. [2007]). Although main features of substorm like event seem to be similar to the terrestrial substorm, the driving mechanism is thought to be different from the solar wind driven terrestrial substorm, that is, internal mass loading and field line stretching in the rapidly rotating magnetosphere drives tailward magnetic reconnection. Smith et al. [2011] suggested that such a back and forth motion of magnetic field is relating to the fluctuation of Io torus position.

Fig.6 shows summery plots of HOM, magnetic field direction, magnetic field strength and dawn-dusk ratio. Approximate HOM observed time is indicated by vertical green dashed line. During the observation period of the VLA, Galileo was located around 100Rj and local time was around 20h. ψ in Fig. 6 shows the azimuthal angle of the local magnetic field from the radial direction and positive with rotational direction. Red hatched region indicates the local magnetic field directed to the tailward when taking into account the Galileo position. Around the large depression of the dawn-dusk ratio on 2nd Feb., the magnetic field direction trended to the tailward and HOM appeared. In addition to that, around the intense HOM/DAM detected period on 4th Feb., southward turning of the magnetic field and sudden decrease of magnetic field intensity were also detected. These results imply that growthphase started around 2nd Feb., substorm like event occurred around 4th Feb., and magnetic field returned to the initial phase soon after. Hence, there is a possibility that magnetospheric activity was high during 2nd Feb. to 4th Feb. and active tailward outflow increased the convection electric field. Consequently, the dawn-dusk ratio is expected to decrease.

## 5. Conclusions

In order to investigate the solar UV/EUV heating effect on total flux density and brightness distribution of JSR, we made radio image analysis using NRAO archived data of the VLA. We derived total flux density and dawn-dusk peak emission ratio of JSR and investigated their relationship to the variations of the solar UV/EUV flux. From the VLA data analysis, following results were suggested.

First, total flux density variations occurred corresponding to the variations of solar UV/EUV flux. This result supports the B-M scenario.

Second, averaged dawn-dusk ratio was larger than unity. This result indicates that the dawn side is brighter than dusk side during this observation period. We estimated diurnal wind velocity from observed dawn-dusk ratio in order to evaluate whether the diurnal wind induced by the solar UV/EUV heating is reasonable or not. Estimated wind velocity is 46 +/- 11 m/s, which is reasonably corresponded to the numerical simulation of Jupiter's upper atmosphere. Thus we can conclude that the steady dawn-dusk asymmetry is caused by steady diurnal wind system and its wind velocity is expected to be several tens m/s.

Third from short term aspect of the variation of dawn-dusk ratio, it cannot be simply explained by the solar UV/EUV variations. The fluctuation of the convection electric field is expected to cause daily order variations of dawn-dusk ratio. Some magnetospheric properties observed by Galileo and WIND suggested the enhancement of the magnetospheric activity during the VLA observation period, which implied occurrence of convection electric field fluctuation via variations of outward plasma motion. Hence there is a possibility that convection electric field could affect the dawn-dusk ratio and become the major factor for the dawn-dusk ratio variation.

To conclude, variations of the total flux density and long term asymmetry of the dawn-dusk ratio can be explained by the solar UV/EUV heating effect. Short term variations of the dawn-dusk ratio cannot be simply explained by solar UV/EUV heating. One of the possible explanations for the short term variations of the dawn-dusk ratio is the effect by the convection electric field caused by the tailward outflow of plasma in Jupiter's magnetosphere. The further confirmation of causalities of the short term variations is deferred to future studies in both observations and modeling analysis.

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