4.7 Observations of Short Term Variation of Jovian Synchrotron Radiation

By

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ABSTRACT

We have made detailed observations of Jovian decimetric radiation (DIM) from relativistic electrons in the Jovian radiation belt by using the Kashima 34 m antenna to seek the existence of DIM short-term variations. In these observations, the sky tipping method was used to correct the terrestrial atmospheric extinction effect. We also evaluated the background radio sources noise, which has caused serious problems in previous observations. As a result we showed for the first time that the Jovian synchrotron radiation has variations in intensity over a period of a few days. We then developed a model of Jovian synchrotron radiation based on the empirical models of Jovian magnetic field and the distribution of particles in the Jovian radiation belt derived from direct measurements made by past spacecraft. By comparing this model with the results of observations, we clarified that when the Jovian synchrotron radiation intensity is increasing, the spatial distribution of electrons in the Jovian radiation belt changes in such a way that the electrons concentrate at Jupiter's magnetic equatorial plane. Next, we developed and numerically tested a computer code relating to the transport of particles in the Jovian radiation belt. We showed that the observed flux increase of Jovian synchrotron radiation for a few days can be explained by a scenario in which the radial diffusion coefficient of electrons in the radiation belt increases. Furthermore, we performed a comparative analysis with the solar F10.7 observed on the earth during the same period, and we showed the possibility that this increase in the radial diffusion coefficient arises from heating of the Jovian ionosphere by solar UV/EUV radiation during the observation period.

Keywords: Jovian synchrotron radiation, Planetary magnetosphere

1. Introduction

The giant planet, Jupiter has the most active and huge magnetosphere in our solar system. Jupiter has a strong magnetic field and rotates at high speed. It emits radio waves at a variety of wavelengths (see, e.g. Reference (1)), and it is known that the non-thermal emissions in the decimeter band (DIM; 0.1-10 GHz) are caused by synchrotron radiation from relativistic electrons in the Jovian radiation belt. In the four decades that have passed since the existence of Jovian synchrotron radiation was first identified in the 1950s[2], observations of various parameters such as the total flux and polarization have clarified the basic properties of DIM (see References (3) and (4)). In recent years, the emission regions have been imaged by interferometry observations, allowing tomography techniques to be applied to inferring the three-dimensional structure of the emission source (see, e.g. Reference (5)), thereby providing large amounts of data to help clarify the electromagnetic environment in the Jovian inner magnetosphere where it is difficult to make in-situ measurements with spacecraft.

Of these observations, the temporal variation of DIM intensity directly reflects increases and decreases in the flux of relativistic electrons in the Jovian radiation belt, which are the source of DIM, and their variations in their distribution. This provides important information for clarifying the temporal variation of particles in the Jovian radiation belt—i.e. the physical processes involved

in their generation, acceleration and dissipation. The characteristics of temporal variations in the DIM intensity have so far been found to exist variations on two time scales. One is associated with Jupiter's 10-hour rotational period, whereby the intensity exhibits a sinusoidal variation ('beaming curve') at each rotation of the planet. This has been explained in terms of a beaming effect originating from a concentration of the relativistic electrons that produce synchrotron radiation in Jupiter's magnetic equatorial plane, and from changes in Jupiter's magnetic latitude as seen from the earth during each rotation of Jupiter due to the planet's rotational and magnetic axes being inclined relative to each other[6]. The other is a long-term variation—identified by patrol observations performed roughly once per month by NASA JPL in the US since the 1970s—whereby the DIM intensity varies by about 20% every 11 years or so[7].

Two possible mechanisms have been proposed to explain this long-term variation. One is that the flux of electrons in the Jovian radiation belt varies with variations in the solar 11-year cycle, causing the DIM intensity to change[8][9]. The other is that the apparent radiation intensity changes according to changes in the angle between Jupiter's rotational axis and the ecliptic plane during the revolution of Jupiter (which has a 12-year period)[10].

It is still unclear whether or not short-term DIM flux variations ranging in length from a few days to a few weeks are present. (However, only when comet Shoe-

maker-Levy 9 (SL-9) crashed into Jupiter in July 1994, the radio intensity was found to increase unusually for a short period[11].) Possible reasons why short-term variations in the DIM intensity have not been identified by observation include the fact that hardly any continuous observations of radio intensity over periods of a few days, and the fact that the DIM radio intensity variations are very weak (just a few Jy), which makes it difficult to ascertain whether any observed radio intensity variations are caused by variations in the DIM intensity or by other effects such as temporal fluctuations in the receiver sensitivity or mixing with background radio waves from the galaxy (see Reference (3)). So far, Gerard[12][13] has reported the existence of short-term temporal variations in DIM based on observations made with the Nançay radio telescope in France, and has suggested that there is a significant correlation between the intensity of the solar radio flux at a wavelength of 10.7 cm (the F10.7 flux) and the DIM flux. On the other hand, based on observations made with the Deep Space Network (DSN) radio telescope in the US, Klein[14][15] has suggested that there are no significant short-term intensity variations in DIM that exceed the observation errors. Recently, based on the results of observations made after the SL-9 impact, a number of groups have reported the existence of short-term intensity fluctuations in DIM that are not associated with the SL-9 impact[16]-[20].

The origin of the relativistic electrons in the Jovian radiation belt is thought to be electrons from the solar wind being transported from the outer magnetosphere to the inner magnetosphere by an adiabatic acceleration process called radial diffusion. Since the particle transport is a diffusion process, it is thought that even if the electron flux in the outer magnetosphere fluctuates with a short period, the flux of transported relativistic electrons into the inner magnetosphere (the DIM radiation region) will only fluctuate very gradually. A theoretical study has suggested that if short-term variations are assumed to exist in the DIM intensity, then temporal variations in the radio intensity must either be caused by sharp changes of electron flux inside the Jovian radiation belt, or by temporal changes in the radial diffusion coefficient. The physical processes that could give rise to such variations are still not understood, so the identification of short-term DIM intensity variations should provide valuable information for studies of the electromagnetic environment in the inner Jovian magnetosphere.

To clarify the particle dynamics in the Jovian radiation belt, our group is using some of largest radio telescopes in Japan to observe the temporal variations in DIM intensity in numerous frequency bands, and also is independently developing a radio telescope specifically for observing the Jovian synchrotron radiation[21]. We are also developing a Jovian synchrotron radiation model and a numerical computation code for the transport of electrons in the radiation belt, which should help us to clarify the physical processes involved in the distribution and transport of electrons in the Jovian radiation belt based on DIM observations. In sections 2 and 3 of this paper,

we present the results of our observations of short-term temporal variations in DIM intensity using the 34 m antenna at the CRL Kashima Space Research Center. And in section 4, we discuss the results of our consideration of the dynamics of relativistic electrons that give rise to short-term variations in DIM intensity with model calculations.

2. Observations

In this study, we used the 34 m dish antenna of the CRL Kashima Space Research Center to observe DIM at a frequency of 2290 MHz. This frequency principally corresponds to the synchrotron radiation from electrons with energy of about 20 MeV in the central radiation region (about 1.7 times Jovian radii). The observations were performed over a five-hour period on each observation day (November 12-14, 16-18, 23 and 24, 1996).

The observations of the radio intensities of DIM and radio sources used for flux calibration were performed using an azimuth scan method whereby the antenna was made to move toward the azimuth centered on the target radio source. As the result of a single scan, we obtained an intensity output reflecting the beam pattern of the antenna. We derived the DIM intensity relative to the background by fitting this output to a Gaussian function, including the correction of antenna pointing errors in the azimuth direction. During the observation period, we also made observations in the elevation scan at hourly intervals, and thereby evaluated the antenna pointing error in the elevation angle direction. To convert the observed DIM intensities into absolute values, we also observed the intensities of the standard calibration radio sources 3C286, 3C295, 3C48 and 3C309.1 at hourly intervals during the observation period. The flux data of these standard calibration radio sources were given from Ott et al.[22]. We also calibrated the absorption effects by the terrestrial atmosphere, which was ignored in almost all previous DIM observations. The absorption effect of the terrestrial atmosphere is given by $\exp(-\tau_0 \sec(Z))$, where τ_0 is the optical depth in the zenith direction, and Z is the zenith angle[23]. The system noise temperature of an antenna with a zenith angle of Z is given by the following expression

$$T_{sys}(Z) = T_{RX} + (1 - e^{-\tau_0 \sec(Z)}) \cdot T_{atm}$$
$$\cong T_{RX} + \tau_0 \sec(Z) T_{atm} \quad \cdots\cdots\cdots\cdots\cdots (1)$$

where T_{RX} is the noise temperature of the receiver, T_{atm} is the average temperature of the terrestrial atmosphere. We therefore measured T_{sys} at a number of zenith angles Z for a particular azimuth, and were able to determine the optical depth τ_0 at the azimuth by fitting the results to Equation (1). This is known as the "sky tipping" method, and is described in more detail in Reference (24). For the observations made in this study, we repeated these measurements every 2 hours and used the results to compensate for the effects of absorption by terrestrial atmosphere in the observed DIM and calibration radio source fluxes. To evaluate the receiver stability, we also used the Y-factor method to derive the receiver noise temperature and calibrate the receiver gain fluctuation

due to temperature variation. We converted the DIM fluxes obtained by the above procedure into values corresponding to a Jupiter-earth distance of 4.04 AU, and we then extracted just the Jovian synchrotron radiation component by subtracting the intensity corresponding to the thermal radiation component from the Jovian disk (2.02 Jy at 2290 MHz)[25].

In this study, since our objective is to extract the short-term variation of DIM intensity, it is important to evaluate the average intensity from the apparent intensity variations associated with Jupiter's rotation (beaming curve). However, since our observations only lasted for about 5 hours on each day, it was not possible to acquire data spanning an entire Jovian day (10 hours). We therefore derived the average DIM intensity over a Jovian day by fitting the observed values to a reference beaming curve. The following CML (System III central meridian longitude) Fourier expansion series has been proposed as a reference beaming curve[7], and we adopted this formula for this study.

$$S(\mathrm{CML}) = A_0\left[1 + \sum_{i=1}^{3} A_i \sin(i(\mathrm{CML}+\phi_i))\right] \quad \cdots\cdots (2)$$

where S is the radio intensity at the CML at the time of observation, and A_0 is the average radio intensity over a Jovian day. A_i and ϕ_i ($i=1,2,3$) are functions of D_E (the declination of the earth), and in this study we used empirical values for the beaming curve at 2290 MHz[7].

3. Results

Figure 1 shows the DIM flux (A_0 in Equation (2)) on each observation day. The DIM flux increased from November 13 to November 17, 1996, and on November 17 the flux was 14% higher than that on November 12.

During this observation period, Jupiter's position in the sky ranged between right ascensions of 19^h04^m to 19^h14^m (J2000) and declinations of $-22°55'$ to $-22°44'$ (J2000). If we assume that an unknown radio structure exists in this region of the sky, then the antenna will detect the radio flux variation of this background structure. Consequently, even if the DIM intensity is constant, there will be an apparent fluctuation in the observed results. This mixing of background radio sources has caused serious problems in past observations of DIM flux variations, and is one of the reasons why it has so far been difficult to identify DIM short-term flux variation. Therefore, we made observations to evaluate this mixing of background radiation. These observations were made using the 64 m dish antenna at the Institute of Space and Astronautical Science (ISAS), Usuda Deep Space Center (UDSC), in October 1997, long after Jupiter had moved away from its position when the observations were made at Kashima (November 1996). Figure 1(b) shows the results of these background observations, which confirm that there are no significant background radio structures in the region. We can thus conclude that the DIM flux variations observed at Kashima originated from variations in the intensity of the Jovian synchrotron radiation itself.
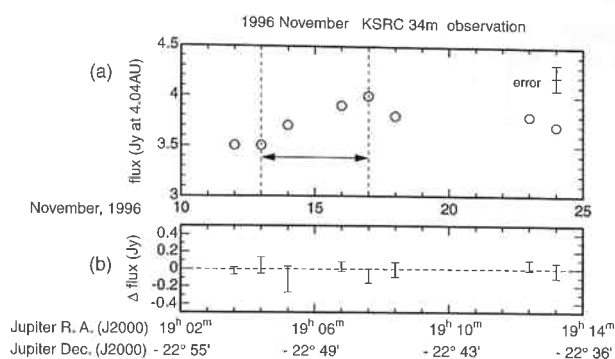
In Fig. 2, the Jovian synchrotron radiation intensity

Fig. 1 (a) Daily average of DIM flux as observed by the 34 m antenna at the CRL Kashima Space Research Center in November 1996. (b) The results of background radio intensity observations made using the ISAS UDSC 64 m antenna in the region corresponding to Jupiter's position in the sky when the observations in (a) were made. The parameter Δflux on the vertical axis shows the difference in background radio intensity between the regions corresponding to the direction of Jupiter and a direction offset from Jupiter in the azimuth scan performed at Kashima.

observed on each day as shown in Fig. 1 is plotted against the Jovian magnetic latitude as seen from the earth. Due to the beaming effect, the peak radiation intensity occurs when Jupiter's magnetic equatorial plane is oriented towards the earth (i.e., when magnetic latitude is 0°) and the radiation intensity decreases when higher latitudes are oriented towards the earth. However, the shape of this curve was found to change from one day to the next. On November 17, when the average radiation intensity reached its highest value, there was a particularly large difference between the radiation intensity when the magnetic equatorial plane was oriented towards the earth and higher latitudes are oriented towards the earth.

In this study, to evaluate the changes in the shape of this curve, we developed a model for calculating the Jovian synchrotron radiation observed on the earth based on the spatial distribution and energy spectrum of relativistic electrons in the Jovian radiation belt, and compared this model with the observed results. The synchrotron radiation intensity $P(E, \nu)$ [W/Hz] at a frequency ν [MHz] due to an electron of energy E [MeV] and pitch angle α located in a background magnetic field B [Gauss] is given by the following formula:

$$P(E, \nu) = 2.34\times10^{-29}B\sin\alpha F(\nu/\nu_c) \quad \cdots\cdots (3)$$

where ν_c [MHz] is the critical frequency, and F is the integral of the modified Bessel function $K_{5/3}$, which are expressed as follows (see, e.g., Reference (26)):

$$\nu_c = 16.08E^2 B\sin\alpha \quad \cdots\cdots (4)$$

$$F(x) = x\int_x^\infty K_{5/3}(\eta)d\eta \quad \cdots\cdots (5)$$

Accordingly, the radiation $W(\nu)$ at a frequency ν due to
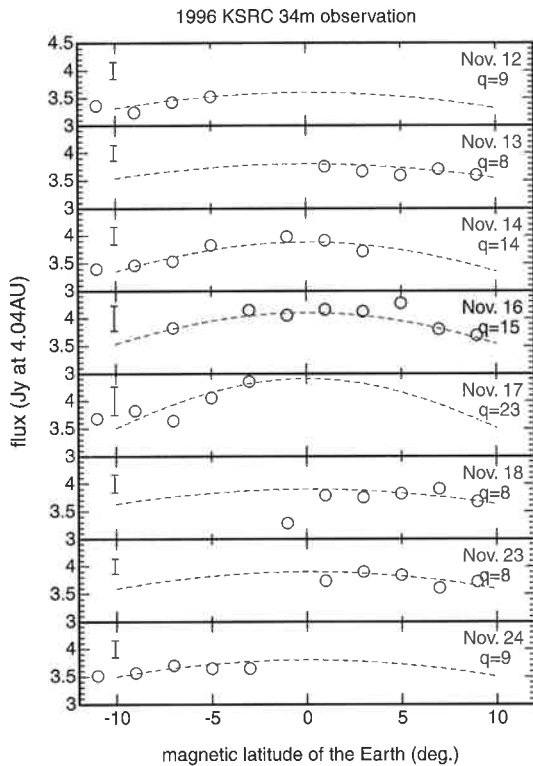
1996 KSRC 34m observation

Fig. 2 The DIM beaming curve for Jupiter's magnetic latitude as seen from the earth. The points represent the observed DIM flux, and the broken line shows the beaming curve obtained from the Jovian synchrotron model by changing the pitch angle distribution of electrons in the Jovian radiation belt. In each figure, q is a parameter for the anisotropy of electrons in the radiation belt used to reproduce the observed beaming curve, which is estimated from model calculations.

all the particles in the Jovian radiation belt can be expressed as follows using the number of particles $N(E, r, \theta, \phi)$ of energy E at a certain point in space (r, θ, ϕ), where r, θ and ϕ are the radius, longitude and latitude:

$$W(\nu) = \int dE \int dr \int d\theta \int d\phi N(E, r, \theta, \phi) P(E, \nu) \cdots (6)$$

This allowed us to calculate the Jovian synchrotron radiation flux, taking effects such as the spreading of radio sources into account. Using these expressions, we calculated the synchrotron radiation observed on the earth at an observation frequency of 2290 MHz, and in particular we quantitatively evaluated the contribution of changes in the spatial electron distribution to the DIM beaming curve. This calculation requires information relating to the magnetic field and particle distribution in the DIM radiation region, and for this purpose we used the empirical magnetic field model[27] and particle distribution model[28] derived from the results of earlier in-situ observations made by the Pioneer spacecraft. Changes in the shape of the curve are generally thought to reflect

changes in the pitch angle distribution of relativistic electrons. Therefore, in these model calculations, we assumed that the distribution of pitch angles α_{eq} in the magnetic equatorial plane is given by $\sin^q \alpha_{eq}$ and calculated the synchrotron radiation flux observed on the earth while varying the anisotropy parameter q of the particle distribution. In this way, we were able to derive the value of q that best reproduced the observed curve. The broken line in Figure 2 shows the curve obtained by model calculations that best fits the observed values. The anisotropy q of the pitch angle distribution derived by comparing the observations with the model calculations showed a large change from 8 to 23 during the period of peak DIM between November 13 and November 17, and then changed back to 8 on November 18. This means that the relativistic electrons in the Jovian radiation belt changed their spatial structure so as to concentrate in the magnetic equatorial plane while the Jovian synchrotron radiation is increasing.

4. Discussion

As stated in section 1, in the current theory relating to relativistic electrons in the Jovian radiation belt, short-term variations of DIM intensity over a time scale of a few days must be caused either by an increase in the relativistic particle flux within the Jovian radiation belt, or by a temporal variation in the radial diffusion coefficient. Focusing on the latter of these possibilities, we used numerical calculations to investigate whether or not temporal changes in the diffusion coefficient are capable of the observed temporal changes of DIM flux.

In this numerical calculation, we tracked the particle transport in phase space by solving the Fokker-Planck equation, which is widely used as a formula for expressing radial diffusion in planetary radiation belts (see, e.g., Reference (29)).

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \sum_{i=1}^{4}\frac{f}{\tau_i} \cdots (7)$$

where f is the phase space density, t is time, and L is a parameter expressing the distance from the planet (known as McIlwain's L). The second terms on the right represent the particle dissipation process in the radial diffusion process by evaluating it as a lifetime. τ_1 and τ_2 represent the dissipation processes due to interaction with Jupiter's rings ($L=1.7$-1.8) and the satellite Amalthea ($L=2.4$-2.7) respectively, of which the lifetime for electrons at 20 MeV is 10^6 [s][10]. τ_3 is the process whereby electrons lose their energy by emitting synchrotron radiation, and is given by $\tau_3 \cong 1/c_1 B^2 E^2$ [s][10]. Here, c_1 is equal to $(2e^4)/(3m_e^4 c^7)$ where e is the elementary charge, m_e is the rest mass of an electron, and c is the speed of light in vacuum. τ_4 represents the process whereby relativistic electrons are scattered by plasma waves in the Jovian radiation belt and disappeared as they precipitated from the magnetosphere into the atmosphere. From the results of the Pioneer and Voyager spacecraft, it has been estimated that $\tau_4 \cong 4.6 \times 10^9 E/L^3$ [s][30].

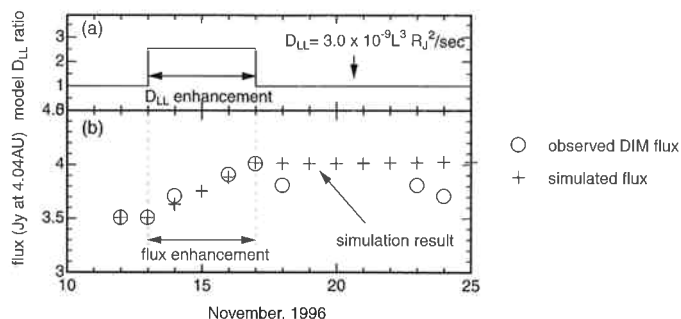In the actual calculation process, we first produced a

Fig. 3 (a) The temporal variation of the diffusion coefficient D_{LL} in the numerical radial diffusion calculations. The horizontal axis shows the date of observations at Kashima, and the vertical axis shows the diffusion coefficient (with the steady-state value normalized to unity). (b) The daily variation of DIM flux observed at Kashima (circles) and the variation of calculated DIM flux while varying the electron distribution in the Jovian radiation belt (solid line).
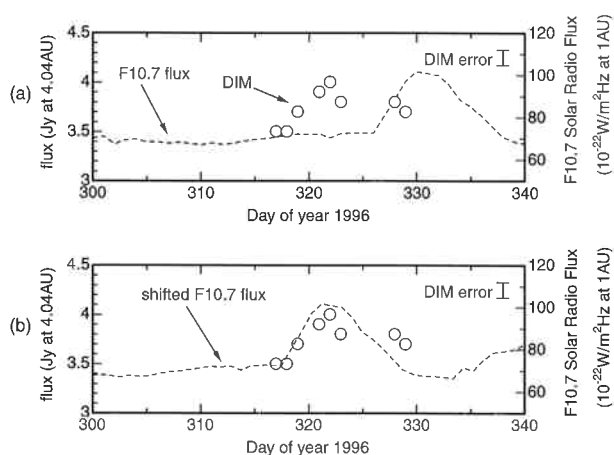

Fig. 4 (a) The DIM flux observed at Kashima (circles) and the daily variation of solar F10.7 observed on the earth (broken line). (b) The DIM flux observed at Kashima (circles) and the F10.7 adjusted for Jupiter's position based on the positional relationship between the earth, the sun and Jupiter in November 1996.

steady-state particle distribution using the value of the diffusion coefficient $D_{LL}=3.0\times10^{-9}L^3R_J^2s^{-1}$ derived from the results of the Pioneer observation[31]. After producing this steady-state distribution, we then changed the value of the diffusion coefficient by a factor of 2.5 in a stepwise function based on the hypothesis that the radial diffusion process was intensified during the period from November 13 to November 17, which is when a larger DIM intensity was observed. Figure 3(a) shows the temporal variation of the diffusion coefficient D_{LL} given by the model calculations. As the boundary conditions for f in the model calculations, we used an external boundary

value derived from the energy spectrum at $L=6$ based on the Pioneer observation[32], and we used an inner boundary value of $f=0$ at $L=1.3$ based on the results of recent observations made by the Galileo probe[33][34].

Figure 3(b) shows the observed daily variation of DIM intensity superposed the DIM intensity calculated from the particle distribution obtained by computing the temporal evolution of the particle distribution while varying D_{LL}. In this figure, to compare the observed results with the calculated results, the calculated DIM intensity is normalized to the observed value for November 12. As the figure shows, the observed increase in DIM intensity is reproduced well in the calculated results. Thus, it is shown that the increase in DIM intensity can be explained by a model where the diffusion coefficient of relativistic electrons increases.

The driving force for the radial transport of relativistic electrons in a planetary radiation belt is generally thought to be local fluctuations in the electromagnetic field. In the terrestrial case, electromagnetic fields fluctuations in the inner magnetosphere are dominated by fluctuations arising from changes in the solar wind rather than fluctuations arising from the dynamo electric field of the terrestrial ionosphere. But since Jupiter has a strong magnetic field of its own, it is thought that changes in the solar wind will have a smaller effect on electromagnetic field fluctuations in the inner magnetosphere, while fluctuations in the ionospheric dynamo electric field will dominate the production of electromagnetic field fluctuations in the magnetosphere[35]. This ionospheric dynamo electric field originates from neutral winds in the Jovian ionosphere, so if there is a change in the neutral wind velocity we can expect increased electromagnetic field fluctuations in the Jovian magnetosphere and changes in the diffusion coefficient. Our model calculations have shown that increasing the radial diffusion coefficient by a factor of 2.5 can explain the observed increase in DIM flux, and — based on Brice and McDonough's theory[35] — is can be deduced that the steady-state diffusion coefficient can be increased by a factor of 2.5 by changing the neutral wind velocity from 95 m/s to 150 m/s at ionospheric altitudes on the field lines corresponding to $L=2$.

So what could be causing such a change in the neutral wind velocity? Brice and McDonough[35] have pointed out that if the solar UV/EUV flux increases, this will promote the heating process in the Jovian ionosphere and may cause the neutral wind velocity to change in the ionosphere. The solar UV/EUV flux is known to have a strong correlation with the solar F10.7, and it has been predicted by Brice and McDonough[35] that a correlation also exist between the solar F10.7 and the DIM flux. Figure 4(a) shows the DIM intensity during the period in November 1996 and the F10.7 observed on the earth. 1996 was a period of low solar activity, and the F10.7 remained more or less stable throughout the DIM observation period and the two previous solar rotation periods. However, it was confirmed that the F10.7 increased for 9 days after the increase in DIM flux. During this period, the solar activity region NOAA 7999 was moving around

the surface of the sun at the same speed as the solar rotation, and the results of observations such as those made by the SOHO spacecraft and the Nobeyama radio heliograph showed that intense radiation was being emitted from this active region over a broad range of frequencies. The data show that this active region was facing towards the earth on November 25, 1996, when there was a peak in the solar F10.7. Judging from the other observation results, the large F10.7 flux observed on the earth at the end of November 1996 was also caused by radiation from this active region.

Therefore, to explain the observed increases in observed DIM flux, we established and investigated the validity of the following working hypothesis: If F10.7 radio waves (i.e., UV/EUV radiation) with a large flux density are radiated directionally within a certain solid angle from an active region of comparatively small size, then due to the difference in longitude of the earth and Jupiter relative to the sun, intense F10.7 radio waves will be radiated toward Jupiter before they are observed on the earth. During the period of observations made at Kashima in November 1996, the angle of longitude formed by the earth, the sun and Jupiter changed from
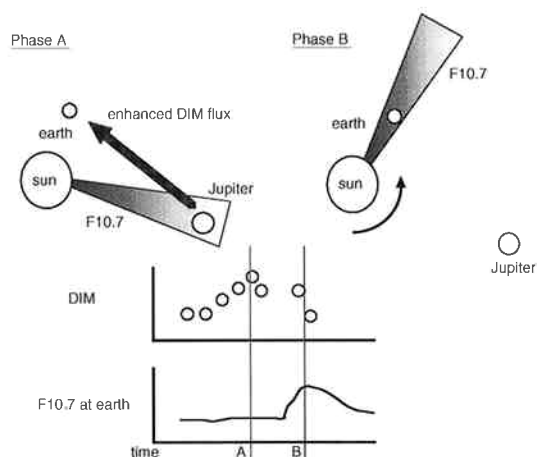

Fig. 5 (Top) A schematic illustration of the positional relationship between the earth, the sun and Jupiter when the Jovian DIM observations were made at Kashima. The shaded region corresponds to the radiation beam of solar F10.7 (UV/EUV). Phase A corresponds to the period when increased DIM flux was observed at Kashima, and Phase B corresponds to the period when increased F10.7 flux was observed on the earth. (Bottom) A schematic illustration of the temporal relationship between DIM observations in the earth and increases in the solar F10.7 as predicted from the scenario in the above figure. In Phase A, increased DIM flux is observed on the earth when intense solar F10.7 radiation (UV/EUV) is directed toward Jupiter, and then in Phase B, an increase in the F10.7 flux is observed on the earth when the solar F10.7 radiation (UV/EUV) is directed towards the earth.

116.5° to 128.4°, with Jupiter situated to the west of the sun as seen from the earth. Accordingly, when F10.7 radio waves are emitted towards Jupiter, resulting in an increase in DIM flux that is observed on the earth, it will not yet be possible to observe the increased F10.7 flux on the earth. But when the active solar region subsequently points towards the earth, the increased F10.7 radio intensity will be picked up by earth-based observations (see Fig. 5).

According to this hypothesis, an observer on the earth should be able to detect a time delay between the increase in DIM flux and the increase in solar F10.7 radio flux. The hypothesis can therefore be tested by deriving the temporal variation of F10.7 radio flux on Jupiter from that observed on the earth, based on the abovementioned phase relationship between the earth, the sun and Jupiter, as shown in Fig. 4(b). As this figure shows, there is a close correspondence between the increased DIM intensity and the increased intensity of F10.7 radio waves at Jupiter's position. This suggests that the increase in DIM intensity observed in November 1996 may be due to increased solar UV/EUV flux (which was previously quiescent), thereby intensifying the radial diffusion in the Jovian radiation belt.

5. Conclusion

In November 1996, we observed the Jovian synchrotron radiation using the 34 m antenna at the CRL Kashima Space Research Center, and confirmed the existence of short-term flux increases with a period of a few days, which have not been identified before. By evaluating the observed beaming curve based on model calculations, we have shown that this increased flux is associated with relativistic electrons in the Jovian radiation belt (which emit synchrotron radiation) changing their spatial distribution so as to concentrate near the magnetic equatorial plane. We have studied enhanced radial diffusion as a possible mechanism for the increase in synchrotron radiation, and by examining numerical simulation based on this scenario, we have shown that the observed increase in synchrotron radiation can be explained by increase in the radial diffusion coefficient. Considering the phase relationship between the earth, the sun and Jupiter at the time of these observations, we also investigated the temporal variation of the solar F10.7, which suggested the possibility that Jupiter has been subjected to intense solar UV/EUV radiation during the period of synchrotron radiation enhancement. This supports the scenario predicted by Brice and McDonough[35], whereby the process of radial diffusion in the Jovian radiation belt is intensified due to the enhanced dynamo electric field in the ionosphere by solar UV/EUV radiation. This result indicates that in the Jovian magnetosphere, disturbances of the electromagnetic field that originate from the planetary atmosphere affect the electromagnetic field of the inner magnetosphere. Our research therefore suggests that the coupling process between a planetary atmosphere and magnetosphere can make an important contribution to the magnetospheric dynamics.

References

(1) Kaiser, M.L., "Time variable magnetospheric radio emissions from Jupiter", J. Geophys. Res., 98, E10, 18757-18765, October 1993.

(2) Sloanaker, R.M., "Apparent temperature of Jupiter at a wavelength of 10 cm", Astron. J., 64, 346, 1959.

(3) Carr, T.D., M.D. Desch, and J.K. Alexanger, "Pheno menology of magnetospheric radio emissions", Physics of Jovian magnetosphere (Edited by A.J.Dessler), pp.226-284, Cambridge Univ. Press, 1983.

(4) de Pater, I., and M.J. Klein, "Time variability in Jupiter's synchrotron radiation", Time variable phenomena in the Jovian system (Edited by M.J.S. Belton, R.A. West, and J. Rahe), pp.139-150, NASA Spec. Publ., SP-494, 1989.

(5) Sault, R.J., T. Oosterloo, G.A. Dulk, and Y. Leblanc, "The first three-dimensional reconstruction of a celestial object at radio wavelengths: Jupiter's radiation belts", Astron. Astrophys., 324, pp.1190-1196, 1997.

(6) de Pater, I., "21 cm maps of Jupiter's radiation belts from all rotational aspects", Astron. Astrophys., 88, No.1-2, pp.175-183, August 1980.

(7) Klein, M.J., T.J. Thompson, and S.J. Bolton, "Systematic observations and correlation studies of variations in the synchrotron radio emission from Jupiter", Time variable phenomena in the Jovian system (Edited by M.J.S. Belton, R.A. West, and J. Rahe), pp.151-155, NASA Spec. Publ., SP-494, 1989.

(8) Bolton, S.J.,S. Gulkis, M.J. Klein, I. de Pater, and T.J. Thompson, "Correlation studies between solar wind parameters and the decimetric radio emission from Jupiter", J. Geophys. Res., 94, A1, pp.121-128, January 1989.

(9) de Pater, I., and C.K. Goertz, "Radial diffusion models of energetic electrons and Jupiter's synchrotron radiation; 2. Time variability", J. Geophys. Res., 99, A2, pp.2271-2287, February 1994.

(10) Hood, L.L., "Long-term changes in Jovian synchrotron radio emission: Intrinsic variations or effects of viewing geometry?", J. Geophys. Res., 98, A4, pp.5769-5783, April 1993.

(11) de Pater, I., C. Heiles, M. Wong, R.J. Maddalena, M.K. Bird, O. Funke, J. Neidhoefer, R.M. Price, M. Kesteven, M. Calabretta, M.J. Klein, S. Gulkis, S.J. Bolton, R.S. Foster, S. Sukumar, R.G. Strom, R.S. LePoole, T. Spoelstra, M. Robinson, R.W. Hunstead, D. Campbell-Wilson, T. Ye, G. Dulk, Y. Leblanc, P. Galopeau, E. Gerard, and A. Lecacheux, "Outburst of Jupiter's synchrotron radiation after the impact of comet Shoemaker-Levy 9", Science, 268, pp.1879-1883, 1995.

(12) Gerard, E., "Long term variations of the decimeter radiation of Jupiter", Radio Sci., 5, No.2, pp.513-516, February 1970.

(13) Gerard, E., "Variation of the radio emission of Jupiter at 21.3 and 6.2 cm wavelength", Astron. Astrophys., 50, No.3, pp.353-360, August 1976.

(14) Klein, M.J., S. Gulkis, and C.T. Stelzried, "Jupiter: new evidence of long-term variations of its decimeter flux density", Astrophys. J., 176, pp.L85-L88, September 1972.

(15) Klein, M.J., "The variability of the total flux density and polarization of Jupiter's decimetric radio emission", J. Geophys. Res., 81, A19, pp.3380-3382, July 1976.

(16) Galopeau, P.H.M., E. Gerard, and A. Lecacheux, "Long-term monitoring of Jupiter's synchrotron radiation with the Nancay radio telescope including the collision with comet P/Shoemaker-Levy 9", Icarus, 121, pp.469-478, 1996.

(17) Galopeau, P.H.M., E. Gerard, and A. Lecacheux, "Modifications of the synchrotron radiation belts of Jupiter two years after the collision with comet SL9", Planetary Radio Emissions IV (Edited by H.O. Bucker, S.J. Bauer, and A. Lecacheux), pp.225-232, Austrian Academy Sci., 1997.

(18) Galopeau, P.H.M., E. Gerard, and A. Lecacheux, "Modifications of the synchrotron radiation belts of Jupiter: evidence for natural variations in addition to SL 9 effects", Planet. Space Sci., 45, No.10, pp.1197-1202, 1997.

(19) Klein, M.J., S. Gulkis, and S.J. Bolton, "Jupiter's synchrotron radiation: observed variations before, during and after the impacts of comet SL-9", Planetary Radio Emissions IV (Edited by H.O. Bucker, S.J. Bauer, and A. Lecacheux), pp.217-224, Austrian Academy Sci., 1997.

(20) Misawa, H., and A. Morioka, "Observations of Jovian decimetric radiation at a frequency of 327 MHz", Adv. Space Res. 26, No.10, pp.1537-1540, 2000.

(21) Misawa, H., Y. Miyoshi, A. Morioka, T. Kondo, M. Kojima, Y. Koyama, and J. Nakajima, "Investigation of Jupiter's inner-magnetosphere with the observations of Jovian decimetric radiations", Proc. 29th ISAS Lunar Planet. Symp., pp.193-196, 1996.

(22) Ott, M., A. Witzel, A. Quirrenbach, T.P. Krichbaum, K.J. Standke, C.J. Schalinski, and C.A. Hummel, "An updated list of radio flux density calibrators", Astron. Astrophys., 284, pp.331-339, 1994.

(23) Kraus, J.D., Radio Astronomy, 2nd edition, Cygnus-Quasar Books, 1986.

(24) Ulich, B.L., J.H. Davis, P.J. Rhodes, and J.M. Hollis, "Absolute brightness temperature measurement at 3.5-mm wavelength", IEEE Trans. Antennas Propagat., AP-28, No.3, pp.367-377, May 1980.

(25) Klein, M.J., S. Gulkis, and S.J. Bolton, "Changes in Jupiter's 13cm synchrotron radio emission following the impacts of Comet SL-9", Geophys. Res. Lett., 22,

No.13, pp.1797-1800, July 1995.

(26) Jackson, J.D., "Classical Electrodynamics", John Wiley and Sons, Inc., 1975.

(27) Smith, E.J., L. Davis, Jr., and D.E. Jones, "Jupiter's magnetic field and magnetosphere", Jupiter (Edited by T. Gehrels), pp.788-829, University of Arizona Press, 1976.

(28) Divine, N., and H.B. Garrett, "Charged particle distribution in Jupiter's magnetosphere", J. Geophys. Res., 88, A9, pp.6889-6903, September 1983.

(29) Schulz, M., and L.J. Lanzerotti, "Particle diffusion in the radiation belts", Springer-Verlag, 1974.

(30) de Pater, I., and C.K. Goertz, "Radial diffusion models of energetic electrons and Jupiter's synchrotron radiation; 1. Steady state solution", J. Geophys. Res., 95, A1, pp.39-50, January 1990.

(31) Goertz, C.K., J.A. Van Allen, and M.F. Thomsen, "Further observational support for the lossly radial diffusion model of the inner Jovian magnetosphere", J. Geophys. Res., 84, A1, pp.87-92, January 1979.

(32) Baker, D.N., and J.A. Van Allen, "Energetic electrons in the Jovian magnetosphere", J. Geophys. Res., 81, A4, pp.617-632, May 1976.

(33) Fischer, H.M., E. Pehlke, G. Wibberenz, L.J. Lanzerotti, and J.D. Mihalov, "High-energy charged particles in the innermost Jovian magnetosphere", Science, 272, pp.856-858, 1996.

(34) Mihalov, J.D., H.M. Fischer, E. Pehlke, and L.J. Lanzerotti, "Energetic trapped electron measurements from the Galileo Jupiter probe", Geophys. Res. Lett., 27, No.16, pp.2445-2448, August 2000.

(35) Brice, N., and T.R. McDonough, "Jupiter's radiation belts", Icarus, 18, pp.206-219, 1973.