A COMPARISON OF RADIO DATA AND MODEL CALCULATIONS OF JUPITER’S SYNCHROTRON RADIATION  
2. EAST-WEST ASYMMETRY IN THE RADIATION BELTS AS A FUNCTION OF JOVIAN LONGITUDE

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Abstract. On the basis of a comparison of radio data and model calculations of Jupiter's synchrotron radiation the 'hot region' or east-west asymmetry in the planet's radiation belts is proposed to be due to the combined effect of an overabundance of electrons at jovianentric longitudes $\lambda_J \sim 240^0-360^0$ and the existence of a dusk to dawn directed electric field over the inner magnetosphere, generated by the wind system in the upper atmosphere. The model calculations were based upon the magnetic field configurations derived from the Pioneer data by Acuna and Ness [1976] (the $O_4$ model) and Davis, Jones and Smith (quoted in Smith and Gulkis [1979]) (the $P_{11}(3,2)A$ model), with an electron distribution derived in the first paper of this series [de Pater, this issue]. We would infer from the calculations that the $O_4$ model gives a slightly better fit to the data; the relatively large number density at $\lambda_J \sim 240^0-360^0$, however, might indicate the presence of even higher order moments in the field.

1. Introduction

This is the second of a series of papers concerning a comparison of radio data and model calculations of Jupiter's synchrotron radiation. The model calculations in this series are carried out such as to produce a two-dimensional display of intensity points similar to a radio map of high resolution data. In order to achieve this, the volume emissivity is calculated at each point in the magnetosphere for different multipolar magnetic field configurations and electron distributions as functions of energy, pitch angle, and spatial coordinates. All the contributions along the line of sight are then summed to produce the model map. In the first paper [de Pater, this issue; henceforth referred to as paper I] as well as in this one, the calculations are based upon the magnetic field configurations derived from the Pioneer data by Acuna and Ness [1976] (the $O_4$ model) and Davis, Jones, and Smith (quoted in Smith and Gulkis [1979]) (the $P_{11}(3,2)A$ model; further cited as the $P_{11}$ model).

The electron motion in these fields is assumed to be completely defined by the adiabatic theory with an inward diffusion as derived from the Pioneer data by Goertz et al. [1979]; we adapted the latter process in order to account for the absorption of electrons and changes in the particles' pitch angle distributions at the orbits of Amalthea and the ring (see paper I for a detailed description of the physics and its mathematical formulation). In paper I we determined the most plausible electron distribution compatible with the synchrotron data at $\lambda_{III} = 200^0$ and the spacecraft observations; in this paper we will compare the radio data with the model while varying the central meridian longitudes. The radio data in this paper are all taken from de Pater [1980: 21 cm data; 1981: 6 cm data].

2. Integrated Flux Density Parameters

Figure 1 shows the variation of the integrated flux density parameters with jovian longitude. The solid line refers to the observations at 21 cm, the dots and triangles indicate the model calculations for the $O_4$ and $P_{11}$ models, respectively, after the total flux density was corrected for a thermal contribution of 0.8 Jy. Indicated are (1) the integrated flux density $S$ in Jy ($= 10^{-26} W m^{-2} Hz^{-1}$), (2) the position angle of the electric vector $PA$ measured eastward from the north in the sky, (3) degree of linear polarization, (4) degree of circular polarization $P_C$ and (5) the magnetic latitude of the earth $\phi_M$ with respect to Jupiter. This latitude was calculated according to the relation $\phi_M = \cos(\lambda_{III} - \lambda_0) [\text{Berge and Gulkis, 1976}]. \lambda_0$ is the declination of the earth relative to Jupiter's rotational equator ($+274\degree$ at this epoch), $\lambda$ is the angle between Jupiter's magnetic and rotational axes taken as $10^0$ and $\lambda_0$ is the longitude of the meridian of the magnetic north pole taken as $210^0$ (Syst. III 1965).

It is clear from the picture that the general beaming characteristics of the models resemble the observations rather well, although the maxima in $S$ are too low and the values in both $P_C$ and $S$ are shifted in longitude. The latter effect appears to be mainly due to the higher order terms in the field ($\geq (2,2)$ term; see paper I), which cause a warping of the magnetic equator, and hence a change in the beaming efficiency. A further discussion/interpretation of these discrepancies is given at the end of this paper.

3. The East-West Asymmetry in the Flux Density Parameters as a Function of Jovian Longitude

The radio data used in this paper show a spatial resolution well enough to clearly distinguish features seen on the left (L) and right (R) sides of Jupiter. We therefore plotted the peak intensities at the L and R sides of each map as a function of central meridian longitude. Figure 2 shows the 21-cm peak intensities of the circularly polarized flux density $V$ (upper part) and the position angle of the electric vector $PA$ (lower part), where $PA$ represents the mean value within a beam area surrounding the peak intensities in the maps of the linearly polarized flux densities. The solid lines represent the observed values at the L side of the planet; the dashed lines at the R side. The various symbols indicate the results of the model calculations for the $O_4$ and $P_{11}$ models: the open dots and triangles represent the peak values at the $R$
were from % side; the fully black symbols at the L side of Jupiter. The small dots show the approximate results for an offset dipole model, for which we have taken the $O_4$ model where all terms $\geq (2,2)$ in the expansion series (equation (2), paper 1) were set equal to zero. It is clear that the trends in the data are matched quite well by the model calculations. The largest deviations in $V$ show up near central meridian longitude $\lambda \sim 20^0$, where the $O_4$ model shows a slightly better fit to the data. The calculations of PA show a rather large discrepancy with the data for the right side of the belt at central meridian longitudes $\lambda \sim 240^0-300^0$. Although certainly observational errors may be partly blamed, the discrepancy, I think, indicates that the field in reality is a little different at the jovieentric longitudes $90^0$ away from these central meridian longitudes. Note, however, that to indicate precisely at which jovieentric longitudes the field deviates from our adopted $O_4$ and $P_{11}$ field models, one needs to consider the data and models in the whole range of longitudes.

Figure 3 shows the ratio of the peak flux densities on the L and R sides of the planet as a function of central meridian longitude. The upper part shows the ratio $S_L/S_R$ for the total intensity, the lower part $P_L/P_R$ for the linearly polarized intensity. The solid line in both parts shows the values observed at 21 cm, the dot-dash line those of 6 cm. Since the total flux density at 6 cm is strongly dominated by the thermal flux density, we could not derive the ratio $S_L/S_R$ at this wavelength with sufficient certainty. The dots and triangles indicate the model calculations for the $O_4$ and $P_{11}$ models, respectively. As in Figure 2 the small dots show the approximate result for the offset dipole model. As predicted in section 3b, paper 1, the 'hot region' in the latter case indeed shows up at the side of the radiation belt where the particles' drift shells lie farthest away from the planet. The higher order terms in the adopted field models, in particular the quadrupole $(2,2)$ terms, cause the calculations to match the observations a little better, which indicates that the so called 'hot region' is formed at least in part, by the difference in the beaming efficiencies between the L and R sides of the belt. The difference between the results for the $O_4$ and $P_{11}$ models can also be explained by this difference in beaming efficiencies.

Although the calculations do fit the curve for the linearly polarized intensities well, it is clear that there is a serious lack of correspondence in the ratio $S_L/S_R$ for the total intensity. In particular, large deviations are found in the central part of the picture ($\lambda \sim 150^0-300^0$). As a first attempt in explaining the large east-west asymmetry here, we increased the number density close to the planet considerably (paper 1), which resulted in a strong disagreement for the calculations in comparison with the observed degrees of polarization and the shape of the emission regions. Moreover, although such an electron distribution fitted the peak value $S_L/S_R$ near $\lambda \sim 200^0$ quite well, it made the agreement at adjacent longitudes in this central part even worse. The increase in electron density hardly influenced the ratio $P_L/P_R$ in the polarized flux densities as function of jovian longitude. Because these curves are mainly governed by the magnetic field structure and because the model calculations of the polarized emission components (Figures 2b and 3) tend to fit the observations (in spite of the discrepancy in Figure 2b at $\lambda \sim 240^0-300^0$), we conclude that the magnetic field configurations represent the field structure quite well. The behavior of the $S$ and $P$ ratios then implies that the observed anomaly in the total flux density must be caused by a longitude variation in the electron density, e.g., by a relative overabundance or underabundance of particles at some specified longitudes. We assumed in this paper, as in paper 1, that the particle distribution in Jupiter's inner magnetosphere is entirely controlled by the magnetic field configuration, where a longitudinal variation in the density of $\leq 30^0$ was induced by the octupole terms in both field models. Since this variation clearly was due to higher order variations in the field configuration, it is not
Fig. 2. (top) The peak values of the circularly polarized flux density $V$, as a function of central meridian longitude on the L (solid line) and R side (dashed line) of the belt from the 21-cm observations. (bottom) The variation of the position angle of the electric vector PA within a beam area surrounding the peak values in the maps of the linearly polarized flux density. The various symbols indicate the model calculations for the O4 and P11 models: the open dots and triangles for the R side of the belt, the fully black symbols for the L side. The small dots show the approximate result for an offset dipole model (see text).

unlikely that we can get larger variations by using even higher order moments in Jupiter’s field. Although the changes in the field itself due to these terms certainly will influence the radiation characteristics, we expect its effect to be small in comparison with the effect of the longitude variation in the electron density. We therefore did not add higher order terms in the field models (which is a rather complicated affair, but probably will be done in the future), but just “played” with the longitude distribution of the electrons to try to find one which fits the variation in $S_L/S_R$ as a function of Jovian longitude. The picture in Figure 3a shows that we need a relative overabundance of electrons at the L side of the belt for the central part of

Fig. 3. The variation of the ratio between the peak intensities L/R in (top panel) the total flux density $S_L/S_R$ and (bottom panel) the linearly polarized flux density $P_L/P_R$ as a function of central meridian longitude. The solid lines refer to the 21 cm observations, and the dot-dash line refers to the 6-cm observations. The dots and triangles indicate the model calculations for the O4 and P11 models, respectively. The small dots show the approximate result for an offset dipole model (see text).
Fig. 4. A sketch of the radiation belts as seen from above. The form of a $B = \text{const}$ contour in the magnetic equator is roughly indicated (too roughly to show a difference between the $Q_4$ and $P_{11}$ models). The only region in common for the L side of the belt at central meridian longitudes in the central region (150°-300°) is shaded.

Considering the sketch of the field in Figure 4, it is obvious that we cannot simply take an overabundance of electrons in a certain longitude range to fit simultaneously the asymmetries observed at both edges of this central part. Moreover, if we could find an overabundance of electrons in a region which would sufficiently raise the radiation from the L side in this region, it would also raise the radiation from the R side outside this region, unless the beaming efficiency then would be very poor. Comparing, however, calculations at central meridian longitudes 180° apart, we would judge from Figure 3 that a difference in beaming effect between both sides of the belt can never account for a large increase in $S_L/S_R$ in the central part and leave the ratios at other longitudes essentially unchanged. We thus can conclude that an overabundance of electrons at certain longitudes alone cannot account for the observed variation in the ratio $S_L/S_R$ as a function of central meridian.

4. The Influence of Electric Fields in Jupiter's Magnetosphere Upon the Distribution of the Relativistic Electrons

In the terrestrial magnetosphere we know that a dawn to dusk directed electric field is induced by the interaction of the solar wind with the earth's field. Fluctuations in this field are taken to be the main driving force for particle diffusion in the magnetosphere. Also winds in the partly ionized upper atmosphere generate electric fields.

In the case of Jupiter, fluctuations in these wind-generated fields are suggested to drive particle diffusion in the magnetosphere [Brice and McDonough, 1973]. Owing to solar heating of the upper atmosphere, a steady wind pattern is set up: pressure gradients will force ions and electrons poleward from the equator on the dayside which returns via an equatorial flow on the nightside. This wind system will cause an approximately dusk-dawn directed electric field $E_J = -\nabla \times B/c$. Brice and McDonough (1973) show that the potential drop over Jupiter due to this wind-generated field $E_J$ might be of the order of several MV; such a potential difference certainly will influence the distribution of the relativistic electrons in Jupiter's radiation belts. In order to determine this effect, we assume the field's radial dependence to be described by $E_{DD} = E_J/L^{3/2}$ [Brice and McDonough, 1973], where $E_{DD}$ stands for the dusk-dawn directed electric field over Jupiter's magnetosphere. We further assume $E_{DD}$ to be aligned with the dusk-dawn direction; thus we neglect possible phase lags in this field, due to Jupiter's rotation.

We can distinguish the following modifications in the electron distribution (see Figure 3):

1. The electrons will gain energy drifting along their paths from the dawnside to the dusk-side and lose it in the other half of their drift paths. Since the particle density decreases with

Fig. 5. A sketch of Jupiter's inner magnetosphere, where the direction of the electric field $E_{DD}$ is indicated, together with the direction of the drift motion of the electrons and protons due to the $V \times B$ term and the direction of the velocity $V_{DE}$ due to the electric field $E_{DD}$. 
increasing energy, there are more electrons with a given energy E at the duskside than at the dawnside, which will result in a larger amount of synchrotron radiation from the duskside. This corresponds to the R side in our maps (see also Brice and McDonough [1973]).

2. Assuming the first adiabatic invariant of the electrons to be conserved, the particles will trace out a slightly different path when their energies change. The velocity $V_{DB} = V_B \times B$ along their drift paths will be modified by the term $V_{DB} = cE \times B/B^2$, which is directed sunward. Although this term is expected to be much smaller than the $V_{DB}$ term, it will cause a noticeable deceleration and acceleration of the electrons at the dawnside and duskside, respectively. Assuming the particle population along their drift paths to be in a steady state, we can write $n \cdot V_B \cdot A = \text{const}$, where $n$ is the number density $\text{cm}^{-3}$ and $A$ is the surface enclosed by two drift shells (see Figure 4 and (11) in paper I). This will yield an increase in the electron density at the dawnside and a decrease at the duskside, just opposite to the effect mentioned in 1.

The model calculations show that all points in Figure 3a are shifted upward by $\Delta 0.15 (0.12-0.18$
might be due to field geometry variations determined by high order moments in Jupiter's field. Since the strength of these terms decreases fast with distance from the planet, we expect the largest variations in the electron density close to the planet. Since the drift shells of the particles near $\lambda_j \sim 240^\circ-360^\circ$ lie much closer to Jupiter than at any other longitude, the field geometry at this side will be relatively strongly influenced by the multipole terms. Thus inserting the appropriate high terms in the magnetic field will allow us to manipulate the equilibrium electron density in the required way.

From a comparison of model calculations to the data, it appears that we require a dusk to dawn directed electric field with a potential across the planet of $\sim 0.5$ MV and some 30% overabundance of electrons in the region $\lambda_j \sim 240^\circ-360^\circ$ to obtain a reasonable fit. The comparison with the data thereby suggests a radial dependence of this excess with a power steeper than $r^{-6}$, which is generated by octupole terms.

The potential across the disk $E_1 \sim 0.5$ MV requires wind speeds of the order of 20 m/s. Figure 6 shows the result for the variation $S_l/S_R$ (upper part) and $P_l/P_R$ (lower part) as a function of central meridian longitude with the above parameters and Figure 7 shows the result for the circularly polarized flux density $V_R-V_L$ and the position angle of the electric vector $PA_R-PA_R$. The latter results mainly show some changes in $V$ with respect to Figure 2, for the L side of the belt in the central region. Figure 8 shows the final result for the integrated flux density parameters as a function of Jovian longitude. A comparison with Figure 1 shows that the beaming characteristics for the $O_4$ model are not changed much, in contrast to those for the $P_{11}$ model, where the agreement with the data has become worse. In fact, all figures together show the $O_4$ model to give a generally better fit to the observations. The most severe discrepancies between the calculations and the data show up in the beaming characteristics of the total flux density at $\lambda \sim 240^\circ-300^\circ$ and the position angle for the R side of the belt at $\lambda \sim 240^\circ-300^\circ$. Perhaps these discrepancies can be settled when we add the appropriate high order terms to Jupiter's field and allow for a slightly different direction of the electric field due to the planet's rotation.

6. Conclusions

On the basis of a comparison of radio data with model calculations of Jupiter's synchrotron radiation, we have shown that the 'hot region' in the planet’s radiation belts cannot be explained by the difference in beaming efficiencies between the left and right sides of the belt alone, which difference is due to the higher order moments in the $O_4$ and $P_{11}$ field models. In addition, we need to have an overabundance of electrons at joviancentric longitudes $\lambda_j \sim 240^\circ-300^\circ$ and the existence of a dusk to dawn directed electric field over the inner magnetosphere. The presence of this field results in a relatively larger amount of radiation from the left (dawn) side of the belt; depending on central meridian longitude the overabundance of electrons will either intensify the radiation from this side at longitudes depending upon Jovian longitude) under the influence of a dusk to dawn directed electric field with a potential across the planet of 1 MV. Hence, effect 2 appears to be stronger than 1. Note, however, that although the disagreement between the calculations and observations in the central part of Figure 3 (at $\lambda \sim 150^\circ-300^\circ$) decreases, we create one at all other longitudes.

5. How to Fit The 'Hot Region'

in Jupiter's Radiation Belts

In sections 3 and 4 we showed that the east-west asymmetry in $S_l/S_R$ (Figure 3a) as a function of Jovian longitude could not be interpreted in terms of a 'hot region' or overabundance of electrons at certain longitudes, nor by a dusk-dawn directed electric field, which effectively increased the synchrotron radiation from the left side in our model calculations at all Jovian longitudes. A third possibility, of course, is a combination of these two effects, such that the too large flux density on the L side Outside the central region can be compensated by an overabundance of electrons on the R side. Looking at Figure 4 the most suitable place for this overabundance is then at joviancentric longitudes $\lambda_j \sim 240^\circ-360^\circ$. In section 3 we suggested that any longitudinal variations in the electron density
\[ \lambda \sim 150^\circ-360^\circ \] or partly compensate for it. As proposed by Brice and McDonough [1973], this electric field may be generated by the wind system in the partly ionized upper atmosphere; a steady wind of \(~20\) m/s is then required for the model which best fits our data. We further propose that the overabundance of electrons could be explained by moments in Jupiter's magnetic field, of higher order than the octupole terms which were included in the calculations.

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References


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