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On elliptical polarization of the decametric radio emission and the linear mode coupling in the Jovian magnetosphere

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Abstract. We consider the origin of the elliptical polarization of Jupiter's decametric emission as a consequence of the moderate linear mode coupling which takes place in the Jovian magnetosphere outside of the source region. We recognize conditions of emission propagation along the ray path which are necessary for forming of the observed polarization characteristic and show that our model explains the main observed properties of the polarization (value of ellipticity, independence of polarization on frequency and time, stability of polarization from storm to storm), does not need low plasma densities in the emission source and does not contradict the modern knowledge on the decametric emission origin. We show that there is no strong correlation between polarization of the emission at the source and the observed polarization. The observed degrees of (linear and circular) polarization have to be assumed as limits of possible degrees of the polarization of the emission escaping the source region. The value of the ellipticity is defined by the level of the magnetospheric plasma density $n_{\rm e}$ in the "transitional region", that is in a part of the ray path where the polarization of the normal waves is essentially elliptical. The plasma density in this region is quite low $n_{\rm e} < 0.4$ cm^{-3} and is related to the local electron gyrofrequency as $n_{\rm e} \propto (f_{\rm Be})^{\nu}$ where $\nu \simeq 1 \div 1.8$.

Key words: planets and satellites: Jupiter – radio continuum: solar system

1. Introduction

The history of investigation of polarization of the Jovian decameter radio emission may be subdivided into two stages. At the first stage, measurements were performed separately using a left-hand (LH) polarized or right-hand (RH) polarized antenna for short times at fixed frequencies (see, e.g., Green & Sherill 1969; Carr et al. 1965) or within a narrow frequency band (Riihimaa 1976). That approach did not claim to obtain a complete pattern of polarization of decameter (DAM) radiation. However, it revealed a number of very interesting details. There is almost total polarization of the emission and a great portion of linear polarization in it, which is unusual for emission of other radio planets (Earth, Saturn, Uranus, and Neptune). It was found that emission of the so-called A and B sources is mainly RH polarized, whereas that of the C and D sources is LH polarized. The major axis of the polarization ellipse is almost perpendicular to the plane between the magnetic field and emission in the region of assumed localization of the sources. Results of those observations gave the possibility to suppose that decameter emission corresponds to the extraordinary mode in the generation region.

The second stage began when qualitatively new results were obtained in ground-based wide-band observations at the Nançay Radio Astronomy Observatory, France (Boudjada & Lecacheux 1991; Lecacheux et al. 1991; Dulk et al. 1992). During those and following experiments, all four Stokes parameters have been measured. This made it possible to calculate the full set of polarization parameters of the emission as a function of both frequency and time: the degree of polarization, the degree of linear and of circular polarization, and the orientation of polarization ellipse. Dulk et al. (1994) report on the complete polarization state of 37 radio storms of decametric radiation from Jupiter as observed with the spectropolarimeter at Nançay. In this work, they summarize results of both left-hand (LH) and right-hand (RH) polarization from all Io-related sources (A,B,C,D), plus two non-Io events. They confirm and extend the findings of three earlier papers. They concluded that emission from all of the sources is 100% elliptically-polarized at all frequencies in the measured range of 10 to 38 MHz, but the degree of linear and circular polarization differs for different sources. This applies specifically to Io-related storms, but the two non-Io storms studied by Dulk et al. (1994) have very similar polarization properties. Emission from the Io-B source shows a higher degree of linear polarization $r_{\rm l}$ and lower degree of circular polarization $r_{\rm c}$ than from other sources. At frequencies near 20 MHz the average degrees of polarization are $\langle r_{\rm l}\rangle \approx 0.87$ and $\langle r_{\rm c}\rangle \approx -0.49$, while for Io-A $\langle r_{\rm l}\rangle \approx 0.66$ and $\langle r_{\rm c}\rangle \approx -0.72$; for Io-C $\langle r_{\rm l}\rangle \approx 0.74$ and $\langle r_{\rm c}\rangle \approx -0.67$. The minus sign corresponds to RH polarization. The LH polarized emission from all sources has a high degree of circular polariza-

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tion and a low degree of linear polarization. At frequencies near 20 MHz, $\langle r_l \rangle \approx 0.51$ and $\langle r_c \rangle \approx 0.85$ (Dulk et al. 1994). In all observations made at Nançay, it was found that the degrees of linear and circular polarization are approximately constant as a function of frequency and time. Dulk et al. (1992) analyzed an extended storm of decametric radiation from the Io-B source which contained both L-bursts and S-bursts, and they found that there is little difference in the ellipticity of L-bursts and S-bursts: at frequencies $f \gtrsim 20$ MHz, the degree of linear polarization of S-bursts is $r_l \approx 0.80$ vs. $r_l \approx 0.87$ for L-bursts.

Warwick (1970) suggests that the observed elliptical polarization results from a linear mode coupling which occurs within the Jovian ionosphere, at the point where the radiation, originally generated in the extraordinary mode towards the planet, is reflected. However, Goertz (1974) has shown that the coupling between two base modes is negligible at the point where the extraordinary wave is reflected. Instead, he suggests that the linear mode coupling occurs in the Jovian magnetosphere. He postulates that mode coupling exists in some "limiting polarization zone", defined as the region of the magnetosphere in which the rate of change of polarization (Ψ^2) of extraordinary and ordinary modes equals the rate of change of phase difference (F^2) between the two modes: $\Psi^2 = F^2$. Beyond this point, the polarization remains constant along the ray path. According to this approach, the observed polarization of the emission is identical to the polarization of the extraordinary mode at the point where $\Psi^2 = F^2$. In his model, the axial ratio (ellipticity of radiation) and inclination of a polarization ellipse essentially depend on the angle between the magnetic field line and a ray path in the "limiting polarization zone", and they change due to rotation of the planet and radiation frequency change. This consequence of his model is in contradiction with new polarization data that we have discussed above. The idea of the "limiting polarization zone" has been used by Calvert (1983), Daigne & Ortega-Malina (1984), Melrose & Dulk (1991) for treating the problem of the origin of decametric radio emission polarization. It is important to note that the theory of linear mode coupling in an inhomogeneous magnetized plasma was developed extensively and independently in studies of solar radio emission polarization (see Zheleznyakov 1970, 1995 and references in these books). These papers clearly show that the "limiting polarization zone" existence does not suffice for effective linear mode coupling and formation of the observed elliptical polarization. For effective coupling, the "limiting polarization zone" must lie in the "transitional region" (TR) where there is transition from quasitransverse (QT) to quasilongitudinal (QL) propagation or vice versa. In other words, the "limiting polarization zone" must be in the region where a radical change of mode polarization takes place. Additionally, it is shown that the quantitative value for estimation of the linear mode coupling efficiency is the ratio Ψ^2/F^2 at some fixed point from TR. This value is not connected directly with the polarization of a normal mode at the point where $\Psi^2 = F^2$ (cf. Goertz 1974). For explanation of the new experimental data, Lecacheux et al. (1991) proposed two possible reasons for the elliptical polarization of the Jovian decametric radio emission. First two linear, characteristic (normal) modes with coherent phases are generated in the source of decametric emission due to a maser generation mechanism. Second, only one mode is generated by a maser mechanism, and the second normal mode is created by strong mode coupling while the emission propagates in a near-vacuum medium. In the first case, the normal modes propagate without mode coupling (or with weak mode coupling) in any part of a path to an observer. Then, the two modes combine at the observer to give elliptical polarization. According to the theory of maser mechanisms, only one mode at most is generated and special conditions are needed in the source to provide simultaneous generation of two coherent modes at the same place and with comparable intensities, for instance $I_o/I_x \simeq 0.3$ (I_o and I_x are the intensities of ordinary and extraordinary waves, respectively) as in the event described by Dulk et al. (1992). If we take into account the unsteady character of the maser mechanism and that the degree of polarization changes very little with frequency and time, then one can infer that this version has a little possibility to be realized in the Jovian magnetosphere. Lecacheux et al. (1991) proposed the second version for the explanation of elliptical polarization of the decametric radiation according to which one elliptical mode is generated, and the original polarization of this mode is retained all the way from the source to the observer. This is the so-called approximation of strong linear mode coupling. This requires that the electron density in and near the source is extremely low $\lesssim 5$ cm^{-3} for 30 MHz. This concept is supported by Melrose & Dulk (1991) who indicated possible reasons for a low density of magnetospheric plasma in the lower magnetosphere and for uniqueness of the polarization at the decametric frequency range.

The linear mode coupling model by Lecacheux et al. (1991) gives a possibility to explain the origin of the ellipticity of the decametric emission. However, this model has a number of serious drawbacks. Among them, extremely low plasma density is needed in and near the source of the emission, which fits badly with the high level of radiation from the source. A frequency and time independence of the observed polarization cannot be understood nor difference of the ellipticity of emission from B and A sources nor the differences between other sources. Different generation mechanisms suggested for decametric emission (e.g. electron cyclotron maser (ECM) instability and plasma mechanisms) are not in agreement with this model. In fact, a plasma model of S-bursts and narrow-band emission developed by Zaitsev et al. (1986); Shaposhnikov & Zaitsev (1996); Shaposhnikov et al. (1996) gives a good self-consistent explanation of many details of the dynamic spectra. However, the corresponding model needs high electron density in the source region, more than that which follows from the linear mode coupling model by Lecacheux et al. (1991). The ECM instability, which is the commonly accepted mechanism for L-bursts, predicts that the axial ratio of the polarization ellipse T is related to the angle of propagation θ relative to the magnetic field in the source region, through $T \approx |\cos\theta|$ for standard ECM theory (Melrose & Dulk 1991) and $T \approx |\cos^3\theta|$ for development theory (Willes et al. 1994). The estimations of Dulk et al. (1994) yield the angle $\theta \simeq 75°$ for Io-B storms, which is consistent with standard cyclotron maser theory. For Io-A and Io-C RH storms, one has $\theta \simeq 66^\circ$, which is only marginally consistent with the theory. However, the standard theory does not work for LH-storms. Development of the standard theory by invoking mildly relativistic electrons streaming along converging field lines as the source of ECM emission does not solve the problem (Willes et al. 1994).

It can easily be seen that all the existing drawbacks of interpretation of polarization observations as a consequence of strong linear mode coupling come from the proposition that the original polarization of emission is retained over the way from the source to the observer and that the observed polarization carries information directly from the source region on the mechanism of emission, e.g. the observed degree of linear polarization of emission hardly depends on the angle of the beam of radiation relative to the magnetic field lines in the source. However, the hard dependency of the observed polarization on the parameters of the emission source is a peculiarity of strong linear mode coupling. In the common case of moderate linear mode coupling considered in the present paper, the polarization characteristics of the observed emission are formed en route from the source to the observer, mainly on those ray path sections where a radical change of mode polarization takes place (in TR), i.e. around the point where the parameters of the magnetospheric (background) plasma satisfy the conditions $|Y \sin^2\theta/2(1-X)\cos\theta| \sim 1$, where $Y = f_{\rm Be}/f$, $X = f_{\rm Pe}^2/f^2$, $f_{\rm Be}$ and $f_{\rm Pe}$ are the gyrofrequency and plasma frequency of electrons, respectively, f being the emission frequency and θ the angle between the magnetic field and the ray path (Zheleznyakov 1970,1995). Thus, the observed polarization does not carry information directly and solely on the source region, but on TR as well, which is not sure to coincide with the source region. Moreover, we show in this paper that giving a strong correlation between the observed polarization and the polarization of the emission in the source allows us to avoid the drawbacks which have been described above.

Our purpose in this paper is to create a model for the origin of the main polarization characteristics of the decametric radio emission based on moderate linear mode coupling in the Jovian magnetosphere which does not contradict modern knowledge on the decametric emission origin, and then to show a possibility to simulate the distribution of plasma density in the Jovian magnetosphere based on the measurement of decametric emission polarization. In Sect.2, we present equations for transfer of polarized emission in inhomogeneous magnetized plasma and give a parameter which defines an efficiency of the linear mode coupling. In Sect.3, we give numerical solutions of the transfer equation and find conditions in the Jovian magnetosphere necessary for the self-consistent explanation of the polarization observations. In Sect.4, we discuss our results.

2. The linear mode coupling of the electromagnetic waves: equations and interaction parameter

It is well known that in a homogeneous magnetoactive plasma electromagnetic radiation propagates as two independent normal waves (extraordinary and ordinary) with refractive index (Budden 1961)

$$n_{\rm e,o}^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y^2\sin^2\theta \mp D},$$
$$D = \sqrt{Y^4\sin^4\theta + 4Y^2(1-X)^2\cos^2\theta}. \quad (1)$$

Here the "minus" sign and the subscript "e" correspond to the extraordinary wave, the "plus" sign and the subscript "o" to the ordinary wave. The part transverse to the direction of propagation of polarization of these waves is generally elliptical; the axial ratio of the polarization ellipse is defined by

$$T_{\rm e,o} \equiv -\imath\frac{E_{\rm x}^{\rm e,o}}{E_{\rm y}^{\rm e,o}} = q \mp {\rm sign}(q)\sqrt{1+q^2} \quad (2)$$

where

$$q = \frac{Y\sin^2\theta}{2(1-X)\cos\theta}, \quad (3)$$

$E_{\rm x,y}^{\rm e,o}$ are components of the electric field of the waves in a plane perpendicular to the direction of propagation. The z-axis is directed along the ray of emission, the x-axis lies in the plane of the vector of the magnetic field $\boldsymbol{B}$ and the ray of emission. The upper sign in Eq. (2) pertains to the extraordinary wave, while the lower sign pertains to the ordinary wave. The sign $T_{\rm e,o}$ determines the sense of polarization: $T_{\rm e} < 0$ and the extraordinary wave is RH polarized while $T_{\rm o} > 0$ and the ordinary wave is LH polarized if $q > 0$, and vice versa if $q < 0$. The degree of circular polarization $r_{\rm c}$ can be represented via the coefficient of polarization $T_{\rm e,o}$, Eq. (2), by

$$r_{\rm c}^{\rm e,o} = \frac{2T_{\rm e,o}}{1+T_{\rm e,o}^2}. \quad (4)$$

For 100% polarized radiation $r_{\rm l} = \sqrt{1-r_{\rm c}^2}$. So, the parameter q determines the polarization of the normal waves. If $q^2 \ll 1$, we have QL propagation and the polarization of waves of both types is close to circular, $T_{\rm e,o} \simeq \mp 1$ and $r_{\rm c}^{\rm e,o} \simeq \mp 1$. If the inverse inequality $q^2 \gg 1$ is valid, we have QT propagation, and the polarization of the normal waves is almost linear $T_{\rm e} \simeq -1/2q$, $T_{\rm o} \simeq 2q$, and $|r_{\rm c}^{\rm e,o}| \ll 1$. In the intermediate case $q^2 \sim 1$, the polarization of the normal waves is essentially elliptical. The region of the magnetosphere along the emission ray path where $q^2 \sim 1$ we call the "transitional region" (TR).

In a smoothly inhomogeneous magnetoactive plasma

$$\frac{2\pi f}{c} n_{\rm e,o}\Lambda \gg 1 \quad (5)$$

radiation may propagate as two independent normal waves. The refractive index and the polarization coefficient of these waves are described by Eqs.(1) through (3), but the parameters X, Y, and θ are functions of space. This is the approximation of a local homogeneous plasma or the geometric-optic (GO) approximation. In Eq (5) Λ is a characteristic scale of inhomogeneity of the magnetic field and the plasma density along the ray path, and c is the velocity of light. If

$$\frac{2\pi f}{c}|n_{\rm e}-n_{\rm o}|\Lambda \lesssim 1 \tag{6}$$

in the range of validity of the inequality Eq. (5), then the propagation of radiation cannot be described in terms of two independent normal waves. However, one can assume that the radiation propagates as two coupling normal modes, i.e. there is a linear transformation of waves of one type into waves of another type.

The transfer of the polarized emission can be described by the equation

$$\frac{{\rm d}T}{{\rm d}\zeta} = \imath\frac{n_{\rm o}-n_{\rm e}}{2\sqrt{1+q^2}}(T+\sqrt{1+q^2}-q)(T-\sqrt{1+q^2}-q) \tag{7}$$

which follows from the Maxwell equations for the ratio $T = -\imath E_{\rm x}/E_{\rm y}$, where $E_{\rm x,y}$ are the components of the complex amplitude of the electric field of emission. In Eq. (7) $\imath = \sqrt{-1}$, $\zeta = (2\pi f/c)z$ is the dimensionless coordinate along the ray path. This equation has been deduced for both weakly inhomogeneous magnetized plasma (Eq.(5)), where opposite propagated waves are independent, and weakly anisotropic plasma

$$|n_{\rm e}-n_{\rm o}| \ll 0.5(n_{\rm e}+n_{\rm e}), \tag{8}$$

where the difference in ray paths of extraordinary and ordinary modes is negligible (see Zheleznyakov et al. 1979, Zheleznyakov 1995 for details). Equation (7) does not take into account a shear of the magnetic field lines. In this case, the degrees of polarization are

$$r_{\rm l} = \cos(2\arctan\Phi) \tag{9}$$

$$r_{\rm c} = \mp\sqrt{1-r_{\rm l}^2} = \mp\sin(2\arctan\Phi) \tag{10}$$

where

$$\Phi = -\frac{4\Re{\rm e}T}{(|T-1|+|T+1|)^2}, \tag{11}$$

$\Re{\rm e}T$ is the real part of T.

It is helpful to rewrite the transfer equation in the form of a Ricatti equation

$$\frac{d{\rm P}}{d\eta} = \imath(P^2-1)+\frac{2\imath}{Q}P \tag{12}$$

which follows from Eq. (7) after substitution of T

$$T = \frac{P-\imath(\sqrt{1+q^2}-q)}{\imath+P(\sqrt{1+q^2}-q)} \tag{13}$$

and new coordinate η along the ray path[1]

$$\eta = \frac{\pi}{4}+\frac{1}{2}\arctan q. \tag{14}$$

[1] q being defined by Eq.(3) as a function of coordinate ζ

In Eq. (12), the function Q introduced by Cohen (1960) is the ratio of the rate of change of polarization (Ψ^2) of normal waves to the rate of change of the phase difference (F^2) between two modes. In a low density plasma, $X \ll 1$, the function Q is

$$Q \equiv \frac{\Psi^2}{F^2} = \frac{c{\rm d}q/{\rm d}z}{2\pi f(n_{\rm e}-n_{\rm o})(1+q^2)} \tag{15}$$

Note that with new the variable η, we can study propagation of polarized emission without specification of the behavior of magnetic field and plasma density along the ray path.

From Eq. (12), we can see that function Q (see Eq. (15)) along the ray completely determines the change of polarization of the propagating emission. This function is a coefficient of a differential equation, while the linear transformation is an integral effect accumulated over all the path from the source to the observer. For analysis of the integral effect of linear mode coupling, the differential parameter Q in the form Eq. (15) is conveniently used either in the limiting cases $|Q| \gg 1,\ \ |Q| \ll 1$ with variable value of Q or in the case $|Q| = const$ over all the path. The limiting case $|Q| \ll 1$ corresponds to validity of the geometric-optic approximation over all the path from the source to the observer. Another limiting case, $|Q| \gg 1$, corresponds to strong linear mode coupling. This case has been discussed by Lecacheux et al. (1991). For arbitrary Q, the efficiency of linear mode coupling depends essentially on the plasma density and magnetic field distribution along the ray path. We can simplify the analysis by taking into account that the ray path of propagated emission can be divided into sections of QT propagation, QL propagation and TR. According to the advanced theory of linear mode coupling (see Zheleznyakov 1970, 1995), effective coupling takes place only in TR. The polarization of the normal waves is elliptical there, and variations of the function Q inside of TR determine the process of the linear mode coupling. If the variations of the function Q inside of TR do not exceed by an order of the magnitude the function itself, this function and the efficiency of the transformation can be characterized by the value Q_0 of the function Q at some fixed point from TR. Since this region obligatorily includes the point of the ray path for which $q^2 = 1$, one can define Q_0 as

$$Q_0 = |Q|_{q^2=1}. \tag{16}$$

Subsequently, the value Q_0 is called as an interaction parameter. If $Q_0 \ll 1$, the emission propagates as two independently normal modes and its polarization changes according to geometric-optic laws. If $Q_0 \gg 1$, the effect of strong linear mode coupling takes place. The emission propagates as in a vacuum. The case $Q_0 \sim 1$ corresponds to the intermediate case of moderate linear mode coupling. This case will be studied in the next section.

3. The effect of linear mode coupling of electromagnetic waves: a model of plasma distribution and numerical solution

The rigid solution of the equation Eq. (12) (or Eq. (7)) under the condition $Q_0 \sim 1$ exists only for specific distributions of plasma density and magnetic field, which are not in agreement with conditions within the magnetosphere of Jupiter. Therefore, in this section we find numerical solutions of the linear mode coupling equation. As follows from the previous section, for numerical solution of the linear mode coupling equation, it is sufficient to describe the distribution of the magnetospheric plasma density along the ray path in TR. The location of TR in the Jovian magnetosphere varies with the emission frequency and time. Its place in the magnetosphere is mainly defined by a height of emission source and the angle θ between the direction towards an observer and the magnetic field in the source. The sources of the decametric emission at different frequencies f are located at heights corresponding to gyrofrequency levels $f_{\rm Be} \simeq f$. This causes changes with frequency of both ray path height and θ. Moreover, the angle θ can vary while CML changes due to planetary rotation and the lack of magnetic field symmetry relative to the planetary spin axis. Note here that ellipticity of emission escaping the Jovian decametric source is completely defined by the angle θ in the source. Thus, for every given decametric radio emission storm occupying some region in frequency-time space, we have a number of "transitional regions" located in a certain domain of the Jovian magnetosphere. In this magnetosphere domain, the essential linear mode coupling may take place. We will call the magnetosphere domain occupied by the "transitional regions" during a storm the "interaction region" of the magnetosphere (IRM) for a given emission storm.

To find a plasma density distribution in an IRM, we use observational data of the polarization taking into account that variations of Q in TR and Q_0 as functions of gyrofrequency $f_{\rm Be}$, plasma frequency $f_{\rm Pe}$, and emission frequency f are the same. In general, the interaction parameter Q_0 depends on the variables[2] $f_{\rm Be}$, $f_{\rm Pe}$, and f. If we take into account that, for Jovian decametric radio emission $f_{\rm Be}$ and $f_{\rm Pe}$ are functions of f (due to dependence of the height of decametric source on emission frequency), then we treat Q_0 as a function of only two variables, $f_{\rm Be}$ and $f_{\rm Pe}$. By fitting values of Q_0 with observed values of emission ellipticity for different frequencies and CML, we can find a relation between $f_{\rm Pe}$ and $f_{\rm Be}$ at every point of the IRM. We search for a recurrent relation between $f_{\rm Pe}$ and $f_{\rm Be}$ in form

$$f_{\rm Pe} = K \cdot (f_{\rm Be})^{\nu}, \tag{17}$$

where the coefficient K is found by fitting the calculated degrees of polarization with those obtained from observations at a fixed frequency, and the power ν is obtained from observed frequency dependency of polarization at fixed time. The distribution of plasma density in IRM and position of IRM in the magnetosphere can be evaluated if we adopt a definite model of the Jovian magnetic field.

The main explanatory abilities of the proposed model can be shown for a simple example of a dipole magnetic field where the magnetic momentum coincides with the spin momentum of the planet. We assume that the sources of the decametric emission at different frequencies f are located along the same magnetic field lines at heights associated with gyrofrequency levels $f^{\rm s}_{\rm Be} \simeq f$. These magnetic force lines belong to L-shells passing through the satellite Io. Only one extraordinary mode is excited in these sources, approximately perpendicular to the magnetic field lines when the condition of QT propagation ($q \gg 1$) is fulfilled. For simplicity, we assume $q > 0$ here and in the rest of the paper.

[2] The angle θ is excluded due to the condition $q^2 = 1$ under which the parameter Q_0 is defined. Variation of the angle θ results in a change of location of TR on the ray path.

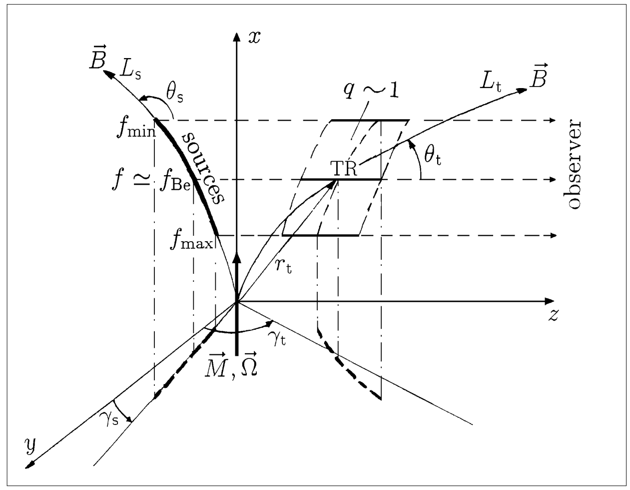

Fig. 1. Schematic view of our model for fixed time. The source at each frequency is located along the magnetic field line; $f_{\max}$ and $f_{\min}$ are the maximum and minimum frequencies of a decametric radio emission storm at the fixed time. The "transitional region" (TR) for emission at a frequency f is located along the ray path from the corresponding source near the point $q = 1$.

The geometry of the problem is shown in Fig. 1: $\theta_{\rm s}$ and $\theta_{\rm t}$ are the angles between the ray path and the magnetic field lines, $\gamma_{\rm s}$ and $\gamma_{\rm t}$ the angles between meridian planes and the Jovian limb (xy-plane), $r_{\rm s,t} = R_{\rm s,t}/R_{\rm J}$, $R_{\rm s}$ and $R_{\rm t}$ the distances from the center of the planet, $R_{\rm J}$ the Jovian radius, $L_{\rm s,t}$ the L-shells of the magnetic field. The z-axis is directed towards the observer, the x-axis directed along the spin momentum of the planet. Values indicated by the subscript "s" pertain to the source region, while those indicated by the subscript "t" pertain to TR. The L-shell along which the sources are located is defined as $L_{\rm s} = 6.0$.

The frequency dependence of the ellipticity of polarization of the observed emission is due both to the frequency dependence of the polarization ellipticity in the source (because of a variation of the angle $\theta_{\rm s}$ between the magnetic field and the direction towards the observer at different gyrofrequency levels) and to the efficiency of the linear mode coupling in TR. If emission is generated approximately perpendicular to the magnetic field, the variation of $\theta_{\rm s}$ with frequency can be neglected, and from Eqs. (1),(3),(15),(16) and the requirement of independence of the polarization ellipticity on frequency, we derive $\nu \simeq 0.66$. This value of ν is used in the following calculations for all values of $\theta_{\rm s}$. We return to a discussion of the value of ν below. The coefficient K in Eq. (17) is a fit to calculated degrees of linear polarization obtained from observations at $f = 20$ MHz. Bearing in mind the interpretation of the polarization data on

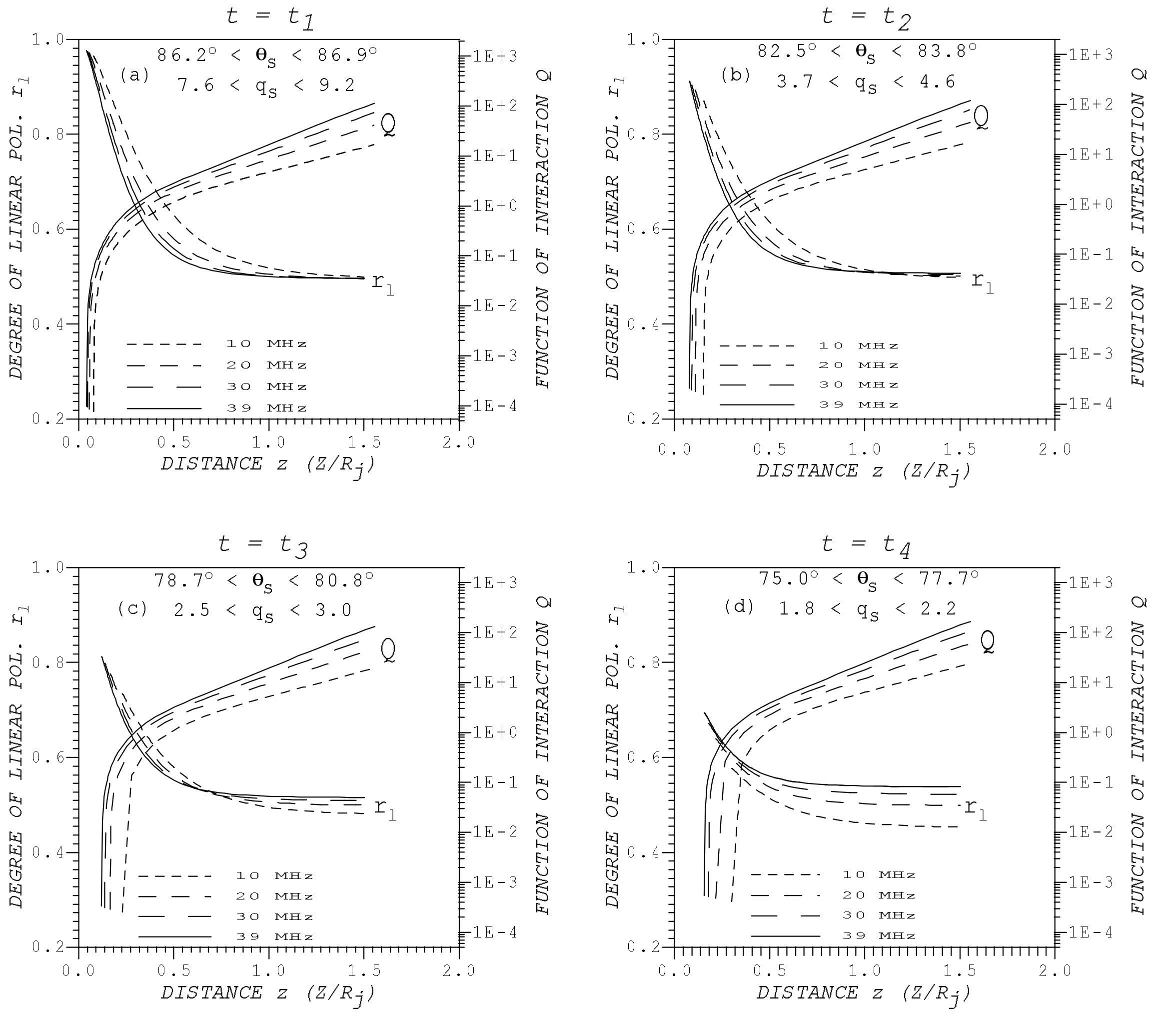

Fig. 2a–d. The degree of linear polarization r_l and the function of interaction Q as function of distance from the source for different angles θ_s and the degree of linear polarization $r_l^{obs} = 0.50$ for 20 MHz.

the Jovian decametric emission, we choose magnitudes of the observed degree of linear polarization as $r_l^{obs} = 0.85,\ 0.65$, and 0.50. These correspond to average values observed near 20 MHz at sources B, A and LH polarized, respectively. For numerical solution of linear mode coupling we have used equation (7).

Fig. 2a-d show the degree of linear polarization r_l and the interaction function Q plotted as functions of distance z from the source assuming the frequencies of emission $f = 39,\ 30,\ 20$, and 10 MHz. These frequencies overlap all the measured decametric frequency ranges. We have assumed that the degree of linear polarization $r_l^{obs} = 0.50$ for 20 MHz corresponds to the observed average ellipticity of the LH polarized emission. In the top of each picture, we show the angle θ_s and the parameter q_s in the sources of emission located along the magnetic field line at gyrofrequency levels from 10 MHz to 39MHz. The different ranges of variation of θ_s in versions (2a) through (2d) simulate changes of this angle in time due to variation of both source longitude and direction of the magnetic field lines in the source. These figures illustrate the dynamics of frequency and time variation of the computed degree of linear polarization along the ray path. The plasma density calculated according Eq. (17) and the coordinates of TR as functions of the emission frequency and angle θ_s are shown in Fig. 3. The curves labeled (t_1) through (t_4) in Fig. 3 correspond to the versions as shown in Fig. 2a through Fig. 2d, respectively, and simulate a distribution of plasma density in IRM and the location of IRM in the magnetosphere for a given decametric radio emission storm. This plasma density distribution provides independence of the observed polarization of frequency and time for emission storms occupying the frequency range from 10 to 39 MHz and time intervals during which the angles θ_s are changed by an amount less than or equal to about 8°. In this case, the polarization variations due to frequency and time dependence of θ_s stay inside the range defined by the accuracy of measurements, defined as 15% (Dulk et al. 1994). Fig. 4 shows the degree of linear polarization for B, A and LH polarized sources at a fixed time, as well as the plasma densities along the curve $q = 1$.

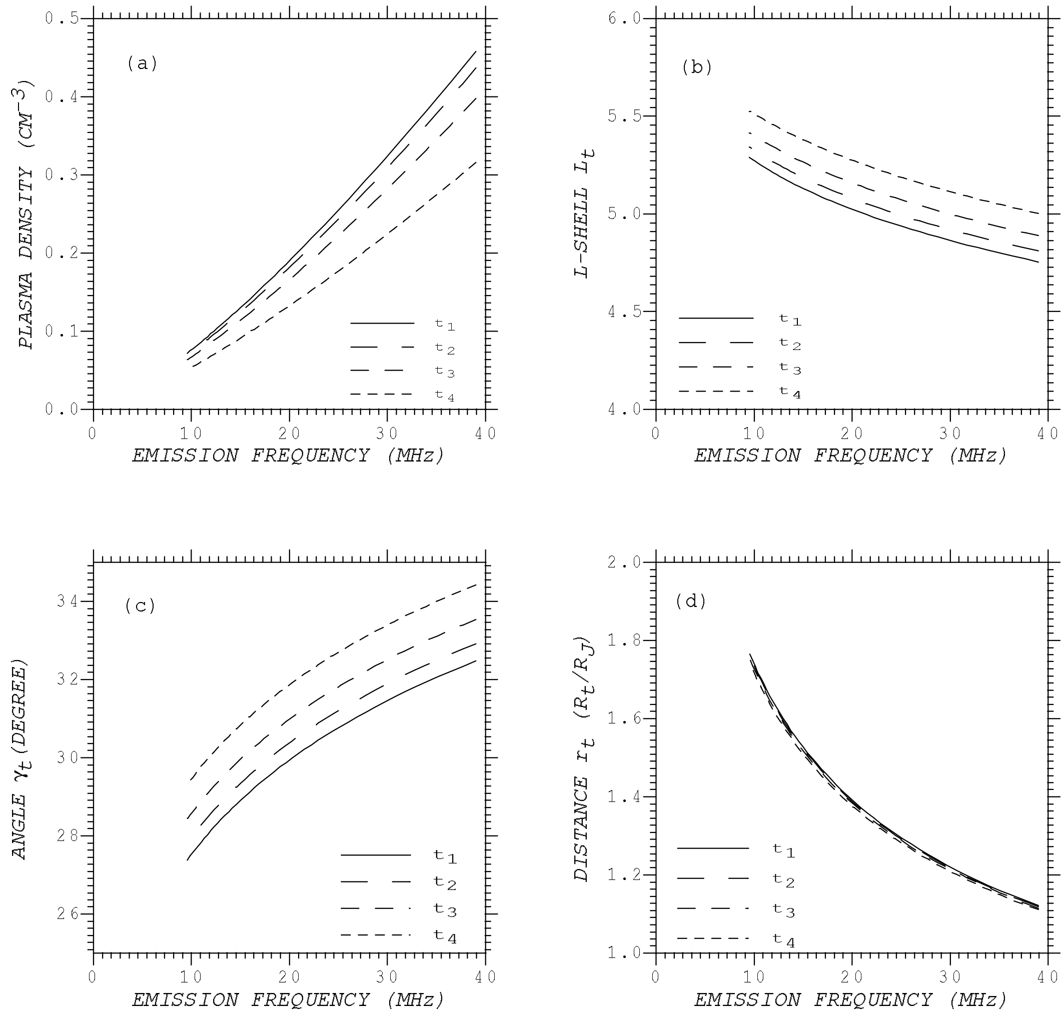

Fig. 3a–d. The plasma density in TR and the location of this region as functions of the emission frequency f and angle θ_s.

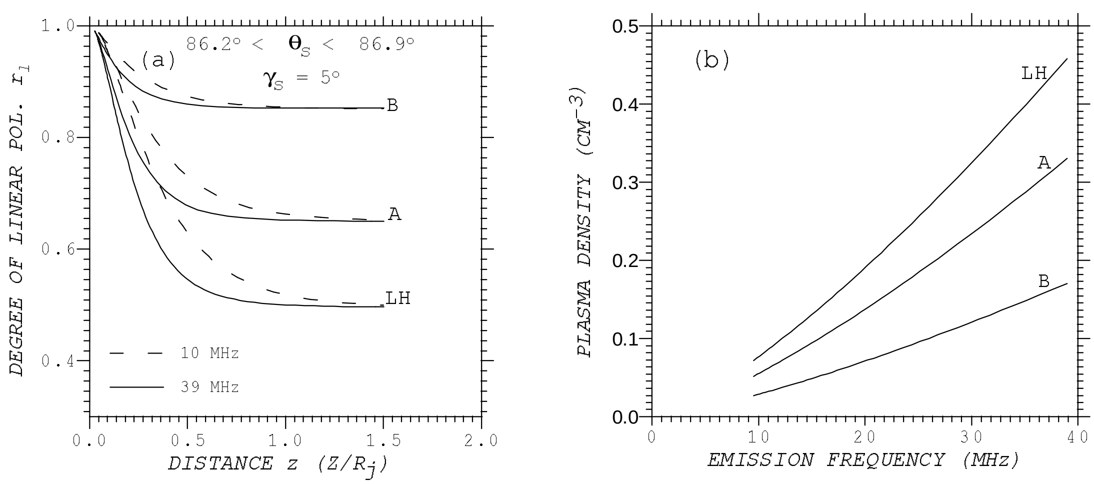

Fig. 4a and b. The degree of linear polarization for sources B (r_l^{obs} = 0.85), A (r_l^{obs} = 0.65), and LH polarized sources (r_l^{obs} = 0.50) at a fixed time (**a**) and the plasma densities in TR (**b**).

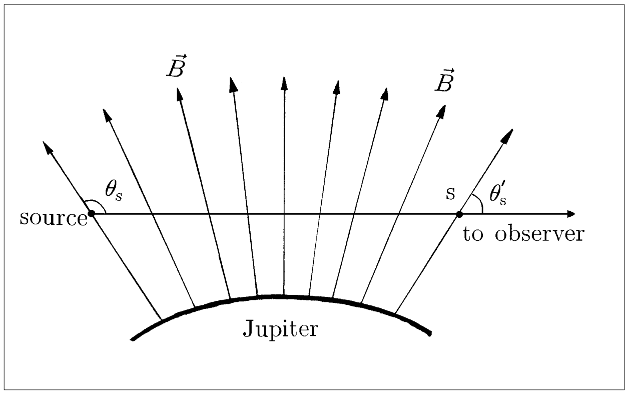

Fig. 5. Propagation of the emission through the Jovian limb

All our calculations are valid for both the east and the west sides of the Jovian globe and for both northern and southern latitudes of the sources. The difference between the northern and southern hemispheres can be seen in the sign of the degree of circular polarization. In the northern hemisphere, we choose the plus sign for q, while the minus sign pertains to the southern hemisphere. Our calculations can be applicable also to some sources located behind the limb (i.e. if $\gamma_s < 0°$) and to the possibility to observe RH polarization in this case, where $\theta_s > 90°$. The LH polarized emission escapes the sources in this case (see Eqs. (2) and (3)). If the emission propagates as in vacuum, i.e. under condition $Q \gg 1$, the LH polarization is retained along the path, while the longitudinal component of the magnetic field will become the opposite. If $Q \ll 1$, the sense of polarization rotation changes sign while the longitudinal component of the magnetic field changes sign. In dipole magnetic fields, the latter variant can occur. In fact, according to our calculations (Fig. 2) the interaction function Q decreases sharply below unity nearby the source. This is a consequence of the emission frequency f being close to f^{s}_{Be}, so that $1 - Y^2 \ll 1$ while $Q \propto 1 - Y^2$. This means that the geometric-optic approximation is valid close to the source. As we will see in the next section, this can occur in the sources of Jovian decametric emission. It can be easily seen from Fig. 5 that the local electron gyrofrequency f_{Be} is higher at the limb region than at the source. This means that the magnitude of the interaction function Q is less here then at the source, i.e. $Q \ll 1$ here as well, and the polarization of emission changes in accordance with the geometric-optic law: the LH polarization behind the limb is replaced by RH polarization in front of the limb. The following change of polarization of this emission is the same as that of emission escaping the source S' which is symmetrically located relative to the limb plane. If we take into consideration magnetic multipoles, the LH polarization can be observed as well. Thus, our calculation can be valid for angles both $\gamma_s > 0°$ and $\gamma_s < 0°$, and the RH polarization can be observed while $\gamma_s < 0°$.

Finally, we discuss the validity of the transfer equation of polarized emission in form Eq. (7) deduced in the approximation of weak anisotropy (inequality Eq (8)) in the Jovian decametric radio emission context. The inequality Eq (8) is violated in the sources where $f \simeq f^{s}_{Be}$ and θ^{s} is close to $\pi/2$. The approximation of weak anisotropy is needed to neglect a difference between the ray paths of extraordinary and ordinary modes when the Eq. (7) is deduced. However, there exists only one mode - extraordinary - in sources of decametric radio emission and their vicinities. In this case, the transfer equation of polarized emission in the form Eq. (7) is valid despite violation of the inequality Eq. (8). The second mode - ordinary mode - appears only in TR due to linear mode coupling, but the inequality Eq. (8) is fulfilled here.

4. Discussion

Fig. 2 shows that violation of the vacuum approximation (i.e. inequality $Q > 1$) in and near the source has no influence on the ellipticity of the observed emission. The violation of the vacuum approximation occurs in the plasma model of sources of the S-bursts and narrow band emission due to high plasma density (but $f_{Pe}/f_{Be} \ll 1$) and generation of electromagnetic emission close to the "cut off" frequency $f_{co} \simeq f_{Pe} + f^2_{Pe}/f_{Be}$. In the electron cyclotron maser (ECM) source the vacuum approximation hardly ever occurs. In fact, the emission in this source is generated due to ECM instability and is confined in narrow frequency bands close to the "cut off" frequency f_{co} (Hewitt et al. 1982). Assuming $1 - Y^2 \simeq X \simeq f^2_{Pe}/f^2_{Be}$, we obtain from Eqs. (1),(3) and (15) the condition of the validity of the vacuum approximation ($Q \gtrsim 1$) in an ECM source

$$\frac{f}{c}\Lambda \lesssim 1, \tag{18}$$

fulfilled in the decametric frequency range if the characteristic scale of change of the magnetospheric plasma in the source region is $\Lambda \lesssim 30$ m. Existence of such scales can hardly be imagined in the Jovian magnetosphere. The condition Eq. (18) is obtained if the dispersion relation of the normal waves is primarily determined by the cold component of the magnetospheric plasma. On the other hand, if the energetic electrons represent the dominant component, the dispersion relation can be affected and modified by these electrons. For an inequilibrium distribution function, a loss-cone one for instance, the dispersion equation has a complicated expression, but we obtain instead of Eq. (18) the following condition for a Maxwellian distribution:

$$\frac{f^2_{P}}{f^2_{Be} c\beta_{th}} f\Lambda \lesssim 1, \tag{19}$$

where f_P and $c\beta_{th}$ are the plasma frequency and the thermal velocity of the energetic component of the plasma, respectively. The condition Eq. (19) is obtained if $f^2_P/f^2_{Be}\beta_{th} \ll 1$ (see in this connection Akhiezer et al. 1974). For instance, for $\beta_{th} \simeq 0.14$ (which corresponds to the energy of the plasma $E \simeq 5$ keV) the inequality $f^2_P/f^2_{Be}\beta_{th} \ll 1$ is valid up to magnitudes of plasma density $\ll 1.5 \cdot 10^6$ cm^{-3} in the 39 MHz sources. However, the inequality Eq. (19) itself can occur in low density plasma $\lesssim 0.3$ cm^{-3}. If the inverse inequality $f^2_P/f^2_{Be}\beta_{th} \gg 1$ is fulfilled, we can use the condition in form Eq. (18).

It can be easily seen from Fig. 2 that there is no strong correlation between the ellipticity of the emission at the observer and the polarization at the source. The ellipticity is determined by the level of the magnetospheric plasma density in TR. The plasma density in this region is quite low $< 0.4\,\mathrm{cm}^{-3}$. The simplest hypothesis for the origin of the low plasma density in the Jovian magnetosphere is discussed by Melrose & Dulk (1991). Following their speculations, we find that the plasma density falls to less then 0.4 cm^{-3} at radial distances $\gtrsim 1.2R_\mathrm{J}$. These values are in good agreement with those predicted by our model. However, we emphasize that our model of the origin of the decametric polarization as the consequence of moderate linear mode coupling does not require low plasma density nor validity of the vacuum approximation in the source itself. The plasma density can be higher there due to electrons present in the magnetic flux tube because of an electrodynamic interaction between Io and the Jovian magnetosphere.

From the observed degrees of polarization of emission, one has to assume limits on the emission escaping the source i.e., $r_\mathrm{l}^\mathrm{s} \geq r_\mathrm{l}^\mathrm{ob}$ and $|r_\mathrm{c}^\mathrm{s}| \leq |r_\mathrm{c}^\mathrm{ob}|$. The observed polarization degree limits the range of the allowable angle between the magnetic field lines and the emission ray at the source: a decrease of θ_s results in an increase of circular polarized emission in the source (see Eqs. (2) through (4)), which is limited by inequality $|r_\mathrm{c}^\mathrm{s}| \leq |r_\mathrm{c}^\mathrm{ob}|$. From Eqs. (2) through (4) and $|r_\mathrm{c}| = \sqrt{1 - r_\mathrm{l}^2}$, we obtain the range of probable angles $\theta_\mathrm{s} \gtrsim 73^\circ$ for source B, the degree of the linear polarization of the emission from which is $r_\mathrm{l} = 0.85$. The latter occurs if the sources locate near the Jovian limb. For source A and $r_\mathrm{l} = 0.65$, we obtain $\theta_\mathrm{s} \gtrsim 63^\circ$. For LH polarized sources with $r_\mathrm{l} = 0.50$, we have $\theta_\mathrm{s} \gtrsim 54^\circ$. Thus, there is no strong correlation between ellipticity of observed emission and the magnitude of the angle between the magnetic field and the direction of the ray path, i.e between the measured ellipticity and the value of the angle of the emission cone.

According to the observations, the ellipticity of emission is approximately constant over all of the frequency range of the decametric emission event with accuracy better than 15% (Dulk et al. 1994). We have shown that the calculated ellipticity of emission passed through IRM is independent of frequency and time if distribution of the magnetospheric plasma density in IRM satisfies the recurrent relation Eq. (17). If the decametric storm is emitted at angles near to $\pi/2$, the power $\nu \simeq 0.66$. When this angle shifts away from $\pi/2$, the dispersion $|\Delta r_\mathrm{l,c}/r_\mathrm{l,c}|$ of the degree of polarization increases. The dispersion can be compensated by a suitable value of ν in Eq. (17). For instance, the dispersion of the degree of polarization is fully compensated for case is shown in Fig. 2c if $\nu \simeq 0.69$. However, there is little difference in the plasma density distribution in IRM in this case. Taking into account the accuracy of measurements and uncertainty of location (i.e. the angle θ_s) of the sources of the decametric storm, values of ν in the recurrent relation Eq. (17) can be $0.5 \div 0.9$. The dispersion increase - occurring simultaneously with a decrease of degree of polarization - was described by Dulk et al. (1994). They concluded that the histograms of smaller r_l or r_c are significantly broadened and explained this phenomenon by an effect of instrumental polarization. We note that a decrease of θ_s results in the same phenomenon. For instance, for LH polarized sources ($r_\mathrm{l} = 0.5, \quad r_\mathrm{c} = 0.87$) in the case shown in Fig. 2d, the dispersion of the degree of polarization is $|\Delta r_\mathrm{l}/r_\mathrm{l}| \simeq 0.19$ and $|\Delta r_\mathrm{c}/r_\mathrm{c}| \simeq 0.09$, which is in good agreement with observations of the source D (see Fig. 2a and b in Dulk et al. 1994).

According to our model, the variation of ellipticity of polarization of an observed emission storm is fully defined by the magnetospheric plasma density distribution in IRM. In particular, the polarization does not depend on frequency and time if the distribution of plasma density in IRM is described by the recurrent relation Eq. (17). A consequence of the above is the dependency of ellipticity of the observed emission on the CML rather than on Io's position. According to observations of Dulk et al. (1994), the polarization of the event that occurred with Io phase near or within the B range but the CML of the observer in the A range is similar to A events. Besides, the polarizations of the non-Io-storms and Io-storms have very similar properties. The relatively small change of ellipticity from storm to storm is a consequence of a relatively small change of the magnetospheric background plasma density in time.

In terms of the simple symmetrical model of the dipole magnetic field, the magnetic momentum of which coincides with the spin momentum of the planet, the independence of the plasma density on longitude is a natural assumption. Therefore, the problem of difference of ellipticity of emission from B and A sources, as well as the difference between other sources, cannot be understood in this model. In fact, to explain the difference in ellipticity between B and A sources, the plasma density has to differ approximately by a factor 2 at the symmetrical points. The difference can be understood if we assume the real model of the Jovian magnetic field, e.g. by the O_4 or O_6 model, with significant variations of the magnetic field and the lack of the polar symmetry due to the presence of magnetic multipoles. In such an improved model of the magnetic field, it is hardly to be expected that the IRM for B and A sources be symmetrically located relative to the plane defined by the point of the observer and the Jovian rotation axis. If we also take into account the different locations of B and A sources and corresponding IRM relative to the range of the anomalous strong magnetic field, than we can expect that different plasma densities occur in the IRM of these sources.

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References

Akhiezer, V. V. et al. 1974, Electrodynamics of plasma. Nauka, Moscow

Boudjada, M. & Lecacheux, A., 1991, A&A 247, 235

Budden, V. V., 1961, Radio waves in the ionosphere. Cambridge University Press, Cambridge

Calvert, W., 1983, JGR, 88, 6165
Carr, T., Gulkis, S., Smith, A., et al., 1965, Radio Sci., 69D, 1530
Cohen, M., 1960, ApJ, 131, 664
Daigne, G., & Ortega-Molina, A., 1984, A&A, 133, 69
Dulk, G., Lecacheux, A., Leblanc, Y., 1992, A&A, 253, 292
Dulk, G., Leblanc, Y., Lecacheux, A., 1994, A&A, 286, 683
Goertz, C. K., 1974, Planet. Space Sci., 22, 1491
Green, T. C. & Sherrill, W. M., 1969, ApJ, 158, 351
Hewitt, R. G., Melrose, D. B., Ronnmark, K. G., 1982, Austr. J. Phys., 35, 447
Lecacheux, A. 1988, in Planetary Radio Emission II, eds H.O. Rucker, S.J. Bauer and B.M.-Pedersen, Publ. Austrian Acad. Sci., p. 311
Lecacheux, A., Boischot, A., Boudjada, M., et al, 1991, A&A, 251, 339
Melrose, D. B. & Dulk, G. A., 1991, A&A, 249, 250
Riihimaa, J. J., 1976, A&A, 53, 121
Shaposhnikov, V.E., Zaitsev, V.V., 1996, A&A, 305, 352
Shaposhnikov, V.E., Rucker, H.O., Zaitsev, V.V., 1996, A&A, 306, 603
Warwick, J. 1970, NASA Report CR1685
Warwick, J., Pearce, J., Riddl, A., et al., 1979, Science, 204, 995
Willes, A.J., Melrose, D.B., Robinson, P.A. 1994, JGR, 99, 21203
Zaitsev V.V., Zlotnik E.Ya., Shaposhnikov V.E. 1986, A&A 169, 345
Zheleznyakov, V. V., 1970, Radio emission from the Sun and planets. Pergamon Press, New-York
Zheleznyakov, V. V., Kocharovskii, Vl. V., Kocharovskii, V. V., 1979, Sov. Phys. JETP, 50, 51
Zheleznyakov, V. V., 1995, Radiation in astrophysical plasmas. Kluwer Academic Publishers, Dordrecht

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