# PROPAGATION EFFECTS INFLUENCING THE OBSERVED POLARIZATION OF THE JOVIAN DECAMETRIC EMISSION

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### Abstract

Jovian decametric emission is known to exhibit 100% elliptical polarization at all frequencies in the measured range from 10 to 38 MHz. The ellipticity of polarization is approximately constant as a function of frequency and time but differs for different sources. We suppose that the elliptical polarization of the observed emission is a consequence of propagation effects along the wave path from the source to the observer. We believe that outside of the source in the Jovian magnetosphere, there exists a region of moderate linear mode coupling which causes the ellipticity of the observed emission. We evidence conditions of the emission propagation along ray paths which are necessary for self–consistent explanation of the observed polarization and show that the observed features of the polarization are determined by the distribution of the magnetospheric plasma within the inner Jovian magnetosphere. The relatively small change of the ellipticity from storm to storm is a consequence of a relative variation of the magnetospheric background plasma in time. The value of the ellipticity is determined by the level of the magnetospheric plasma density $n_\mathrm{e}$ in the so–called "transitional region". This plasma density is quite low $n_\mathrm{e} < 0.4\ \mathrm{cm}^{-4}$ and is related with the local electron gyrofrequency as $n_\mathrm{e} \propto (f_\mathrm{Be})^\nu$ where $\nu \simeq 1 \div 1.8$.

## 1 Introduction

During ground-based wide-band observations at the Nançay Radio Astronomy Observatory, France, all the four Stokes parameters have been measured [Lecacheux et al., 1991; Dulk et al., 1992, 1994]. Therefore it is possible to calculate the full set of polarization parameters of the emission as a function of both frequency and time. Due to these observations we recognized that the decametric emission is 100% elliptically polarized at all frequencies in the measured range of 10 to 38 MHz, but the degree of linear and

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circular polarization differs for different sources. This phenomenon applies specifically to Io–related storms, but the two non–Io storms which are studied by Dulk et al. [1994] have very similar polarization properties. For 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–busts and S–bursts, and they found that there is a little difference concerning 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 ($\Psi^2$) 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 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 the inclination of the polarization ellipse essentially depend on the angle between the magnetic field line and a ray path in the "limiting polarization zone" and they change according to the rotation of the planet and change in radiation frequency. The consequence of his model is in contradiction with new polarization data from Nançay observatory. For explanation of the new experimental data Lecacheux et al. [1991] proposed that one elliptical mode is generated in the source, and the original polarization of this mode is retained all the way from the source to the observer, therefore the elliptical polarization is a consequence of strong linear mode coupling in the Jovian magnetosphere. He estimates the required plasma density in and near the source as $\lesssim 5$ cm$^{-3}$ for 30 MHz. 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 that is badly fitted with the high level of radiation from this source. The frequency and time independence of the observed polarization during of an emission storm, weakly variations of the polarization from storm to storm, and difference of the ellipticity of emission from B and A sources as well as the difference between other sources cannot be understood in terms of this model. Moreover, different mechanisms of generation of decametric emission which are suggested as generation mechanisms (e.g. electron cyclotron maser (ECM) instability and plasma mechanism) are not in agreement with this model.

Our purpose in this paper is to create a model of the origin of the main polarization characteristics of the Jovian decametric radio emission which does not contradict the modern knowledge on the decametric emission origin. We show a possibility to simulate a model of plasma density in the Jovian magnetosphere based on the measurement of the polarization of decametric emission.

## 2 The effect of the linear mode coupling of electromagnetic waves: a model of plasma distribution and numerical solution

To characterize the conditions of the propagation of polarized emission in an inhomogeneous magnetoactive plasma the function of interaction $Q$ was introduced by Cohen [1960]. This function is the ratio of the rate of change of polarization ($\Psi^2$) 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

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

where $n_\mathrm{e,o}$ is the refractive index of extraordinary ("e") and ordinary ("o") modes, $z$ is the distance along the ray path, $c$ is the velocity of light,

$$q = \frac{Y\sin^2\theta}{2(1-X)\cos\theta}. \tag{2}$$

In Equations (1) and (2) $Y = f_\mathrm{Be}/f$, $X = f_\mathrm{Pe}^2/f^2$, $f_\mathrm{Be}$ and $f_\mathrm{Pe}$ are the gyrofrequency and plasma frequency of electrons, respectively, $f$ being the emission frequency and $\theta$ the angle between the magnetic field and the ray path. The limited case $|Q| \ll 1$ corresponds to validity of geometric-optic approximation. Another limited case, $|Q| \gg 1$, corresponds to strong linear mode coupling. In this case the emission's polarization is retained all the way where $|Q| \gg 1$, which means that the emission propagates as in a vacuum media. The last case has been discussed by Lecacheux et al. [1991]. For arbitrary $Q$ which we consider in the present paper the efficiency of linear mode coupling essentially depends on the plasma density and magnetic field distribution along the ray path.

In smoothly inhomogeneous magnetoactive plasma, when the inequalities

$$\frac{2\pi f}{c} n_\mathrm{e,o}\Lambda \gg 1, \qquad \frac{2\pi f}{c}|n_\mathrm{e} - n_\mathrm{o}|\Lambda \lesssim 1, \qquad |n_\mathrm{e} - n_\mathrm{o}| \ll 0.5(n_\mathrm{e} + n_\mathrm{e}) \tag{3}$$

are fulfilled, the transfer of the polarized emission can be described by equation

$$\frac{\mathrm{d}T}{\mathrm{d}\zeta} = \imath\frac{n_\mathrm{o} - n_\mathrm{e}}{2\sqrt{1+q^2}}(T + \sqrt{1+q^2} - q)(T - \sqrt{1+q^2} - q) \tag{4}$$

which follows from the Maxwell equations for the ratio $T = -\imath E_\mathrm{x}/E_\mathrm{y}$ where $E_\mathrm{x,y}$ are the components of complex amplitude of electric field of emission [Zheleznyakov et al., 1979; Zheleznyakov, 1995]. In Equations (3) and (4) $\Lambda$ is a characteristic scale of inhomogeneity of the magnetic field and the plasma density along the ray path, $\imath = \sqrt{-1}$, $\zeta = (2\pi f/c)z$ is a dimensionless coordinate along the ray path. In this case the degree of linear and circular polarization, $r_\mathrm{l}$ and $r_\mathrm{c}$, respectively, is

$$r_\mathrm{l} = \cos(2\arctan(\frac{4\Re\mathrm{e}T}{(|T-1|+|T+1|)^2})) \tag{5}$$

and

$$r_{\mathrm{c}} = \mp\sqrt{1 - r_{\mathrm{l}}^2}. \tag{6}$$

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

The rigid solution of Equation (4) exists only for specific distributions of plasma density and magnetic field which are not in agreement with conditions within the magnetosphere of Jupiter. Therefore, we find numerical solutions of the linear mode coupling equation. Following the theory of the linear mode coupling for numerical solution, it is sufficient to describe the distribution of the magnetospheric plasma density along the ray path in that part where the parameter $q^2 \sim 1$. The region of the magnetosphere along the ray path where $q^2 \sim 1$ we call the "transitional region" (TR). The location of the TR in the Jovian magnetosphere varies depending on the emission frequency and time. The point is that its location in the magnetosphere is mainly defined by the height of the emission source and an angle $\theta$ between the direction towards the observer and the magnetic field in the source. The sources of the decametric emission emitting at different frequencies $f$ are located at heights corresponding to gyrofrequency levels $f_{\mathrm{Be}} \simeq f$. This causes the change with frequency for both, the ray path height and the angle $\theta$. Moreover, the angle $\theta$ can vary with CML change due to the planetary rotation and the lack of the 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 $\theta$ 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 magnetospheric domain the essential linear mode coupling may take place. The magnetospheric domain occupied by the "transitional regions" during the storm we will call the interaction region of the magnetosphere (IRM) for a given emission storm.

Plasma density distribution in IRM can be found to fit data of observed polarization and to calculate polarization for different frequencies and CML. It appears that due to this fit we are able to find a relation between $f_{\mathrm{Pe}}$ and $f_{\mathrm{Be}}$ at every point of IRM. We search the relation between $f_{\mathrm{Pe}}$ and $f_{\mathrm{Be}}$ in form

$$f_{\mathrm{Pe}} = K \cdot (f_{\mathrm{Be}})^{\nu}, \tag{7}$$

where the coefficient $K$ is found by fitting calculated degrees of polarization with those obtained from observations at given frequency; the power $\nu$ is obtained from observed frequency dependence of polarization at given time. The distribution of plasma density in IRM and position of IRM in the magnetosphere can be evaluated if we are provided with a definite model of the Jovian magnetic field.

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 emitting at different frequencies $f$ are located along the same magnetic field lines at heights associated with gyrofrequency levels $f_{\mathrm{Be}}^{\mathrm{s}} \simeq f$. These magnetic field lines belong to L–shells passing through the Io satellite. Only the 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 the sake of simplicity we assume $q > 0$ here and in the rest of the paper.

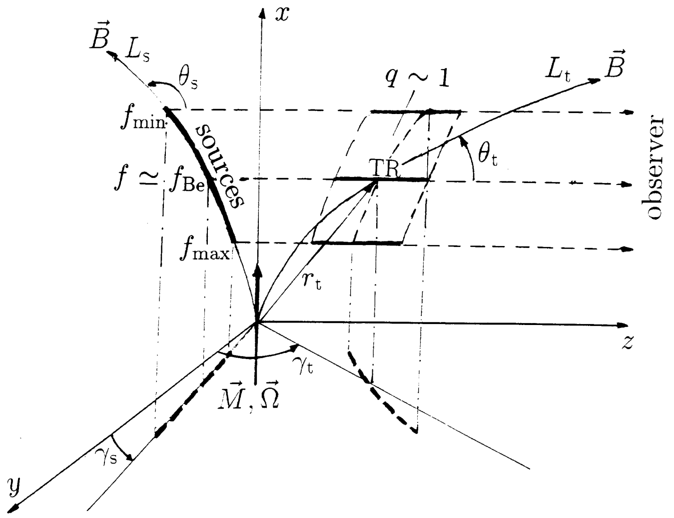

*Figure 1: Schematic view of our model for fixed time. The source at each frequency is located along the magnetic field line;* $f_{max}$ *and* $f_{min}$ *are the maximum and minimum frequencies of a decametric radio emission storm at the fixed time. The "transitional region" (TR) for emission at a frequency*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

The geometry of the problem is shown in Figure 1: $\theta_s$ and $\theta_t$ are the angles between the ray path and the magnetic field lines, $\gamma_s$ and $\gamma_t$ are the angles between meridian planes and the Jovian limb (xy-plane), $r_{s,t} = R_{s,t}/R_J$, $R_s$ and $R_t$ are the distances from the center of the planet, $R_J$ is the Jovian radius, $L_{s,t}$ are the L-shells of magnetic field, the z-axis is directed towards the observer, the x-axis is 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. Sources are located at $L_s = 6.0$.

The frequency dependence of the ellipticity of polarization of the observed emission is due to the frequency dependence of both the polarization ellipticity in the source (because of a variation of the angle $\theta_s$ between the magnetic field and the direction towards the observer at different gyrofrequency levels) and the efficiency of the linear mode coupling in TR. If the ellipticity of polarization is independent on frequency we derive $\nu \simeq 2/3$. This magnitude of the power $\nu$ is used in the following calculation for any values of the angle $\theta_s$. We return below to a discussion of the value $\nu$. The coefficient $K$ in Equation (7) is a fit according to calculated degrees of linear polarization which are obtained from observations at $f = 20$ MHz.

Having in mind the interpretation of the polarization data of 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. Those values correspond to average values observed near 20 MHz at sources B,A and LH polarized sources, respectively. For numerical solution of the linear mode coupling we have used Equation (4). Figures 2a–2d show the degree of linear polarization $r_l$ and the function of interaction $Q$ 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. Assuming the degree

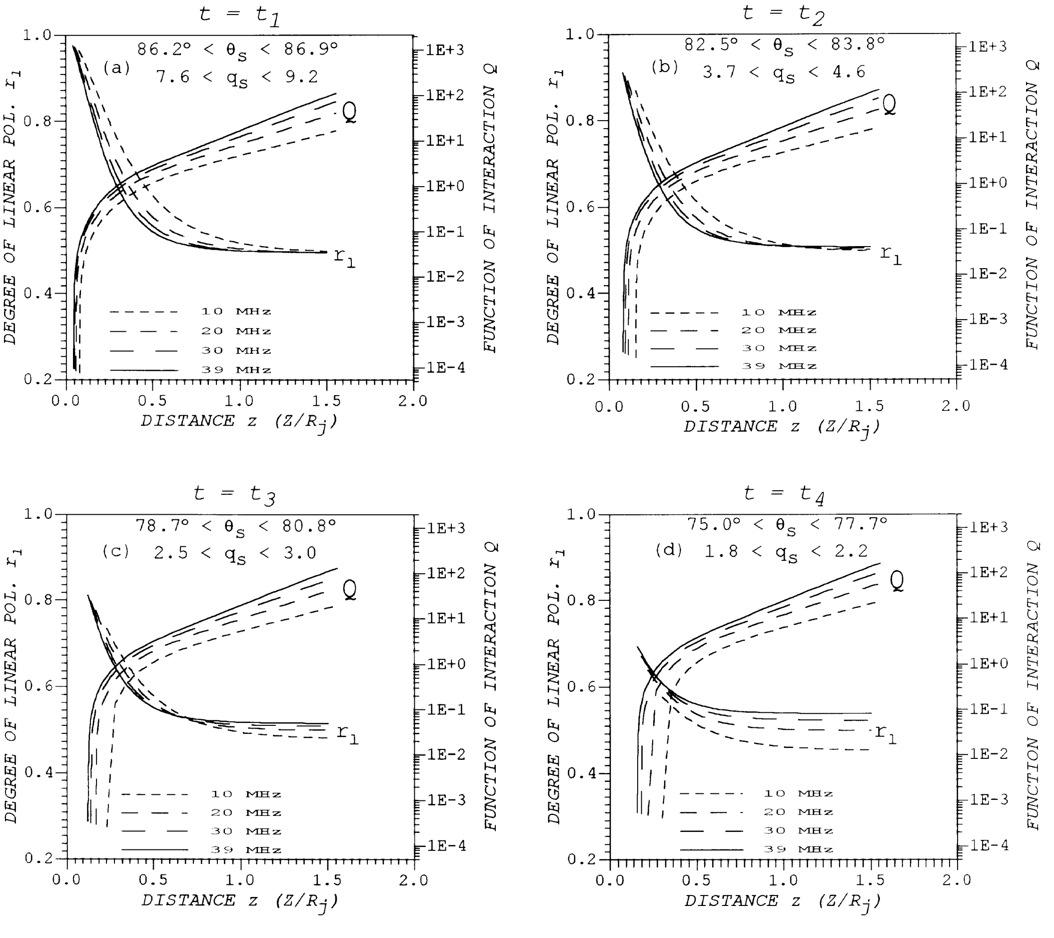

*Figure 2: Degree of linear polarization $r_1$ interaction coefficient Q as function of distance from the source for different angles $\theta_s$ and Degree of linear polarization $r_1^{\mathrm{obs}} = 0.50$ for 20 MHz.*

the linear polarization $r_1^{\mathrm{obs}} = 0.50$ for 20 MHz corresponds to observed average ellipticity of the LH polarized emission. In the top of each picture we show the angle $\theta_s$ and the parameter $q_s$ in the sources of the emission which are located along the magnetic field line at the gyrofrequency levels from 10 MHz to 39 MHz. The different ranges of variation of the angle $\theta_s$ in versions (2a) through (2d) simulate the change 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 dynamic behavior of frequency and time variations of computed degree of linear polarization along the ray path. The plasma density calculated according to Equation (7) and coordinates of TR as functions of the emission frequency and angle $\theta_s$ are shown in Figure 3. The curves labeled ($t_1$) through ($t_2$) in Figure 3 correspond to the versions as shown in Figure 2a through Figure 2d, respectively, and simulate the distribution of plasma density in IRM and place of IRM in the magnetosphere for a given decametric radio emission storm. This plasma density distribution provides independence of the observed polarization on frequency and time for the emission storm occupying the frequency range from 10 to 39 MHz and time interval during which the angles $\theta_s$ are changed by an amount less than 8°. In this case the polarization variations due to a frequency and time dependence of $\theta_s$ stay inside the range which is defined by

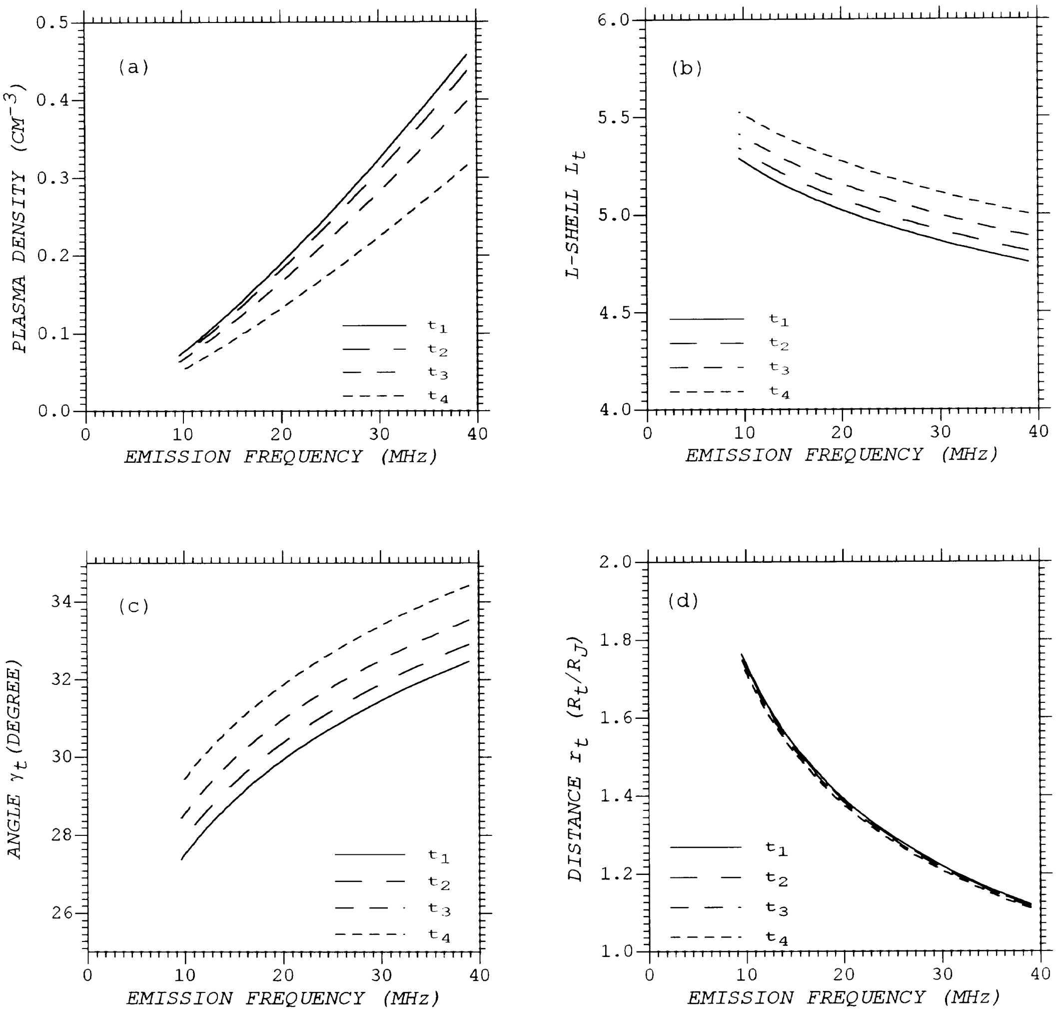

*Figure 3: The plasma density in TR and the location of this region as functions of the emission frequency $f$ and angle $\theta_s$.*

the accuracy of measurements. The latter is defined as 15% [Dulk et al., 1994]. In Figure 4 the degree of linear polarization for Io–B, Io–A and LH polarized sources at fixed time as well as the plasma densities along the curve $q = 1$ are shown.

## 3 Discussion

It can be easily seen from Figure 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 $< 0.4$ cm$^{-3}$. The simplest hypothesis for the origin of the low plasma density in the Jovian magnetosphere is discussed by Melrose and Dulk [1991]. Following their speculations, we find that the plasma density falls to less then 0.4 cm$^{-3}$ at radial distances $\gtrsim 1.2R_J$. These values are in good agreement with those predicted by our model. However, we want to emphasize here that our model of the origin of

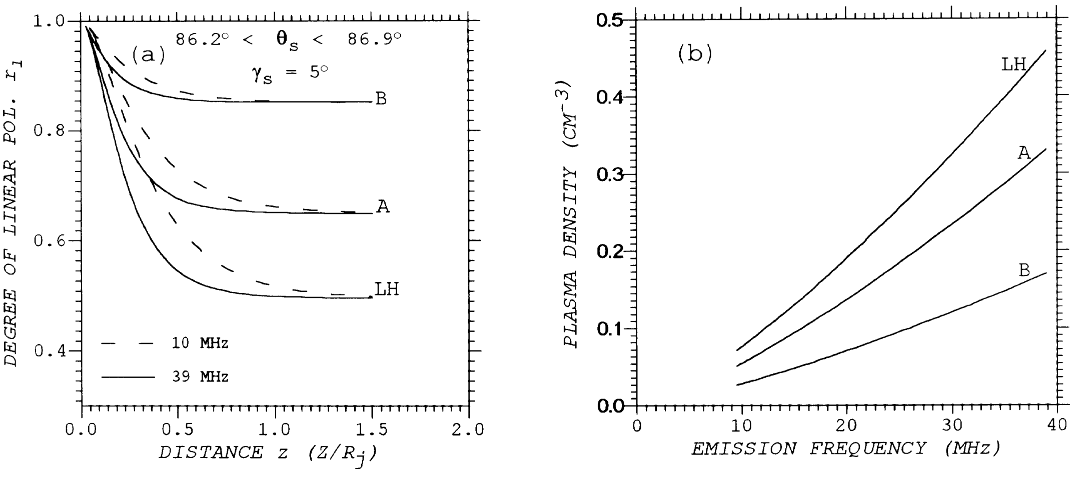

*Figure 4: Degree of linear polarization for sources Io–B ($r_l^{\rm obs} = 0.85$), Io–A ($r_l^{\rm obs} = 0.65$), and LH polarized sources ($r_l^{\rm obs} = 0.50$) at a fixed time (a) and the plasma densities in TR (b).*

the decametric polarization as a consequence of the moderate linear mode coupling does not require low plasma density and validity of the vacuum approximation in the source itself. In fact, from Figure 2, we can see 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. In the source regions the plasma density can be higher due to electrons which are present in the magnetic flux tube because of an electrodynamic interaction between Io and the Jovian magnetosphere.

The relation between the observed degrees of polarization and source polarization is given by $r_l^{\rm s} \geq r_l^{\rm ob}$ and $|r_c^{\rm s}| \leq |r_c^{\rm ob}|$. The observed polarization degree limits the range of allowable angles between the magnetic field lines and emission ray at the source. The crucial point is that a decrease of the angle $\theta_{\rm s}$ results in the increase of circular polarized emission in the source which is limited by the inequality $|r_c^{\rm s}| \leq |r_c^{\rm ob}|$. For source Io–B ($r_l = 0.85$) we obtain the range of possible angles $\theta_{\rm s} \gtrsim 73°$. The latter occurs if the sources are located near the Jovian limb. For source A and $r_l = 0.65$ we obtain $\theta_{\rm s} \gtrsim 63°$. For LH polarized sources with $r_l = 0.50$ we have $\theta_{\rm s} \gtrsim 54°$. Therefore, we can see that there is no strong correlation between ellipticity of observed emission and the magnitude of the angle between the magnetic field and the direction of 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 the accuracy better than 15% [Dulk et al., 1994]. We have shown that the calculated ellipticity of emission passing through IRM is independent on frequency and time if the distribution of the magnetospheric plasma density in IRM satisfies the recurrent relation in Equation (7). For the decametric storm which is emitted at angles close to $\pi/2$ the power $\nu$ is approximately $\simeq 0.66$. While this angle shifts away from $\pi/2$ the dispersion $|\Delta r_{\rm l,c}/r_{\rm l,c}|$ of the degree of polarization increases. The dispersion can be compensated by suitable magnitude of the power $\nu$ in Equation (7). For instance, for the case shown in Figure 2c the dispersion of the degree of polarization is fully compensated if $\nu \simeq 0.69$. However, there is only 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 $\theta_s$) of the sources of the decametric storm, values of the power $\nu$ in the recurrent relation Equation (7) can be $0.5 \div 0.9$. The dispersion increases – simultaneously occurring with a decrease of degree of polarization – as was described by Dulk et al. [1994]. They concluded that the histograms of smaller $r_l$ or $r_c$ are significantly broadened and they explained this phenomenon by the presence of instrumental polarization. We would like to note here that the decrease of the angle $\theta_s$ results in the same phenomenon. For instance, for LH polarized sources ($r_l = 0.5, \quad r_c = 0.87$) in the case shown in Figure 2d the dispersion of the degree of polarization is $|\Delta r_l/r_l| \simeq 0.19$ and $|\Delta r_c/r_c| \simeq 0.09$ which is in good agreement with observations of the source D (see Figures 2a and 2b in Dulk et al. [1994].

According to our model the variation of ellipticity of the 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 distributions of plasma density in IRM is described by the recurrent relation Equation (7). Consequence of the above statement is a dependence of the ellipticity of the observed emission on CML rather than on the Io position. According to observations of Dulk et al. [1994] the polarization of the event that occurred with Io phase near or within the Io–B range but the CML of the observer in the Io–A range is similar to Io–A events. Moreover, the polarizations of the non-Io-storms and Io-storms have very similar properties. The relatively small change of the 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 with respect to longitude is a natural assumption. Therefore, the problem of difference of ellipticity of emission from Io–B and Io–A sources as well as the difference between other sources cannot be understood in this model. In fact, to explain the difference of the ellipticity from the Io–B and Io–A sources, the plasma density has to differ approximately by a factor 2 at the respective longitudes. The difference can be understood if we assume the real model of the Jovian magnetic field, e.g. by the O4 or O6 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 expect that the IRM for Io–B and Io–A sources are symmetrically located relative to the plane defined by the point of the observer and the Jovian rotation axis. If we take into account also the different location of Io–B and Io–A sources and corresponding IRM relative to the range of the anomalous strong magnetic field, than we can expect that the different plasma densities in IRM of these sources occur.

*Acknowledgements:* The authors are thankful for helpful discussions with Dr. M.Y. Boudjada. This work has been supported by the Russian Foundation of Fundamental Researches, Grant No 95-02-04272 and by the Commission for International Cooperation of the Austrian Academy of Sciences.