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Origin of emission polarization in the great arc of the Io-A decametric storm

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Abstract. We consider the origin of a circular polarization which was observed in the great arc in the Io-A decametric storm of Nov.2, 1988. Our consideration is based on the model of the origin of a decametric emission polarization employing the idea of moderate linear mode coupling. We show that a reasonable explanation of the polarization of the great arc is possible if the emission is generated in the instantaneous Io flux tube (IFT). We conclude that the plasma density in IFT is approximately three times greater than the one in the vicinity of IFT. At the heights corresponding to the 30 MHz electron gyrofrequency level, we estimate the plasma density in IFT to be $N \gtrsim 1.9$ cm^{-3}, whereas outside the tube it is $N \approx 0.7$ cm^{-3}.

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

1. Introduction

Jovian decametric (DAM) radio emission essentially appears to be elliptically polarized. The recent observations made at Nançay Radio Astronomy Observatory, France (Lecacheux et al. 1991; Dulk et al. 1992, 1994) show that this emission is 100% elliptically-polarized at all frequencies in the measured range of 10 to 38 MHz. The ellipticity of the emission polarization (ratio of polarization ellipse axes) varies weakly from storm to storm and average values of the ellipticity can be considered as specific signatures of the “source” to be distinguished in the central meridian longitude (CML) and Io phase diagram. For example, at frequencies near 20 MHz the average degrees of linear $r_{\rm l}$ and circular $r_{\rm c}$ polarization are $\langle r_{\rm l} \rangle \approx 0.87$ and $\langle r_{\rm c} \rangle \approx -0.49$ for the emission from the Io-B “source”, while for Io-A it is $\langle r_{\rm l} \rangle \approx 0.66$ and $\langle r_{\rm c} \rangle \approx -0.72$; for Io-C $\langle r_{\rm l} \rangle \approx 0.74$ and $\langle r_{\rm c} \rangle \approx -0.67$ (Dulk et al. 1994). The minus sign corresponds to the right-hand polarization. Moreover, during an emission storm the ellipticity is approximately constant as a function of frequency and time. There are only a few exceptions to this rule. Lecacheux et al. (1991) have studied the spectral feature, which looked like a great arc in the Io-A event which occurred on 1988 Nov.2. They found that the spectral feature was superimposed on the main emission and had a considerably higher degree of circular polarization than the other part of the burst. For this spectral feature the average degrees of polarization were $|\langle r_{\rm c} \rangle| \gtrsim 0.95$ and $\langle r_{\rm l} \rangle \approx 0.2$ versus $\langle r_{\rm c} \rangle \simeq -0.76$ and $\langle r_{\rm l} \rangle \approx 0.66$ in another part of the storm.

The origin of the elliptical polarization of DAM emission is studied in a number of articles (e.g. Warwick 1970; Goertz 1974; Lecacheux 1988; Lecacheux et al. 1991; Melrose & Dulk 1991; Shaposhnikov et al. 1997). All of them consider the origin of the elliptical polarization as a result of the violation of the geometrical optics approximation in the Jovian magnetosphere. These studies can be divided in two groups. The first group (Lecacheux 1988; Lecacheux et al. 1991; Melrose & Dulk 1991) assumes that violation of the geometrical optics approximation took place already in the emission source itself, and the original polarization has been retained from the emission source to the observer. In this case, the observed polarization ellipticity is only determined by the angle $\theta_{\rm s}$ between the magnetic field lines and the direction of the ray path at the emission point. This theory may explain the origin of the elliptical polarization and gives a means to find quite precisely the location of the source. However, it has a number of serious drawbacks. For example, following this model Leblanc et al. (1994) found that a number of the Io-C events (the average circular polarization $\langle r_{\rm c} \rangle \approx -0.67$) were generated in the magnetic tubes which were in front of the instantaneous Io flux tube (IFT) at a distance of about 10°. This requires Io to extend its influence upstream of the satellite. Another group of the papers (Warwick 1970; Goertz 1974; Shaposhnikov et al. 1997) assumes that the violation of the geometrical optics approximation can take place outside the emission source and some change of the polarization ellipticity occurs along the way. In the detailed polarization model of Shaposhnikov et al. (1997) there is no hard relation between the ellipticity of the observed emission and the angle $\theta_{\rm s}$. The observed ellipticity of the emission polarization is determined by two parameters: angle $\theta_{\rm s}$ and, mainly, the magnetospheric plasma density $N_{\rm t}$ in the transitional region (TR) where the polarization of electromagnetic modes is essentially elliptical. The second parameter $N_{\rm t}$ involved in this consideration permits us to avoid the drawbacks mentioned above. However, including the second parameter in the model makes it impossible to find the location of the emission source by the polarization obser-

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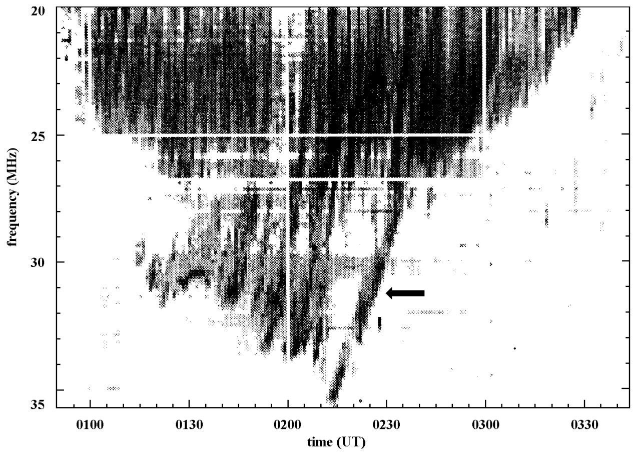

Fig. 1. Dynamic spectrum of the flux density of the Io-A emission of 1988 Nov. 2. The great arc is indicated by the arrow

vational data. None of the papers discusses the origin of the time variations of the ellipticity during the burst similar to those observed in the Io-A event of Nov.2. 1988

In the present study, in order to explain the time features of emission polarization, we develop the model of the origin of the elliptical polarization suggested by Shaposhnikov et al. (1997). In addition, we show that the observed polarization feature of the great arc gives us the possibility both to locate quite precisely the position of the emission source and to estimate the level of the magnetospheric plasma density in IFT.

2. The event of November 2, 1988

The Io-A event was observed on Nov. 2, 1988 for approximately 3 hours at the Nançay (France) observatory. The observation results were published in the paper of Lecacheux et al. (1991). During the event, the central meridian longitude (CML) ranged from $CML = 189°$ to $294°$, and the Io phase ($\gamma_{\rm Io}$) ranged from $\simeq 233°$ to $\gamma_{\rm Io} \simeq 257°$. Fig. 1 (Fig. 4a in Lecacheux et al. 1991) shows the dynamic spectrum of the flux density of the event. The spectral feature discussed in the present article extends from the highest frequency of the burst (more than 35 MHz) to approximately 27 MHz at the dynamic spectrum. At a fixed frequency the spectral feature is about 5 minutes long. The emission in the spectral feature and the emission which precedes it immediately have an essentially higher degree of the circular polarization than any other part of the storm. Lecacheux et al. (1991) found that the average degrees of the circular and linear polarization of the emission in the feature were $|\langle r_{\rm c}\rangle| \gtrsim 0.95$ and $\langle r_{\rm l}\rangle \simeq 0.2$, respectively, while in the remaining part of the burst they were $\langle r_{\rm c}\rangle \simeq -0.76$ and $\langle r_{\rm l}\rangle \simeq 0.66$. Along the spectral feature the ellipticity of the polarization varies weakly with frequency. This is usual for the polarization observations of the Jovian decametric radio emission (Lecacheux et al. 1991; Dulk et al. 1992; 1994). Lecacheux et al. (1991) assume that this spectral feature is a great arc. This type of fine structure was noted for the first time on the Jovian emission dynamic spectra of Boischot et al. (1981).

3. The origin of the emission polarization in the event of November 2, 1988

High ellipticity of the observed DAM emission forces us to assume both that the emission is generated almost perpendicular to the planetary magnetic field lines in the emission source and the geometrical optics approximation is no longer valid where the polarization of electromagnetic modes is elliptical. Under these conditions, the variation of the polarization along the emission way is described by the following equation (Zheleznyakov, 1995):

$$\frac{d\mathrm{P}}{d\eta} = \imath\left(P^2 - 1\right) + \frac{2\imath}{Q}P \qquad (1)$$

where $P(\eta)$ is a function related to the emission polarization ellipticity T by the equation

$$T = \frac{P - \imath\left(\sqrt{1+q^2} - q\right)}{\imath + P\left(\sqrt{1+q^2} - q\right)}, \qquad (2)$$

function Q is the ratio of the rate of change of polarization of the electromagnetic modes to the rate of change of the phase difference between the modes,

$$Q = \frac{c\mathrm{d}q/\mathrm{d}z}{2\pi f(n_{\rm x} - n_{\rm o})(1+q^2)}, \qquad (3)$$

η is the coordinate associated with coordinate z along the ray path by

$$\eta = \frac{\pi}{4} + \frac{1}{2}\arctan q, \qquad (4)$$

$n_{\rm x,o}$ is the refractive index of extraordinary (x) and ordinary (o) modes, and the parameter q is defined as

$$q = \frac{f_{\rm Be}\sin^2\theta}{2f\cos\theta}. \qquad (5)$$

Gyrofrequency $f_{\rm Be}$ and the angle between the direction of propagation and the magnetic field lines θ in Eq. (5) are functions of space. The parameter q determines the polarization of the electromagnetic modes and the limits of validity of the quasi-longitudinal ($q^2 \ll 1$) and quasitranverse ($q^2 \gg 1$) description of electromagnetic wave propagation within the condition of validity of the geometrical optics approximation.

From Eq. (1) it is easily seen that both the generation condition at the emission point and the variation of function Q along the emission ray determine completely the observed emission polarization. According to the advanced theory of the linear mode coupling (Zheleznyakov 1995), variation of the function Q within the transitional region (TR) exerts appreciable influence on the observed polarization. In the articles of the first group (see Sect. 1) it is assumed that function Q is much greater than unity, $Q \gg 1$, along the part of the emission ray within the Jovian magnetosphere including the source itself and its TR. We are not interested in the part of the emission way within the Io plasma torus and the Earth's ionosphere where the inverse inequality, $Q \ll 1$, is valid. Here, the conditions of the geometrical

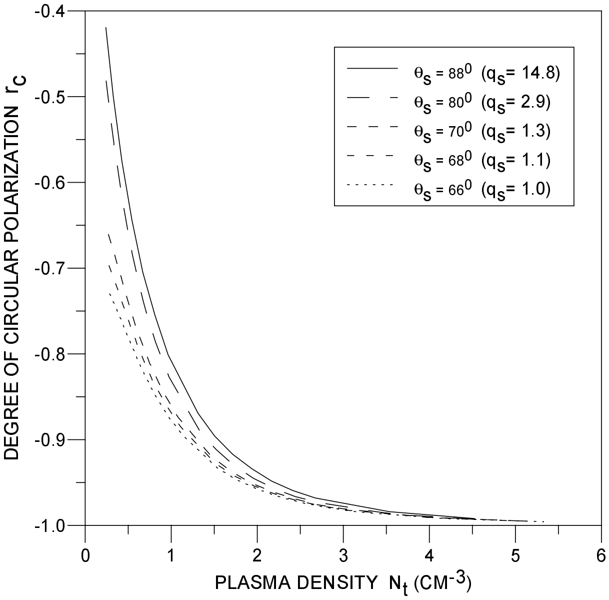

Fig. 2. The degree of circular polarization r_c as a function of plasma density in the transitional region for different values of angle θs and for a fixed frequency ($f = 30$ MHz;, q_s is the value of parameter q at the emission point).

optics approximation and the quasi-longitudinal propagation are fulfilled, and the variation of the radiation polarization just manifests itself as the rotation of the polarization ellipse without any change in the ellipticity. It is easily seen from Eq. (1) that in the case of $Q \gg 1$ the solution of the transfer equation is independent of the condition along the emission way and is determined by the initial conditions. It means that the observed polarization ellipticity is determined by the angle θ_s between the direction of emission and the magnetic field lines at the generation point. Substituting $|r_c| \gtrsim 0.95$ into the expression for the degree of circular polarization, which in this case is $r_c \simeq \sin(2\cos\theta_s)$ (see, for details, Melrose & Dulk 1991), we find that this emission polarization could be observed if the emission generates at angles $\theta_s \lesssim 43°$ relative to the magnetic field lines. However, following Leblanc et al. (1994) it is easily shown that the decametric radiation emitted in the frequency band 27 – 35 MHz at angles $\theta_s \lesssim 43°$ cannot be observed by the ground-based observer. In this case the Earth is out of the emission beam.

Shaposhnikov et al. (1997) assume that inequality $Q \gg 1$ is violated in the decametric emission source and its TR. Within the TR the function Q can reach magnitudes of the order of or less than unity. In this case the observed ellipticity depends on one more parameter: the level of the Jovian magnetospheric plasma density N_t in TR. Following Shaposhnikov et al. (1997) we calculate the dependence of the degree of circular polarization of the observed emission on the plasma density, N_t, for different values of the angle θ_s and for a fixed emission frequency (Fig. 2). To find the degree of polarization, we use the transfer equation (1) and the simple symmetrical model of the dipole magnetic field. We take into account also the frequency independence of the polarization ellipticity. Specific features of

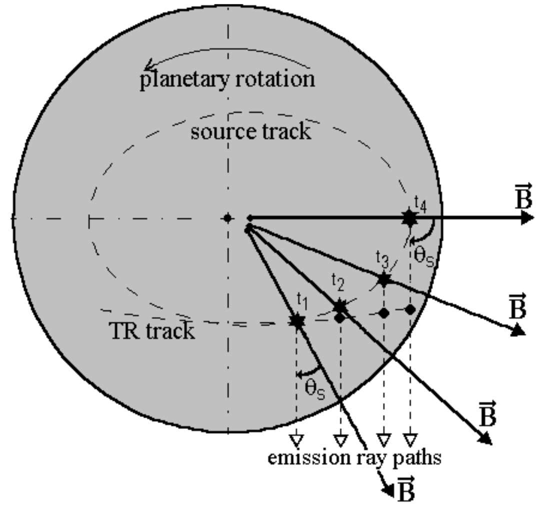

Fig. 3. The tracks (dashed lines) of the source emitting at a fixed frequency and the associated transitional region (schematic view from above the north pole). Asterisks and solid circles show positions of the emission source and of the transitional region, respectively, at different times, t_1 through t_4.

the Jovian magnetic field influence only the position of TR at the magnetosphere and will be taken into further consideration. The degree of the circular polarization is calculated using the following equation (Shaposhnikov et al. 1997)

$$r_c = \sin\left(2\arctan\left(\frac{4\Re e T}{(|T-1|+|T+1|)^2}\right)\right), \quad (6)$$

where $\Re eT$ is the real part of T. Fig. 2 shows that the observed ellipticity of the emission polarization is mainly determined by the level of plasma density within the TR. Some exceptions occur in the case when TR includes the emission source itself. In this case the influence of the initial condition becomes slightly greater. As it is noted in the previous sections the emission in the great arc has an essentially higher degree of the circular polarization than other parts of the burst, $\langle r_c\rangle \lesssim -0.95$ versus $\langle r_c\rangle \simeq -0.76$. This means that the plasma density is about three times greater at the transitional region associated with the source of the great arc than at the transitional regions associated with the sources of the remaining part of the burst.

To understand the reason of the sudden increase of the plasma density within TR we need to trace the variations of TR location in the Jovian magnetosphere during the emission event of Nov.2, 1988. Fig. 3 illustrates schematically the variation of the position of the emission source emitting at fixed frequency f and the associated transitional region at different times, t_1 through t_4. The variation is due to the motion of the source together with the planet.

At the emission ray the location of TR is determined from the condition of $q \sim 1$ (Shaposhnikov et al. 1997). From Eq. (5) it is seen that the value of parameter q depends on angle θ between the direction of emission propagation and the local magnetic field lines. This angle, in turn, is determined by angle θ_s between the direction of emission and the magnetic field lines at the emission point. Due both to the planetary rotation and the orbital

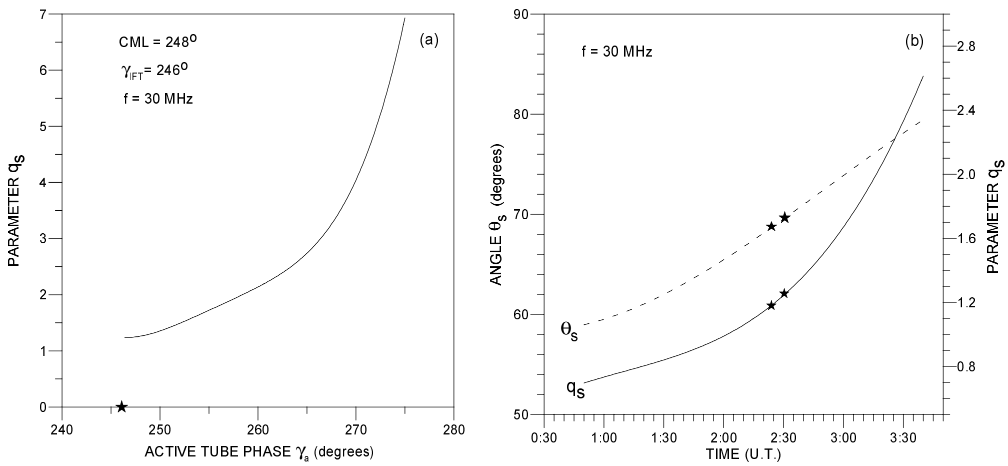

Fig. 4a and b. a Variation of parameter q as a function of the phase of the active flux tube at the moment when CML=248° and $\phi_{\rm Io} = 246°$. The asterisk marks the phase of the Io flux tube; **b** Variation of parameter q and angle θ as functions of time at the Io flux tube at the height which corresponds to the 30 MHz gyrofrequency level. The asterisks mark the start and end times of observation of the highly circularly polarized emission at the frequency of 30 MHz.

motion of the Io, angle $\theta_{\rm s}$ changes with time. The variation of $\theta_{\rm s}$ results in a change of both the mutual position of the source and its TR and the location of TR in the magnetosphere. Moreover, there is a situation where TR envelops the emission point (time t_1 in Fig. 3).

The direct way, namely, calculation of parameter q along the emission ray paths, requires the knowledge of the exact source position in the magnetosphere at every moment in time. Up to now the positions of the decametric sources are still not determined exactly. Besides, there is no sufficiently good plasma model for the Jovian low magnetosphere. Therefore, as the first step, we define a magnetosphere region at the way of the emission propagation where plasma density is likely to be enhanced. Then we find positions of the source with the transitional region being located in this magnetosphere region at the time when the highly circularly polarized emission is observed.

It is generally accepted that generation of the decametric emission occurs along the Io flux shells at the active magnetic flux tubes. In general, the active flux tube is not the same as the instantaneous Io flux tube. Note that the concept of the active flux tube is the same as the concept of an active longitude proposed by Dulk et al. (1992). It is also generally accepted that the sources emitting at different frequencies f are situated at heights which correspond to different electron gyrofrequency levels $f_{\rm Be} \simeq f$. The latter implies that the decametric sources are located quite close to the planetary surface, within a few tenths of the Jovian radius. Shaposhnikov et al. (1997) have found that the positions of TR are at distances less than or equal to half of the radius from the source. This estimation was obtained for the simple dipole models of the planetary magnetic field. However, more realistic models of the magnetic field, O4 and O6, considered in place of the simple dipole one, lead to negligible corrections. Near the emission source region, the enhanced density can be reasonably expected only at the Io flux shells themselves. Here the density can be increased due to particle precipitation from the Io plasma torus. Therefore, we conclude that the relevant situation occurs when the transitional region is in the vicinity of the Io flux shells. In other words, we have to find the situation where the condition of $q \sim 1$ is fulfilled in the vicinity of the source.

Fig. 4a shows the variation of parameter q in the sources plotted as a function of phase ($\gamma_{\rm a}$) of the active flux tube for a fixed CML. The fixed CML corresponds to the moment in time when the emission with a high degree of circular polarization was observed in the event of Nov.2, 1988. For simplicity, we consider the sources which emit at a fixed frequency, e.g. $f = 30$ MHz. Here and further on we will use the O4 model of the planetary magnetic field. The O6 model as well as a variation of emission frequency from 25 MHz to 35 MHz give negligible differences in the numerical results. From Fig. 4a it can be seen that the required case (coincidence of the position of the emission source and corresponding TR) occurs when the source of the highly circularly polarized emission is situated in the vicinity of the instantaneous Io flux tube. This conclusion is confirmed in Fig. 4b which shows variations of parameter q in the Io flux tube during the event under consideration. Again, we consider the source which emits at 30 MHz. From Fig. 4b it is seen that the positions of TR and of the Io flux tube coincide ($q_{\rm s} \sim 1$) at the time when the great arc and the highly circularly polarized emission are observed.

Thus, we conclude that in the event of Nov. 2, 1988 the highly circularly polarized emission was observed at times when both the emission source and its transitional region were in the Io flux tube. From Fig. 4b, where the variation of the angle between the direction to the remote observer and the magnetic field lines in the source are also shown, it is seen that the angle is about $\theta_{\rm s} \simeq 69°$ in the 30 MHz emission source at those times ($67.5° \lesssim \theta_{\rm s} \lesssim 70.5°$ for the sources emitting at frequencies 35 MHz $\gtrsim f \gtrsim 25$ MHz). Observations show that a high degree of circular polarization occurs during a very short time interval (about 5 minutes). The short time interval of observation of the circularly polarized emission implies that it is generated in the IFT within a very narrow angle range. For example, at the frequency of $f_{\rm Be} \simeq 30$ MHz the diagram beam is about $\Delta\theta \simeq 1°$ around the angle $\theta \simeq 69°$. We can also conclude that the remaining part of the burst is generated in the active tubes which are at a distance from the IFT (see Fig. 4a). We estimate the level of the magnetospheric plasma density which is found as high as $N \gtrsim 1.9$ cm^{-3} in the IFT at the heights corresponding to the 30 MHz gyrofrequency level. This plasma density provides the degree of circular polarization $r_\mathrm{c} \lesssim -0.95$. Outside of the IFT the plasma density is lower. From $r_\mathrm{c} \simeq -0.65$ one finds $N \simeq 0.7\ \mathrm{cm}^{-3}$.

4. Discussion

We show that the sudden increase in the circularly polarized component of the decametric emission in the event of Nov. 2, 1988 can be reasonably understood if the source of the highly circularly polarized emission is situated in the instantaneous Io flux tube. This conclusion agrees quite well with the results of other papers. Indeed, Lecacheux et al. (1991) proposed that the discussed emission belongs to the great arc. Riddle (1983), who has investigated the great arcs, found evidence that the emission appearing as the great arc on the dynamic spectra is created in the instantaneous Io flux tube. Genova & Aubier (1985) studied the high frequency limit of DAM emission storms and confirmed his result. Moreover, they found that most of the DAM emission is emitted from active magnetic flux tubes which certainly do not coincide with the instantaneous Io flux tube. The active magnetic flux tubes have to be shifted from Io position in the equatorial plane, by at least 70° of longitude. Our investigation shows also that the total emission of the burst with exception of the highly circularly polarized component is emitted outside of the IFT. However, from the considered polarization measurements we cannot define the positions of these active magnetic tubes (the shift from the Io position) because of the fact that in our model the emission polarization ellipticity depends mainly on the plasma density in the transitional region rather than on the angle between the direction of emission generation and the magnetic field lines in the source. But on the other hand, it is the weak dependence on the angle that allows us to understand the observed stability of the emission polarization ellipticity during almost the whole burst as a simple consequence of the magnetospheric plasma density stability outside the IFT.

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