

POLARIZATION ASPECTS FROM PLANETARY RADIO EMISSIONS

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1. Introduction

The low frequency, non thermal, highly polarized radio emissions coming from the four planets, the Earth, Jupiter, Saturn and Uranus, are thought to be produced by coherent amplification of electromagnetic waves at the electron gyrofrequency, due to the conversion of the energy contained in anisotropic distributions of energetic electrons. The proposed mechanisms predict a preferenced emission in the extraordinary, right-hand polarized (R-X) mode with respect to the local magnetic field, as actually confirmed, in most of the cases, by observations.

In this paper, a comparative review is made of the observed polarization properties of the planetary radiations, with special emphasis on the measured ellipticity of the waves, which appears as an important, and so far unused, observational constraint for any theoretical mechanism. It also appears as a possible means to remotely sense the properties of the medium close to the source region.

Section 2 is devoted to a brief description of the instruments and methods which have been used in measuring the polarization of planetary radio emissions. Section 3 summarizes the main properties of the polarization which were observed in each planet. In Section 4 the observed polarization is compared to the expected ones, in the source region and after propagation through the anisotropic plasma representative of the planetary inner magnetospheres. Section 5 is a discussion of the results.

2. The instruments and the methods

2.1 *The measurements of the radio wave polarization*

Any wave of arbitrary polarization is entirely defined by its coherency matrix:

$$\begin{pmatrix} E_x(t)E_x^*(t) & E_x(t)E_y^*(t) \\ E_x^*(t)E_y(t) & E_y(t)E_y^*(t) \end{pmatrix}$$

E_x and E_y being the instantaneous complex amplitudes of the wave electric field, measured along two orthogonal directions perpendicular to the travelling direction of the wave.

Taking into account the finite bandwidth of the observations and the necessary corresponding time-averaging operation, the wave coherency matrix is usually written in terms of Stokes parameters:

$$\frac{1}{2}S \begin{pmatrix} 1+Q & U+jV \\ U-jV & 1-Q \end{pmatrix}$$

where S is the magnitude of the total Poynting vector of the wave, and (Q, U, V) are the normalized Stokes parameters, with the following properties:

- $(Q^2 + U^2 + V^2)^{1/2}$ is the polarization degree
i.e. = 1 for a completely polarized wave
= 0 for a randomly polarized wave
- $(Q^2 + U^2)^{1/2}$ is the degree of linear polarization
- V is the degree of circular polarization

The electric field vector of the polarized component describes an ellipse. The axial ratio R and the tilt angle χ of the polarization ellipse are given by:

$$V = \frac{2R}{1+R^2} \quad (1)$$

$$\chi = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right) \quad (2)$$

The sign of V determines the sense of the circular polarization, e.g., with the radioastronomical convention, $V = +$ (resp. $-$) 1 corresponds to a left (resp. right) -handed circularly polarized wave.

A wide variety of techniques is used to measure the polarization of radio waves (Cohen, 1958). The measurements are based on combinations of differently polarized antennas and of receivers which are measuring total power outputs and relative phases of the antenna signals. For example, one can measure the left circularly polarized power response W_l and the right circularly polarized response W_r with two circularly polarized antennas of opposite hand and same aperture, such as two left- and right-handed helical beam antennas or two orthogonal linear antennas in quadrature. The circular degree of polarization V is then directly given by the ratio $(W_l - W_r)/(W_l + W_r)$.

In ground-based experiments, it is easy to show that the polarization of the received waves can be completely determined (e.g. by the knowledge of four independent quantities), by using two antennas in any orthogonal states of polarization and by measuring the total power outputs and the real and imaginary parts of the correlation voltage. The main difficulties lie in accurate balancing of the antenna system and in the sky background and interference effects on the measurement accuracy of relatively weak signals.

In space experiments, an additional difficulty arises because the wire antennas, usually erected on spacecraft to observe low frequency waves, have a low directivity. The arrival direction of the wave is a priori unknown with respect to the antenna polarization pattern, so that a direction finding capability has to be added (two more quantities to

determine) in order to achieve a measurement of the polarization. The combination of telemetry constraints and weight and power consumption requirements have prevented so far unambiguous measurements in space of the polarization of planetary radiations.

Because of the experimental difficulties, no extensive study of the polarization of the planetary low frequency radiations was done so far. But a lot of observations are nevertheless available, involving a number of different techniques and methods. Before comparing their results in order to give a picture of the general observed properties, the next sections briefly describe the experiments involved.

2.2 *Ground-based polarimeters and the terrestrial ionospheric Faraday effect*

From the ground, the observations dealt with the high frequency part of the Jovian decametric emission (DAM), starting from 5 to 10 MHz up to 40 MHz. Quantitative results on the DAM polarization have come from several studies involving polarimeters operating at a fixed frequency (Green and Sherrill, 1969; Kennedy, 1969; Carr et al., 1965; Barrow, 1971). Spectral studies (Riihimaa, 1976) were also carried out: they are essentially qualitative descriptions of the variations of the sense of circular polarization in a relatively small range of frequencies. The Faraday effect due to the terrestrial ionosphere was used by several authors (Parker et al., 1969; Lecacheux, 1976) to study the linear polarization of DAM. The terrestrial ionosphere acts as a birefringent medium for the DAM low-frequency waves: each propagating mode has a different phase velocity leading to an accumulated phase shift between the two modes, after their wave path through the ionosphere. It corresponds to a rotation of the major axis of the polarization ellipse with respect to its direction before entering the ionosphere. The rotation angle is approximately proportional to the electron content along the ray path and to the squared inverse of the frequency. The amount of the rotation is usually of the order of 10^2 radians. When the radiation is observed by using broadband, linearly polarized antennas, the dynamic spectrum is modulated by several, parallel intensity fringes, unequally spaced in frequency, whose contrast depends on the amount of linear polarization.

2.3 *Spacecraft measurements*

Besides the Planetary Radio Astronomy (PRA) experiment aboard Voyager 1 and 2 spacecraft, which could give a homogeneous set of observations of all the four planets, several other experiments, aboard spacecraft orbiting around the Earth, contributed to a great extension of our knowledge of the terrestrial kilometric radiation (TKR).

2.3.1 *Spinning spacecraft*

The most pertinent results concerning the TKR polarization, are provided by spinning (1-axis stabilized) spacecraft: Hawkeye 1, IMP 6, ISIS-1, DE-1, ISEE-3 and Viking.

All these spacecraft have a long dipole antenna (with respect to the spacecraft body, but short with respect to the wavelength) which rotates perpendicularly to the spacecraft spin axis. The spin period is of the order of a few seconds. The Fourier analysis of the spin modulation of the recorded intensity (if its time variability is not faster than the spin period) allows to infer the direction of arrival of the wave and the orientation of the

linear polarization, if any. If the radiation is not linearly polarized, intensity minima are recorded when the radio source is coplanar with the antenna and the spin axis; otherwise, the phase of the minima depends also on the orientation of the linear polarization.

ISEE-3 and DE-1 have an additional antenna along the spin axis. This antenna gives a signal which is not spin modulated and may serve as phase reference to measure separately the direction of arrival and the linear polarization.

The DE-1 correlator system has the additional capability to determine unambiguously the sense of the circular polarization. Except DE-1, none of these spacecraft could analyze the circular polarization.

2.3.2 *The Planetary Radio Astronomy (PRA) experiment aboard Voyager 1 and 2*

The PRA experiment is unique in having observed all kinds of planetary radiations. The accumulated set of data is therefore invaluable for the analysis and comparison of the properties of these radiations. In addition, the experiment was designed to be especially sensitive to the circular polarization, in contrast to the other plasma wave experiments aboard circumterrestrial spacecraft.

Voyager spacecraft are 3-axis stabilized. Two 10-meters orthogonal monopoles are erected on the spacecraft and thought to act as orthogonal dipoles in the so-called "turnstile" configuration. In this configuration, two polarization channel outputs are obtained after combination of the antenna signals in two quadrature hybrids of opposite signs. In the direction normal to the antenna plane, both channels are equivalent to the outputs of two circular antennas of opposite hand. In the antenna plane, the response is unpolarized (equality between the two channels) whatever the polarization of the incident wave. At intermediate elevation, the equivalent antennas are elliptical so that the apparent degree of circular polarization differs from the true ones by a factor which reflects the elevation angle. The sense of the measured circular polarization reverses at the antenna plane.

This simplified description of the PRA experiment does not account for its actual capability. At frequencies above a few MHz, the PRA monopoles are no longer short with respect to the wavelength. The polarization response of the system is much more complicated (Ortega-Molina, 1983) and cannot be deduced from the observations. So, the PRA measurement of the Jovian DAM polarization is, at present time, highly qualitative.

At lower frequencies, antenna impedance variations and mutual electrical interaction between the different booms erected on the Voyager spacecraft, lead one to expect some distortion of the equivalent electrical antennas with respect to the physical ones. Leblanc and Daigne (Daigne and Leblanc, 1986) showed that the null polarization plane was at about 20° of the expected one in a substantial range of directions. A recent analysis of the PRA observations of Saturn and Uranus, allowed Lecacheux and Ortega (Lecacheux and Ortega-Molina, 1987) to accurately reproduce the PRA response to the incident polarization, by using a model of two quasi-orthogonal dipoles tilted of 23.3° from the physical monopole plane. This model allows the computation of the true Stokes parameter V, with a precision better than 10%, so long as the radio source direction is known.

3. The observed properties of the polarization of planetary emissions

3.1 *The Earth (TKR)*

The spin modulation of the recorded intensity due to the dipolar shape of the rotating antenna pattern, was successfully used to locate the sources of TKR above the terrestrial auroral regions.

The exact location of the radio sources, above the terrestrial auroral zones, was obtained, by direct measurements from a number of spacecraft (ISIS 1, Hawkeye, DE-1, Viking). The radiation was observed as being mainly emitted in the X-mode by several spacecraft [Voyager (Kaiser et al., 1978), ISIS 1 (Calvert, 1981a), DE-1 (Shawhan and Gurnett, 1982), Viking (De Feraudy et al., 1987)], but weaker O-mode and Z-mode were also detected, when spacecraft approached the source [DE-1 (Gurnett et al., 1983a), EXOS-B (Jijiken) (Oya and Morioka, 1983), Viking (De Feraudy et al., 1987)].

The radiation appears nearly 100% circularly polarized: the amount of linear polarization must be very small to be in agreement with the direction finding measurements, obtained by using spinning, linearly polarized antennas (DE-1) (Mellot et al., 1985; Calvert, 1985b). A small (less than 30%) and variable linear polarization component was recently found in the ISEE-3 data (Lecacheux and Hoang, 1988), obtained when the spacecraft was flying-by the Earth, in its trajectory change towards comet Giacobinni-Zinner.

3.2 *Jupiter*

3.2.1 *Io-controlled and non-Io controlled DAM emission*

Since the DAM is conspicuously affected by the Faraday rotation in the terrestrial ionosphere, it was formerly considered an established fact that the radiation is elliptically polarized when escaping Jupiter (Parker et al., 1969; Lecacheux, 1976).

Quantitative comparisons of the amount of QL-Faraday rotation with simultaneous ionosonde data showed that at least 90% of QL-Faraday effect occur in the terrestrial ionosphere (Parker et al., 1969). The typical measured rotation (Parker et al., 1969) is 30–60 rad. at 30 MHz. The absence of any significant Faraday rotation occurring in the Jovian inner magnetosphere was explained by the fact that the radiation occurs above the denser part of the Jovian medium. These measurements were obtained prior to any in situ measurement of the Jovian magnetosphere, in particular, before the discovery of the Io-torus. The expected rotation that should be suffered by a 30 MHz wave during its path through the Io-torus can be evaluated to be 5–10 rad (Ortega-Molina, 1983). The possible contradiction between the former results about a negligible Faraday rotation in the Jovian plasma and the present knowledge of the Jovian environment should now urgently be investigated.

The few reliable, quantitative measurements of the DAM polarization which were obtained using polarimeters working at fixed-frequency, showed that the radiation is highly (nearly 100%) polarized (for example, Green and Sherill, 1969). The radiation is right-handed elliptically polarized in general, but left-handed elliptical polarization was also observed.

The measured axial ratio of the polarization ellipse was found to vary: i) in function of the CML–Io phase diagram (Kennedy, 1969), ii) in function of the frequency (Carr et al., 1965; Barrow, 1971).

The determination of the emission mode is still somewhat ambiguous because the radio sources are not clearly localized; but the case for an emission in the R–X mode, coming sometimes simultaneously from both hemispheres, is the most probable explanation of the observations. The PRA Voyager data have confirmed this point.

Complex polarization events were observed. Using the large aperture Arecibo telescope, Gordon and Warwick (1967) described the phenomenon they called "polarization diversity", showing fast alternate reversals of the polarization at time scales of 1 sec or less. The authors explained their observations by a special case of Faraday rotation occurring close to the source region where the characteristic polarization is still elliptical. This kind of event has to be reexamined in the light of the present knowledge of the Jovian plasma parameters. Other authors (Barrow, 1971; Riihimaa, 1976) reported observation of a mixture of left-handed, right-handed and linearly polarized events, randomly distributed on time scale of a few 10 sec. On the other hand, fringe systems, very similar in appearance to Faraday fringes when observed with linearly polarized antennas, but observed in circular polarization with the PRA experiment (Ortega–Molina, 1983; Calvert, 1983; Winglee, 1986), have been found in the data when the spacecraft was at a distance less than a few tens of planetary radii from Jupiter. All these observations show the complexity of the apparent polarization of the DAM radiation and call for new and more extended measurements.

3.2.2 *HOM emissions*

The HOM component is thought to be a low frequency continuation of the DAM radiation. Because of the resolution capability change of the PRA experiment around 1.3 MHz, it is difficult to demonstrate this assertion. In any case, quantitative measurements of the polarization of the HOM component were not carried out thus far. Dynamic spectra (for example, Alexander et al., 1981) show a great complexity with alternating left and right circular polarizations at time scales of one hour or less.

3.2.3 *nKOM and bKOM emissions*

The bKOM radiation (Leblanc and Daigne, 1985a) was described as coming from an extended source all around the planet on the magnetic shell $L=6$, lying close to the inner edge of the Io torus. The emission is observed in the X-mode and there is no quantitative polarization measurement.

The origin of nKOM radiation is more puzzling. The most popular model (Daigne and Leblanc, 1986) is a source probably located at the outer edge of the Io torus, in the equatorial region. The radiation would be emitted at the plasma frequency, in the O-mode.

3.3 *Saturn (SKR)*

The SKR radiation comes from two distinct radio sources, associated with the dayside cusp in each hemisphere of the planet (Kaiser and Desch, 1982; Lecacheux and Genova, 1983). The observed polarization corresponds to an emission in the X-mode. The radiation is 100% circularly polarized (Lecacheux and Ortega-Molina, 1987). No time-variation and therefore no dependence on the geometry of the emission (Kaiser et al., 1984) was found. The polarization does not depend on the frequency.

3.4 *Uranus (UKR)*

Two main radiation components (Warwick et al., 1986) are described in the recent literature to compose the last discovered magnetospheric radio emission. A narrowband (20–250 kHz) component (SLF) was observed in left-handed sense of polarization when observed from the planetary dayside, and in right-handed sense from the nightside. The broadband (20–850 kHz) component (SHF) was observed in left-handed sense of polarization only from the nightside. Analysis of the data shows that the SHF component comes most probably from the dark (southern) magnetic pole, therefore the radiation is emitted in the X-mode. The SLF component is emitted in the O-mode if its source is associated with the dayside (northern) magnetic pole (Leblanc et al., 1987; Lecacheux and Ortega-Molina, 1987). It is emitted in the X-mode if its source is associated with the nightside pole (Desch and Kaiser, 1987; Gulkis and Carr, 1987). The SLF radiation was observed to be 100% circularly polarized. The SHF degree of circular polarization exceeds 80% (lower limit) in the range 200 to 700 kHz (Lecacheux and Ortega-Molina, 1987).

3.5 Summary of the polarization properties of the planetary radio emissions

The preceding discussion can be summarized in a comparative table,

in which the observed polarizations and the deduced emission modes are indicated for each planetary radiation:

radiation	freq. range	mode	polarization	freq. effect	rot. effect
TKR	50 - 500 kHz	R-X	(quasi)circular	?	?
Io-DAM	1 - 40 MHz	R-X (L-O)	elliptical	?	?
non Io-DAM and HOM	0.4 - 38 MHz	R-X (L-O)	elliptical	yes	yes
bKOM	20 - 1000 kHz	R-X	?	?	?
nKOM	50 - 175 kHz	L-O	?	?	?
SKR	3 - 1200 kHz	R-X	circular	no	no
UKR - SLF	1 - 250 kHz	?	circular	no	?
UKR - SHF	20 - 850 kHz	R-X	circular	no	?

Examination of the table shows that all cases of polarization ellipticity can be observed. In the two right columns, we have indicated whether or not any morphological relationship was observed between the observed changes in polarization and gross features of the planetary radiations: the observing frequency and the directivity (beaming effect) of the radiation.

4. Interpretation of the polarization measurements

Only a small number of papers among those dealing with the theory of the planetary non thermal radiations have used the polarization measurements as a constraint in their models. The polarization measurements were mainly used to determine the emission mode, but no prediction or explanation of the wave ellipticity can be found, at our knowledge, in the literature, in spite of the numerous experimental results which have been summarized in the previous section.

However, the experimental results raise immediately two a priori unresolved questions: i) Why do the planetary emissions mainly appear as purely circularly polarized whereas the radiation is thought to be emitted at very large angle from the local magnetic field ?

ii) Could the fact that the Jovian DAM polarization is very different from that of the other planetary radiations, be an indication that the magnetospheric properties or the involved mechanisms are different?

In this section, we will roughly sketch out answers to these questions, hoping that more precise studies will be carried out in the near future.

4.1 Predictions of the emission mechanism

In order to compare with the observations, the first useful task is to compute, in the frame of any emission mechanism, what should be the polarization of the emitted wave when it

just leaves the source. For that, we will recall a few of the wellknown results about the wave polarization in an homogeneous plasma.

We define $\rho = +1$ (resp. -1) for the ordinary O (resp. extraordinary X) -mode and introduce, as usual in the high frequency approximation and by neglecting the collisions, the characteristic frequencies of the medium

$$\begin{aligned} X &= (f_p/f)^2 \\ Y &= f_c/f \end{aligned}$$

and the wave propagation angle $\theta = (\vec{B}, \vec{k})$.

The refractive index is given by:

$$n_\rho^2 = 1 - \frac{X R_\rho}{R_\rho - Y \cos \theta}$$

where R_ρ is the axial ratio of the polarization ellipse, given by:

$$R_\rho = A + \rho \sqrt{1 + A^2} \operatorname{sign}(\cos \theta)$$

with

$$A = \frac{1}{2} \frac{Y}{1 - X} \frac{\sin^2 \theta}{\cos \theta}$$

The sign of $|A| - 1$ defines two different propagation regimes: the case $|A| \ll 1$ corresponds to the quasi-longitudinal (QL) propagation regime, in which the polarization is nearly circular; the axial ratio is given by $R_\rho = \rho \operatorname{sign}(\cos \theta)$. The alternate case $|A| \gg 1$ defines the quasi-transverse (QT) propagation in which the polarization is linear ($R_- = 0, R_+ = \infty$). In the high-frequency approximation ($X, Y \ll 1$), one has $|A| \ll 1 \iff |\frac{\pi}{2} - \theta| \ll \frac{Y}{2}$.

The Stokes parameter V can then be expressed as:

$$V_\rho = 2R_\rho(1 + R_\rho^2)^{-1/2} = (1 + A^2)^{-1/2} \rho \operatorname{sign}(\cos \theta) \quad (3)$$

The last equation shows that the measurement of the degree of circular polarization, if the radiation could be observed when the wave just leaves the source, gives a relation between the plasma parameters X and Y and the emission angle.

For illustration we will apply this result to the context of the cyclotron maser mechanism. A number of authors (for example: Wu and Lee, 1979; Omidi et al., 1984; Le Quéau et al., 1984b) showed that in an homogeneous, magnetized, strongly depleted plasma ($\varepsilon = (f_p/f_c)^2 \ll 1$), the X-mode can be amplified by the cyclotron maser process, if, essentially, there is an energetic, non thermal population of electrons with an inversion of population at parallel velocity lying around $\beta_{\parallel} = \varepsilon^{1/2}$. The radiation will occur in a very small frequency range, namely $1 - 2\varepsilon < Y < 1 - \varepsilon$, and inside the boundary of a cone with semi-apical angle $\theta_{em} = \sin^{-1}((1 + 4\varepsilon)^{-1})$. The existence of inhomogeneity in the

medium, for instance a gradient of the magnetic field, modifies the resonance condition, so that the favoured emission angle becomes $\theta_{em} \simeq \cos^{-1}(\sqrt{2}\varepsilon^{-1/4})$.

Writing $X = \varepsilon Y^2 \ll 1$ and replacing in Equation (1) for V_{-1} , we obtain a relation between V and ε which is displayed in Figure 1. The range of possible values for V is in accordance with the expectation of a large wave ellipticity due to the large emission angle: of course, a number of refinements in this computation are needed, but, with particles energy from 1 to 10 keV corresponding to $\varepsilon \sim 10^{-3}$, typical circular polarization degree less than 50% should be usually observed, in contradiction with the main part of the observations reported in the previous section.

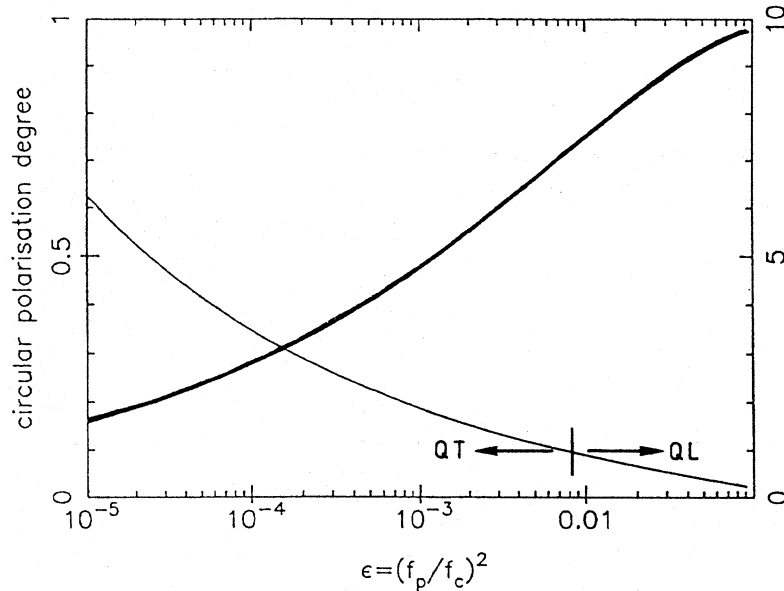


Fig. 1: Variation of the degree of circular polarization in function of the ε parameter, for a wave amplified at the gyrofrequency by the cyclotron maser process.

4.2 Polarization transfer and propagation effects

Our reasoning was made in the context of the magnetoionic theory which was developed for an infinite, homogeneous plasma. The planetary magnetospheres are, of course, not homogeneous. Therefore, in order to relate the observed polarization to wave polarization at the source boundary, we must examine the change of the wave polarization during its propagation through a varying medium, namely the magnetospheric plasma along the first planetary radii between the source and the observer.

In the problem of the polarization transfer in an inhomogeneous plasma, two different regimes can be distinguished, allowing for a more or less complete quantitative handling.

If the medium is changing slowly enough (in a sense that we shall define further), the magnetoionic modes propagate independently: they can exist separately and their identities are preserved along the ray path; the medium is said "locally homogeneous". This means, for example, that there is a Faraday rotation (due to the difference between the

phase velocities) and that the sense of circular polarization is reversing whenever the longitudinal component of the magnetic field changes direction. These properties were extensively used in the literature devoted to the interpretation of the observations, in particular about the localization of the radio sources.

When the medium is changing more rapidly the simple theory no longer applies. The effects of the inhomogeneity are then described as "coupling" between the natural modes. In the context of the radio astronomy, this was investigated mainly by Cohen (1960) and, more recently, by Daigne and Ortega-Molina (1984). These authors introduced, for simplification, the additional $X, Y, Z \ll 1$ hypothesis, which is referred to as the "weakly inhomogeneous" case. It is worth noticing, that in the case of planetary emissions which are radiating near the electron gyrofrequency f_c , i.e., at $Y \simeq 1$, this approximation has to be carefully justified.

The influence of the medium upon the propagation depends on the magnitude of the frequency relative to the characteristic frequencies. A trivial case is the limit of the very high frequencies, in which case the medium acts like a vacuum. In his work, Cohen (1960) defines a "transitional" frequency f_t , such that, if $f \ll f_t$, the modes are weakly or not coupled and the ordinary magnetoionic theory prevails, and, if $f \gg f_t$, the modes are strongly coupled so that the waves propagate essentially as in a vacuum. Obviously, in a medium where the plasma density and the magnetic field intensity decrease towards outer space, the definition of the transitional frequency is equivalent, for a wave propagating at a given frequency f , to the definition of the "limiting polarization zone" (LPZ) for the frequency f , which is the region where the wave reaches the polarization which is actually observed from outer space (Budden, 1952; Ratcliffe, 1962).

In CGS units, the transitional frequency can be estimated by (Cohen, 1960):

$$f_t \simeq 3.10^{-3} \cdot N_e \cdot \left(\frac{1}{B} \frac{dB}{ds} \right)^{-1}$$

In a dipolar magnetic field, the scale height $\left(\frac{1}{B} \frac{dB}{ds} \right)^{-1}$ is $\simeq 3/r$, so that:

$$f_t \text{ (kHz)} \simeq 6.10^3 \cdot N_{e(cm^{-3})}$$

For a wave radiated at 1 MHz, the limiting polarization zone is reached as soon as $N_e \simeq \frac{1}{6} cm^{-3}$. This value of electron density in the planetary magnetospheric plasma is quite common at a distance of a few radii from the center of the planet. The gyrofrequency is there also much lower than 1 MHz. Therefore the polarization of such a wave, in its limiting polarization zone and as observed from the outer space, is nearly purely circular.

This may satisfactorily explain the observations of the TKR, SKR and UKR. The radiation escapes from the source, at large angle with respect to the local magnetic field, in the *elliptical* polarization of the X-mode. The waves then propagate through a QL region (of the order of 1 planetary radius); their polarization become more and more circular, until they reach their LPZ in which the characteristic X-mode polarization is purely *circular*. That is the polarization which is ultimately observed.

The preceding formulation is adequate to describe the QL propagation regime. In the QT propagation regime, the coupling may be much stronger, because the characteristic polarization changes rapidly with the propagation angle. The notion of transitional frequency is still usable, and the coupling is weak or strong according to whether $f^4 \ll f_t^4$ or $f^4 \gg f_t^4$. But it is more convenient to define a "coupling factor", describing quantitatively the degree of coupling as the ratio of the characteristic polarization change, due to the varying medium or geometry, to the polarization difference between both modes (Budden, 1952; Ratcliffe, 1962). Daigne and Ortega-Molina (1984) showed that the coupling factor C could be defined as the ratio of two rotations in the Poincaré's sphere, one describing the amount of coupling, the other corresponding to the generalized Faraday rotation:

$$C = \frac{-d\psi/ds}{\omega_F}$$

where $\tan \frac{\psi}{2} = A$.

In the approximation $X \ll 1$ and $Y^2 \ll 1$,

$$\begin{aligned} -\frac{d\psi}{ds} &\simeq \frac{A}{1+A^2} \left\{ \frac{1}{Y} \frac{dY}{ds} + \left(\frac{2}{\tan \theta} + \tan \theta \right) \frac{d\theta}{ds} \right\} \\ \omega_F &\simeq \frac{2\pi f}{c} X Y \cos \theta \frac{(1+A^2)^{-\frac{1}{2}}}{1-Y^2} \end{aligned}$$

The transitional frequency can be found again from the limiting cases:

$$\begin{array}{ll} \text{QL case} & |A| \ll 1 \quad C = C_L \propto f \\ \text{QT case} & |A| \gg 1 \quad C = C_T \propto f^4 \end{array}$$

A model of the plasma studied, allows one to compute C as a function of the plasma parameters (X, Y, θ) scaled by a normalizing factor depending on the planet:

$$C = C(X, Y, \theta) (\lambda/R_{planet}) \quad (4)$$

where λ is the wavelength.

As an illustration, we have computed the variation of the coupling factor C , for a wave emitted slightly above the extraordinary mode cutoff level and perpendicularly to the magnetic field in a layered medium where the main inhomogeneity is due to the vertical decrease of the magnetic field intensity. This computation may serve as a zero order approximation of the polarization transfer of a wave emitted in the context of the cyclotron maser mechanism.

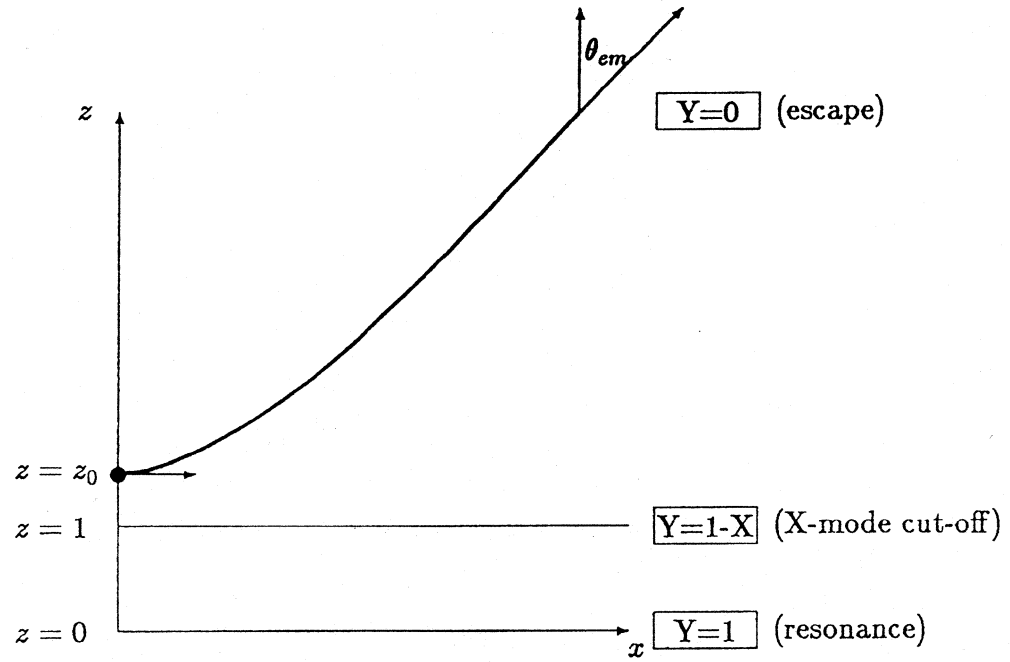


Fig. 2: Inhomogeneous plasma and radiating source model (see text).

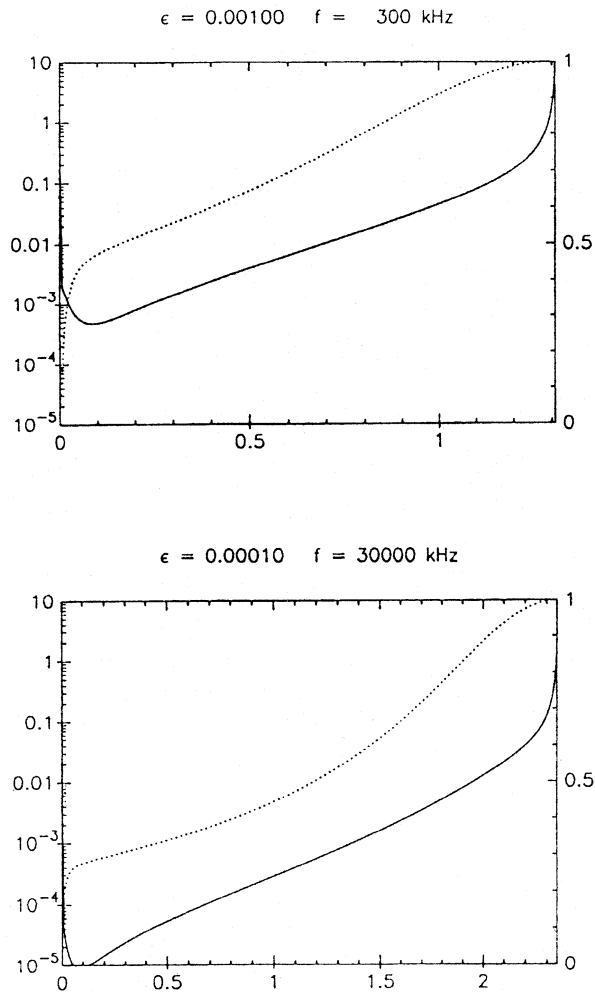


Fig. 3: Variation of the coupling factor (full curve) and of the degree of circular polarization (dotted curve), in function of the horizontal coordinate (perpendicular to the magnetic field) expressed in planetary radii, during the wave propagation in the model of Figure 2. Top: for a $f = 300$ kHz wave and $N_e \sim 1 \text{ cm}^{-3}$. Bottom: for a $f = 30$ MHz wave and $N_e \sim 10^3 \text{ cm}^{-3}$.

The plasma is described (Figure 2) by a constant plasma frequency ($X = X_0$) and a linearly decreasing magnetic field along the vertical z -axis. The horizontal and vertical coordinates (x, z) are scaled by putting $z = 0$ at the altitude where $Y = 1$ and $z = 1$ at the altitude of the X-mode cutoff ($Y = 1 - X$). Let z_0 be the altitude of the radiating source. The X-mode dispersion equation in this very simplified geometry and the Descartes-Snell's law leads to the ray equation:

$$\tan^2 \theta = \left(\frac{dx}{dz} \right)^2 = \frac{2z(z_0 - 1)}{z - z_0}$$

The emission angle θ_{em} is related to the source altitude z_0 by:

$$\theta_{em} = \tan^{-1} \sqrt{2(z_0 - 1)}$$

We can introduce the parameter ε and write the coupling factor C as a function of only ε and the space coordinate x expressed in planetary radii. Two examples, computed for $\varepsilon = 10^{-3}$ and $f = 300$ kHz and for $\varepsilon = 10^{-4}$ and $f = 30$ MHz, are shown in Figures 3a and 3b.

They show that no coupling is expected outside the source region, as previously quoted in a more qualitative way. Inside the source itself, and because our hypothesis of an emission at right angle with respect to the magnetic field, transverse coupling is observed. This should be reexamined precisely, by using the full mathematical treatment of the cyclotron maser mechanism in an inhomogeneous (magnetic field dependent) medium.

Conclusion: Are the measurements in agreement with a common mechanism for the production of planetary low-frequency radio emissions ?

One of the most conspicuous property of planetary non-thermal low-frequency radiations is its polarization. A large amount of observations, mainly provided by the Voyager Planetary Radio Astronomy experiment, is now available to compare the polarization properties of the different radio components observed for each planet.

The common property is the high degree of polarization, which is very close, if not equal, to 100%. In most of the cases, the emission is observed as propagating in only one characteristic mode of polarization, mainly the extraordinary, right-hand polarized mode, radiated at a large angle from the local magnetic field.

In so far as the polarization could be quantitatively measured, the kilo hectometric emissions of the Earth, Saturn and Uranus appear as purely circularly polarized. This can be explained by a change of the wave polarization, from quasi-linear or elliptical within the emission source to nearly circular at a distance of a few planetary radii during their propagation through the planetary inner magnetospheres.

Second order effects such as the presence of the ordinary mode or variable amounts of linear polarization might lead to interesting constraints upon the emission mechanism or the plasma properties in the source region.

The case of DAM is more puzzling. The well established elliptical polarization, dominant above 20 MHz, must be explained.

Let us assume that the radiation leaves the source of Jovian decametric radiation being elliptically polarized, merely in the X mode. In order not to become circularly polarized by the outwards propagation, the limiting polarization zone must be at the source. This implies that the cold electron density should be as low as $N_e \leq 5 \text{ cm}^{-3}$ at $f = 30 \text{ MHz}$ in the source. Since the radiation is assumed to be produced near the gyrofrequency, the $\varepsilon = (f_p/f_c)^2$ ratio should not exceed $5 \cdot 10^{-7}$. This value seems too low to be meaningful in the context of the cyclotron maser mechanism.

On the other hand, the radiation is observed after propagating through the Io plasma torus. A substantial rotation of the polarization ellipse, due to the QL Faraday effect within the Io-torus, should be measured in the ground-based records of the DAM. Earlier observations showed that this is not the case. Even if the radiation entering the Io-torus was not in a pure base mode, but was a mixture of extraordinary and ordinary circularly polarized waves, the waves should leave the Io-torus in an elliptical state of polarization. Because the differential phase shift between the two modes is a function of the frequency, an observable Faraday effect should be still measured.

Therefore, the remaining possibility is that the DAM radiation leaves its source being elliptically polarized, in the extraordinary mode, then becomes circularly polarized before it reaches the Io-torus. The subsequently observed elliptical polarization could be created inside the Io-torus by quasi-transverse mode coupling, due to the fact that planetary, dipolar magnetic field lines can be found to be nearly perpendicular to the ray path. This possibility was already suggested (Calvert, 1983; Daigne and Ortega-Molina, 1984), in order to explain fringe patterns recorded by the PRA experiment aboard the Voyager spacecraft. It could be tested by measuring the variation of the observed wave ellipticity as function of the frequency (Daigne and Ortega-Molina, 1984).

New measurements are needed to better understand the polarization properties of the planetary radiations. By using the available data from spacecraft, the polarization of TKR and, particularly, that of the low frequency (KOM and HOM) components of Jupiter, remain to be quantitatively studied. Future studies, made possible by the Ulysses and Galileo spacecraft, are promising because they will complete the results of Voyager spacecraft, by the use of more powerful wave experiments. New ground-based measurements of the Jovian DAM radiation are also needed; they are in progress at Nançay, France, where a new spectropolarimeter is now operating, able to provide the four Stokes parameters of the Jovian radiation in a broad range of frequencies.

