THE ELLIPTICAL POLARIZATION OF THE JOVIAN DECAMETRIC EMISSION AND THE MAGNETOSPHERE OF JUPITER

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Abstract

We summarize several new results on Jovian decametric radiation, which have been recently obtained by using the decameter broadband spectropolarimeter in Nançay, France. The DAM polarization ellipse was measured (shape and orientation) on several long lived, Io–controlled storms. An upper limit for the cold plasma density in the source was derived. Measurements were done for L bursts as well as for S bursts: Both kind of bursts are 100% polarized and exhibit the same polarization. The change in orientation of the polarization ellipse with frequency (Faraday rotation) was analyzed; the existence of Faraday rotation in the Jovian magnetosphere was demonstrated: Most of the rotation likely occurs in the Io–torus. The observed properties of DAM polarization are not consistent with simple ideas on Io's control and suggest an extended interaction region between Io and Jupiter's magnetic field.

1 Introduction

Elliptical polarization is rare in cosmic radiosources. It is unambiguously observed only for Jupiter's decameter radiation and for some pulsars. The Jovian Decameter Radiation (DAM) is observed since several decades from the ground in the frequency range extending from 39.6 MHz down to about 10 MHz [Carr et al., 1983]. Because of the presence of the terrestrial ionosphere, the low frequency extent of DAM, especially that of its Io controlled part, is not well determined. It probably merges with the HOM component discovered by the PRA experiment aboard Voyager spacecraft, at frequencies below a few Megahertz [Boischot, 1988].

Most of the properties of DAM are controlled by the direction of the observer within the planetary magnetic field geometry (dependence in Central Meridian Longitude (CML)). At the highest frequencies, the properties display a number of asymmetries, likely due to the non dipolar character of the Jovian magnetic field. A fraction of the emission, the most

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*Observatoire de Paris, Section de Meudon, 92195 Meudon Cedex, France intense, is also controlled by the orbital position of the moon Io relative to the observer (dependence in Io phase). Besides these angular dependencies, an additional outstanding property of DAM is its strongly elliptical polarization. Although, in the case of Jupiter, the association between DAM radiation and Jovian auroral activity is still not directly demonstrated, a number of indirect facts allowed to explain DAM as cyclotron maser radiation produced in the Jovian northern (resp. southern) auroral zones in right–handed (resp. left–handed) elliptical polarization, consistent with an X–mode emission. This scenario is common to the auroral low frequency radio emissions from four other planets: The Earth, Saturn, Uranus and Neptune. But the polarization of their radiation, in the limit of the observing accuracy, is observed as purely circular [Lecacheux, 1988].

Previous polarization measurements of Jovian DAM, done at several fixed frequencies, showed that the degree of circular polarization ranges between 30% and 70% and that of linear polarization ranges from 20% to 90% [Barrow and Morrow, 1968]. The linearly polarized component exhibits Faraday rotation. The largest part certainly occurs along the radiation path through the terrestrial ionosphere; but it could also occur in Jupiter's magnetosphere, although the latter is controversial [Phillips et al., 1989].

2 Observations of DAM Stokes parameters with the Nançay spectropolarimeter

The high sensitivity Nançay spectropolarimeter is fed to two antenna arrays, 72 conical helix antenna each, covering an effective area of about 4000 m^2 at 30 MHz [Boischot, 1980]. One array is sensitive to the right–handed circular (RHC) polarization, the other to the left–handed circular (LHC) polarization. In the measurement mode used in the observations reported here, the frequency was stepped from 10 to 41 MHz in 2.5 sec (250 frequency channels sweep). The complete polarization (full set of the four Stokes parameters) was computed, at each stepped frequency, with an integration time of 5 msec and an instantaneous bandwidth of 30 kHz. On line and off line calibrations allowed to obtain measurement accuracy always better than 10%, aside from the frequency channels contaminated by interferences.

Several Io controlled, long duration events were carefully examined [Boudjada and Lecacheux, 1991; Lecacheux et al., 1991; Dulk et al., 1992]. Our main results are the following:

- The radiation is always 100% elliptically polarized, with Io–A events being more circularly polarized than linear and conversely for Io–B events. Io–A and Io–B events are mainly right–hand polarized, sometimes with superimposed Io–C or Io–D left–handed events below about 25 MHz.

	circular	linear	total
Io–A	75 %	65 %	100 %
Io–B	50 %	85 %	100 %

- In a given Io–A or Io–B event, the polarization remains nearly constant for times of several hours, as well as along the entire frequency range. During the studied events, the CML changed by 70° to 140° and the Io–phase by 15° to 30° without any measurable change of the polarization degrees.

- Conspicuous Faraday rotation is visible on any events with measurable linear polarization. It is in particular observed for all Io–related events and for both L–bursts and (millisecond) S–bursts.

The long lasting, Io related storm of 1991 Jan. 20 [Dulk et al., 1992] contained both L–bursts and S–bursts of both RH and LH elliptical polarizations. It allowed to compare the polarization properties of these different kinds of bursts:

- The shape of the polarization ellipses is nearly the same for RH L–bursts and S–bursts, but that of LH S–bursts is different:

	circular	linear	total
RH L–bursts	50 %	87 %	100 %
RH S–bursts	60 %	80 %	100 %
LH S–bursts	$\geq$ 85 %	$\geq$ 30 %	$\geq$ 90 %

- The orientation of polarization ellipses of RH and LH bursts is not the same. The difference in orientation is changing with frequency, from which it is derived that there was 7% more Faraday rotation on the observed RH bursts than on the LH bursts.

3 Implications

3.1 Implications of existence of elliptical polarization

As discussed by Lecacheux [1988] the elliptical polarization of DAM is somewhat perplexing. The auroral planetary radiations are likely emitted at large angle from the magnetic field near the electron gyrofrequency on the extraordinary mode. The polarization of the radiation which just leaves the source must then be linear or strongly elliptical. A change of the wave polarization must occur, from elliptical within the emission source to circular at a distance of a few planetary radii, when the radiation propagates outwards inside the low density magnetosphere or out to free space. As far as their polarization could be quantitatively measured, the kilometric and hectometric emissions of the Earth, Jupiter, Saturn and Uranus indeed appear as purely circular.

The fact that the decametric radiation appears as still elliptically polarized when observed from space can be explained in two ways:
(i) Some (extreme) conditions of mode coupling or limiting polarization exist somewhere on the ray path. These conditions are rare in natural plasmas and seem to be inconsistent with the constancy of the observed polarization over several hours.
(ii) The electron density, in and near the source region, is already low enough to maintain the original polarization. The second explanation was already suggested by Parker et al.

[1969] and Lecacheux et al. [1988], which inferred an electron number density lower than about 5 cm^{-3} in Jupiter's low altitude, polar magnetosphere.

This idea was recently refined by Melrose and Dulk [1991], who derived the condition $N_e \leq 5 \cdot (\mathrm{f[MHz]}/25)$. In terms of the plasma frequency (f_p) and electron gyrofrequency (f_c) expressed in MHz, it becomes $f_p/f_c \leq (15/f_c)^{1/2}$ or $f_p/f_c \leq 10^{-3}$ to 10^{-2} for $0.3 \leq f_c \leq 30$ MHz. Even a relation of f_p/f_c 10–100 times higher would be sufficient for the CMI for growth in the X–mode at the fundamental. We suggest that this condition, allowing for elliptical polarization to be observed, is fulfilled only for the decametric radiation from Jupiter and that it is never satisfied for radiation at $f \leq 1$ MHz from any planet, including Jupiter.

Such a low plasma density in the Jovian inner polar magnetosphere might imply that the only electrons in that region are the energetic ones producing the cyclotron maser radiation. Calculations in Melrose and Dulk [1991] show that $N_e \approx 5$ cm^{-3} is sufficient to produce the observed DAM intensity. Such a plasma depletion is plausible when one takes into account the possible sources of plasma and their confinement. The thermal ionospheric plasma is confined to low altitudes by gravity: A typical altitude–density profile measured by Voyager is N_e $[\mathrm{cm}^{-3}] = 2 \cdot 10^5 \cdot e^{(-h/H)}$ (H=960 km); an electron number density lower than 5 cm^{-3} is reached at an altitude of 0.17 R_J. This is close to the surface, where the highest observed DAM frequency of 39.6 MHz can be produced. On the other hand, the plasma from the Io torus – another important potential source of magnetospheric plasma – is confined towards the equator by centrifugal forces: As pointed out by Melrose [1967], the centrifugal force due to Jupiter's rotation exceeds gravity at distance larger than 2.3 Jovian radii from the rotation axis. This might tend to drive plasma away from the DAM sources.

3.2 Implications of observed constancy of polarization over several hours

The constancy of DAM polarization in Io–related events observed during several hours – a noticeable part of the Jovian rotation – leads to several interesting conclusions. First of all, a unique polarization (e.g. shape of the polarization ellipse) is only found for events with 'simple' dynamic spectra; conversely, when the dynamic spectrum obviously consists of superimposed dynamic spectral features as, for example, arcs of opposite curvatures, the apparent polarization may vary in time or in frequency. We infer that such superimposed dynamic spectral features correspond to different radiosources emitting uncorrelated radiations from different, unresolved locations. An illustration is given by the 1988 Nov. 2 Io–A event (cf. Figure 2 in Lecacheux et al. [1991]) in which a short duration, prominent, high frequency arc, with a polarization almost circular, is embedded in an emission background with a strongly elliptical polarization. Clearly, polarimetry may serve to distinguish radiosources which cannot be separated by interferometry at long wavelengths.

In the case of the events corresponding to emissions from a unique source, we could observe constancy of the polarization over more than four hours. During this time, Jupiter's CML changes by about 140° and Io's position changes by about 30°. Assuming that the Io–controlled radiation is on the instantaneous Io flux tube, the angle θ between the magnetic field and the observer's direction would also change by about 30°. Radiation produced by a cyclotron maser is emitted with an axial ratio $T \approx \cos\theta$ [Melrose and Dulk, 1991]. Typical observed values of the axial ratio are ≈ 0.30 (i.e. $\theta \approx 72°$) for Io–B events and ≈ 0.45 (i.e. $\theta \approx 63°$) for Io–A. The constancy with time of these derived values of θ dismisses the assumption that the radiation originates only from the Io instantaneous flux tube.

Another observation is also in such a disagreement. During the major part of many Io–B events, the Io phase is less than 90°, so that the emission angle θ is greater than 90° in the northern hemisphere. However, the measured polarization is RH, when LH polarization should be observed. Subsequent reversal of the polarization does not occur when θ goes through 90°.

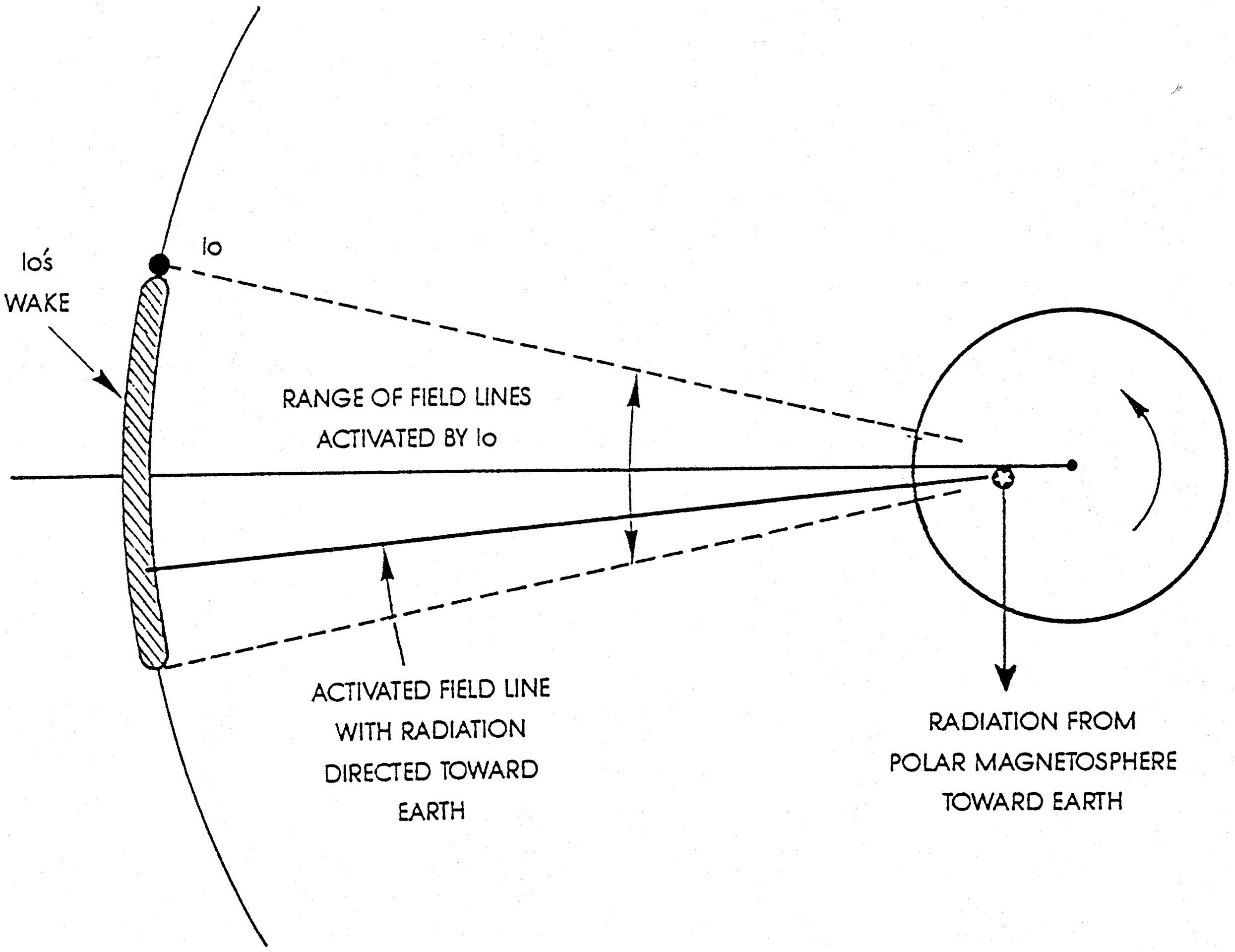

Figure 1: Sketch of the proposed model of interaction between Io and Jupiter's magnetic field, compatible with polarization constancy.

We therefore propose the following model (Figure 1) of Io controlled DAM emission in order to account for these observations. Io excites continuously the DAM source on a set of L ≈ 6 field lines extending over a longitude sector of 30° or more, mainly downstream of Io. At each longitude in the sector, the radiation is beamed on the surface of a hollow cone of ≈ 75° half–opening angle; but only the radiation of a very small range of longitudes is oriented towards the Earth. As Jupiter rotates the radiation directed towards the Earth continuously changes from one field line to the other and, as Io revolves, the portion of the active sector which produces the radiation directed towards the Earth also changes. However, the corresponding 'visible' DAM source region remains fixed, on the near side of Jupiter's limb. This model conciliates both observations i) that the Io control may extend over an appreciable active longitude sector around Jupiter (for example by multiple reflections of Alfvén waves as proposed by Gurnett and Goertz [1981], and ii) that most of the properties of the corresponding radio emission yet remain very similar during several hours.

3.3 Implications of observed Faraday rotation in Jupiter magnetosphere

We have reported in the previous section the evidence for a sizable amount of Faraday rotation occurring within Jupiter's magnetosphere. Since the existence of elliptical polarization implies very low plasma density in the inner polar magnetosphere, it is very unlikely that the excess of Faraday rotation occurs here. However, as discussed by Dulk et al. [1992], this excess may occur in the Io torus. By using the Voyager model of Io torus [Divine and Garrett, 1983] and the circumstances of the 1991 Jan.20 event (Figure 2) we can find that the computed rotation along ray path from a northern hemisphere source is $+0.7\pi$ radians, and that along a southern ray path is -1.6π radians. The difference of 2.3π radians is quite consistent with the observed excess of 3.4π radians, taking into account that the plasma density in the Io torus may depart from the average model of Divine and Garrett [1983]. Note that, in this observation, the Faraday rotation occurring in the terrestrial ionosphere was 46π radians. As far as the amount of Faraday rotation at decameter wavelengths in the terrestrial ionosphere could be accurately measured, the measurement of the total Faraday rotation on Jupiter's DAM might give an easy and very cheap method to repeatedly measure the electron column density in the Io torus.

4 Conclusions

- The existence of elliptical polarization implies that the plasma density in the low altitude, polar magnetosphere of Jupiter is very low. This is not compatible with the Divine and Garrett [1983] model of that region.

- Io activates a large longitude range of field lines, but only a small range is seen by a given observer. As Jupiter rotates and Io revolves, beams from different ones of the activated field lines are directed towards the observer.

- Depending on CML and Io phase, the radiation traverses the Io torus more or less centrally, and undergoes Faraday rotation there. The observed amount is in good agreement with electron density model of the torus.

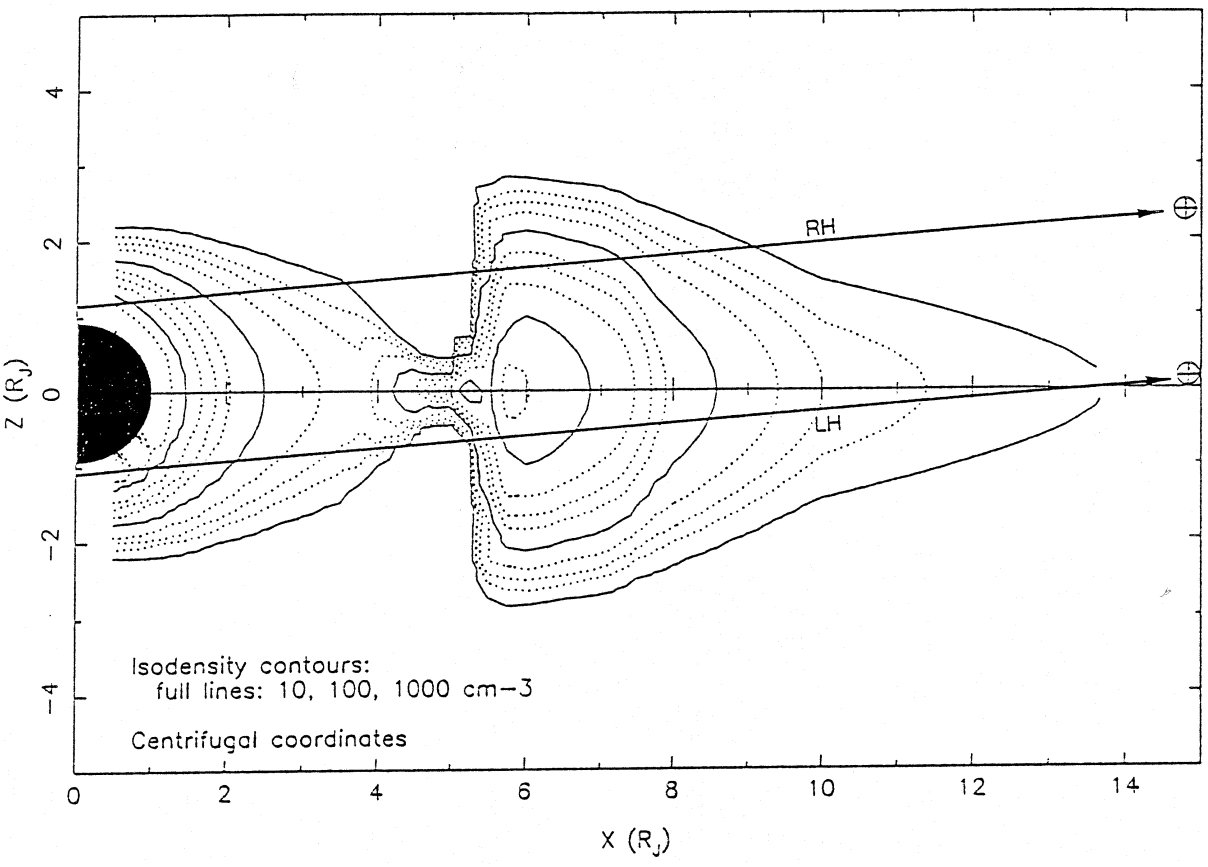

Figure 2: Voyager model of plasma density in Jupiter's inner magnetosphere [Divine and Garrett, 1983], superimposed with representative 18 MHz ray paths from the northern and southern auroral zones at the time when RH and LH bursts were being observed.

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