JOVIAN ACTIVE LONGITUDE: A PARAMETRIC STUDY

P. H. M. Galopeau*, M. Y. Boudjada†, and H. O. Rucker†

Abstract

We have developed a model allowing a theoretical location of the Io-controlled decameter radio sources (Io-A, Io-B, Io-C and Io-D) in the central meridian longitude-Io phase diagram. This model considers the cyclotron maser instability to be at the origin of most auroral planetary radio emissions. We derive the efficiency of this theoretical mechanism at the footprint of the Io flux tube during a complete revolution of the satellite around Jupiter and we show that some longitudes in the northern and southern hemispheres favor the radio decameter emission and lead to a higher occurrence probability. In order to simplify the calculation, we suppose that electrons are accelerated in the neighborhood of Io and follow an adiabatic motion along magnetic field lines carried by the satellite. We also assume that the source of free energy needed by the cyclotron maser instability to amplify the waves derives from a loss cone distribution function built up by electrons which have disappeared in Jupiter's ionosphere. We study the effect of several parameters on the theoretical location of the sources in the central meridian longitude-Io phase diagram, in particular the jovicentric declination of the Earth and the frequency of emission.

1 Introduction

Long term ground observations of the jovian decameter radio emission (hereafter DAM) show that the occurrence probability of the radiation depends on two essential parameters: the central meridian longitude (CML, System III) which is linked to the rotating magnetic field and the orbital phase of the satellite Io [Bigg, 1964]. The CML-Φ_{Io} diagram, which displays the occurrence of the emission as a function of the CML and Φ_{Io}, reveals several zones of enhanced occurrence probability which have been named Io-controlled sources: Io-A, Io-B, Io-C and Io-D [Carr and Desch, 1976]. In a recent paper [Galopeau et al., 2004], within the framework of the cyclotron maser instability, which is supposed to be

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the mechanism at the origin of most non-thermal planetary radio emissions, we showed that some longitudes in the northern and southern jovian hemispheres favor the radio decameter emission and induce a higher occurrence probability. We computed the efficiency of this theoretical mechanism at the footprint of the Io flux tube during a complete revolution of this satellite around Jupiter. In the present paper, we investigate the role of different parameters (frequency, half-angle of the emission cone, lead angle of the active flux tube, declination of the Earth, see Figure 1) on the location of the active longitude range and on the theoretical CML-Φ_{Io} diagram.

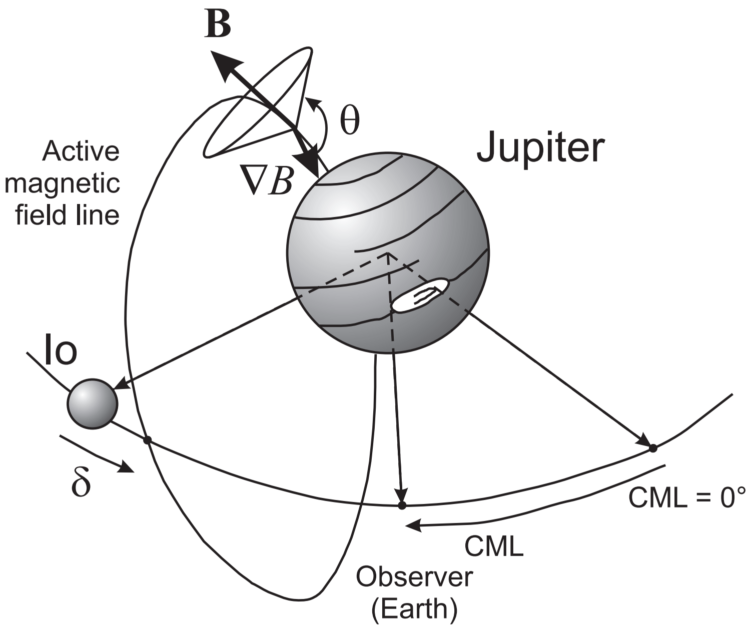

Figure 1: Schematic illustration of the parameters of our model. The radiation is supposed to be emitted at the local gyrofrequency along an active magnetic field line intersecting Io's wake with a lead angle δ. The radio emission is beamed into a hollow cone with half-angle θ and axis parallel to the direction of the gradient of the magnetic field modulus ∇B.

2 Theoretical outlines

In our model, we assume that electrons are accelerated in the neighborhood of Io's wake and follow an adiabatic motion along an "active" magnetic field line shifted by an angle δ relatively to Io. We also suppose that some electrons disappear by collision in Jupiter's ionosphere leading to a loss-cone distribution function supposed to be the source of free energy needed by the cyclotron maser instability to produce the radiation.

The generation of planetary radio emissions (in particular the jovian decametric emissions) is attributed to the cyclotron maser instability (CMI) theory introduced by Wu and Lee [1979]. This mechanism is a resonant coupling between right-handed electromagnetic waves (relatively to the local magnetic field) and an electron population forming a magnetized plasma. The source of free energy needed by the CMI is contained in a positive gradient in perpendicular velocity $v_\perp$ of the electron distribution function f; i.e. $\partial f/\partial v_\perp$ must be positive in certain domains of the momentum space [Le Quéau et al., 1884a, 1984b; Ladreiter, 1991].

In order to compute the maximum growth rate of the waves produced by the CMI, we made several simplifying hypotheses. First we supposed that the radiation generated by the CMI was emitted at the local gyrofrequency within a hollow cone of half-angle θ, the axis of which is parallel to the gradient of the local magnetic field modulus ∇B. The source of free energy needed by the CMI is a loss cone built up by electrons which disappear in Jupiter's ionosphere. We have also assumed that these electrons, accelerated in the vicinity of Io's wake, follow an adiabatic motion along a magnetic field lines linked to Io with a lead angle δ. When they penetrate into the jovian ionosphere, their probability of disappearance is assumed to be proportional to the length of their actual path and to the ionosphere density. Finally we made the assumption that the distribution function of the electrons responsible for the radiation was Maxwellian at Io. All the details of the calculation are presented in [Galopeau et al., 2004].

The general dispersion equation for a right-handed mode is:

$$k^2 - \frac{\omega^2}{c^2} - \frac{\mu_0 e^2}{4\pi m}\,\omega \iint \frac{\partial f/\partial v_\perp}{\omega - k_\parallel v_\parallel - \omega_c/\gamma}\, v_\perp^2\, dv_\perp\, dv_\parallel \;=\; 0 \tag{1}$$

where $\mathbf{k}$ and ω are the wave-number and the frequency of the wave, $v_\perp$ and $v_\parallel$ are the components of the electron velocity perpendicular and parallel relatively to the ambient magnetic field, ω_c refers to the local gyrofrequency, γ the Lorentz factor and m the electron mass. Here the frequency is a complex parameter:

$$\omega \;=\; \omega_r + i\,\omega_i\,, \quad \omega \in \mathbf{C}\,, \quad \omega_r, \omega_i \in \mathbf{R}\,. \tag{2}$$

The growth rate ω_i (imaginary part of the frequency) can be derived from equation (1), ω_p denoting the plasma frequency and $\delta()$ the Dirac function:

$$\omega_i \;=\; \frac{\omega_p^2}{8} \int_0^{+\infty} v_\perp^2\, dv_\perp \int_{-\infty}^{+\infty} \frac{\partial f}{\partial v_\perp}\, \delta\left(\omega_r - k_\parallel v_\parallel - \frac{\omega_c}{\gamma}\right) dv_\parallel \tag{3}$$

with the following normalization:

$$\iiint f(v_\parallel, v_\perp)\, d^3\mathbf{v} \;=\; 1\,. \tag{4}$$

The growth rate is significant when the resonance condition $\omega_r - k_\parallel v_\parallel - \omega_c/\gamma = 0$ in the integral of equation (1) is fulfilled. In the phase space $(v_\parallel, v_\perp)$, this condition can be approximated by a circle, the radius of which is:

$$\Xi \;=\; c\left[\frac{k_\parallel^2 c^2}{\omega_c^2} + 2\left(1 - \frac{\omega_r}{\omega_c}\right)\right]^{1/2} \tag{5}$$

and the center of which is positioned at the point $v_\perp = 0$, $v_\parallel = v_0 = k_\parallel c^2/\omega_c^2$.

Supposing that the electron distribution function in the vicinity of Io's wake is a Maxwellian characterized by a temperature T, we can derive the distribution function $f(s,\alpha,v)$ at any position s upon a magnetic field line carried away by Io and shifted in longitude by an angle δ. α denotes the pitch angle and v the velocity. So, in the case of down-going electrons toward Jupiter, we get:

$$f_{\mathrm{down}}(s,\alpha,v) \;=\; \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT} \tag{6}$$

for pitch angles in the interval $\pi/2 \le \alpha \le \pi$ for the northern hemisphere or $0 \le \alpha \le \pi/2$ for the southern hemisphere. Concerning up-going electrons (toward Io), a part of them has disappeared in the jovian ionosphere. Let $\mathcal{P}(s,\alpha)$ be the probability of collision in the ionosphere for an up-going electron as a function of the pitch angle α and the current abscissa s, then the distribution function is:

$$f_{\mathrm{up}}(s,\alpha,v) \;=\; [1-\mathcal{P}(s,\alpha)] \left(\frac{m}{2\pi kT}\right)^{3/2} \frac{e^{-mv^2/2kT}}{\cos^2\frac{\alpha_c}{2}} \tag{7}$$

where α_c denotes the angle of the loss cone and corresponds to $\mathcal{P}(s,\alpha_c)=1$. This equation applies to the situation $\alpha_c \le \alpha \le \pi/2$ (north) or $\pi/2 \le \alpha \le \pi-\alpha_c$ (south). Everywhere else $f_{\mathrm{up}}(s,\alpha,v)=0$. A precise expression of $\mathcal{P}(s,\alpha)$ is given in [Galopeau et al., 2004].

Finally it is possible to derive the maximum growth rate ω_i of the CMI from an integration along the resonance circle (v_0,Ξ).

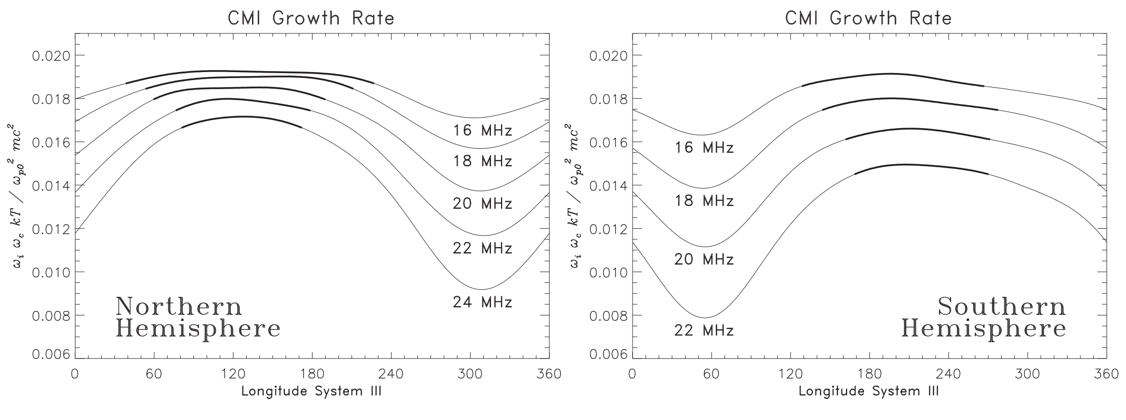

Figure 2: Dimensionless normalized growth rate of the cyclotron maser instability versus jovian longitude (System III), calculated for both hemispheres for five frequencies: 16, 18, 20, 22 and 24 MHz. The growth rate ω_i is normalized to $\omega_{p0}^2\,mc^2/\omega_c\,kT$, where ω_{p0}^2 and T are the plasma frequency and the temperature of the initial electron distribution function at Io and ω_c the local gyrofrequency. The thick parts of the curves define an active longitude range and correspond to a growth rate greater than 97% of the maximum rate.

We numerically determine, at a given frequency of emission, the position of the resonance circle (v_0,Ξ) for which the growth rate ω_i is positive and maximum, for each position of the active magnetic field line characterized by its longitude. In Figure 2, the maximum growth rate (actually a dimensionless normalized growth rate $\omega_i\,\omega_c\,kT/\omega_{p0}^2\,mc^2$ where ω_{p0} is the plasma frequency at Io's orbit) is plotted as a function of the jovian longitude of the active magnetic field line along which the radio emission is supposed to occur. The calculation has been made for several frequencies: 16, 18, 20, 22 MHz for both hemispheres and also 24 MHz for the northern hemisphere. With regard to the DAM radiation coming from the northern and southern hemispheres, the maxima of the CMI efficiency are around 130° and 200°, respectively.

3 CML-Io phase diagram

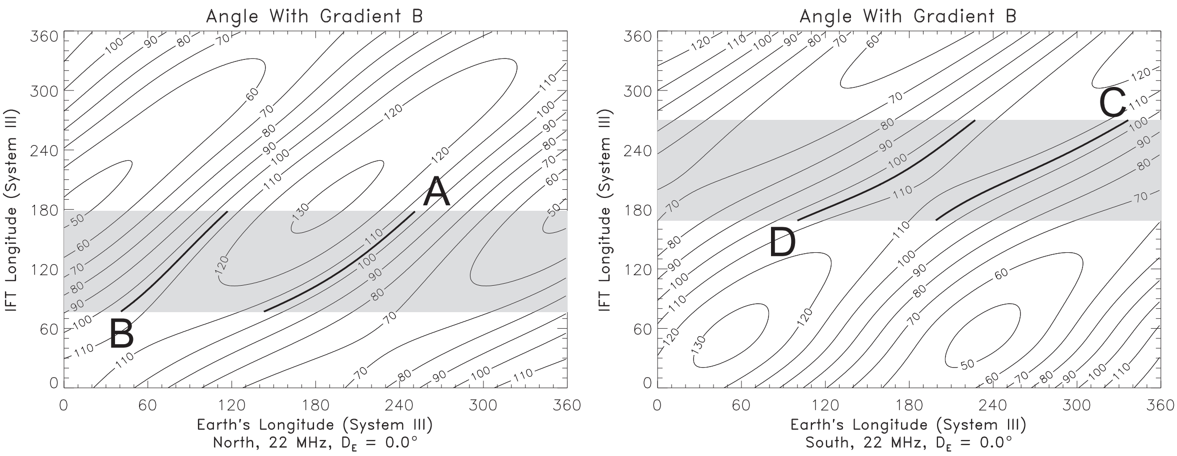

Figure 3: Contours of the angle between the gradient of the local magnetic field and the direction of the observer (located at the Earth) for a radiation at 22 MHz. An active longitude range is deduced from the curves in Figure 2 and displayed in grey. The thick segments A, B, C, D correspond to the intersection of an emission cone (with half-angle θ =105°) with the active longitude range. These segments are supposed to define the emissions with the highest occurrence probability.

Figure 3 displays the contours of the angle between the direction of the observer (located at the Earth) and the gradient of the local magnetic field, at the place where the emission occurs. The abscissa is the jovicentric longitude (System III) of the Earth and the ordinate is the longitude of the active field line. The grey area corresponds to a certain domain of active longitude, carried away by Jupiter, and deduced from the curves in Figure 2. Two conditions are needed for the radio emission to be observed at the Earth's orbit: (i) the active magnetic field line must cross the CMI active domain linked to Jupiter, and in the same time (ii) the observer must be on the hollow cone representing the beaming of the radiation. In our model, this hollow cone has its axis parallel to the direction of ∇B and is characterized by its half-angle θ (measured from ∇B, see Figure 1). Because of the propagation of the waves, $\theta \geq 90°$.

In order to compare the theoretical zones of high emission probability with the observations, in particular with the occurrence diagram, it is relevant to use a representation involving the phase of Io rather than its longitude. Thus in Figure 4, the four segments of high occurrence probability are displayed in a usual CML-Io phase diagram.

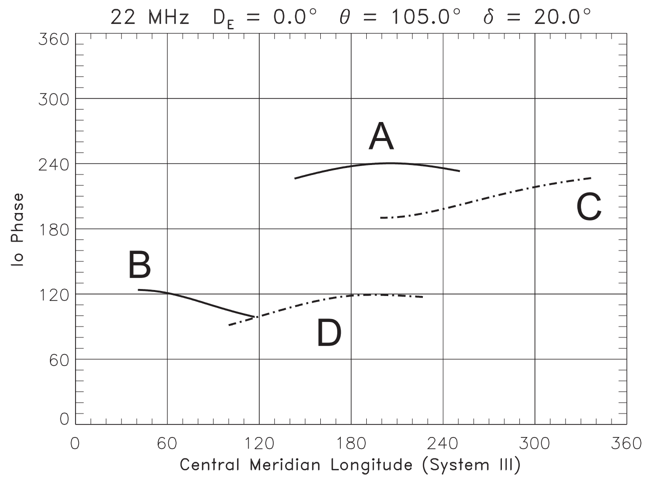

Figure 4: Curves of high occurrence probability versus central meridian longitude and Io phase derived from Figure 3. Here the frequency is 22 MHz, the half-angle of the emission cone θ is 105°, the lead angle δ is 20° and the declination of the Earth D_{E} is 0°.

4 Parametric study

We analyze the variation of the source occurrence region for different values of the following parameters: the lead angle δ (0°, 20°, 40°), the half-angle θ of the beaming cone (100°, 105°, 110°), the observation frequency f (20, 22, 24 MHz), and the jovicentric declination of the Earth D_{E} (-3°, 0°, +3°). Figure 5 displays the different CML-Io phase diagrams obtained for different sets of values given for (δ, θ, f, D_{E}).

Lead angle δ: The change of δ from 0° to 40° corresponds to an equal decrease of all sources in Io phase while their longitudes remain unchanged.

Declination of the Earth D_{E}: The high occurrence pairs Io-A-B and Io-C-D present unalike movements when the jovicentric declination of the Earth varies from -3° to +3°. All these sources have their longitudes quasi-constant but their Io phase increases (Io-A and Io-C) or decreases (Io-B and Io-D).

Half-angle θ: The half-angle θ is considered to vary from 100° to 110° for fixed values of the other parameters (f = 22 MHz, δ = 20°, D_{E} = 0°). θ seems to be the parameter playing the most decisive role in the location of the sources: the northern and southern hemisphere sources Io-A-B and Io-C-D are found to converge towards the central point of the CML-Io phase diagram when θ tends towards 110°.

Observed frequency f: As it can be noticed in Figure 2, the active longitude range is wider at low frequencies. As a consequence the corresponding zones of high occurrence in the CML-Io phase diagram spread over a larger longitude range (e.g., 20 MHz in Figure 5). At 24 MHz the source pair Io-C-D has disappeared.

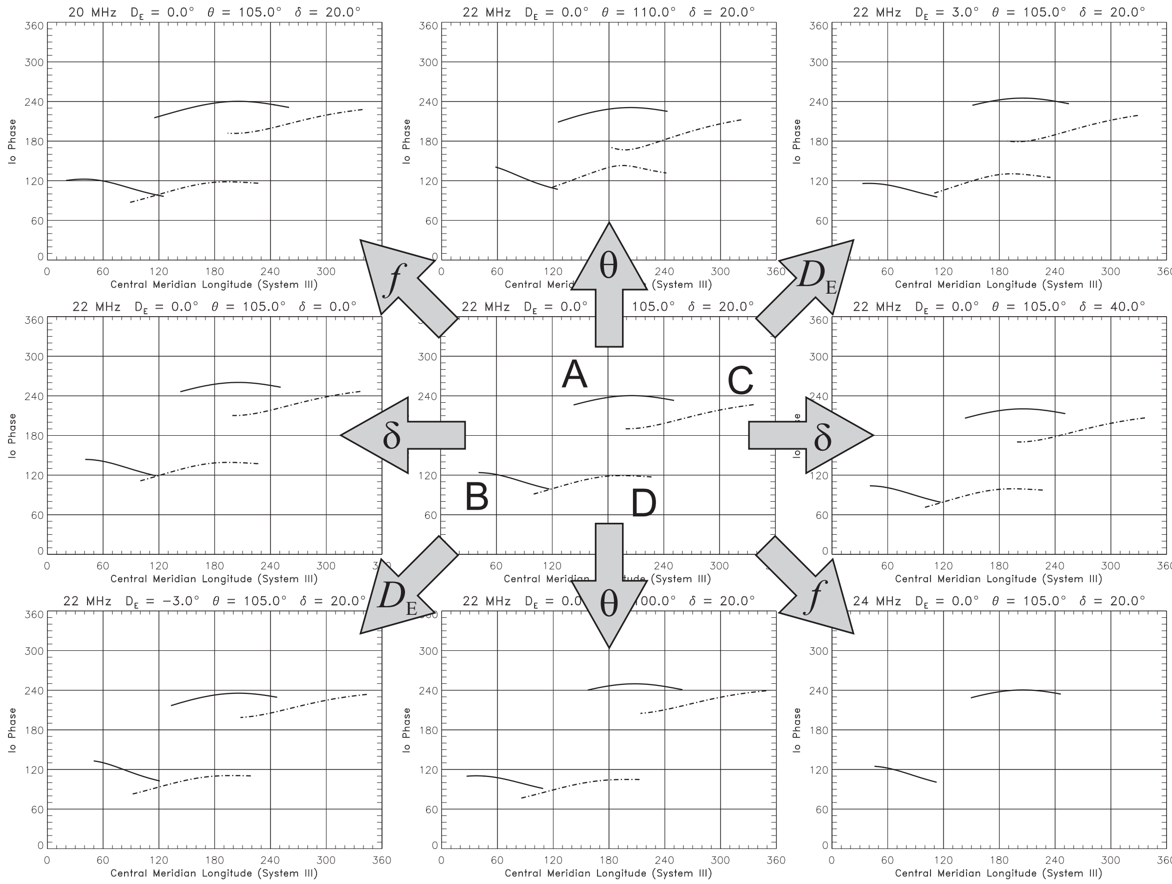

Figure 5: Curves of high occurrence probability versus central meridian longitude and Io phase computed for several values of the lead angle δ (0°, 20°, 40°), of the half-angle θ (100°, 105°, 110°), of the frequency f (20, 22, 24 MHz), and of the declination of the Earth $D_{\rm E}$ (-3°, 0°, 3°).

5 Conclusion

In the framework of the CMI theory, it is possible to prove the existence of an active longitude, rotating with Jupiter, and favoring the radio decameter emissions. ¿From the model developed by Galopeau et al. [2004], we have investigated the role of some parameters on the CML-Io phase diagram: the lead angle δ, the half-angle θ of the beaming cone, the observation frequency f, and the jovicentric declination of the Earth $D_{\rm E}$. Some of these parameters were studied in-depth by Imai et al. [2002 and references therein; 2005, this issue] who proposed a model explaining the production of modulation lanes in Jupiter's dynamic spectra. Some effects are similar to the observations: it is notably the case for $D_{\rm E}$ and f. However it is difficult to fit simultaneously the four observed sources Io-A, Io-B, Io-C and Io-D, in particular Io-C and Io-D for which the agreement in longitude is difficult. Moreover our model only allows a right-hand polarization for the northern sources and a left-hand polarization for the southern ones. In our study, the location of the active longitude (displayed in Figure 2) is governed mainly by the variation of ∇B at the footprint of the active magnetic field line (see Figure 1) whereas the electron distribution function is supposed to be constant at Io's orbit. Another model, proposed by Zaitsev et al. [2003] (see also [Shaposhnikov et al., 2006]), considers that the origin of the active longitudes is due to a change of the efficiency of the particle acceleration in Io's ionosphere and an electron scattering in the Io plasma plasma torus. An interesting solution might lie in a combination of both models.

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