ORIGIN OF ACTIVE LONGITUDES IN JOVIAN DECAMETRIC RADIO EMISSION

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Abstract

It is shown that the origin of "active" longitudes in the decametric radio emission of Jupiter is due to the joint action of two factors - the change in the efficiency of particle acceleration in Io's ionosphere due to the variation in the planetary magnetic field near Io and the change in the degree of broadening the angular spectrum of accelerated particles during their passage through the plasma torus. This broadening is caused by the electron scattering by plasma waves and whistlers existing in the torus, and its value depends on Io's longitude. Due to the broadening the accelerated electrons exit from a very narrow range of pitch angles inside which the electrons can reach the heights where the decametric radio emission is generated. The latter effect is a main reason of predominance of the Jovian decametric emission from the sources located in the northern hemisphere of Jupiter. It is shown that the predicted "active" longitudes are in good agreement with observations.

1 Introduction

A statistical analysis of occurrence of the Jovian decametric radio (DAM) emission reveals a clear bunching of the emission bursts in some domains in the "central meridian longitude (CML) - Io phase (γ_{Io})" diagram (Fig. 1). These domains are called the Io-related sources (Io-A, -A′, -B, -C, and -D) due to which the appearance of this emission correlates with the location of the satellite on its orbit. The latter made it possible suppose with high confidence that the directivity diagram of the decametric radio emission is a hollow cone and the observed correlation is caused by sequential passages of the surface of the hollow cone through the "source-observer" line [Dulk, 1965]. It is also seen in Fig. 1a that the appearance of Io-related DAM emission depends on one more parameter - the longitude of the central meridian. In this formulation, the longitude of the central meridian of a DAM burst determines the time of its observation. The dependence of DAM emission on CML is actually a result of both the existence of "active" longitudes of Io and the fairly narrow width (in longitude) of the lobe of the DAM emission beam. The "active"

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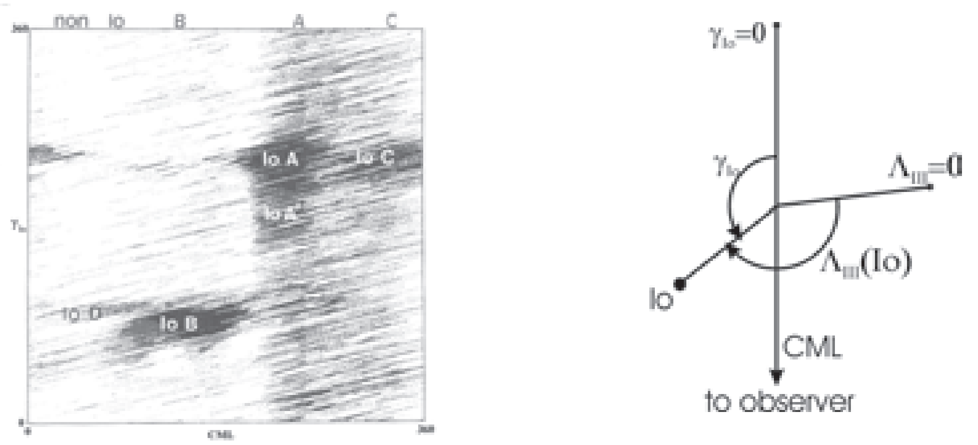

Figure 1: (a) Two-dimensional dependence of DAM activity on the longitude of the central meridian (CML) and Io phase (γ_{Io}). The picture is taken from [Genova, 1985]. (b) Coordinate convention. The view is from above the north pole.

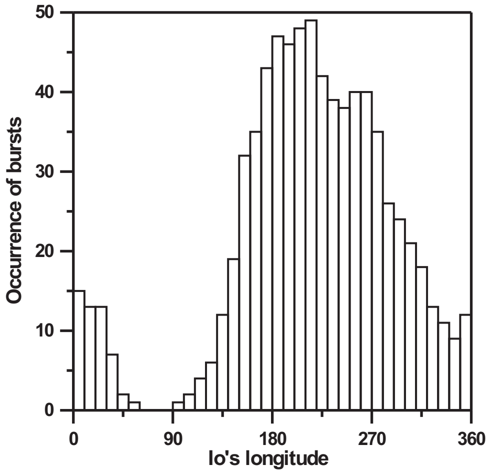

Figure 2: Variation in the probability of occurrence of DAM as a function of Io's longitude in the Jovian frame III from Io-related sources. The probability was plotted using the data from [Leblanc et al., 1993; Dulk et al., 1994; Boudjada, 1995].

longitudes are special parts of the satellite orbit where decametric radio bursts occur most probably. Variation in the occurrence of DAM emission as a function of Io's longitude (λ_{Io}) in the Jovian frame III (see Fig. 1b) from Io-related sources is shown in Fig. 2. The Io's longitude in the Jovian frame III characterizes the location of Io relative to the magnetic field of the planet. It is seen in Fig. 2 that the occurrence of Io-related DAM emission increases sharply where Io is in the longitude interval $\lambda_{\mathrm{III}}(Io) \simeq 120° - 300°$.

According to our model, the existence of the "active" longitudes is caused by two reasons: 1) the change of the efficiency of particle acceleration in Io's ionosphere due to the change in the value of the planetary magnetic field that Io "sees" during its motion along the orbit, and 2) the change in the degree of broadening of the angular spectrum of accelerated particles during their passage through the plasma torus, depending on Io's longitude.

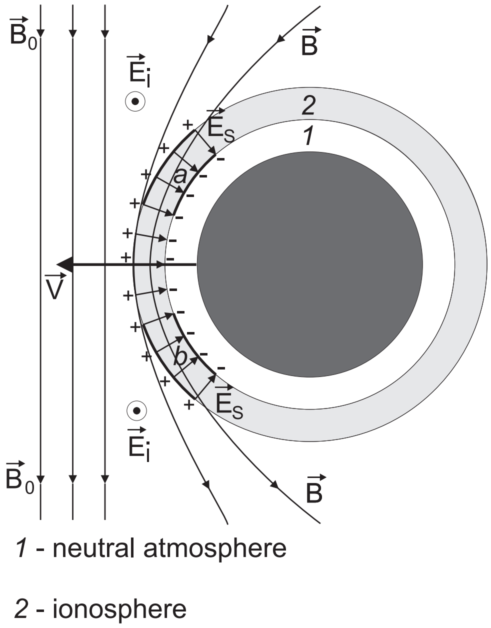

Figure 3: Field system generated by the motion of Io with velocity $\vec{V}$ through the planetary magnetic field $\vec{B}_0$. The component of the charge-separation field $\vec{E}_\mathrm{s}$ along the magnetic field $\vec{B}$ has different signs in regions a and b. $\vec{B}$ is the self-consistent magnetic field in the acceleration region.

2 Electron acceleration

The electrodynamic interaction between Jupiter and its satellite Io occurs mainly in the rather dense Io ionosphere (region 2 on Fig. 3), which is separated from the surface by a layer of neutral gas (region 1 in Fig. 3). The motion of Io induces an electric field in the Io ionosphere $E_\mathrm{i} = (1/c)[\vec{V} \times \vec{B}_0]$. This electric field cannot directly accelerate the particles, since it is perpendicular to the magnetic field. However, due to the anisotropic conductivity of the satellite ionosphere, the electric field $\vec{E}_\mathrm{i}$ induces Pedersen electric currents along $\vec{E}_\mathrm{i}$ and also tends to generate Hall currents, whose direction in the ionosphere "face" (i.e. the leading side) of Io is approximately orthogonal to the moon surface (see Fig. 3). Hall currents cannot be closed through the surface due to the neutral atmosphere near the surface. Therefore, a considerable separation of charges occurs in the Io ionosphere. This electric field of charge separation E_s has its projection on the direction of the magnetic field $E_\parallel$ and the value is comparable with that of the induced electric field. According to Zaitsev et al. [2003], the projection of the electric field E_s along the planetary magnetic field is

$$E_\parallel = \frac{1}{c} V B \frac{\omega_\mathrm{e}\tau_\mathrm{e} \sin\alpha\cos\alpha}{1 + \xi\omega_\mathrm{e}\tau_\mathrm{e}\omega_\mathrm{i}\tau_\mathrm{i} + (\xi\omega_\mathrm{e}\tau_\mathrm{e}\omega_\mathrm{i}\tau_\mathrm{i} + \xi^2\omega_\mathrm{e}^2\tau_\mathrm{e}^2\omega_\mathrm{i}^2\tau_\mathrm{i}^2 + \omega_\mathrm{e}^2\tau_\mathrm{e}^2)\sin^2\alpha}, \tag{1}$$

where α is the angle between $\vec{V}$ and $\vec{B}$, $\omega_\mathrm{e,i}$ is the gyrofrequency of electrons and ions, respectively, $\tau_\mathrm{e,i}$ is the electron and ion free path time in Io's ionosphere, and ξ is the relative portion of neutral gas. The longitudinal projection of the electric field reaches its maximum value

$$E_{\|}^{\max} = \frac{1}{c} V B \frac{\omega_{\mathrm{e}} \tau_e \cos\alpha^*}{2\sqrt{\omega_{\mathrm{e}} \tau_e \cos\alpha^* \left(1 + \xi \omega_{\mathrm{e}} \tau_e \omega_{\mathrm{i}} \tau_i\right)}} \tag{2}$$

for the angle α^* defined by the expression

$$\sin\alpha^* = \sqrt{\frac{1 + \xi \omega_{\mathrm{e}} \tau_e \omega_{\mathrm{i}} \tau_i}{\xi \omega_{\mathrm{e}} \tau_e \omega_{\mathrm{i}} \tau_i + \xi^2 \omega_{\mathrm{e}}^2 \tau_e^2 \omega_{\mathrm{i}}^2 \tau_i^2 + \omega_{\mathrm{e}}^2 \tau_e^2}}, \tag{3}$$

The largest value of $E_{\|}^{\max}$ takes place if the electrons are magnetized and the ions are unmagnetized, i.e., if $\omega_{\mathrm{e}} \tau_{\mathrm{e}} >> 1$, and $\omega_{\mathrm{i}} \tau_{\mathrm{i}} \sim 1$, but $\xi \omega_{\mathrm{e}} \tau_{\mathrm{e}} \omega_{\mathrm{i}} \tau_{\mathrm{i}} >> 1$. In this case,

$$\sin\alpha^* \simeq \sqrt{\xi} \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}\right)^{1/4}, \tag{4}$$

and the longitudinal component of the electric field of charge separation

$$E_{\|}^{\max} \simeq E_{\mathrm{i}} = \frac{1}{c} V B. \tag{5}$$

For dimensions of the order of Io's radius, the longitudinal component of the electric field of magnitudes close to $E_{\|}^{\max}$, can accelerate electrons up to energies $W_{\mathrm{e}}^{\max} \sim e V_{\mathrm{Io}} B R_{\mathrm{Io}}/c \simeq$ 160 keV.

Besides the electric field, fast electrons are also affected by the resistance force, caused by electron-atom collisions. For sufficiently fast electrons satisfying the inequality $v \gg v_{\mathrm{B}} = e^2/\hbar$ (the velocity v_{B} is equivalent to an electron energy of 10 eV), the cross section decreases with increasing velocity. Only these electrons will considerably increase their velocity due to the effect of the electric force ("runaway" electrons). In the case of regular ionosphere conditions only a small number of ionospheric electrons have velocities greater than v_{B}. The electrical field $E_{\|}$ will accelerate the electrons of Io's ionosphere until the force $eE_{\|}$ is balanced by the frictional force produced by the neutrals. The estimates of Zaitsev et al. [2003] show that the average electron velocity arising under the action of these forces appears to be greater than the electron thermal velocity, thus leading to the onset of the Buneman instability and the additional heating of electrons. As a result, the amount of electrons which can "runaway" or be accelerated to maximum energies drastically increases. It was shown by Zaitsev et al. [2003] that the concentration of accelerated electrons can be estimated by the formula

$$n_{\mathrm{r}} = \frac{n}{2\sqrt{\pi} Z} \exp(-Z^2), \tag{6}$$

where

$$Z^2 \simeq 23 \left(\frac{n_{\mathrm{a}}}{3 \times 10^9}\right) \left(\frac{6 \times 10^4}{n}\right)^{1/7} \left(\frac{1{,}2 \times 10^{-2}}{B}\right)^{11/7} \left(\frac{5{,}7 \times 10^6}{V_{\mathrm{Io}}}\right)^{11/7} \left(\frac{10^7}{L_{\|}}\right)^{4/7}, \tag{7}$$

where $L_{\|}$ is the characteristic scale of change in the electron temperature along the magnetic field. The number of "runaway" electrons strongly depends on the value of the planetary magnetic field in the vicinity of Io. Formally, this follows from Eg.(7) for Z^2

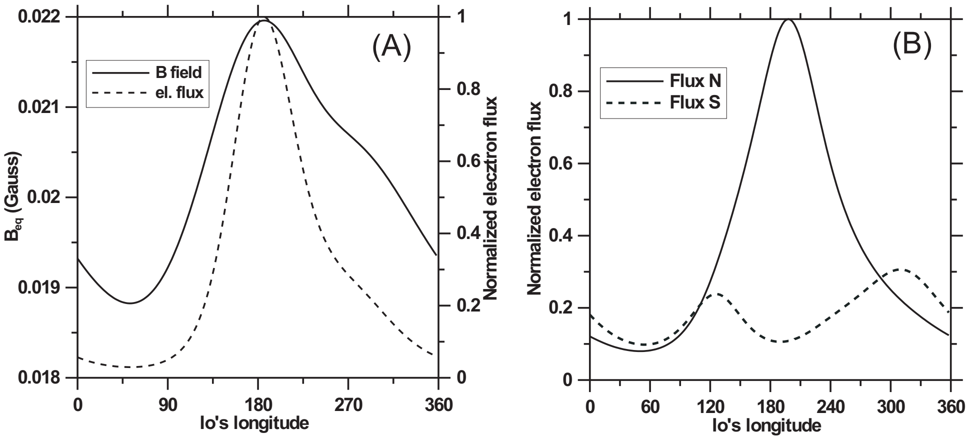

Figure 4: (a) Magnetic field variations along the trajectory of Io and normalized flux of accelerated electrons near Io as a function of Io's longitude in the Jovian frame III ($\lambda_{\rm III}(Io)$). (b) Variation of accelerated electron fluxes near the north and south Io's footprints as a function of $\lambda_{\rm III}(Io)$. The fluxes are normalized with the same value.

and Eg.(6) for $n_{\rm r}$. Since $Z^2 \gg 1$, even a small decrease in Z^2 results in a substantial increase in the density of accelerated electrons. Figure 4a shows the variations in both the planetary magnetic field along Io's orbit according to the model O4 and the normalized flux of accelerated electrons near Io as a function of Io's longitude in the Jovian frame III.

The "Active" longitudes existing in the decametric radio emission of Jupiter, i.e., existing of the specific parts of Io's orbit where the probability of decametric outbursts is very high, are due to the joint effect of two factors - the change of the efficiency in particle acceleration in Io's ionosphere considered above and the change in the degree of the broadening the angular spectrum of accelerated particles during their passage through the plasma torus, depending on Io's longitude. Io is periodically immersed in the plasma torus as it rotates about Jupiter. In order to reach the region of decametric radio emission generation, the accelerated electrons should cross the plasma torus, where they are scattered in pitch-angles owing to their interaction with plasma waves and whistlers, which are in the torus. The scattering can lead to a cansiderable broadening of the angular spectrum of accelerated electrons and to the exit of accelerated electrons from a very narrow range of pitch angles of the order of

$$\Delta\theta_0 = \arcsin\sqrt{\frac{B_{\rm Io}(\lambda_{\rm Io})}{B_{\rm J}}} \simeq 2,0^\circ - 2,7^\circ, \qquad (8)$$

inside which the electrons can reach the heights at which decametric radio emission arises. Here, θ is the angle between the electron velocity and the magnetic field line, $B_{\rm Io}$ and $B_{\rm J}$ are the value of the planetary magnetic field on Io's orbit and the Jovian ionosphere, respectively, and $\lambda_{\rm Io}$ is Io's longitude in the frame III. The particles outside the angle interval $\Delta\theta_0$ are reflected due to the magnetic field increase at heights higher than the heights of the DAM source.

Accelerated electrons have pitch-angles in the interval

$$\Delta\theta_{\mathrm{r}} \simeq v_{\mathrm{Te}} \left(V_{\mathrm{Io}} R_{\mathrm{Io}} \frac{eB_{\mathrm{Io}}}{m_{\mathrm{e}}c} \right)^{-1/2} \simeq 1,0^{\circ} - 1,5^{\circ}, \tag{9}$$

in the vicinity of Io, which is less than $\Delta\theta_0$. This means that each accelerated electron can reach the emission source in the absence of pitch-angle scattering. If the pitch-angle scattering extends the interval $\Delta\theta_{\mathrm{r}}$ up to the value $\Delta\theta > \Delta\theta_0$, then the flux of accelerated electrons that reaches the emission source, is reduced by a factor approximately as large as $\left(\frac{\Delta\theta}{\Delta\theta_0}\right)^2$. Under conditions of strong pitch-angle broadening in the Io plasma torus, the electron flux is drastically reduced. As a result, the efficiency of the emission generation decreases.

The plasma frequency ω_{pe} in Io's plasma torus is about the electron gyrofrequency ω_e, therefore the increment of the plasma waves and whistlers created by a beam of accelerated electrons has the same order of magnitude (see, e.g., Zheleznyakov [1995]), $\gamma \simeq (n_{\mathrm{r}}/n)\omega_{\mathrm{pe}} \simeq 60$ c^{-1} for the density of accelerated electrons $n_{\mathrm{r}} \simeq 5 \times 10^{-2}$ cm^{-3} and the density of plasma in the torus $n \simeq 2 \times 10^3$ cm^{-3}. The time for passage of fast electrons through Io's plasma torus is $t \simeq 0.8$ c for particles with energy 80 keV. Therefore, $\gamma t \simeq 50 \gg 1$, the level of the created wave can be fairly high. If we assume that the scattering by created waves in the plasma torus is weak, such that the optical depth for scattering $\tau_{\mathrm{sc}}(\lambda_{\mathrm{Io}})$ is much less than unity i.e., if $\tau_{\mathrm{sc}}(\lambda_{\mathrm{Io}}) \ll 1$, then we can introduce a model function of electron flux reducing as

$$K(\lambda_{\mathrm{Io}}) \simeq \frac{(\Delta\theta_0)^2}{\left(1 + \frac{\pi\tau_{\mathrm{sc}}(\lambda_{\mathrm{Io}})}{\Delta\theta_0}\right)^2}, \tag{10}$$

where

$$\tau_{\mathrm{sc}}(\lambda_{\mathrm{Io}}) \equiv \xi n_{\mathrm{r}}(\lambda_{\mathrm{Io}}) R_{\mathrm{Io}} (1 - \cos(\lambda_{\mathrm{Io}} - 200^{\circ})), \tag{11}$$

ξ is a constant depennt on the features of the distribution function of accelerated electrons. In this case, the flux of accelerated electrons which reaches the DAM emission source can be written as follows

$$F_{\mathrm{eJ}} \simeq \frac{S_{\mathrm{Io}}}{S_{\mathrm{J}}} n_{\mathrm{r}} v_{\mathrm{r}} K(\lambda_{\mathrm{Io}}) \tag{12}$$

$$\simeq \left(1 + \frac{\pi\tau(\lambda_{\mathrm{Io}})}{\Delta\theta_0}\right)^{-2} \left(\frac{eV_{\mathrm{Io}} B_{\mathrm{Io}}(\lambda_{\mathrm{Io}}) R_{\mathrm{Io}}}{m_{\mathrm{e}}c}\right)^{1/2} \frac{B_{\mathrm{J}}}{B_{\mathrm{Io}}} \frac{n}{2\sqrt{\pi} Z(\lambda_{\mathrm{Io}})} \exp\left[-Z^2(\lambda_{\mathrm{Io}})\right]. \tag{13}$$

In (13) we take into account the increase of electron flux due to the decrease of cross-section area of Io magnetic flux tube when electron flux propagates downstream along the tube. Variation in the accelerated electron fluxes near the northern and southern Io's footprints as a function of Io's longitude in the Jovian frame III is shown in Fig. 4b. The fluxes are normalized with the same value. In Fig. 5, these fluxes are shown together with the occurrence of right-hand polarized emission bursts from the Io-A,-A', and -B sources (Fig. 5a) and left-hand polarization emission from the Io-C and Io-D sources (Fig. 5b).

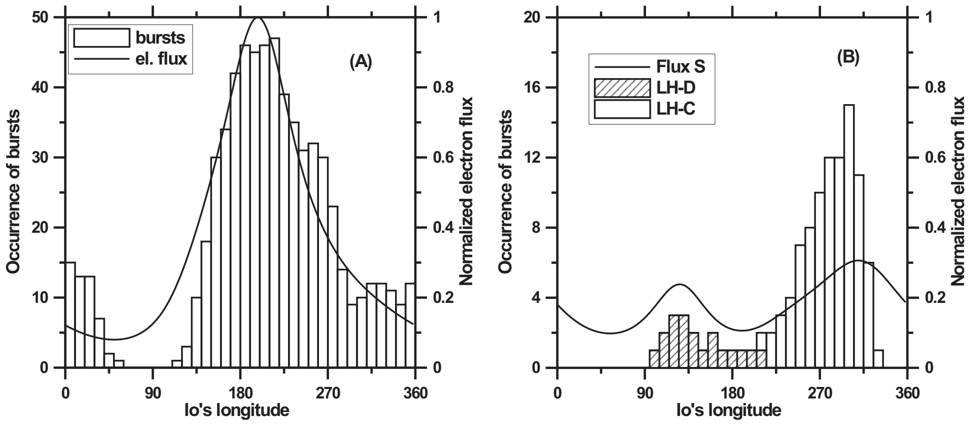

Figure 5: (a) Normalized flux of accelerated electrons at the northern Io's magnetic footprint and occurrence of right-hand polarized emission bursts from the Io-A,-A', and -B sources. (b) Normalized flux of accelerated electrons at the southern Io's magnetic footprint and occurrence of left-hand polarized emission bursts from Io-C and Io-D sources.

From Eq.(13) and Figs. 4b and 5 it follows that the "northern" fluxes of accelerated electrons are much greater than those propagated toward the southern hemisphere. This is the reason why the DAM emission is mainly observed from sources located in the northern hemisphere of Jupiter. Moreover, the fluxes of accelerated electrons that follows from our model agree well with a date of occurrence of DAM emission, both for the right-hand and left-hand.

3 Conclusions

The model considered in this paper can explain the existence of "active" longitudes of Io which follows from observations of the Io-related DAM radio emission, as well as the predominant location of most DAM sources in the northern hemisphere. The appearance of "active" longitudes of Io and the predominance of the emission from the northern sources are a result of the joint effect of two factors - the change in the efficiency of particle acceleration in the ionosphere of the satellite Io and the variation in the degree of broadening of the angular spectrum of the accelerated particles during their passage through the plasma torus of Io due to the change in the longitude. The latter is caused by the electron scattering by plasma waves and whistlers existing in the torus. The emission occurrence increases when Io is at longitudes $\lambda_{\mathrm{Io}} \simeq 120^{\circ} - 300^{\circ}$. This is the case when the fluxes of accelerated electrons are increased due to increased magnetic field in the vicinity of Io, and there is no appreciable pitch-angle scattering of the electrons moving in the northward direction due to the minimum influence of Io's torus. On the contrary, the electrons moving in the southward direction are screened by Io's torus from the southern DAM emission sources.

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