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Dependence of the Io-related decametric radio emission of Jupiter on the central meridian longitude and Io's "active" longitudes

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ABSTRACT

Context. The statistical analysis of the Io-related decametric radio emission of Jupiter shows that this emission depends precisely on the central meridian longitude. This dependence is the result of the existence of Io's "active" longitudes, i.e. particular regions of Io's orbit, which are fixed with respect to the Jovian magnetic field and at which Io-related emission occurs more often.
Aims. The paper considers the mechanism of the formation of Io's "active" longitudes.
Methods. The formation of Io's "active" longitudes is caused by two factors: first, the change of the efficiency of particle acceleration in Io's ionosphere, depending on Io's longitude, and second, the degree of broadening of the angular spectrum of accelerated electrons during their passing through the plasma torus.
Results. It is shown that the mechanism considered explains rather well why Io-related decametric bursts begin to appear much more often in longitudes of the range $120° \lesssim \lambda_{\rm Io} \lesssim 300°$ ($\lambda_{\rm Io}$ is the longitude in the frame III), and why one predominantly observes the emission from the sources located in the northern Jovian hemisphere.

Key words. acceleration of particles – scattering – planets and satellites: individual: Io – planets and satellites: individual: Jupiter

1. Introduction

The statistical analysis of the occurrence of the Jovian decametric radio (DAM) emission reveals a clear-cut bunching of this emission in domains on the "central meridian longitude-Io phase" diagram (Fig. 1). These domains were called Io-related emission because the emission appearance correlates with the location of Io on its orbit. The maximum occurrence is observed near Io phases (the Io phase determines the satellite location relative to the observer) 90° and 250° (so-called Io "active" phases) and is assumed to be due to the sequential passing of the directivity diagram of the decametric radio emission (which has the form of a hollow cone) through the line "source-observer" (Dulk 1965). It is also seen from Fig. 1 that the appearance of Io-related DAM emission depends on one more parameter – the central meridian longitude. In this case, the bunching of Io-related emission in some ranges of the central meridian longitude (presented in Fig. 1) is the result of both a rather narrow (with respect to the longitude) directivity diagram of decametric emission and the existence of "active" Io's longitudes – specific regions of Io's orbit that are fixed with respect to the Jovian magnetic field, where decametric bursts most probably appear. The diagram (Fig. 2) "occurrence of Io-related emission – Io's longitude in frame III" (Io's longitude in frame III determines the satellite location relative to the Jovian magnetic field) constructed for Io-related emission shows that the occurrence of emission increases when Io is in the longitude range 120°–300°. The diagram given in Fig. 2 is based on the data from papers by Leblanc et al. (1993), Dulk et al. (1994), and Boudjada et al. (1995). The dependence of the occurrence of decametric radio bursts on Io's longitude (the existence of "active" longitudes) remains unclear, and this is the topic of the present paper.

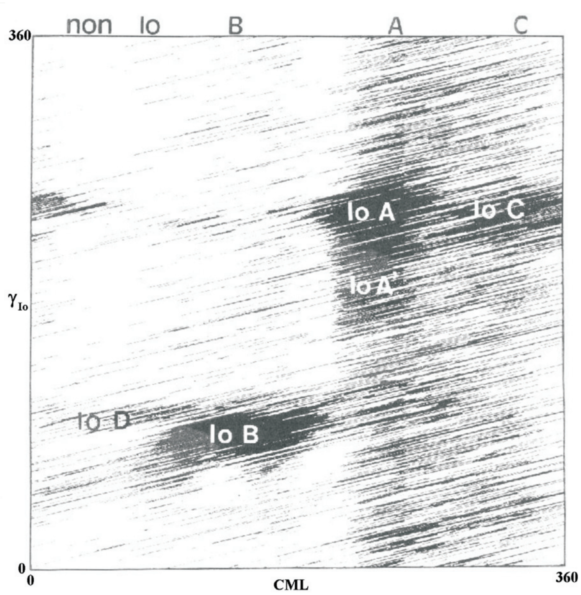

Fig. 1. The central meridian longitude and Io phase of the observed Jovian decametric radio emission (figure from Genova 1985).

The given paper interprets the origin of "active" longitudes as the result of the effect of two factors: 1) the modulation of the efficiency of particle acceleration in Io's ionosphere during its motion through the Jovian inhomogeneous magnetic field; and

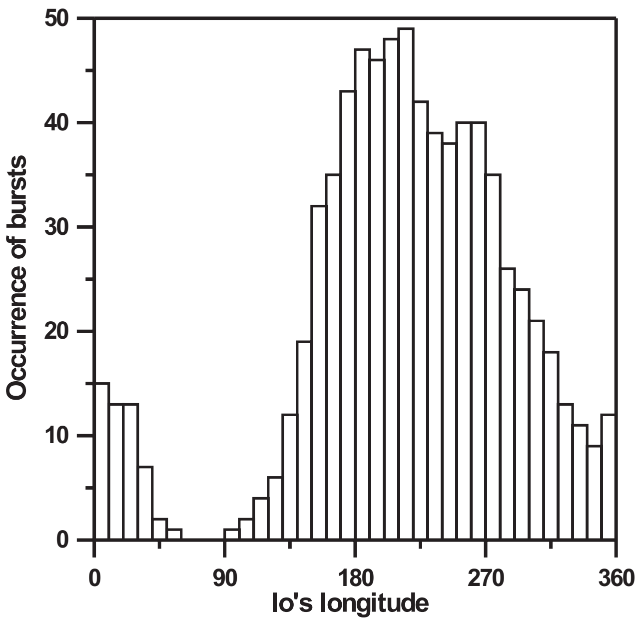

Fig. 2. The occurrence of the Jovian decametric radio emission from Io-related sources as a function of Io's longitude in the frame III.

2) the scattering of accelerated electrons in pitch angle due to the collision with plasma waves in Io's torus. The Jovian decametric emission, which depends on Io location, occurs near the base of the magnetic field force lines intersecting the satellite. These force lines form a so-called magnetic tube. The magnetic tube is a channel through which the particles (accelerated near Io) find themselves in the lower magnetosphere and the Jovian ionosphere, and in which they generate decametric radio bursts. Zaitsev et al. (2003) have shown that the acceleration efficiency depends considerably on the value of the Jovian magnetic field with which the satellite interacts at this moment of time. Since the center of the Jovian magnetic dipole is shifted relative to the center of masses by $0.1 R_J$ ($R_J = 71\,000$ km is the Jovian radius) and the dipole axis is inclined by approximately 10° to the rotation axis in the direction of the longitude $\lambda_{III} \simeq 200°$, the magnetic field (with which Io's ionosphere interacts) will change periodically, influencing the efficiency of particle acceleration. The periodic submersion into the plasma torus of Io changes the angular spectrum of the accelerated particles due to their scattering in the torus and modulates a quantity of fast particles that reach the region of the decametric emission generation owing to the adiabatic motion in the inhomogeneous magnetic tube.

This work is a development of the paper by Zaitsev et al. (2003) about the mechanism of electron acceleration in Io's ionosphere. In the present work, we consider the problem of the origin of Io's active longitudes in detail and give only a basic statement of the acceleration mechanism to better understand the mechanism of active longitude formation.

In Sect. 2 we briefly deal with the mechanism of particle acceleration in Io's ionosphere (it was thoroughly considered by Zaitsev et al. 2003), which is the basis of our analysis. In Sect. 3 the density of accelerated electrons is found. In Sect. 4 the fluxes of accelerated electrons, which reach the region of decametric emission generation, are calculated, and their dependence on Io's longitude is found. In Sect. 5 we discuss the obtained results and generalize them.

2. Electron acceleration

The electrodynamic interaction between Jupiter and its satellite Io occurs mainly due to a rather dense ionosphere of Io, which basically consists of SO_2 molecules and originates from the volcanic activity and evaporation of the surface hoar-frost. The neutral atmosphere of Io is ionized under the action of the sun radiation and the flux of energetic particles of Jupiter magnetosphere. This leads to the existence of the ionosphere around Io, which is separated from the surface by a layer of neutral gas (Summers & Strobel 1996). According to the data obtained by "Galileo" (Frank et al. 1996), the Io ionosphere is at rest with respect to the satellite. Therefore, when Io passes the Jovian magnetic field, the electric field is induced in the satellite ionosphere, equal to

$$\boldsymbol{E}_{\mathrm{i}} = \frac{1}{c}\,[\boldsymbol{V} \times \boldsymbol{B}]\,, \tag{1}$$

if we are in the coordinate system moving with Io. Here, $\boldsymbol{V}$ is Io's velocity with respect to the co-rotating Jovian magnetospheric plasma, $\boldsymbol{B}$ is the magnetic field near Io, and c is the light velocity. However, this electric field cannot directly accelerate the particles, since it is perpendicular to the magnetic field. Nonetheless, recent observations performed near Io by "Galileo" gave new evidence of particle acceleration near Io. "Galileo" discovered beams of fast electrons with an energy greater than 15 keV on force lines of the magnetic field passing through Io. The beams propagated in two directions along the magnetic field and had approximately equal intensity (Frank et al. 1996; Kivelson et al. 1996; Williams et al. 1996; Bagenal 1997; Hinson et al. 1998). The problem, how the induced electric field (1), applied to satellite Io, manifests itself in the form of accelerated electrons moving along the magnetic field, has been studied in a number of papers. In particular, it was hypothesized that double plasma layers appear in the electric circuit "Io-magnetic tube-Jovian ionosphere" (Gurnett 1972; Shawhan 1976; Smith & Goertz 1978). Crary (1997) has considered the acceleration by Alfven waves. According to the model of Langmayr et al. (2001), the location of the ion and electron mirror points at different positions along the Io magnetic tube result in a charge separation and the generation of an electric field that is parallel to the magnetic field. Cheng & Paranicas (1998) supposed that the longitudinal electric field appears due to the processes of ionization in the ionosphere. However, these suppositions lack solid ground and these processes are discussed by Zaitsev et al. (2003). They also pay attention to the significant role of anisotropy in the conductivity of Io's ionosphere, which is the result of the longitudinal (with respect to the Jovian magnetic field) electric field component. Due to the conductivity anisotropy, the electric field $\boldsymbol{E}_{\mathrm{i}}$, induced by the Io motion not only causes Pedersen currents along $\boldsymbol{E}_{\mathrm{i}}$, but also tends to generate Hall currents $j \sim \boldsymbol{E}_{\mathrm{i}} \times \boldsymbol{B}$ whose direction in the ionosphere "face" (i.e. leading side) of Io is approximately orthogonal to the moon surface (see Fig. 3 taken from paper of Zaitsev et al. 2003) in the Io ionosphere. Hall currents cannot be closed through the surface due to the neutral atmosphere near the surface. Therefore, a considerable separation of charges takes place in the Io ionosphere. This electric field of charge separation has its projection on the direction of the magnetic field, and the value is comparable with that of the electric field.

It should be noted here that the electric field of charge separation can take place not only at the "face" of Io's ionosphere, but also at other places near Io, for example in Io's wake, where a relative motion of weakly ionized plasma and the planet magnetic field still exist. However, the value of the charge separation electric field is weaker than that in the "face" ionosphere.

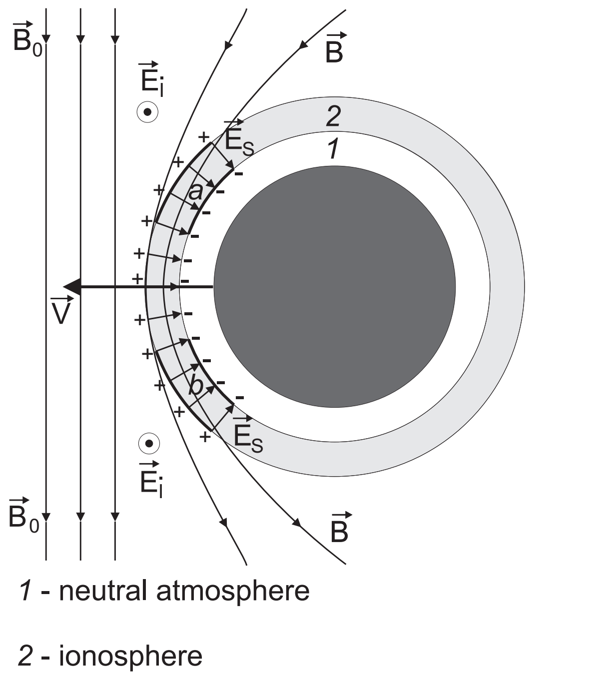

Fig. 3. The field system generated by the motion of Io through the planetary magnetic field.

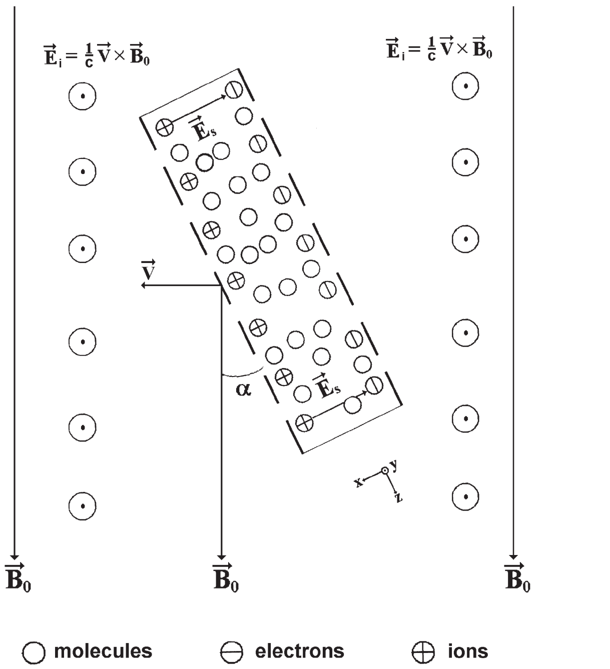

Fig. 4. Schematic illustration of motion of a two-dimensional layer of partially ionized plasma through the external magnetic field.

In Zaitsev et al. (2003), the "face" side of the Io ionosphere is modeled by the two-dimensional layer of a partially ionized plasma with thickness $L \ll R_{\mathrm{Io}}$. This layer moves relative to the external magnetic field $\boldsymbol{B}_0$ with the velocity $\boldsymbol{V}$ (see Fig. 4). To study electric fields arising in the plasma layer, we use the generalized Ohm law in the form (Zaitsev & Stepanov 1992):

$$\begin{aligned}\boldsymbol{E} + \boldsymbol{E}_{\mathrm{i}} = \frac{\boldsymbol{j}}{\sigma} + \frac{1}{nec}\,[\boldsymbol{j}\times\boldsymbol{B}] - \frac{\nabla p_{\mathrm{e}}}{en}\\ -\xi\frac{F}{c^2 n m_{\mathrm{i}}\nu'_{\mathrm{ia}}}\,[[\boldsymbol{j}\times\boldsymbol{B}]\times\boldsymbol{B}],\end{aligned} \tag{2}$$

the equation of motion

$$\nabla p = \frac{1}{c}\,[\boldsymbol{j}\times\boldsymbol{B}], \qquad \nabla p = \nabla p_{\mathrm{a}} + \nabla p_{\mathrm{i}} + \nabla p_{\mathrm{e}}, \tag{3}$$

and the equation of induction

$$\nabla\times\boldsymbol{E} = -\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t}, \tag{4}$$

where the indices a, i, and e refer to neutral particles, ions, and electrons, respectively. In Eqs. (2) and (3), $F \simeq \dfrac{n_{\mathrm{a}}m_{\mathrm{a}}}{n_{\mathrm{a}}m_{\mathrm{a}} + n_{\mathrm{i}}m_{\mathrm{i}}}$, $\xi = \dfrac{F^2 m_{\mathrm{i}}}{2m_{\mathrm{a}}(1-F) + m_{\mathrm{i}}F}$; $\sigma = \dfrac{e^2 n}{m_{\mathrm{e}}(\nu'_{\mathrm{ei}} + \nu'_{\mathrm{ea}})}$ is the conductivity; ν'_{ei}, ν'_{ea}, and ν'_{ia} are the effective collision frequencies of particles; m_{a}, m_{e}, and m_{i} are masses of particles; p_{a}, p_{e}, and p_{i} are partial pressures; and $n = n_{\mathrm{e}} = Zn_{\mathrm{i}}$, where $Z = 1$, is the concentration of plasma, which for simplicity is assumed to be single ionized ($Z = 1$). In the coordinate system related to the layer and shown in Fig. 4, the problem is stationary and all parameters depend only on the coordinate x.

In this case, we obtain from Eqs. (2)–(4)

$$E_y = -\frac{1}{c}VB, \qquad E_z = 0, \tag{5}$$

$$E_\parallel = |E_x|\sin\alpha = \frac{1}{c}VB\,\frac{\omega_{\mathrm{e}}\tau_{\mathrm{e}}\sin\alpha\cos\alpha}{\Psi(\xi,\omega_{\mathrm{e}}\tau_{\mathrm{e}},\omega_{\mathrm{i}}\tau_{\mathrm{i}})}, \tag{6}$$

where $E_\parallel$ is the projection of the arising electric field of the charge separation on the magnetic field direction. This field leads to the particle acceleration. In Eq. (6)

$$\begin{aligned}\Psi(\xi,\omega_{\mathrm{e}}\tau_{\mathrm{e}},\omega_{\mathrm{i}}\tau_{\mathrm{i}}) &= 1 + \xi\omega_{\mathrm{e}}\tau_{\mathrm{e}}\omega_{\mathrm{i}}\tau_{\mathrm{i}}\\ &+ \left(\xi\omega_{\mathrm{e}}\tau_{\mathrm{e}}\omega_{\mathrm{i}}\tau_{\mathrm{i}} + \xi^2\omega_{\mathrm{e}}^2\tau_{\mathrm{e}}^2\omega_{\mathrm{i}}^2\tau_{\mathrm{i}}^2 + \omega_{\mathrm{e}}^2\tau_{\mathrm{e}}^2\right)\sin^2\alpha,\end{aligned} \tag{7}$$

where $\omega_{\mathrm{e,i}} = \dfrac{eB}{m_{\mathrm{e,i}}c}$ are gyrofrequencies of electrons and ions, $\tau_{\mathrm{e}} = (\nu'_{\mathrm{ei}} + \nu'_{\mathrm{ea}})^{-1}$, and $\tau_{\mathrm{i}} = (\nu'_{\mathrm{ea}})^{-1}$. It follows from Eqs. (6) and (7) that the maximum value of the longitudinal component of the electric field of the charge separation appears at the angle α^*, determined by the relation

$$\sin\alpha^* = \sqrt{\frac{1 + \xi\omega_{\mathrm{e}}\tau_{\mathrm{e}}\omega_{\mathrm{i}}\tau_{\mathrm{i}}}{\xi\omega_{\mathrm{e}}\tau_{\mathrm{e}}\omega_{\mathrm{i}}\tau_{\mathrm{i}} + \xi^2\omega_{\mathrm{e}}^2\tau_{\mathrm{e}}^2\omega_{\mathrm{i}}^2\tau_{\mathrm{i}}^2 + \omega_{\mathrm{e}}^2\tau_{\mathrm{e}}^2}}, \tag{8}$$

and attains the value

$$E_\parallel^{\max} = \frac{1}{c}VB\frac{\omega_{\mathrm{e}}\tau_{\mathrm{e}}\cos\alpha^*}{2\sqrt{\omega_{\mathrm{e}}\tau_{\mathrm{e}}\cos\alpha^*\,(1 + \xi\omega_{\mathrm{e}}\tau_{\mathrm{i}}\omega_{\mathrm{e}}\tau_{\mathrm{i}})}}. \tag{9}$$

The greatest value $E_\parallel^{\max}$ takes place when the electrons are magnetized and the ions are not, i.e. $\omega_{\mathrm{e}}\tau_{\mathrm{e}} \gg 1$, $\omega_{\mathrm{i}}\tau_{\mathrm{i}} \sim 1$, but $\xi\omega_{\mathrm{e}}\tau_{\mathrm{e}}\omega_{\mathrm{i}}\tau_{\mathrm{i}} \gg 1$. In this case,

$$\sin\alpha^* \simeq \sqrt{\xi}\left(\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}\right)^{1/4}, \tag{10}$$

and the longitudinal component of the electric field of the charge separation may reach the value of the induced field

$$E_\parallel^{\max} \simeq E_{\mathrm{i}} = \frac{1}{c}VB. \tag{11}$$

When deriving Eqs. (10) and (11), we take into account that $\omega_i\tau_i/\omega_e\tau_e \approx \sqrt{m_e/m_i}$ (see for example Pickelner 1966).

It can easily be seen from the above that the charge separation and the electric field of charge separation result from different velocities of electrons and ions diffused through the magnetic field. The point is that under the condition $\omega_e\tau_e \gg 1$, the electrons are magnetized and move together with the planetary magnetic field, while the ions are under the condition $\omega_i\tau_i \sim 1$. Under this condition, the ions are nonmagnetized and aspire after the neutral particles of Io's ionosphere. The motion with different velocities leads to the creation of charge separation and the associated charge separation electric field. The electric field reduces the ion diffusion velocities and increases the electron diffusion velocity. As a result of the steady state, the ion and electron diffusion velocities are equal. This phenomenon is known as ambipolar diffusion.

The structure of the magnetic field near Io has not been studied. But we may suppose that owing to Io's conductivity, the magnetic field is deformed near the satellite in such a way that the force lines drape around Io (Goertz & Haschick 1973). Thus, it is probable that the longitudinal component of the magnetic field with values close to $E_{\parallel}^{\max}$ may exist in scales of the order of the Io radius, accelerating electrons till energies $W_e^{\max} \sim \frac{e}{2c}V_{Io}BR_{Io} \simeq 100$ keV. It should be noted that "Galileo" did not discover fast electrons with energies exceeding 150–200 keV. Therefore, the estimate of the maximum electron energy given above agrees well with the up-to-date experimental data.

3. The density of accelerated electrons

The plasma of the Io atmosphere is weakly ionized. According to the model given by Kumar & Hunten (1982), the electron density in the maximum of the ionosphere layer located at a height of approximately 50 km reaches $n \simeq 6\times10^4$ cm^{-3} for the density of neutral particles $n_a \simeq 10^{10}$ cm^{-3}. The ions of sulfur oxide SO^+ and SO^{++} lead on average to a charge number of 1.5; the temperature at the height of the maximum of the F-layer is $T \simeq$ 900 K.

In addition to the electric field $E_{\parallel}$, the accelerated particles are also affected by the resistance force caused by electron-ion and electron-atom collisions. The electric field (11) turns to be essentially greater than the Dreicer electric field (Dreicer 1959, 1960); thus, we may neglect electron-ion collisions. The electric field $E_{\parallel}$ will accelerate all electrons of the ionosphere until the moment when the force $eE_{\parallel}$ is placed in equilibrium with the friction force of neutral particles. According to the estimates made by Zaitsev et al. (2003), the arising mean electron velocity appears to be greater than the thermal electron velocity. This leads to the onset of Bunemann instability and the additional heating of electrons. As a result, the number of electrons with velocities $v > v_B = \frac{e^2}{\hbar}$ that might "runaway" due to collisions with neutral particles essentially increases. At velocities $v > v_B$, the cross-section of electron collisions with atoms begins to decrease with velocity increase. Therefore "runaway" electrons might be accelerated by the electric field (11) until they reach their maximum energies.

It may be shown (Zaitsev et al. 2003) that the concentration of accelerated electrons is determined by the formula

$$n_r = \frac{n}{2\sqrt{\pi}Z}\exp(-Z^2), \tag{12}$$

where

$$Z = \frac{v_* - v_{en}}{\sqrt{2}v_T}, \tag{13}$$

$$v_* = \left(\frac{2cm_e n_a S_0 v_B^4}{eVB}\right)^{1/2}, \tag{14}$$

and

$$v_{en} = \frac{1}{2en}\left(\frac{m_i}{m_e}\right)^{1/3}\omega_{pe}\frac{VB}{c}, \tag{15}$$

where $\omega_{pe} = \left(\frac{4\pi e^2 n}{m_e}\right)^{1/2}$ is the Langmuir frequency, $v_{Te} = \left(\frac{\kappa_B T_e}{m_e}\right)^{1/2}$ is the thermal electron velocity, and $S_0 = 5\times10^{-14}$ cm^2 is the cross-section of collisions of neutral particles for $v < v_B$. The velocity of "runaway" electrons can be estimated by

$$v_r \simeq \left(\frac{eV_{Io}B_{Io}(\lambda_{Io})R_{Io}}{m_e c}\right)^{1/2}. \tag{16}$$

The electron temperature is determined from the condition of a balance between the velocity of electron heating (due to the Bunemann instability) and the velocity of cooling down due to the electron heat conduction along the magnetic field:

$$\frac{1}{2}\left(\frac{m_i}{m_e}\right)^{1/3}\omega_{pe}\left(\frac{VB}{c}\right)^2 = 0,92\times10^{-6}\frac{T_e^{7/2}}{L_{\parallel}^2}, \tag{17}$$

which yields

$$T_e \simeq 4,6\times10^5\left(\frac{L_{\parallel}}{R_{Io}}\right)^{4/7}\ \mathrm{K}. \tag{18}$$

Here, $L_{\parallel}$ is the characteristic scale of the variation of the electron temperature along the magnetic field. Assuming $n_a = 6\times10^9$ cm^{-3}, $B = 2\times10^{-2}$ G, and $V = V_{Io} \simeq 5.7\times10^6$ cm s^{-1}, we obtain the minimal velocity of "runaway" electrons $v_* \simeq 10^9$ cm s^{-1}. In this case, the relative velocity of electrons and ions during the development of Bunemann instability $u \simeq 1.3\times10^7$ cm s^{-1} is much smaller than v_*; thus, we may approximately write

$$Z^2 \simeq 23\left(\frac{n_a}{3\times10^9}\right)\left(\frac{6\times10^4}{n}\right)^{1/7}\left(\frac{1,2\times10^{-2}}{B}\right)^{11/7} \times\left(\frac{5,7\times10^6}{V_{Io}}\right)^{11/7}\left(\frac{10^7}{L_{\parallel}}\right)^{4/7}. \tag{19}$$

Assuming that $L_{\parallel} \sim 10^8$ cm and $n_a \sim 6\times10^9$ cm^{-3}, from Eqs. (12) and (19), we obtain the density of the "runaway" electrons $n_r \sim 2\times10^{-5}$ cm^{-3} and the energy 80 keV, which corresponds to the flux $\Phi_e = n_r v_r \sim 0.05$ erg cm^{-2} s^{-1}, coinciding with the data from the "Galileo" observations (Williams et al. 1996). When Io detects the magnetic field, almost equal to the maximum one on the orbit, the number of accelerated electrons increases sharply because the exponent Z^2 in the formula (12) decreases sharply. For example at $B = 1.8\times10^{-2}$ G, we get $n_r \sim 5\times10^{-2}$ cm^{-3} and $\Phi_e \sim 10^2$ erg cm^{-2}s^{-1}. This corresponds to the source power of the order of 10^{11} W at the area of the flux cross-section $S \sim 10^{16}$ cm^2, which is two orders greater than the power of the electromagnetic emission in the decametric range.

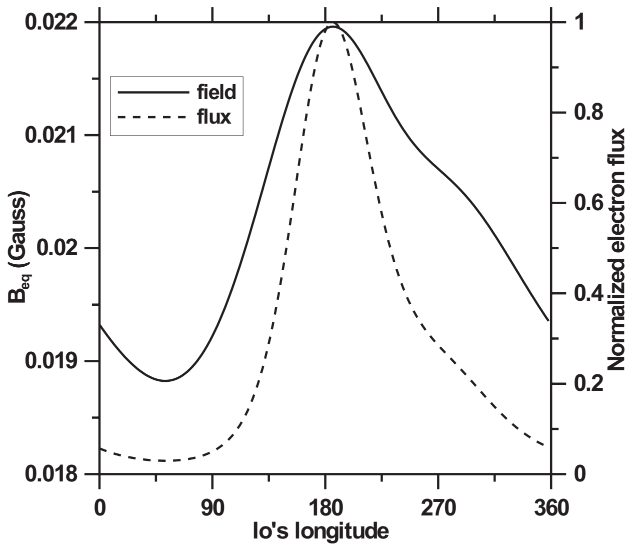

Fig. 5. The magnetic field along the orbit of Io, B_{eq}, and the normalized flux of accelerated electrons at the exit from the acceleration region, $f_e = \Phi_e/\Phi_{e,\max}$, as the function of Io's longitude in the frame III.

4. The origin of active longitudes

As the estimates of the previous section show, the number of the electrons accelerated in the ionosphere of satellite Io depends strongly on the value of the Jovian magnetic field, which interacts with Io at the given moment. This field changes periodically due to the Jupiter rotation, since the plane of the rotational equator, in which Io exists, does not coincide with the plane of the magnetic equator. Besides, the center of the magnetic dipole is displaced from the center of masses of Jupiter by approximately 700 km. Figure 5 shows the variation of the magnetic field (B_{eq}) along Io's orbit and the normalized flux ($f_e = \Phi_e/\Phi_{e,\max}$) of accelerated particles at their exit from the acceleration region, as the function of the longitude in Frame III. The model O4 is used for the calculation of the magnetic field (the model O6 gives negligible corrections of the distribution and the value of the magnetic field on Io's orbit). When calculating the magnetic field, we did not take into account the fact that Io's orbit is elliptical and that the orbit deviates from the Jovian equatorial plane. This is because we discuss the statistical results obtained by many years of observations of the Jovian decametric radio emission. In this case, the effects caused by the above-mentioned and neglected features of Io's orbit are not so important. The variation of the magnetic field along this orbit leads to an essential modulation of the flux of accelerated electrons (Fig. 5) and is one of the factors determining the existence of "active" longitudes.

The other factor is that during its motion, Io periodically "submerges" itself into the plasma torus. This torus is located in the plane of the centrifugal equator, which forms the angle $\simeq 7°$ with the plane of the rotational equator. To reach the Jovian ionosphere, the accelerated electrons should cross the plasma torus, where they may undergo considerable pitch-angle scattering due to their interaction with plasma waves and whistlers existing in the torus. Plasma wave observations in Io's plasma torus are reported by Gurnett et al. (1996). The scattering may lead to the escape of accelerated electrons from a very narrow range of pitch angles of the order of

$$\Delta\theta_0 = \arcsin\sqrt{\frac{B_{\rm Io}(\lambda_{\rm Io})}{B_{\rm J}}} \simeq 2,0° - 2,7°, \tag{20}$$

in which they should be present to reach gyro-resonance layers in the lower Jovian magnetosphere and ionosphere, corresponding to the frequencies of the decametric range. Here, θ is the angle between the particle velocity direction and the magnetic field, $B_{\rm Io}$ and $B_{\rm J}$ are the values of the magnetic field on Io's orbit and in the Jovian ionosphere, respectively, and $\lambda_{\rm Io}$ is the longitude of Io in the frame III. The particles whose pitch angles are outside the range $\Delta\theta_0$ will be reflected from the increasing magnetic field at the levels located higher than the ionosphere, and they will not contribute to the generation of the decametric radio emission. The pitch-angle scattering of accelerated electrons in the plasma torus of Io is the second factor that determines the existence of "active" longitudes and the main reason why the emission from the sources located in the northern hemisphere predominate.

At the outlet of the acceleration region, fast electrons have pitch angles in the range

$$\Delta\theta_{\rm r} \simeq v_{\rm Te}\left(V_{\rm Io}R_{\rm Io}\frac{eB_{\rm Io}}{m_{\rm e}c}\right)^{-1/2} \simeq 1.0° - 1.5°, \tag{21}$$

which is smaller than the range $\Delta\theta_0$. This means that if there were no pitch-angle scattering when accelerated electrons pass Io's torus, all accelerated electrons would reach the Jovian ionosphere. In practice, if the fast electrons' angular spectrum broadens up to the value $\Delta\theta > \Delta\theta_0$, the flux of electrons that reaches the Jovian ionosphere will be approximately attenuated by $\left(\frac{\Delta\theta}{\Delta\theta_0}\right)^2$. If the broadening of pitch angles is essential in Io's torus, this attenuation may be rather considerable.

In Io's torus, the plasma frequency $\omega_{\rm pe}$ is of the order of electron gyro-frequency $\omega_{\rm Be}$; therefore, the increments of excitation of whistlers and plasma waves by the beam of accelerated electrons have equal orders of magnitude (see for example Zheleznyakov 1996), where

$$\gamma \simeq \left(\frac{n_{\rm r}}{n}\right)\omega_{\rm pe} \simeq 60\ {\rm s}^{-1} \tag{22}$$

at $n_{\rm r} \simeq 5\times10^{-2}$ cm^{-3} and $n \simeq 2\times10^3$ cm^{-3}. The time of the flight of fast electrons through the plasma torus of Io constitutes $t \sim \frac{2R_{\rm J}(1-\cos(\lambda_{\rm III}-200°))}{v}$. If $1-\cos(\lambda_{\rm III}-200°) \sim 1$ for the particles with energy 80 keV, then the amplification of plasma waves and whistlers in the bulk of the torus may be great,

$$\tau = \gamma t \simeq \left(\frac{n_{\rm r}}{n}\right)\omega_{\rm pe}\frac{2R_{\rm J}(1-\cos(\lambda_{\rm III}-200°))}{v} \simeq 50, \tag{23}$$

and the accelerated electrons may essentially be pitch-angle scattered due to their interaction with plasma waves and whistlers. Here, $\lambda_{\rm III}$ is a longitude in the frame III.

We introduce a model function to describe the broadening of the angular spectrum of accelerated electrons passing the plasma torus of Io in the longitude $\lambda_{\rm III} = \lambda_{\rm Io}$, due to the scattering by whistlers and plasma waves:

$$\Theta(\lambda_{\rm Io}) = \pi\Bigg[1-\left(1-\frac{\Delta\theta_0}{\pi}\right)\exp\big[-\zeta n_{\rm r}(\lambda_{\rm Io})R_{\rm J} \times(1-\cos(\lambda_{\rm Io}-200°))\big]\Bigg]. \tag{24}$$

The optical depth of the process of scattering is proportional to the accelerated electron density $n_{\rm r}$ and the distance $R_{\rm J}(1-\cos(\lambda_{\rm Io}-200°))$, which the electrons cover in the plasma torus during their motion towards the Jovian ionosphere. The numerical coefficient ζ depends on the features of the fast particle distribution function. At small optical depths Eq. (24) yields $\Theta = \Delta\theta_0$, while at great optical depth, the pitch-angle scattering is $\Theta = \pi$, i.e. the spectrum of scattered waves becomes isotropic.

Taking into account the previous statement we may write the formula for the flux of accelerated electrons escaping Io's torus by taking into account the attenuation due to the pitch-angle scattering in the torus:

$$F_e = \Phi_e(\lambda_{Io})K(\lambda_{Io}) \simeq \left(\frac{eV_{Io}B_{Io}(\lambda_{Io})R_{Io}}{m_e c}\right)^{1/2} \times \frac{n}{2\sqrt{\pi}Z(\lambda_{Io})}K(\lambda_{Io})\exp\left[-Z^2(\lambda_{Io})\right], \quad (25)$$

where $Z(\lambda_{Io})$ is defined by Eq. (19), in which $B_{Io}(\lambda_{Io})$ is the magnetic field on Io's orbit as the function of the longitude, and $K(\lambda_{Io})$ is the function of attenuation due to the pitch-angle scattering in Io's torus:

$$K(\lambda_{Io}) = \begin{cases} 1, & \Theta(\lambda_{Io}) < \Delta\theta_0, \\ \dfrac{(\Delta\theta_0)^2}{2(1-\cos\Theta(\lambda_{Io}))}, & \Theta(\lambda_{Io}) > \Delta\theta_0. \end{cases} \quad (26)$$

Thus, Eq. (26) denotes the effect of two factors determining the dependence of the flux of fast electrons reaching the Jovian ionosphere on Io's longitude: the mechanism of acceleration in Io's ionosphere (via $Z(\lambda_{Io})$) and the pitch-angle scattering in the plasma torus of Io (via $K(\lambda_{Io})$).

The value F_e increases in the direction of the Jovian surface due to the decrease of the area of the cross-section of the magnetic tube of Io,

$$B_{Io}S_{Io} = B_J S_J, \quad (27)$$

where the indices Io and J refer to Io's orbit and Jovian ionosphere, respectively. Since the total particle flux through the tube cross-section preserves, we determine the particle flux in the Jovian ionosphere to be

$$F_{eJ} = \frac{S_{Io}}{S_J}F_e \simeq \frac{1}{(\Delta\theta_0)^2}F_e. \quad (28)$$

We may make Eq. (28) more simple by taking into account Eqs. (24)–(26), if we assume that scattering in the torus is rather weak, i.e. $\tau_{sc}(\lambda_{Io}) \ll 1$, where

$$\tau_{sc}(\lambda_{Io}) \equiv \xi n_r(\lambda_{Io})R_{Io}(1-\cos(\lambda_{Io}-200°)). \quad (29)$$

In this case,

$$K(\lambda_{Io}) \simeq \frac{(\Delta\theta_0)^2}{\left(1+\dfrac{\pi\tau_{sc}(\lambda_{Io})}{\Delta\theta_0}\right)^2}; \quad (30)$$

therefore, we finally have

$$F_{eJ} \simeq \left(1+\frac{\pi\tau(\lambda_{Io})}{\Delta\theta_0}\right)^{-2}\left(\frac{eV_{Io}B_{Io}(\lambda_{Io})R_{Io}}{m_e c}\right)^{1/2} \times \frac{B_J}{B_{Io}}\frac{n}{2\sqrt{\pi}Z(\lambda_{Io})}\exp\left[-Z^2(\lambda_{Io})\right]. \quad (31)$$

Figure 6 shows the variation of accelerated electron flux near the northern and southern feet of the magnetic force tube of Io, depending on the longitude in the frame III. It follows from Eq. (31) and Fig. 6 that the "northern" fluxes of accelerated electrons essentially exceed the corresponding fluxes to the southern direction. This is the reason why the emission from the sources located in the northern hemisphere prevails. Moreover, the fluxes of accelerated electrons, calculated in our model, correspond to the observed data of the occurrence of decametric bursts (depending on Io's longitude) in the frame III both for "northern" sources (Fig. 7) and for "southern" sources (Fig. 8).

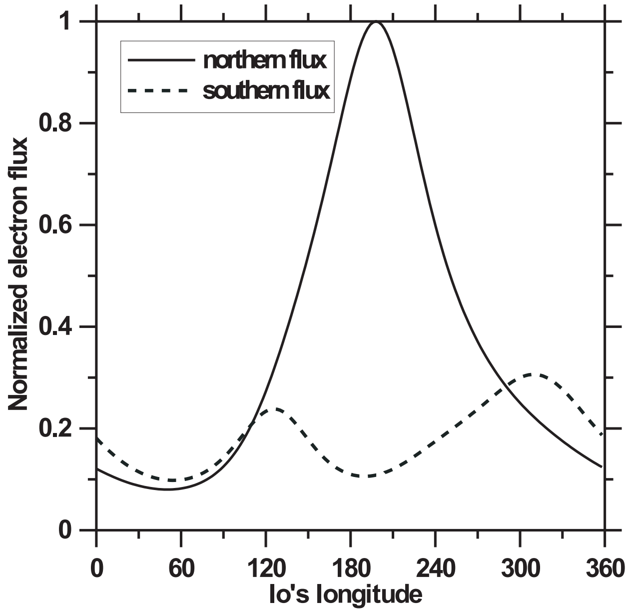

Fig. 6. The normalized fluxes of accelerated electrons, $f_{eJ} = F_{eJ}/F_{eJ}^{max}$, in the northern and southern feet of the magnetic tube of Io, as the functions of Io's longitude in frame III.

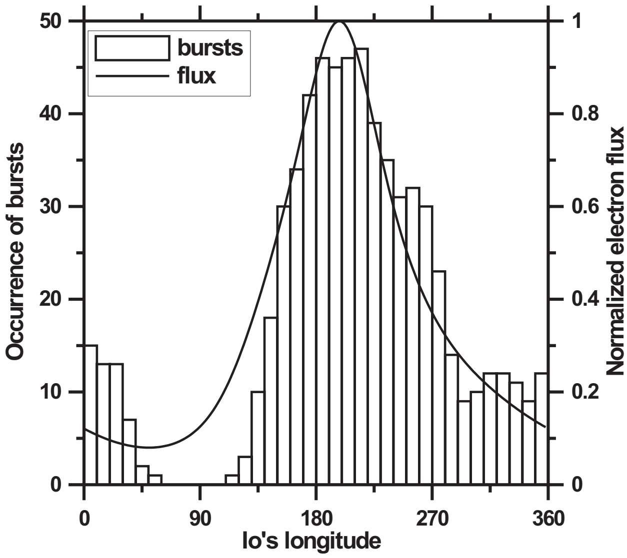

Fig. 7. The normalized flux of accelerated electrons, $f_{eJ} = F_{eJ}/F_{eJ}^{max}$, in the northern foot of the magnetic tube of Io, and the occurrence of the Jovian right-hand polarized decametric radio emission from Io-related sources Io-A, -A', and -B, as the functions of Io's longitude in frame III.

5. Discussion

We interpret the occurrence of "active" longitudes in the Jovian DAM emission and the predominance of the sources in the northern hemisphere as the result of the joint effect of two factors - the variation of the efficiency of particle acceleration in the

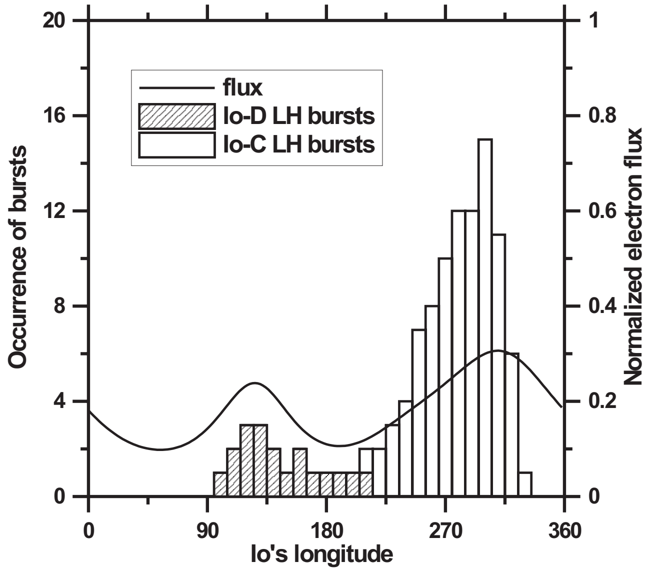

Fig. 8. The normalized flux of accelerated electrons in the southern foot of the magnetic tube of Io, and the occurrence of the Jovian left-hand polarized decametric radio emission from Io-related sources Io-C and Io-D, as the function of Io's longitude in frame III.

ionosphere of the satellite Io and the variation of the broadening of the angular spectrum of accelerated particles during their pass through Io's plasma torus, depending on Io's longitude. The planes of the rotational, magnetic, and centrifugal (for Io's torus) equators do not coincide. As a result, the magnetic field near the satellite Io, which determines the accelerated particle efficiency, changes periodically. The most effective acceleration takes place in the longitude range $120° \lesssim \lambda_{\mathrm{Io}} \lesssim 300°$ (see Fig. 3). In this longitude range only, the satellite Io appears to be "screened" by the plasma torus of the southern hemisphere (see Fig. 4). Making their way to the southern hemisphere, the particles are scattered in the torus plasma and withdrawn from a narrow range of pitch angles, $\Delta\theta_0 \simeq 2°$, within which they can reach the southern hemisphere. Therefore, in the longitude range indicated above, northern sources of DAM emission should be concentrated. At the same time, in the longitude range, where the "screening" effect of the plasma torus in the southern direction is negligible, the efficiency of the accelerated mechanism is essentially smaller due to the decrease of the magnetic field near Io. Therefore, the southern sources turn out to be weaker and are mainly located outside the longitude range, where the emission from the northern sources predominates. Since the emission from the northern sources predominates, the active longitudes are basically determined by this emission and are in the range $120° \lesssim \lambda_{\mathrm{Io}} \lesssim 300°$. The distribution of accelerated electron fluxes near the southern foot of the magnetic tube of Io coincides well with the distribution of the occurrence of the left-hand polarized emission from the sources Io-C and Io-D. This is an indirect verification of the fact that the source of this emission is in the southern hemisphere of Jupiter.

Dessler & Hill (1979) believe that that the existence of "active" longitudes is due to the existence of nondipole anomalies of the Jovian magnetic field that result in the increased particle precipitation from radiation belts of Jupiter, the growth of ionosphere plasma ionization, and the increase of ionosphere conductivity. As a result, the Birkeland current flows between Io and Jupiter and the associated radio emissions increase. Their interpretation of "active" longitude explains the location of the northern emission sources rather well, but encounters serious obstacles in explaining the location of the southern sources. Another mechanism of the occurrence of active longitudes was considered by Galopeau et al. (2004). The authors studied the effect of magnetic field inhomogeneities near the surface of the planet on the increments of cyclotron instability occurring in the Jovian ionosphere. The angular anisotropy of the distribution function, on which the instability increment depends, was determined by Coulomb collisions of fast electrons with the ions of ionospheric plasma. The length of the free path of electrons with velocities $v \sim 10^{10}$ cm s^{-1} in the ionospheric plasma with the concentration $n \sim 10^5$ cm^{-3}, typical of the ionospheric maximum, constitutes $l_{\mathrm{st}} \sim 2 \times 10^{16}$ cm; in other words, it exceeds the ionosphere's thickness by many orders. Therefore, this mechanism of active longitudes will evidently not be efficient. Besides, the calculation of the increment of electron-cyclotron maser (ECM) instability, performed by Galopeau et al. (2004), is valid if the emission generation by the ECM mechanism occurs along the magnetic field. It should be noted, however, that the increment of the ECM mechanism is maximal in the direction close to the orthogonal magnetic field (Melrose et al. 1984). The correct calculation of the increment of ECM instability may change the conclusion of Galopeau et al. (2004).

A number of works (e.g. Thieman & Smith 1979; Genova & Calvert 1988; Leblanc et al. 1994; Imai et al. 1997; Queinnec & Zarka 1998) suppose that there is a significant difference (the so-called lead angle of up to 70°) between IFT and the active magnetic tube where the Io-related decametric emissions are generated. There can be different reasons for the existence of the lead angle. One of them, as is indicated in the papers of Leblanc et al. (1994) and Imai et al. (1997), is as a consequence of the model that authors propose as an explanation of some features of the Jovian decametric emission. In other papers (Thieman & Smith 1979; Genova & Calvert 1988), the necessity of the existence of the large lead angle can be associated with the choice of the model of the Jovian magnetic field. Near the planet surface, all existing models of the magnetic field are more uncertain, due to the existence of magnetic multipoles that are not very well determined. It should be noted here that the proposed model of "active" longitude formation slightly depends on the choice of the model of the planet's magnetic field. The point is that the value of electron acceleration and the value of accelerated electron fluxes depend on the magnetic field strength on Io's orbit, where the influence of magnetic multipoles are weak. Queinnec & Zarka (1998) conclude that the emission comes from the magnetic tubes, which are at 5°–30° angles from IFT, due to the analysis of individual decametric emission arcs. This result can be interpreted in the following way. The source of the Io-related emission extends some distance in the longitudinal direction, and at the given time we can see a part of the source. The existence of the extended (with respect to the longitude) source, which also includes IFT, follows from the analysis of the peculiarities of the polarization of the decametric radio emission (Shaposhnikov et al. 2000). It is shown by Shaposhnikov et al. (2000) that the polarization in the great arc of the Io-A decametric storm can only be unambiguously explained if we suppose the source extends in the longitudinal direction, and the great arc is formed in IFT, while the rest of the emission storm is formed in the active tubes, which are at a certain angle from IFT. Note here that a supposition on the source extent does not contradict the model of the electron acceleration that was proposed by Zaitsev et al. (2003). First, there are electrons in the magntic tubes behind Io, which having been accelerated on Io were reflected in the regions with strong magnetic fields near the planet. Second, the proposed mechanism of acceleration can also operate in Io's wake, where a relative motion of weakly ionized plasma and the planet magnetic field still exists. However, in both cases, the fluxes of accelerated electrons will be weaker than the fluxes in IFT.

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