

JOVIAN S-EMISSION: DECAMETRIC HIGH-SENSITIVITY OBSERVATIONS AND MODEL OF RADIATION SOURCE

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Abstract

A physical model of the radiation source and an excitation mechanism have been suggested for the S-component in Jupiter's sporadic radio emission. The model provides a unique explanation to most of the interrelated phenomena observed, allowing a consistent interpretation of the emission cone structure, behavior of the integrated radio spectrum, occurrence probability of S-bursts, location and size of the radiation source, and fine structure of dynamic spectra. The mechanism responsible for the S-bursts is also discussed in its connection with the L-type emission. Relations are traced between parameters of the radio emission and geometry of the Io flux tube (IFT). Fluctuations in the current amplitude through the tube are estimated, along with the refractive index value and mass density of the plasma near the radiation source.

1 Introduction

Recent observations of radio emission from Jupiter in the frequency range of 10 to 23 MHz [Ryabov et al., 1985] performed with the world largest decametric radio-telescope UTR-2 (Braude et al., 1978] have cast some new light on the complex phenomenon. The results concerning southern location of the main S-radiation source [Ryabov, 1986, 1990a] and the frequency dependent S-emission cone structure vs. the IFT footprint longitude [Ryabov, 1990b] have allowed to give a consistent explanation of some important details in the physical pattern of the Io-related emission. Thus, it is found to be possible to suggest a physical model of the radiation source and establish a mechanism responsible for the S-component in the Jovian DAM radiation [Ryabov, 1987; Ryabov and Gerasimova, 1990], consistent with angular parameters of the emission cone, estimated location of the source and with observed characteristics of the S-bursts fine structure [Ellis, 1979, 1982; Leblanc et al., 1980; Leblanc and Genova, 1981]. In constructing the model, the azimuthal field $\mathbf{B}_T$ produced by the electric current through the IFT upward stream branch is taken into account along with the planetary magnetic field $\mathbf{B}_J$, because the current may reach values $\geq 10^8$ A [Dessler and Hill, 1979].

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2 The magneto–drift (curvature) radiation as a source of S–bursts

One of the possible physical mechanisms to explain the appearance of upper limit frequencies, f_m , of S–burst storms [Ryabov, 1986, 1990a] is connected with the Alfvén wave arising near the surface of Jupiter and stimulating a long–duration pulse of integral electro–motive force (e.m.f.) ($\mathbf{E}_{\text{Io}}$) on Io. The pulse results in an increase of the tube current $\mathbf{i}_T$ up to $\geq 10^8$ A and a local growth in the magnetic field strength, $\mathbf{B}_s$, within the zone of S–bursts excitation. The field $\mathbf{B}_s$ is given by

$$\mathbf{B}_s \simeq \mathbf{B}_T + \mathbf{B}'_j, \quad (2.1)$$

where $\mathbf{B}'_j \simeq \mathbf{B}_j - \mathbf{B}_{T\parallel}$, $\mathbf{B}_{T\parallel}$ is the field component owing to the current $\mathbf{i}_T$, parallel to the tube axis. It is produced by the electrons moving along the Larmor helices. $\mathbf{B}_T$ is the azimuthal magnetic field produced by the current $\mathbf{i}_T$, and $\mathbf{B}_j$ is the planetary field. Obviously, there are electrons on the tube surface moving along the helical magnetic field $\mathbf{B}_s$, which has a strength maximum there. The excitation mechanism we suggest is the coherent magneto–drift (curvature) radiation from bunches of relativistic electrons moving along the field $\mathbf{B}_s$ at the IFT surface. That radiation is amplified in the cyclotron maser operating at the local gyrofrequency near the radiation source. Admittedly, the electron bunches are formed and accelerated (up to relativistic velocities) at those points where the elementary current filaments in the surface layer of the IFT near Jupiter break up abruptly. The reason for the break–up is the increased value of the tube current $\mathbf{i}_T$ and its transverse velocity $\mathbf{v}_s$ through the inner magnetosphere at two active Jovian longitudes, i.e. $\lambda_{III \text{ Io}} \approx 200^\circ \pm 70^\circ$ and $40^\circ \pm 40^\circ$ [Ryabov, 1986]. The break–up results in a pulse of the self–induction e.m.f.,

$$\mathbf{E}_x = -L d\mathbf{i}/dt,$$

and an electric field of local strength of tens MV/m, which is capable of accelerating bunches of N_x in–phase radiating electrons. The velocity vector $\mathbf{v}_e$ of the bunch is directed along the field $\mathbf{B}_s$. The relativistic electron bunches moving almost along the helical field $\mathbf{B}_s$ produce a pencil beam radiation pattern directed to its velocity vector $|\mathbf{v}_e| \approx c$ (Figure 1).

Further, the rotation of the pencil beam caused by the motion of electrons along the helical field line around IFT gives rise to a hollow conical pattern of the S–radiation. The observations indicate that the radiation cone is nearly circular, the conical sheet is narrow ($\delta_i \approx 0.5^\circ$), and the upper frequencies of S–burst storms correspond to local gyrofrequencies of the total field $\mathbf{B}_s$. In the framework of this model a reasonable explanation can be given for the dependencies of Ψ (apex angle of surface of emission cone) and δ (angular thickness of cone) upon the emission frequency f , and the longitude $\lambda_{III \text{ Io}}$ [Ryabov, 1990b], the drifting burst lifetime Δt , frequency drift rates [Ellis, 1979, 1982], upper frequency limits f_m and cutoff frequency of the integral spectrum, as well as for the radio emission power of the S–source [Alexander et al., 1981], and some other data. In further parts of the paper we shall consider interpretation of the various experimental data from the viewpoint of the proposed physical model of the S–radiation source.

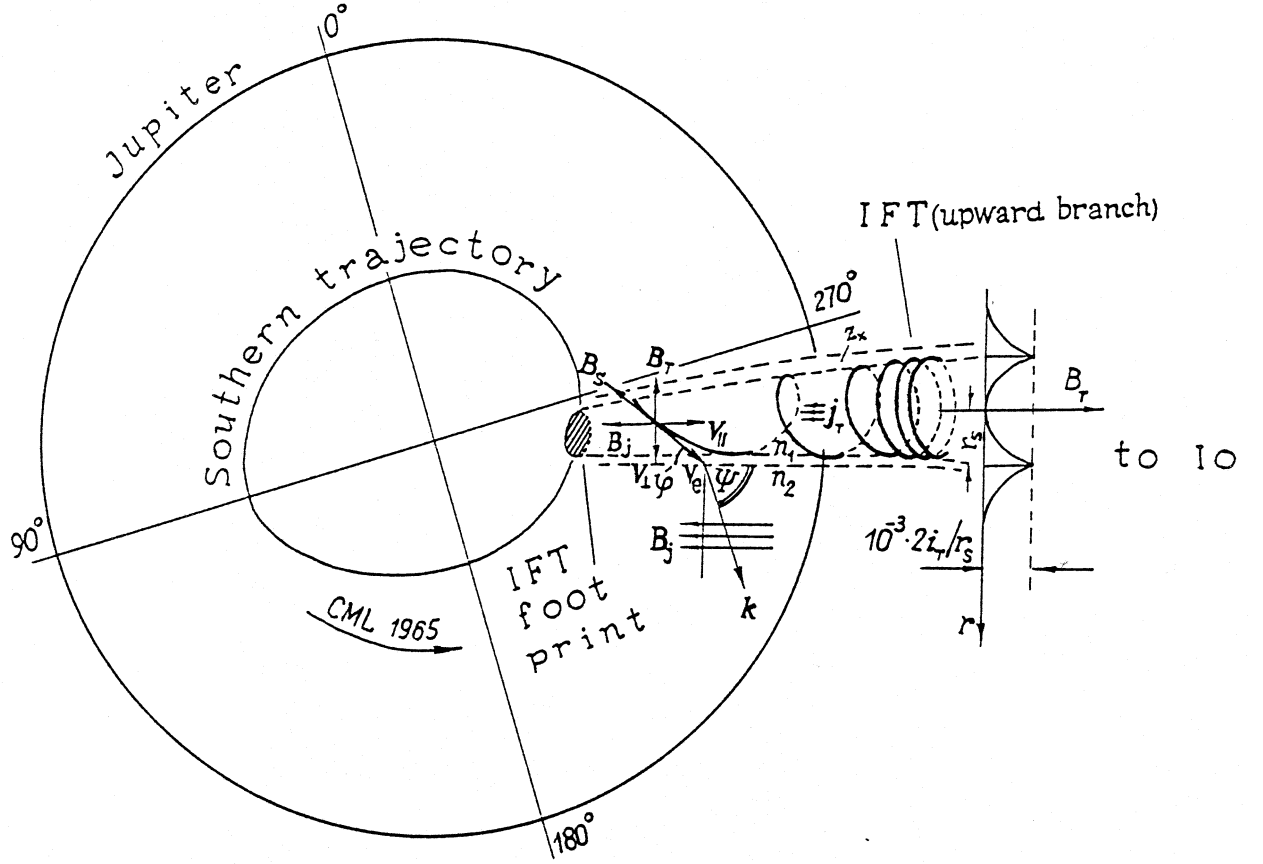


Figure 1: Schematic of the IFT. The helical field line of the net magnetic field $\mathbf{B}_s \approx \mathbf{B}_T + \mathbf{B}_J$ is shown on the surface of Io's tube. The relativistic electron bunches producing S-bursts move along this line. $\mathbf{B}_T$ is the azimuthal magnetic field of the IFT upward stream current and $\mathbf{B}_J$ Jupiter's own magnetic field.

3 Interpretation of the conical S-emission pattern structure

The radiation pattern of S-emission [Ryabov, 1990b] is a cone with an apex angle 2Ψ varying within the limits $\sim 140^\circ$ – 180° . It depends upon the Jovigraphic longitude $\lambda_{III Io}$ of the source, and the emission frequency $(90^\circ - \Psi) \sim 1/f$ (see Figure 2).

As can be seen from Figure 3(a,b), the angle Ψ_e (apex angle of external surface of emission cone) increases to $\sim 90^\circ$ in the first active longitude sector ($\lambda_{III Io} \approx 150^\circ - 360^\circ$) at both frequencies, which is definitely related to an increase of the location altitude h_s of the S-emission zone [Ryabov, 1990a]. Maximization of Ψ_e occurs at the longitude of $\lambda_{III Io} \approx 245^\circ$, showing a $\sim 20^\circ$ delay of the Ψ_e maximum from the maximum altitude $h_s(\lambda_{III Io})$. Within the second active longitude region, ($\lambda_{III Io} \approx 0^\circ - 100^\circ$), Ψ_e decreases to $\sim 71^\circ$ at $f = 15$ MHz and to $\sim 76^\circ$ at $f = 11$ MHz.

As follows from Figure 3(c) the cone axis oscillates periodically, and the maximum of β is reached at the longitude of the maximum h_s and of IFT current strength i_T . At 23 MHz, the S-radiation exists only within the source longitude sector of $190^\circ \leq \lambda_{III Io} \leq 260^\circ$.

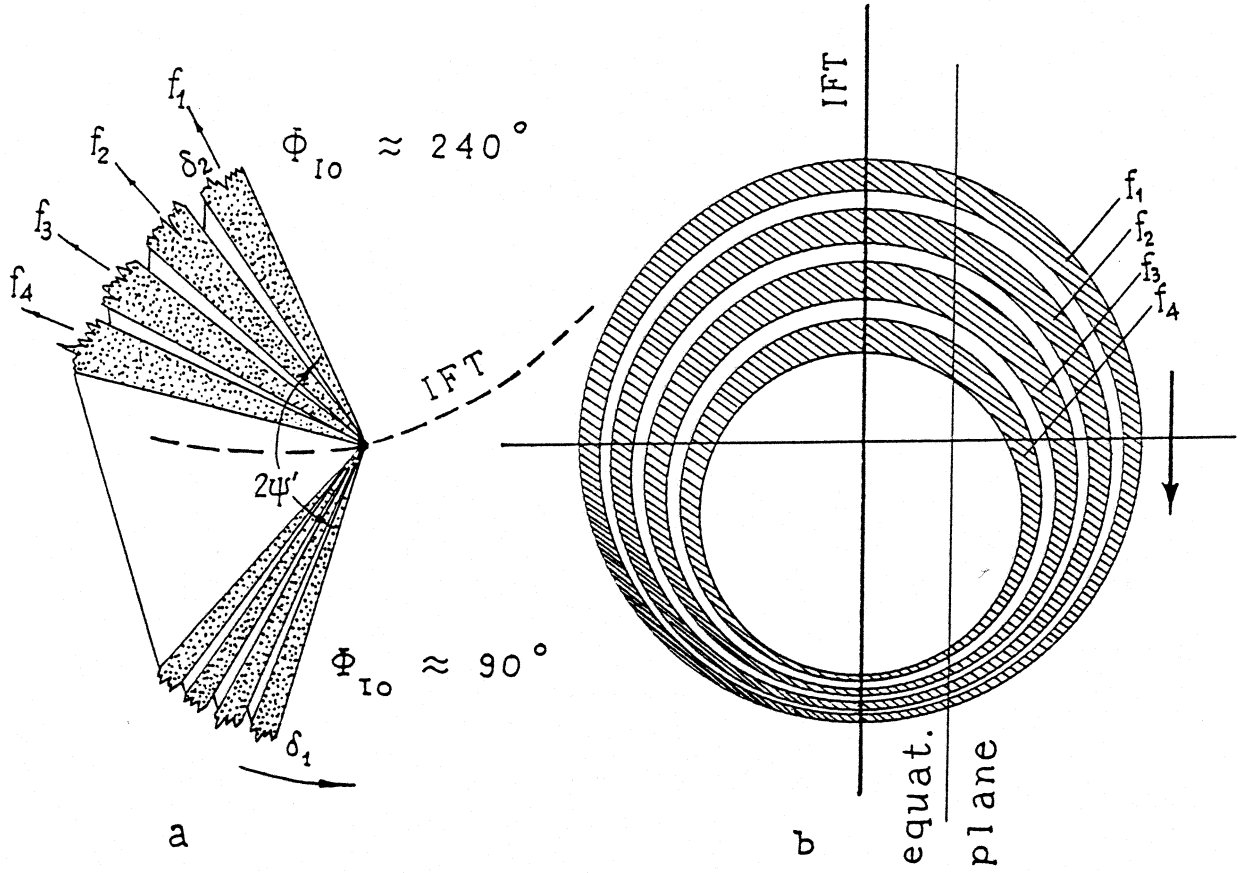


Figure 2: Schematic of the conical S-emission radiation pattern at various frequencies $f_1 < f_2 < f_3 < f_4$, (a) section by the line of sight plane of a terrestrial observer, (b) section by the picture plane.

The cone angles at this frequency are given in Table 1.

It is evident that in the second longitude sector $\lambda_{III I_o} \approx 0^\circ - 90^\circ$ the weak S-burst storms are excited at small altitudes h_s , and the angular thicknesses δ_1 and δ_2 are almost identical and not dependent on radiation frequency. At $\lambda_{III I_o} \approx 200^\circ - 300^\circ$ the values of δ_1 and δ_2 are essentially different. For $\Phi_{I_o} \approx 90^\circ$ the angular width of δ_1 decreases to $\sim 0.5^\circ$ and does not depend upon frequency. For $\Phi_{I_o} \approx 240^\circ$ the width δ_2 of the opposite cone wall increases considerably (up to 8°), and a frequency dependence appears.

3.1 Apex angle Ψ of the S-emission cone and the refractive index

According to the model given, the apex angle in Io's tube plasma is determined by the angle Φ between the IFT axis and the electron velocity vector $\mathbf{v}_e$ on the tube surface. Since $\mathbf{v}_e \parallel \mathbf{B}_s$, we have

$$\Phi \approx \arctan \frac{B_T}{B'_j}. \quad (3.1)$$

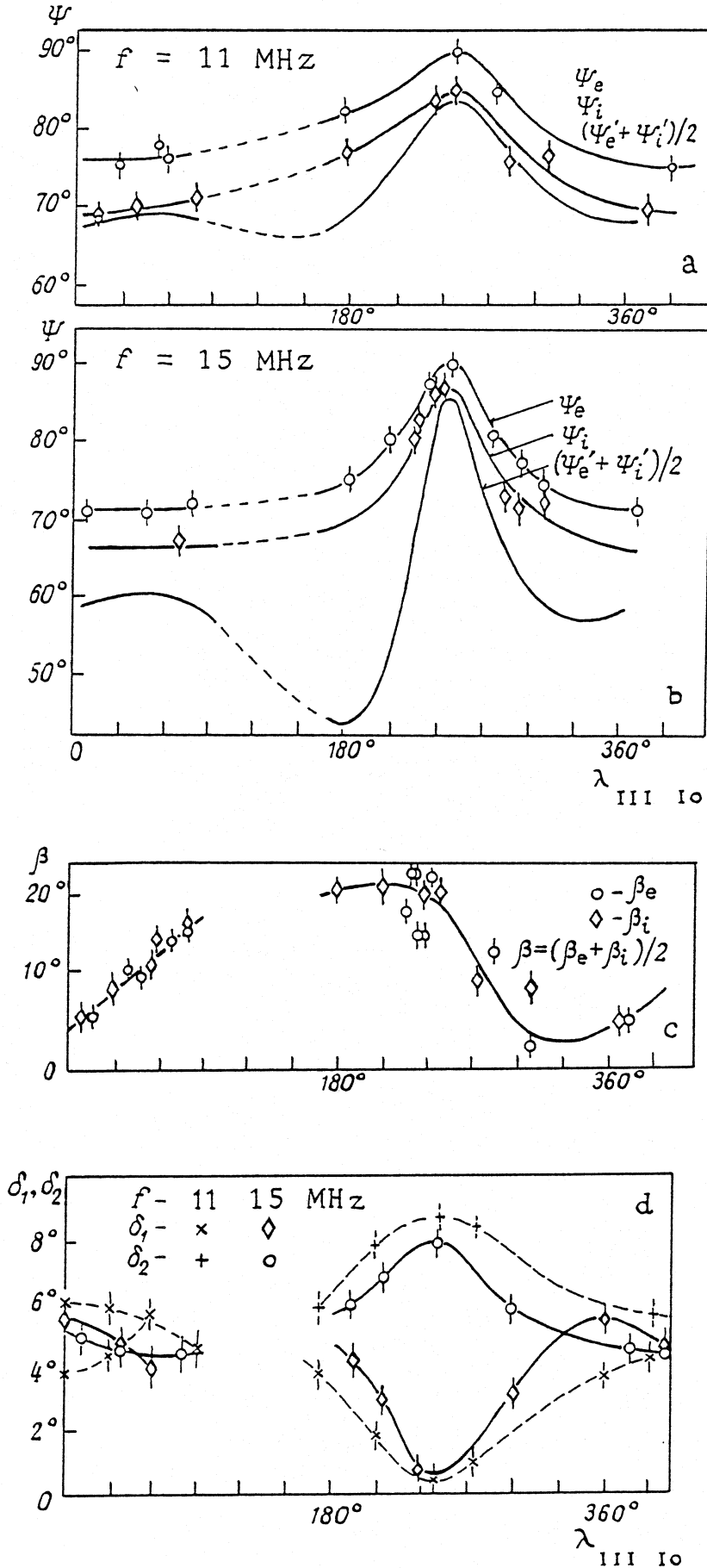


Figure 3: Angular characteristics of the S-emission cone vs longitude, $\lambda_{III Io}$, (a) and (b) apex angles at the frequencies 11 MHz and 15 MHz, Ψ' is the apex angle in the equatorial plane section, (c) cone axis orientation angle β , (d) angular thicknesses δ_1 and δ_2 of the hollow cone walls in the main cross-section plane at frequencies 11 and 15 MHz vs longitude $\lambda_{III Io}$.

Table 1: Cone angles (deg) of the S-emission at 23 MHz (Ψ_e and Ψ_i are apex angles of external resp. internal surface of emission cones)

$\lambda_{III\ I_o}$	Ψ_e	Ψ_i	β
255 ± 28	87	85	15
259 ± 30	85	82	28
296 ± 28	74	69	12

When the apex angle Ψ of the conical radiation pattern observed at the Earth is greater than ϕ , then the refraction of the DAM wave coming out of the IFT becomes essential. Using the Snell's law at a boundary separating two media, with $n_{2+} \approx 1$, we have

$$\Psi \approx \arccos(n_{1+} \cos \Phi), \quad (3.2)$$

where n_{1+} and n_{2+} are refractive indices of the extraordinary wave in the tube and outside, respectively. The definitions of Ψ and Φ are shown in Figure 1. In order to determine n_{1+} , let us calculate Φ (at $\lambda_{III\ I_o} \approx 220^\circ \pm 40^\circ$ and $f = 10\text{--}35$ MHz) by substituting the following relations to Eq. (3.1):

$$B_T \approx 10^{-6} \times 2i_T/r_s \quad [G], \quad (3.3)$$

$$B'_j \approx (B_{FS}^{-1/3} + h_s/2R_{jp})^{-3} - \pi B_T \sin \alpha \quad [G], \quad (3.4)$$

$$r_s \approx 7.6 \times 10^2 (B_{FS}^{-1/3} + h_s/2R_{jp} - 0.37) \quad [km], \quad (3.5)$$

$$h_s \approx 1.46 \times 10^6 f^{-1.44} \quad [km], \quad (3.6)$$

Here, i_T is in Amperes, $B_{FS} \approx 7\text{--}10$ G, (i.e. the planetary surface field strength at the southern polar trajectory of IFT footprint [Connerney et al., 1981]); $R_{jp} \approx 67 \times 10^3$ km (the polar radius of Jupiter); r_s the radius of IFT section plane, $\alpha \approx 5^\circ$, the angle between $\mathbf{B}_j$ and the electron velocity vector $\mathbf{v}_e$ in the main stream and h_s , the emission zone altitude, dependent upon $\lambda_{III\ I_o}$ and f [Ryabov, 1990a]. Then, by using the inferred values of the apex angle Ψ (see also Figure 3), n_{1+} can be determined from Equ. (3.2). The calculations give $n_{1+} \approx 0.3$, a value which is slightly dependent upon $\lambda_{III\ I_o}$ and f in the band 10–23 MHz. For active longitudes ($\lambda_{III\ I_o} \approx 220^\circ$ and $\approx 45^\circ$) the tube current magnitudes are taken equal to $i_{T1} \approx 5 \times 10^8$ A and $i_{T2} \approx 10^7$ A, respectively. Using the formulae (3.1)–(3.5), one can see, that the cone apex angle Ψ obeys the observed law of frequency variation $(90^\circ - \Psi) \sim 1/f$ [Ryabov et al., 1985; Ryabov, 1990a]. On the other hand, the same experiment shows (see Figure 3) that the apparent apex angle Ψ increases to 88° in the first $\lambda_{III\ I_o}$ sector, where the tube current grows to 5×10^8 A. This can be explained by a considerable increase of the azimuthal field $\mathbf{B}_T$ with a nearly constant value of the field $\mathbf{B}'_j$ (see Eq. (3.1)).

3.2 Angular thickness δ of the conical sheet and electron energies

At longitudes $\lambda_{III\ I_o} \approx 220^\circ \pm 40^\circ$, the observed angular thickness δ_1 decreases to about 0.5° . In this case, the conical sheet thickness $\Delta\Phi_1$ at the point of generation can be approximated as

$$\Delta\Phi_1 \approx \delta_1/n_{1+}.$$

Hence, it follows that $\Delta\Phi_1 \approx 1.7^\circ$, being independent of frequency. The radiation pencil beam produced by relativistic electron bunches moving along the helical field lines of $\mathbf{B}_s$ around IFT shows similar directivity properties. It may be shown for Io's tube source, that the radiation pattern width $\Theta_{0.5}$ measured at various frequencies at longitudes about $\lambda_{III\ I_o} \approx 220^\circ$, where $\sin \Phi \approx \text{const}$, is almost independent of frequency within the DAM waveband, being determined by the energy of relativistic electrons ϵ/mc^2 alone

$$\Theta_{0.5} \approx 3 \times 10^{-3} \sqrt{\frac{\epsilon}{mc^2}} \sin \Phi. \quad (3.7)$$

Apparently, this explains the observations, that a rather weak dependence of the thickness δ_1 upon frequency is noted, since the thickness of the narrow wall $\Delta\Phi_1$ is mainly determined by the pencil beam width $2\Theta_{0.5}$ of the relativistic electron bunches.

It is further assumed that at source longitudes $\lambda_{III\ I_o} \approx 220^\circ$ the initial energy ϵ_0/mc^2 of radiating electrons does not depend on the S-source altitude h_s . In this case the electron energy ϵ in the S-source can be estimated from measured values of the original conical sheet thickness $\Delta\Phi_1 \approx 2\Theta_{0.5} \approx 1.7^\circ$ (from Eq. (3.7)), and $\epsilon_0 \approx 12.5$ MeV.

3.3 Asymmetry of the conical sheet pattern and the tube current fluctuations

At the S-source longitude $\lambda_{III\ I_o} \approx 220^\circ$ the S-emission cone is strongly asymmetric (see Figure 2 and Figure 3). In our view, this can be explained by the geometric effect, resulting from the curvature of Io's tube axis and, hence, of the axis of the helical field line of $\mathbf{B}_s$ in the S-emission radiation zone. The curvature is maximal at $\lambda_{III\ I_o} \approx 220^\circ$, as it is shown by variations of the angle β (see Figure 3c). As is clear from Figure 4a, the ratio of the helical line step to the Io tube radius, H/r_s , decreases with an increase of altitude h_s . This is the principal factor to cause the asymmetry in the conical sheet thickness, if the axis is curved. At $\Phi_{I_o} \approx 90^\circ$ the convexity of the curved tube axis is faced to the Earth (the axis curvature is positive). Hence the observer receives radiation from those points at which the velocity vectors $\mathbf{v}_{e1}$ and wave vectors $\mathbf{k}_{e1}$ are parallel for a few adjacent laps of the helical field line $\mathbf{B}_s$, since the deviation $\Delta\Phi$ of the screw pitch angle with increasing h_s is compensated by the turn of Io's tube axis.

In this case, the angular thickness δ_1 of the conical sheet coincides with that of the pencil beam radiation pattern $2\Theta_{0.5}$ of a relativistic electron (taking into account the refractive index at the tube boundary, i.e. $\delta_1 \approx 2\Theta_{0.5}n_{1+}$).

The opposite wall of the conical sheet (with δ_2) is observed at $\Phi_{I_o} \approx 240^\circ$, when the convexity of Io's tube axis is oriented outward from the observer (the axis curvature is

negative). In this position, the deviation $\Delta\Phi$ in the screw pitch angle and the turn angle of the tube axis are summed up, and the radioemission arrives from the directions of the $\mathbf{v}_{e2}$ vectors. The corresponding wave vectors $\mathbf{k}_{e2}$ of a few adjacent turns form a fan shaped pattern (in the observer line of sight plane) with the opening angle $\Delta\Phi = \Delta\Phi_2 - 2\Theta_{0.5}$, i.e. the sheet thickness $\delta_2 = \Delta\Phi_2 n_{1+}$ reaches the value of 8° .

It may be found that the angles Φ_1 and Φ_2 of the S-emission cone axis made by $\mathbf{k}_{e1}$ and $\mathbf{k}_{e2}$ are

$$\begin{aligned}\Phi_1 &= \frac{\pi}{2} + \frac{\mu_{01} + \mu_{02}}{2} - \mu_1 \\ \Phi_2 &= \frac{\pi}{2} - \frac{\mu_{01} + \mu_{02}}{2} + \mu_2,\end{aligned}\quad (3.8)$$

where

$$\mu_1 \approx \arctan \left(\frac{\eta/\eta_0 + 1}{\sqrt{\eta/\eta_0}} \cot \Phi \right), \quad (3.9)$$

$$\mu_2 \approx \arctan \left(\frac{\eta/\eta_0 - 1 + 0.5/\eta_0}{\sqrt{\eta/\eta_0}} \cot \Phi \right). \quad (3.10)$$

Here, η is the turn number of the helical field line of $\mathbf{B}_s$ as counted from the $\gamma = 0$ direction and η_0 the lap number at which $d\mu_1/d\eta=0$, i.e.

$$\eta_0 = \frac{1}{4\pi} \frac{\rho_0}{r_s}, \quad (3.11)$$

where ρ_0 is the curvature radius of Io's tube axis; μ_{01} and μ_{02} correspond to the values of μ_1 and μ_2 at $\eta = \eta_0$. Using the observed values of $\Delta\Phi_2 \approx \delta_2/n_{1+} \approx 27^\circ$ and $2\Theta_{0.5} \approx 1.7^\circ$, and Eqs. (3.8)–(3.11) we are able to estimate the active interval l_s radiating at a fixed frequency. For $f = 15$ MHz, the interval l_s is about 3.3×10^3 km, while the variation in the local gyrofrequency is about 1.5 MHz.

Obviously, the local gyrofrequency is not determined by the steady planetary field $\mathbf{B}_j$ alone, but also by the tube current field $\mathbf{B}_T$ which can fluctuate because of fluctuations in the current $\mathbf{i}_T$. So, the ‘instantaneous’ size of the S-source at $f = \text{const.}$ does not exceed a few kilometers, but the altitude h_s of this compact source fluctuates within the interval l_s during the period of the S-burst storm.

Using the estimates of the interval l_s , the corresponding magnitude Δi_T of fluctuations in Io's tube current can be found

$$\Delta i_T \approx 2.8 B_T \left[1 + 6 \frac{B_j^2}{B_T^2} (1 - 0.37 B_j^{1/3}) \right] l_s, \quad (3.12)$$

where

$$B_T \approx \sqrt{(f_s/2.8)^2 - B_j^2}, \quad (3.13)$$

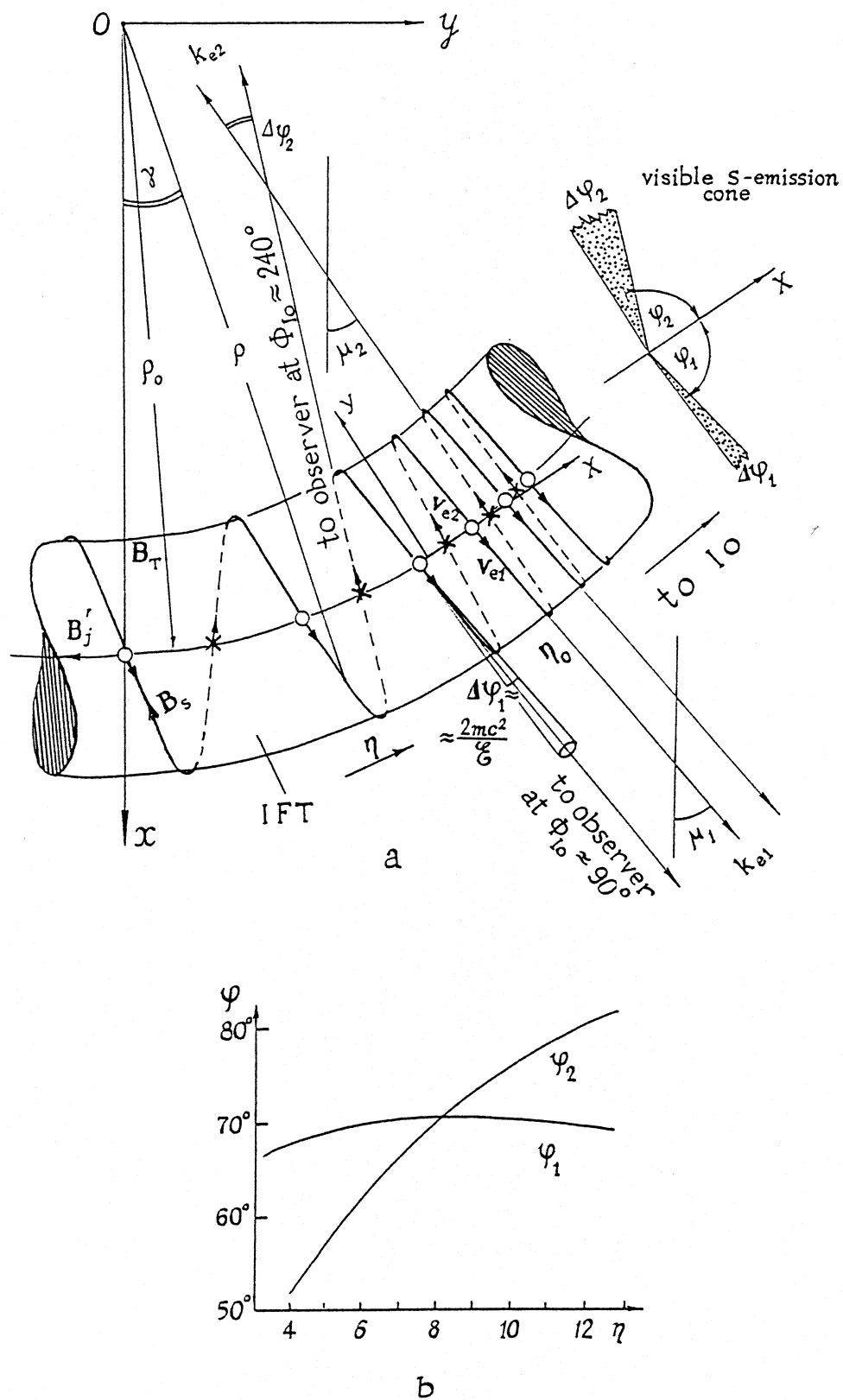


Figure 4: Schematic of the observed asymmetry in the S -emission cone, (a) the curved segment of Io's tube, (b) dependencies of the cone apices Φ_1 and Φ_2 in the observer line of sight plane upon the lap number of the helical field line of $\mathbf{B}_s$.

$$B_j \approx \left(B_{FS}^{-1/3} + \frac{h_s}{2R_{jp}} \right)^{-3}. \quad (3.14)$$

For $\lambda_{III I_o} \approx 220^\circ$, $f = 15$ MHz, $h_s = 2.8 \times 10^4$ km and $l_s = 3.3 \times 10^3$ km we obtain $\Delta i_T \approx 10^8$ A. The relative current fluctuation is $\Delta i_T / i_T \approx 0.2$ at that longitude. The existence of current fluctuations in the IFT is confirmed independently by the following experimental facts:

- a) Low occurrence probability of S-bursts during the storm, $W_{st}(f) \approx 0.1$ at a fixed frequency [Ryabov et al., 1985].
- b) Scatter in the drift rate df_s/dt shown by the fine structure of S-bursts at $f = \text{const}$ [Ellis, 1982; Leblanc et al., 1980b].
- a) The tube current fluctuations produce fluctuations of the direction of the field vector $\mathbf{B}_s$, and of the radiation beam of the magneto-drift emission. As a result, series of S-bursts would be received by an observer at those times only, when his line of sight passes through the relativistic pencil beam of width $\Theta_{0.5} \approx 1.7^\circ$, which results in low values of W_{st} .
- b) The fluctuations of altitude h_s within the interval l_s , associated with the current fluctuations, bring about a scatter in the drift rate Δd_s , which can be shown to be

$$\Delta d_s \approx 4.5 \times 10^8 \frac{1}{i_T} f_s \frac{\Delta i_T}{i_T}, \quad (3.15)$$

with i_T in Amp s.

The observed width Δd_s of the scattering histogram at a fixed frequency [Ellis, 1982] can be approximated by

$$\Delta d_s \approx 0.2 f_s, \quad (3.16)$$

which is consistent with Eq. (3.15) at $\Delta i_T / i_T \approx 0.2$, and $i_T \approx 5 \times 10^8$ A. Thus, on the basis of the model considered, it seems to be possible to reconcile two completely independent experimental facts, namely the measured integrated radiation pattern of the S-emission [Ryabov, 1990b] and fine structure characteristics of S-bursts [Ellis, 1982].

4 The generation mechanism and fine structure of the S-bursts

An individual drifting S-burst is generated at a single rupture moment of current filament on the tube surface (see Figure 5), taking place under the action of tension forces due to the filament magnetic field B_x (specific tension $B_x^2/4\pi$). At that instant the force balance is violated by drift currents of the corotating plasma. The specific force $\mathbf{F}_j$ is defined by the following expression

$$\mathbf{F}_j = \mathbf{J} \times \mathbf{B}_j = \sum q N_q \mathbf{v}_s \times \mathbf{B}_j, \quad (4.1)$$

where $\mathbf{J}$ is the drift current density, q and N_q are the particle charge and number densities, respectively, in the corotating magnetosphere. The summation is made over different kinds of ionized particles. The important role of the velocity $\mathbf{v}_s$ is also confirmed experimentally by the correlation between longitudinal ($\lambda_{III I_o}$) dependencies of the power characteristics of S-burst storms and maxima in $\mathbf{v}_s$ [Ryabov, 1986].

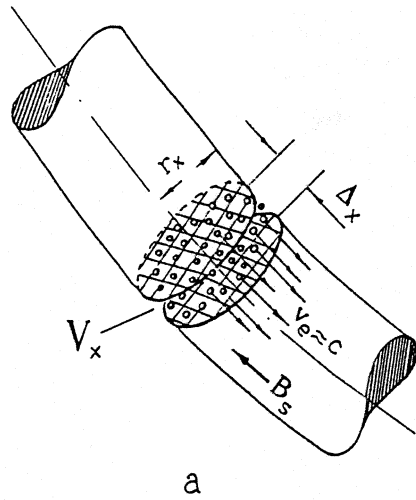
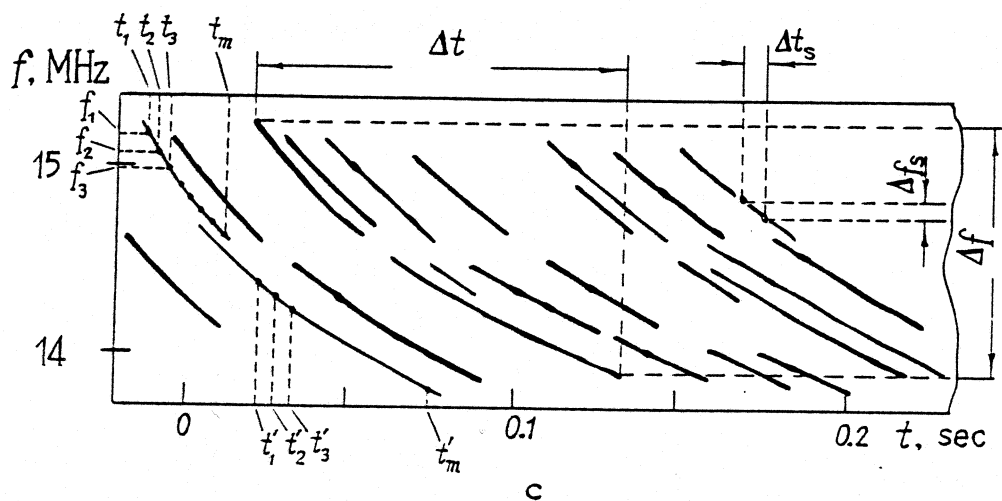
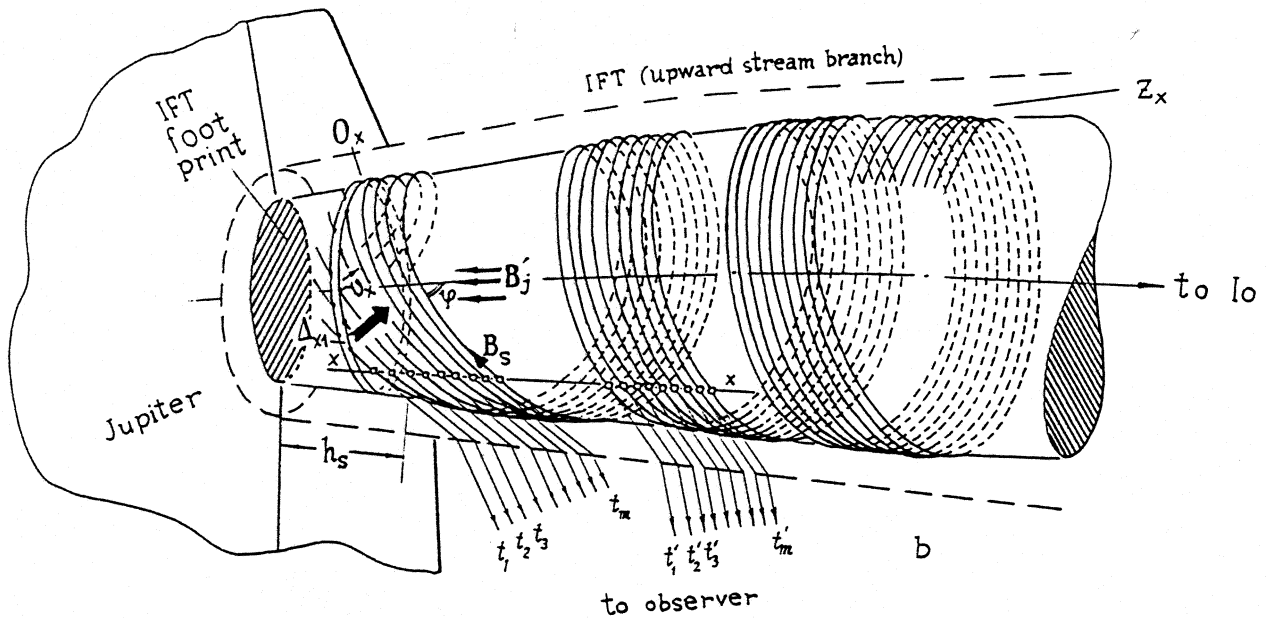


Figure 5: Interpretation of dynamic spectrum formation of S-bursts: (a) An elemental segment of Io's tube current filament at the point of break-up, (b) surface layer of Io's tube current filaments placed along the field B_s (at the moment when the xx line is crossed by electron bunches, a terrestrial observer receives a sequence of magneto-drift radiation pulses forming a drifting track on the time-frequency spectrogram), (c) part of the S-burst spectrogram [Ellis, 1979].



4.1 Dynamic spectrum formation of S–bursts

The electrons in the volume V_x (see Figure 5a) are collectively accelerated to relativistic velocities and radiate DAM waves coherently along the velocity vector $\mathbf{v}_e$ into a pencil beam of width $\Theta_{0.5}$. After a propagation time delay an external observer will receive a short radio pulse from the first bunch at the time moment t_1 when the line xx is crossed (see Figure 5b). While propagating through the layer z , the emitted radiowave is amplified by the cyclotron maser mechanism in a narrow frequency range Δf_s around the local gyrofrequency and is refracted, when it escapes from Io's tube. At the time moment t_1 (see Figure 5c) a compact spot of intrinsic dimensions $\Delta f_s - \Delta t_s$ centered at the upper frequency $f_1 \approx f_{Be1}$ appears. The energy $W_L = Li_x^2/2$ produced at the rupture point is spent to excite a fast magneto–sound wave, propagating at the velocity $\mathbf{v}_x$, perpendicular to magnetic field $\mathbf{B}_s$, and causing ruptures of adjacent current filaments. The direction of the wave vector $\mathbf{k}_x$ is marked by a heavy arrow. As a result a cascade process of filament break–up arises along the path of the propagating wave. The time before the coincidence of a pencil beam with the observer's line of sight takes place is

$$dt \approx \frac{ds}{v_x} + \frac{db}{c}, \quad (4.2)$$

where ds is the distance between two adjacent turns, db the length passed by the bunch along the helical line $\mathbf{B}_s$ from the rupture point to the place where the relativistic pencil beam hits the line of sight. Thus, the bunch crosses the xx line at a greater height h_s , and the local gyrofrequency f_{Be2} becomes somewhat lower. Consequently, the new spectrogram point corresponds to a lower frequency $f_2 \approx f_{Be2}$. Other points of the dynamic spectrum of S–bursts are formed in a similar manner, hence the emission signature in time–frequency plane looks like a solid line segment of negative slope df/dt .

4.2 Drift rates of the spectral fine structure and mass density in the emission zone

The magnitude and sign of the frequency drift rate in the model given are defined by the obvious expression

$$d_s = \frac{df}{dt} \approx 2.8 \frac{dB_s dh_s}{dh_s dt}. \quad (4.3)$$

Here

$$f_s = 2.8 \sqrt{B_T^2 + (B'_j)^2}, \quad (4.4)$$

where B_T and B'_j are determined by expressions (3.3)–(3.5), and

$$\frac{dh_s}{dt} \approx \frac{v_x}{\sin \Phi} \frac{1}{1 + (v_x/c) \cot \Phi}, \quad (4.5)$$

where $v_x \approx v_A$, v_A is the Alfvén velocity (m/s)

$$v_A = 10^{-2} \frac{B_s}{\sqrt{4\pi\rho_m}}. \quad (4.6)$$

Here ρ_m (g cm^{-3}) is the plasma mass density in the emission zone, and B_s is measured in Gauss. As follows from the available data [Ryabov, 1990a], the $B_s^2(h_s)$ dependence in the sector of highest S-activity ($\lambda_{III\ Io} \approx 180^\circ\text{--}260^\circ$) can be approximated by the following expression

$$B_s^2 \approx 3.2 \times 10^3 h_s^{-1.39}, \quad (4.7)$$

where B_s (G) and h_s (in thousands of km).

Taking (4.3)–(4.7) into account we get following formula for the frequency drift of the S-burst emitted at the helical field B_s

$$d_s \approx -\frac{6.1 \times 10^9 h_s^{-1.39}}{R_{jp} i_T \sqrt{4\pi \rho_m}} f_s, \quad (4.8)$$

where f_s (MHz), i_T (A) and R_{jp} (m).

Note that experimentally measured drift rates [Ellis, 1982] obey

$$d_s = \left\langle \frac{df}{dt} \right\rangle \approx -0.9f, \quad (4.9)$$

where df/dt (MHz/s) and f (MHz). Then the value of ρ_m can be found as

$$\rho_m \approx 2.2 \times 10^{-15} h_s^{-2.78}, \quad (4.10)$$

where h_s (thousands km) and ρ (g/cm^{-3}).

Equation (4.10) can be regarded as an independent estimate of the plasma mass density $\rho_m(h_s)$ at the southern end of IFT. Using (4.8) to (4.10), we can obtain the formula (3.15) correlating the measured scatter in the drift rates Δd_s [Ellis, 1982] with the magnitude of current fluctuations $\Delta i_T/i_T$, that was found from the measured asymmetry [Ryabov, 1990b] in the angular thicknesses δ_1 and δ_2 of the S-emission cone.

4.3 S-burst lifetime and geometrical model of Io's tube

A drifting S-burst that has been generated by a cascade disconnection process of adjacent current filaments continues until some moment t_m (see Figure 5b,c), when the process comes to stop. The duration of the disjunction process can be interpreted in terms of diameter modulation of Io's tube along its axis, as shown in Figure 6a. The magnetic tension of filaments at the surface, $B_s^2/4\pi$, weakens at the wider places, since $B_s \sim 1/r_s$. Therefore, the stability of the surface filaments is decreased and the consequent disjunction process is possible. Hence it follows, that S-emission sources are located mainly at wide zones of the tube. The scale length M_x of the inhomogeneity is of the order $v_x \Delta t$. The S-bursts are excited at frequencies close to the local gyrofrequency in M_x (see Figure 6a).

It is worth noting that the existence of regular diameter variations of Io's tube along its axis is confirmed independently by the periodic frequency dependence of the S-burst occurrence probability $W_{st}(f)$ revealed in the observations and shown in Figure 6b [Ryabov

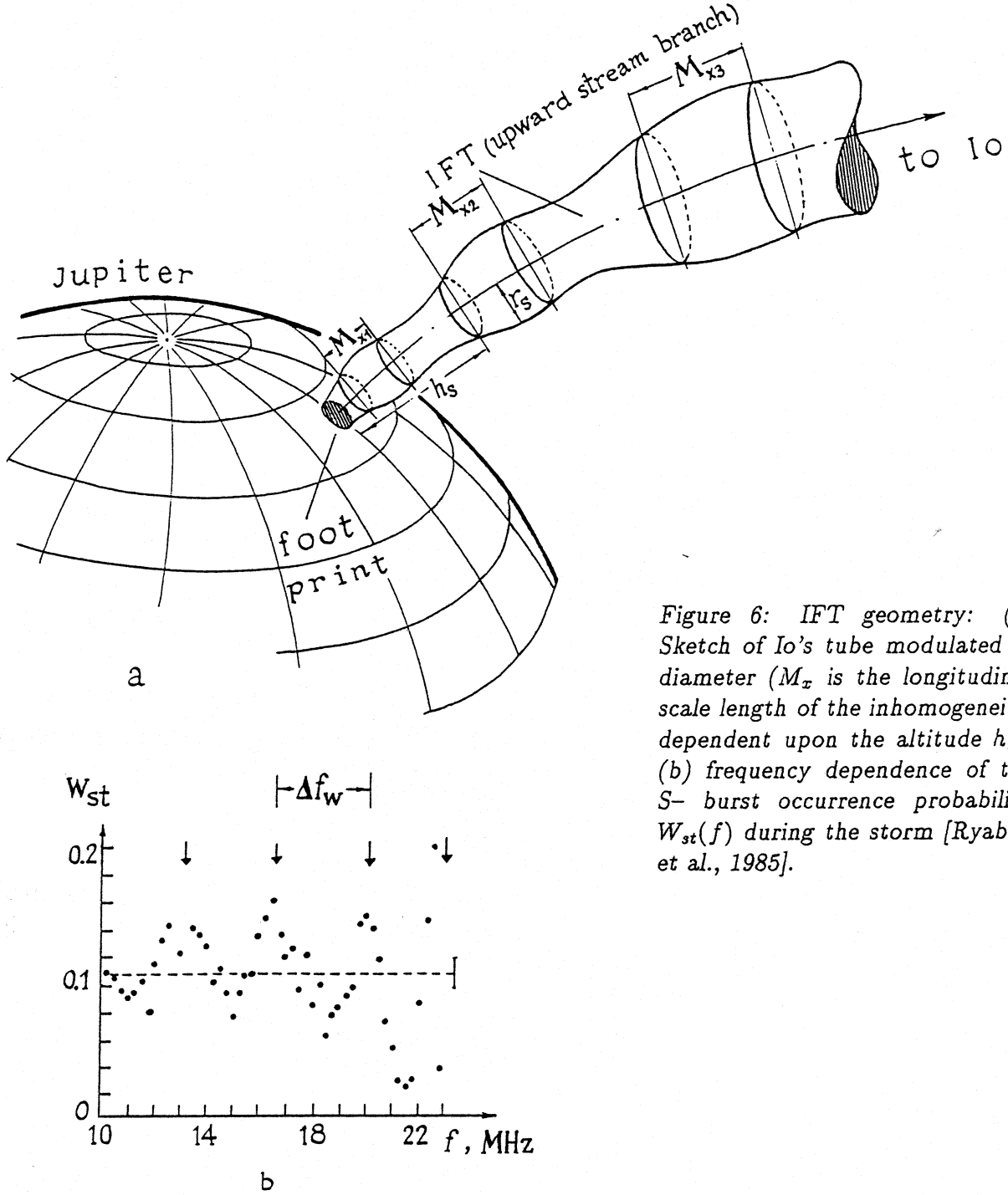


Figure 6: IFT geometry: (a) Sketch of Io's tube modulated in diameter (M_x is the longitudinal scale length of the inhomogeneity, dependent upon the altitude h_s), (b) frequency dependence of the S- burst occurrence probability $W_{st}(f)$ during the storm [Ryabov et al., 1985].

et al., 1985]. The variation period Δf_W of the probability $W_{st}(f)$ is about 3.5 MHz. Substituting the relation $f \approx 2.8B_s$ into (4.7) and differentiating, we can find for dh_s

$$dh_s \approx |2.1 \times 10^3 f^{-2.44}| df. \quad (4.11)$$

Obviously, Δf_W and the variation period of the IFT radius r_s show some conformity. Hence, the intrinsic size M_x of the active IFT sector can be found by substituting $df \approx$

$\Delta f_W/3$ and $dh_s = M_x$ into (4.11), viz

$$M_x \approx 2.45 \times 10^6 f^{-2.44} \text{ km}, \quad (4.12)$$

where f (MHz). The velocity v_x of the disjunction point over Io's surface in the DAM-active zone is obtained from (4.6), (4.8) and (4.10)

$$v_x \approx v_A \approx 5.4 \times 10^5 f^{-1} \text{ km/s}. \quad (4.13)$$

Finally, we find the lifetime Δt from the obvious relation $M_x \approx v_x \Delta t \sin \Phi$,

$$\Delta t \approx 4.5 \times f^{-1.44} \text{ s}. \quad (4.14)$$

This is in good agreement with measured values of Δt in the DAM frequency range [Ellis, 1982].

Thus, the S-burst lifetime estimates based on the proposed Io tube model and the occurrence probability $W_{st}(f)$ (see Figure 6b) are consistent with direct measurements of the S-burst fine structure.

5 Power of the S-emitter; relation to the L-component, and integrated radio spectrum

As soon as the elemental current filament (see Figure 5a) is disconnected, a pulsed accelerating force $\mathbf{F}_x$ appears, giving rise to synphased acceleration of the group of N_x electrons contained in the volume $V_x = \pi r_x^2 \Delta x$. As a result, all the relativistic electrons in the bunch of total charge eN_x will radiate in phase.

The integrated power P_* is given by the following expression

$$-\frac{dW}{dt} = P_* = \frac{2(eN_x)^2 c \sin^4 \Phi}{3r_s^2} \left(\frac{\epsilon}{mc^2} \right)^4, \quad (5.1)$$

where $W = \epsilon N_x$ is the total energy in the electron bunch. It is evident that, in the limiting case, the power of the phased radio emission from the electron bunch can be increased by a factor N_x compared with the mere power summation of individual electrons. As a result, the electrons in the bunch lose their energy rapidly because of coherent magneto-drift emission. By solving Equation (5) with respect to W we can obtain the law according to which the bunch energy decreases, i.e.

$$W(t) = W_0 (1 + 3ZW_0^3 t)^{-1/3}, \quad (5.2)$$

where

$$Z = \frac{2(eN_x)^2 c \sin^4 \Phi}{3r_s^2 (N_x mc^2)^4} \quad \text{and} \quad W_0 = N_x \epsilon_0.$$

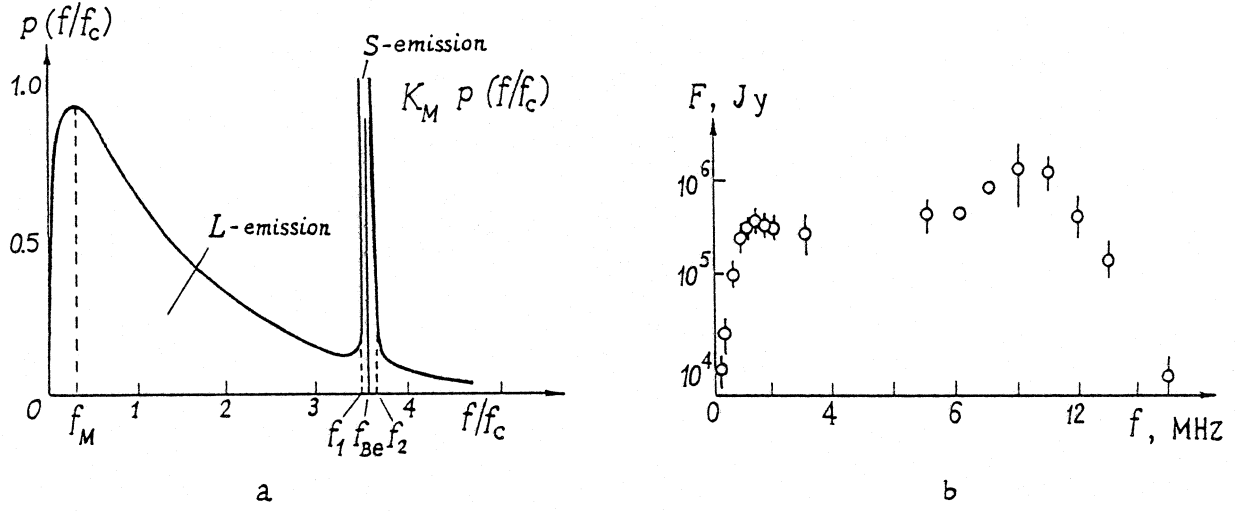


Figure 7: The spectra of Jupiter's emission at decameter and hectometer wavelengths, (a) magneto-drift spectrum $p(f/f_c)$, with $f_c = f_M/0.29$, of a bunch of relativistic electrons moving in the field $\mathbf{B}_s$ of Io's tube (account has been taken of the maser amplification at the local gyrofrequency f_{Be} ; (b) measured spectrum of the sum of L- and S-components [Alexander et al., 1981].

At $W(t) = \kappa_E W_0$ we obtain an expression for the scale time t_x , for the DAM power decay

$$t_x \approx \frac{r_s^2 m c^2}{c e^2 N_x \sin^4 \Phi} \left(\frac{m c^2}{\epsilon_0} \right)^3. \quad (5.3)$$

Assuming the luminous power of the bunch to decay approximately over the time of a single rotation of the helix around Io's tube, we can find the number of electrons in the bunch, $N_x \approx 1.4 \times 10^{15}$ and the bunch volume $V_x \approx 1.4 \times 10^5 \text{ m}^3$ with the electron density $N_{e1} \approx 10^4 \text{ cm}^{-3}$, and $\epsilon_0 = 12 \text{ MeV}$ at 15 MHz. The spectral density of radiation from a bunch of relativistic electrons is the same as from an individual electron, i.e. at $f \gg f_M$

$$P(f/f_M) \sim \exp(-0.29 f/f_M). \quad (5.4)$$

In Figure 7a one can see the mutual location of characteristic frequencies f_M and f_{Be} for $\epsilon_0 = 12 \text{ MeV}$.

By evaluating the gain factor $K_M \approx 10$ of the cyclotron maser for Jupiter's S-emitter, it can be found that the ratio of spectral densities received at the frequencies f_M and f_{Be} is about 1/6. This implies that a continuum component with a spectrum of the type $p(f/f_c)$ must be observable simultaneously with the narrow band one.

Probably, this is in fact the well known Io-related L-component of the Jovian DAM emission. It is generally observed together with the S-component; nevertheless, it is characterized by a lower intensity and appears at lower frequencies [Ryabov, et al., 1985]. The measured spectrum of Jovian DAM emission has its first maximum near 1.5 MHz (see Figure 7a). The second one about 10 MHz is probably determined by the S-component.

Its average width can be explained by the relatively broad variation range of local gyrofrequencies along Io's tube where the S-component undergoes the maser amplification. The disappearance of Jupiter's sporadic radioemission at $f \geq 140$ MHz admittedly results from the law $\exp(-0.29f/f_M)$ followed by the spectral density. Indeed, the magnitude drops down by a factor of 10^{-5} at $f = 40$ MHz compared with the maximum at $f_M \approx 1$ MHz.

6 Arc structure of dynamic spectra and axis curvature of Io's tube

Proceeding from the above discussed model of the emission source we can suggest a possible physical mechanism responsible for arc formation in the dynamic spectra which is able to easily explain the observed arc types with both signs of their curvature. The involved physics include the following properties of the S-emission zone:

- i) The emitter is located in a distinct magnetic field tube.
- ii) The emission occurs within a narrow frequency range, and a one-to-one correspondence exists between the emission frequency and the source altitude.
- iii) The emission is directed into a hollow cone whose axis is oriented along the tangent line to the tube axis at the place of generation.
- iv) The observed apex angle 2Ψ decreases at higher emission frequencies, i.e. when the emitter approaches to the planet.

The process of arc formation in the dynamic spectrum is shown in Figure 8.

7 Conclusion

The magneto-drift emitter model and the generation mechanism in the helical magnetic field $\mathbf{B}_s$, that have been proposed, allow to establish and interpret the relations between different observational characteristics of the Jovian S-emission, such as the average, frequency dependent angular structure of the emission cone, burst lifetime Δt , occurrence probability $\langle W_{st} \rangle \approx 0.1$ of S-bursts and periodical frequency dependence $W_{st}(f)$, frequency drift $df/dt \approx -0.9f$ MHz/s and its variance with $f = \text{const.}$, and the shape of the integrated DAM radio spectrum. On the basis of the model, the process of fine structure formation in the S-burst dynamic spectra has been analyzed as well as the arc structure formation. Estimates have been made of the refractive index $n_{1+} \approx 0.3$ in the Io tube surface layer, plasma mass density in the active zone, $\rho_m \approx 2.2 \times 10^{-15} h_s^{-2.78}$ g/cm³, (h_s in thousand km), and of the fluctuations in the tube current $\Delta i_T/i_T \approx 0.2$. The energy of the emitting electrons, $\epsilon_0 \approx 12$ MeV, has been determined by measuring the thickness of the conical radiation pattern walls ($\delta_1 \approx 0.5^\circ$). The amount of electrons in a coherently emitting bunch $N_x \approx 1.4 \times 10^{15}$ and its volume $V_x \approx 1.4 \times 10^5$ m³ have also been estimated. It has been established that the radius r_s of Io's tube varies periodically

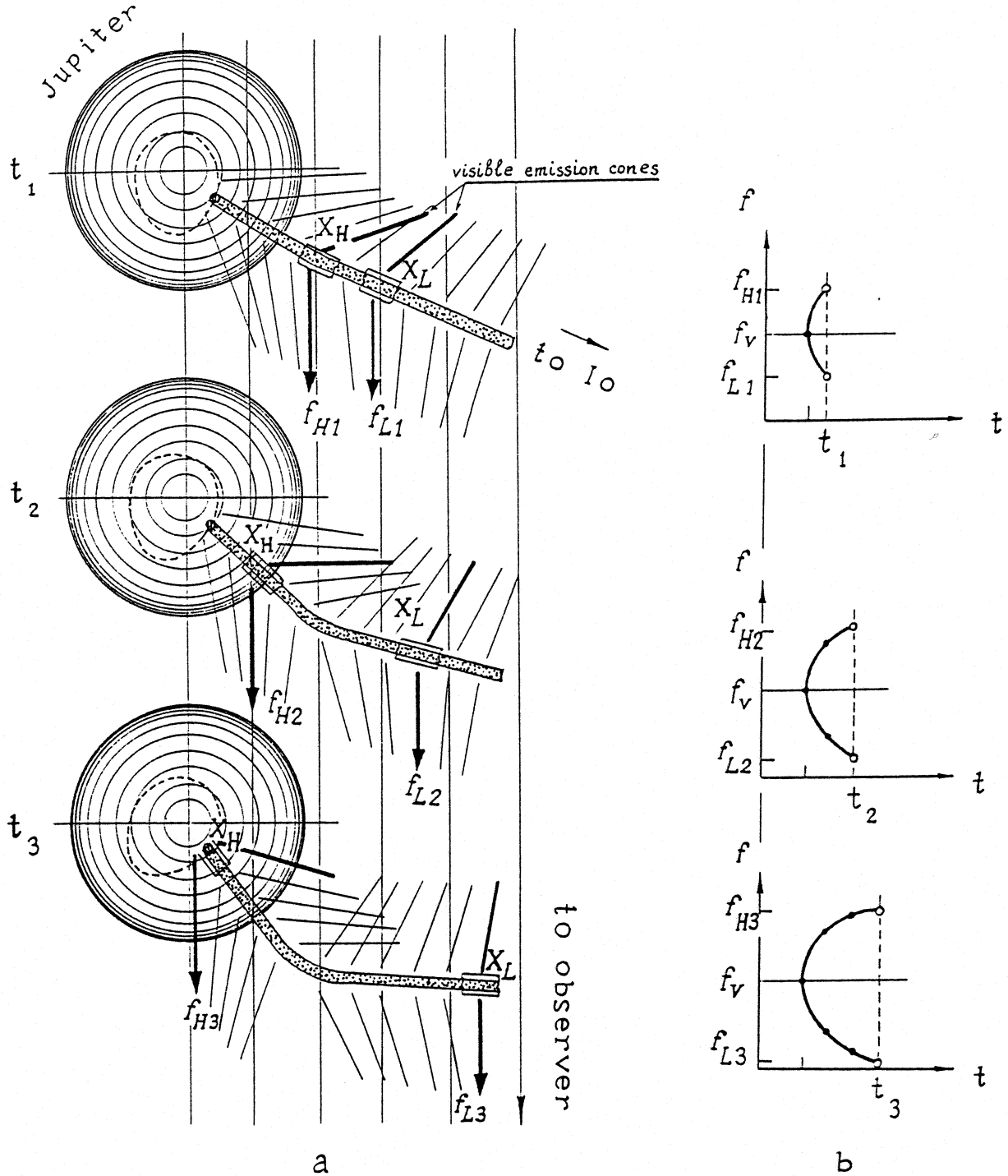


Figure 8: Arc formation, (a) a sketch of a magnetic tube and the related conical radiation patterns projected onto the equatorial plane showing a time developing curve over the DAM active interval of the tube, (b) resulting picture of the observed vertex early arcs (X_L and X_H are a pair of tube emitting zones observed at the frequencies f_L and f_H simultaneously).

along the tube, with the scale length M_x of the wider parts in the DAM active zone being $M_x \approx 2.45 \times 10^6 f^{-2.44}$ km, where f (MHz).

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References

- Alexander J. K., T. D. Carr, J. R. Thieman et al., Synoptic observations of Jupiter's radioemission: Average statistical properties observed by Voyager, *J. Geophys. Res.*, **86**, 8529, 1981.
- Braude S. Ya., A. V. Megn, B. P. Ryabov, N. K. Sharykin, I. N. Zhouck, Decametric survey of discrete sources in the Northern sky. I. The UTR-2 radiotelescope. Experimental techniques and data processing, *Astrophys. and Space Sci.*, **54**, No.1, 3, 1978.
- Connerney J. E. P., M. H. Acuña, and N. F. Ness, Modeling the Jovian current sheet and inner magnetosphere, *J. Geophys. Res.*, **86**, No.A10, 8370, 1981.
- Dessler, A. J., and T. W. Hill, Jovian longitudinal control of Io-related radio emission, *Astrophys. J.*, **227**, No.2, 664, 1979.
- Ellis, G. R. A., An atlas of selected spectra of the Jupiter S-bursts, Univ. of Tasmania, Hobart, Tas., Australia, 1979.
- Ellis, G. R. A., Observations of the Jupiter S-bursts between 3.2 and 32 MHz, *Austral. J. Phys.*, **35**, 165, 1982.
- Leblanc, Y., and F. Genova, The Jovian S-burst sources, *J. Geophys. Res.*, **86**, 8564, 1981.
- Leblanc Y., F. Genova, and J. de la Noë, The Jovian S-bursts. I. Occurrence with L-bursts and frequency limit, *Astron. Astrophys.*, **86**, 342, 1982a.
- Leblanc, Y., M. G. Aubier, C. Rosolen, F. Genova, and J. de la Noë, The Jovian S-bursts. II. Frequency drift measurements at different frequencies throughout several storms, *Astron. Astrophys.*, **86**, 349, 1982b.
- Ryabov, B. P., Decametric radio emission of Jupiter. II. Localization of S-component sources, *Astron. Vestnik*, **20**, No.1, 20, 1986 (in Russian).
- Ryabov, B. P., Decametric radio emission of Jupiter. V. A model of the S-burst source, *Preprint of Ukr. Acad. of Sci.*, Inst. Radio Astron., **No.9**, Kharkov, USSR, 1987.
- Ryabov, B. P., Decametric radio emission of Jupiter. III. Some physical characteristics of the S-burst sources, *Astron. Vestnik*, **24**, No.2, 103, 1990a (in Russian).

- Ryabov, B. P., Radiation pattern of the S-component in the decametric radio emission of Jupiter, *Astron. Vestnik*, **24**, No.3, 221, 1990b (in Russian).
- Ryabov, B. P., A. V. Arkhipov, and V. A. Shevchenko, Decametric radio emission of Jupiter. I. The morphology of S-burst storms, *Astron. Vestnik*, **19**, No.4, 296, 1985 (in Russian).
- Ryabov, B. P. and N. N. Gerassimova, Sporadic radio emission of Jupiter at decameter wavelength, *Naukova Dumka*, Kiev, USSR, 1990 (in Russian).