SUPERRADIATION OF MAGNETIZED ELECTRONS AND THE POWER OF DECAMETER RADIATION OF THE JUPITER—IO SYSTEM

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UDC 537.86

The effect of superradiation of the inverted electrons in the magnetic field on high Landau levels, described in [1], is applied to interpret the main features of the superpower decameter radiation of the system Jupiter—Io. The theory describes the observed data on the superpower radiation on the quantitative level.

Introduction

In our recent paper [1], we have shown that under definite conditions in the inverted system of electrons on high Landau levels in the magnetic field, the polarization phase transition in the state of superradiation (SR) could occur. In this state, all N_0 rotating dipoles within the "coherency domain" are arranged in the same direction (phasing). As a result, the intensity of collective radiation of the domain turns out to be proportional to N_0^2 (instead $\sim N_0$ before the phasing). A typical size of the domain R_0 is considerably less than the cyclotron radiation wavelength λ. The breaking of the whole system into the coherency domains is similar to the breaking into domains in ferromagnetics and ferroelectrics and associated with the anisotropy of the dipole-dipole interaction that arranges the dipoles of domain in the same direction. The threshold of the polarization phase transition on an electron density number in the domain is defined by the relation [1]

$$n_e > n_{ec} = 0.18\frac{H^2kT}{mc^2E_\perp}, \tag{1}$$

where n_e is the density number of inverted electrons on high Landau levels in the magnetic field H. They have the average transversal (with respect to the magnetic field) rotation energy $E_\perp \gg kT$ (k is the Boltzmann constant, T is the absolute temperature). It is known [3] that this energy is quantized: $E_\perp = \hbar\omega n$ (n is an integer, $\omega = eH/mc$ is the cyclotron frequency). We have to note that criterion (1) may be violated pretty soon due to decreasing the energy $E_\perp$ in the process of radiation if at the beginning n_e was closed to n_{ec}. Thus, for the efficient work of (1) during the radiation time, we must enforce it at least by one order to provide some allowance of this inequality. That is why, we require

$$n_e > n_{ec}^{\text{eff}} \approx 1.8\frac{H^2kT}{mc^2E_\perp} \tag{2}$$

instead of (1). In this paper, we use criterion (2) and other relations of the SR theory for the interpretation of the nature and main features of the super power decameter radiation (DCM) of the Jupiter—Io system [4]. The problem of theoretical interpretation of the features of the sporadic DCM radiation of Jupiter discovered in 1955 is discussed more than forty years. In spite of a considerable progress in the deciphering of many aspects of the DCM achieved last time, we still did not obtain the generally accepted and consistent answers to many important questions. The first and most important question concerns the nature of the coherent collective mechanism of radiation providing a gigantic pick power of the DCM-pulses observed. It reaches $\sim 10^{17} \div 10^{18}$erg/s that corresponds to the brightness temperature of a source around 10^{17}K. The approaches developed in the literature (see, for example, [4—9]) mainly use one or another type of the plasma instabilities. However, due to a considerable scattering and uncertainty in the initial parameters of models, there is no unique answer to the question.

We show below that enlisting the SR mechanism simplifies the problem and allows us to explain the observed powers of DCM-pulses practically without usage of free parameters.

1. The Main Relations of the Cyclotron Superradiation Theory

Further, in addition to criterion (2), we will use a few formulas of the theory. The intensity of radiation of one individual electron is

$$I = \frac{2}{3}\frac{e^2\omega^2 V_\perp^2}{c^3} = \frac{4e^2\omega^2}{3mc^3}E_\perp, \tag{3}$$

$$I = -\dot{E}_\perp(t) = \frac{E_\perp(t)}{\tau}\ , \tau = \frac{3mc^3}{4e^2\omega^2}; \tag{4}$$

$$E_\perp(t) = E_\perp(0)e^{-t/\tau}. \tag{5}$$

In a typical time τ, a lot of quanta $\hbar\omega$ is radiated provided that $E_\perp(0)/\hbar\omega \gg 1$. We accept that the latter inequality holds true. A time of radiation of one quantum t_1 is much smaller than τ:

$$t_1 \sim \frac{\hbar\omega}{E_\perp}\tau = \frac{3}{4}\frac{\hbar c}{e^2}\frac{mc^2}{E_\perp}\frac{1}{\omega}. \tag{6}$$

For frequencies of the DCM range $\nu \sim 3 \cdot 10^7$ Hz, (4) gives the estimation

$$\tau \sim 2.5 \cdot 10^6\,\text{s}. \tag{7}$$

At the same time for t_1 at $E_\perp \sim 1$ keV, we obtain from (6) that

$$t_1 \sim 2.8 \cdot 10^{-4}\,\text{s} \sim 10^{-10} \cdot \tau. \tag{8}$$

A time of the coherent radiation of the domain in the SR regime is by N_0 times smaller than τ,

$$\tau_{\text{coh}} \sim \tau/N_0, \tag{9}$$

where N_0 is the number of phased electrons (rotating dipoles) of the domain of size $R_0 \ll \lambda$. Taking $R_0 \sim \lambda/10$, we get the estimate

$$N_0 \sim n_e(\lambda/10)^3. \tag{10}$$

With account of (4), (9), (10), we have

$$\tau_{\text{coh}} \sim \frac{3 \cdot 10^3 mc^3}{4e^2 n_e \lambda^3\omega^2}. \tag{11}$$

Since $c/\lambda = \nu = \omega/2\pi$,

$$\tau_{\text{coh}} \sim \frac{3 \cdot 10^3 m\omega}{4(2\pi)^3 e^2 n_e} \sim 3\frac{H}{ecn_e}. \tag{12}$$

In CGSE units,

$$\tau_{\text{coh}}(\text{s}) \sim \frac{H(\text{Gs})}{4.8 n_e(\text{cm}^{-3})} \tag{13}$$

For example, for $H \sim 12$ Gs and $n_e \sim 10^4\,\text{cm}^{-3}$,

$$\tau_{\text{coh}} \sim 0.25 \cdot 10^{-3}\text{s} = \tau \cdot 10^{-10}. \tag{14}$$

The next important feature of the SR regime is the phasing time (arrangement) of all N_0 rotating dipoles of the domain that is called the delay time t_d. To find the delay time, we note that after the moment when the system parameters satisfies criterion (2), the phase transition in the SR state happens in the avalanche form. It means that the rate of growth of the phased dipoles is proportional to the number of these dipoles:

$$\dot{N}_c(t) = N_c(t)/\tau_c\ , \tag{15}$$

$$N_c(t) = N_c(0)e^{t/\tau_c}. \tag{16}$$

The initial and final conditions are as follows:

$$N_c(0) \sim 1\ ,\ N_c(t_d) = N_0. \tag{17}$$

That gives

$$t_d = \tau_c \ln N_0. \tag{18}$$

To define the typical time τ_c when the number of correlated dipoles $N_c(t)$ increases by $e \approx 2.7$ times, we note that the phase transition under consideration relates to a class of self-organization processes in the nonequilibrium dissipative systems [11]. The dissipation in our case is connected with removing energy from the system in the form of photons $\hbar\omega$. In the corresponding transitions of electrons downstairs on the energy levels

$$E_\perp(n) = \hbar\omega \cdot n,\ n \to (n-1) \to (n-2) \to ...,$$

the radiated photons seemingly push electrons to the phasing. At the same time, the energy of dipole-dipole attraction responsible for the phasing, that releases in the process, is added to the main energy of photons $\hbar\omega$. Keeping this in mind, we accept that the typical correlation time τ_c is defined in average by the time of radiation of a few subsequent quanta

$$t_c = x \cdot t_1 \ , \ x > 1, \tag{19}$$

where t_1 is the radiation time of one quantum that is given by formula (6). A factor x will be evaluated further from the comparison of the theory with data on the DCM radiation. It gives $x \approx 2.2$.

2. The Main Features of the Jupiter—Io System

Now we give a short enumeration of the data necessary for our problem on the Jupiter magnetosphere and the closest Galilei satellite Io that plays an important role in the formation of the DCM radiation.

The radius of the Io orbit $r_{\rm Io} \approx 420000$ km or approximately 6 radii of Jupiter. A diameter of Io $D_{\rm Io} \approx 3640$ km. The Jupiter dipole magnetic field on the Io orbit is as much as

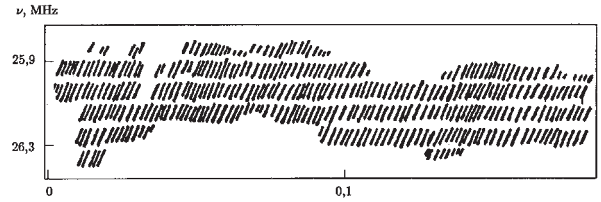
$$H_J(r_{\rm Io}) \approx H(R_J)(R_J/r_{\rm Io})^3 \approx 2 \cdot 10^{-2}\,{\rm Gs}. \tag{20}$$

Here, $H(R_J) \approx 4.2$ Gs is the magnetic field near the Jupiter equator. The field near the Jupiter north magnetic pole is $H_N \sim 14$ Gs, and, near the south one, $H_S \sim 11$ Gs. The difference is a result of the displacement of the Jupiter magnetic dipole μ_J from its center.

At the Io orbit, the magnetic field and rarefied plasma of the magnetosphere rotate as a whole with the planet with a period $T_J \sim 10$ years due to the plasma freezing-in effect to magnetic force lines. A linear velocity of rotation of the magnetosphere at the Io orbit is about 74 km/s and the Io orbital velocity is close to 17 km/s. A difference of these velocities $\triangle V \approx 57$ km/s corresponds to the velocity of crossing Io by the magnetic force lines. As a result, in the Io bulk, a comparatively large electromotive force is induced

$$V_{\rm Io} = \frac{\triangle V}{c} D_{\rm Io} H_J(r_{\rm Io}) \approx 400\,{\rm keV}. \tag{21}$$

Affecting the Io ionosphere and the Jupiter magnetosphere, this potential generates a complex global system of currents [12] and gives rise to sporadic outbursts of bunches of electrons with energies up to a



Typical region of the millisecond S-spectrum

few keV and the density number $n_e \sim 10^2\,{\rm cm}^{-3}$. It is worth noting that the density numbers of electrons in the Io upper ionosphere reach $\sim 10^4 \div 10^5\,{\rm cm}^{-3}$ and, along the Io orbit in the so-called "Io torus" formed by the volcano gas and dust outbursts, it is $10^3\,{\rm cm}^{-3}$ [12].

Accelerated in the magnetosphere, the fast electron bunches (with a velocity $V_e \sim 0.1c$, c is the velocity of light) move to the Jupiter magnetic poles along the "Io magnetic tube" that gets narrower closing to the Jupiter. A diameter of this tube near the Io surface is of the order of the Io diameter $D_{\rm Io}$. Near the Jupiter magnetic poles, it becomes approximately by one order smaller:

$$d \leq 364\,{\rm km}. \tag{22}$$

An important result of this is the corresponding growth of the electron bunch density, that moves along the tube, approximately by two orders comparing to its initial value, i.e. from $(n_e)_{\rm Io} \sim 10^2\,{\rm cm}^{-3}$ to $(n_e)_J \sim 10^4\,{\rm cm}^{-3}$. These values of electron density satisfy criterion (2) of the SR phase transition at $H \sim 10$ Gs, $E_\perp \sim 1$ keV, and $T \sim 10^3$ K. Therefore, it is possible to expect the appearance of a powerful cyclotron SR near the Jupiter magnetic poles. Observations show that the generation of DCM radiation is in fact localized in the region of $<$ 400 km near the Io flux tube foot [4].

3. DCM Radiation Spectra and Parameters of Radiating Electron Bunches

The frequency and time spectra of the DCM radiation have rather diverse and complex character [4—6]. In the classification by time characteristics, they can be divided in the so-called "long" decasecond L-spectra and "short" millisecond S-spectra. To be specific, we will analyze only one of the simplest and most ordered

S-spectra, which is presented in Figure (we call it S_A-spectra). From it, we try to extract the information concerning the parameters of electron bunches that move along the Io tube from its foot and radiate in the SR regime.

Firstly, the negative drift of frequencies ($\dot{\nu}(t) < 0$) witnesses that the electrons radiating in the cyclotron regime move upstairs along the tube from Jupiter in the direction of decreasing its magnetic field. According to the model of electron acceleration in the Io vicinity [5], this means that electron bunches initially move along a magnetic tube from Io to Jupiter and, after reflection from its upper ionosphere, change the direction of motion. At this, they change the density number and some other parameters (see below) and enter into the SR regime. The reflection mechanism from the ionosphere is associated with the formation of double layers at entering the bunches of fast electrons with density numbers $n_e \sim 10^4\,\mathrm{cm}^{-3}$ in the ionosphere at heights where the density number of ionosphere ions n_i approximately equals to n_e. The available data on the Jupiter upper atmosphere witness that a value $n_i \sim 10^4\,\mathrm{cm}^{-3}$ is practically acceptable.

The values of frequency drift of the S_A-spectrum are the following:

$$(\dot{\nu})_A = -32.5\,\mathrm{MHz/s}. \tag{23}$$

The rising speed of electrons that corresponds to (23) can be obtained with the help of the law of decreasing the Jupiter dipole magnetic field and the formula for the cyclotron frequency

$$\vec{H}_J(r) = \frac{3\vec{n}(\vec{n}\vec{\mu}_J) - \vec{\mu}_J}{r^3},\ \vec{n} = \vec{r}/r, \tag{24}$$

$$\dot{\nu} = \frac{eH'(r)}{2\pi mc}\dot{r} \approx -\nu\frac{3\dot{r}}{r}, \tag{25}$$

where μ_J is the Jupiter magnetic dipole moment. For the S_A-spectrum with an average frequency $\bar{\nu}_A \approx 26.1$ MHz (see Figure), we obtain, at $r \sim R_J \sim 72000$ km,

$$\dot{r}_A \approx -\frac{r}{3}\left(\frac{\dot{\nu}}{\nu}\right)_A \approx 2.9 \cdot 10^9\,\frac{\mathrm{cm}}{\mathrm{s}} \sim 0.1c. \tag{26}$$

This value corresponds to the longitudinal energy of magnetized electrons

$$(E_\parallel)_A = \frac{m\dot{r}_A^2}{2} \approx 2.4\,\mathrm{keV}. \tag{27}$$

It is natural to expect that the transversal energies $E_\perp$ of electrons, which are responsible for the cyclotron radiation, are of the same order as $E_\parallel$. The sum of these energies $E_\parallel + E_\perp$ is completely acceptable within the framework of the acceleration model at the expense of the Io electromotive force because it requires only a few percents of potential (21). Further, we set $E_\perp \sim$ 1 keV.

Now we consider the time duration $(\triangle\tau)_A$ of the S_A-pulses at a fixed frequency. From Figure for S_A-pulses, we obtain

$$(\triangle\tau)_A \leq 0.6 \cdot 10^{-3}\,\mathrm{s}. \tag{28}$$

This evaluation allows us to find the length $\triangle L$ of the electron bunches that rise along the Io tube:

$$\triangle L = V_\parallel \cdot \triangle\tau. \tag{29}$$

Substituting $V_\parallel = \dot{r}$ according to (26), we obtain

$$\begin{aligned}(\triangle L)_A &= 2.9 \cdot 10^9 \cdot 0.6 \cdot 10^{-3}\,\mathrm{cm} = \\ &= 1.74 \cdot 10^6\,\mathrm{cm} = 17.4\,\mathrm{km}.\end{aligned} \tag{30}$$

4. Superradiation of the Electrons near the Flux Tube Foot and the Power of DCM Radiation Pulses

The experimentally registered pike power of the sources of S_A-pulses is evaluated as $10^{17} \div 10^{18}$ erg/s [4, 12] in the assumption that the source radiates isotropicaly. Actually, there is some visible anisotropy that underestimates the evaluation of the necessary power by several times approximately. We show below that the proposed mechanism of SR can naturally provide the required powers within the framework of our model.

According to our evaluations of the parameters of electron bunches moving upstairs along the Io current tube, their density numbers can reach above-critical values

$$n_e \sim 10^4\,\mathrm{cm}^{-3}, \tag{31}$$

that satisfy criterion (2) of the polarization phase transition in the SR regime. Now we can evaluate the typical times t_d and τ_{coh} (see formulas (14, 18—19)) and the radiated power. According to the above-reported, we assume that a bunch of electrons that moves up from the magnetic tube foot (after the reflection from the Jupiter upper atmosphere) and generates the S_A-pulses has the shape of flattened cylinder of thickness $(\triangle L)_A \sim 17$ km and a diameter $D \sim 300$ km. Its volume is

$$V \sim \pi(D/2)^2 \cdot \triangle L \sim 10^{21}\,\mathrm{cm}^3. \quad (32)$$

At the density numbers $n_e \sim 10^4\,\mathrm{cm}^{-3}$, one domain of coherency with volume $V_{\mathrm{coh}} \sim (\lambda/10)^3 \sim 10^6\,\mathrm{cm}^3$ contains $N_0 \sim 10^{10}$ electrons. With account of the interdomain transition regions, we obtain that $N_d \sim V/(2V_{\mathrm{coh}}) \sim 5 \cdot 10^{14}$ coherency domains can be formed in the bunch bulk. They radiate, in the SR regime, the intensity per one domain

$$I_{\mathrm{dom}} \sim \frac{N_0^2 E_\perp}{\tau} \sim \frac{10^{20} \cdot 1\,\mathrm{keV}}{2.5 \cdot 10^6\,\mathrm{s}} \sim 0.64 \cdot 10^5\,\mathrm{erg/s}. \quad (33)$$

Before multiplying this quantity by the total number of domains in the bunch, we have to take into account the following very important remark. There is no reason to assume that all $N_d \sim 5 \cdot 10^{14}$ domains of the moving bunch of electrons will be phased and pass in the SR regime simultaneously. Conversely, it is more probable that the phase transitions in different domains take place independently and at different moments of time. For the whole set of domains N_d, this process may be prolonged up to the time of the order of the delay time $t_d \sim 1.5 \cdot 10^{-2}$ s. Really, as seen from relations (18—19), in the formation time of phasing an individual domain t_d, there is a stochastic element presented by the factor x that is the number of radiated quanta $\hbar\omega$. They provide the phasing of electrons that were independent but have close rotation phases. Due to the fact that x is small, the fluctuations of this coefficient may of the order of x itself, $\delta x \sim x \sim 2$. Therefore, we may expect the same for the delay time dispersion

$$\delta t_d \sim t_d \sim 1.5 \cdot 10^{-2}\,\mathrm{s}. \quad (34)$$

After the transition in the SR regime, an individual domain quickly radiates for the time $t_{\mathrm{coh}} \sim 0.25 \cdot 10^{-3}$ s. This allows us to assume that only a small part of domains in the bunch bulk $\sim \tau_{\mathrm{coh}}/t_d \sim 1.7 \cdot 10^{-2}$ is in the SR regime, i.e.,

$$(N_d)_{\mathrm{SR}} \sim 1.7 \cdot 10^{-2} N_d \sim 8.5 \cdot 10^{12}\,\mathrm{domains}. \quad (35)$$

The instant total intensity of the SR of the bunch equals

$$I_{\mathrm{SR}} = (N_d)_{\mathrm{SR}} \cdot I_{\mathrm{coh}}^{(1)} \sim 5.4 \cdot 10^{17}\,\mathrm{erg/s}. \quad (36)$$

It is in good agreement by the order of magnitude with the observable powers of the DCM radiation.

Obviously, that, due to the dispersion of the delay time δt_d, the total time of radiation of the whole bunch of electrons in the SR regime will be of the same order:

$$(\triangle t)_{\mathrm{SR}} \sim \delta t_d \sim t_d \sim 1.5 \cdot 10^{-2}\,\mathrm{s}. \quad (37)$$

This evaluation is consistent with the data on S_A-spectra (see Figure) if we set the average value $x \approx 2.2$ in formula (19). This consistency may be considered as reasoning for such a selection of the parameter.

Conclusions

Thus, we have constructed the model of DCM pulses source and explained the registered power using only the observational data on the Jupiter—Io system and the parameters of S-spectra recruiting the SR mechanism. The nature of the fine structure of S-spectra is not considered here (a possible explanation of the millisecond quasiperiodicity of these spectra is discussed in [13]). We do not concern as well many other aspects of the spectral variety of DCM pulses. These problems are out of the frames of the present article. We do not take into account the influences of plasma processes on the SR, because of their smallness. The plasma frequencies in the Jupiter magnetosphere are less by a few orders than cyclotron DCM frequencies.

Eventually, we emphasize that, as shown in [2] and subsequent works on the SR (see, for example, review [14]), the SR mechanism provides the anisotropy of radiation depending on the geometry of a source. In our model, the source has the form of strongly flattened cylinder with diameter ~ 300 km and height ~ 17 km. This yields that the SR is directed mainly along the planes of the cylinder, i.e. perpendicularly to the axis of a flux tube. Such an assumption is well coordinated with observations [4—6].

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Received 6.02.03

НАДВИПРОМІНЮВАННЯ ЕЛЕКТРОНІВ В МАГНІТНОМУ ПОЛІ ТА ПОТУЖНІСТЬ ДЕКАМЕТРОВОГО ВИПРОМІНЮВАННЯ СИСТЕМИ ЮПІТЕР—ІО

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Р е з ю м е

Ефект супервипромінювання електронів в магнітному полі з інвертованою заселеністю високих рівнів Ландау, що було описано в [1], застосовано для інтерпретації основних рис надпотужного декаметрового випромінювання системою Юпітер — Іо. Розвинена теорія дозволяє описати дані спостережень надпотужного випромінювання на кількісному рівні.