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Maser amplification of Jupiter decametric radiation in magnetized plasma torus at Io orbit

A. Fomina

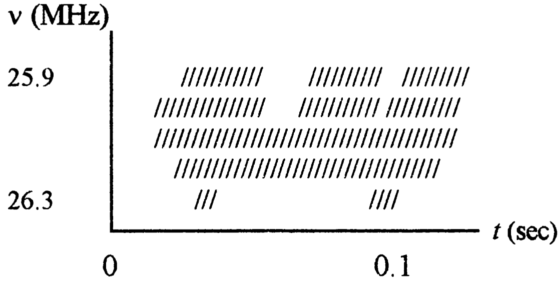
Shevchenko Kiev University, Ukraine

MASER AMPLIFICATION OF JUPITER DECAMETRIC RADIATION IN MAGNETIZED PLASMA TORUS AT IO ORBIT, by Fomina A. – A new approach is proposed, that the primary decametric radio emission is arising near the foot of magnetic force tube by cyclotron radiation mechanism. Than the primary wave is amplified via maser effect on the resonant frequencies up to the observing power values when passing through the magnetized Io torus.

МАЗЕРНОЕ УСИЛЕНИЕ ДЕКАМЕТРОВОГО ИЗЛУЧЕНИЯ ЮПИТЕРА В ТОРЕ НАМАГНИЧЕННОЙ ПЛАЗМЫ НА ОРБИТЕ ИО, Фомина А. – Предлагается новый подход, согласно которому первичное декаметровое радиоизлучение возбуждается механизмом циклотронного излучения около основания трубки магнитных силовых линий, после чего первичная волна при прохождении магнитного тора Ио усиливается мазерным эффектом на резонансных частотах до наблюдаемых значений мощности.

МАЗЕРНЕ ПІДСИЛЕННЯ ДЕКАМЕТРОВОГО ВИПРОМІНЮВАННЯ ЮПІТЕРА В ТОРІ НАМАГНІЧЕНОЇ ПЛАЗМИ НА ОРБІТІ ІО, Фоміна А. – Пропонується новий підхід, згідно якого первинне декаметровое радіовипромінювання збуджується механізмом циклотронного випромінювання біля основи трубки магнітних силових ліній, після чого первинна хвиля при проходженні магнітного тора Ио посилюється мазерним ефектом на резонансних частотах до спостережуваних значень потужності.

Last decades, many active cosmic objects were discovered, the physical nature of which can be understood only on the base of quantum physics. One of such intriguing objects is the Jupiter–Io system with its powerful decametric radiation which has some specific and puzzling discrete temporal and frequency structures [1].



It was found that this short-impulse S-radiation is related to the perturbation of Jupiter's magnetosphere by its nearest satellite Io. This latter has a powerful volcanic activity injecting more than a tone of gaseous substance per second in the outer space. The volcanic gas from Io is gradually ionized and, spreading along the Io's orbit, forms a plasma torus with particle density ~3000 cm^{-3} and transverse cross-section ~70.000 km, which is involved into rotation around Jupiter with velocity ~ 75 km/s by Jupiter's powerful rigidly rotating magnetosphere. The magnetic field on the Io orbit is $\sim 2*10^{-2}$ Gs. The observations have shown, in particular, that the S-radiation power achieves maximum values at two positions of Io on its orbit, namely, at $90^0 \pm 20^0$ and at $240^0 \pm 20^0$ relative to the direction towards Earth [4].

Many modern approaches describe the magnetic Io force tube connecting Io with Jupiter [2]. It is forming by magnetic field lines frozen to the ionized and magnetized medium, surrounding Io. A system of electric currents is flowing along this tube, driven by the electromotive force (~ 500 kilovolt), which is generated in the Io's body due to its relative motion through the magnetosphere of Jupiter.

In this paper a new approach is proposed, that the primary decametric radio emission (not very powerful) is arising near the foot of this tube by cyclotron radiation mechanism. Than the primary wave is amplified via maser effect on the resonant frequencies up to the observing power values when passing through the magnetized Io torus on the way towards Earth.

Thus, the following two-stepped model of S-spectra formation is proposed:

1) primary decametric emission, with continuous spectrum and cut off at frequency 39.5 MHz, is generated by electric currents in the low part of Io's tube;
2) this emission is amplified and modulated in frequency and time via «cosmic maser» in Io torus.

The first step permits (attachment to the low part of Io tube) to explain such important feature as frequency cut-off of the DAM radiation spectra at $\nu_{max} = 39.5$ MHz. Calculation of electron hyrofrequency in Jupiter's maximum magnetic field H = 14 Gs (near the Northern magnetic pole) gives the maximum frequency of S-spectra:

$$\nu_{max} = \frac{e \cdot H_{max}}{2\pi \cdot m_e c} \approx 39.53 MHz \qquad (1)$$

The lower frequencies are generated when electrons flow up along the force tube.

The dipole law of magnetic field is :

$$\vec{H}_j = \frac{3\vec{n}(\vec{n} \cdot \vec{\mu}_j) - \vec{\mu}_j}{r^3} \text{ or } \vec{H}(r) \approx \vec{H}(R_j)\left(\frac{R_j}{r}\right)^3 \qquad (2)$$

The complete power of this cyclotron emission is on several orders smaller then the observed one. The amplification is provided by maser effect in the Io torus, where each of the electrons can emit up to 10^8 quants. Thus power peaks (~ 10^{11} Watt) can easily be obtained.

The equidistant discrete structure of the S-spectrum is its most intriguing and important feature. The width of the frequency «stair step» is $\Delta\nu \approx 0.1$ MHz. It tells us about the quantum nature of the spectrum. The main hypothesis of the present paper is that we actually deal with induced collective electron transitions in the magnetic field at the Io orbit from high to low Landau levels , with $\Delta n \sim 500$ and the cyclotron frequency $\nu = eH / 2\pi mc \sim 56$ kHz.

The Landau levels are almost equidistant [3]:

$$E_n = \sqrt{(mc^2)^2 + (P_z c)^2 + 2c\hbar eH(n + \tfrac{1}{2} + \sigma)} = mc^2 + \frac{P_z^2}{2m} + \hbar\frac{eH}{mc}(n + \tfrac{1}{2} + \sigma) + \ldots \qquad (3)$$

where $n = 0, 1, 2, \ldots$, $\sigma = \pm 1/2$ is a spin projection . The frequency $\nu \sim 26$ MHz corresponds to $\Delta n \sim 460$. To explain the width of the frequency "stair steps" we compare two neighboring levels with numbers n and n-1 but at different points of the radiating cylinder» directed towards Earth and connected by the laser ray of length $l = c\Delta t$, where $\Delta t \sim 10^{-3}$ sec. The corresponding frequency difference is given by formula

$$\nu_n(\vec{r}) - \nu_{n-1}(\vec{r}+\vec{l}) = \frac{ne}{2\pi mc}\vec{H}(\vec{r}) - \frac{(n-1)e}{2\pi mc}\vec{H}(\vec{r}+\vec{l}) =$$

$$= \frac{e}{2\pi mc}\left[n\vec{H}(\vec{r}) - (n-1)\left(\vec{H}(\vec{r}) + \frac{\partial \vec{H}}{\partial \vec{r}}\vec{l}\right)\right] = \qquad (4)$$

$$= \nu_0\left[1 + \frac{3l}{r_{io}}(n-1)\right] \approx \nu_0 \cdot 1.9 \approx 0.1 Mhz$$

This result agrees with the observed frequency step $\Delta\nu \sim 0.1$ MHz. In deriving this formula we have taken into account that the Jupiter's magnetic field has dipole structure (2), therefore $H'(r) \approx -\frac{3H}{r}$. This law also naturally explains the observed temporal drift of the S-burst frequencies. Indeed,

$$\dot{\nu}(t) = n\dot{\nu}_0(t) = n\frac{eH'(r)\dot{r}}{2\pi mc} = -\frac{3c}{r_{io}}\nu(t) \approx -2\frac{\nu(t)}{\text{sec}} \qquad (5)$$

The temporal «stair-like» structure of the S-spectrum (see figure) can be related to discreteness of the resonant layers location for given maser-amplified frequency:

$$\nu_{\Delta n}(r) = \Delta n \nu_1(r) = \Delta n \frac{eH(r)}{mc};$$

$$\nu_{\Delta n}(r) = \nu_{\Delta n+1}(r + c\Delta t) \qquad (6)$$

$$\nu_{\Delta n+1}(r + c\Delta t) = \nu_{\Delta n+1}(r) + \nu'_{\Delta n+1}(r)c\Delta t$$

$$\nu'_{\Delta n+1}(r) \approx -\frac{3}{r}\nu_{\Delta n+1}(r)$$

$$\nu'(r) \equiv \dot{\nu}(t) = -\frac{3c}{r}\nu \qquad (7)$$

Therefore:

$$\nu_{\Delta n}(r) = \nu_{\Delta n+1}(r)\left\{1 - \frac{3c}{r}\Delta t\right\}$$

$$\Delta n = (\Delta n + 1)\left\{1 - \frac{3c}{r}\Delta t\right\}$$

$$\Delta t = \frac{r}{3c}\frac{1}{n+1} = -\frac{\nu}{\dot{\nu}}\frac{1}{\Delta n + 1} \approx 1.1 \cdot 10^{-3}\ \text{sec}, \qquad (8)$$

$$\textit{for}\quad \Delta n = 466 \quad \textit{and} \quad \frac{\dot{\nu}}{\nu} \approx 2\,\text{sec}^{-1}$$

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