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GENERATION OF PLANETARY AURORAL RADIOEMISSION IN THE INHOMOGENEOUS PLASMA

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1. Introduction

The flight of interplanetary stations *Voyager* has revealed than high-latitude areas of ionospheres of planets with strong own magnetic field are sources of an intensive radioemission. The small size of a source and, consequently, high brightness temperature indicates a coherent radiation mechanism. The radiation of planets has a high polarization level (corresponding to an extraordinary wave), its frequency is close to the local electron cyclotron frequency. All these peculiarities (and especially — high efficiency of particles energy to waves energy transformation) make the maser cyclotron resonance a most attractive candidate for the role of radiation mechanism.

At present time due to rich experimental material many researches have been devoted to generation of terrestrial auroral kilometer radiation. Much less information is available about other planets' ionospheres. Therefore, the study of radioemission processes in extraterrestrial ionospheres can be used not only for checking the theories, developed for AKR of Earth, but also as a tool for studying properties of those ionospheres.

In this article the research of auroral kilometer radiation of Saturn, Uranus and Neptune is carried out. The principal point of the used theory, which has been earlier developed for AKR of the Earth [1, 2], considers inhomogeneities of magnetic field and plasma.

2. Theory

As it was noted above, the most probable mechanizm of auroral radioemission generation is the maser cyclotron resonance:

$$\dot{\psi} = \omega - k_{\|}v_{\|} - \omega_c/\Gamma = 0,$$

Amplification factor of an electromagnetic wave

$$K = \exp(2\gamma\Delta t),$$

where γ is temporal increment and Δt is time of resonance (i.e. time period, during which amplification of wave takes place)

The sources of radiation with use of maser cyclotron resonance (MCR) are auroral electron beams. As calculations show, that for the increment γ being positive, presence of a region with a positive slope in electron beam distribution function ($\frac{\partial f_b}{\partial v_\perp} > 0$) is essential. Some variants of such distribution are known, in particular: trapped electron beam in the region of reflection from a magnetic mirror, hollow beam with deficiency of electrons with small transverse velocities.

Another, more essential obstacle on the way of interpretation of auroral radioemission generation as a result of MCR is influence of magnetic field inhomogeneity. This inhomogeneity leads to fast escape of waves from resonance due to the large values of $\dot{k}_{\|}$. However, this problem can be solved if to take into account influence of plasma density inhomogeneity. At certain values of plasma inhomogeneity (namely, at $L_{p\|} \simeq -\frac{\omega_p^2}{\omega_c^2}L_{c\|}$), inhomogeneities of plasma and the magnetic field compensate each other, that allows the electromagnetic wave to be amplified to observable values. It is essential that for compensation gradients of magnetic field and plasma density must have different signs, that can be satisfied only at the expence of the small-scale inhomogeneity (turbulence) of plasma and only in relatively narrow altitude intervals $\Delta r_{\|}$. The last fact leads to discreteness of radioemission spectrum with line width

$$\frac{\Delta f}{f} \sim \frac{\Delta r_{\|}}{L_{c\|}}.$$

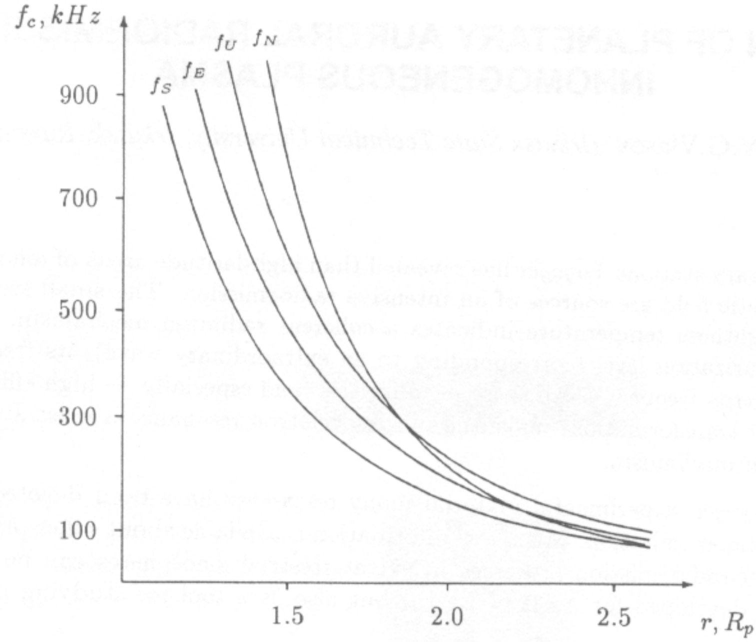

Figure 1: Dependence of cyclotron frequency on distance from the center of planet.

3. Experimental data, method of study and results

The radioemission of Saturn, Uranus, Neptune, as well as terrestrial one, is mainly confined in the interval 100–800 kHz, what is explained by close values of magnetic field strength in the generation region (see Fig.1).

Concrete values of radiation flow density are given, for example, in [4, 5, 8], it allows us to estimate amplification factor as $\ln K \sim 35$. For magnetic fields the dipole approximation [4, 6, 7] is acceptable.

As a source of radiation the hollow electron beam is used in this article:

$$f_b(v,\theta) = \frac{\varphi(\theta)}{2\pi^{3/2}\Delta v_b v_b^2} \exp\left[-\left(\frac{v-v_b}{\Delta v_b}\right)^2\right]$$

$$\varphi(\theta) = \frac{1}{(\Delta\theta_b)^2}\begin{cases} \dfrac{\theta}{\Delta\theta_b}, & 0 \le \theta < \Delta\theta_b, \\ 2 - \dfrac{\theta}{\Delta\theta_b}, & \Delta\theta_b \le \theta \le 2\Delta\theta_b, \\ 0, & 2\Delta\theta_b < \theta \end{cases}$$

Parameters of distribution are v_b, $\Delta v_b/v_b$ и $\Delta\theta_b$.

Let's consider conditions, under which auroral radioemission energy flow, calculated using the above formulae, will correspond to observed one. Let's set follows parameters of the electron beam: energy, $\Delta v_b/v_b$, $\Delta\theta_b$, density n_{b0} in the point, where $f_c = 100$ kHz (because density of beam, moving along magnetic force lines, is proportional to f_c). It allows us to find plasma density at different heights as the solution of the equation

$$\ln K(n) = \ln K_{obs}.$$

It is supposed in the solution that compensation of inhomogeneities of the magnetic field and plasma takes place. Monoenergetic level of the beam $\Delta v_b/v_b$ in the Earth's ionosphere is usually close to 1/3, pitch angle $\Delta\theta_b$ takes the same value.

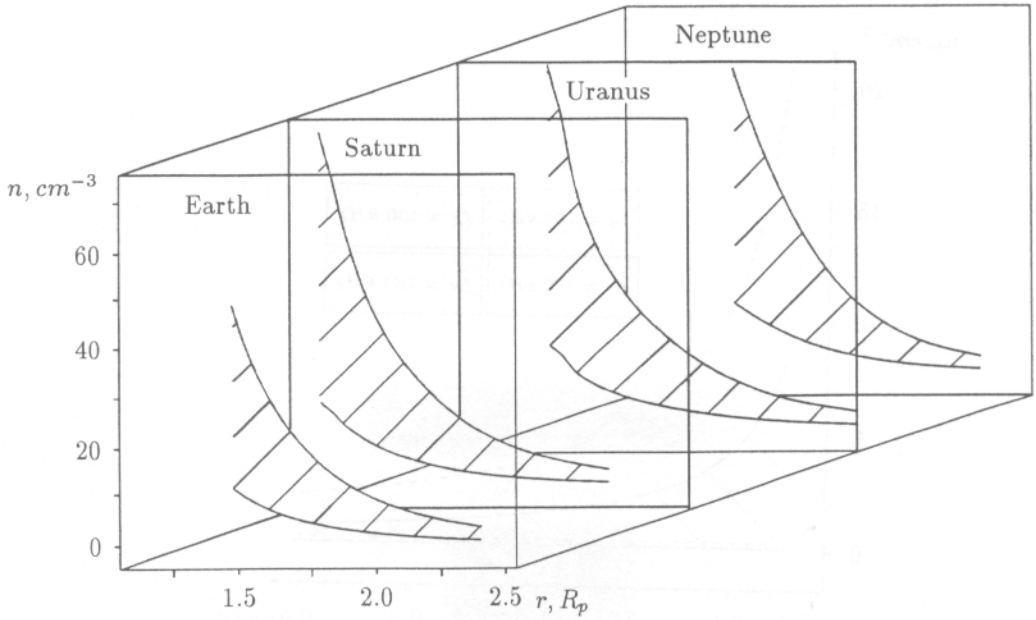

Figure 2: Intervals of ionospheric plasma density, favorable to generation of radiation on maser cyclotron resonance in X1-mode.

Dependence of plasma density on distance from the center of a planet, obtained this way, is close to the exponent. This conclusion remains correct when initial parameters of the electron beam change. Areas of plasma density, favorable for generation of X1-mode on MCR at the Saturn, the Uranus, the Neptune and also at the Earth are shown in Fig.2. The lower limit of density corresponds to beam energy of 0.5 keV (this energy is determined by the condition $E_b \gg T$), upper limit is 50 keV.

Let's consider parameters of the electron beams, which can be stabilized by MCR in X1-mode. The upper limit of stabilization can be estimated as

$$n_b v_b < 9\pi \frac{\omega_c c}{R_p} \ln K \qquad \text{(CGS)}$$

— beams with higher density are able to generate radiation with required energy even without compensation of inhomogeneities of magnetic field and plasma. The lower limit of beam density is determined by ability of generation of radioemission under condition of compensation (at the presence of small-scale plasma inhomogeneity).

$$n_b \geq \frac{9\pi \ln K \omega_c}{R_p} \frac{\Delta v_b}{v_b} \qquad \text{(CGS)}$$

Fig.3 shows the interval of densities and velocities of electron beams, which can cause generation but, in general case, are stabilized on MCR — for the Saturn, the Uranus and the Neptune (shaded area) and for the Earth (limited with dashed lines). The curve, limiting the characteristics, is given for the Saturn at f_S = 400 kHz, for the Uranus at f_U = 170 kHz, for the Neptune at f_N = 164 kHz, for the Earth at f_E = 100 kHz. It is seen that the upper limit of stabilization exceeds significantly the observed values of beam density (or leads to very large values of n_b/n), i.e. the electron beams will be stabilized over all their track from the area of formation to the bottom layers of the ionosphere when there's no small-scale inhomogeneity. At the same time in those areas, where compensation of inhomogeneities of magnetic field and plasma and therefore breakdown of stabilization take place, the electron beams even with relatively small density ($n_b \geq 0.2\ cm^{-3}$ — for given frequencies) are able to cause generation of auroral radioemission.

The scale of plasma density inhomogeneity, required for compensation of magnetic field inhomogeneity, has of the order of tens kilometers and the sign, opposite to that of magnetic field gradient. Corresponding width of the radiation spectral line varies from tens hertz in the area of high frequencies to thousands

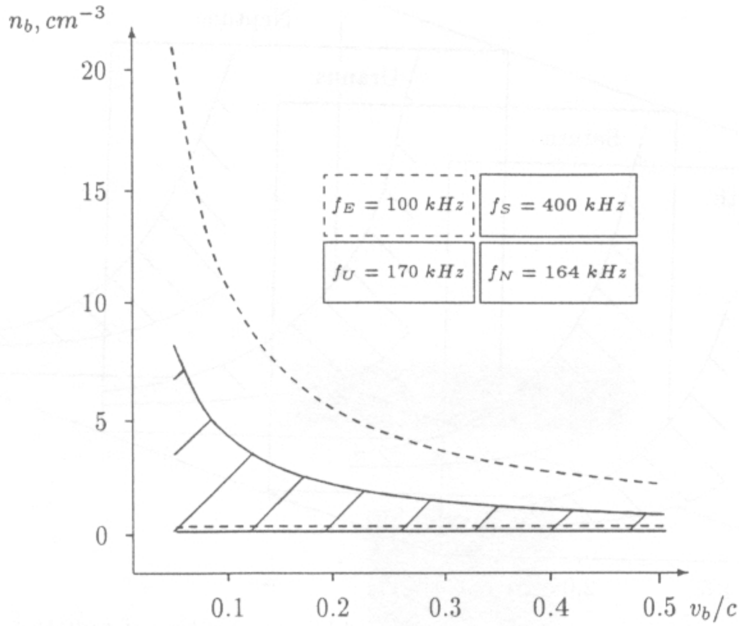

Figure 3: Parameters of the electron beams, capable to cause generation of radioemission on maser cyclotron resonance in X1-mode.

herts in the top of generation altitude interval. Note, that during the flight of *Voyager* stations near the researched planets there were experimentally observed events with line width not larger, than 20 kHz — it was the resolution of equipment.

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