**THEORY OF RADAR ECHOES FROM THE SUN**

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The plasma theory of radar reflection from turbulence generated by Type III electrons is considered. This theory allows to explain the main results of the well-known James experiments.

From 1961 to 1969 James [6, 7] observed the solar radio echoes at 38 MHz with surprisingly high bandwidth and intensity. The typical bandwidth was found of about 40 kHz with quasisymmetrical profiles. He obtained the high (up to $800\pi R_\odot^2$), moderate ($\approx 1-2\pi R_\odot^2$) and low ($< \pi R_\odot^2$) values of scattering cross section, $\sigma$. In accordance with James the echo scattering occurs mainly in the heights range from 1.3 to $1.6R_\odot$. All these properties cannot be explained assuming reflection from the plasma layer (where the radar, $\omega_0$, and Langmuir plasma, $\omega_{pe}$, frequencies become equal) [1]. Other models by Gordon [4], Gordon *et al.* [5] Wentzel [11] and Chashei and Shishov [2] also failed in the main James' results interpretation.

In 1999 [8, 9] the plasma theory of radar reflection was proposed. According to the theory, a radar signal is scattered by both the anisotropic Langmuir and ion-sound turbulences generated by Type III electrons. The assumptions regarding the anisotropic turbulence were made. Electrons generate Langmuir waves with the spectral energy density $W_+(\vec{k}_l)$ along the direction of their propagation into a cone with angle $\varphi_l(\approx 10°-20°)$. There is turbulence $W_-(\vec{k}_l)$ in the opposite direction in the same cone because of the process $l+i=l+i$ that changes plasmon wave vector direction, $\vec{k}_l' = -\vec{k}_l$. Turbulence in other directions, $W_\perp$, is not so significant: $W_\perp \ll W_+$. The Langmuir turbulence is concentrated near wave number $k_l^* \approx \omega_{pe}/v_{ph}$ ($v_{ph}$ is phase velocity which is approximately equal to electron velocity $v_0$) with width $\delta k_l = k_l^*/3$. Since electron flux density $n'/n = 10^{-5}-10^{-7}$ the turbulence energy density $W_l/nT \approx (n'/n)(mv_0^2/mv_{Te}^2) = 10^{-3}-10^{-5}$ at $v_{Te} = 5\times10^8$ cm/s and $v_0 = 0.3\,c$. This turbulence occupies the corona volume with the length along the direction of electron propagation $\triangle z \approx v_0 \triangle t$ (axis $z \parallel \vec{v}_0$ and $\triangle t$ is the burst duration) and cross section, $S$, in the perpendicular plane that coincides with the visible site of Type III bursts.

For a description of the spectral energy density of electromagnetic waves $W_t(\vec{k}_t)$ we use the kinetic equation

$$\frac{\partial W_t(\vec{k}_t)}{\partial t} + \vec{v}\frac{\partial W_t(\vec{k}_t)}{\partial \vec{r}} = I, \tag{1}$$

where $I$ is the collision integral of electromagnetic waves with other waves and particles, and $\vec{v}_{gr} = \partial\omega_t/\partial\vec{k}_t$ is the photon group velocity. The photon interacts with Langmuir plasmons through the different processes: $t+l=t+l$, $t+l=t$ and others. It is shown below that the main properties of the reflected signals can be obtained through the processes $t+l=t+l$ of radar scattering by the anisotropic turbulence.

Taking into account that electrons propagate along the open magnetic field lines, which coincides with the direction of coronal density decrease, and that $W_t \ll W_l$ Equation (1) takes the form

$$\frac{\partial W_t(\vec{k}_t)}{\partial t} + v_{gr}cos\theta\frac{\partial W_t(\vec{k}_t)}{\partial z} = a - bW_t(\vec{k}_t), \tag{2}$$

where $a$ and $b$ are emissivity and scattering coefficients, respectively. $\theta$ is an angle between $\vec{v}_0$ and $\vec{k}_t$.

In order that the radar wave interacts with Langmuir turbulence effectively the optical thickness $\tau = \triangle zb/v_{gr}$ needs to be $\geq 1$. It can be shown that $\tau \ll 1$ at the altitudes where $\omega_{pe} \ll \omega_0$. So, electromagnetic waves do not interact with the turbulence in the higher corona. First $\tau \approx 1$ when $k_l^* \approx k_t$ ($k_l$ and $k_t$ are wavenumbers of interacting waves) or $\omega_{pe} \approx \omega_0 v_{ph}/c$.

Let us consider the scattering of electromagnetic wave ($t$) by plasmon ($l$), when electrons move i) from the Sun to the Earth and ii) away from the Earth.

In the first case, $b$ reaches its maximum when the wave $(t)$ is scattered by plasmon $(l)$ from $W_+$ with moving to $W_-$ [8, 9]. Then the scattered wave $(t')$ propagates towards the Earth into the solid angle $\Omega \approx \pi\varphi_l^2$. For $b$ one has

$$b \approx \frac{\pi^4}{16}\omega_0(\frac{\omega_p}{\omega_0})^3 \frac{W_+W_-}{(nT)^2}\frac{v_0}{c}\frac{k_l^*}{\delta k_l}. \tag{3}$$

$b \approx 4 - 40\ \mathrm{s}^{-1}$ at $W_+/nT \approx W_-/nT = 10^{-3}$, $\varphi_l = 1/3 - 1/6$, $\delta k_l/k_l^* = 1/3$ and the optical thickness is more than 1. Since there is the backscattering into preferred direction, the amplification should be $4\pi/\Omega$ [11] and cross section $\sigma \approx 4\pi S/\Omega = 4S/\varphi_l^2 = 10 \div 100S$ is roughly compared with the cross section of solar disk $\pi R_\odot^2$ at 40 MHz. So, $\sigma = 10 - 100\pi R_\odot^2$.

In the second case, $b$ has a maximum when the scattered wave $(t')$ is directed away from the Earth [8]. The scattered wave $(t')$ comes in the direction of the Earth if plasmon moves from $W_+$ to $W_\perp$. In this case, parameter $b$ is expressed by Equation (3) when $W_\perp$ is replaced by $W_-$. So, $\tau < 1$ because of $W_\perp \ll W_+$ and, consequently, the radar echo observed has a small cross section $\sigma < S$ or $\sigma < \pi R_\odot^2$ at 40 MHz.

Thus, when active regions are close to the center of the solar disk (case i), the radar cross sections increase, and when these regions are on the limb (case ii), the cross sections decrease. A similar tendency was found from analysis of James' experiments [4, 3].

Bandwidth of radar echoes in our model is determined by $T_e$, $\delta k_l/k_l^*$, $v_{ph}$ and has the form

$$\triangle\omega_t = \omega_t - \omega_t' \approx 3\omega_0 \frac{\omega_{pe}}{\omega_0}\frac{v^2 k_l^* \delta k_l}{\omega_{pe}^2} \tag{4}$$

The observed values from 20 kHz to 60 kHz can be easily obtained for reasonable choices of parameter values.

If there are regions with $T_e > T_i$ in the solar corona then Langmuir turbulence is source of ion-sound waves due to processes $l = l + s$. The spectrum of these waves is from $k_s = 2\omega_{pl}/v_{ph}$ to $1/r_{De}$, and their level is $W_{s\pm} = 10^{-2}W_l$ [10]. The numerical analysis of scattering processes $t + s = t$ shows that $\tau \approx 1$ can be realized up to $R = 5R_\odot$. These are precisely the maximum altitudes observed in James' experiments [6]. Frequency shifts of reflected signals for processes $t + s = t$ $\triangle\omega = \omega_0(T_e/Mc^2)^{1/2}$ are defined by electron temperature and equal to $10\,\mathrm{kHz} - 20\,\mathrm{kHz}$ that also are close to the observed values [7].

According to the plasma theory the main reflections occur in the region $R = 1.3 - 1.6R_\odot$ due to processes $t + l = t + l$, and beyond $1.6R_\odot$ in the regions with nonisothermal plasma due to processes $t + s = t$.

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