Plasma theory of solar radar echoes

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[1] Radar scattering by the ion-sound turbulence accompanied by Type III Langmuir turbulence is considered. It is shown that such scattering explains reflections from heights $>1.6R_0$ observed by *James* [1966, 1970]. *INDEX TERMS:* 6949 Radio Science: Radar astronomy; 6954 Radio Science: Radio astronomy; 6984 Radio Science: Waves in plasma; *KEYWORDS:* Sun, radar experiments, Type III electrons, ion-sound turbulance

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[2] One of the surprising results of *James*' [1966, 1970] experiments was solar radar echoes from high heights (up to $5R_0$) (see Figure 1). In the standard theories of radar scattering by the solar corona [*Bass and Braude*, 1957] the height of the reflection layer must be approximately equal to $1.3-1.4R_0$ for radar frequency $38.25MHz$. In the plasma theory of solar radar echoes [*Mel'nik*, 1999] the reflections from heights $1.4-1.6R_0$ with high, moderate and low scattering cross sections, σ, as well as the symmetrical frequency spectrum of echoes with the width about $60kHz$ were explained. In this theory radar scattering occurs due to processes $t + l = t + l$, where t, l denote the electromagnetic and Langmuir waves, respectively. At heights $R > 1.6R_0$ the effectiveness of these processes is low. So there is the problem of echo reflections from high heights. According to *James* [1970] these reflections have nonregular frequency displacements. *Gordon* [1967, 1973] speculated that such reflections could happen because of radar signal scattering on ion-sound turbulence in processes $t + s = t$ (s is the ion-sound wave), but he did not indicate the source of this turbulence. Also he did not define heights at which such processes were effective.

[3] In this paper we show, that in the plasma theory [*Mel'nik*, 1999], the anisotropic Langmuir turbulence generated by Type III electrons can be a source of ion-sound turbulence. Energy in this turbulence is high enough to produce effective reflection of radio signal in processes $t + s = t$ at heights $>1.3-1.4R_0$. Also we demonstrate that if the density of Type III electron flux is large $n' \approx 10^{-5}\ n$ (n is the plasma density) then scattering on ion-sound turbulence can happen up to $5R_0$.

[4] In the plasma theory the Langmuir turbulence $W_+(\vec{k}_l)$ is generated by Type III electrons along the direction of their propagation into the cone with angle $\varphi_l = 10° \div 20°$. There is also turbulence $W_-(\vec{k}_l)$ in the opposite direction in the same cone because of the process $l + i = l + i$ (i denotes the ion) that changes the direction of the plasmon wave vector, $\vec{k}_l \rightarrow -\vec{k}_l$. The level of turbulence in other directions, $W_\perp$, is not so high: $W_\perp \ll W_+$. The Langmuir waves have mainly wave number $k_l^* = \omega_{pe}/v_{ph}$ (v_{ph} is the phase velocity which approximately equals to the electron velocity v_0). The width of the spectral density of Langmuir waves is $\delta k_l \approx k_l^*/3$. Since the density of electron flux is $n'/n = 10^{-5} - 10^{-7}$ the turbulence energy density is $W_l/nT = (n'/n)(mv_0^2/mv_{Te}^2) = 10^{-5} - 10^{-7}$ at $v_{Te} = 5 \cdot 10^8 cm \cdot s^{-1}$ and $v_0 = 0.3 \cdot c$. The spatial sizes of the corona volume occupied with this turbulence are $\Delta z = v_0 \Delta t_{III}$ along the electron propagation direction (the axis z is parallel to v_0 and Δt_{III} is the burst duration) and the cross section, S, in the perpendicular plane that coincides with the visible site of Type III bursts.

[5] A necessary condition for the existence of ion sound waves is the availability of regions, where $T_e > T_i (T_e, T_i$ are the temperatures of electrons and ions, respectively). Because the plasma of the solar corona is under a steady exposure to particle and wave fluxes, it can be inferred that there are regions with the required characteristics. So when Type III electrons propagate through the solar corona they initiate both Langmuir and ion-sound waves. As was shown by *Vedenov and Rudakov* [1964], the process $l = l + s$ is the powerful source of ion-sound waves. This source situated near the wave number

$$k_s^* \approx 2k_l^* = 2\omega_{pl}/v_{ph} \tag{1}$$

and the wave vectors of the ion-sound waves are in the solid angle

$$\Omega_s = \Omega_l = \pi\varphi_l^2 \tag{2}$$

along the direction of electron propagation. The width of the spectral energy density of the ion-sound wave source approximately equals

$$\delta k_s \approx 2\delta k_l. \tag{3}$$

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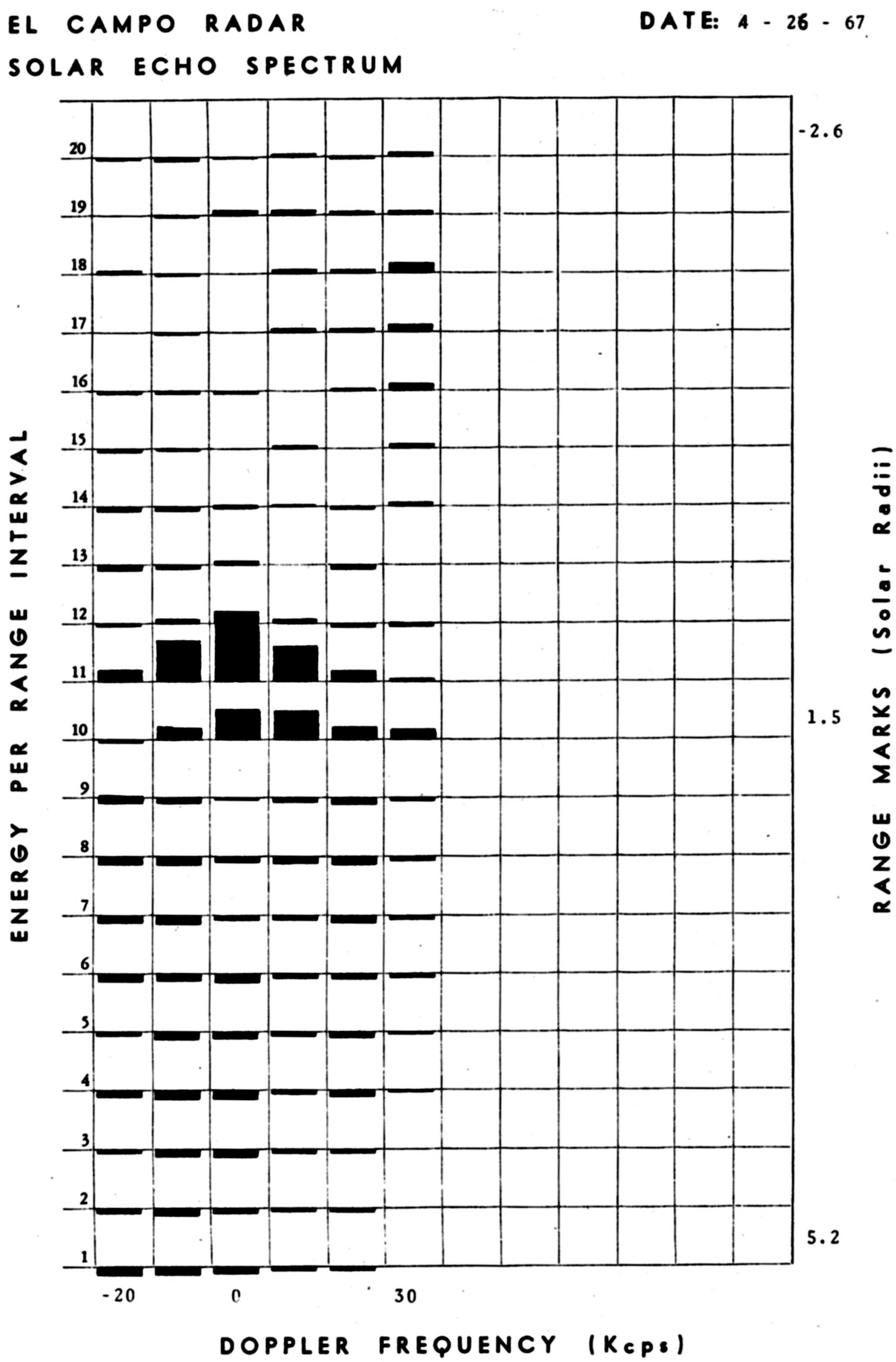

Figure 1. The echo spectrum obtained by *James* [1970] with reflections from high altitudes.

As the growth rate of process $l = l + s$ is very high, the ion-sound turbulence achieves very rapidly the saturation level that is defined from the equality of ion-sound ($N_{s\pm}$) and Langmuir ($N_{l\pm}$) occupation numbers

$$N_{s\pm} \approx N_{l\pm}. \tag{4}$$

From (4) we derive for the energy density of ion-sound waves

$$W_{s\pm} \approx \frac{\omega_s}{\omega_l} W_{l\pm} \approx 10^{-2} W_{l\pm}. \quad (5)$$

[6] The ion-sound waves with large wave numbers arise in the processes $s + s = s$. They are absorbed by the thermal ions in the region $k_s \approx 1/r_{De}$. It is known that in this case the power spectrum

$$W_s(k_s) \propto 1/k_s^{3/2} \quad (6)$$

is formed [*Artsimovich and Sagdeev*, 1979].

[7] Let us discuss the effectiveness of radar scattering by the ion-sound turbulence with the spectral energy density (6). The kinetic equation for the transfer and scattering of a radar signal can be written as

$$\frac{\partial W_t(\vec{k}_t)}{\partial t} + v_{gr} \cos\theta \frac{\partial W_t(\vec{k}_t)}{\partial z} = a - bW_t(\vec{k}_t), \quad (7)$$

where $W_t(\vec{k}_t)$ is the spectral energy density of electromagnetic waves; a and b are the emissivity and scattering (absorption) coefficients; θ is the angle between the direction of motion of electrons (which move along the z axis) and the wave vector $\vec{k}_t$; v_{gr} is the group velocity of electromagnetic wave.

[8] Coefficient b for processes $t + s = t$ and $t = s + t$ in equation (7) has the form

$$b = \frac{(2\pi)^3 e^2 \omega_{pe}^2}{16\pi m^2 v_{Te}^2 \omega_t} \int \frac{1}{\omega_t'} (1 + \cos^2\angle \vec{k}_t \vec{k}_t') W_s(\vec{k}_s)$$
$$\times [\delta(\vec{k}_t - \vec{k}_t' - \vec{k}_s)\delta(\omega_t - \omega_t' - \omega_s) + \delta(\vec{k}_t' - \vec{k}_t - \vec{k}_s)$$
$$\cdot \delta(\omega_t' - \omega_t - \omega_s)] d\vec{k}_t' d\vec{k}_s. \quad (8)$$

[9] In equation (8) the first item in the square brackets corresponds to the coalescence process $t + s = t$, and the second one corresponds to the decay process $t = s + t$. At the backward reflection the frequency shift, $\Delta\omega$, is negative $\Delta\omega = \omega_t - \omega_t' = -\omega_s$ for the process $t = s + t$ and it is positive $\Delta\omega = \omega_t - \omega_t' = \omega_s$ for the process $t + s = t$. In the both cases, electromagnetic waves scattered backward are into the solid angle

$$\Omega_t = \pi\theta'^2, \quad (9)$$

where $\theta' \approx 2\varphi_l$ due to the momentum conservation for the processes $t = s + t$ and $t + s = t$ [*Gordon*, 1967, 1968]. Taking into account (5) and (6), we have for $b_\pm$

$$b_\pm = \frac{\pi}{4} \omega_0 \frac{W_{s\pm}}{nT_e} \frac{1}{\varphi_s^2} \left(\frac{\omega_{pe}}{\omega_0}\right)^4 \quad (10)$$

or

$$b_\pm = 3 \cdot 10^3 \left(\frac{\omega_{pe}}{\omega_0}\right)^4 s^{-1} \quad (11)$$

at $n'/n = 10^{-6}$, $\varphi_l = 1/3$. In equations (10) and (11), ω_0 is the radar frequency. Altitudes at which radar signals can be scattered via processes $t = s + t$, $t + s = t$ are derived from the condition

$$\tau = \Delta z b_\pm / c \geq 1. \quad (12)$$

[10] For the Baumbach-Allen density we found $R \leq 3R_0$ at 40 *MHz* from (11). If the density of Type III electrons is $n' = 10^{-5}n$, the condition (12) is fulfilled for the altitudes up to $R \approx 5R_0$. Since in James' experiments the reflections from such high altitudes were rare, we could conclude that Type III bursts were mainly prompted by the electrons streams with density $n' \leq 10^{-6}n$. This is in agreement with the conclusion done in *Mel'nik* [1999] at analysis of cross sections via processes $t + l = t + l$.

[11] Comparing the observed cross sections of reflections from altitudes $R > 1.6R_0$ with equation $\sigma = 4\pi S_s/\Omega_{s\pm}$, where S_s is cross section of region with a nonisothermal ($T_e > T_i$) plasmas, we can say that there are such regions in the corona, but they are not very large. Thus all principal results of James' experiments such as cross sections, heights of reflections, and echo spectrum can be understood in the plasma theory [*Mel'nik*, 1999].

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