

Interpretation of James' Experiments in Plasma Theory of Solar Radar Echoes

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Abstract. In the framework of the plasma theory of solar radar echoes results of the known James' experiments such as the values of effective cross-sections, the anisotropy of reflections, the spectrum of reflected signals, the heights of radar scattering and others are explained. In particular in this theory reflection of radar signal with high effective cross-sections ($\sigma = (10 - 100)\pi R_{\odot}^2$) occur in processes $t+l \rightleftharpoons t+l$ on the Langmuir turbulence generated by Type III electrons at altitudes $(1.4 - 1.6)R_{\odot}$ when electron streams propagate towards the Earth. If the electrons move away from the Earth then the scattering cross-sections due to process $t+l \rightleftharpoons t+l$ are small ($\sigma < \pi R_{\odot}^2$). Reflections from the heights up to $5R_{\odot}$ can occur at scattering of radar wave on the ion-sound turbulence (processes $t+s \rightleftharpoons t$) accompanied the Langmuir turbulence.

From 1961 to 1969 James (James 1966, 1970) carried out the solar radar experiments at frequency $f_0 = 38.25$ MHz. He obtained the following results: scattering cross-sections, σ , changed from day to day and were high (up to $800\pi R_{\odot}^2$), moderate ($(1 - 2)\pi R_{\odot}^2$) and low ($< \pi R_{\odot}^2$); main reflections occurred at heights $(1.3 - 1.6)R_{\odot}$ though there were reflections from heights $(2 - 3)R_{\odot}$ and sometimes even up to $5R_{\odot}$, but with small cross-sections; frequency shifts of echoes were 20 - 60 kHz. James pointed out that there was good correlation between the radio echo data and solar activity specifically the locality of active region on the solar disk.

The standard theory (Kerr 1952; Bass & Braude 1957) predicts practically steady reflections from the heights where the local plasma frequency equals the radar frequency $\omega_{pe} = \omega_0 = 2\pi f_0$ with cross-sections $\sigma = (1 - 2)\pi R_{\odot}^2$. In models (Gordon 1967; Gordon, Liperovskii, & Tsytoich 1971; Gordon 1973) Gordon explained widths of echo spectra with the help of scattering by micro-turbulence but as indicated by Gerasimova (Gerasimova 1979) the very high levels of Langmuir and ion-sound turbulence needed for reflections with cross-sections $\sigma = 10\pi R_{\odot}^2$. For derivation of large cross-sections in the model (Wentzel 1981) some rigid constraints on solar magnetic fields are required. According to Chashei and Shishov (Chashei, & Shisov 1994) scattering on large scale irregularities at heights $R = 2R_{\odot}$ in solar corona can provide an explanation of $10\pi R_{\odot}^2$ cross sections. So until recently there were not understanding the main James' results.

In 1998 (Mel'nik 1998; Mel'nik 1999) the plasma theory of radar echo was suggested. It is development of the idea proposed by Gordon in 1967 about the important role of microturbulence in radar scattering. In this model radar signal

is scattered by Langmuir and ion-sound turbulences that generated by Type III electrons. These electrons are said to have velocities $v_0 = (0.3 - 0.6)c$ and propagate along open magnetic field lines in the solar corona. At each heights they generate Langmuir waves that are transformed into electromagnetic ones in the processes $l + i \rightleftharpoons t + i$, $l + l \rightleftharpoons t$ producing the fundamental and harmonic components of Type III bursts. The level of Langmuir turbulence estimated as $W = n' m v_0^2 / 12$ is enough high $W = (10^{-3} - 10^{-4}) n T_e$. Another property of this turbulence is its anisotropy - wave vectors of Langmuir waves are directed along (primary waves) and against (secondary waves) direction of electron propagation into narrow cone with $\theta_l = 10 - 20^\circ$. If electrons travel through regions with non-isothermal plasmas $T_e > T_i$ then Langmuir turbulence is the source of near isotropy ion-sound turbulence with the level $W_s = 10^{-2} W_l$. Radar signal can be scattered by these Langmuir and ion-sound turbulences. Because Langmuir turbulence is anisotropy the scattering properties strongly depend on the relative orientations of propagation of high energy electron stream and radar signal. There are two cases.

If electrons propagate from the Sun to the Earth (in this case the active region is situated in the centre of the Sun) then wave vectors of Langmuir waves are parallel or antiparallel to wave vector of radar wave. The echo scattered in the processes $t + l \rightleftharpoons t + l$ travels backward to the Earth in the narrow cone $\pi\theta_l^2$. Scattering is most effective (the optical depth $\tau \geq 1$) at heights where Langmuir wave number equals radar wave number (Mel'nik 1999)

$$k_l = k_t.$$

As Langmuir waves are concentrated near wave number $k_l = \omega_{pe}/v_0$ then this equality is equivalent to

$$\omega_{pe}/v_0 = \omega_0/c.$$

Because of sharp directionality the scattering cross-section in this case is increased in comparison with that for isotropy scattering by a factor of $4\pi/\pi\theta_l^2$ (Wentzel 1981) and equals $\sigma = 4S/\theta_l^2$, where S is the visible section of Type III region. At heights $(1.3 - 1.6)R_\odot$ $S \approx \pi R_\odot^2$ (R_\odot is the solar radius) so one finds $\sigma \approx 100\pi R_\odot^2$.

If electrons travel out of the Earth (active region is placed close to limb) the reflected signal coming on the Earth is weak (Mel'nik 1999), i.e. scattering cross section is small $\sigma < \pi R_\odot^2$.

When the radar signal reaches the heights where $\delta k_l = k_t$ (δk_l is the width of Langmuir turbulence spectrum) scattering via processes $t + l \rightleftharpoons t + l$ is isotropic and $\sigma \approx \pi R_\odot^2$ in both cases of electron propagation (Mel'nik 1999).

Frequency shifts of radar echo is

$$\Delta\omega = 3\omega_0 \frac{\omega_{pe}}{\omega_0} \frac{v_{T_e}^2}{v_0^2} \frac{\delta k_l}{k_l}$$

and is determined by the electron temperature, the width of Langmuir turbulence and the electron velocity. For reasonable values of these parameters one can obtain observational frequency shifts from 20kHz to 60kHz.

At the heights $(R > 1.6R_\odot)$ where $k_l \ll k_t$ scattering due to processes $t + l \rightleftharpoons t + l$ is not effective (the optical depth $\tau \ll 1$) because of the small

ratio $(\omega_{pe}/\omega_0)^3$. However at these heights scattering by ion-sound turbulence (processes $t + s \rightarrow t$, $t \rightarrow t + s$) is more efficient (the limiting height obtained from the condition $\tau = 1$ for electron streams $n'/n = 10^{-5}$ equals $R \approx 5R_\odot$). In this case the reflected signal consists of two symmetrical signals with respect to the frequency ω_0 with

$$\Delta\omega = \pm k_s v_s = \pm 2 \frac{\omega_0}{c} \left(\frac{T_e}{M} \right)^{1/2}.$$

As the ion-sound turbulence is near isotropical the cross-section of scattering is defined only by the section S_s of region with non-isothermal plasma $T_e > T_i$ and approximately equals $\sigma \approx S_s$. According to James' experiments reflections at great heights have different values $\Delta\omega$ and small cross-sections $\sigma < \pi R_\odot^2$, i.e. plasma consists of many regions with various electron temperatures. Because such reflections registered frequently we can conclude that the coronal plasma is irregular at these heights. The rarity of reflection at heights $R = 5R_\odot$ points to Type III electron stream has density $n'/n \approx 10^{-6}$.

Thus our model allows to understand the main results of James' experiments. Besides his data give an opportunity to make conclusions about properties of the coronal plasma. Since the reflection heights, scattering cross-section and frequency shifts are determined by plasma parameters (density, temperature) and turbulence we can consider the radar experiments as a powerful method for diagnostic of the coronal plasma at the heights beyond the power of investigations by other methods. For this aim it is worthwhile using telescope with big effective areas such as UTR-2 ($1.5 \cdot 10^5 \text{ m}^2$) and LOFAR (10^6 m^2).

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