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On the theory of type III radio bursts in the nonhomogeneous interplanetary space (quasi-linear approximation)

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ABSTRACT

Within the limits of geometrical optics frequency characteristics of perturbations of one-dimensionally non-uniform system "electron beam–solar wind plasma" are investigated in linear approximation on the basis of Maxwell equations closed by the derived constitutive equation. The beam is generated by the active region during solar flares and it appears as a source of type III radio emission in the interplanetary space. The appropriate dispersion equation is solved. Resonance interaction of wave with electron beam appears to happen only in two space points. Such transient (pointwise) mechanism of resonance throws light on one of the basic problems of physics of electron beams generated by solar flares: incomparably more long-term time of their existence compared to the time of existence resulting from the former theoretical estimates of velocity of beam energy loss on radiation within the limits of homogeneous medium. The degree and time of electron beam dissipation were determined in quasi-linear approximation.

1. Introduction

Investigation of the nature of type III solar radio bursts is important both in theory and also for experiment. The basic conception of the mechanisms of radio bursts generation in solar active regions has been already developed long-time ago, actually from the time of starting radio monitoring of the Sun. Electron beam accelerated in the solar flare region while arising upwards is assumed to excite oscillations of the environmental plasma whose frequency $\omega_L = \sqrt{ne^2/\varepsilon_0 m}$ damps as coronal plasma density decreases. Owing to non-linear interaction, two longitudinal plasma waves merge in one transverse wave with doubled frequency (Ginzburg and Zheleznjakov, 1958; Parker, 1959). These transverse waves represent radio bursts of type III.

As frequency reduces to several MHz, the signal is blocked by ionosphere and becomes inaccessible for recording on the Earth. Last decade, radio meters have been located outside the ionosphere, which allowed observation of radio-frequency emission of electron beams injected by active solar regions at the distance of one and even two astronomical units (Benz et al., 2005). The length of radio wave generated at the distance of 1 AU makes $\approx n \cdot 1$ km while for corona it is $\approx n \cdot 10$ cm.

The paper by Cane et al. (2002) studies the correlations between solar flares, solar proton events, coronal mass ejections (CMEs) and radio bursts. It essentially found that all of the proton events are preceded by groups of type III bursts and all are preceded by CMEs. These type III bursts are caused by streams of electrons traveling from close to the solar surface out to 1 AU.

This brings up the question on the reasons of beam stability, since it is known that electron beam spreading in background plasma of higher density with velocity higher than thermal one is unstable (Robinson, 1992), and under conditions of solar corona it must have quickly dissipated in ≈ 0.3 s, which would have prevented it from penetrating into the interplanetary space (Kaplan and Tsytovich, 1972). Monograph by Kaplan et al. (1977) reviews possible mechanisms of beam stabilization, including cross conversion of Langmuir longitudinal and transverse electromagnetic waves and non-linear scattering of beam-excited plasma

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waves on density fluctuations of the interplanetary plasma leading to their coming out of resonance with a beam because of changing phase velocity of the wave.

The paper by Vasguez and Gomez (2004) covers theoretical study of evolution of a beam of superthermal electrons propagating in the background plasma. To generate radio-frequency radiation of type III, Langmuir plasmons traveling along the field should undergo merging. Two mechanisms of merging are suggested and considered. The paper by Ledenev and Starygin (2002) also analyses the process of quasi-linear relaxation of flow of electrons generating radio bursts of type III. The kinematical effect of electron spread in space caused by the difference in their velocity was shown to be the main effect governing stream relaxation.

The theory built on the conception of interchange of generation and dead zones in the space (in these regions the wave comes out of resonance with a beam) is called as "stochastic growth theory" (SGT) (Robinson and Cairns, 1994; Robinson, 1997). Later the following results were obtained along this line. Electromagnetic emissivities are estimated by extending the developed theory of interplanetary type III bursts to coronal emissions, including its features of stochastic Langmuir-wave growth and three-wave interactions. The results are investigated for heating on open and closed coronal field lines and are compared with observations of normal, reverse-slope, bidirectional and inverted-J and -U coronal type III radio bursts (Robinson and Benz, 2000). In a recent paper (Li et al., 2006a), the generation of beam-driven Langmuir waves and the propagation of an electron beam in the presence of ambient density fluctuations are numerically studied using quasi-linear calculations in one spatial dimension. A conclusion was drawn that the statistics of the Langmuir-wave field show good agreement with SGT predictions, thus indicating the beam–Langmuir-wave system is in a SGT state. In the other paper of these authors (Li et al., 2006b) the generation of beam-driven Langmuir waves and the propagation of an electron beam in the presence of ambient density fluctuations is numerically studied using quasi-linear calculations in one spatial dimension. Possible mechanisms of merging of longitudinal plasmons into a transverse electromagnetic wave are considered. Conclusion is also made that the statistics of the Langmuir-wave field show good agreement with SGT predictions, thus indicating the beam–Langmuir-wave system is in a SGT state.

However, till now there is no consistent theory of type III radio bursts in the interplanetary space. Various aspects of non-linear stage of radio wave generation are being researched, such as cascade theory (Kontorovich et al., 1993), a problem of wave amplitude increase restriction by reaching distribution function on "plateau" section (Robinson, 1997), etc., but dispersion properties of the oscillating beam–plasma system are still insufficiently studied.

This paper successively raises the following problems: first, investigation of amplitude–frequency characteristics of disturbances of space – nonhomogeneous electron beam–solar wind plasma system in linear approximation; second, study of non-linear stage of instability of the considered system in quasi-linear approach and, finally, examination of some problems of electron beam dissipation on this basis.

2. Investigation of amplitude–frequency characteristics of perturbations of the electron beam–interplanetary plasma system in linear approximation

Electron beam accelerated in the solar flare region to subrelativistic speeds and propagating in the interplanetary space may be assumed to be compensated (space charge of electrons is neutralized by the background plasma) as its density n_b is much less than that of solar wind plasma n_p. At the distance of 1 AU $n_b \approx 5\times10^{-7}\,\mathrm{cm^{-3}}$ (calculation was made based on satellite data GOES10 and GOES12 (http://www.sec.noaa.gov/)). Data for electrons in the (38–53) keV energy interval were taken for calculation. The density of solar wind plasma in orbit of the Earth is well known and this yields $n_p \approx 5\,\mathrm{cm^{-3}}$; i.e., $n_b/n_p \approx 10^{-7}$.

Proper electric and magnetic fields of such beam may be neglected as compared to external magnetic field of the interplanetary space. The radial component of induction of the interplanetary magnetic field at the distance of 1 AU yields $B_r \approx 2.5\times10^{-5}$ G, while the time at the level of photosphere of the Sun $B_r \approx 1$ G (Akasofu and Chapman, 1974, p. 44).

Density of solar wind plasma decreases from $\approx 10^9\,\mathrm{cm^{-3}}$ in the upper corona to $\approx 5\,\mathrm{cm^{-3}}$ in the Earth orbit. The interplanetary medium is not uniform in the radial direction.

Electron beam being scattered in the irregularities of the interplanetary magnetic field propagates along the magnetic power line which is in the form of Archimedes' spiral in some cone opening. We model a real system with a cylindrical monochromatic electron beam moving in the stationary background plasma of high concentration. The interplanetary space plasma may be assumed to be static because solar wind velocity is $v_s = n\cdot10^5$ km/s which is much less than that of the electron beam $v_b = 10^8$ km/s (for electrons of 40 keV energy).

Various problems of non-linear stage of generation of radio-frequency radiation were investigated. However, the reason of beam stability still requires further examination, and dispersion properties of generating beam–plasma system are also insufficiently studied.

Investigation of amplitude–frequency characteristics of perturbations of the electron beam–interplanetary space plasma system is based on the solution of set of Maxwell equations without external sources

$$\begin{cases} c^2\varepsilon_0 rot\delta\vec{B} = \partial\delta\vec{D}\,\partial t, \quad div\delta\vec{B} = 0, rot\delta\vec{E} = -\dfrac{\partial\delta\vec{B}}{\partial t}, \quad div\delta\vec{D} = 0, \end{cases} \tag{1}$$

where $\delta\vec{B}(t,\vec{r})$ and $\delta\vec{D}(t,\vec{r})$ are, respectively, perturbations of magnetic and electric field of the system under study. To solve the problem the perturbation method is used

$$\vec{E}(\vec{r},t) = \vec{E}_0(z) + \delta\vec{E}(\vec{r},t),$$
$$\vec{B}(\vec{r},t) = \vec{B}_0(z) + \delta\vec{B}(\vec{r},t),$$

Besides, since the electron beam is compensated, equilibrium electric field $\vec{E}_0(z) = 0$.

Maxwell equation (1) is closed by constitutive equation which for weakly nonhomogeneous plasma (in geometrical optics approximation) may be represented as

$$\delta D_i(t,\vec{r}) = \varepsilon_0\int_{-\infty}^{t} dt' \int d\vec{r}'\,\hat{\varepsilon}_{ij}(t-t',\vec{r}-\vec{r}',z)\delta E_j(t',\vec{r}'). \tag{2}$$

The beam is directed along the magnetic field radially from the Sun; density of solar wind plasma and beam, and also magnetic field is radially nonhomogeneous. Axis $\vec{z}$ is directed along a radius from the Sun (refer to Fig. 1).

Solution of a problem with one-dimensional nonhomogeneity allows application of the method of geometrical optics as relation $\lambda < L$ is fulfilled, where λ stands for the length of waves under study, and L stand for the typical size of nonhomogeneity of solar wind plasma. Weak nonhomogeneity of medium is formally characterized by the fact that dependence of integral relation kernal on difference $\vec{r}-\vec{r}'$ is considered to be stronger than dependence on z. Having substituted in Eq. (2) the expansion of electric-field intensity vector into Fourier series in geometrical