INFLUENCE OF REVERSE CURRENT ON THE EXCITATION OF LANGMUIR WAVES IN THE PLASMA OF SOLAR FLARES

© 2025 I. V. Kudryavtsev*, P. V. Vatagin

A.F. Ioffe Institute of Physics and Technology, St. Petersburg, Russia

**e-mail: igor.koudriavtsev@mail.ioffe.ru*

Received March 02, 2025

Revised April 10, 2025

Accepted June 17, 2025

Abstract. It is known that during solar flares, electrons are accelerated to high energies and generate electromagnetic radiation in a wide range of frequencies. Fast electrons generate hard X-rays in the solar plasma and can also excite plasma waves. The latter generate electromagnetic waves that are detected by radio telescopes on Earth. It is also known that electron beams injected into the plasma generate a reverse current, which consists of thermal plasma electrons. In this paper, the effect of the reverse current electric field on the generation of plasma waves is considered. It is shown that the reverse current electric field can lead to a decrease in the intensity of Langmuir waves excited in the plasma and, consequently, to a decrease in the intensity of radio emission generated by plasma waves.

DOI: 10.31857/S00167940250706e8

1. INTRODUCTION

The study of the evolution of the distribution function of fast electrons in the plasma of the solar atmosphere is important for studying the processes of plasma heating and acceleration of charged particles. The parameters of these distributions are reflected in the characteristics of the X-ray and radio emission generated by these electrons. However, the place where electrons are accelerated to high energies differs from the place where they generate electromagnetic radiation registered on the Earth and on spacecraft. Therefore, the question arises of a detailed consideration of the dynamics of fast electrons from the place of acceleration to the place of their generation of electromagnetic radiation. In addition, fast electrons excite Langmuir waves in the solar plasma, which also generate electromagnetic radiation recorded on Earth by radio telescopes (e.g., [Ginzburg and Zheleznyakov, 1958; Zheleznyakov and Zaitsev, 1970; Kaplan and Tsytovich, 1972; Zaitsev and Stepanov, 1983; Ratcliffe et al, 2014; Kudryavtsev et al., 2022; Kudryavtsev and Kaltman, 2021]). The dynamics of fast electrons taking into account their Coulomb interaction with the surrounding plasma particles is quite well studied (see, for example, [Nocera et al., 1985; Diakonov and Somov, 1988; Reznikova et al., 2009; Zharkova et al., 2010; Melnikov et al., 2013]).

These studies were explained primarily by the need to describe the parameters of the hard X-ray emission of solar flares: energy spectra, polarization, and directivity. Less attention has been paid to accounting for the interaction in the flare plasma of fast electrons with plasma waves (see, for example, [Ratcliffe et al., 2012, 2014; Kontar et al., 2012, 2014; Kudryavtsev et al., 2012, 2014; Kudryavtsev et al., 2019; Vatagin and Kudryavtsev, 2021]), although this interaction influences the generation of radio emission [Zheleznyakov and Zaitsev, 1970; Ratcliffe and Kontar, 2014].

Another source of changes in the distribution function of fast electrons is their interaction with the electric field of the reverse current, which is generated in the plasma during the invasion of fast particles as a result of electromagnetic induction. Applied to the plasma of the solar atmosphere, this phenomenon was considered in [Sermulyns and Somov, 1982; Diakonov and Somov, 1988; Zharkova et al., 2010; Charikov and Shabalin, 2015]. These works consider the situation when the reverse current completely compensates the electric current of fast electrons, and when the magnetic field of the fast electron beam (i.e., the magnetic field of the forward current) disappears and some electrostatic field associated with the reverse current remains. The purpose of this paper is to consider the effect of this electric field on the generation of Langmuir waves by fast electrons as a result of some change in their distribution function, as well as to clarify the role of this field in the generation of radio emission generated by plasma waves. The results of this consideration may be relevant in interpreting the measured radio emission of solar flares.

2. REVERSE CURRENT ELECTRIC FIELD AND GENERATION OF LANGMUIR WAVES

Let us consider in this approximation the problem of the influence of the reverse current electric field on the process of generation of Langmuir waves in the solar plasma by fast electrons. That is, we will assume that in the plasma there exists an electric field *E* associated with the reverse current. The system of equations for the electron distribution function *f* and the spectral energy density of Langmuir waves $W_k$in the homogeneous approximation according to the works [Zheleznyakov and Zaitsev, 1970; Diakonov and Somov, 1988; Tsytovich, 1971; Kontar et al., 2012] has the form:

$$\frac{\partial f}{\partial t}-\frac{eE}{m}\frac{\partial f}{\partial v}=\frac{\partial}{\partial v}\left(D\frac{\partial f}{\partial v}+\nu_e\left(vf+v_{Te}^2\frac{\partial f}{\partial v}\right)\right), \tag{1}$$

$$\frac{\partial W_k}{\partial t}=(\gamma_k-\nu_{eff})W_k+Q_k \quad , \tag{2}$$

$$D=\frac{\pi\omega_e^2}{m_e n_e v}(W_k)_{k=\omega_e/v};\ ,\gamma_k=\left(\frac{\pi\omega_e}{n_e}v^2\frac{\partial f}{\partial v}\right)_{v=\omega_e/k} \tag{3}$$

where t and v - time and projection of electron velocity on the OZ axis (k - wave number of Langmuir waves; ν_e- frequency of collisions of electrons with plasma particles; ω_e- electron plasma frequency; v_{Te}- thermal velocity of electrons; γ_k is the beam instability increment; ν_{eff} is the effective frequency of Langmuir wave attenuation due to collisions of plasma particles; n_e is the plasma electron concentration; Q_k is the power of spontaneous emission of Langmuir waves; e is the electron charge modulus.

The reverse current is a flow of "thermal" electrons moving in the opposite direction to the direction of motion of the accelerated electrons, and according to [Diakonov and Somov, 1988] it is assumed that the reverse current density $j_{rc}$is modulo equal to the current density of the accelerated electrons j, i.e., the condition is fulfilled

$$j_{rc}(t) = j(t) = e \int_{v_{min}}^{v_{max}} v \cdot f(t, v) dv . \tag{4}$$

The electric field *E is* related to j_{rc} by the relation

$$j_{rc} = \sigma E . \tag{5}$$

Then we obtain

$$E = j_{rc} / \sigma , \tag{6}$$

where σ is the classical plasma conductivity (Spicer, 1977)

$$\sigma = \frac{(k_B T_e)^{3/2}}{\pi e^2 (m_e)^{1/2} \ln \Lambda} . \tag{7}$$

In the present work, as well as in [Kontar et al., 2012], we will use the following expression for the function Q_k

$$Q_k(t) = \frac{\omega_e^3 m_e}{4\pi n_e} \left(v \cdot \ln(\frac{v}{v_{Te}}) f \right)_{v=\omega_e/k} . \tag{8}$$

In the absence of fast electrons, $Q_k$describes the spontaneous emission of Langmuir waves by thermal plasma electrons.

Let us supplement the system of equations (1-3) with an initial condition for various plasma and fast electron parameters. Let us consider a monotonically decreasing distribution of fast (suprathermal) electrons. In this case, as in [Kontar et al., 2012], we will assume that at the initial moment of time the electron function *f* is the sum of the Maxwell distribution of thermal plasma electrons f_M and the "beam" distribution of fast electrons f_b:

$$f(t = 0, v) = f_M + f_b ; f_M = \frac{n_e}{\sqrt{2\pi}\, v_{Te}} \exp(-\frac{v^2}{2 v_{Te}^2}); f_b = C \left(1 + \left(\frac{v}{v_b} \right)^2 \right)^{-\delta} , \tag{9}$$

where $C = \frac{2 n_b}{\sqrt{\pi}\, v_b} \frac{\Gamma(\delta)}{\Gamma(\delta - 1/2)}$, n_b is the concentration of fast electrons, Γ is the gamma function.

As an initial condition for W_k, similar to the work (Kontar et al., 2012), we will use the following expression

$$W_k(t=0) = \frac{k_B T_e}{4\pi^2} k^2 \ln(\frac{1}{k\lambda_{de}}) \Bigg/ \left(1 + \frac{\ln\Lambda}{16\pi n_e} \sqrt{\frac{2}{\pi}} k^3 \exp\left(\frac{1}{2k^2\lambda_{de}^2} \right) \right). \quad (10)$$

Equations (1-3) were solved by the finite difference method [Samarsky, 1989].

Fig. 1 shows the results of calculations for the electron distribution function neglecting the generation of Langmuir waves, i.e., only equation (1) is solved. only equation (1) is solved without taking into account equation (2) (the coefficient D is set equal to zero) at $n_e = 5\cdot10^{10}\text{cm}^{-3}$, $n_b = 10^9\text{cm}^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$, without taking into account the influence of the reverse current electric field and with taking into account this influence. The values of the fast electron parameters δ and $v_b$are taken according to [Kontar et al., 2012]. Two effects arising in the propagation of fast electrons should be noted here. First, an area with a positive derivative is formed on the distribution function of fast electrons, which will be the cause of Langmuir wave excitation (see, for example, [Zheleznyakov and Zaitsev, 1970]). Secondly, the appearance of the reverse current electric field leads to some additional inhibition of fast electrons.

Fig. 1.

Now let us consider the influence of the reverse current electric field on the generation of Langmuir waves. Fig. 2 shows the results of calculations of the fast electron functions f and the spectral energy density of Langmuir waves $W_k$at $n_e = 5\cdot10^{10}\text{cm}^{-3}$, $n_b = 10^9\text{cm}^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$. As can be seen, the effect of the reverse current electric field at the considered parameters of the plasma and fast electrons weakly changes the electron distribution function f, but leads to a decrease in the spectral energy density of Langmuir waves by a factor of about 1.5. The merging of plasma waves produces electromagnetic waves, which are registered as radio waves. Considering that the power of this radiation is $\sim W_k^2$, the intensity of radio waves decreases by a factor of$\approx$ 2.

Fig. 2.

Let us consider how the reduction of the plasma concentration will affect the evolution of the fast electron distribution f and the spectral energy density of Langmuir waves W_k. Fig. 3 shows the results of calculations at $n_e = 10^{10}$ cm^{-3}, $n_b = 10^9\text{cm}^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$. As can be seen, the influence of electric field at considered parameters of plasma and fast electrons leads to faster relaxation of fast electrons and reduces the spectral energy density of plasma waves $W_k$approximately in 5 times and accordingly the intensity of radio waves decreases in$\approx$ 25 times.

Comparing the results of calculations presented in Figs. 2 and 3, we can conclude that the effect of the reverse current electric field on the distribution function of fast electrons becomes significant only at sufficiently large concentrations of fast electrons, i.e., at $n_b > 2\text{-}10^{-2}$ ne.

Fig. 3.

Fig. 4 shows the results of calculations at $n_e= 5\cdot10^{10}cm^{-3}$, $n_b= 10^9cm^{-3}$, $T_e= 10^7$ K, $\delta = 4$, $v_b= 10v_{Te}$. The figure shows that the reverse current electric field also leads to a ≈ 1.5-fold decrease in the Langmuir wave energy. Note that these calculations reflect not only an increase in temperature from 10^6K to 10^7 K, but also a significant change in the initial distribution of fast electrons due to the parameter $v_b= 10v_{Te}$, i.e., when $T_e$increases from 10^6 K to 10^7 K, the value of $v_b$increases from $3.89\cdot10^9$cm/s to $1.23\cdot10^{10}$ cm/s. While keeping the value of $v_b=3.89\cdot10^9$cm/c equal to the value in Figures 2 and 3 results in the fact that the effect of reverse current is almost completely absent.

Fig. 4.

3. CONCLUSIONS

The influence of the reverse current electric field on the generation of Langmuir waves excited in the solar plasma by fast electrons has been considered. It is shown that additional inhibition of fast electrons by the reverse current electric field leads to a decrease in the intensity of excited plasma waves, which will cause a decrease in the intensity of electromagnetic waves generated in the region of the double plasma frequency at the merging of Langmuir plasmons. At the same time, a decrease in the ratio of the plasma electron concentration to the fast electron concentration will enhance this effect. Increasing the plasma temperature while keeping $v_b$constant leads to a decrease in the effect of the reverse current electric field as a result of a decrease in the number of suprathermal electrons, while increasing $v_b$enhances the effect.

FUNDING

This work was funded from the Institute's budget. No additional grants were received to conduct or supervise this particular study.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

REFERENCES

1. *Ginzburg V.L. and Zheleznyakov V.V.* On possible mechanisms of sporadic radio emission from the Sun (Radiation in isotropic plasma) // Astronomical Journal, V. 35, No. 5, P. 694-712, 1958.
2. *Zheleznyakov V.V., Zaitsev V.V.* On the theory of solar radio emission flashes of type III // Astron. Journal. V. 47. No. 1. P. 60. 1970.
3. *Kaplan S.A., Tsytovich V.N.* Plasma astrophysics. - M. N.: Nauka. – 440 c. 1972.
4. Samara State University Named After A. N.A. N. Theory Of Difference Schemes, Moscow: Nauka. - 616 p. ill. 1989.
5. *Sermulynsh V.A., Somov B.V. T*he problem of reverse current during heating of the solar atmosphere by accelerated electrons // Proceedings of the XII Leningrad Seminar on

Cosmophysics "Complex study of the Sun", Leningrad, February 6-8, 1982. Under the reaction of V.A. Dergachev and G.E. Kocharov. Leningrad: LIAF, 1982. P. 90-95.
6. *Tsytovich V.N.* Theory of turbulent plasma - M. N.: Atomizdat. - 424 p. ill. 1971.
7. *Charikov Yu.E., A.N. Shabalin.* Influence of Magnetic Turbulence on the Propagation of Accelerated Electrons and Hard X_Ray Brightness Distribution in Solar Flares // Geomagnetism and Aeronomy, 2015, Vol. 55, No. 8, pp. 1104–1111.
8. *Diakonov S.V., Somov B.V.* Thermal electrons runaway from a hot plasma during a flare in the reverse-current model and their X-ray bremsstrahlung // Solar Physics. V. 116, P. 119-139. 1988.
9. *Kontar E.P., Ratcliffe H., and Bian N.H.* Wave-particle interactions in non-uniform plasma and the interpretation of hard X-ray spectra in solar flares // Astronomy and Astrophysics. V. 539. A43. 2012.
10. *Kudryavtsev I.V. and Kaltman T.I.* On the influence of Langmuir wave spectra on the spectra of electromagnetic waves generated in solar plasma with double plasma frequency // MNRAS. V. 503, P. 5740. 2021.
11. *Kudryavtsev I.V., Kaltman T.I. and M. Karlický.* Diagnostics of the dynamics of the Langmuir spectrum based on radio emission during the 12 March 2015 solar radio burst // A&A, 665, A98, 2022.
12. *Kudryavtsev I.V., Kaltman T.I., Vatagin P.V. and Charikov Yu.E.* Dynamics of Fast Electrons in an Inhomogeneous Plasma with Plasma Beam Instability // Geomagnetism and Aeronomy. V. 59. No. 7. pp. 838–842. 2019.
13. *Melnikov V.F., Charikov Yu.E., and Kudryavtsev I.V.* Spatial Brightness Distribution of Hard X_Ray Emission along Flare Loops // Geomagnetism and Aeronomy. V. 53. No. 7. P. 863–866. 2013.
14. *Nocera L., Skrynnikov Iu.I., Somov B.V.* Hard X-Ray Bremsstrahlung Produced by Electrons Escaping a High-Temperature Thermal Source in a Solar Flare // Solar Physics. V. 97. P. 81-105. 1985.
15. *Ratcliffe H. and Kontar E.P.* Plasma radio emission from inhomogeneous collisional plasma of a flaring loop// Astronomy and Astrophysics. V 562, A57. 2014.
16. *Ratcliffe H., Bian N.H. and Kontar E.P.* Density fluctuations and the acceleration of electrons by beam-generated langmuir waves in the solar corona//The Astrophysical Journal, 2012, 761:176 (8pp).
17. *Ratcliffe H., Kontar E.P., Reid A.S.* Large-scale simulations of solar type III radio bursts: flux density, drift rate, duration, and bandwidth // Astronomy and Astrophysics. V. 572. A111. 2014.

18. *Reznikova V.E., Melnikov V.F., Shibasaki K., et al.* // The Astrophysical Journal. V. 697. P. 735-749. 2009.

19. *Spicer D.S.* A comment on the acceleration of charged particles in the presence of micro-turbulence as related to solar flares // Solar Physics, V. 51. P431. 1977.

20. *Vatagin P.V. and Kudryavtsev I.V.* Spatio-temporal Dynamics of Fast Electrons and Plasma Turbulence in an Inhomogeneous Flare Plasma // Geomagnetism and Aeronomy. V. 61, No.8, pp. 1135 - 1140. 2021.

21. *Zaitsev V.V. and Stepanov, A.V.* The plasma radiation of flare kernels // Sol. Phys., 1983, vol. 88, pp. 297‑313.

22. *Zharkova V.V., Kuznetsov A.A., Siversky T.V.* Diagnostics of energetic electrons with anisotropic distributions in solar flares. I. Hard X-rays bremsstrahlung emission // Astronomy and Astrophysics. V. 512. A8. 2010.

FIGURE CAPTIONS

Fig. 1. Distribution function of fast electrons when only Coulomb collisions are considered (solid line) and when Coulomb collisions and the reverse current electric field are considered together (dashed line) when $n_e = 5\cdot 10^{10} cm^{-3}$, $n_b = 10^9 cm^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$.

Fig. 2. (a) Evolution of the electron distribution function f without (solid line) and with consideration of the reverse current electric field (dashed line); (b) Langmuir wave energy spectral density $W_k$without consideration of the reverse current electric field and with consideration (c) at $n_e = 5\cdot 10^{10} cm^{-3}$, $n_b = 10^9 cm^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$.

Fig. 3. (a) Evolution of the electron distribution function f without (solid line) and with consideration of the reverse current electric field (dashed line); (b) Langmuir wave energy spectral density $W_k$without consideration of the reverse current electric field and with consideration (c) at $n_e = 10^{10} cm^{-3}$, $n_b = 10^9 cm^{-3}$, $T_e = 10^6$ K, $\delta = 4$, $v_b = 10v_{Te}$.

Fig. 4. Langmuir wave spectral energy densities $W_k$without considering the reverse current electric field (a) and with considering the reverse current electric field (b) at $n_{(e)} = 5\cdot 10^{10} cm^{-3}$, $n_b = 10^9 cm^{-3}$, $T_e = 10^7$ K, $\delta = 4$, $v_b = 10v_{Te}$.

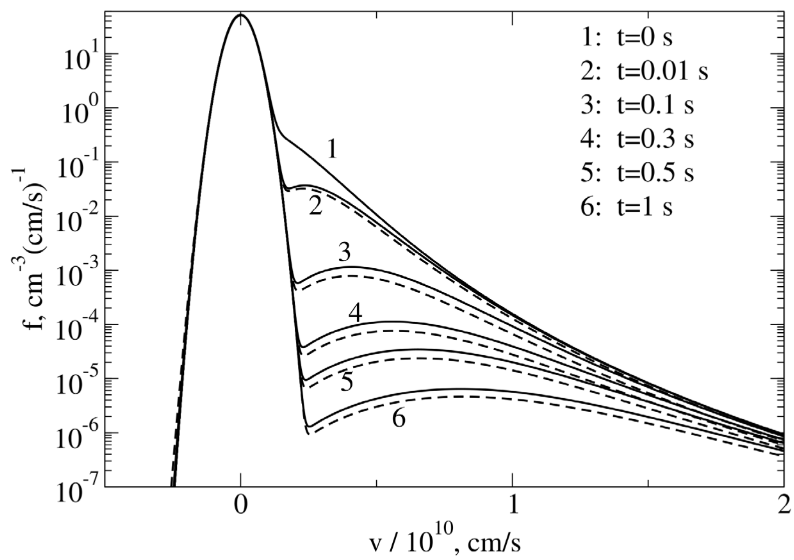
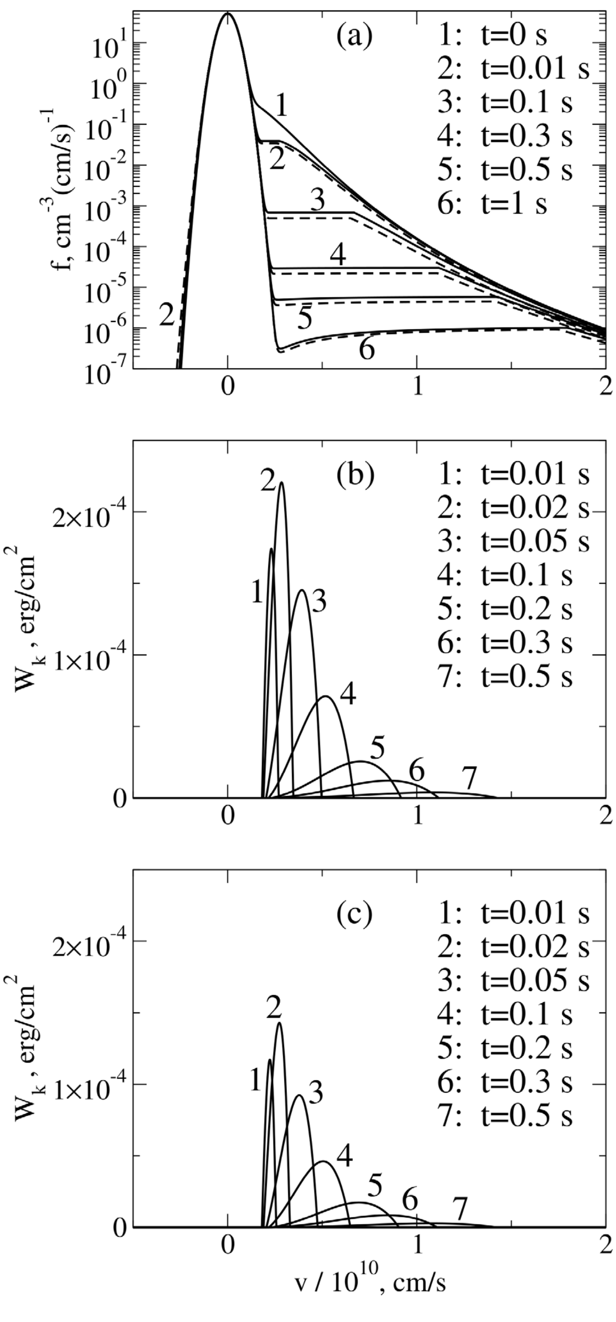


Fig. 1.



(a)
1: t=0 s
2: t=0.01 s
3: t=0.1 s
4: t=0.3 s
5: t=0.5 s
6: t=1 s
f, cm^{-3}(cm/s)$^{-1}$
(b)
1: t=0.01 s
2: t=0.02 s
3: t=0.05 s
4: t=0.1 s
5: t=0.2 s
6: t=0.3 s
7: t=0.5 s
W$_k$, erg/cm^2
(c)
1: t=0.01 s
2: t=0.02 s
3: t=0.05 s
4: t=0.1 s
5: t=0.2 s
6: t=0.3 s
7: t=0.5 s
W$_k$, erg/cm^2
v / 10^{10}, cm/s

Fig. 2.

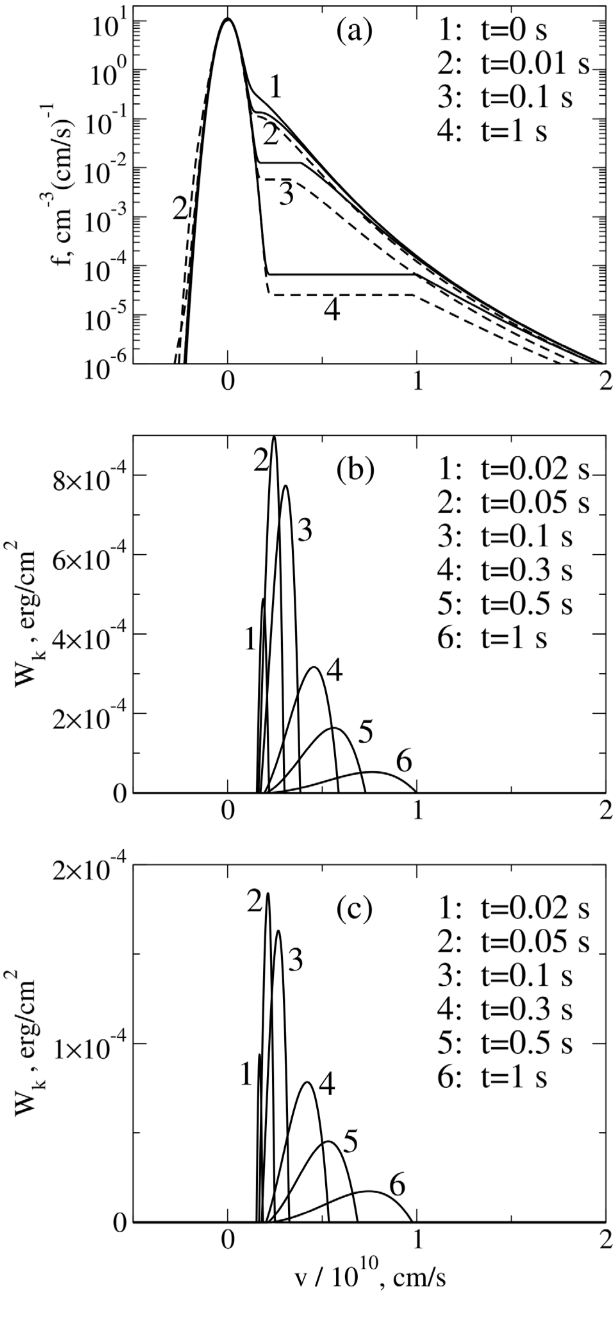

(a)
1: t=0 s
2: t=0.01 s
3: t=0.1 s
4: t=1 s
f, cm^-3 (cm/s)^-1
(b)
1: t=0.02 s
2: t=0.05 s
3: t=0.1 s
4: t=0.3 s
5: t=0.5 s
6: t=1 s
W_k , erg/cm^2
(c)
1: t=0.02 s
2: t=0.05 s
3: t=0.1 s
4: t=0.3 s
5: t=0.5 s
6: t=1 s
W_k , erg/cm^2
v / 10^10, cm/s

Fig. 3.

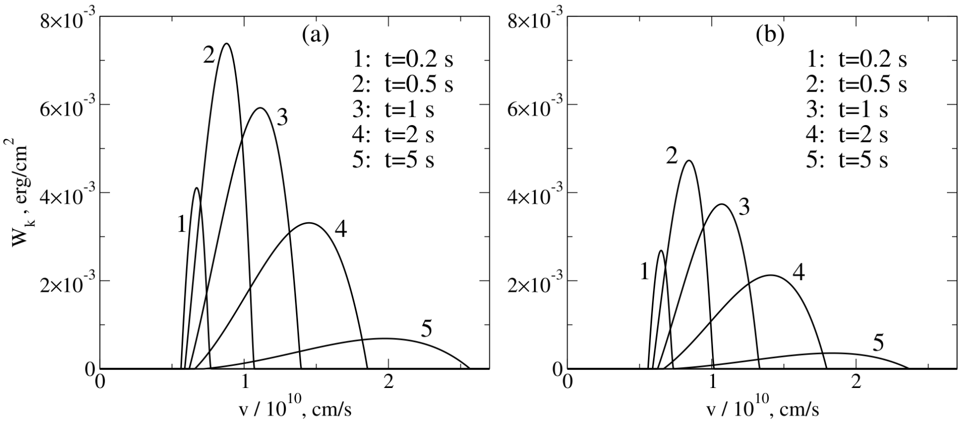


Fig. 4.