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COLLISIONLESS SLOWING DOWN OF NOVA AND SUPERNOVA SHELLS IN MAGNETIZED INTERSTELLAR MEDIUM

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The collisionless interaction of an expanding plasma cloud with a magnetized background plasma is examined in the framework of a 3D kinetic-hydrodynamic model. The slowing down of a hydrogen cloud is studied for high Alfven-Mach numbers and magneto-laminar interaction parameters. A particle-in-cell method is used to study the dynamics of the magnetic field, plasma cloud, background plasma, and collisionless shock wave generated by the intense particle flux. A numerical simulation is consistent with the nonstationary interactions between the plasma shells formed during nova and supernova explosions and the interstellar plasma medium.
Keywords: *(stars:) novae, supernovae -ISM: magnetic fields*

1. Introduction

The problem of the interaction rarefied plasma flows with a surrounding background magnetized plasma arises during research on the dynamics of solar flares and on the flow of the solar wind around the earth's magnetosphere, in active experiments with plasma clouds in space, and in the course of interpreting a number of astrophysical observations [1-6]. Research on this problem is of considerable interest in connection with experiments on controlled thermonuclear fusion [7,8] and laboratory simulations of laser plasmas in external magnetic fields [3,9].

Phenomena of this sort, of course on substantially higher energy and spatial-temporal scales, have recently been under intense discussion in connection with explosive astrophysical processes, which are characterized by the release of immense energy and are accompanied by the formation of powerful high-velocity plasma structures— expanding spherical and annular shells, jets, etc. According to astrophysical observations and theoretical studies [10], the rather massive shells ejected during explosions interact strongly with the interstellar medium and with the intergalactic magnetic field. Thus, free expansion of the ejected shell of a supernova is possible only in the early stages of its evolution. Then it is slowed down with the transfer of energy-momentum to the surrounding plasma background and magnetic field. The problem

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of the collisionless slowing down of the residue of supernovae was first formulated by Oort [11] and subsequently analyzed in detail by Shklovskii [12].

The slowing down process is characterized by the radius for slowing down of the cloud by the magnetic field, R_H, and the gas dynamic slowing down radius $\widetilde{R}$. An expression for R_H can be obtained by equating the initial kinetic energy W_0 of a spherical cloud to the energy of the magnetic field that it pushes out in expanding to radius R_H [13], i.e., $R_H = \left(6W_0/H_0^2\right)^{1/3}$. Here H_0 is the intensity of the unperturbed magnetic field.

As the cloud expands, it draws the background plasma into a combined motion. Along with this, the mass of expelled plasma increases. The radius of the sphere within which the mass of the cloud and that of the background plasma drawn into the combined motion become equal is referred to as the gas dynamic slowing down radius: $\widetilde{R} = \left(3M/4\pi n_* m_*\right)^{1/3}$, where n_* and m_* are the density and mass of the background plasma ions ("snowplow" model [12]) and M is the mass of the ejected shell. Taking $n_* \cong 0.1\,\mathrm{cm}^{-3}$, $M = 10^{-3}\,M_\odot$ ($M_\odot = 2\cdot 10^{33}$ g is the mass of the sun), and $m_*=m_H$ (m_H is the mass of a hydrogen ion) as typical values of the parameters, we obtain $\widetilde{R} = 0.46$ pc.

The smaller of the radii, R_H or $\widetilde{R}$, determines the predominant mechanism for slowing down of the cloud—magnetic or gas dynamic. The relationship $R_H/\widetilde{R} = M_A^{2/3}$, where $M_A = u_0/V_A$ is the Alfven-Mach number (u_0 is the initial expansion velocity of the cloud) and $V_A = H_0/\sqrt{4\pi n_* m_*}$ is the Alfven velocity in the background plasma, implies that for $M_A \ll 1$ the cloud loses energy as a result of the deformation and displacement of the magnetic field, while for $M_A \gg 1$ the slowing down is caused by the interaction with the background plasma [14-18]. Since the characteristic velocities of supernova shells are of order $u_0 \cong 10^8 \div 10^9$ cm/s for typical magnetic fields $H_0 \cong 3\cdot 10^{-6}$ G, we find that $M_A \cong 50 \div 500$. Thus, the ejected shells of supernovae can only be slowed down as a result of their interaction with the background plasma medium; that is, the slowing down is gas dynamic in character. In this paper, we study this problem using a hybrid model for the plasma with a numerical simulation employing a particle-in-cell method.

2. Statement of the problem

An analysis shows that the gas dynamic slowing down can only be ensured by a collisionless laminar (or turbulent) mechanism [3] associated with the generation of vortical electric fields E_i in the leading edge of the cloud or by a collisional mechanism owing to pairwise collisions of ions from the shell with ions, neutral atoms, and electrons in the interstellar medium.

We begin by briefly examining the effects of pairwise collisions, based on an analysis of Refs. 19 and 20. The ions in the cloud lose their energy and transfer it to the ions in the background plasma in multiple Coulomb ion-ion or ion-electron scattering events with a mean free path given by

$$\lambda_{ii} = \left(\frac{mu_0^2}{2}\right)^2 \frac{1}{\pi(1+m/m_*)ZZ_* n_* e^4 \ln\Lambda}, \tag{1}$$

or $\lambda_{ie} = (m_e/m)(1+m/m_*)\lambda_{ii}$, respectively, and in screened Coulomb repulsions with a mean free path given by

$$\lambda_{iN} = \frac{mu_0^2}{2}\sqrt{S^{2/3}+S_*^{2/3}}\,\frac{1}{a_0 S S_* n_* e^2}. \tag{2}$$

Here Z and Z_* are the charges of the background and cloud ions, S and S_* are the charges of the nuclei in the cloud and background (in a hydrogen plasma Z=S=1), a_0 is the Bohr radius, $\ln\Lambda$ is the Coulomb logarithm of the background plasma, and m is the mass of the cloud ions. As for screened polarization nuclear attraction processes, they are of no importance here since the mean free path for that process under astrophysical conditions is enormously greater than λ_{ii} and λ_{iN} [19,20]. Note also, that Eqs. (1) and (2) have been obtained for conditions such that the magnetic field does not influence the Coulomb scattering process. In fact, for $H_0 \cong 3\cdot 10^{-6}$ G, $n_* \cong 0.1$ cm^{-3}, and $m_* = m_H$ (hydrogen plasma), we obtain the following estimates for the electron cyclotron and plasma frequencies: $\omega_{pe} = 1.8\cdot 10^4$ s^{-1} and $\omega_{ce}/\omega_{pe} \cong 3\cdot 10^{-3} << 1$, which is the condition for applicability of Eqs. (1) and (2).

We now estimate the mean free paths for these collisional processes during propagation of supernova residues at a characteristic velocity u_0=10^9 cm/s through the interstellar medium in the case of hydrogen shell and background plasmas with an electron temperature on the order of T_e=1 eV ($\ln\Lambda \cong 25$) and with the parameter values given above. The gas dynamic slowing down radius for a typical supernova is ...pc.., while Eqs. (1) and (2) imply that $\widetilde{R} = 0.46$ pc, $\lambda_{ii} = 2.75\cdot 10^5$ pc, and $\lambda_{iN} = 3.15\cdot 10^3$ pc. These estimates imply that collisional processes cannot slow the cloud down, since $\widetilde{R} << \lambda_{ie}$, λ_{iN}, and λ_{ii}. Thus, it is important to examine collisionless mechanisms for this interaction.

The first group of collisionless interaction mechanisms are collective turbulent mechanisms (anomalous viscosity, anomalous resistivity) during the development of ion-ion or electron-ion beam instabilities [21]. The condition for excitation of the ion-ion instability has the form [22] $u_0^2 \le V_A^2 + 2c_s^2$ or

$$M_A^2 \le 1 + \frac{2c_s^2}{V_A^2}, \tag{3}$$

where $c_s = \sqrt{T_e/m_*}$ is the ion sound speed in the plasma. For typical values of the parameters, $c_s \cong 10^6$ cm/s and $V_A \cong 2\cdot 10^6$ cm/s. Thus, according to Eq. (3), M_A<2 and the observed slowing down of the expanding clouds cannot be caused by turbulent anomalous viscosity, since the characteristic Alfven-Mach number $M_A \cong 50 \div 500$.

The second group is the collisionless laminar slowing down mechanism associated with the generation of vortical electric fields. It is known that the role of vortical electric fields becomes predominant as M_A increases, since $E_i/E_p \sim M_A^2$ [3,6], where E_p is the polarization electric field that arises as a result of the drop in the gas dynamic and magnetic pressure at the boundary of the cloud. A model for energy exchange between the cloud and the background plasma owing to the combined effect of the gyrorotation of the ions and the generation of vortical electric fields when M_A>1 (the "magnetic laminar mechanism" (MLM) for slowing down) has been proposed [14,15]. Analytic solutions for the initial expansion phase, when only a vortical electric field E_i develops, showed that the fraction of energy given up by the cloud is proportional to $\delta = \left(\widetilde{R}/R_L\right)^2$ (the MLM interaction parameter), where R_L is the Larmor radius of the cloud ions. Thus, the intensity of the collisionless interaction between the cloud and the background plasma is determined by the parameter δ, as well as by the Alfven-Mach number M_A.

3. Numerical simulation based on a hybrid plasma model

We shall carry out a numerical simulation of the collisionless interaction of a supernova shell with the interstellar medium using a hybrid plasma model, in which the ion component is described by a Vlasov kinetic equation and the electron component, by the equations of gas dynamics. Note that this kind of method has been used extensively elsewhere. (See, for example, Refs. 14-18). This hybrid model is justified by the fact that, because of the slowing down of the shell, a collisionless shock wave can be generated in the background plasma with hydrodynamic breaking of the leading edge and formation of a multiflux flow. Thus, the structure of this sort of supercritical collisionless shock wave on spatial scales of $R \sim \widetilde{R}$ can only be described adequately in terms of a hybrid approximation [6]. Note also, that, although the approximation of collisionless magnetohydrodynamics is valid for $\delta >> 1$, it is unsuitable for describing the formation and dynamics of a collisionless shock wave.

The initial system of equations consists of a Vlasov kinetic equation for the ions, the equations of motion and internal energy for the electron component, and Maxwell's equations for the electromagnetic field. In the case of a hydrogen cloud being slowed down in a hydrogen background plasma this system of equations has the following form:

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \frac{\partial f_i}{\partial \mathbf{r}} + \mathbf{F} \cdot \frac{\partial f_i}{\partial \mathbf{v}} = 0, \quad \mathbf{F} = \frac{e}{m_H}\left(\mathbf{E} + \frac{1}{c}[\mathbf{v} \times \mathbf{H}]\right), \tag{4}$$

$$\frac{\partial \mathbf{v}_e}{\partial t} + (\mathbf{v}_e \nabla)\mathbf{v}_e = -\frac{e}{m_e}\left(\mathbf{E} + \frac{1}{c}[\mathbf{v}_e \times \mathbf{H}]\right) - \frac{1}{m_e n}\nabla(nT_e), \tag{5}$$

$$\frac{\partial T_e}{\partial t} + (\mathbf{v}_e \nabla)T_e + \frac{2}{3}T_e \nabla \mathbf{v}_e = 0, \tag{6}$$

$$\frac{\partial n}{\partial t} + \nabla(n\mathbf{v}_e) = \frac{\partial n}{\partial t} + \nabla(n\mathbf{v}_i) = 0, \tag{7}$$

$$\nabla \times \mathbf{H} = \frac{4\pi ne}{c}(\mathbf{v}_i - \mathbf{v}_e), \quad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \quad \nabla \cdot \mathbf{H} = \nabla \cdot \mathbf{E} = 0 \tag{8}$$

$$n = n_e = n_i = \int f_i(\mathbf{r}, \mathbf{v}, t)\, d\mathbf{v}, \quad \mathbf{v}_i(\mathbf{r}, t) = \langle \mathbf{v} \rangle = \frac{1}{n}\int \mathbf{v} f_i(\mathbf{r}, \mathbf{v}, t)\, d\mathbf{v}. \tag{9}$$

Here $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field intensities, m_H is the mass of the hydrogen ion, $\mathbf{v}_e$, and $\mathbf{v}_i$ are the mass averaged electron and ion velocities, and T_e is the electron temperature. Note that in Eqs. (4)-(6) we have omitted all the dissipative terms associated with the finite conductivity, viscosity, and thermal conductivity of the plasma. It is easy to show that this approximation is satisfied with wide margins under the conditions of expanding plasma shells in the rarefied interstellar medium. In fact, for example, we can estimate the characteristic diffusion time for the magnetic field: $\tau_m = 4\pi R_L^2 \sigma / c^2$, where σ is the conductivity of the plasma. This implies that $\tau_m / T = 2 M_A^2 (\lambda_{ii} / \widetilde{R}) >> 1$. Here $T = \widetilde{R}/u_0$ is the characteristic slowing down time and λ_{ii} is given by Eq. (1). Similar estimates can also be obtained for the other transport coefficients. In addition, in the Maxwell equations we neglect the displacement current because of the expansion of the cloud is nonrelativistic.

These approximations form the basis of the hybrid collisionless plasma model employed in this paper. It should, however, be emphasized that, although earlier calculations and simulations have demonstrated the practical realizability of this laminar interaction mechanism [3], they were carried out only over a fairly narrow range of parameters $\delta < 4$ and $M_A \leq 10$, while typical supernovae have $R_L \cong 10^{11} \div 10^{12}$ cm and, therefore, $\delta = \left(\widetilde{R}/R_L\right)^2 \cong 10^{14} \div 10^{16}$ for $M_A \cong 50 \div 500$. Although numerical simulations with these parameters are not reproducible at the present time and will scarcely be possible even in the distant future, the numerical simulations in the earlier papers and in this paper do show that, for sufficiently high values of $\delta > 10$ and $M_A > 10$, the energy loss curves acquire a universal character. Thus, there is every reason to suppose that this collisionless interaction mechanism can provide for the slowing down of the ejected shell under the conditions of a typical supernova.

This universality can easily be grasped if we convert Eqs. (4)-(9) for the hybrid model to dimensionless form using the following variables:

$$\widetilde{\mathbf{r}} \to \frac{\omega_{pi}}{c}\mathbf{r}, \quad \widetilde{t} \to \omega_{ci}\, t, \quad \left(\widetilde{\mathbf{v}}_i, \widetilde{\mathbf{v}}_e\right) \to \frac{1}{V_A}\left(\mathbf{v}_i, \mathbf{v}_e\right), \tag{10}$$

$$\widetilde{\mathbf{H}} \to \frac{\mathbf{H}}{H_0}, \quad \widetilde{\mathbf{E}} \to \frac{\mathbf{E}}{\left(V_A/c\right)H_0}, \quad \widetilde{T}_e \to \frac{T_e}{m_H V_A^2}, \tag{11}$$

$$\widetilde{f}_i\left(\widetilde{\mathbf{r}}, \widetilde{\mathbf{v}}, \widetilde{t}\right) \to \frac{V_A^3}{n_*} f_i\left(\mathbf{r}, \mathbf{v}, t\right), \quad \widetilde{n} \to \frac{n}{n_*}, \quad \widetilde{\mathbf{F}} \to \frac{\mathbf{F}}{V_A\, \omega_{ci}}, \tag{12}$$

where ω_{pi} and ω_{ci} are the ion plasma and cyclotron frequencies. Then it is easily seen that solutions of Eqs. (4)-(9) depend only on the parameter m_e/m_H.

Let us consider a two-dimensional, axially symmetric model for the dynamics of a point explosion that forms a cloud of dense plasma expanding into a magnetized background.

At the initial time t=0, an explosion occurs at the point r = 0, z = 0 in a cylindrical region $0 \leq r \leq L_r$, $-L_z \leq z \leq L_z$ with a uniform magnetic field $\mathbf{H}_0 = \left(0, 0, H_0\right)$ and filled with a plasma of density n. The explosion forms a cloud of dense plasma of radius R_0 containing N particles with a total kinetic energy W_0. At the initial time, the velocity of the ions in the cloud is distributed linearly along the radius, i.e.,

$$u(R,0) = \begin{cases} u_m \dfrac{R}{R_0}, & R \leq R_0 \\ 0, & R > R_0\,. \end{cases} \tag{13}$$

Here $R = \sqrt{r^2 + z^2}$ is the magnitude of the radius vector in spherical coordinates and u_m is the maximum velocity of the ions in the cloud and is determined by the initial energy W_0 of the cloud, with $u_m = \left(10\, W_0/3\, N m_H\right)^{1/2} = u_0 \left(5/3\right)^{1/2}$.

The equation for the conservation of energy in this system has the form

$$W = 4\pi L_z \int_0^{L_r} \left(\frac{3}{2} n T_e + \frac{n m_e\, v_e^2}{2} + \frac{H^2}{8\pi}\right) r dr + W_{kin}\,. \tag{14}$$

The total energy of the system consists of the thermal and kinetic energies of the electron gas (the first two terms), the energy of the magnetic field, and the kinetic energy W_{kin} of the ions.

The cloud radius R_0 is considerably smaller than the step size h of the computational grid; that is, we can assume that at the initial time the cloud is concentrated at a point. At the initial time $t = 0$ the background particles are distributed uniformly over the entire region and the particles in the cloud are distributed uniformly in the cloud. The unperturbed values of all quantities are specified at the boundaries of the region $r=L_r$ and $z=\pm L_z$ on the axis $r = 0$ we have

$$\frac{\partial H_z}{\partial r} = \frac{\partial E_z}{\partial r} = \frac{\partial v_{ez}}{\partial r} = \frac{\partial n}{\partial r} = \frac{\partial T_e}{\partial r} = 0, \quad v_{er} = v_{e\varphi} = E_r = E_\varphi = H_r = H_\varphi = 0. \tag{15}$$

With these boundary conditions the calculation can be continued until the time the perturbation reaches the boundary of the region.

The equations of motion for the ions are the equations of the characteristics of the kinetic equation, i.e.,

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i, \quad \frac{d\mathbf{v}_i}{dt} = \mathbf{F}. \tag{16}$$

We have used a particle-in-cell technique to solve these equations. The Maxwell equations and the heat conduction equation are solved using finite difference resolution schemes. A more detailed description of the mathematical model for the process and the numerical simulation algorithm can be found, for example, in Refs. 23-25.

4. Results of the numerical simulations

Numerical simulations were done using a particle-in-cell method and a study was made of the energy and dynamical characteristics of the expansion of a hydrogen plasma into a uniform magnetized background hydrogen plasma at large Alfven-Mach numbers $M_A=45.6$ for a magnetic-laminar interaction parameter $\delta = 84.2$. We emphasize that, as noted above, the following results reflect real astrophysical processes only with an accuracy corresponding to the scales of the resulting curves.

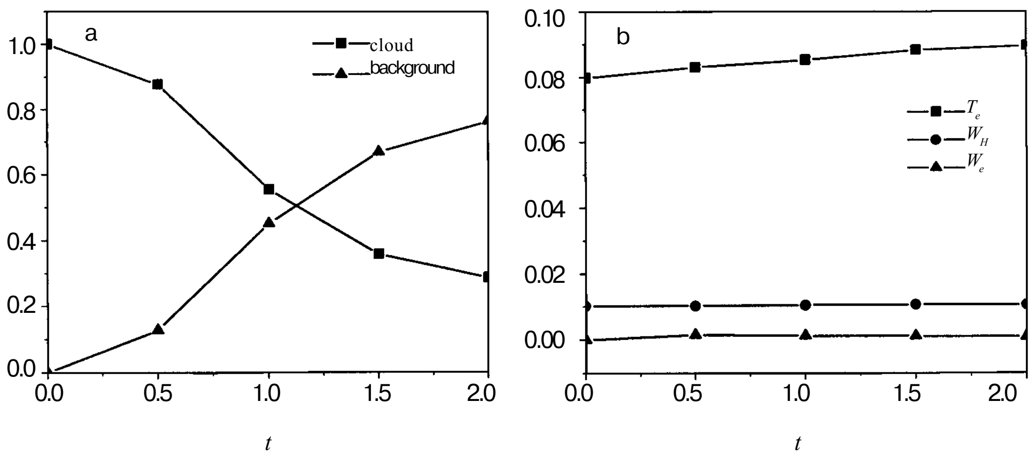

Fig. 1. The time variation in the energy of the cloud and background plasma for $M_A = 45.6$ and δ=84.2. (a) The variation in the total energy of the background plasma (▲) and cloud (■). (b) The variation in the total thermal energy of the electrons (■) and of the magnetic field (●), and in the kinetic energy of the electrons (▲).

TABLE 1. Values of the Parameters for the Numerical Simulation ($M_A = 45.6$, $\delta = 84.2$)

R_L = 2.88 cm	$\tilde{R}$ = 26.4 cm	R_H = 337 cm	T = 9.56 μs
H_0 = 100 G	$W_0 = 4.1 \cdot 10^4$ erg	$u_0 = 2.76 \cdot 10^6$ cm/s	$T_e^{(0)}$ = 0.01 eV
$n_* = 1.3 \cdot 10^{17}$ cm^{-3}	$V_A = 6.05 \cdot 10^4$ cm/s	$\omega_{ci} = 9.58 \cdot 10^5$ s^{-1}	$\omega_{pi} = 4.74 \cdot 10^{11}$ s^{-1}

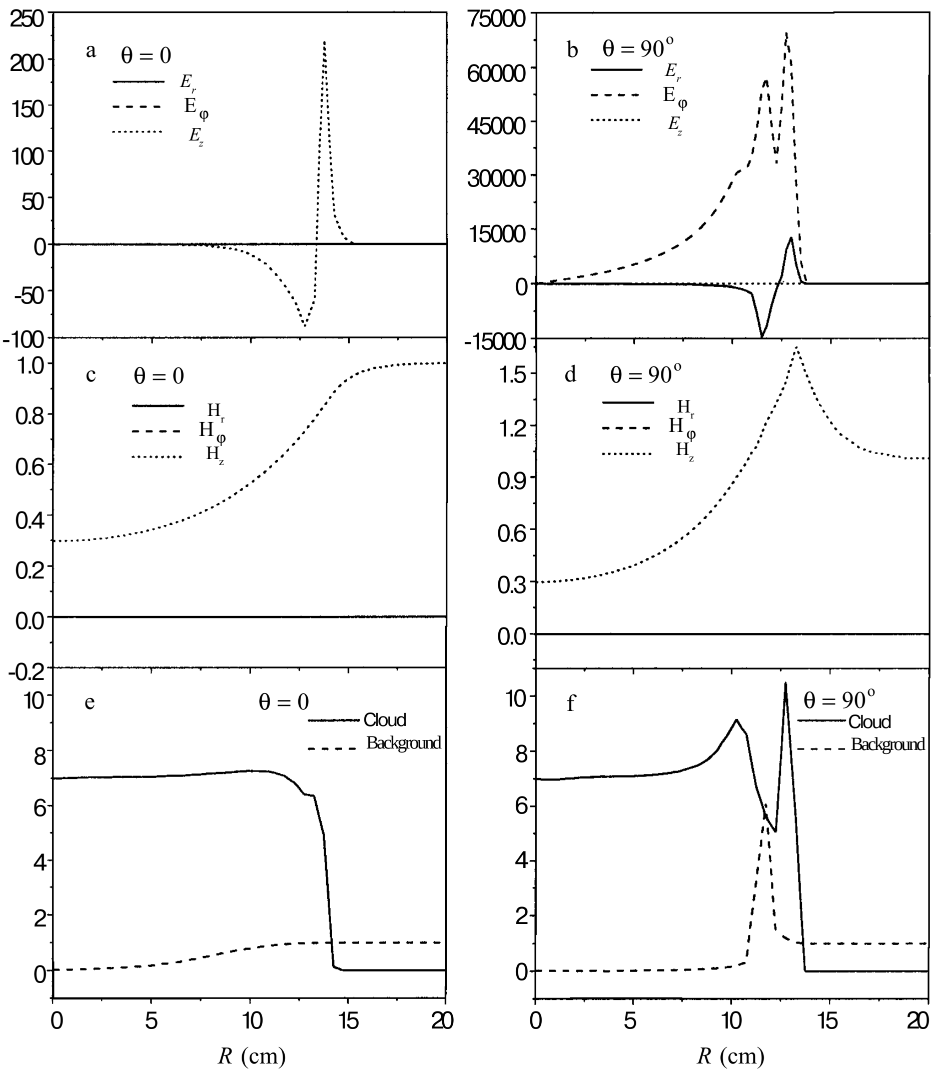

Fig. 2. The distribution over R (in cm) of the electromagnetic fields and densities of the cloud and background plasma for $t = 0.5T$, $M_A = 45.6$, and $\delta = 84.2$ and for two angles θ. (a) and (b) show the distributions of the r (smooth curve), φ (dashed), and z (fine dots) components of the electric field for $\theta = 0$ and $\theta = 90^\circ$, respectively. (c) and (d) show the same for the magnetic field. (e) and (f) show the densities of the cloud (smooth curves) and background plasma (dotted) for $\theta = 0$ and $\theta = 90^\circ$, respectively.

Figure 1 shows plots of the cloud and background energies, and of the variation in magnetic field energy and electron energy, as functions of time. The cloud and background energies are normalized to the initial cloud energy W_0 and the time is expressed in units of the gas dynamic slowing down time $T = \widetilde{R}/u_0$. The values of the characteristic quantities are listed in Table 1, where $T_e^{(0)}$ is the initial electron temperature.

For $t < T$, the energy of the plasma is concentrated mainly in the kinetic energy of the cloud (Fig. 1a). With the passage of time, this energy decreases and at $t = T$, about 50% of the initial cloud energy has been converted to kinetic energy of the background plasma, which represents slowing down by the MLM (magnetic-laminar mechanism). The thermal energy of the electrons has risen by 12% and the magnetic energy has increased by ~5-6% (Fig. 1b).

Figures 2-4 show plots of the electric and magnetic fields, cloud and background densities, and electron temperature as functions of R at times t = 0.5T (Figs. 2 and 4a) and t = 1.5T (Figs. 3 and 4b) at angles $\theta = 0$ and $\theta = 90^0$ to the

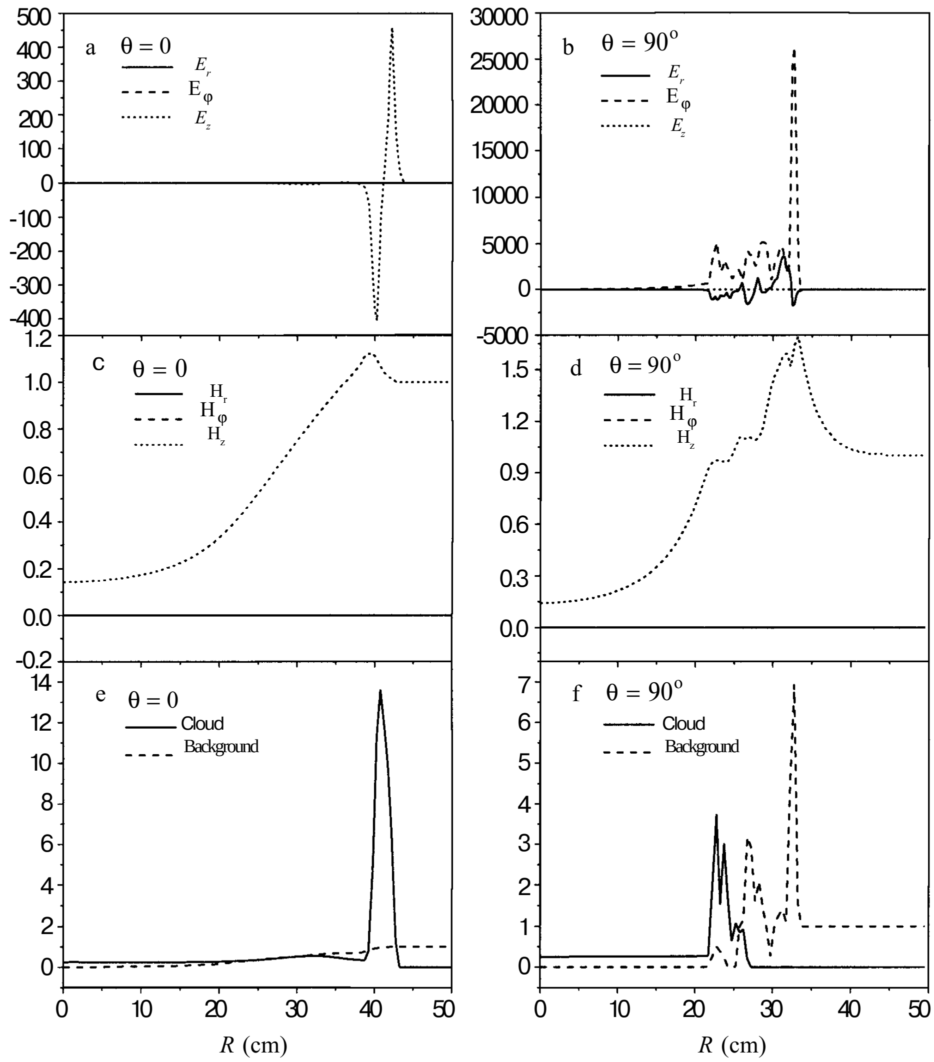

Fig. 3. Same as in Fig. 2, but for t = 1.5T.

lines of force of the magnetic field. All of these quantities are normalized in accordance with Eqs. (11) and (12).

As expected, for $\theta = 0$ the electric field is mainly directed along z ($E_r = E_\varphi = 0$, $E_z \neq 0$) and for $\theta = 90^0$ its azimuthal component predominates ($E_z = 0$, $E_r << E_\varphi$). For arbitrary angles θ, the magnetic field is mainly directed along $\mathbf{H}_0$ ($H_r, H_\varphi \cong 0$, $H_z \neq 0$).

The slowing down of the cloud is accompanied by the formation of an axially symmetric layer of compressed plasma in the background plasma that moves along with the compressed magnetic field; i.e., a collisionless shock wave develops. The amplitude of the magnetic field at the shock front is 1.6 times the unperturbed value. The thickness of the layer is on the order of the ion Larmor radius $R_L = 2.88$ cm, in agreement with an estimate of the thickness of the collisionless shock wave, $\Delta \sim R_L$ [4], for the case of breaking and formation of a multiflux motion. The plasma cloud acquires the shape of an almost spherical shell in which almost all the kinetic energy and mass of the initially spherical cloud is concentrated (Figs. 2 and 3), with the latter being deformed mainly along the direction of the unperturbed magnetic field $\mathbf{H}_0$.

Background particles are transported out of the expansion region; this leads to the formation of a plasma cavity. It correlates with the magnetic cavity, a region of radius $\sim \widetilde{R}$, in which the magnetic field is lower than the unperturbed field because it is squeezed out (Figs. 2 and 3). Thus, there is essentially no electric field in the cavity. In the initial phase of expansion (Fig. 2), the amplitude of the azimuthal component ..... is considerably greater than that of the radial component E_φ; i.e., E_r, $E_\varphi^{max} / E_r^{max} \sim 5$. At time t = 0.5T, the positions of their maxima essentially coincide with the peak density of the cloud.

With the passage of time, the outer boundary of the region transfers energy to the background plasma through electromagnetic interactions. For this reason the distance between the outer boundary of the cloud and the inner boundary of the collisionless shock wave increases. At time t = 1.5T the ratio $E_\varphi^{max} / E_r^{max} \sim 7.2$. Here the position of E_φ^{max} is essentially the same as the outer boundary of the collisionless shock, and E_r is a maximum in the shock front.

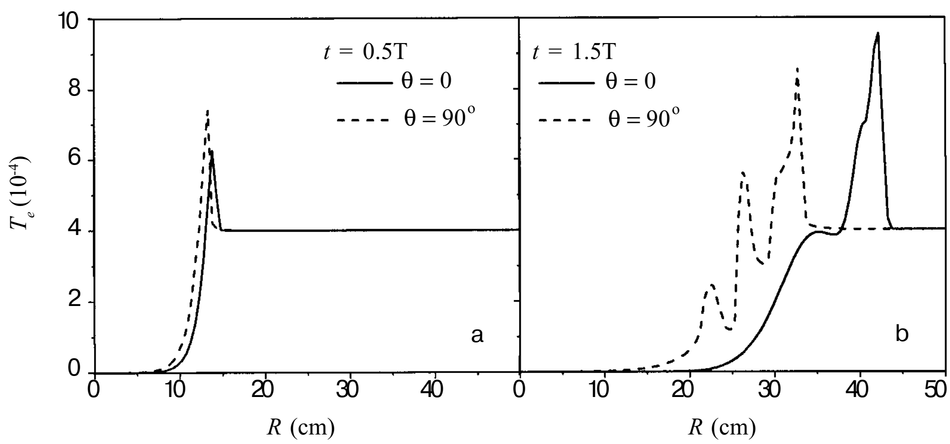

Fig. 4. Distribution over R (in cm) of the electron temperature for M_A = 45.6, δ = 84.2, and t = 0.5T (a) and t = 1.5T (b) for two angles $\theta = 0$ (smooth curves) and $\theta = 90^\circ$ (dashed curves).

An electron thermal wave is generated in the plasma along with the collisionless shock. The spatial distribution of that wave depends significantly on θ (Fig. 4). A layer of electrons heated by the collisionless shock accompanies the shock wave (compare Figs. 2-4) and is distributed in a way so as to compensate the ion charge of the plasma (see Eq. (9)).

This model for the expansion of plasma clouds is valid for t < 2T. At later times the expansion velocity of the cloud and, therefore, the Alfven-Mach number, decrease and our model fails. An analysis shows that under those conditions, the background plasma ions undergo a complicated multiflux motion and quasiperiodic loop structures show up distinctly in the phase planes. (The distance between them is $\sim R_L$.) These are evidence of the breaking of the wave. In addition, we might expect that at long expansion times, turbulent slowing down mechanisms will play an important role. Studies of these questions are currently under way and the results will be published later.

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