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Density cavities generated by plasma–field interactions in the far wake region of a space vehicle*

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Under the consideration of non-steady case, a set of equations is derived, which describes the non-steady nonlinear interactions between plasma and field in the far wake region of a space vehicle. Numerical calculations are also made and the numerical results show that density cavities and electromagnetic solitary waves are generated due to the modulation instability, if the envelope of high frequency modulation field is strong enough. This is of great significance to the detection of disguised space vehicles.

Keywords: plasmas, modulation instability, density cavity
PACC: 5235P, 5240, 5225D

1. Introduction

Since the successful launch of the first artificial satellite, the study of the effects of outer space environment on the motion of space vehicles has become not only an important part in the research of space vehicles, but also valuable in practical applications. It is known that when a space vehicle moves in a low ionosphere, some complicated interactions take place between the vehicle and its surrounding plasma. As more and more space vehicles enter the outer space and/or re-enter the atmosphere (such as missiles), it has become important to study such interactions. Now, there have been a large number of experimental and theoretical researches on the effects in the neighbouring region of a space vehicle.[1] In the study of interactions between the space vehicle and its surrounding plasma, one of the major aims is to seek for an effective way to detect disguised space vehicles.[2,3] Because of the rapid development of material science, the reflected radar waves have become weaker and weaker, so the effective detection of disguised space vehicles has become even more challenging. In the early work, restricted by the technical conditions of that time, the study was limited to the case of steady state. Therefore, the influence of the nonlinear effect on the density distribution of particles was not considered,[4] which is one of their shortcomings. As is well known, when a vehicle moves in an ionosphere, various plasma waves are stimulated and plasma instability is caused. In the meantime, the antenna system of the space vehicle is emitting high frequency electromagnetic waves. When these waves interact with the plasma, nonlinear effect will lead to some violent variations in the wave intensity, hence to the generation of electromagnetic solitary waves.[5] In fact, some electromagnetic solitary waves with large amplitudes have been observed already.[6] On the other hand, any variation in the density of charged particles can take place, and such a density variation may be easily detected by radar. So, if we have a good knowledge of and can grasp such variations in both the field and the density, we will acquire some information about the motion of the vehicle. Although the vehicles have some features so disguised that they cannot be detected directly by radar waves, the variations in the field and in the density of charged particles as well as their own features cannot be eliminated, which makes it possible to locate the disguised space vehicles by detecting the variations in both the field and the density of charged particles. However, up to now the theoretical study

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on this problem is still very complicated.

The characteristic size of space vehicles is generally on the order of metres, which is much less than the mean free path L of the particles ($L > 10^2$ m) in an ionosphere, so collision effects of the particles can be neglected and their density distribution can be described by the theory of dynamics.[7,8] In addition, as the instabilities of plasma waves and plasmas are typically non-steady and nonlinear, it is very important to consider non-steady-state and nonlinear effects in the study.[9−14] In this paper, a set of non-steady nonlinear coupling equations is derived, which describes the non-steady nonlinear interactions between plasma and field in the far wake region of a space vehicle, and by numerical simulations the distributions of the electric field and the density of particles in the wake region of a space vehicle are obtained.

2. Non-steady nonlinear coupling equations

As the speed of the space vehicle v_0 is typically intermediate between the ion and electron speeds ($v_{\rm Ti} \ll v_0 \ll v_{\rm Te}$), its effect is very small on the electrons in equilibrium. So, we can take the MHD equations to describe the motion of the electrons. Combining them with Maxwell's equations, we have

$$\frac{\partial n_{\rm e}}{\partial t} + \nabla \cdot (n_{\rm e}\boldsymbol{v}_{\rm e}) = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{v}_{\rm e}}{\partial t} + (\boldsymbol{v}_{\rm e}\cdot\nabla)\boldsymbol{v}_{\rm e} = \frac{e}{m_{\rm e}}\Big(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}_{\rm e}\times\boldsymbol{B}\Big) - \frac{\gamma_{\rm e}T_{\rm e}}{m_{\rm e}n_{\rm e}}\nabla n_{\rm e}, \tag{2}$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \tag{3}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{4\pi e}{c}(n_{\rm e}\boldsymbol{v}_{\rm e} - n_{\rm i}\boldsymbol{v}_{\rm i}), \tag{4}$$

$$\nabla \cdot \boldsymbol{B} = 0, \tag{5}$$

In these equations n and $\boldsymbol{v}$ are the density and velocity (subscripts i and e denote ion and electron respectively). $\boldsymbol{E}$, $\boldsymbol{B}$, $\gamma_{\rm e}$ and $T_{\rm e}$ are the intensities of the electric and magnetic fields, the ratio of specific heats, and the electron temperature in energy units respectively. All the other symbols have their usual meanings. The small collision terms have been omitted.

Adopting a two-timescale approximation, each field quantity is decomposed into a fast timescale component ($\sim \omega_{\rm pe}^{-1}$) and a slow timescale component ($\sim \omega_{\rm pi}^{-1}$), and it is assumed that the fast component average is zero on the slow timescale, $A = A_{\rm f} + A_{\rm s}$, i.e. $\langle A_{\rm f}\rangle = 0$. Also, on the slow timescale the condition of quasi-neutrality holds, i.e. we have $\langle en_{\rm e} - en_{\rm i}\rangle = 0$, $n_{\rm s}^{\rm e} = n_{\rm s}^{\rm i} = n_{\rm s}$. Substituting the fast and slow components of each field quantity into the above equations, we have

$$\frac{\partial n_{\rm s}}{\partial t} + \nabla \cdot (n_{\rm s}\boldsymbol{v}_{\rm s}) = 0, \tag{6}$$

$$\frac{\partial \boldsymbol{v}_{\rm s}}{\partial t} + (\boldsymbol{v}_{\rm s}\nabla)\boldsymbol{v}_{\rm s} = \frac{e}{m_{\rm e}}\boldsymbol{E}_{\rm s} - \frac{\gamma_{\rm e}T_{\rm e}}{m_{\rm e}n_{\rm s}}\nabla n_{\rm s} - \frac{1}{2}\nabla\langle(v_{\rm f})^2\rangle, \tag{7}$$

$$\frac{\partial^2 \boldsymbol{E}_{\rm f}}{\partial t^2} + c^2\nabla\times\nabla\times\boldsymbol{E}_{\rm f} + \omega_{\rm pe}^2\boldsymbol{E}_{\rm f} + \frac{\delta n}{n_0}\omega_{\rm pe}^2\boldsymbol{E}_{\rm f} - \gamma_{\rm e}v_{\rm Te}^2\nabla(\nabla\cdot\boldsymbol{E}_{\rm f}) = 0. \tag{8}$$

On the right-hand side of Eq.(7), the small term of the earth geomagnetic field $\boldsymbol{B}_{\rm s}$ has been omitted, and in Eq.(8) $\omega_{\rm pe}^2 = (4\pi n_0 e^2)/m_{\rm e}$. In the calculations $W = E_{\rm f}^2/(4\pi n_0 T_{\rm e}) \leq 1$ should be satisfied.

We introduce the high-frequency modulation field with the following shapes:

$$\boldsymbol{v}_{\rm f} = \frac{1}{2}[\boldsymbol{v}(\boldsymbol{r},t)\mathrm{e}^{\mathrm{i}\omega t} + \text{c.c.}],$$

$$\boldsymbol{E}_{\rm f} = \frac{1}{2}[\boldsymbol{E}(\boldsymbol{r},t)\mathrm{e}^{\mathrm{i}\omega t} + \text{c.c.}], \tag{9}$$

in which $\boldsymbol{v}(\boldsymbol{r},t)$ and $\boldsymbol{E}(\boldsymbol{r},t)$ are slow time-varying functions, and c.c. represents the conjugate complex. Substituting Eq.(9) into Eq.(8), when $\omega \approx \omega_{\rm pe}$, we can obtain the transfer equation of the amplitude of the fast varying field as follows:

$$2\mathrm{i}\omega_{\rm pe}\frac{\partial \boldsymbol{E}}{\partial t} + c^2\nabla\times\nabla\times\boldsymbol{E} - \gamma_{\rm e}v_{\rm Te}^2\nabla(\nabla\cdot\boldsymbol{E}) + \frac{\delta n}{n_0}\omega_{\rm pe}^2\boldsymbol{E} = 0. \tag{10}$$

Similarly, Eq.(7) can be reduced to

$$\frac{\partial \boldsymbol{v}_{\rm s}}{\partial t} + (\boldsymbol{v}_{\rm s}\cdot\nabla)\boldsymbol{v}_{\rm s} = -\frac{e}{m_{\rm e}}\nabla\phi - \frac{\gamma_{\rm e}T_{\rm e}}{m_{\rm e}}\frac{\nabla(n_0+\delta n)}{n_0+\delta n} - \frac{1}{16\pi n_0 m_{\rm e}}\nabla(|\boldsymbol{E}|^2), \tag{11}$$

in which $\boldsymbol{E}_{\rm s} = -\nabla\phi$. Combining Eq.(6) with Eq.(7), we obtain[8]

$$\Big(\frac{\partial^2}{\partial t^2} - \gamma_{\rm e}v_{\rm Te}^2\nabla^2\Big)\frac{\delta n}{n_0} = \frac{e}{m_{\rm e}}\nabla^2\phi + \frac{1}{m_{\rm e}}\nabla^2\Big(\frac{|\boldsymbol{E}|^2}{16\pi n_0}\Big). \tag{12}$$

Under the static limit, the first item on the left-hand side of the above function is much less than the second one, i.e. we can omit the second derivative with respect to time, thus we have

$$\frac{\delta n}{n_0} = -\frac{U_{\rm eff} + e\varphi}{\gamma_{\rm e}T_{\rm e}}, \tag{13}$$

where $U_{\rm eff} = |\boldsymbol{E}|^2/(16\pi n_0)$ denoting the potential function of the high frequency field.

For closing Eqs.(10) and (13), we have to study the effect of the slow varying field ϕ on ions flow. Because the vehicle speed is much greater than the ion thermal speed, only the perturbation caused by the interactions between the vehicle and the ion flow is important. In the kinematical coordinate system of the vehicle, the ion distribution function $f_{\rm i}$ satisfies the collisionless Boltzmann equation

$$\frac{\partial f_{\rm i}}{\partial t} + \boldsymbol{v}\frac{\partial f_{\rm i}}{\partial r} - e_{\rm i}\frac{\partial \phi}{\partial \boldsymbol{r}}\frac{\partial f_{\rm i}}{\partial \boldsymbol{p}} = A_{\rm i}(\boldsymbol{r},\boldsymbol{v},t)\delta(F), \tag{14}$$

in which $A_{\rm i}$ represents the interaction between the vehicle surface and the plasma, $F(\boldsymbol{r}_{\rm s}) = 0$ is the equation of the vehicle surface, $\boldsymbol{r}_{\rm s}$ is the vehicle radius, $\boldsymbol{p}$ is the ion momentum. We assume $f_{\rm i} = f_0 + \delta f$, $(\delta f \ll f_0)$, where

$$f_0 = n_0\frac{(2\pi)^{3/2}}{(m_{\rm i}V_{\rm Ti})^3}\exp\Big(-\frac{\boldsymbol{p}_{\rm u}^2}{2m_{\rm i}^2V_{\rm Ti}^2}\Big)$$

is the equilibrium distribution of the unperturbed ions, which satisfies $n_0 = \int f_0(\mathrm{d}\boldsymbol{p})/(2\pi)^3$. From these equations we can obtain

$$\frac{\delta n}{n_0} = -\frac{e_{\rm i}L}{\gamma_{\rm e}T_{\rm e}}\phi + Q \tag{15}$$

in which

$$L = \frac{\gamma_{\rm e}T_{\rm e}}{n_0}\int \frac{\boldsymbol{K}\cdot(\partial f_0/\partial \boldsymbol{p}_{\rm u})}{\Omega_0 - \boldsymbol{K}\cdot\boldsymbol{u} + \mathrm{i}\varepsilon}\frac{\mathrm{d}\boldsymbol{p}_{\rm u}}{(2\pi)^3}, \tag{16}$$

$$\begin{aligned} Q &= \frac{\mathrm{i}}{n_0}\int \frac{I_\Omega(\boldsymbol{p}_{\rm u})}{\Omega_0 - \boldsymbol{K}\cdot\boldsymbol{u} + \mathrm{i}\varepsilon} \\ &\quad\times \mathrm{e}^{-\mathrm{i}\Omega t + \mathrm{i}\boldsymbol{K}\cdot\boldsymbol{r}}\frac{\mathrm{d}\boldsymbol{p}_{\rm u}}{(2\pi)^3}\mathrm{d}\boldsymbol{\Omega}\mathrm{d}\boldsymbol{K} \\ &= \mathrm{i}\int Q_{\boldsymbol{k}}\mathrm{e}^{\mathrm{i}\boldsymbol{K}\cdot\boldsymbol{r}}\mathrm{d}\boldsymbol{K}, \end{aligned} \tag{17}$$

and in this equation

$$\begin{aligned} I_\Omega(\boldsymbol{p}_{\rm u}) = \frac{1}{(2\pi)^3}\Big[&\int A_{\rm i}(\boldsymbol{r},\boldsymbol{v},t)\frac{\mathrm{d}S_0}{|\nabla F|} \\ &+ \int \frac{\partial(\delta f)}{\partial \boldsymbol{p}_{\rm u}}\cdot\frac{\partial(e_{\rm i}\varphi)}{\partial \boldsymbol{r}}\mathrm{d}\boldsymbol{r}\Big]. \end{aligned} \tag{18}$$

The expression within the brackets of Eq.(18) is just the I function defined by Al'pert *et al.*[1] It is proportional to the number of ions with momentum $\boldsymbol{p}_{\rm u}$ acquired in unit time from the scattering on the vehicle and its surrounding field. The I function is generally determined by the interactions between the vehicle and its surrounding plasma. In the situation of this paper, if the scattering is mirror symmetric, then[1]

$$I_\Omega(\boldsymbol{p}_{\rm u}) \approx -\frac{1}{(2\pi)^3}\pi R_0^2 v_0 f_0(\boldsymbol{p}_{\rm u}), \tag{19}$$

From Eqs.(17) and (19), we can obtain

$$Q = -\frac{v_0^2}{v_{\rm Ti}^2}\frac{\pi R_0^2}{2\pi z^2}\exp\Big(-\frac{v_0^2}{2v_{\rm Ti}^2}\frac{x^2+y^2}{z^2}\Big). \tag{20}$$

In the case of low frequencies $\boldsymbol{v}_{\rm Ti} \gg \boldsymbol{\Omega}_0/\boldsymbol{K}$, $\boldsymbol{\Omega}_0 = \boldsymbol{\Omega} + \boldsymbol{K}\cdot\boldsymbol{v}_0 \approx \boldsymbol{K}\cdot\boldsymbol{v}_0$, we have $L \approx (\gamma_{\rm e}T_{\rm e})/T_{\rm i}$, and by combining Eqs.(13) with Eq.(15), we obtain

$$\begin{aligned} \frac{\delta n}{n_0} = &-\frac{|\boldsymbol{E}|^2}{16\pi n_0(\gamma_{\rm e}T_{\rm e} + T_{\rm i})} \\ &-\frac{T_{\rm i}}{\gamma_{\rm e}T_{\rm e} + T_{\rm i}}\Big(\frac{v_0}{v_{\rm Ti}}\Big)^2\frac{\pi R_0^2}{2\pi z} \\ &\times\exp\Big(-\frac{v_0^2}{2v_{\rm Ti}^2}\frac{x^2+y^2}{z^2}\Big). \end{aligned} \tag{21}$$

Introducing the following dimensionless variables:

$$\hat{\boldsymbol{r}} = \frac{2}{3}\frac{\omega_{\rm pe}}{c_{\rm s}}\mu\boldsymbol{r}, \quad \tau = \frac{2}{3}\mu\omega_{\rm pe}t, \quad n = \frac{3}{4\mu}\frac{\delta n}{n_0},$$

$$\hat{E} = \frac{\sqrt{3}\boldsymbol{E}}{8[\pi n_0\mu(\gamma_{\rm e}T_{\rm e} + T_{\rm i})]^{1/2}}, \quad \hat{\boldsymbol{v}}_0 = \frac{\boldsymbol{v}_0}{C_{\rm s}},$$

$$\mu = \frac{m_{\rm e}}{m_{\rm i}}, \quad \alpha = \frac{C^2}{3v_{\rm Te}^2}, \quad C_{\rm s}^2 = \frac{T_{\rm e}}{m_{\rm i}},$$

we can rewrite Eqs.(10) and (21) as

$$\mathrm{i}\frac{\partial \boldsymbol{E}'}{\partial t} + \alpha\nabla\times\nabla\times\boldsymbol{E}' - \nabla(\nabla\cdot\boldsymbol{E}') + n\boldsymbol{E}' = 0, \tag{22}$$

$$\begin{aligned} n = &-|\boldsymbol{E}'|^2 - \frac{3}{4\mu}\frac{T_{\rm e}}{\gamma_{\rm e}T_{\rm e} + T_{\rm i}}v_0^2\frac{\pi R_0^2}{2\pi z^2} \\ &\times\exp\Big(-\frac{T_{\rm e}}{2T_{\rm i}}v_0^2\frac{r^2}{z^2}\Big). \end{aligned} \tag{23}$$

In this equation R_0, v_0, r and z are dimensionless. Up to now, under the non-steady limit, we have derived the equations that are the nonlinear coupling equations between the high frequency modulation field and the density perturbation, i.e. Eqs.(22) and (23) respectively.

3. Numerical simulation

The distributions of $\boldsymbol{E}$ and δn can be obtained by numerically calculating Eqs.(22) and (23). As the wake region of the vehicle is axially symmetrical about the direction of the vehicle velocity $\boldsymbol{v}_0$, we can take the two-dimensional, three-component form for the electric field $\boldsymbol{E}$ with periodic boundary condition in the

z-direction, and natural boundary condition in the r-direction. The initial perturbing transverse field is taken as

$$\begin{aligned}\boldsymbol{E}'(\boldsymbol{r},\tau=0) = {} & E_0 \sin\Big(\frac{2\pi z}{z_0}\Big)\exp\Big[-\frac{(r-10)^2}{r_0^2}\Big]\boldsymbol{e}_r \\ & + E_0 \sin\Big(\frac{2\pi z}{z_0}\Big)\exp\Big[-\frac{(r-10)^2}{r_0^2}\Big]\boldsymbol{e}_\varphi \\ & + E_0\Big[\frac{z_0}{2\pi(r-10)} - \frac{z_0(r-10)}{\pi r_0^2}\Big] \\ & \times \cos\Big(\frac{2\pi z}{z_0}\Big)\exp\Big[-\frac{(r-10)^2}{r_0^2}\Big]\boldsymbol{e}_z, \quad (24)\end{aligned}$$

in which z, z_0, r and r_0 are dimensionless quantities, z_0 is the period, r_0 is the width of the envelope of the electric field. In the calculations, we select the vehicle and ionization parameters as follows: $v_0 = 10^6$ cm/s,[1] $R_0 = 100$ cm, $T_\mathrm{i} = T_\mathrm{e} = 3000$ K, $n_\mathrm{e} = 10^5/\mathrm{cm}^3$, and $E_0 = 0.8$. The initial perturbing field satisfies the condition of transverse waves $\nabla \cdot \boldsymbol{E}(r, \tau = 0) = 0$, and the period and width are taken as $z_0 = 50$ and $r_0 = 10$ respectively. The spatial limits in simulation are $\Delta z = 50$ and $\Delta r = 25$. They are dimensionless. Converted to dimensional quantities, they correspond to $\Delta z \approx 40$ m, and $\Delta r \approx 20$ m. The distance from the rear surface of the vehicle to the simulating region is $L_0 = 15$, corresponding to $L_0 \approx 12$ m. Under the initial condition of Eq.(24), the solution of Eqs.(22) and (23) is obtained, and the time evolutions of the particle density and electric field are respectively displayed in Figs.1 and 2, in which $n = \delta n/n_0$, $\tau = \tau_n \times \delta\tau$, $\delta\tau = 0.000005$, and $\varphi = \varphi/(\gamma_\mathrm{e} T_\mathrm{e})$.

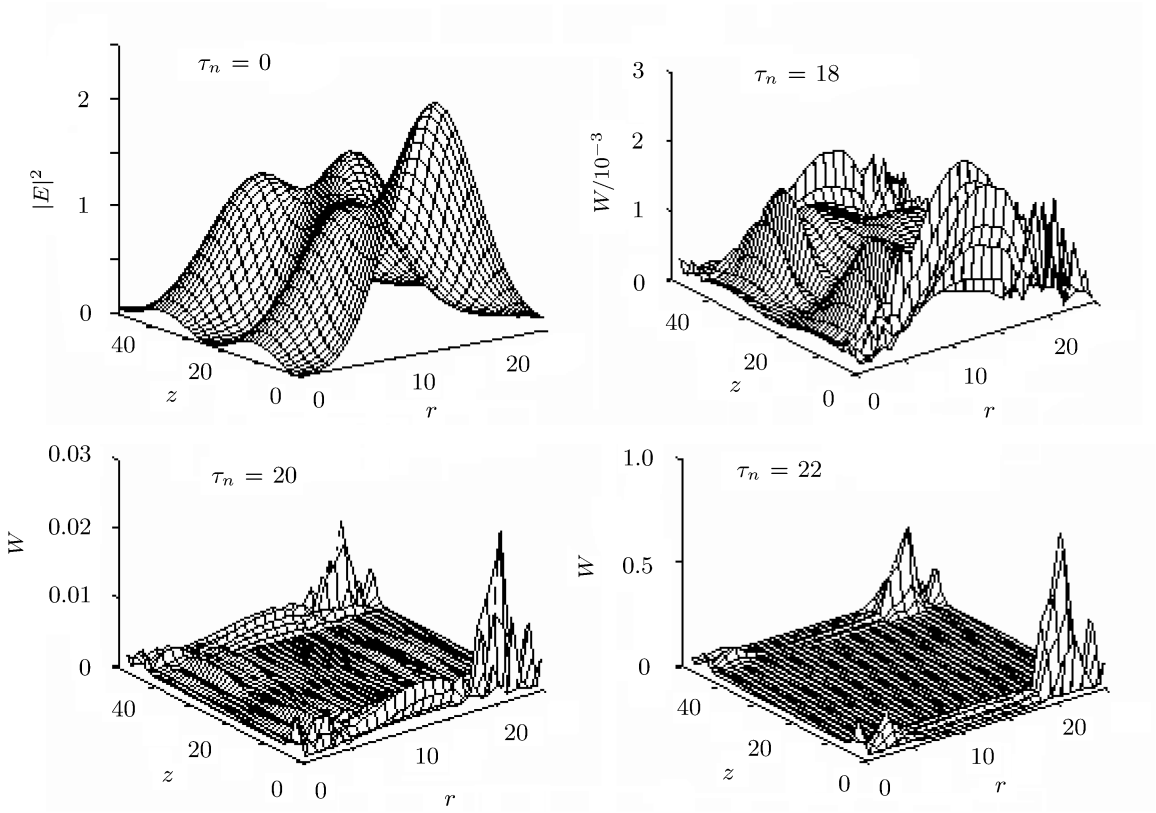


Fig.1. Collapse evolution of the electric field.

4. Results and discussion

The distributions of the electric field and density cavities at four instants of time are shown in Figs.1 and 2. From these figures we can see that the growth ratio of perturbation varies over the calculated space, and is rather large around the peak of the collapse. In Fig.2, we find that the collapse leads to the formation of an electromagnetic solitary wave, and the growth ratio of perturbation is proportional to the electric field, as analysed by the theoretical anticipation.[7]

From Eq.(22) we learn that density perturbation, the field derivative and the intensity all affect the shape of the collapsing field. From Fig.1 we can find

that at the beginning the main part of the density perturbation comes from a non-standard term. Although the non-standard term has a rather small value and the initial distribution of the electric field is also determined by the initial condition, the variation of the derivative of the electric field caused by the non-standard term is very important, because it makes the collapses of field more easily take place around the origin. Actually, it is reasonable that the vehicle will greatly affect the region very close to its rear surface, and cause collapse very easily there. Of course, the final position of the collapse is determined by the combined action of both the non-standard term and the initial perturbation. The non-standard term seems to be more important only for determining the initial position of the collapse, and this point is also indicated by Fig.2.

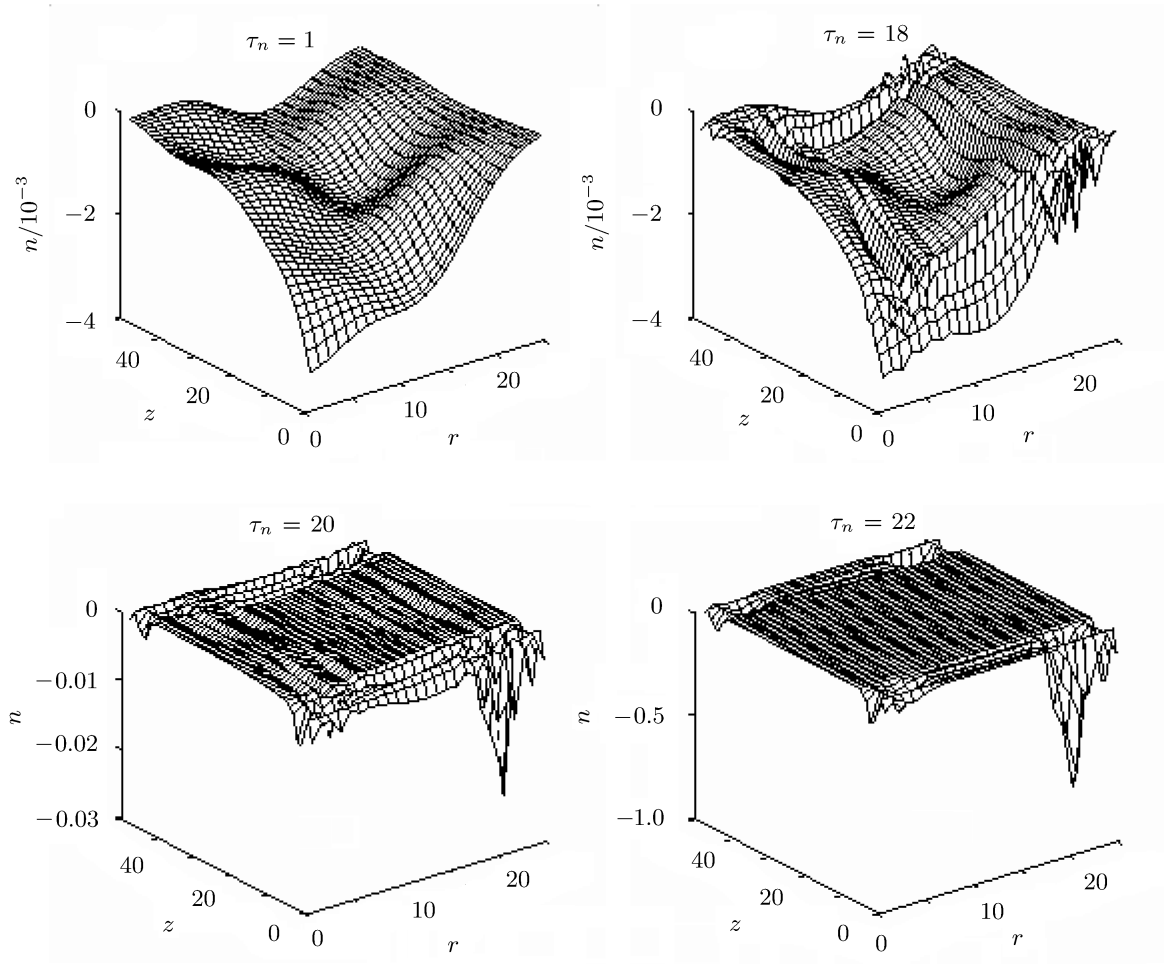


Fig.2. Collapse evolution of density particles.

In Eq.(23), the first term on the right-hand side (i.e. the non-standard term) takes a maximal value at the origin of the simulation region, and it decreases rapidly with increasing distance from the origin. Meanwhile, $|\boldsymbol{E}'|^2$ of the second term on the right-hand side of the density perturbation originates from the massive motive force of the high frequency modulation field, and this means that the maximal density perturbation will occur at the place where the field intensity is maximal. From the figures we know that initially, the first term on the right-hand side of Eq.(23), i.e. the non-standard term, is greater than the term of massive motive force, when it plays a main role. As time goes on, the term of massive motive force gradually becomes important. This point is shown in both Fig.1 and Fig.2. In addition, Fig.1 demonstrates the formation of the density cavity caused by collapse of field. As such density cavities may be exposed to the track of a disguised vehicle, this point is very important for us, thus we will be able to locate the disguised

vehicle by detecting the density cavities.

Finally, we should point out that for transverse plasma waves, the group speed is less than the light speed. So they cannot escape easily from the source region and will interact with the particles sufficiently, and this makes the waves collapse easily. In addition, from our foregoing discussion and analysis we can find that the initial condition Eq.(24) is not the only choice. Any propagating field featuring slow time-varying amplitude may be taken as the initial condition, as long as the condition of transverse waves is satisfied. Different initial conditions may lead to some different distributions of the peaks of collapse, as well as some different collapse speeds, but the general trend of the collapse of the enveloping field will be similar.

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