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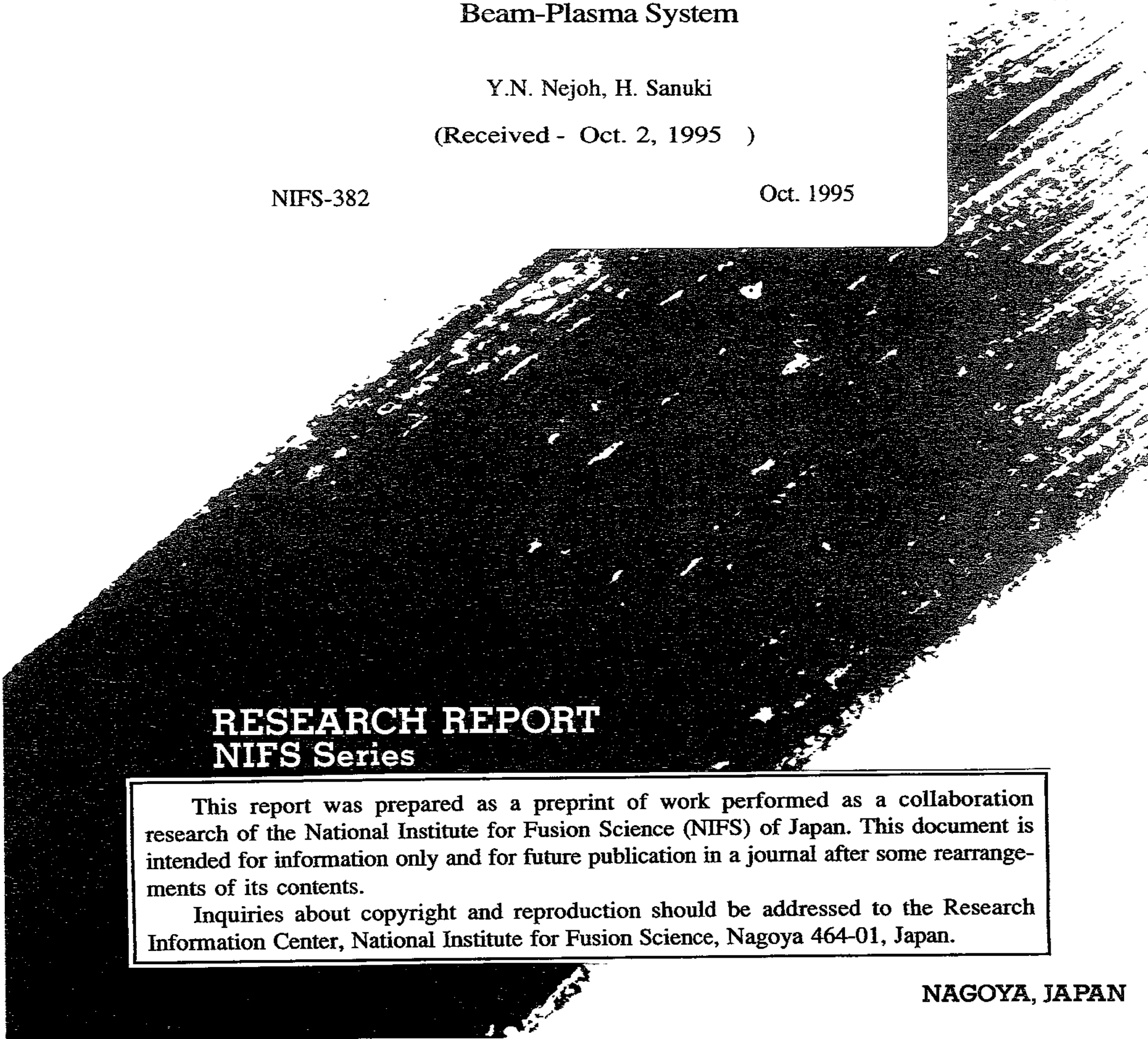

RESEARCH REPORT
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The Effects of the Beam and Ion Temperatures on Ion-Acoustic Waves in an Electron Beam-Plasma System

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The nonlinear wave structures of large amplitude ion-acoustic waves are investigated in a plasma with an electron beam, by the pseudopotential method. The region of the existence of ion-acoustic waves is examined, showing that the condition of the existence sensitively depends on the parameters such as the electron beam temperature, beam density, the ion temperature and the electrostatic potential. It turns out that the region of the existence spreads as the beam temperature increases but the effect of the electron beam velocity is relatively small. New findings of large amplitude ion-acoustic waves in a plasma with an electron beam, are predicted.

Key words: the electron beam temperature, the ion temperature, the region of the existence, the pseudopotential

I. INTRODUCTION

Nonlinear waves may play important roles in rarefied space plasmas in the Earth's auroral zone[1-3], the physics of solar atmosphere[4] and other astrophysical plasmas[5,6]. There has been an increasing interest in interpreting the low frequency nonlinear Langmuir soliton in space observations[7,8]. Observations convince us of the fact that stationary nonlinear ion-acoustic waves may be excited when an electron beam is injected into a plasma[9,10]. In the actual situations, an electron beam component is frequently observed in the region where the ion-acoustic waves exist. On the other hand, it is known that high-speed electrons have an influence on the excitation of various kinds of nonlinear waves in the interplanetary space and the Earth's magnetosphere [11-14]. The ion-acoustic solitons have been reported[15] in the plasma with drifting electrons. However, not many theoretical works on these topics have been done in a plasma with an electron beam.

In this article, we make an attempt to theoretically investigate the possibility of the existence of the large amplitude ion-acoustic waves under the influence of a relativistic electron beam in a plasma consisting of warm ions and hot isothermal electrons. We also demonstrate the region of the existence of the large amplitude ion-acoustic waves and study the dependence of the region of the existence on the parameters such as the electron beam temperature, the beam density, and so on.

The layout of this article is as follows. In Sec.II, we present the basic equations for a plasma with an electron beam and derive the pseudopotential for large amplitude ion-acoustic waves. In Sec.III, we define the condition of the existence of large amplitude ion-acoustic waves and illustrate the dependency of the region of the existence on the several parameters. The last section is devoted to the concluding discussion.

II. BASIC EQUATIONS AND FORMULATION

We assume a plasma consisting of warm ions and hot isothermal electrons traversed by a warm electron beam, and consider one dimensional propagation. We adopt the fluid equations for the ions and beam electrons.

The continuity equation and the equation of motion for ions are described by,

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(n v) = 0 \quad , \qquad (1)$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{3\sigma}{(1+\alpha)^2} n \frac{\partial n}{\partial x} + \frac{\partial \phi}{\partial x} = 0 \ , \qquad (2)$$

where we express the pressure term in eq.(2) by the thermodynamic equation of state. Here, $\sigma = T_i / T_e$ and $\alpha = n_{b0}/n_0$, where $T_i(T_e)$, $n_0(n_{b0})$ are the ion (electron) temperature, the unperturbed background electron(electron beam)density, respectively.

We have the following two equations for the beam electrons,

$$\frac{\partial n_b}{\partial t} + \frac{\partial}{\partial x}(n_b v_b) = 0 \ , \qquad (3)$$

$$\frac{\partial v_b}{\partial t} + v_b \frac{\partial v_b}{\partial x} + \frac{\nu}{\mu} \frac{1}{n_b} \frac{\partial n_b}{\partial x} - \frac{1}{\mu} \frac{\partial \phi}{\partial x} = 0 \ . \qquad (4)$$

We assume an isothermal equation of state for the beam electrons, because of the existence of the finite beam electron temperature. In eq.(4), $\mu = m_e / m_i$, $\nu = T_b / T_e$, where m_e, m_i, T_b denote the electron mass, the ion mass and the beam electron temperature, respectively.

The electron density follows the Boltzmann distribution,

$$n_e = \exp(\phi). \tag{5}$$

The Poisson's equation is given by

$$\frac{\partial^2 \phi}{\partial x^2} = n_e + n_b - n \quad . \tag{6}$$

The variables n_e, n_b, n, v_b, v and ϕ refer to the electron density, the beam electron density, the ion density, the beam electron velocity, the ion velocity and the electrostatic potential, respectively. The velocities are normalized by the ion sound speed $v_s = (\kappa T_e/m_i)^{1/2}$; the time t and the distance x by the ion plasma frequency $\omega_{pi}{}^{-1} = (\varepsilon_0 m_i/n_0 e^2)^{1/2}$ and the electron Debye length $\lambda_D = (\varepsilon_0 \kappa T_e/n_0 e^2)^{1/2}$; the densities by the background electron density n_0 , the potential by $\kappa T_e/e$, where e is the charge of the electron.

In order to solve eqs.(1)-(6), we introduce the variable $\xi = x - Mt$, which is the moving frame with the velocity M. Then the basic equations (1)-(4) and (6) become,

$$-M\frac{\partial n}{\partial \xi} + \frac{\partial}{\partial \xi}(n\, v) = 0 \ , \tag{7}$$

$$-M\frac{\partial v}{\partial \xi} + v\frac{\partial v}{\partial \xi} + \frac{3\sigma}{(1+\alpha)^2} n \frac{\partial n}{\partial \xi} + \frac{\partial \phi}{\partial \xi} = 0 \ , \tag{8}$$

$$-M\frac{\partial n_b}{\partial \xi} + \frac{\partial}{\partial \xi}(n_b v_b) = 0 \quad , \tag{9}$$

$$-M\frac{\partial v_b}{\partial \xi}+v_b\frac{\partial v_b}{\partial \xi}+\frac{\nu}{\mu}\frac{1}{n_b}\frac{\partial n_b}{\partial \xi}-\frac{1}{\mu}\frac{\partial \phi}{\partial \xi}=0, \tag{10}$$

$$\frac{\partial^2 \phi}{\partial \xi^2}=n_e+n_b-n\ . \tag{11}$$

Integrating eqs.(7) and (8) and using the boundary conditions,

$$\phi\to 0,\quad n\to 1+\alpha,\quad n_b\to\alpha,\quad v\to 0,\quad v_b\to v_0\quad \text{at}\quad \xi\to\infty,$$

we obtain

$$n=\frac{1+\alpha}{\sqrt{1-\dfrac{2\phi}{M^2-3\sigma}}}\ . \tag{12}$$

Integrating eqs.(9) and (10) and using the same boundary conditions, we get an equation,

$$n_b=\frac{\alpha}{\sqrt{1-\dfrac{1}{1-(\mu/\nu)(v_0-M)^2}\dfrac{2\phi}{\nu}}}\ , \tag{13}$$

after the brief calculation.

Using eqs.(5), (12) and (13), the Poisson's equation (11) reduces to

$$\frac{d^2\phi}{d\xi^2}=\exp(\phi)+\frac{\alpha}{\sqrt{1-\dfrac{1}{1-(\mu/\nu)(v_0-M)^2}\dfrac{2\phi}{\nu}}}$$

$$-\frac{1+\alpha}{\sqrt{1-\dfrac{2\phi}{M^2-3\sigma}}}=-\frac{dV(\phi)}{d\phi}\ . \tag{14}$$

where $V(\phi)$ denotes the pseudopotential. Integration of eq.(14) gives the *Energy Law,*

$$\frac{1}{2}\left(\frac{d\phi}{d\xi}\right)^2 + V(\phi) = 0 \quad . \tag{15}$$

From eq.(14), the pseudopotential $V(\phi)$ becomes

$$-V(\phi)$$

$$= \exp(\phi) - 1$$

$$- \left[\frac{2\alpha}{\dfrac{1}{1-(\mu/\nu)(v_0-M)^2}\dfrac{2}{\nu}} \right] \left[\sqrt{1-\frac{1}{1-(\mu/\nu)(v_0-M)^2}\frac{2\phi}{\nu}} - 1 \right]$$

$$+ \frac{2(1+\alpha)}{\dfrac{2}{M^2-3\sigma}} \left[\sqrt{1-\frac{2\phi}{M^2-3\sigma}} - 1 \right] . \tag{16}$$

The oscillatory solution of the large amplitude nonlinear ion-acoustic waves exists when the following two conditions are satisfied:

(i) The potential $V(\phi)$ has the maximum value if $d^2V(\phi)/d\phi^2 < 0$ at $\phi=0$. This condition derives the inequality,

$$M^2 > 3\sigma + \frac{1+\alpha}{1+\alpha/\nu} \quad , \tag{17}$$

where we assumed $1 \gg (\mu/\nu)(v_0-M)^2$. Although the subsonic and supersonic ion-acoustic waves can exist in the plasma under consideration, we are now interested only in the supersonic wave. It should be noted that $V(\phi)$ is real, when

$$0<\phi< \frac{\nu}{2}\left[1-\left[\frac{\mu}{\nu}\right](v_0-M)^2\right]$$

and

$$0<\phi<(M^2-3\sigma)/2 \quad .$$

The region of the existence of ϕ is characterized by these conditions.

(ii) Nonlinear ion-acoustic waves exist only when $V(\phi_M)\geqq 0$, where the maximum potential ϕ_M is determined by $\phi_M=(\nu/2)\,[1-(\mu/\nu)(v_0-M)^2]$. This implies that the inequality

$$(1+\alpha)(M^2-3\sigma)\;[1-(1-\frac{\nu}{M^2-3\sigma})^{1/2}]\leqq \alpha\nu+\exp(\nu/2)-1, \qquad (18)$$

holds, where we use the approximation $1\gg(\mu/\nu)(v_0-M)^2$. We show the maximum Mach number as a function of α in Fig.1, where $\nu=0.2$ and $\sigma=0.4$. The maximum Mach number and, correspondingly, the maximum amplitude of the ion-acoustic wave significantly depends on the parameters α, ν and σ.

A complete analytical investigation of the ion-acoustic solitons in an electron beam plasma is possible for small amplitude wave limit($\phi\ll 1$). The specific results can be obtained by expanding $V(\phi)$ in powers of ϕ and keeping up to the third-order terms ϕ^3. Accordingly, equation (16) takes the form

$$-V(\phi)\simeq\frac{1}{2}\left[1+\frac{\alpha}{\nu}-\frac{1+\alpha}{M^2-3\sigma}\right]\phi^2$$

$$+\frac{1}{6}\left[1+3\left(\frac{\alpha}{\nu^2}-\frac{1+\alpha}{(M^2-3\sigma)^2}\right)\right]\phi^3 .$$

Then, integrating (15), we obtain a soliton solution

$$\phi = \frac{3\left[1+\dfrac{\alpha}{\nu} - \dfrac{1+\alpha}{M^2-3\sigma}\right]}{1+3\left[\dfrac{\alpha}{\nu^2} - \dfrac{1+\alpha}{(M^2-3\sigma)^2}\right]} \operatorname{sech}^2\left[\frac{1}{2}\sqrt{1+\frac{\alpha}{\nu} - \frac{1+\alpha}{M^2-3\sigma}}\,(\xi-\xi_0)\right].$$

It should be noted that the ion-acoustic soliton exists in the limiting case with $\phi \ll 1$.

We next consider the region of the existence of the large amplitude ion-acoustic waves in the plasma with an electron beam.

III. THE REGION OF THE EXISTENCE OF LARGE AMPLITUDE ION-ACOUSTIC WAVES

We show a bird's eye view of $-V(\phi)$ in Fig.2, in the case of $\nu=0.2$, $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\mu=1/1836$. Figure 3 illustrates the dependence of the pseudopotential $-V(\phi)$ on the potential ϕ when the ratio of the concentration of the electron beam density to the back ground electron density is fixed to be $\alpha=0.104$, in the case of $\nu=0.2$. In Fig.4, we show a bird's eye view of the pseudopotential when $\nu=0.4$, $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\mu=1/1836$. The pseudopotential $-V(\phi)$ versus potential ϕ in this case is also illustrated in Fig.5 for $\alpha=0.55$.

From Figs.2 and 3, in the case of $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\mu=1/1836$, we can understand the following by the numerical calculation:

(1)In the range of $\alpha>0.280$, the pseudopotential is always positive. In this case, the potential well is not formed.

(2)If $0.086<\alpha<0.280$, the pseudopotential forms the potential well. In the well, large amplitude ion-acoustic waves can propagate. As an example of this case, we illustrate the pseudopotential in Fig.3

when $\alpha=0.104$. The potential well becomes deep as α decreases.

(3)In the range of $0.086>\alpha$, the pseudopotential is always negative. In this case, the well is not formed.

We also understand that the similar properties are described from Figs.4 and 5.

In Fig.6, we illustrate the region of the existence of large amplitude ion-acoustic waves depending on the ratio α of concentration of the electron beam density to the background electron density and the ratio ν of the electron beam temperature to free electron temperature, in the case of $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\mu=1/1836$. Large amplitude ion-acoustic waves propagate in the region bounded by the two curves but do not exist in other regions. In addition, we show the region of the existence of large amplitude ion waves in $\phi-\alpha$ plane in Fig.7-(a), (b) and (c) for $\nu=0.2$, 0.3 and 0.4, respectively. Large amplitude ion-acoustic waves exist in the lower region of the curves.

It turns out that large amplitude nonlinear ion-acoustic waves can exist under proper conditions mentioned above.

IV. CONCLUDING DISCUSSION

The nonlinear wave structures of large amplitude ion-acoustic waves are studied in a plasma with an electron beam. We present the region of the existence of the large amplitude ion-acoustic waves on the basis of the fluid equations for an electron beam-plasma system.

We investigate the conditions of the existence for the stationary supersonic ion-acoustic waves, by analyzing the structure of pseudopotential. Typical results are illustrated in Figs.1-7. The results are briefly summarized as follows:

(1)The conditions of the existence of large amplitude ion-acoustic waves sensitively depend on the electron beam density, the temperature of electron beams and also the ratio of the bulk ion temperature to the electron temperature.

(2)The effect of the concentration of the electron beam density reduces the propagation speed of the ion-acoustic waves.

(3)The allowable range of the concentration of the electron density becomes wider as the beam temperature decreases.

(4)The allowable range of the electrostatic potential becomes wider as the beam temperature increases.

(5)The effect of the velocity of the electron beam is small, compared with the effects of the electron beam temperature, the beam density and the ion temperature.

(6)The region in ($\phi-\alpha$) plane where large amplitude ion-acoustic waves exist, spreads as the beam temperature increases.

The present investigation predicts new findings on large amplitude nonlinear ion-acoustic waves in a plasma with an electron beam. In actual situations, large amplitude ion-acoustic wave events associated with electron beams are frequently observed in interplanetary space[1,5,8]. Hence, referring to the present studies, we can understand the properties of large amplitude ion-acoustic waves in space plasmas where the electron beam exists. Although we have not referred to any specific observation, the present theory is applicable to analyzing large amplitude ion-acoustic waves, such as shock and solitary waves, associated with electron beams which may occur in space and laboratory plasmas.

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Figure captions

Fig. 1 The maximum Mach number depending on the concentration of the electron beam density α, in the case of $\sigma=0.4$ and $\nu=0.2$.

Fig. 2 Bird's eye view of the pseudopotential under the conditions of $v_0=1.25$, $M=1.3$, $\sigma=0.4$, $\nu=0.2$ and $\mu=1/1836$.

Fig. 3 A pseudopotential curve of large amplitude ion waves for $v_0=1.25$, $M=1.3$, $\sigma=0.4$, $\nu=0.2$ and $\alpha=0.104$.

Fig. 4 Bird's eye view of the pseudopotential under the conditions of $v_0=1.25$, $M=1.3$, $\sigma=0.4$, $\nu=0.4$ and $\mu=1/1836$.

Fig. 5 A pseudopotential curve of large amplitude ion waves for $v_0=1.25$, $M=1.3$, $\sigma=0.4$, $\nu=0.4$ and $\alpha=0.55$.

Fig. 6 The region of the existence of large amplitude ion-acoustic waves depending on the concentration of the electron beam density α and the electron beam temperature ν, in the case of $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\mu=1/1836$. Large amplitude ion-acoustic waves can exist in the region bounded by the two curves.

Fig. 7 The $\phi-\alpha$ plane where ion-acoustic waves exist, in the case of (a) $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\nu=0.2$; (b) $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\nu=0.3$; (c) $v_0=1.25$, $M=1.3$, $\sigma=0.4$ and $\nu=0.4$. Large amplitude ion-acoustic waves can exist in the lower region of the curve.

Fig.1

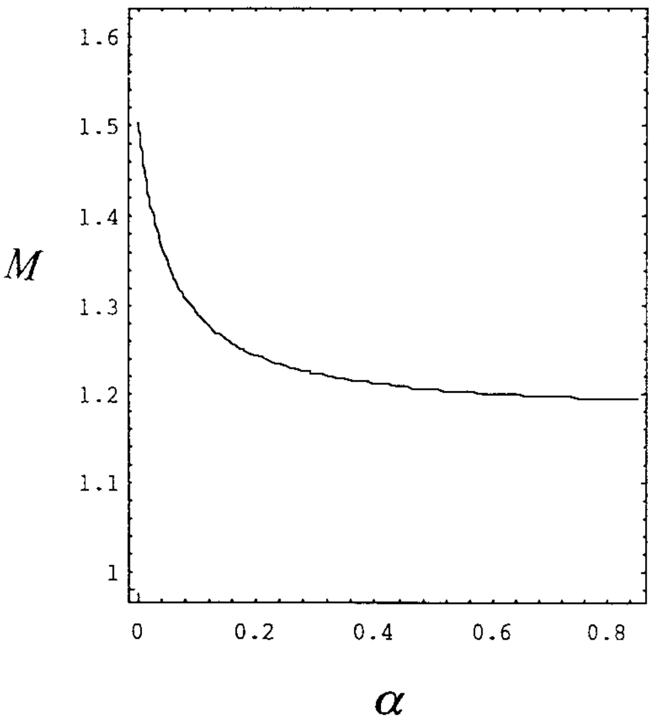


Fig.2

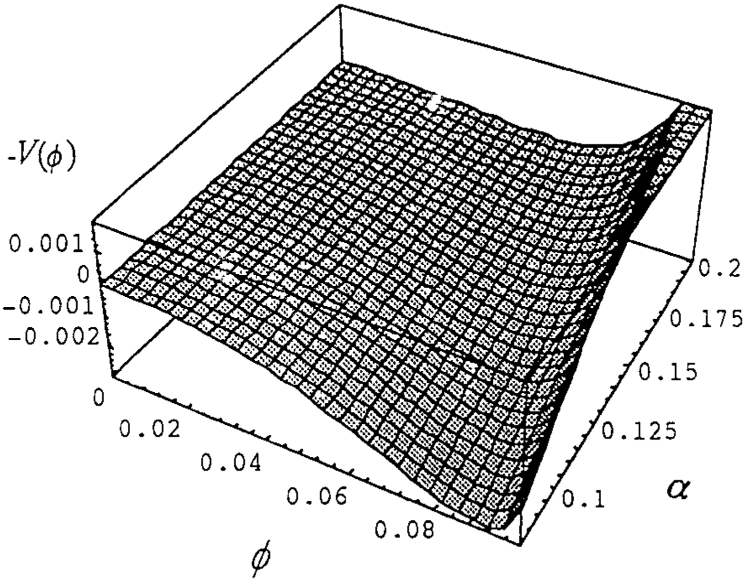


Fig.3

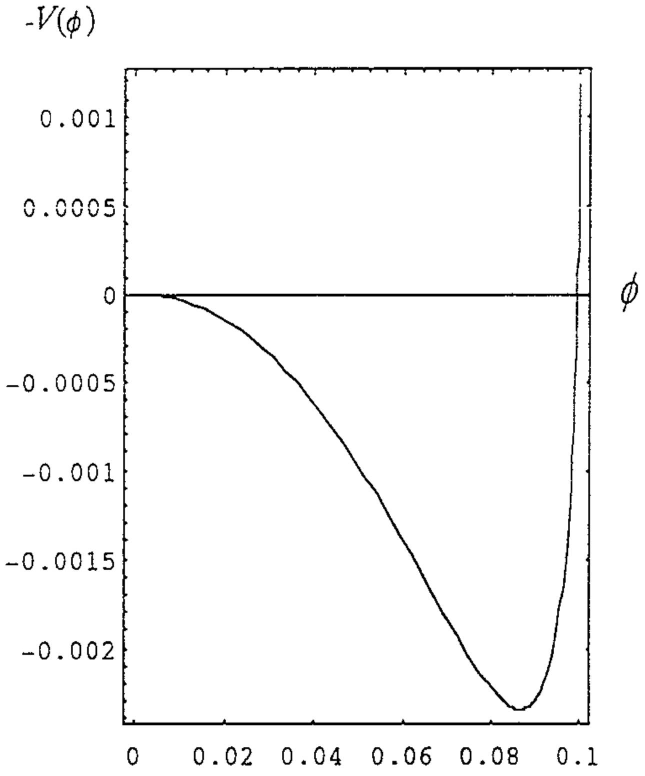


Fig.4

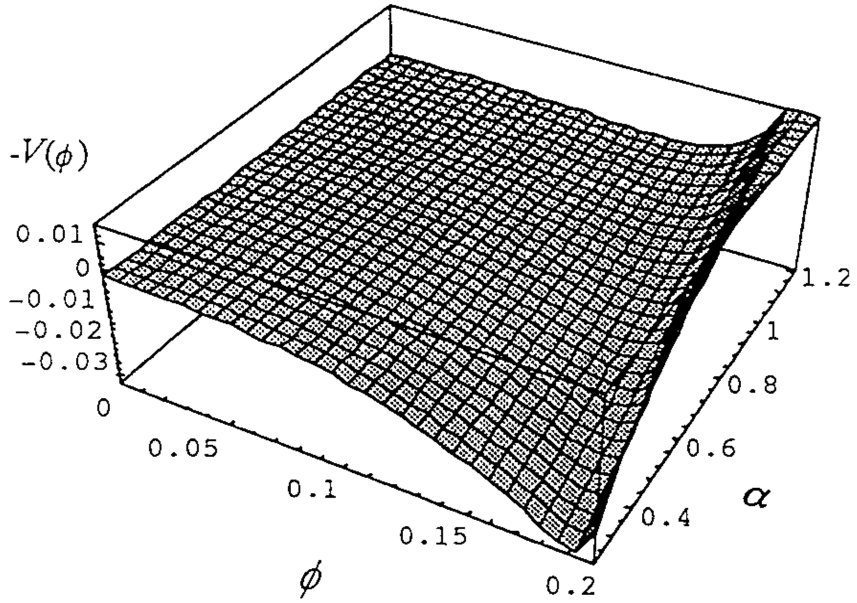


Fig.5

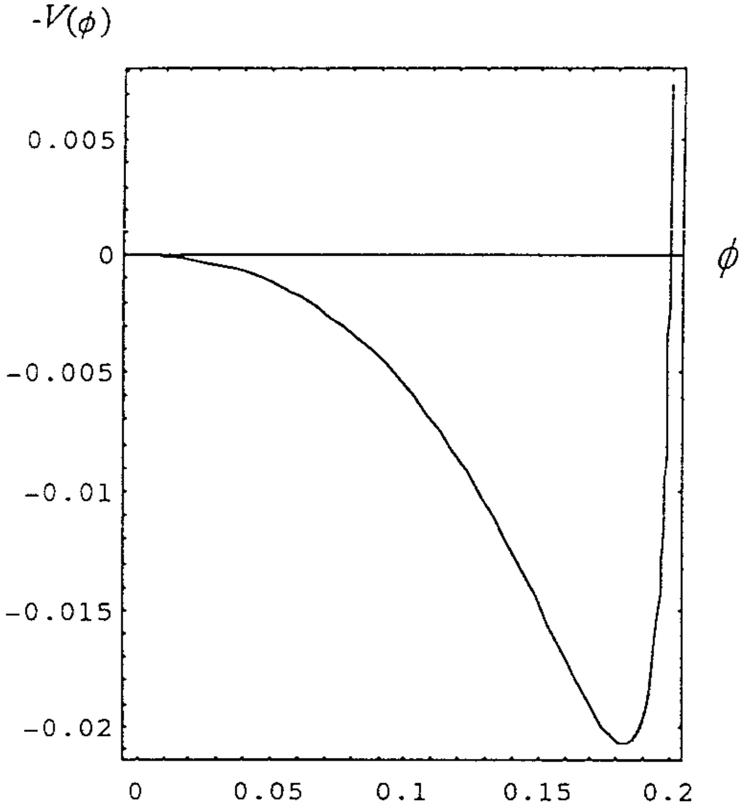


Fig.6

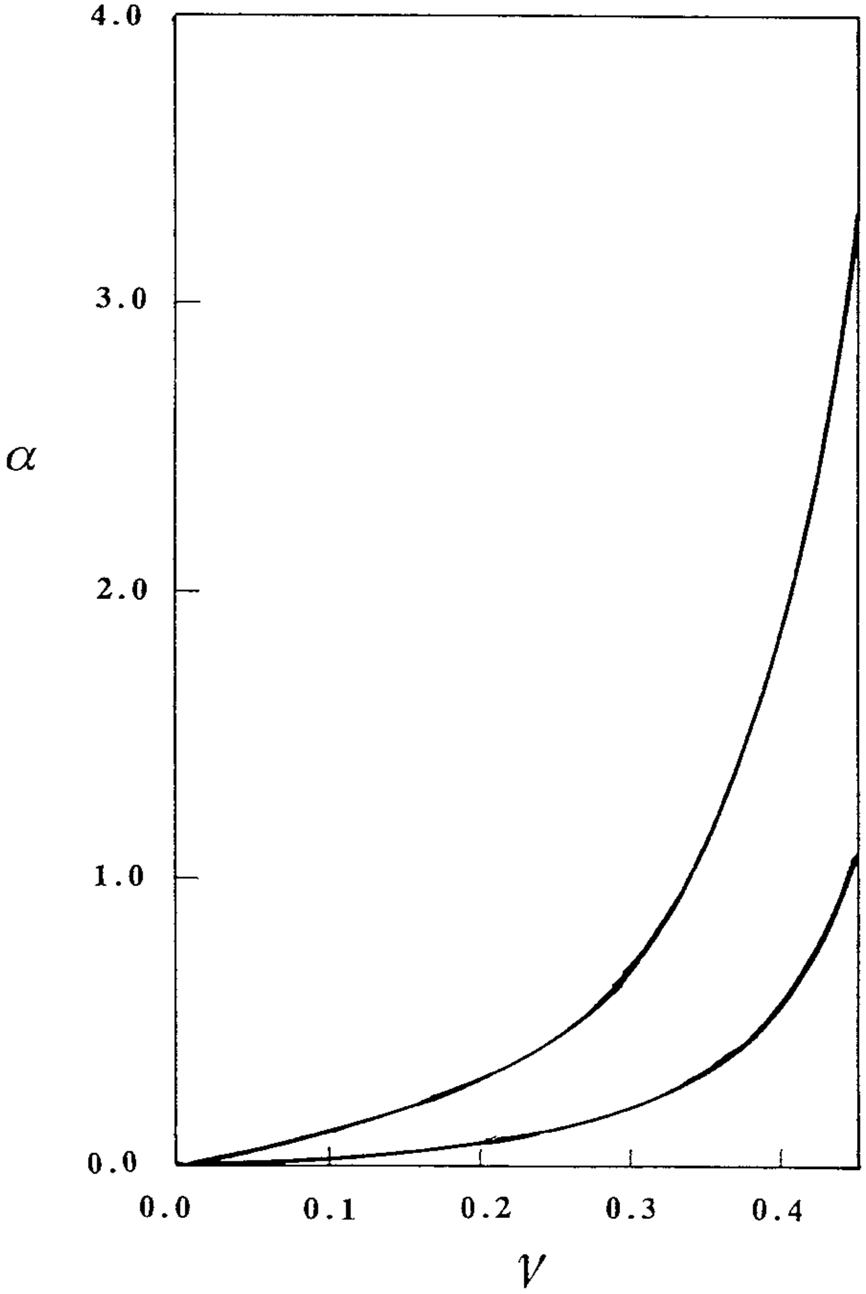
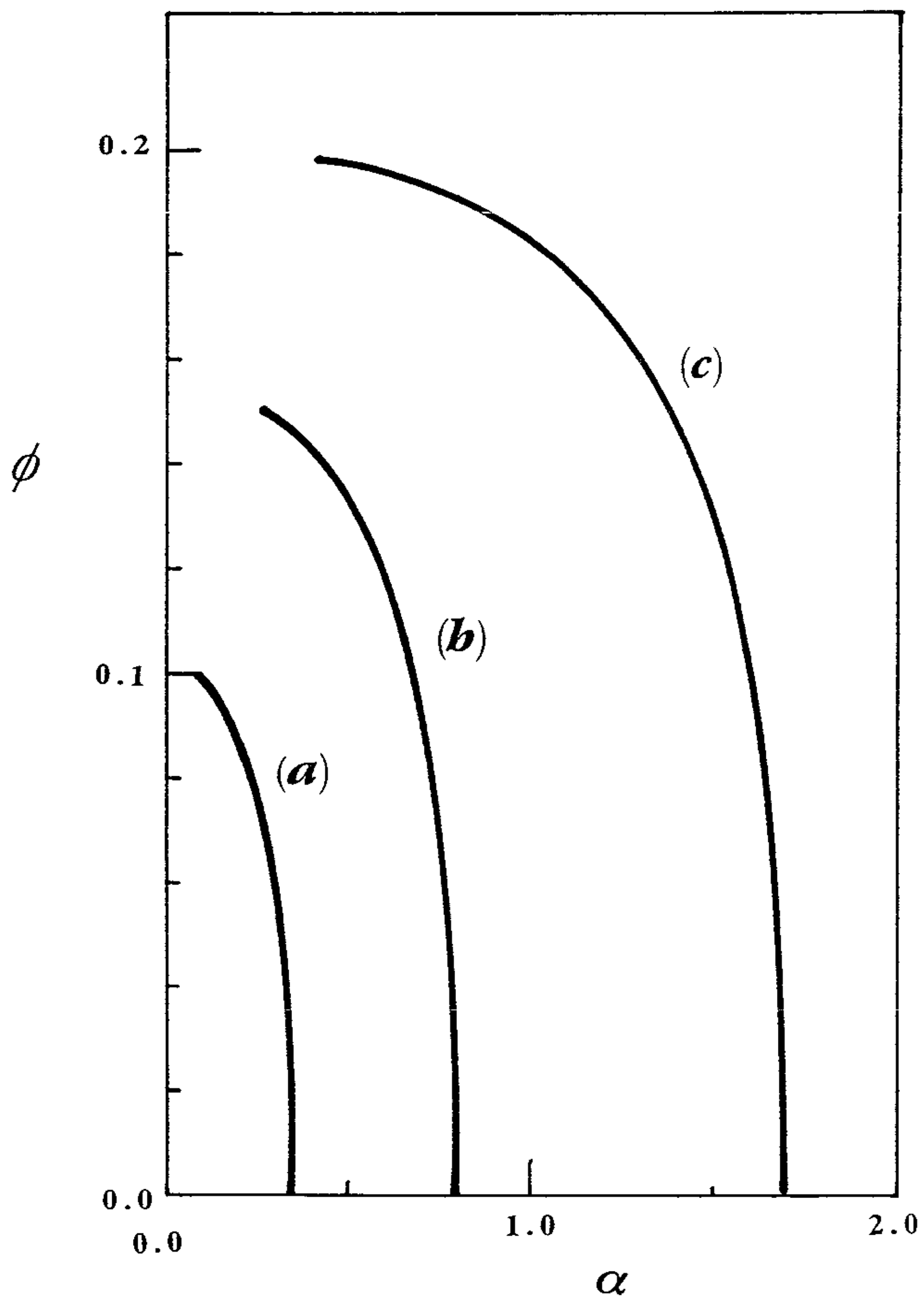


Fig.7



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