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Arbitrary amplitude ion-acoustic waves in a relativistic electron-beam plasma system

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Nonlinear wave structures of arbitrary amplitude ion-acoustic waves in a relativistic electron-beam plasma system are studied using the pseudopotential method. The region of existence of arbitrary amplitude ion-acoustic waves is examined, and it is shown that the condition for their existence depends sensitively on parameters such as the relativistic effect of the electron-beam, the ion temperature, the electrostatic potential and the electron-beam density. It turns out that the region of existence spreads as the relativistic effect increases and the ion temperature decreases. New properties of large amplitude ion-acoustic waves in a plasma with a relativistic electron-beam are predicted.

Key words: arbitrary amplitude nonlinear waves, ion-acoustic waves, relativistic electron beam, the region of existence

1. Introduction

In a historical current of nonlinear wave studies on plasmas, electrostatic ion-acoustic waves have been drawing attention by a lot of investigators (Temerin et al. 1982; Bostrom et al. 1988; Block and Falthammar 1990; Alfven 1986; Gurnett and Frank 1973; Chang and Porkolab 1970; Gurnett et al. 1976). Observations have indicated that stationary nonlinear ion-acoustic waves may be excited when an electron beam is injected into a plasma (Witt and Lotko 1983; Alpert 1990).

A relativistic high-speed electron beam component is frequently observed in the region where ion-acoustic waves exist. On the other hand, it is known that high-speed electrons influence the excitation of various kinds of nonlinear waves in the interplanetary space and the Earth's magnetosphere (Nejoh 1992, 1994; Nejoh and Sanuki 1994, 1995). However, little attention has been given to relativistic electron beams associated with the plasma dynamics under the fluid description. Although the effect of singular behaviour has been investigated, the analysis is not valid for ion-acoustic waves (Bharuthram and Yu 1993).

In this paper, we investigate theoretically the possibility of the existence of 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 existence of large amplitude ion-acoustic waves, and study its dependence on parameters such as the ion temperature and the beam density.

The layout of this paper is as follows. In §2, we present the basic equations for a plasma with an electron beam and derive the pseudopotential for large amplitude ion-acoustic waves. In §3, we define the condition for the existence of large amplitude ion-acoustic waves, and illustrate the dependency of the region of existence on the parameters such as the electron beam density, the electrostatic potential and the Mach number. Section 4 is devoted to a concluding discussion.

2. Theory

We assume a plasma consisting of warm ions and hot isothermal electrons traversed by a relativistic 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 the ions are described by,

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

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

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 and the unperturbed background electron (electron beam) density, respectively.

We have the following two equations for the relativistic beam electron:

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

$$\left[\frac{\partial}{\partial t} + v_b \frac{\partial}{\partial x} \right] \gamma_b v_b - \frac{1}{\mu} \frac{\partial \phi}{\partial x} = 0 \quad , \tag{4}$$

where $\gamma_b = [1-(v_b/c)^2]^{-1/2}$, with c the velocity of light. In (4), $\mu = m_e/m_i$, where m_e (m_i) denotes the electron (ion) mass.

The electron density follows the Boltzmann distribution

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

The Poisson's equation is

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

The variables n_e, n_b, n, v_b, v and ϕ are 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,

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

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

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

$$\left[-M\frac{\partial}{\partial \xi}+v_b\frac{\partial}{\partial \xi}\right]\gamma_b v_b-\frac{1}{\mu}\frac{\partial \phi}{\partial \xi}=0, \tag{10}$$

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

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

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

we obtain

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

Integration of eqs.(9) and (10) gives rise to

$$-M(\gamma_b v_b-\gamma_0 v_0)+c^2(\gamma_b-\gamma_0)-\frac{\phi}{\mu}=0. \tag{13}$$

where $\gamma_0=[1-(v_0/c)^2]^{-1/2}$. Here, we assume that the electron beam velocity v_b is of the order of $0.01c\sim 0.1c$, and take the weakly relativistic approximation, $\gamma_b\to 1+v_b{}^2/2c^2$. Then, after a brief calculation, we obtain the electron beam density as:

$$n_b=\frac{\alpha}{\left\{\dfrac{1+\dfrac{2\phi}{\mu(v_0-M)^2}}{1-3\left(\dfrac{M}{c}\right)^2\left(1+\dfrac{1}{2}\dfrac{M}{v_0-M}\right)}\right\}^{1/2}} \quad , \tag{14}$$

Using eqs.(5), (12) and (14), (11) reduces to the nonlinear Poisson equation

$$\frac{d^2\phi}{d\xi^2}=\exp(\phi)+\frac{\alpha}{\left\{\dfrac{1+\dfrac{2\phi}{\mu(v_0-M)^2}}{1-3\left[\dfrac{M}{c}\right]^2\left[1+\dfrac{1}{2}\dfrac{M}{v_0-M}\right]}\right\}^{1/2}}$$

$$-\frac{1+\alpha}{\left\{1-\dfrac{2\phi}{M^2-3\sigma}\right\}^{1/2}}=-\frac{dV(\phi)}{d\phi}\quad . \tag{15}$$

where $V(\phi)$ denotes the pseudopotential. Integration of eq.(15) gives the *Energy Law,*

$$\frac{1}{2}\left[\frac{d\phi}{d\xi}\right]^2+V(\phi)=0\quad . \tag{16}$$

From eq.(15), the pseudopotential $V(\phi)$ becomes

$$V(\phi)$$

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

$$-\alpha\mu(v_0-M)^2\left\{1-3\left[\frac{M}{c}\right]^2\left[1+\frac{1}{2}\frac{M}{v_0-M}\right]\right\}^{1/2}$$

$$\times\left[\left\{1+\frac{2\phi}{\mu(v_0-M)^2}\right\}^{1/2}-1\right]$$

$$-(1+\alpha)(M^2-3\sigma)\left[\left\{1-\frac{2\phi}{M^2-3\sigma}\right\}^{1/2}-1\right]. \tag{17}$$

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

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

$$\frac{\alpha}{\mu(v_0-M)^2}\left\{1-3\left[\frac{M}{c}\right]^2\left[1+\frac{1}{2}\frac{M}{v_0-M}\right]\right\}^{1/2}+\frac{1+\alpha}{M^2-3\sigma}<1. \qquad (18)$$

It should be noted that $V(\phi)$ is real when

$$-\frac{\mu(v_0-M)^2}{2}<\phi<\frac{M^2-3\sigma}{2} \quad .$$

(ii) Nonlinear ion-acoustic waves exist only when $V(\phi_M)\geqq 0$, where the maximum potential ϕ_M is determined by $\phi_M=(M^2-3\sigma)/2$. This implies that the inequality

$$1-\exp\left\{\frac{M^2-3\sigma}{2}\right\}$$

$$-\alpha\mu(v_0-M)^2\left\{1-3\left[\frac{M}{c}\right]^2\left[1+\frac{1}{2}\frac{M}{v_0-M}\right]\right\}^{1/2}$$

$$\times\left[\left\{1+\frac{M^2-3\sigma}{\mu(v_0-M)^2}\right\}^{1/2}-1\right]$$

$$+(1+\alpha)(M^2-3\sigma)\geqq 0 \, , \qquad (19)$$

holds. We show the maximum Mach number M as a function of α in Fig.1, where $\sigma=0.2$, $v_0=1.8$ and $c=30.0$. It can be seen that only supersonic ion-acoustic waves can propagate in the plasma under consideration. The allowable upper range of the relativistic effect is $0.06<M/c<0.08$. The maximum Mach number and, correspondingly, the maximum amplitude of the ion-acoustic wave depends significantly on the parameters α and σ. The region of existence of ϕ is characterized by these conditions.

A complete analytical investigation of the ion-acoustic solitons in a relativistic electron beam-plasma system is possible in the small amplitude limit ($\phi \ll 1$). Specific results can be obtained by expanding $V(\phi)$ in powers of ϕ and keeping terms of up to third-order, ϕ^3. Accordingly, eq.(17) takes the form

$$-V(\phi) \simeq \frac{1}{2}\left[1-\frac{1}{4}(AS^2+NI)\right]\phi^2$$

$$+\frac{1}{6}\left[1+\frac{3}{8}AS^3-\frac{3}{4}NI^2\right]\Big]\phi^3 , \qquad (20)$$

where

$$I=\frac{2}{M^2-3\sigma} ,$$

$$N=1+\alpha ,$$

$$A=\alpha\mu(v_0-M)^2\left\{1-3\left[\frac{M}{c}\right]^2\left[1+\frac{1}{2}\frac{M}{v_0-M}\right]\right\}^{1/2},$$

and

$$S=\frac{2}{\mu(v_0-M)^2} .$$

Then, integrating (16) with (20), we obtain a soliton solution

$$\phi = \frac{3\left[1-\frac{1}{4}(AS^2+NI)\right]}{1+\frac{3}{8}AS^3-\frac{3}{4}NI^2}\,\mathrm{sech}^2\left[\frac{1}{2}\left[1-\frac{1}{4}(AS^2+NI)\right]^{1/2}(\xi-\xi_0)\right].$$

It should be noted that ion-acoustic solitons exist in the limiting case with $\phi \ll 1$, as seen in this section.

We next consider the region of existence of large amplitude ion-acoustic waves in the next section.

3. The region of existence of large amplitude ion-acoustic waves

In order to investigate large amplitude ion-acoustic waves, we calculate the pseudopotential (17) exactly.

We show a bird's eye view of the pseudopotential $-V(\phi)$ in Fig.2a, for the case M=1.4, v_0=1.8, c=30.0, σ=0.2 and μ=1/1836, obtained by a numerical calculation. Here, we assume that T_e=1MeV, that is, v_s=9.8×10^6m/s, so that c=30.0, because the velocity of light is normalized by the sound velocity. Figure 3a illustrates the dependence of $-V(\phi)$ on the potential ϕ when the ratio of the electron beam density to the background electron density is fixed to be α=0.005. For the case where the relativistic effect M/c increases, we show a bird's eye view of the pseudopotential in Fig.2b when M=1.6, v_0=1.8, c=30.0, σ=0.2 and μ=1/1836. The pseudopotential $-V(\phi)$ versus the potential ϕ for this case is illustrated in Fig.3b for α=0.025. For the case where the ion temperature decreases (σ=0.1), we show a bird's eye view in Fig. 2c with M=1.4, v_0=1.8, c=30.0 and μ=1/1836. Figure 3c shows $-V(\phi)$

versus ϕ for $\alpha=0.007$.

3.1 *The case* $\sigma=0.2$, $M=1.4$ *and* $v_0=1.8$ ($M/c=0.043$)

From Figs.2a and 3a, we see the following: In the range of $\alpha>0.02$, the pseudopotential is always positive. In this case, the potential well is not formed. If $0<\alpha<0.02$, the pseudopotential forms a potential well. Large amplitude ion-acoustic waves can propagate in the well. As an example of this case, we illustrate the pseudopotential in Fig.3a for $\alpha=0.005$. The potential well becomes deeper as α decreases.

3.2 *The case where the relativistic effect increases* ($M/c=0.053$)

In the case where the Mach number $M=1.6$, we also see that similar properties are described from Figs.2b and 3b. The difference between the case of $M=1.4$ and that of $M=1.6$ is that the region of existence in the latter case becomes wider than in the formar.

3.3 *The case where the ion temperature decreases* ($\sigma=0.1$)

Large amplitude ion-acoustic waves exist even when the ion temperature decreases. The region of existence is wider rather than that in the case where $M=1.4$ and $\sigma=0.2$, as seen in Figs.2c and 3c.

In Fig.4(a), we illustrate the region of existence of large amplitude ion-acoustic waves depending on the ratio α of the electron beam density to the background electron density, in the case of $M=1.4$, $v_0=1.8$, $\sigma=0.2$ and $\mu=1/1836$. Large amplitude ion-acoustic waves propagate in the region bounded by the curve, but do not exist in other regions. We show the region of existence in (ϕ, α) plane in Fig.4(b) for $M=1.6$, $v_0=1.8$, $\sigma=0.2$ and $\mu=1/1836$. Large amplitude ion-acoustic waves exist in the region bounded by the curve. Figure 4(c) illustrates the region of existence in (ϕ, α) plane for M=1.4, v_0=1.8, σ=0.1 and μ=1/1836.

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

4. Concluding discussion

The nonlinear wave structures of large amplitude ion-acoustic waves have been studied in a relativistic electron-beam plasma system. We have present the region of existence of such waves on the basis of the fluid equations.

We have investigated the conditions of the existence of stationary supersonic ion-acoustic waves by analysing the structure of the pseudo-potential. Typical results are illustrated in Figs.1-4. The results can be summarized as follows.

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

(ii) The relativistic effect (the propagation speed of the ion-acoustic wave) increases as the electron beam density increases..

(iii) Large amplitude ion-acoustic waves occur when the electron beam density is much smaller than the background electron density.

(iv) The region in the (ϕ, α) plane where large amplitude ion-acoustic waves exist spreads as the relativistic effect increases and the ion temperature decreases.

The present investigation predicts new properties of large amplitude nonlinear ion-acoustic waves in a relativistic electron-beam plasma system. Large amplitude ion-acoustic wave events associated with high-speed electron beams are frequently observed in interplanetary space. Hence, with reference to the present study, we can understand the properties of large amplitude ion-acoustic waves in space where the relativistic electron beam exists. Although we have not referred to any specific observations, the present theory is applicable to the analysis of large amplitude ion-acoustic waves, such as shock and solitary waves, associated with relativistic electron beams that may occur in space and the laboratory.

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Captions of figures

Figure 1 The maximum Mach number depending on the concentration of the electron beam density α, in the case of σ=0.2, v_0=1.8, c=30.0 and μ=1/1836.

Figure 2 Bird's eye view of the pseudopotential $V(\phi)$ for (a)the case of σ=0.2, v_0=1.8 and M=1.4, (b)the case of σ=0.2, v_0=1.8 and M=1.6 and (c)the case of σ=0.1, v_0=1.8, M=1.4.

Figure 3 Pseudopotential against the electrostatic potential for (a) σ=0.2, v_0=1.8, M=1.4 and α=0.005, (b) σ=0.2, v_0=1.8, M=1.6 and α=0.025 and (c) σ=0.1, v_0=1.8, M=1.4 and α=0.007.

Figure 4 The $\phi-\alpha$ plane where ion-acoustic waves exist, in the case of (a) σ=0.2, M=1.4; (b) σ=0.2, M=1.6; (c) σ=0.1, M=1.4. Here, v_0=1.8, c=30.0 and μ=1/1836. Large amplitude ion-acoustic waves can exist in the region bounded by the curve.

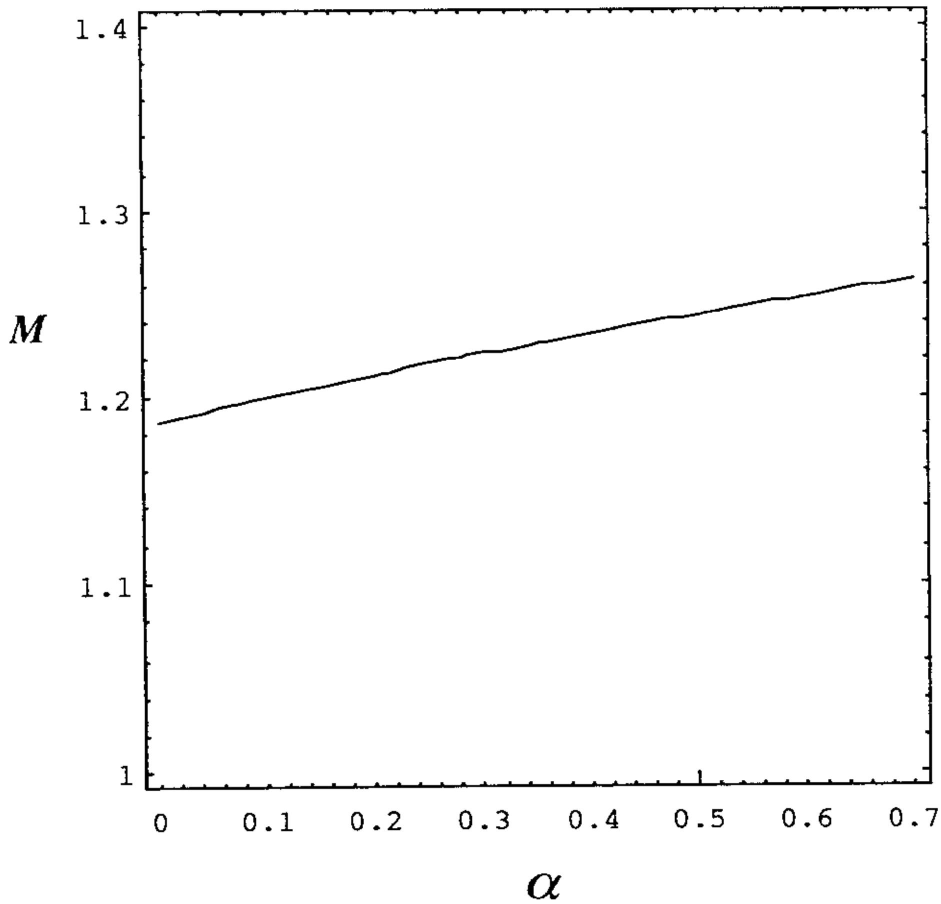


Fig.1

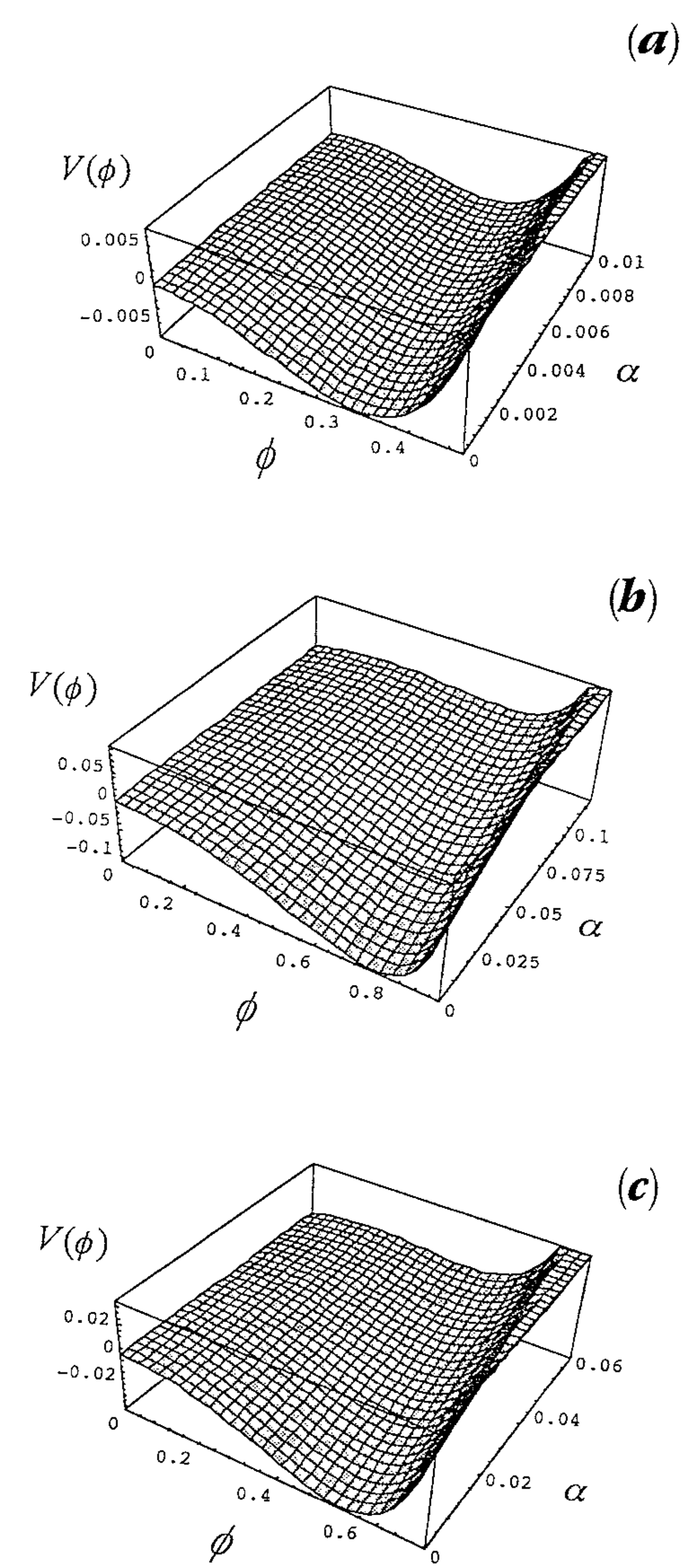
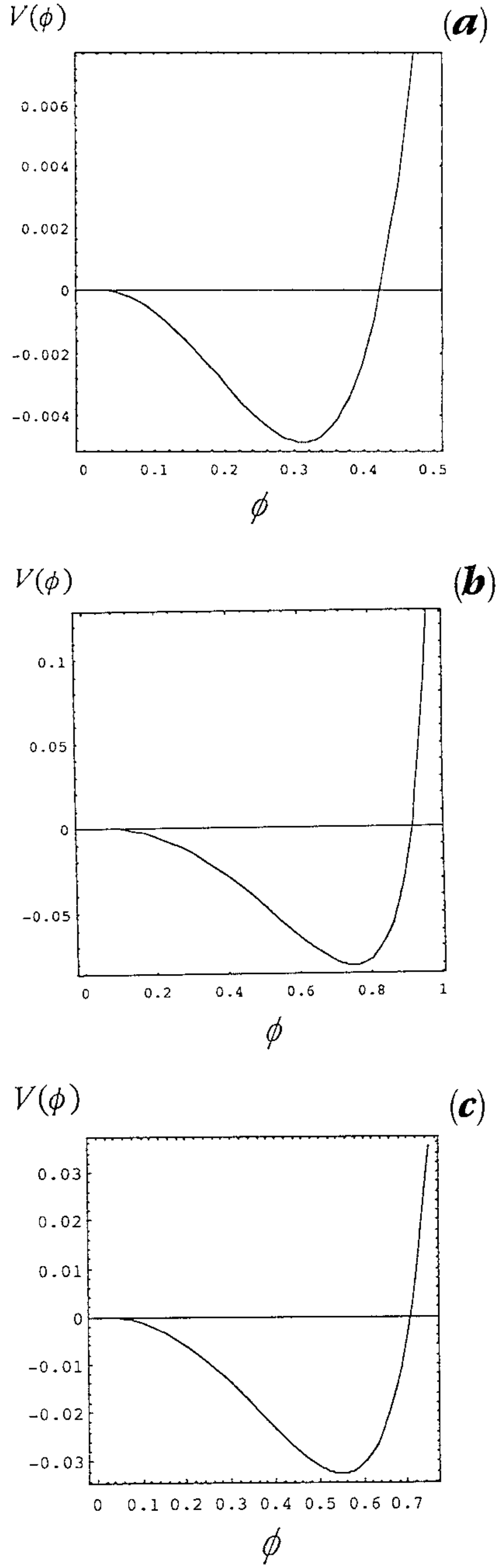

(a)
V(φ)
0.005
0
-0.005
0
0.1
0.2
0.3
0.4
φ
0.01
0.008
0.006
0.004
0.002
0
α
(b)
V(φ)
0.05
0
-0.05
-0.1
0
0.2
0.4
0.6
0.8
φ
0.1
0.075
0.05
0.025
0
α
(c)
V(φ)
0.02
0
-0.02
0
0.2
0.4
0.6
φ
0.06
0.04
0.02
0
α

Fig.2



V(ϕ)
(a)
0.006
0.004
0.002
0
-0.002
-0.004
0 0.1 0.2 0.3 0.4 0.5
ϕ
V(ϕ)
(b)
0.1
0.05
0
-0.05
0 0.2 0.4 0.6 0.8 1
ϕ
V(ϕ)
(c)
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
ϕ

Fig.3

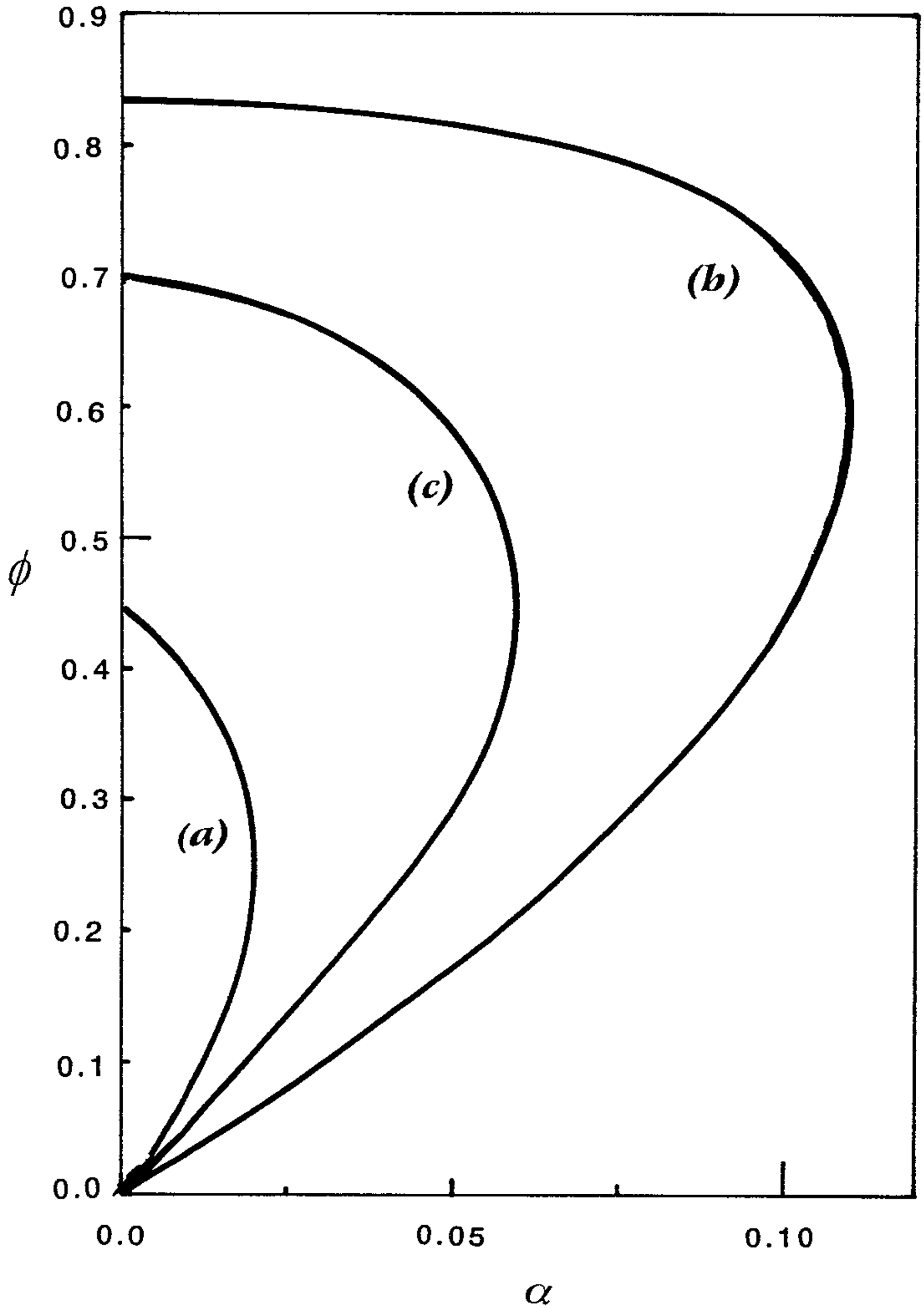


Fig. 4

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