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NEGATIVE ION CRYSTAL FORMATION IN NONEQUILIBRIUM PLASMAS

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The crystal formation of heavy negative ions is considered in following system. The plasma flow with positive ions and electrons propagates vertically up and extends in radial direction. The flow propagates relative to heavy negative ions, subjected to gravity. The flow excites the perturbations of large amplitudes. The properties and evolution of these excited perturbations are considered. The evolution equation is derived for the case of any amplitudes. It is shown that these perturbations of large amplitude lead to spatial ordering of heavy negative ions in nonequilibrium plasma.

Plasma with heavy negative ions, strongly coupled dusty plasmas (or so called colloidal plasmas), plasma crystal formation (or so called ion crystal formation) and wave propagation through a plasma crystal are investigated now intensively (see, for example, [1, 2]). In particular, the formation of the plasma crystals has been observed in experiments at providing of nonequilibrium state. If in equilibrium plasma there was no plasma crystal but at propagation of laser radiation through plasma or at providing of small nonequilibrium state by electric probe in plasma in experiment an ion crystal has been formed. The ion crystals have been formed also in plasma flow relative to heavy negative ions.

In this paper the formation of crystals of heavy negative ions is considered in plasma flow relative to these negative ions. Namely, the plasma flow with positive ions and electrons propagates vertically up and extends in radial direction. The flow propagates relative to heavy negative ions, subjected to gravity. The flow excites the perturbations of large amplitudes. The properties and evolution of these excited perturbations are considered. The generalised equation is derived for the spatial distribution of field of any amplitudes for the case of the plasma crystal formation on generalised dust ion-acoustic mode. Also the evolution equation is derived. It is shown that these perturbations of large amplitude lead to spatial ordering of heavy negative ions in nonequilibrium plasma. Considered state of plasma constitutes a special form of colloidal plasmas, i.e. plasmas containing micron-sized particles (dust grains).

We investigate theoretically of a plasma crystal formation in colloidal nonequilibrium plasmas. The considered plasma crystal is the lattice of heavy negative ions of grains.

Investigations of a plasma crystal formation are performed for the case of strong magnetic field with field strength so that the gyro radii of ions comparable with distance between the grains in the lattice.

We show theoretically that the plasma crystal is formed at providing of nonequilibrium state. If in equilibrium plasma there is no plasma crystal but at providing of small nonequilibrium state by propagation of plasma flow through cloud of colloidal particles a plasma crystal is formed.

The formation of a plasma crystal is considered in dusty colloidal plasma with relative propagation of grains and plasma with light ions with small flow velocity.

It is shown that the longitudinal chain of solitary perturbations (similar to [3]) of large amplitudes is formed on generalised ion-acoustic mode in plasma flow; the velocity of this mode in system, propagating with light ions, is faster than the ion-acoustic velocity, but in laboratory system the velocity of this mode is near zero; these perturbations of large amplitude lead to trapping of heavy negative ions of grains and to spatial ordering of them in nonequilibrium dusty colloidal plasmas. Though gravity provide relative propagation of heavy grains downwards relative to light positive ions, the plasma crystal is motionless, because grains are trapped by chain of solitary perturbations formed due to instability development on generalised dust ion-acoustic mode with velocity equal zero.

The excitation by a plasma flow, propagating relative to negative heavy ions, linear perturbations is described by a following ratio

$$1+1/(kr_{de})^2-\omega^2_{p+}/(\omega-kV_{o+})^2-\omega^2_{p-}/\omega^2=0 \qquad (1)$$

Here ω, k are frequency and wave vector of the perturbations; $\omega_{p\pm}$, ω_{p-} are the plasma frequencies of the positive and negative ions; r_{de} is the electron Debye's radius; V_{o+} is the flow velocity of the positive ions.

From (1) one can obtain, that one can select the plasma flow velocity such, that

$$V_{ph}=\omega/k\approx(V_{o+}/2^{4/3})(n_-m_+q_-^2/ n_+m_-q_+^2)^{1/3}<<V_{s+},$$
$$\lambda=2\pi/k=2\pi r_{de}/(V_{s+}^2n_+q_+^2/V_{o+}^2n_ee^2-1)^{1/2}>>r_{de} \qquad (2)$$

the periodic in space field is motionless, that is $V_{ph}<<V_{s+}$. $V_{s+}=(T/m_+)^{1/2}$ is the ion-acoustic velocity of the positive ions.

From (1) one can obtain, that the growth rate of the perturbation equals

$$\gamma= =(1.5)^{1/2}(V_{o+}/r_{de})(n_-m_+q_-^2/n_+m_-q_+^2)^{1/3}(V_{s+}^2q_+/V_{o+}^2e-1)^{1/2} \qquad (3)$$

At non-linear stage of instability development an electrical potential φ of the perturbation represents the chain of the solitary narrow humps of finite amplitudes φ_o. Let us consider properties of the separate solitary perturbation. Because the negative ions are heavy and their density is small, we suppose, that the shape of a quasistationary perturbation is determined by dynamics and distribution in space of electrons and positive ions. The interaction of this perturbation with heavy negative ions results in excitation of a perturbation, that is to growth its amplitude.

With growth of the amplitude of the perturbation the adiabatic stage of the evolution starts early for electrons $\varphi_o > (m_e/e)(\gamma/k)^2$. Then the velocity distribution function of electrons, located outside of a separatrix, has the following kind

$$f_e(v)=[n_{oe}/V_{te}(2\pi)^{1/2}]\exp(e\varphi/T_e - m_e v^2/2T_e) \quad (4)$$

For the trapped electrons, i.e. for electrons, located inside a separatrix, the distribution function does not depend on velocity due to adiabatic evolution.

Integrating the velocity distribution function of electrons one can derive the expression for electron density

$$n_e = (n_o/(2\pi)^{1/2})(2/T)^{3/2}\int^{\infty}_{o} d\varepsilon(\varepsilon+e\varphi)^{1/2}\exp(-\varepsilon/T) \quad (5)$$

The expression for density of the positive ions one can get from hydrodynamic equations

$$n_+ = n_{o+}/[1-2q_+\varphi/m_+(V_{o+}-V_h)^2]^{1/2} \quad (6)$$

Here q_+, m_+, V_{o+} are charge, mass and velocity of the positive ions; V_h is the velocity of the solitary perturbation.

Substituting (5), (6) in Poisson's equation, one can derive the equation for spatial distribution of an electrical potential of the perturbation of any amplitudes

$$\phi'' = (2/\sqrt{\pi})\int^{\infty}_{o} da e^{-a}(a+\phi)^{1/2} - 1/(1-2Q\phi/v_{oh}^2)^{1/2} \quad (7)$$

$Q = q_+/e$, $\phi = e\varphi/T$, "''"$=\partial/\partial x$, $x=z/r_{de}$, $v_{oh}=(V_{o+}-V_h)/V_{s+}$.

The equation (7) can be transformed to following kind

$$(\phi')^2 = (8/3\sqrt{\pi})\int^{\infty}_{o} da e^{-a}(a+\phi)^{3/2} - 4 + (2v^2_{oh}/Q)[(1-2Q\phi/v_{oh}^2)^{1/2} - 1] \quad (8)$$

From a condition $\phi'|_{\phi=\phi o}=0$ and (8) the nonlinear dispersion relation follows

$$v_{oh}^2/Q=(A-2)^2/2(A-2-\phi_o),$$
$$A=(8/3\sqrt{\pi})\int^{\infty}_{o} da e^{-a}(a+\phi)^{3/2} \quad (9)$$

In approximation of small amplitudes from (8), (9) on can get for v_{oh} and width of the solitary perturbation L

$$v_{oh}^2 \approx Q, \quad L \approx [(15\sqrt{\pi}/4(1-1/\sqrt{2})]^{1/2}\phi_o^{-1/4} \quad (10)$$

Therefore, if to select the velocity of the plasma motion, equal $(q_+/e)^{1/2}V_{s+}$, then the perturbation is approximately fixed in a laboratory system. Then also we have from (2) $\lambda >> L$. That is the perturbations represent the chain of the narrow potential humps with a large distance between them. Because the potential humps trap the negative heavy ions, then last are localised in space.

Until now we considered a quasistationary longitudinal structure of a field, determined by dynamics of electrons and light positive ions. Now we consider the growth in time of the amplitude of separate solitary perturbation due to its interaction with negative heavy ions. For that we take into account in hydrodynamic equations for positive and negative ions the next terms of expansion on small parameter γ/kV_{tr-}, $V_{tr-} = (q_-\varphi_o/m_-)^{1/2}$. Substituting them in Poisson's equation, we obtain the evolution equation

$$2\omega^2_{p+}\,\partial^3\varphi/\partial t^3/(V_{o+}-V_h)^3 = -\omega^2_{p-}\partial^3\varphi/\partial z^3 \quad (11)$$

From (11) one can get that the growth rate in time of the nonlinear perturbation amplitude equals

$$\gamma_{NL} \approx \omega_{p+}(e\varphi_o/T)^{1/2}(n_{o-}m_+q^2_-/n_{o+}m_+q^2_+)^{1/3} \quad (12)$$

Let us show that the plasma flow also excites the transversal oscillations with growth rate closed to the growth rate of longitudinal oscillations. From [4] one can obtain that in the case $\cos\theta << \omega_{p-}/\omega_{pe}$, when the term ω^2_{p-}/ω^2 in the dispersion law, determining the instability development and oscillation excitation, is essential, then the dispersion law has following kind

$$1+\omega^2_{pe}/\omega^2_{ce} - \omega^2_{p+}/((\omega-kV_{o+})^2 - \omega^2_{c+}) - \omega^2_{p-}/\omega^2 \approx 0 \quad (13)$$

Here θ is the angle between direction of transversal perturbation propagation and vertical direction.

At first, neglecting the last term, in the first approximation on ω/ω_{p+} from (13) one can find the wave vector of the most unstable wave

$$k \approx \omega_{p+}/V_{o+}(1+\omega^2_{pe}/\omega^2_{ce})^{1/2} \quad (14)$$

In the next approximation on ω/ω_{p+}, taking into account the last term, from (13) one can find, that the growth rate of the excitation of the transversal spatially periodic field

$$\gamma = (1.5)^{1/2}\omega_{p+}(n_- m_+ q_-^2/n_+ m_- q_+^2)^{1/3}/2(1+\omega^2_{pe}/\omega^2_{ce})^{1/2} \quad (15)$$

is closed to the growth rate of longitudinal periodic field excitation. In the same approximation from (13) one can obtain, that the transversal perturbation propagates with velocity, approximately equal to the phase velocity of the longitudinal perturbation. The last promotes for trapping of negative ions by transversal field as well as by longitudinal field.

From (2), (14) one can see that the transversal period of the lattice approximately equals to the longitudinal spatial period. Therefore, if density of negative ions is such one n_{o-}, that a single negative ion appears in area, which radius is equal to the wavelength λ, and volume is equal $(4\pi/3)\lambda^3$, i.e. $n_{o-}(4\pi/3)\lambda^3 = 1$, then the trapped heavy negative ions form crystal with the same dimensions in a longitudinal direction and in a transversal direction. If the density of the negative ions is small, $n_{o-}(4\pi/3)\lambda^3 < 1$, then nonideal crystal is formed. Nonideal crystal is due to that not each longitudinal and transversal spatial interval, equal to wavelength, contains the negative ion.

From (2) one can obtain that the crystal is formed, when amplitude of perturbation φ_o reaches the amplitude of negative ion trapping

$$e\varphi_o/T > (n_-^2 m_- q_-^4/2^{11} n_+^2 m_+ q_+^4)^{1/3} \quad (16)$$

From (16) one can see that the density of negative ions should be small for crystal formation at final amplitude of perturbation.

References

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