PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 80, No. 2
February 2013
pp. 283–287

Drift wave in pair-ion plasma

SAMIRAN GHOSH[1,*], NIKHIL CHAKRABARTI[2],
MANORANJAN KHAN[3] and M R GUPTA[3]

[1]Department of Applied Mathematics, University of Calcutta, 92, Acharya Prafulla Chandra Road, Kolkata 700 009, India
[2]Saha Institute of Nuclear Physics, Sector-1, Block-AF, Bidhan Nagar, Kolkata 700 064, India
[3]Department of Instrumentation Science, Jadavpur University, Kolkata 700 032, India
*Corresponding author. E-mail: sran_g@yahoo.com

MS received 21 April 2011; revised 3 September 2012; accepted 18 September 2012

Abstract. The conditions for the existence of low-frequency electrostatic drift wave in pair-ion plasma are discussed. It is shown that the temperature and/or mass difference of both species could produce drift wave in a pair-ion plasma. The results are discussed in the context of the fullerene pair-ion plasma experiment.

Keywords. Pair-ion plasma; low-frequency modes; drift waves.

PACS Nos 52.25.Xz; 52.27.Cm; 52.35.Kt

1. Introduction

There has been an accrued interest in pair-ion plasmas, motivated by a recent experiment [1] on particles with equal charge-to-mass ratio. Pair plasmas are also found in astrophysical environments [2]. The collective mode analyses in pair plasmas have attracted special attention because of the space-time symmetry (in contrast with the typical plasma consisting of electron-ion with wide mass difference) that arises due to the same mobility of charged particles in electromagnetic fields. The linear and nonlinear collective modes in electron-positron plasma have been investigated theoretically [3–6]. Recently, Oohara and Hatakeyama [7] have developed a novel method for generating a pair plasma consisting of only negative and positive ions with equal mass by using positive and negative fullerene ions $\left(C_{60}^{+}, C_{60}^{-}\right)$ as the ion source. Such type of pair-ion plasma is expected to be used for the synthesis of dimers directly from carbon allotropes, as well as in nanotechnology. In such pair-ion plasma, three electrostatic collective modes were observed along the axial magnetic field direction [8–10]. These three collective modes are the ion thermal wave (ITW), ion plasma wave (IPW) and a new intermediate-frequency wave (IFW). Later, it was shown that the newly found IFW can be identified with the incompressible (surface) ion wave of pair-ion plasma whose frequency lies between the IPW and IAW [11].

It is well-known that the presence of magnetic field in spatial inhomogeneous (density or temperature gradient) plasma gives rise to drift wave transverse to the direction of magnetic field [12,13]. Various theoretical studies on linear as well as nonlinear collective modes have been conducted [14–16] on pair-ion plasma. The magnetization of a pair-ion plasma is also demonstrated [17]. Thus, it is pertinent to study the possibility of the existence of drift wave in such pair-ion (negative and positive) plasmas.

In this paper, the conditions for the existence of the drift wave in purely pair-ion (positive and negative) plasma with slightly different mass and/or temperature are outlined. Here, we consider a slightly different model of pair-ion plasma where the temperature-to-mass ratio of positive and negative ions are slightly different. As a general case, the masses and the temperatures of both the species are taken to be different. In such a situation, it has been shown that a 'drift'-like mode could exist in an inhomogeneous collisionless pair-ion plasma. It is different from the usual 'drift mode', which exists in normal electron-ion plasma where electron inertia effect is negligible, and forms Boltzmann distribution. Finally, the results are discussed in the context of the fullerene pair-ion plasma experiment [8–10].

The paper is organized in the following manner. The plasma model and the existence of linear drift mode in pair-ion plasma are discussed in §2. Finally, the results are discussed in the context of pair-ion plasma experiment in §3.

2. Linear drift mode in pair-ion plasma

A weakly inhomogeneous magnetoplasma consisting of negative and positive ions with equal charge is considered. Both the positive and negative ions are strongly magnetized. The pressure is isotropic $p_\pm = n_\pm T_\pm$, where $n_\pm$ and $T_\pm$ are respectively the number density and temperature of positive (negative) ions. The constant external magnetic field is $\mathbf{B} = B_0\hat{e}_z$, where $\hat{e}_z$ is the unit vector along the Z-direction and the plasma density is assumed to vary in the X-direction. We assume that the pair-ion plasma is quasineutral, i.e., $n_+ \approx n_- = n$. Hereafter, notation with $\pm$ means the variables with positive and negative ions. Both the ions are treated from a fluid point of view. Then, the continuity and momentum equations are respectively,

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}_\pm) = 0 \tag{1}$$

and

$$\frac{\partial \mathbf{u}_\pm}{\partial t} + (\mathbf{u}_\pm \cdot \nabla)\,\mathbf{u}_\pm = \pm\frac{e}{m_\pm}\left(\mathbf{E} + \frac{B_0}{c}\mathbf{u}_\pm \times \hat{e}_z\right) - \frac{\nabla p_\pm}{nm_\pm}. \tag{2}$$

In writing the above equations, the quasineutrality condition is used.

Let us consider the low frequency, $\omega \ll \Omega_\pm\,(=|e|\,B_0/cm_\pm)$, long wavelength, $k_\perp\rho_\pm \ll 1$, and longitudinal electrostatic oscillations ($\nabla \times \mathbf{E} = 0$), i.e. $\mathbf{E} = -\nabla\varphi$, where $\Omega_\pm$ is the ion cyclotron frequency, $\rho_\pm$ is the Larmor radius and φ is the electrostatic potential. Therefore, the directed perpendicular velocities of both species can be obtained from the momentum eq. (2) as follows:

$$\mathbf{u}_{+\perp} = \frac{c}{B_0}(\hat{e}_z \times \nabla_\perp \varphi) - \frac{cT_+}{enB_0}(\hat{e}_z \times \nabla n) \tag{3}$$

and

$$\mathbf{u}_{-\perp} = \frac{c}{B_0}(\hat{e}_z \times \nabla_\perp \varphi) + \frac{cT_-}{enB_0}(\hat{e}_z \times \nabla n). \tag{4}$$

Here, in both velocities the first term is $\mathbf{E}\times\mathbf{B}$ drift and the second term is the diamagnetic drift. Note here that in the standard drift approach, $\partial/\partial t \ll \Omega_\pm$ has been used so that the polarization drift is not kept for the simplicity [13].

Next, adding and subtracting continuity eq. (1) for positive and negative ions, we have

$$\frac{\partial n}{\partial t} + \frac{1}{2}\nabla_\perp \cdot [n(\mathbf{u}_+ + \mathbf{u}_-)_\perp] + \frac{1}{2}\nabla_\parallel [n(\mathbf{u}_+ + \mathbf{u}_-)_\parallel] = 0 \tag{5}$$

and

$$\nabla_\perp \cdot [n(\mathbf{u}_- - \mathbf{u}_+)_\perp] + \nabla_\parallel [n(\mathbf{u}_- - \mathbf{u}_+)_\parallel] = 0. \tag{6}$$

A little algebra using eqs (3)–(6) yields the following linearized equations:

$$\frac{\partial \tilde{n}}{\partial t} + \frac{cT'}{eB_0}\hat{e}_z \times \nabla_\perp \phi \cdot \ln n_0 + \frac{1}{2}\nabla_\parallel (u_+ + u_-)_\parallel = 0 \tag{7}$$

and

$$\nabla_\parallel \, (u_- - u_+)_\parallel = 0. \tag{8}$$

In the above equations, the dimensionless variables $\tilde{n}(=n_1/n_0)$ denote density perturbation and $\phi(=e\varphi/T')$ denotes the potential perturbations, where T' is some constant temperature introduced for normalization. The equilibrium density is denoted by n_0 and it is a function of x, i.e., $n_0 = n_0(x)$.

In a similar way, the linearized momentum equations for both the ions in parallel direction can be written as

$$\frac{\partial}{\partial t}\,(u_+ + u_-)_\parallel = -T'\left(\frac{1}{m_+} - \frac{1}{m_-}\right)\nabla_\parallel \phi - \left(\frac{T_+}{m_+} + \frac{T_-}{m_-}\right)\nabla_\parallel \tilde{n} \tag{9}$$

and

$$\frac{\partial}{\partial t}\,(u_- - u_+)_\parallel = T'\left(\frac{1}{m_+} + \frac{1}{m_-}\right)\nabla_\parallel \phi - \left(\frac{T_-}{m_-} - \frac{T_+}{m_+}\right)\nabla_\parallel \tilde{n}. \tag{10}$$

In the standard technique, we can assume the small-amplitude solution of ϕ and $\tilde{n}$ in terms of Fourier modes which are proportional to $\exp(k_y + k_\parallel z - \omega t)$, where $k_y(k_\parallel)$ and ω are wave number (Y and Z directions) and frequency, respectively, and thus readily obtain from eqs (8) and (10)

$$\tilde{n} = \left[\frac{T'(m_+ + m_-)}{m_+T_- - m_-T_+}\right]\phi. \tag{11}$$

Substituting this $\tilde{n} - \phi$ relation in eqs (7) and (9) by assuming equilibrium density distribution as $n_0 = n_{00}\exp(-x/L_n)$, we have the dispersion relation for the drift wave in pair-ion plasma as

$$\omega^2 - \omega_*\omega - k_\parallel^2\left(\frac{T_+ + T_-}{m_+ + m_-}\right) = 0, \tag{12}$$

where ω_* is the drift frequency given by

$$\omega_* = \frac{c(m_+T_- - T_+m_-)k_y}{2eB_0(m_+ + m_-)L_N}, \tag{13}$$

where L_N denote the density gradient scale length. Therefore, if there are temperature and/or mass difference in a pair-ion plasma, there is a possibility of drift wave. In the case of equal temperature-to-mass ratio, i.e., for $T_+/T_- = m_+/m_-$, then from the above equations, we find $\omega_* = 0$ and we are left with longitudinal sound wave $\omega = k_\parallel c_s$ from eq. (13), where $c_{s+} = \sqrt{T_+/m_+} = c_{s-} = \sqrt{T_-/m_-}$ is the ion sound speed. Thus, for different temperature-to-mass ratios ($T_+/T_- \neq m_+/m_-$), i.e., for the slight difference of any one of the physical parameters (temperatures or mass), there is a possibility of drift wave in pair-ion plasmas.

3. Discussion

In this paper, the possibility of the existence of electrostatic drift wave in pair-ion (positive and negative) plasma is discussed. It is seen that only longitudinal sound mode exists in a pair-ion plasma having equal mass and temperature. However, the drift wave exists in pair-ion plasma having different temperature and/or mass of the pair-ion species in plasma. Recently, purely pair-ion plasma (without electrons) consisting of fullerene ions (C_{60}^+ and C_{60}^-) in a uniform magnetic field is observed in experiment [7–10]. The masses of both the ions (positive and negative) are equal because they are generated by the same source (fullerene ion source), but their temperatures are slightly different (range of 0.3–0.5 eV) due to the different charging processes of both the positive and negative fullerene ions [7–10]. Thus, our present investigation shows that low-frequency wave can exist in the fullerene pair-ion plasma experiment. According to the experimental observation, let us assume $m_+ = m_- = m$, $T_+ \neq T_-$ and $T = (T_+ + T_-)/2$. Then the dispersion relation for the drift wave in fullerene pair-ion plasma becomes (from eq. (12))

$$\omega^2 - \omega_*\omega - k_\parallel^2 c_s^2 = 0 \Rightarrow \omega = \frac{1}{2}\left[\omega_* \pm \sqrt{\omega_*^2 + 4k_\parallel^2 c_s^2}\right],$$

where $c_s = \sqrt{T/m}$. The drift frequency ω_* is given by (eq. (13))

$$\omega_* = \frac{c_s^2(1-\sigma)k_y}{2\Omega L_N},$$

where $\sigma = T_+/T$ and $\Omega(= eB_0/cm)$ is the ion cyclotron frequency in fullerene pair plasma. The investigation of collective phenomena in pair-ion plasma is extremely important from a diagnostic point of view [7] and thus the findings of the present investigation can be used in diagnosing the pair-ion plasma.

Acknowledgement

This work was supported by CSIR (Council for Science and Industrial Research), Government of India sanction no. 03(1125)/08/EMR-II.

References

[1] R G Greaves and C M Surko, *Phys. Rev. Lett.* **75**, 3846 (1995); **85**, 1883 (2000)
[2] M L Burns, *Positron–electron pairs in astrophysics* edited by M L Burns, A K Hardling and R Ramaty (American Institute of Physics, New York, 1983)
[3] N Iwamoto, *Phys. Rev.* **E47**, 604 (1993)
[4] J Zhao, J I Sakai, K I Nishikawa and T Neubert, *Phys. Plasmas* **1**, 103 (1994)
[5] G P Zank and R G Greaves, *Phys. Rev.* **E51**, 6079 (1995)
[6] D B Melrose, *Plasma Phys. Control. Fusion* **39**, A93 (1997)
[7] W Oohara and R Hatakeyama, *Phys. Rev. Lett.* **91**, 205005 (2003)
[8] W Oohara, D Date and R Hatakeyama, *Phys. Rev. Lett.* **95**, 175003 (2005)
[9] W Oohara, Y Kuwabara and R Hatakeyama, *Phys. Rev.* **E75**, 056403 (2007)
[10] W Oohara and R Hatakeyama, *Phys. Plasmas* **14**, 055704 (2007)
R Hatakeyama and W Oohara, *Phys. Scr.* **T116**, 101 (2005)
[11] A Hasegawa and P K Shukla, *Phys. Scr.* **T116**, 105 (2005)
[12] A Hasegawa and K Mima, *Phys. Rev. Lett.* **39**, 205 (1977)
[13] J Weiland, *Collective modes in inhomogeneous plasma* (Institute of Physics, Bristol, 2000)
[14] B Elliasson and P K Shukla, *Phys. Rev.* **E71**, 046402 (2005)
[15] P K Shukla and M Khan, *Phys. Plasmas* **12**, 014504 (2005)
[16] H Saleem, *Phys. Plasmas* **13**, 044502 (2006)
[17] P K Shukla, *Phys. Lett.* **A341**, 184 (2005)