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Generation of Coherent Structures in Electron Magnetohydrodynamics

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Generation of coherent structures in electron magnetohydrodynamics by modulational instability

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Abstract

Nonlinear coherent vortices of two dimensional electron magnetohydrodynamics (EMHD) have been investigated in a flow in which curl of generalized electron momenta is frozen into electron component of flow against immobile ions background. The vortices are found to be generated through nonlinear self interaction of relatively fast whistler modes, when they are subject to modulational instability. Conditions of existence of whistler vortices are identified for the length scales bigger and smaller than collisionless skin depth length.

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I. INTRODUCTION

Nonlinear coherent structures have long been a subject of active research in ordinary fluids as governed by Navier-Stockes or Euler equation of motion, as well as in conducting fluid such as plasmas. The fact that these structures emerge intermittently, in time and space, in the nonlinear turbulent fluids, makes them increasingly complex. Their occurrence have been demonstrated in a number of analytic theories, numerical simulations and experiments in the context of a variety of relevant physical phenomena. In the present paper, we specifically concentrate upon the generation of coherent structures through nonlinear processes within the paradigm known as electron magnetohydrodynamics (EMHD) [1]. The EMHD is a single fluid description of quasi-neutral plasma phenomena in which the characteristic time scales are smaller than ion- and greater than electron-gyroperiods, and length scales are longer than electron gyroradius and smaller than ion gyroradius. Under these conditions plasma dynamics is essentially governed by electron species only and ions being immobile, merely provide a neutralizing background. The EMHD paradigm has been found useful in describing a variety of observed plasma phenomena such as Fast plasma opening switches (POS), Z-pinch, and plasma focusing devices etc. The whole whistler wave dynamics in the ionosphere and magnetosphere is also basically governed by EMHD theory. Similarly the physics of solar flares and reconnection of magnetic field lines in astrophysical plasmas is another set of topics where the EMHD model is being applied lately.

Although nonlinear features of the EMHD model have been relatively less explored as compared to its counter part MHD model (relatively low frequency and large length scale so as to involve ion motion), there has been recently some work on exploration of various nonlinear features of this model [2–8] (and references therein). These studies show that collisionless skin depth is an important length scale in EMHD, since this is where wave dispersion effects are strong [5–8]. Earlier Flippov et al [9] have analytically studied the stability of EMHD vortices in presence of homogeneous as well as inhomogeneous plasma density and observed that density inhomogeneity in the plasma does not alter the stability of EMHD vortices. Later Isichenko et al [10] have obtained, analytical conditions for the existence of exact nonlinear localized solutions of EMHD equations in two as well as three dimensions and shown that monopolar as well as dipolar structures are stable solutions of EMHD equations. Numerical simulations of Das [11] demonstrate various collisional interaction of EMHD vortices in 2D, which are understood on the basis of point vortex model. Interestingly, Urrutia et al [12] experimentally observe that 3D EMHD vortices propagating along an external magnetic field interact very much linearly as long as whistler vortex field doesn't exceed ambient dc field, which is unlikely in Alfvén or sound waves. Jovanović et al [13] constructed tripolar, quadrapolar and vortex chain in 2D EMHD by taking into account local shear in the ambient magnetic field. In compressible 2D EMHD, wherein electron density perturbations are finite, Kuvshinov et al [14] have investigated propagating dipole and spherical electron vortices and considered their mutual interactions. It has been shown by Abdalla et al [15] that strong localized heating of nonuniform plasma on EMHD time scales can give rise to magnetic structures. Often such nonlinear structures are sought through analytic method whose various dynamical features are then understood by their governing equations. However it is rather important to understand how such entities are generated through physical mechanism and this is what the prime objective of the present work is, purely within the context of EMHD phenomena.

The present work deals with the generation of electromagnetic electron fluid vortices in purely two dimensional, incompressible, EMHD flows for which electron fluid velocity is divergence free. The coherent vortices are shown to be excited through nonlinear self-interaction of whistler modes, when they are driven modulationally unstable. The whistler waves are fundamental oscillatory electromagnetic modes of EMHD system. Conditions for the existence of nonlinearly generated whistler vortices have been identified for the modulationally unstable length scales that are smaller as well as larger than collisionless skin depth. In section II, assumptions of EMHD, basic equations and related linear dispersion relation are described. Section III deals with the nonlinear excitation of whistler vortices, while section IV considers modulation of whistler wave packets that can give rise to whistler vortices. Finally section V contains discussion on the results.

II. BASIC EQUATIONS

The basic assumptions under which EMHD model [1] is invoked are as follows; (i) The characteristic frequency lies between electron and ion gyrofrequency i.e., $\omega_{ci} \ll \omega \ll \omega_{ce}$, where ω_{ci} and ω_{ce} are ion and electron gyrofrequencies respectively (ii) characteristic length scale lies between electron gyroradius and ion gyroradius i.e., $\rho_e \ll \mathcal{L} \ll \rho_i$, (iii) Electrons being massless compared to ions, their current velocity is greater than mass flow velocity, (iv) ions are stationary and form neutralizing background, and (v) ideally magnetic field is frozen into electron component of flows. The basic equations describing the evolution of electromagnetic perturbations in EMHD thus comprise of only electron's fluid equations, Maxwell's relations, and can be cast into two dimensions as follows;

$$\left(\frac{\partial}{\partial t} + \hat{\mathbf{z}} \times \nabla\phi \cdot \nabla\right)(\phi - \nabla^2\phi) + \hat{\mathbf{z}} \times \nabla\psi \cdot \nabla(\psi - \nabla^2\psi) + \Omega_{c_0}\frac{\partial}{\partial y}\nabla^2\psi = \mu\nabla^2\phi \tag{1}$$

and

$$\left(\frac{\partial}{\partial t} + \hat{\mathbf{z}} \times \nabla\phi \cdot \nabla\right)(\psi - \nabla^2\psi) - \Omega_{c_0}\frac{\partial\phi}{\partial y} = \mu\nabla^2\psi \tag{2}$$

All the variations are restricted only to 2D plane i.e, xy-plane, and no variations are assumed in the third direction, hence $\partial/\partial z = 0$. Here $\Omega_{c_0} = eB_0/m_e c$, where B_0 is a constant equilibrium magnetic field oriented along y-direction. Eqs. (1) & (2) represent evolution of out of plane (axial) and in plane (poloidal) components of perturbed magnetic field respectively. The two components are associated with the total magnetic field as $\tilde{\mathbf{B}} = \hat{\mathbf{z}} \times \nabla\psi(x, y, t) + \phi(x, y, t)\hat{\mathbf{z}}$. The perturbed magnetic field represented by flux functions $\phi(x, y, t)$ and $\psi(x, y, t)$ in Eqs. (1) & (2) retain all the three components along three directions ($\hat{\mathbf{x}}$,$\hat{\mathbf{y}}$,$\hat{\mathbf{z}}$), but they depend upon only two co-ordinates *viz* x and y. The transport parameter, μ, proportional to electron ion collision frequency causes the magnetic field perturbations to diffuse on account of finite resistivity effects. We normalize length by inertial electron skin depth ($d_e = c/\omega_{pe}$), time by ω_{ce}^{-1}, and magnetic field by typical field magnitude B_0. The linearized dispersion relation about constant magnetic field B_0 yields,

$$\omega_k = \sigma_k \frac{k_y k \Omega c_0}{(1 + k^2)} \tag{3}$$

where $k^2 = k_x^2 + k_y^2$. This is the whistler wave dispersion relation, and $\sigma_k = \pm 1$ corresponds to forward and backward propagation of the wave. Inclusion of μ in the linear dispersion relation will merely cause damping of the whistler waves. Furthermore, it is worth noting here that inertial electron skin depth ($d_e = c/\omega_{pe}$) has been absorbed in the normalization of modes k throughout the analysis, as $k = k' d_e$.

III. EXCITATION OF COHERENT STRUCTURES

We now investigate the generation of two dimensional whistler vortices in the EMHD plasmas. The reductive perturbation method [17, 18] has been applied to the set of coupled nonlinear 2D EMHD Eqs. (1) & (2). The variables can be represented in terms of an expansion as shown below;

$$\Theta = \sum_{\alpha} \varepsilon^{\alpha} \Theta^{(\alpha)}, \tag{4}$$

with

$$\Theta^{(\alpha)} = \sum_{\ell} \Theta_{\ell}^{(\alpha)}(x, \xi, \tau) \exp[i\ell(k_y y - \omega t),$$

where Θ corresponds to the dynamical in-plane (ϕ) and out of plane (ψ) variables, ε is the parameter characterizing smallness of the amplitude of variables associated with the field quantities (ϕ, ψ) and $x = x, \xi = \varepsilon(y - ut), \tau = \varepsilon^2 t$. Here u is the phase velocity of the whistler waves. The transport coefficient (μ) orders as $\sim (\varepsilon^2)$. The boundary conditions are $\Theta^{(\alpha)}(0, \xi, \tau) = \Theta^{(\alpha)}(L, \xi, \tau) = 0$ where L is the system dimension along x-direction. The amplitudes are subject to the reality condition as $\Theta_{\ell}^{(\alpha)} = \Theta_{-\ell}^{(\alpha)^*}$. We thus consider the nonlinear modulation of a quasi-monochromatic EMHD whistler mode, thus $\Theta_{\ell}^{(1)} \neq 0$ only for $\ell = \pm 1$.

On substituting the expansion of Eq. (4) in the governing equations of 2D EMHD i.e., Eqs. (1) & (2), the first order ε^1 equation in the expansion then readily yields

$$D_{\ell}(\omega, k)\psi_{\ell}^{(1)} = 0 \tag{5}$$

where

$$D_{\ell}(\omega, k) = 1 - \frac{\Omega {c_0}^2 k_y^2 \Delta_{\ell}^2}{\omega^2 (1 - \Delta_{\ell}^2)^2}, \tag{6}$$

is the dispersion relation operator. Here $\Delta_{\ell}^2 = \partial^2/\partial x^2 - \ell^2 k_y^2$. Considering sinusoidal variation of the perturbed variable as follows,

$$\psi_{\ell}^{(1)}(\xi, \tau) = \Psi_{\ell}^{(1)}(\xi, \tau) \sin k_m x \tag{7}$$

where $k_m = m(2\pi/L)$ with $m = 1, 2, \ldots$, we can easily obtain the dispersion relation for $\ell = 1$ mode as follows.

$$\omega = \pm \frac{k_y \hat{k} \Omega c_0}{(1 + \hat{k}^2)}.$$

This is consistent with the linear dispersion relation of whistler waves as given by Eq. (3) in earlier section. Here $\hat{k}^2 = k_m^2 + k_y^2$.

To the next order i.e., ε^2, on substituting Eq. (4) into Eqs. (1) & (2) and carrying out further algebra, we obtain

$$iD_\ell(\omega,k)\psi_\ell^{(2)} + (u-u_g)\frac{\partial\psi_\ell^{(1)}}{\partial\xi} = 0. \tag{8}$$

As $\psi_\ell^{(2)}$ varies as $\sin k_m x$, and $D_1(\omega,k)\to 0$ for $\ell=1$, hence $u=u_g$ as $\partial\psi_1^{(1)}/\partial\xi \neq 0$ which consequently leads to the expression for the group velocity ($u=\partial\omega/\partial k_y$) of the whistler modes in EMHD as follows,

$$u_g = \frac{\partial\omega}{\partial k_y} = \frac{\Omega c_0}{(1+\hat{k}^2)^2}\left\{(1+\hat{k}^2)\left(\frac{k_y^2}{\hat{k}}+\hat{k}\right) - 2k_y^2\hat{k}\right\}.$$

In the next order (ε^3),

$$(1-\Delta_\ell^2)\frac{\partial\psi_\ell^{(1)}}{\partial\tau} + i\ell\left[-\omega(1-\Delta_\ell^2)\psi_\ell^{(3)} - \Omega c_0 k_y\phi_\ell^{(3)}\right] - \left[2\ell^2\omega k_y + u(1-\Delta_\ell^2)\right]\frac{\partial\psi_\ell^{(2)}}{\partial\xi}$$
$$+ i\ell\left[\omega - 2uk_y\right]\frac{\partial^2\psi_\ell^{(1)}}{\partial\xi^2} - \Omega c_0\frac{\partial\phi_\ell^{(2)}}{\partial\xi} = i\ell k_y\left(\phi_\ell^{(1)}\frac{\partial\psi_0^{(2)}}{\partial x} - \psi_\ell^{(1)}\frac{\partial\phi_0^{(2)}}{\partial x}\right)$$
$$-k_y\gamma\left(\Delta_\ell^2+\frac{1}{2}\right)\frac{\partial}{\partial x}\frac{\partial}{\partial\xi}|\psi_\ell^{(1)}|^2 \tag{9}$$

and

$$(1-\Delta_\ell^2)\frac{\partial\phi_\ell^{(1)}}{\partial\tau} + i\ell\left[-\omega(1-\Delta_\ell^2)\psi_\ell^{(3)} + \Omega c_0 k_y\Delta_\ell^2\phi_\ell^{(3)}\right] + \Omega c_0(\Delta_\ell^2 - 2\ell^2k_y^2)\frac{\partial\psi_\ell^{(2)}}{\partial\xi} +$$
$$3i\ell\Omega c_0 k_y\frac{\partial^2\psi_\ell^{(1)}}{\partial\xi^2} - \left[2\ell^2\omega k_y + u(1-\Delta_\ell^2)\right]\frac{\partial\phi_\ell^{(2)}}{\partial\xi} - i\ell(2uk_y-\omega)\frac{\partial^2\phi_\ell^{(1)}}{\partial\xi^2} =$$
$$i\ell k_y\phi_\ell^{(1)}\left[\Delta_\ell^2\frac{\partial\phi_0^{(2)}}{\partial x} - \frac{\partial^3\phi_0^{(2)}}{\partial x^3}\right] + i\ell k_y\psi_\ell^{(1)}\left[\Delta_\ell^2\frac{\partial\psi_0^{(2)}}{\partial x} - \frac{\partial^3\psi_0^{(2)}}{\partial x^3}\right] -$$
$$2k_y^2\frac{\partial}{\partial x}\frac{\partial}{\partial\xi}\left(|\psi_\ell^{(1)}|^2 + |\phi_\ell^{(1)}|^2\right). \tag{10}$$

The slowly varying component of magnetic flux functions can be obtained by substituting $\ell=0$ in Eqs. (9) & (10),

$$\phi_0^{(2)} = F\frac{\partial}{\partial x}|\psi_1^{(1)}|^2, \tag{11}$$

$$\psi_0^{(2)} = G\frac{\partial}{\partial x}|\psi_1^{(1)}|^2. \tag{12}$$

The field components as depicted by Eqs. (11) & (12) represent essentially large scale, zero frequency convective cell structures or whistler vortices of 2D EMHD which are nonlinearly excited through the ponderomotive forces that are proportional to $\sim |\psi_1^{(1)}|^2$. The coefficients in Eqs. (11) & (12) are as follows,

$$
\begin{aligned}
F &= \frac{2k_y^2(1+k_m^2) - 2uk_y(1+\hat{k}^2)(1/2-k_m^2)\gamma}{\Omega c_0 k_m^2 - \frac{u^2}{\Omega c_0}(1+\hat{k}^2)}, \\
G &= 2(1/2-k_m^2)\gamma - \frac{u}{\Omega c_0}F(1+\hat{k}^2), \\
\gamma &= \frac{k_m}{k_y} - \frac{u}{\Omega c_0}(1+k_m^2).
\end{aligned}
$$

The terms associated with the diffusive coefficient (μ) in the governing equations of EMHD Eqs. (1) & (2) do not appear in the Eqs. (9) & (10) as they are higher order terms, and hence neglected. While arriving at Eqs. (9) & (10), the nonlinear interaction mechanism tends to generate a few more terms corresponding to the fluxes in the in plane and out of plane components of the magnetic field perturbations. These nonlinear fluxes are expected to be balanced by the corresponding sources or sinks in the respective equations.

The excitation mechanism of large scale coherent vortices adapted here has been previously used in many other two dimensional systems such as hydromagnetic flows [16], drift waves [17, 18], and interchange mode turbulence [19]. However, generation of these nonlinear vortices are subject to certain critical conditions, and shall be considered in the next section.

IV. MODULATIONAL INSTABILITY IN EMHD

The Eqs. (9) & (10) can further be manipulated algebraically to put into a well known nonlinear Schrödinger (NLS) like equation by substituting the zero frequency components in them and using the linear dispersion relation to yield

$$
i\mathbf{P}\frac{\partial \Psi_1^{(1)}}{\partial \tau} + \mathbf{Q}\frac{\partial^2 \Psi_1^{(1)}}{\partial \xi^2} + \mathbf{R}|\Psi_1^{(1)}|^2\Psi_1^{(1)} = 0. \tag{13}
$$

The coefficients of the Eq. (13) are as follows;

$$
\begin{aligned}
\mathbf{P} &= \Omega c_0 k_y \hat{k} + (1+\hat{k}^2), \\
\mathbf{Q} &= \Omega c_0 \left\{ \frac{k_y}{\hat{k}} - \hat{k} - \frac{3k_y\hat{k}}{1+\hat{k}^2} \right\} - \frac{u}{k_y}(1+\hat{k}^2), \\
\mathbf{R} &= \frac{k_m^2}{k_y\hat{k}^2\Omega c_0}(Fk_m^2 - G\hat{k}^2) + k_y k_m^2 \hat{k} F + G k_m^2 k_y,
\end{aligned}
$$

where the terms F and G have already been defined in the previous section. We are now basically interested in generation of large scale whistler vortices, as identified by the Eqs. (11) & (12). These coherent structures are localized along y direction due to modulational instability mechanism and in x due to imposed boundary conditions. It has been seen in the previous section that the coherent structures described by the Eqs. (11) & (12) are excited by self-interaction of fast whistler modes as a result of nonlinear forcing imparted by the ponderomotive force, $|\psi_1^{(1)}|^2$, whose evolution is primarily governed by the NLS Eq. (13). Under certain circumstances, the NLS equation is known to exhibit an instability which is explicitly driven by modulation of the wave packets [18]. The problem then basically refrains to exploring the conditions under which Eq. (13) exhibits modulational instability. The well known criteria for Eq. (13) to be driven modulationally unstable is the one when the product of the coefficients $\mathbf{Q}$ and $\mathbf{R}$ associated respectively with the linear and nonlinear terms takes on real positive values such that $\mathcal{F} = \mathbf{Q} \cdot \mathbf{R} > \mathbf{0}$ [18]. Thus when $\mathbf{Q} \cdot \mathbf{R} > \mathbf{0}$, a plane whistler wave is unstable for modulation. The condition $\mathcal{F} > 0$ appears to be rather restrictive and is complicated to analyze theoretically. We therefore resort to its numerical solution to locate the region where the NLS equation can become modulationally unstable.

In the regime where EMHD excitation length scales are larger than the skin depth (i.e. $k < 1$), the function $\mathcal{F}$ has been plotted in Fig (1). The figure shows constant contour lines of $\mathcal{F}(k_m, k_y)$ for a given value of an external magnetic field B_0. The positive region ($\mathbf{Q} \cdot \mathbf{R} > \mathbf{0}$) in the figure has been indicated. It can be seen here that the function $\mathcal{F}(k_m, k_y)$ spans certain region where the characteristic wavenumbers in EMHD exhibit modulational instability. There exists certain wavenumbers that are fairly stable and can be categorically seen as the region where $\mathcal{F}(k_m, k_y)$ takes negative values in k_y-k_m spectrum in Fig (1). These modulationally stable wavenumbers may not be responsible for the generation of coherent structures. On the other hand, it can be seen from Fig (2) that the spectrum of wavenumbers demonstrating modulational instability in the regime where EMHD length scales are smaller than d_e (i.e. $k > 1$ modes) is shifted towards higher mode number. This is unlike $k < 1$ regime. It can be then realized from Fig (1) and Fig (2) that the wavenumbers exhibiting modulational instability in $k < 1$ and $k > 1$ regimes acquire entirely different attributes in the Fourier spectrum. For example, the largest length scales (or smallest Fourier modes) in the regime $k < 1$ are most susceptible to the modulational instability, while relatively smaller length scales (or larger modes) in $k > 1$ regime are more prone to the instability.

Hence there exists a wider spectral gap between the modulationally unstable wavenumbers in the whole spectrum around $k \simeq 1$ due to the two regimes. It thus means collisionless skin depth d_e is an important inherent length scale in the EMHD phenomena and the modes in the close vicinity of the domain $k \simeq 1$ exhibit entirely different features as compared with the domain far from it. It is to be noted here that the wave numbers (k_y, k_m) are normalized to inertial electron skin depth (d_e), hence to achieve the regime of length scale larger or smaller than skin depth, we adjust the value of parameter d_e in our calculation.

The NLS equation described by Eq. (13) has widely been studied in physics for understanding a variety of nonlinear phenomena associated with hydrodynamical fluids [20–22] and various others. The most commonly known solution of Eq. (13) is so-called 'soliton' and has rigorously been pursued in the literature. Nevertheless, within the parameter regime where characteristic EMHD length scales exhibit modulational instability, numerical solution of Eq. (13) at a given time demonstrates spatially well localized structure for $k < 1$ modes as shown in Fig (3).

V. DISCUSSION

Large scale zero frequency localized coherent structures, namely electron fluid vortices, have been investigated in an incompressible two dimensional electron magnetohydrodynamics plasmas, wherein typical time scales permit electron motion only, while ions merely provide stationary neutralizing background. These vortices are supposedly excited by the action of ponderomotive forces due to an explicit nonlinear self-interaction between two relatively fast whistler modes, when they are driven modulationally unstable. Interestingly such whistler modes can be stable to the modulation of wave packets in the vicinity of regime of length scales that are comparable to the inertial electron skin depth. This regime of wavenumbers may therefore be forbidden to the modulational instability. On the other hand, far away from the region of stable wavenumbers, EMHD modes can likely to exhibit modulational instability and lead to coherent vortices.

The importance of inertial skin depth in EMHD has already been realized particularly within the context of turbulent phenomenon [5–8] which indicates that EMHD characteristic wavenumbers in the regime $k < 1$ possess dominant wave attribute, while they behave more like hydrodynamical eddies in the other regime $(k > 1)$. Interestingly, here it has been observed that these relatively longest and the shortest eddies in the regimes $k < 1$ and $k > 1$ respectively can lead to excitation of large scale vortices when they undergo modulational instability processes.

The phenomenon of generation of large scale whistler vortices in EMHD plasmas through the mechanism of nonlinear self-interaction of the whistler modes, as reported here, could be of great interest to understand experimentally observed propagating whistler vortices along an external magnetic field [12], translating dipolar structures of EMHD [11, 13, 14] and EMHD turbulence [2, 5–8].

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- **Fig (1)** Constant contour lines of modulational instability condition as deduced from $\mathcal{F} = \mathbf{U} \cdot \mathbf{Q} > \mathbf{0}$. Positive region has been indicated by shading, while the remaining region corresponds to negative values of $\mathcal{F}$. Here $k < 1$ and $L = -50\pi : 50\pi$.

- **Fig (2)** Wavenumbers exhibiting modulational instability in the regime of length scales smaller than electron skin depth $k > 1$ as indicated by the unshaded region labeled as 'positive region'. $L = -50\pi : 50\pi$. The shaded region represents $\mathcal{F} < 0$.

- **Fig (3)** Localized coherent structure of EMHD in the regime $k < 1$ for the parameters $k_y = k_m = 2{\times}10^{-3}$. $k > 1$ regime also demonstrates similar structure but with different magnitude (not shown here).