Modeling Lower Hybrid Waves Generated by Charged Space Objects

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ABSTRACT
Orbital debris can cause catastrophic damage to satellites. Pieces of debris <10 cm in size are numerous and difficult to track using optical techniques. It has been proposed to track this debris using the waves they generate in ionospheric plasma. In situ measurements have potentially shown the presence of waves propagating at a variety of frequencies including the lower hybrid frequency ω_{LH}. This paper summarizes a hybrid PIC fluid model that has been developed. Results showing the generation of waves near the lower hybrid frequency in the wake of space debris using this model are also discussed.

KEYWORDS
Plasma Simulation; Plasma Waves; Orbital debris; Lower Hybrid Waves

1. Introduction

Orbital debris can cause catastrophic damage to satellites. Satellites in Low Earth Orbit (LEO), travel through the ionosphere, which is a part of earth's upper atmosphere in which photo-ionization from the sun produces a plasma environment. Pieces of debris smaller than 10 cm are difficult to observe with current optical techniques, and it has been estimated that there are over 35 millions pieces of debris between 0.1 cm and 10 cm (**?**). Debris this small traveling at high speeds can do substantial damage to spacecrafts and endanger human life in space. It has been proposed to track this debris using the waves they generate in the ionospheric plasma. In situ measurements of plasma waves in the ionosphere show that objects may produce waves at a range of frequencies (**?**). Considerable previous theoretical work and simulations have focused on the creation of nonlinear ion acoustic solitary structures produced in the wake of the debris as well as precursor waves (**?**).

This work focuses on the possible generation of waves near the lower hybrid frequency ω_{LH}, in the wake of space debris, consistent with recent observations (**?**). For typical Low Earth Orbit (LEO) observations, this corresponds to a frequency in the 10kHz range. A new two-dimensional (2D) hybrid plasma simulation model will be discussed and then results on plasma waves in the debris wake will be presented. The simulation model used in this study is an adaptation of the electrostatic 2D hybrid model originally developed for investigation of plasma waves produced by expanding dust clouds (**?**).

2. Numerical Model

A two-dimensional (2-D) plane perpendicular to the geomagnetic field $\vec{B}$, is considered. The plasma electrons are treated as a fluid with density n_e and velocity $\vec{v}_e$, where Eqs. 1 and 2 are the continuity and momentum equations, respectively

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}_e) = \left. \frac{dn_e}{dt} \right|_{chg} \tag{1}$$

$$\vec{v}_e = \frac{(\vec{E} \times \vec{B})}{B^2} \tag{2}$$

Note the term on the right hand side of Eq. 1 describes the reduction of the electron density due to charging. Also note that the electron fluid velocity in Eq. 2 is approximated to just be due to $\vec{E} \times \vec{B}$ drift which is a strongly magnetized assumption. The plasma ions are treated as a fluid with density n_i and velocity $\vec{v}_i$, where Eqs. 3 and 4 are the continuity and momentum equations, respectively

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}_i) = \left. \frac{dn_i}{dt} \right|_{chg} \tag{3}$$

$$\frac{\partial \vec{v}_i}{\partial t} + (\vec{v}_i \cdot \nabla)\vec{v}_i = \frac{q_i}{m_i}\vec{E} + \gamma \frac{T_i}{m_i}\frac{1}{n_i}\nabla n_i + \nu_{in}\vec{v}_i \tag{4}$$

The term on the right hand side of Eq. 3 is the change in ion density due to charging onto the debris. Eq. 4 assumes unmagnetized ions. In Eq. 4, T_i, q_i, and m_i, are the ion temperature, charge, and mass, γ is the ratio of specific heats, and ν_{in} is the ion-neutral collision frequency. The electron and ions are initialized as 10000 cm^{-3}, with a small random variation. The debris is modeled using the Particle-In-Cell (PIC) method which allows for time dependent charging and evolution of the debris charge Q. The debris is assumed to be made up of a large number of simulation particles loaded in a Gaussian spatial distribution each with subscript j which obeys the following position, velocity, and charge evolution.

$$\frac{dx_j(t)}{dt} = v_d \tag{5}$$

$$\frac{dQ_j(t)}{dt} = I_{ej} + I_{ij} \tag{6}$$

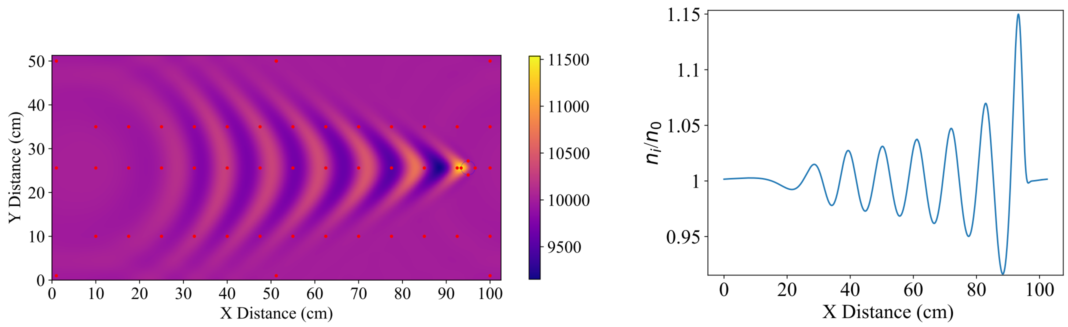
Note that v_d is the constant speed of the debris particle and I_{ej} and I_{ij} are electron and ion currents which are obtained from Orbit Limited Motion (OLM) charging theory (**?**). The electrostatic potential is solved using Poisson's equation where ρ_e, ρ_i, ρ_d are the electron, ion, and debris particle charge density, and ε_0 is the permittivity of free space. Also $\vec{E} = -\nabla\phi$.

$$\varepsilon_0 \nabla^2 \phi = -(\rho_e + \rho_i + \rho_d) \tag{7}$$

The computational domain chosen for this study is 1024 cells by 512 cells. 48 cells were chosen to collect ion density time evolution data during the simulation to later calculate frequency power spectra. These cells were spread evenly throughout the domain to obtain a complete picture of the frequencies in the domain. For simplicity, this initial result considers the case with a constant charge on the debris particle. Subsequent studies will consider the full dynamical evolution of the debris charge state. The debris was given a constant speed of Mach 2, that is, the debris moves at twice the ion thermal velocity. The physical dimensions of the simulation domain are approximately 1 meter with timescales of 10 milliseconds or less. The debris particle is approximately 10 cm or less with a velocity of approximately 5 km/s.

3. Results

This section presents the results of the described simulation. Figure 1 shows the ion density at the end of the simulation. The debris is moving left to right at Mach 2. Wave structures are observed to be trailing the debris particle which is denoted by the circle near the right side on the x-axis. The x and y axis scales of 1(a) are in centimeters, implying the x simulation domain size is approximately 1 meter. The x axis of 1(b) is also in cm, while the y axis is the ion density normalized to the background ion density, n_0. These structures are similar to the so-called pinned solitons associated with ion acoustic solitary wave generation by debris particles (**?**). This figure shows the generation of nonlinear solitary structures that follow the debris throughout the duration of the simulation maintaining the same spatial form.



(a) 2-D Psuedo-color plot of the ion density

(b) 1-D Cross section of the ion density

Figure 1.: 2D and 1D plots of the ion density taken at the end of the simulation

Figure 2 shows the fluctuation in ion density of one cell and the Fourier transform of this ion density data to obtain the frequency power spectrum of the waves. Note τ_{LH} is the lower hybrid wave period. The horizontal axis of the Fourier transform graph is normalized to the lower hybrid frequency. The vertical axis of the ion density graph is normalized such that 0 corresponds to the background ion density. The Fourier transform graph shows an enhancement in power near ω_{LH} which implies these nonlinear solitary wave structures are associated with oscillations near the lower hybrid frequency.

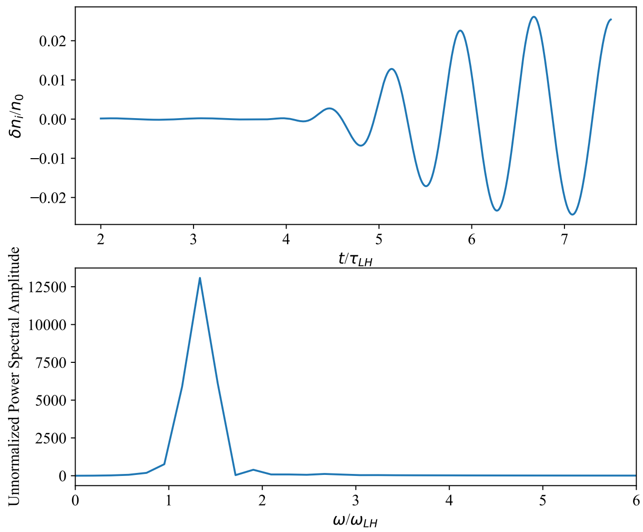


Figure 2.: Frequency power spectral analysis of one cell showing lower hybrid oscillations

4. Summary

A 2-D hybrid model has been used to investigate the generation of lower hybrid waves by orbital debris. Nonlinear solitary wave structures are observed in the simulations which are reminiscent of so-called 'pinned solitons' observed to be associated with nonlinear ion acoustic wave generation by moving charged objects in a plasma. The structures observed in the present simulations are associated with oscillations near the lower hybrid frequency in the ion density. Future work will include a detailed study of the impact of Mach number, self-consistent charging, and varying magnetic field angle on these structures and their oscillation frequency.

5. Acknowledgements

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