Precursor magneto-sonic solitons in a plasma from a moving charge bunch

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Abstract

The nature of fore-wake excitations created by a charge bunch moving in a magnetized plasma is investigated using particle-in-cell simulations. Our studies establish for the first time the existence of precursor magneto-sonic solitons traveling ahead of a moving charge bunch. The nature of these excitations and the conditions governing their existence are delineated. We also confirm earlier molecular dynamic and fluid simulation results related to electrostatic precursor solitons obtained in the absence of a magnetic field. The electromagnetic precursors could have interesting practical applications such as in the interpretation of observed nonlinear structures during the interaction of the solar wind with the Earth and the Moon and may also serve as useful tracking signatures of charged space debris traveling in the ionosphere.

1. Introduction

Precursors that travel faster than a source pulse exciting them are of much fundamental and practical interest in many areas of physics. For example, optical precursors that were theoretically predicted many years ago by Sommerfeld and Brillouin [1, 2], provide insights into questions related to group velocity in a dispersive medium [3] and can be potentially useful in applications like underwater communications [4] or deep imaging of biological tissue [5]. Optical precursors have been experimentally observed when light pulses have been launched in a deionized water column [4] and also in a linear dispersive medium consisting of a gas of cold potassium atoms [6]. Their occurrence is associated with the existence of anomalous dispersion in the medium, namely, a negative value of the derivative of the refractive index with respect to frequency at the source pulse carrier frequency. In principle, such a linear phenomenon can also take place in a gaseous plasma medium as has been pointed out in past studies [7–9]. However in a plasma there can be other competing mechanisms of precursor generation that do not depend on anomalous dispersion but exploit the nonlinear properties of the medium. One such process is the excitation of nonlinear structures like solitons or shocks that can propagate faster than the moving excitation source. The generation of such nonlinear precursor pulses has been conjectured a long time ago in hydrodynamics and studied in the context of fore-wake structures generated by moving ships [10–12] but has received scant attention in plasmas until recently. Theoretical studies in the framework of a fluid model have now shown the existence of electrostatic precursor pulses ahead of a super-sonically moving charged object in a plasma [13–15] and experimental support has come from observations in a laboratory dusty plasma device [16, 17]. One of the advantages of these solitonic precursors over the Brillouin or Sommerfeld type precursors is that they can propagate over long distances without any attenuation and can thus prove more useful in communication applications or in transferring packets of energy to a target. To date, the theoretical/simulation studies of such precursors in plasmas have been limited to the excitation of low frequency electrostatic pulses in a fluid plasma model [13, 14] or in a strongly coupled Yukawa fluid system [15]. In the present work we take a more fundamental approach of investigating this phenomenon at a particulate level and also consider the excitation of electromagnetic pulses. Using two dimensional
particle-in-cell simulations we establish from first principles the existence of precursor magnetosonic solitons propagating ahead of a moving charge bunch in a magnetized plasma and explore the excitation conditions and the nature of these solitons. We also point out the potential uses of our results in a few practical applications ranging from space debris detection to interpretation of precursor waves in Earth solar wind interactions.

The paper is organized as follows. In section 2 we briefly describe the physical model used for our simulations and also give the essential computational details. Our main results are presented in section 3 with separate subsections devoted to confirmation of earlier electrostatic precursor results section 3.1, magnetosonic solitons section 3.2, pinned solitons section 3.3 and precursors from a two dimensional source section 4. Section 5 gives a summary of our results and discusses their possible occurrences in nature and also their potential applications.

2. Simulation model

Our 2d-3V particle-in-cell simulations have been carried out using the OSIRIS-4.0 code [18–20] for a quasi-neutral plasma system consisting of positive ions and electrons. For simplicity and shorter simulation times the ion to electron mass ratio has been taken to be 25. In this system a short pulsed beam of positive (or negative) ions is made to travel at various velocities and the resultant wave excitations are studied. A constant magnetic field $B_0$ is imposed in the $\hat{z}$ direction while the beam travels in the perpendicular $\hat{x}$ direction. A schematic of the simulation geometry and the start-up scenario is shown in figure 1. The magnetic field strength is chosen to be such that the following condition holds, namely, $\omega_{ci} < \omega_{pi} \ll \omega_{pe}$, where $\omega_{ci}$, $\omega_{ce}$, $\omega_{pe}$ and $\omega_{pi}$ are the ion cyclotron, the electron cyclotron, the electron plasma and the ion plasma frequencies respectively. In this situation the electrons are strongly magnetized while the ions are not. The beam width in the direction of propagation is chosen to be of the order of a few electron skin depths, $c/\omega_{pe}$, where $c$ is the velocity of light in vacuum. The beam pulse, which acts as a moving current source for the electromagnetic excitations and a moving charge density source for the electrostatic excitations, is considered to be rigid and free streaming with no loss in its energy as it propagates through the plasma. Its typical charge density is $\sim 1.15n_0e$ where $n_0$ is the equilibrium plasma density and $e$ is the electronic charge. A rectangular area of $1500c/\omega_{pe} \times 100c/\omega_{pe}$ in the $x$--$y$ plane has been chosen for the simulations with $n_0 = 3.19 \times 10^{20}$ cm$^{-3}$. The spatial resolution chosen in the simulation is 10 cells per electron skin depth ($c/\omega_{pe}$) with 64 particles per cell for each species corresponding to a grid size of $\Delta x = 0.1c/\omega_{pe}$ and the temporal resolution is given by the time step $\Delta t = 0.0707\omega_{pe}^{-1}$. The cubic order interpolation schemes and sufficient number of particles per cell used in the simulations carried out in this work reduces the intrinsic noise to very very low level [19]. For our own simulations, the accuracy of our results has been verified by decreasing the time steps and grid sizes by factors of 10 and found no significant changes. Therefore, a tiny initial noise in the form of thermal velocities $v_{th1} = 0.000\,442c$ and $v_{th2} = 0.000\,0884c$ (corresponding to 0.1 eV for each species), is added to electrons and ions respectively to trigger excitations in our system. This is then supplemented by providing an actual temperature to the electrons, for the $B = 0$ case where one is looking for electrostatic ion acoustic excitations which require warm electrons and cold ions. The electron temperature is such that the ion acoustic sound speed in the medium is 0.1$c$. For the electromagnetic case the electrons are once again assumed to be cold (i.e. at $v_{the} = v_{th1} = 0.000\,442c$) so that they remain magnetised in the presence of the background magnetic field. The boundary conditions for the electromagnetic fields and particles are

![Figure 1](image-url)
periodic in the \( \hat{y} \) direction and absorbing in the \( \hat{x} \) direction. The value of the magnetic field is taken to be \( B_0 = 2.5 m_e c \omega_{pe} / e \) where \( m_e \) is the electronic mass.

3. Results

3.1. Electrostatic precursors

Prior to investigating electromagnetic precursors we carried out a series of simulations in the absence of the background magnetic field \((B = 0)\) in order to benchmark our code and to also examine the earlier fluid and molecular dynamic results of electrostatic precursors in the framework of a PIC simulation. As is well known [21, 22], a charged source traveling in a dielectric medium can excite various collective modes of the medium depending on its speed relative to the phase velocities of the modes. In the present case we therefore make the pulsed beam travel close to the ion acoustic speed in order to study the excitation of low frequency electrostatic waves. For undamped ion acoustic waves to exist in the plasma we need to have \( T_e \gg T_i \). Accordingly, as discussed in the previous section we assign an appropriate temperature to the electrons and define the ion acoustic speed (in the absence of the beam) as \( V_{cs} = \sqrt{\frac{\hbar k_B}{m_i}} = v_{the} / \sqrt{\frac{m_i}{m_e}} \)

where \( v_{the} \) is the electron thermal velocity and \( k_B \) is the Boltzmann constant. To test the earlier fluid results we examine two cases, namely when (i) \( V_b < V_{cs} \) and (ii) \( V_b > V_{cs} \) where \( V_b \) is the beam velocity. For our simulations we have chosen \( V_{cs} = 0.1c \) and (i) \( V_b = 0.06c \) and (ii) \( V_b = 0.11c \) so that the two cases correspond to \( M = 0.6 \) and \( M = 1.1 \) respectively, where \( M = V_b / V_{cs} \) is the Mach number. It may be noted that our definition of the Mach number is based on the definition of the ion acoustic speed in the unperturbed plasma and ignores any change in the sound speed due to the presence of the beam. In practice, as we show later, the measured phase velocities of the linear ion acoustic waves excited as wakes by the beam are in fact very close (upto a few percent) of the \( V_{cs} \) value used in our definition of the Mach number.

Figure 2 illustrates the simulation results for these two cases in the form of 2d snapshots of the electron density at \( t = 353.5 \) and \( t = 700.0 \). Superposed on the snapshots we have plotted the \( y \) averaged density values (line plots) as a function of \( x \). From the figures it is evident that for \( V_b < V_{cs} \) one only gets wake fields excited behind the source whereas for \( V_b > V_{cs} \) a series of precursor pulses are generated ahead of the traveling source. These precursor pulses are formed in front of the source due to the rapid piling up of the density at the expense of a density depression behind the source. If the beam is moving at a subsonic speed then the accumulated mass at its front can disperse away at the linear phase velocity of the sound waves in that region. However if the beam moves supersonically then the accumulated mass cannot disperse away fast enough and it keeps growing leading to nonlinear steepening. When this steepening balances the dispersion it can lead to the formation of a soliton which can move at a speed faster than the speed of the beam and thereby move away from it. The pile up develops again leading to the formation of another soliton and thereby resulting in a series of solitons ahead. We have independently ascertained the solitonic nature of these pulses by checking the constancy of the product of their amplitudes with the square of their widths—a procedure that will be described in more details when we discuss the electromagnetic solitons. We have also examined the nature of the trailing wakes behind the charge bunch which according to the linear theory of wakes should consist of ion acoustic waves [21–23]. To verify this in our simulations we have obtained the frequency spectrum of these waves in the far-wake region and shown it in figure 3(a).

The wavelength of these structures is estimated from the distance between the oscillation peaks and then the phase speed is estimated as \( \omega / k \). For an additional confirmation we have also directly obtained the phase velocity of the waves from the simulation data by measuring the distance traveled by a wave peak over a prescribed time period. This is shown in figure 3(b) and the measured phase speed comes out to be 0.0925c which differs from the theoretical ion sound speed value (in the absence of the beam) of 0.1c by about 7.5%.

Figure 4 shows the plots of the electric fields in the \( x \) and \( y \) directions. The extremely weak values of the electromagnetic component \( E_y \) compared to \( E_x \) further establishes the electrostatic nature of these excitations. Our electrostatic PIC simulation results are thus in accord with the earlier fluid and MD simulation results and not only serve as a good benchmark of our code but also provide a first principles confirmation of this phenomenon at a particulate level.

3.2. Electromagnetic precursors

We now discuss our simulation results carried out in the presence of an ambient magnetic field with the short pulse beam source traveling perpendicular to the field (as shown schematically in figure 1). For this case we take the both electrons and ions to be cold i.e. at a noise level with thermal velocities...
$V_b < V_{cs}$ and $V_b > V_{cs}$ propagation velocities of the beam. The line plots superposed on the snapshots are the $y$ averaged density values providing a one dimensional profile of the perturbations as a function of $x$.

Figure 3. Spectrum analysis of far wake region for electrostatic case.

$v_{th1} = 0.000\,442c$ and $v_{th2} = 0.000\,0884c$ for electrons and ions respectively, corresponding to a temperature of 0.1 ev. We discuss two cases, namely, (i) $V_b < V_{ms}$ and (ii) $V_b > V_{ms}$, where $V_{ms}$ is the phase velocity of linear magneto-sonic waves and which for our cold plasma case is close to the Alfvén velocity $V_A = (m_e/m_i)^{1/2} \omega_{ce}/\omega_{pe} = 0.5c$ for our choice of parameters. For our simulations we have chosen (i) $V_b = 0.3c$ and (ii) $V_b = 0.505$ so that the two cases correspond to $M = 0.6$ and $M = 1.01$ respectively. Here $M = V_b/V_{ms}$ is the Mach number. Figure 5 illustrates the simulation results for these two cases where we have again superposed the $y$ averaged density values as line plots on the 2d density snapshots.

Figure 6 displays the electric field components of the wake-fields and precursors. Unlike the electrostatic case we now find that the excitations have both an $E_x$ as well as an $E_y$ component thereby establishing their electromagnetic nature. These are in fact nonlinear magneto-sonic waves of the fast kind with the precursors taking the form of magneto-sonic solitons. In the present case the solitons are found to propagate with a Mach speed of around $M = 1.13$ with the taller solitons moving faster than the smaller amplitude ones. In fact their peaks lie on an ascending straight line as shown in figure 6 which is a characteristic of soliton solutions of the Korteweg de Vries (KdV) equation [24]. Another signature of a KdV type soliton is the constancy of the product of its amplitude ($a$) with the square of their width ($L$). To
Figure 4. Plots of the electric fields in the $x$ and $y$ directions for the $V_b < V_{cs}$ and $V_b > V_{cs}$ cases.

Figure 5. Two dimensional snap shots of the electron density at $t = 353.5$ and $t = 707$ for ($V_b < V_{ms}$) and ($V_b > V_{ms}$) propagation velocities of the beam. The line plots superposed on the snapshots are the $y$ averaged density values providing a one dimensional profile of the perturbations as a function of $x$.

Further establish the solitonic nature of the precursors we have measured the amplitudes and widths of a number of them and checked the constancy of $aL^2$. Our findings are given in table 1.

As can be seen from the table, the parameter $aL^2$ changes very little in simulations and essentially remains constant for the observed precursor magnetosonic KdV solitons $A$, $B$ and $C$ of figure 6. The percentage variation in $a$ is 24% and 22% for $L^2$ but $aL^2$ varies only by 4.3% in the data shown above.

We also notice from figure 5 that precursors are generated even when $V_b < V_{ms}$ but they are considerably weaker than the $V_b > V_{ms}$ case. This is distinctly different from the electrostatic case where for $V_b < V_{cs}$ no precursors were generated at all and therefore is suggestive of a fundamental difference in the excitation mechanism of the two kinds of solitons. Electrostatic solitons are born in front of the source pulse due to a rapid pile up of the density when its velocity exceeds the phase velocity of the ion acoustic...
wave. The electromagnetic solitons on the other hand are primarily created in the wake region when the wake fields become nonlinear and can then overtake the source pulse due to their faster velocity when \( V_b < V_{ms} \). As in the electrostatic case, we have also analyzed the nature of the wakes for the magnetized plasma case, particularly in the far wake region where the waves are expected to be linear. As before we have looked at the frequency spectrum as well as the phase velocity of the waves as measured from the simulation data. The results are shown in figure 7(a) and figure 7(b) which show them to be magneto-sonic waves.

Magneto-sonic solitons have been studied in the past both analytically (using the KdV and its variants) [25–27] as well as in various numerical simulation studies [28, 29]. Most recently they have been observed in PIC simulations in the wake region of an intense laser pulse passing through a plasma [30]. However, we
Figure 8. The excitation of a pinned soliton when the beam travels at $V_b = 0.85$ corresponding to $M = 1.7$. The inset shows a magnified view of the structure of the soliton that envelops the source and travels at the same speed as the source.

Figure 9. Plots for $E_x$ and $E_y$ for Pinned soliton case where beam is moving with $0.85c$ ($M = 1.7$). It is evident from the figure that the pinned solitons are also electromagnetic, magnetosonic solitons.

believe they have never been studied or seen in the context of precursor pulses and our present results are the first to establish their existence ahead of a charged source traveling in a magnetized plasma.

3.3. Pinned solitons
As discussed in the previous section, the precursor magneto-sonic solitons are of the KdV type and propagate with velocities that have $M > 1$. In our case when the beam velocity was $M = 1.01$ the precursor soliton speed was found to be $M = 1.13$. What happens if we increase the beam speed to higher Mach numbers? To explore this question we have carried out simulations at $M = 1.7$ and the results are shown in figure 8. One notices that there are no precursor solitons ahead of the moving source but an envelope structure develops around the source which travels at the same speed as the source. Such a structure known as a ‘pinned’ soliton has been predicted theoretically for a driven KdV equation [31, 32] but has not been captured in any PIC simulation studies. The structure is a few electron skin depths wide and has the characteristic bell shape form of a soliton. The longitudinal and transverse electric fields associated with the pinned soliton are shown in figure 9 establishing once more that these are electromagnetic structures.

4. Two dimensional sources
Our simulation results, presented in the preceding sections, were based on a simplification of the source term by assuming it to be of a one dimensional nature. This helped us to establish in principle the existence of the precursor and pinned solitons and to appropriately compare them to past fluid simulation results. However in an actual physical situation the moving charged object will be of a three dimensional nature and the size and shape of the object will likely influence the nature of the excitations. While a detailed study based on 3d-3V simulations is presently in progress and will be reported by us later, we present here a preliminary result obtained with a two dimensional circular source term that illustrates such an effect. Figure 10 shows a typical snapshot of the electron density for a circular source (of radius $r = 2c/\omega_{pe}$) moving at $M = 1.01$ across the magnetic field in the plasma. The basic results remain the same, namely, the excitation of wake structures in the downstream region and precursor pulses in the upstream region. The only noticeable difference from the 1d simulation is in the shape of the wakes and precursors which are now
Figure 10. Typical snapshots of the electron density for a circular charged source moving at a Mach speed of 1.01 in the magnetized plasma.

curved in nature. This means that the presence of the wakes and precursors will not be uniformly felt in the $y$ direction due to the curvature effect.

5. Discussion

To summarize, we have carried out detailed PIC simulations to study the phenomenon of precursor excitations of nonlinear pulses ahead of a charged source moving in a plasma. Our particular focus has been on the emission of electromagnetic pulses which have hitherto not been studied in this context. Our simulations establish for the first time the existence of such precursors in the form of magneto-sonic solitons that can either travel faster than the source or appear as stationary structures pinned to the source. Pinned solitons appear when the source speed is at a Mach number that is higher than about 1.6. As a benchmark exercise we have also confirmed the existence of electrostatic precursors in the form of ion acoustic solitons when the simulations were done in the absence of a magnetic field. These electrostatic results agree well with previously obtained fluid and molecular dynamic simulations. A comparison between the electrostatic and electromagnetic precursors reveals some interesting differences. The electrostatic wake fields are quite weak for low Mach numbers in comparison to those for the electromagnetic runs. Also while electrostatic precursors in the form of ion acoustic solitons occur only when the beam speed is supersonic ($V_b > V_{cs}$) the (electromagnetic) magnetosonic solitons appear even when $V_b < V_{ms}$. The difference can be traced to the basic mechanism for the creation of the solitons. The ion acoustic solitons arise from the pile up of the density in front of the charged source due to a balance between the nonlinear steepening and thermal broadening effects. Once formed they detach from the source and move away as their speed is faster than the source. The electromagnetic solitons on the other hand are not dependent on the density pile up and are created from the large amplitude wake fields that arise in the downstream region. If the source is moving at a sub-magnetosonic speed then the solitons can easily overtake the source and move ahead of it. The wake field excitations get larger as the source speed approaches or slightly exceeds the magnetosonic speed and the resultant solitons then acquire a higher speed and again move ahead of the source. If the source speed exceeds a certain limit (in this case $M = 1.6$) then one does not get any precursors but the soliton generated from the wake sticks to the source as a pinned soliton. Our simulations also reveal that the strength of the electromagnetic wake fields not only depends on the Mach number but also on the sign of the electrical charge of the source. Thus a positive ion beam source creates larger and sharper wakes than a corresponding negative ion beam of the same strength. Correspondingly the precursors created by the positive ion beam are sharper and larger in magnitude. These and other features of the wakes associated with the characteristics of the beam are currently under further investigation. Furthermore, the above studies have been carried out assuming an unrealistic mass ratio of ions to electrons $m_i/m_e = 25$. This has been done primarily to reduce the computation time. However we believe that increasing the mass ratio to a realistic value will not change the fundamental nature of our findings but might require a stronger impulse (by increasing the amount of charge and/or size of the charge bunch) in order to sufficiently disturb the ions for excitation of wakes and precursors.

We now briefly discuss the possible natural occurrences of such solitons and also their potential practical applications. Flowing plasmas interacting with obstacles or charged objects moving through a plasma are common occurrences in nature. The most common example is the streaming solar wind plasma impinging on the Earth and giving rise to the magnetosphere and a host of wave activity. From the perspective of our present simulations one could view the Earth as moving through the solar wind in the latter’s frame of reference. The solar wind has components that can be supersonic or even super-Alfvenic. One can thus
expect precursor pulses to be generated in the vicinity of the Earth’s bow shock and travel in the upstream (sunward) direction. There have indeed been several satellite observations of upstream waves that range in frequency from mHz to tens of kHz [33] and comprise of both electrostatic and electromagnetic disturbances. Some of these structures have also been identified with electrostatic solitons and occasionally with electromagnetic solitons that correspond to magnetic holes or magnetosonic solitons. Our simulation results provide a new paradigm for the interpretation of these wave structures by appropriately correlating them with the solar wind flow dynamics in these regions. It should be mentioned here that although our simulations have been done for an idealized ‘charged object’ which does not change its mass or charge as it travels through the plasma—factors that would influence a real object—our fundamental findings could still be realistically applied in many practical situations. For example, objects like artificial satellites and space debris that become naturally charged through interactions with the ionospheric plasma and other processes, possess so much kinetic energy and the collision mean free path in the ionosphere is so long that they do not suffer much energy change. The charge fluctuations due to interaction with the plasma are also of the order of a few percent of the ambient charge and can be neglected. Such objects can therefore give rise to precursors as they travel. Such precursors traveling ahead of the objects can be detected from the ground using radar scattering for example, and could prove useful in tracking dangerous objects like small scale space debris that can damage live satellites [13]. Electromagnetic solitons would be particularly useful in this regard as their spatial extent of a few electron skin depths would have a large footprint in the ionosphere and therefore be easy to remotely detect.

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