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Particle acceleration in tangential discontinuities by lower hybrid waves

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Abstract. We consider the role that the lower-hybrid wave turbulence plays in providing the necessary resistivity at collisionless reconnection sights. The mechanism for generating the waves is considered to be the lower-hybrid drift instability. We find that the level of the wave amplitude is sufficient enough to heat and accelerate both electrons and ions.

1 Introduction

The fact that the existence of phenomena in the ideal magnetohydrodynamics (MHD) limit would be called either a tangential or rotational discontinuity is demonstrated by both laboratory experiments and in situ detection of such phenomena in the Earth's magnetosphere by spacecraft. Such discontinuities are also believed to be common in solar and astrophysical plasmas and are often used to explain numerous phenomena, such as coronal heating, solar flares, coronal mass ejections and accretion disk phenomena. With rare exceptions, tangential discontinuities are invoked in the context of the reconnection process with any simultaneous particle acceleration being attributed to the electric fields generated by the reconnection process. On the other hand, shocks (a discontinuity in the ideal MHD limit) are frequently used to explain particle acceleration. This state of affairs is somewhat puzzling considering the fact that many of the conditions commonly found in shocks are typical of tangential and rotational discontinuities, such as steep gradients in all the physical quantities characterizing the discontinuities, as well as reflected ions. In this paper, we demonstrate the ease in which particles can be accelerated in a tangential discontinuity, using the Earth's magnetotail as an example. However, we want to emphasize that the same analysis can be used in other space phenomena with similar success.

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A tangential discontinuity in the ideal MHD limit has zero thickness but in reality it is typically tens of ion Larmor radii thick in collisionless plasmas. This means that under certain circumstances, ions may become unmagnetized, while electrons remain magnetized. In particular, this situation is typical of a class of tangential discontinuities called neutral sheets, where the component of the magnetic field parallel to the current sheet vanishes. Under such circumstances, a particularly powerful resonate particle acceleration mechanism can operate through the production of large amplitude ion density fluctuations. This mechanism is the lower hybrid drift instability (LHDI) which was first proposed by Huba et al. (1977, 1978) as a mechanism for producing anomalous resistivity in the Earth's magnetotail. As ions approach the magnetic field null, they become unmagnetized when their Larmor radius exceeds the thickness of the current layer. The electrons, with much smaller Larmor radii, remain magnetized. Under these circumstances, the ions form a cross field flow that results in the excitation of lower hybrid waves (LHW) through the LHDI. The LHW can resonate with both slow moving ions, perpendicular to the magnetic field, and electrons moving parallel to the magnetic field. The waves provide an effective means of transferring energy between the ions and electrons, thus providing a means of energizing electrons to high energies. It is our conjecture that mechanisms such as the LHDI can easily operate in tangential discontinuities and depending on the parameter regime, can also lead to accelerated electrons, heated electrons, or both, with concurrent ion heating.

Here, we will focus our attention on particle acceleration in the magnetotail, following the suggestion of Huba et al. (1977, 1978) that the LHDI may also accelerate particles in the process that leads to magnetic reconnection. However, we emphasize that the reconnection process itself is not necessary but simply a contemporaneous phenomena.

To accomplish our goal, we first summarize the conditions needed to excite the LHDI. In particular, we assume that the magnetic merging process is a steady state, permitting the assumption of marginal stability. This allows us to obtain an expression for the characteristic scale length required to maintain the LHDI at marginal stability. In the steady-state Petchek reconnection, we assume the LHDI is driven by the gradients in the magnetic field produced by the inflowing plasma. This allows us to obtain the level of anomalous resistivity required to achieve a steady state in terms of the length of the reconnection region, L, and the magnitude of the magnetic field $\boldsymbol{B}$. The incompressibility assumption permits a relationship between L and the thickness of the reconnection dissipation region, $\Delta x_\perp$, which closes the system and provides a complete set of equations in terms of spacecraft "observables". Once this is determined, we derive the level of ion density fluctuations at marginal stability. Estimates of the electron and ion temperatures are then obtained, together with non-thermal electron energies and numbers.

2 Lower Hybrid Drift Instability (LHDI)

We assume that the LHDI is operating in the kinetic regime $V_{Di} \ll V_{Ti}$, where $V_{Di} = V_{Ti}^2/2\Omega_{ci}\Delta x_\perp$ is the diamagnetic ion drift speed and V_{Ti} is the ion thermal speed. Its maximum growth rate is:

$$\gamma = \frac{\sqrt{2\pi}}{8}\left(\frac{V_{Di}}{V_{Ti}}\right)^2 \omega_{lh} \tag{1}$$

with a perpendicular wave number of

$$k_m = \sqrt{2}\frac{\omega_{lh}}{V_{Ti}} = \sqrt{2}\left(\frac{m_e}{m_i}\right)^{1/2}\frac{\Omega_{ce}}{V_{Ti}}, \tag{2}$$

where

$$\frac{V_{Di}}{V_{Ti}} = \frac{1}{2}\left(\frac{r_{Li}}{\Delta x_\perp}\right), \tag{3}$$

$$\Delta x_\perp^{-1} = \frac{\partial \ell n\rho}{\partial x_\perp} \approx \frac{\partial \ell n B}{\partial x_\perp}, \tag{4}$$

$$\omega_{lh} = \sqrt{\Omega_{ce}\Omega_{ci}},\, r_{Li} = V_{Ti}/\Omega_{ci},$$

where the ion thermal Larmor radius, and Ω_{ci} and Ω_{ce} are, respectively, the ion and electron gyrofrequencies.

In order to obtain a marginally stable state, we require the LHDI be damped. The most likely candidate is the modulational instability since there are many indications that the LHDI can evolve by the collapse of LH wave packets due to a modulational instability (Musher and Sturman, 1975; Sotnikov et al., 1980; Shapiro et al., 1994). The growth rate for the modulational instability is given by (Sotnikov et al. (1980)

$$\gamma_{IM} = \omega_{lh}\frac{r_{Li}}{|\Delta x_\perp|}\frac{T_i}{T_e}\frac{k_\perp r_{Li}^*}{\alpha^2(1+\beta)^2}, \tag{5}$$

where

$\beta = 8\pi P/B^2,\, r_{Li}^* = r_{Li}\,(m_e/m_i)^{1/2}$,

and $k_\perp r_{Li}^* \approx \left(\frac{1+\beta}{5}\right)^{1/2}$.

Equating Eqs. (1) and (5) yields the characteristic scale length required to maintain the drift current at marginal stability and thus the thickness of the reconnection dissipation layer. We find

$$\Delta x_\perp \approx \frac{\sqrt{10\pi}}{32} r_{Li}\frac{T_e}{T_i}\alpha^2(1+\beta)^{3/2}, \tag{6}$$

where α can be estimated from Sotnikov et al. (1980)

$$\alpha^3 e^{-\alpha^2/2} = \left(\frac{2}{\pi}\right)^{1/2}\left[(1+\beta)\left(1+\frac{6T_e}{5T_i}\right)\right]^{-1}. \tag{7}$$

To obtain the plasma turbulence level at marginal stability, we use the MHD fluid model of reconnection due to Petschek reconnection. The maximum inflow speed permitted by Petschek reconnection is given by

$$u_{o\,\max} = \frac{\pi}{8}\frac{V_A}{\ln(R_m)}, \tag{8}$$

while the definition of R_m, the magnetic Reynolds number, is

$$R_m = \frac{4\pi V_A L}{c^2\eta} = \left(\frac{u_e}{u_{o\,\max}}\right)^2, \tag{9}$$

where $u_e = \sqrt{2}V_A$ is the maximum outflow velocity, c the speed of light and V_A is the Alfvén speed. Using $u_{o\,\max}$ and u_e, and solving for η, one finds

$$\eta = \frac{4\pi^3}{128}\frac{V_A}{c^2}\frac{L}{c}\frac{1}{\ln^2(R_m)} = \frac{4\pi\nu}{\omega_{pe}^2} = \frac{4\pi}{\omega_{pe}}\frac{\langle\delta E^2\rangle}{8\pi nkT}. \tag{10}$$

Solving for $\frac{\langle\delta E^2\rangle}{8\pi nkT}$ yields

$$\frac{\langle\delta E^2\rangle}{8\pi nkT} = \frac{\pi^2}{128}\frac{V_A}{c}\frac{L}{c}\frac{\omega_{pe}}{\ln^2(R_m)}. \tag{11}$$

Here, we identify

$$\frac{\langle\delta E^2\rangle}{8\pi nkT}$$

as the ratio of the fluctuating electric field energy density produced by the LHDI at marginal stability and the thermal energy of the plasma. If we use $\ln(R_m) \approx 10$, a reasonable assumption for magnetotail parameters, then it follows that

$$\frac{\langle\delta E^2\rangle}{8\pi nkT} \approx 1.05\times10^{-8}BL, \tag{12}$$

where B is the magnitude of the incoming magnetic field and L is the length of the reconnection region. To determine L, we use the incompressible assumption

$$\frac{\Delta x_\perp}{L} = \frac{u_o}{u_e}, \tag{13}$$

which relates the thickness of the dissipation layer to the length of the dissipation layer, in order to find

$$L = \frac{\sqrt{128}}{\pi} \ln(R_m)\, \Delta x_\perp \approx 36 \Delta x_\perp \ , \tag{13a}$$

for $\ln(R_m) \approx 10$, where we have used $u_{o\,\max}$ and the maximum outflow velocity $u_e = \sqrt{2} V_A$. Eliminating L from Eq. (12) yields

$$\frac{\langle \delta E^2 \rangle}{8\pi nkT} \approx 3.8 \times 10^{-7} B \Delta x_\perp \ , \tag{14}$$

where $\Delta x_\perp$ is given by Eq. (6).

However, since the modulational instability is non-linear, there is a minimum level of lower hybrid turbulence required before the LHDI will become modulationally unstable. This level is given by Shapiro et al. (1994)

$$\left(\frac{\langle \delta E^2 \rangle}{8\pi nkT_i} \right)_{\min} \geq \frac{V_A^2}{c^2} \left(1 + \frac{T_e}{T_i} \right). \tag{15}$$

Hence it follows that for Eq. (11) to be valid, it must satisfy Eq. (15).

Using the same set of parameters used by Huba et al. (1977), i.e.

$B \approx 2.0 \times 10^{-4}$ gauss, $n \approx 10$, and $kT_i \approx 10^{-3} m_i c^2$,

we find $\Delta x_\perp \approx 0.12 r_{Li}$, $r_{Li} \approx 1.15 \times 10^7$cm,

$V_{Ti} \approx 2.2 \times 10^7$cm/s, $\lambda_{pe} \approx 1.68 \times 10^6$cm,

and for the Alfvén speed $V_A \approx 1.38 \times 10^7$cm/s, we find

$$\left(\frac{\langle \delta E^2 \rangle}{8\pi nkT_i} \right)_{\min} \approx 2. \times 10^{-7},$$

while Eq. (12) yields

$$\frac{\langle \delta E^2 \rangle}{8\pi nkT_i} \approx 1.0 \times 10^{-4}, \tag{15a}$$

thereby easily satisfying the minimum threshold condition. With Eqs. (14) and (15a), we can now compute the energies and fluxes of nonthermal electrons.

3 Electron temperature

A rough estimate of the change in temperature of the electrons due to the Ohmic heating can be obtained by noting that as the plasma flows through and out of the region of instability, electrons will experience Ohmic heating for a time

$$\Delta t \approx L/\sqrt{2} V_A,$$

hence, the change in electron temperature during this period is

$$\Delta k_B T \approx \frac{\eta J^2}{n} \frac{L}{V_A} \approx 36 \frac{\eta}{n} \left(\frac{cB}{4\pi \Delta x_\perp} \right)^2 \frac{\Delta x_\perp}{\sqrt{2} V_a} \tag{16}$$

or by using Eqs. (10), (14) and (15a) in Eq. (16), together with the parameters previously used, we find

$$\Delta T(\mathrm{eV}) \approx 140\,\mathrm{eV},$$

implying that electron temperatures of the order of a few hundred eV are expected.

4 Ion temperature

The LHDI leads to strong ion heating perpendicular to the magnetic field. Equipartition of energy indicates that two-thirds of the available free energy ends up in ion heating and one-third ends up in heating the electrons parallel to the magnetic field. The simple calculation below confirms this argument. To estimate the ion temperature, we utilize the fact that the ratio of ion and electron drifts is given by

$$\frac{V_{Di}}{V_{De}} = \frac{T_i}{T_e},$$

together with Ampere's equation, yields

$$T_i = T_e \left(1 + 2 \frac{V_A}{u} \frac{\Delta x_\perp}{L} \right) . \tag{17}$$

Since $V_A/u \simeq 25$ and $\Delta x_\perp / L \simeq 1/36$, we find $T_i \simeq 2T_e$ as argued above.

5 Electron nonthermal energies

To estimate the nonthermal energies of the electrons and their fluxes, we follow a standard approach used by previous authors (Lampe and Papadopoulos, 1977; Spicer et al., 1981; Bingham et al., 1991). Following Bingham et al. (1991) specifically, we find that the characteristic energy gained by the electrons with finite $k_\parallel$ is

$$\mathcal{E}_e \approx \left[\left(\frac{\omega_{pe}}{\Omega_{ce}} \right)^2 \frac{\langle \delta E^2 \rangle}{4\pi n} m_e V_{Ae}^2 \omega_{lh} L \sqrt{m_e} \right]^{2/5}$$

or

$$\mathcal{E}_e \approx \left[\frac{\omega_{pe}^2}{\Omega_{ce}} \frac{\langle \delta E^2 \rangle}{4\pi nk_B T_e} C_s^2 m_i m_e V_{Ae}^2 \left(\frac{m_e}{m_i} \right)^{1/2} L \sqrt{m_e} \right]^{2/5} , \tag{18}$$

where $C_s^2 = k_B T_e / m_i$ is the ion acoustic speed and V_{Ae} is the electron Alfvén velocity $= c\Omega_{ce}/\omega_{pe}$. Using the set of parameters that we previously employed and those computed, we find $\mathcal{E}_e = 280 eV$.

6 Electron nonthermal fluxes

In order to estimate the number density n_T of particles that are stochastically accelerated, we take as the initial distribution a maxwellian distribution and integrate it from ϵV_{Te} to ∞ to yield

$$\frac{n_T}{n} \approx \frac{1}{\sqrt{\pi}} \frac{e^{-\epsilon^2}}{\epsilon},$$

where ϵ is the smallest number of thermal speeds that we expect the LHW (with finite $k_\parallel$) to resonantly interact with. Since

$$k_\parallel \approx (m_e/m_i)^{1/2} k_\perp$$

for maximum growth and

$$k_\perp \approx \sqrt{2} \times (m_e/m_i)^{1/2}\, \Omega_{ce}/V_{Ti}\,,$$

it follows that

$$V_p^{\min} \approx 2.3 V_{Te}\,,$$

so that

$$n_T/n \approx 2.8 \times 10^{-3}.$$

The total number of nonthermal electrons accelerated per second, $\dot{N}_{nt}$, within the tangential discontinuity by LHW is just

$$\dot{N}_{nt} \approx \frac{n V_{Te} e^{-\epsilon^2}}{\sqrt{\pi}} \Delta x_\perp \Delta x_\wedge \,.$$

If we take $\Delta x_\wedge \approx L$, we find for the parameter set used above, $\dot{N}_{nt} \approx 3 \times 10^{22}$ electrons/s.

7 Discussion

We have demonstrated that the LHDI can generate relatively large amplitude lower-hybrid waves in the current sheet of the magnetotail. These LHW are shown to be capable of accelerating electrons and heating ions in the magnetotail during the reconnection process. The process describes the micro-physics of particle heating and generation during reconnection. The mechanism is important in the magnetosphere andother space environments where reconnection is invoked to explain particle heating and acceleration.

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