Energetic electrons downstream of Earth's bow shock: Simulations of acceleration by shock structure

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Abstract. Energetic electrons have been widely observed downstream of the Earth's bow shock, although the exact electron acceleration mechanism is not completely understood. Using a combination of hybrid shock simulation and electron test particles, we show how trapping by two dimensional structure in the form of ripples can cause electrons to be convected downstream with the magnetic field, despite having magnetic moments which suggest that they should be reflected upstream. These electrons undergo considerable Fermi acceleration during this shock transition and may explain the observed energetic downstream populations.

Introduction

Observations downstream of the Earth's bow shock reveal a population of suprathermal electrons whose energy spectrum has a power law tail [*Gosling et al.*, 1989]. The most studied mechanism for electron acceleration from the upstream distribution assumes conservation of magnetic moment, and produces greatest energisation for those electrons reflected back upstream by the field increase at the shock (i.e. a fast Fermi process). Using simulations, we show how shock structure can provide an additional mechanism for accelerating electrons that can account for these energetic downstream electrons.

Ripples are ion scale features seen at the shock front in two-dimensional hybrid simulations [*Winske and Quest*, 1989]. The process that generates the ripples remains poorly understood because high field gradients at the overshoot cause difficulty in identifying instabilities there. One possible mechanism is an instability driven by reflected ions gyrating back into the shock [*McKean et al.*, 1995]. Ripples could also be caused by wave trapping at the front due to the variation of the Alfvén speed through the shock ramp and overshoot, and work is currently in progress to study this latter possibility. In our simulations, ripples are seen to move along the ramp and overshoot. They are most clearly visible in the shock normal component of the magnetic field, B_x (Figure 1); a strictly one dimensional shock has a constant normal magnetic field component. An important effect of the shock front ripples is to introduce considerable variations in the magnetic field strength along a field line as it convects through the shock.

Using a two dimensional hybrid simulation and a test particle code, we examine these ripples and their effect on electron acceleration. This is done by taking the time varying fields from a self consistent hybrid (particle ions, electron fluid) shock simulation and using them in a test particle simulation of suprathermal electron motion.

Shock ripples

Our simulation of the shock fields uses the CAM-CL hybrid algorithm [*Matthews*, 1994], which models the plasma as ion macroparticles and an inertialess electron fluid. Our code is self-consistent and our implementation is 2-D in space and 3-D in velocity. The test particle electrons are not self-consistent and electron physics is not well modelled by the hybrid code, so it is possible that accelerated electrons might damp the ripples. Our hybrid simulation is also unable to model electron scale turbulence and electron scale ripples, which are seen in full particle PIC codes and may affect the dynamics. Micro-turbulence associated with currents along the shock, for example, could alter the growth and structure of the ion scale ripples. Whilst electron inertial scales could be included by using a full particle code, the time and length scales associated with the observed electron acceleration mechanism are generally too long to be modelled in this way. Ion scale physics is worth studying in the context of electron acceleration since it dominates the shock structure. This paper builds on previous work using hybrid simulations to study electron acceleration [*Krauss-Varban et al.*, 1989].

We generate a shock by reflecting homogeneous plasma moving at constant velocity off a stationary, perfectly conducting barrier, which provides a clean shock once the shock front is clear of the reflecting barrier. We conduct simulations using two orientations of the upstream magnetic field, $\mathbf{B_0}$. The first has $\mathbf{B_0}$ lying in the plane of the simulation, allowing electrons to move along the field line and feel the full 2-D field structure. The second has $\mathbf{B_0}$ pointing out of the simulation plane, so that the electrons feel no variation along the field line associated with 2-D structure. This configuration is intended to mimic a 1-D simulation. In our example, we use an angle between the shock normal and the upstream magetic field $\theta_{Bn} = 85°$ and an inflow velocity of $4V_A$ in the simulation frame, giving a shock Alfvén Mach number $M_A \approx 5.7$. We use an Alfvén speed $V_A = 60$ km/s and an electron plasma beta $\beta_e = 0.5$. These parameters are chosen to resemble conditions in the Earth's bow shock.

As can be seen from Figure 1, the ripples have a wavelength of a few ion inertial lengths and an amplitude in B_x of around $2B_0$. Standard theories of adiabatic reflection assume that the shock structure is stationary and one-dimensional and that the electron gyroradius is much smaller than the shock thickness. In our simulations, the first two of these approximations are violated: we observe magnetic structures that cannot be approximated as one-dimensional. Since the structure is time dependent, there
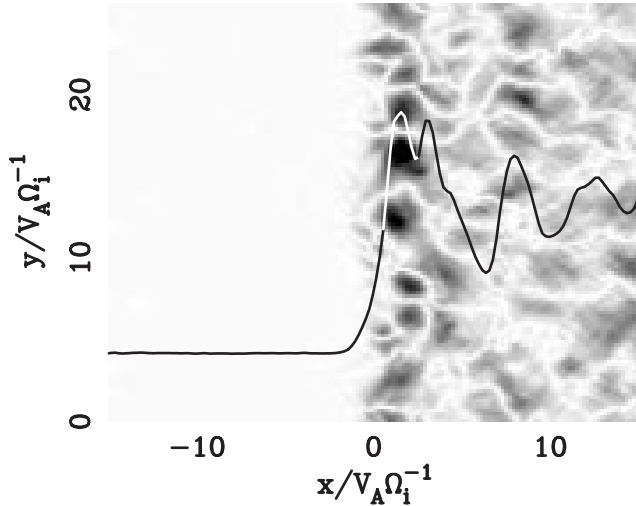
Figure 1. Shock ripples shown using a map of the shock normal component of the magnetic field, B_x, with the $|\mathbf{B}|$ profile superimposed. The scale shows a maximum B_x value of $2B_0$, which corresponds to the amplitude of the ripples.

also exists the possibility of First Order Fermi acceleration. We see power in the ripples over a range of frequencies, which could lead to electron pitch angle scattering.

Electron acceleration

We investigate electron behaviour by following the trajectories of test particles. We use a high order integration scheme (as in *Krauss-Varban et al.* [1989]) and ensure smoothness in the fields by using interpolation that is bicubic in space and linear in time between ion time steps. Our implementation of the code is relativistic and, in test conditions, conserves both energy and magnetic moment well. The electrons are released upstream with a common gyrocentre at an energy of 100 eV, representative of the solar wind halo distribution. In velocity space, the initial electron distribution is a uniformly covered spherical shell with a cut-off corresponding to electrons that escape upstream without interacting with the shock.

Adiabatic reflection provides a mechanism for accelerating electrons by reflection from a quasi-perpendicular shock, assuming conservation of energy and magnetic moment in the de Hoffmann-Teller frame, in which the motional electric field ($-\mathbf{V} \times \mathbf{B}$) is zero [*Leroy and Mangeney*, 1984; *Wu*, 1984]. In order for a reflected electron to escape upstream, it must also travel along the upstream field at a sufficient speed to overcome the flow of plasma into the shock. This introduces an additional cut-off parallel velocity to the reflected distribution.

We measure an overshoot magnetic field, $B_1 \approx 5.2B_0$. If we assume a canonical value of 85 eV for the potential difference between the upstream and the overshoot [*Krauss-Varban et al.*, 1989], adiabatic theory predicts that electrons should reflect if their pitch angle, α, is between $36°$ and $131°$. Reflection at constant energy in the de Hoffmann-Teller frame produces acceleration after transforming back to the upstream plasma frame. In this case, the energies of the reflected population in the upstream plasma frame should lie between 150 eV and 390 eV.

We observe reflected electron fractions (Figure 2) and energy spectra (Figure 3) that are broadly consistent with adiabatic theory when $\mathbf{B_0}$ is directed out of the simulation plane. The distributions when $\mathbf{B_0}$ is in the simulation plane, however, differ. There is an additional population of downstream electrons, with pitch angles between $60°$ and $105°$, that we would expect to reflect upstream. Electrons with a high magnetic moment are reflected away from the regions of high field created by the ripples and towards the regions of reduced field. They are therefore trapped whilst initially feeling a lower magnetic field than they would in the case of no rippling. The peaks of reflected electrons on either side of this range have sufficiently high parallel velocities that they are able to reflect rapidly enough to avoid feeling significant magnetic structure in the upstream field.

Electrons at these energies are essentially tied to the field lines, so that an electron that is dragged through the shock in this way will reflect multiple times and may experience considerable Fermi acceleration, either between ripples or between a ripple and the shock overshoot. The latter case is a collapsing magnetic trap and will result in considerable First Order Fermi acceleration [*Gisler and Lemons*, 1990]. This scenario is evident in our example electron trajectory. Figure 4 shows the trajectory of one of the downstream energetic electrons. It shows an eight-fold increase in energy, which allows magnetic moment to be conserved during the shock crossing. This magnetic moment conservation, in con-
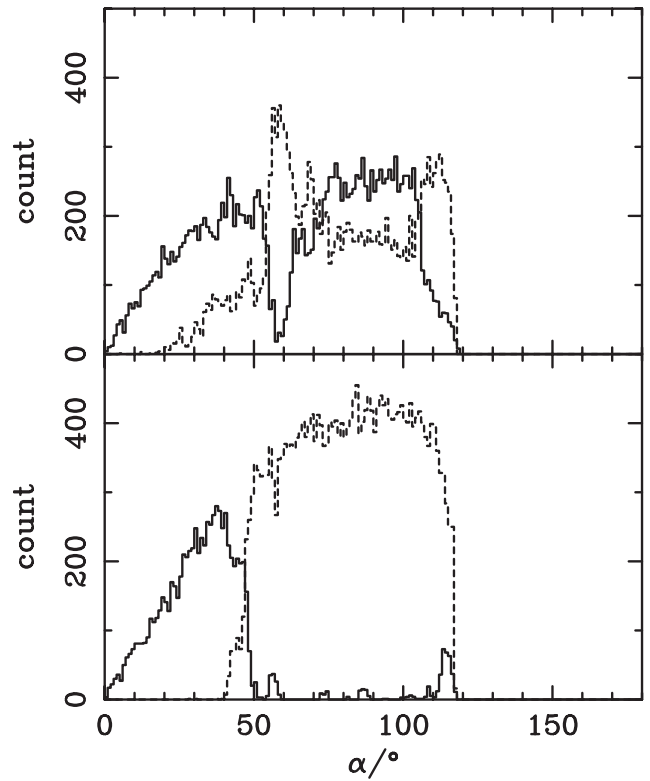
Figure 2. The distribution of initial pitch angle, α, for electrons that end the simulation upstream (dashed) and downstream (solid), for $\mathbf{B_0}$ out of the simulation plane (bottom) and in the simulation plane (top). For $\mathbf{B_0}$ in the plane, some electrons (α between $60°$ and $105°$) are trapped and dragged downstream by the convecting field lines. For $\mathbf{B_0}$ out of the plane reflection for $35° < \alpha < 130°$ is consistent with adiabatic theory.
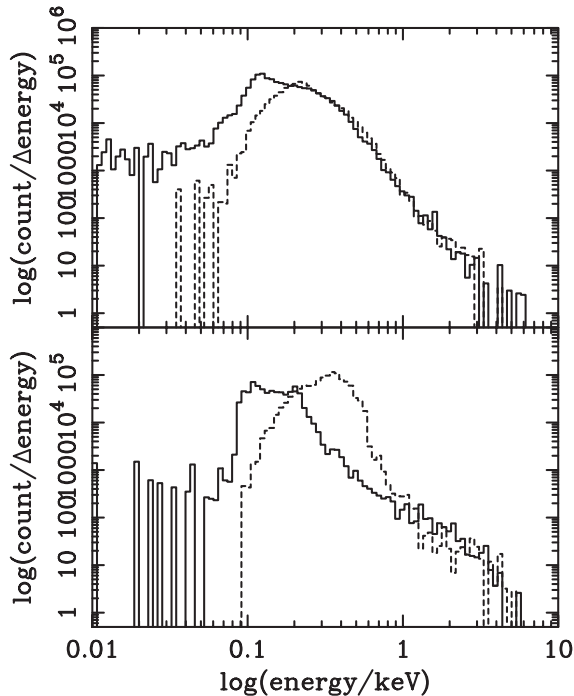
Figure 3. Electron differential energy spectra in the upstream plasma frame (solid lines downstream, dashed lines upstream). With the upstream field, $\mathbf{B_0}$, out of the simulation plane (bottom), the spectrum is consistent with adiabatic reflection at the shock producing an upstream population with energies between 150 eV and 390 eV. With $\mathbf{B_0}$ in the simulation plane (top), the spectra show similar upstream and downstream levels with a power law tail.

junction with the graph of pitch angle, also shows that electron scattering is not important and the dominant acceleration mechanism is reflection within the shock ramp. The magnetic field felt by the electron shows how the particle is initially trapped whilst it is feeling a low magnetic field, consistent with the fact that it would be expected to reflect back upstream. We can see how the electron is able to conserve μ in progressively higher fields as its energy increases. The spatial trajectory of the electron shows how it is trapped between field fluctuations whilst traversing the shock. The electron is reflected multiple times and is effectively dragged downstream with the magnetic field.

Our simulations produce differential energy spectra with a power law tail whose slope is approximately -4 when $\mathbf{B_0}$ is directed in the plane of the simulation. This is consistent with the observed power law index of between -3 and -4 [*Gosling et al.*, 1989], although our initial electron distribution function does not mimic the full solar wind distribution. It is also significant that the upstream and downstream distributions are similar when $\mathbf{B_0}$ is in the simulation plane and electrons are allowed to feel the spatial variations in the magnetic field. This suggests that reflections occur within the shock to such an extent that the final destinations of the electrons are randomised and the upstream and downstream distributions become similar, apart from the upstream cutoff imposed by the shock geometry.

This reflection and trapping by the shock structure means that the distance travelled by electrons along the shock is much reduced when compared to that in the case of a 1-D

shock. This lessens the importance of shock curvature as studied by *Krauss-Varban* [1994]. Electron response to ion scale variations along the field could also have important implications for theories of bulk electron heating, where the macroscopic fields dominates, but some degree of electron scattering is required to explain observations.

Conclusions

Hybrid simulations in 2-D have ripples in the fields that move along the shock front at the overshoot Alfvén speed. We have shown that the suprathermal portion of the electron distribution function is heavily dependant on 2-D shock structure. This structure provides a mechanism to acceler-
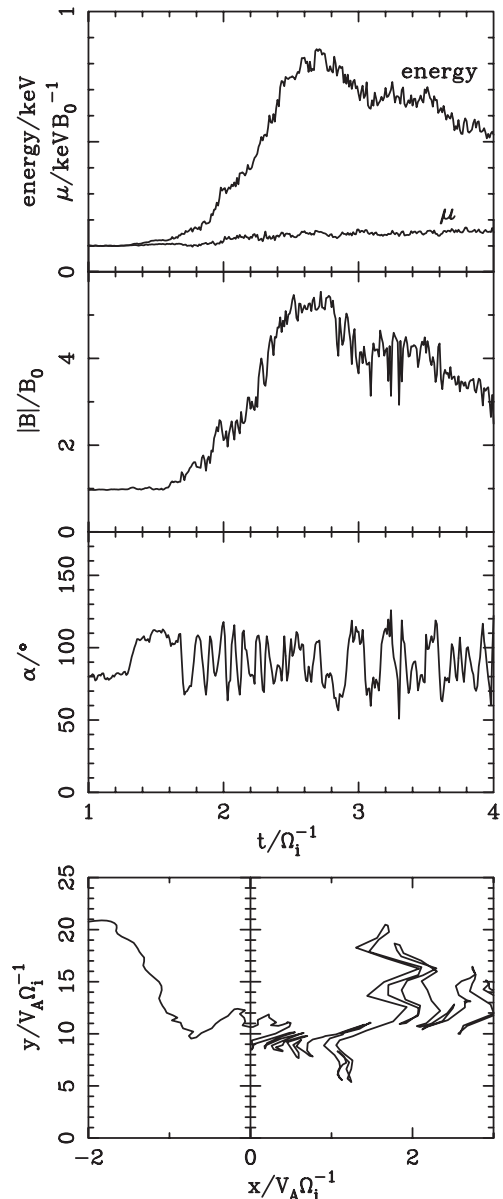
Figure 4. Energy, magnetic moment μ, pitch angle α, total magnetic field $|B|$ and spatial trajectories for one of the downstream energetic electrons that is convected downstream with a field line. In the absence of shock structure, this electron would have reflected upstream. The electron gyroradius is around $0.05\Omega_i^{-1}$ and is not resolved.

ate electrons downstream, in agreement with observations near Earth's bow shock. The high energy tail of the electron energy spectrum is similar for both the upstream and downstream populations. This suggests that pitch angle scattering by shock structure is an important process for extremely energetic electrons.

We are proposing a new mechanism for electron acceleration based on Fermi acceleration by field aligned structure within the shock transition. In common with adiabatic reflection, this mechanism's effectiveness depends on θ_{Bn}. The mechanism may be more robust when one includes the effects of both large and small scale inhomogeneities, such as waves, in the upstream field. The addition of such inhomogeneities will more accurately resemble the conditions seen at actual shocks and may increase the range of θ_{Bn} over which ripples are significant.

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