Particle Acceleration and Plasma Heating at Collisionless Shocks in Solar Flares

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Abstract

Recent observations suggest that the energy release in solar flares may occur in many small bursts. If these bursts give rise to plasma heating, a large number of collisionless shocks will be generated. These shocks can individually heat plasma and accelerate particles, but the interaction of particles with many shocks as well as of shocks with each other can give rise to further heating and acceleration.

Introduction

Recent observations by both the Solar Maximum Mission (SMM) and balloon-carried instruments have shed new light on the nature of the energy release process in solar flares. These data suggest that there is the need for a radical revision in the theoretical mechanisms invoked to account for both the energy release and co-temporal particle acceleration processes. Prior to SMM, it was thought that particle acceleration occurred in two phases, the first producing non-relativistic electrons and the second ions and relativistic electrons. The SMM results from both the Gamma Ray Spectrometer (GRS) and Hard X-Ray Burst Spectrometer (HXRBS) showed this postulate to be untrue, and demonstrated that 10 MeV protons were accelerated within 2 secs. of the low energy (100 KeV) electrons (Chupp, 1984). Other data, from both balloon flights and radio observations have led other workers to suggest that the solar flare energy release occurs in many small bursts (Lin et al., 1983; Benz, 1985; Vlahos et al., 1986; Parker, 1988) rather than in the previously conjectured topology of one large magnetic reconnection site (e.g., articles in Priest, 1981).

Let us assume that the flare itself is due to the almost synchronous firing of many small dissipation sites throughout a coronal magnetic field configuration. This could arise if, for example, the R.M.S. coronal current exceeds a critical value, resulting in multiple sites of rapid energy dissipation as opposed to the localized dissipation seen by Lin et al. The ambient plasma will then undergo strong heating so that the plasma beta ($\beta = 8\pi p/B^2$) exceeds unity. These hot sources will expand into the ambient cool plasma giving rise to pairs of collisionless shocks. One hence has a situation where, in any localized part of the corona, there are many shocks moving almost randomly with respect to the ambient magnetic field direction.

We identify four questions that the multi-shock model raises if it is to have any hope of success. Two pertain to the physics of individuals shocks and two to the global consequences of the model.

1) How fast can these shocks form?

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2) How fast can an individual shock accelerate ions to 10 MeV?

3) How do single particles interact with a population of shocks?

4) How do the shocks interact with each other?

We have made substantial progress on issues (1), (2) and (4) in recent years and are beginning both an investigation of (3) and an attempt to link (1) - (4) into a model of shock acceleration in a fibrous corona.

Shock Formation

We study the process of shock formation by examining the evolution of a hot - cold plasma interface, which represents the interaction between the hot energy release region (either ions or electrons) and cold coronal plasma. This interaction has been studied using a one dimensional hybrid simulation code (Winske, 1985). Cargill et al., (1988) showed that for quasi-perpendicular expansion (i.e. the shock moves normal to the ambient magnetic field) the shock formation time is typically a few Ω_i^{-1} where Ω_i is the ion Larmor frequency. This is << 1 sec. for solar parameters. The rapid coupling is due to simple steepening of magnetosonic waves due to finite ion Larmor radius effects. This process can also produce energetic "seed" particles which can then be accelerated to higher energies by other shock acceleration mechanisms. When the electrons are heated, there is a super-Alfvenic ion beam at the hot-cold plasma interface (behind the shock). This is unstable to low frequency waves ($<< \Omega_i$) and the resultant pitch angle scattering of the beam could redirect ions into the shock vicinity (Winske and Leroy, 1984). When the ions are heated, a small fraction of the ions can stream ahead of the shock before it forms, so that the decoupling from the piston is incomplete. Recently we have simulated the formation of quasi-parallel shocks (in this case, the shock propagates parallel to the magnetic field lines). The formation time is much slower (of order 100 Ω_i^{-1}), but still << 1 sec. The slower formation time is due to the fact that the coupling must take place by means of collective plasma interactions. For a hot electron source, a beam of ions is reflected at the hot-cold boundary and this beam is subsequently unstable to resonant hydromagnetic waves which nonlinearly give a shock. When the ions are heated, the coupling takes even longer, since the instability appears to be driven by a temperature anisotropy upstream of the interface which takes a long time to develop. In each case, seed populations of particles are generated. Quest (1988) has clearly outlined the nature of the steady state parallel shock.

Single Shock Acceleration

Acceleration at an individual shock is commonly thought to take place by two means: drift acceleration or diffusive acceleration. In the former, a particle drifts along the shock, gaining energy from the shock electric field until it escapes. It is a fast process, but the energy gain is limited. Diffusive acceleration can give large energy gains, but since the incremental gain is very small at each interaction, it tends to be fairly slow. A problem then, for shocks in solar flares is to explain how the particles can quickly gain enough energy. Decker and Vlahos (1986) suggested that this might be achieved by combining the two mechanisms. In this way, one combines both the rapidity of drift acceleration, yet the particles are not lost from the shock

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completely since the fluctuations arising in diffusive acceleration scatter them back into the shock vicinity. Typically they found that for an injection energy of 100 KeV, about 10% of the injected ions were accelerated to over 10 MeV in < 10 msecs for a moderately oblique shock ($\theta_{BN} = 60^o$ where θ_{BN} is the angle between the shock normal and the magnetic field). Increasing θ_{BN} closer to 90^o produced more rapid acceleration to higher energies. For angles closer to parallel, drift acceleration becomes increasingly less effective and the main energy gain must then be due entirely to diffusive acceleration. However, we note that if the shocks are created randomly, then both perpendicular and parallel shocks will be created. Given their much faster formation time (see above), perpendicular shocks can start accelerating particles long before their parallel counterparts. In summary, it is clear that shocks can both form and accelerate ions in much less than the 2 sec. constraint imposed by the GRS data, and so are a viable means of accelerating ions.

Interaction of a Particle with Multiple Shocks

We have recently begun a study of the interaction of charged particles with an ensemble of collisionless shocks. In a population of shocks, particles do not just gain energy from a single shocks, but when they escape from the vicinity of one, they can travel substantial distances and interact with another. Two forms of energy gain are possible. The particle can gain energy from specular reflection which simply implies that the normal component of the particle's velocity is reversed when it encounters a shock. Alternatively, the particle can be trapped in the shock electric and magnetic fields and undergo acceleration by either drift or diffusive processes. It is clear that the latter process is going to be much more efficient, especially if drift acceleration is the operative process, since it is so fast. We have recently carried out some trial test particle simulations involving a population of 10 88^o shocks, which implies very efficient drift acceleration. After about 0.1 sec., a 1 MeV injected particle has gained a factor of about 100 in energy implying that for these parameters at least, that this process is somewhat less efficient than single shock acceleration.

Shock-Shock Interactions

The slowest process of the four mentioned above is that of the interaction of pairs of collisionless shocks. This can take two forms: head on collisions or overtaking of one shock by another. The results of each case are very different. Typically we would expect these processes to take place on a timescale L/V_A where L is the shock separation distance and V_A is the local Alfven speed. For V_A of 1000 Km/sec., this is 2 secs for L = 2000 km (or 3 arc secs.). Since we expect much shorter length scales than this, the plasma heating due to this mechanism may be indistinguishable from the ion acceleration, at least with current instrumentation. Cargill and Goodrich (1987) have studied these processes using a 1-D hybrid code. When shocks collide, there is both strong plasma heating, but also a fraction of the ambient ions are accelerated, increasing their energy by an order of magnitude. Such acceleration could be important in the solar context since it provides a new injection of seed ions to renew the acceleration processes. More recently Cargill (1989) has shown that this ion acceleration is most important when roughly equal shocks collide: strongly unequal shocks produce no really significant acceleration, but still give strong plasma heating. The overtaking of one shock by another does not appear to produce strong ion acceleration, but the resulting single shock is much stronger than the two coalescing shocks and may be an efficient accelerator of particle in it's own right (Cargill, 1989).

Discussion

The above is a brief synopsis of the physical issues that arise in a population of shocks and energetic particles. Finally, there are two points that are worth making. Firstly, we have said very little about electron acceleration. Shock diffusive acceleration of electrons is a very difficult thing to accomplish, because of the difficulty in scattering the electrons due to the severe resonance condition. A very effective injection mechanism is required to get electrons to a high enough energy to initiate the scattering. It is not clear at present what this is. Drift acceleration is still quite fast, but in the absence of scattering, it is difficult to see how it can work at an individual shock. The concepts introduced in (3) above may well be of great importance in accelerating electrons, since their interaction with (and scattering by) multiple shocks does not depend on the satisfaction of the whistler resonance condition.

A second comment relates to the commonly held view that a flare can be split into distinct thermal and non-thermal parts. We have argued above that the heating of a plasma (thermal) gives rise to shocks, which then produce energetic particles (non-thermal) and further plasma heating (thermal). It is clear that in the above model, thermal and non-thermal plasmas are inextricably mixed. It therefore makes little or no sense to talk about thermal and non-thermal parts of a flare as if they were distinct entities. The point that does not seem to be appreciated is that thermal plasmas are capable of generating non-thermal plasma by some intermediary such as collisionless shock waves.

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