Collisionless Plasma Shocks
Field Generation and Particle Acceleration

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Gamma ray bursts are among the most energetic events in the known universe. A highly relativistic fireball is ejected. In most cases the burst itself is followed by an afterglow, emitted under deceleration as the fireball plunges through the circum–stellar media. To interpret the observations of the afterglow emission, two physical aspects need to be understood: 1) The origin and nature of the magnetic field in the fireball and 2) the particle velocity distribution function behind the shock. Both are necessary in existing afterglow models to account for what is believed to be synchrotron radiation. To answer these questions, we need to understand the microphysics at play in collisionless shocks. Using 3D particle–in–cell simulations we can gain insight in the microphysical processes that take place in such shocks. We discuss the results of such computer experiments. It is shown how a Weibel–like two–stream plasma instability is able to create a strong transverse intermittent magnetic field and how this points to a connected mechanism for in situ particle acceleration in the shock region.

1. Introduction

Many compact relativistic objects have strong outflows of plasma, which emit non thermal radiation in internal collisions (e.g. clumps in quasar, micro quasar and AGN jets, internal shocks in gamma ray bursts (GRBs) and when colliding with the surrounding medium (e.g. afterglows in GBRs, supernova remnants; terminal AGN shocks). The non–thermal radiation is emitted in strongly collisionless shocks [e.g. Kumar 2000, Panaitescu & Kumar 2001]. Despite their importance and universality collisionless shocks are poorly understood. The non–thermal radiation is believed to be emitted in the shock by relativistic particles accelerated by strong electromagnetic fields. Naturally this fact poses the questions which mechanism is responsible for the electromagnetic field and how are the particles accelerated to the ultra–relativistic energies implied by observations. In 1999 Medvedev & Loeb suggested that the Weibel or two stream instability was responsible for creating a strong magnetic field in the shock interface. It was recently confirmed numerically in computer experiments using particle–in–cell (PIC) codes. [Frederiksen et al. 2003; Frederiksen et al. 2004; Nishikawa et al. 2003; Silva et al. 2003]. Frederiksen et al. 2004] showed that the magnetic field reaches an energy content of a few per cent of the equipartition value. Fermi acceleration has, so far, been used to explain the existence of a power law distributed non–thermal electron population. It has been shown to occur in test particle Monte Carlo simulation under assumptions of the structure of the magnetic field; but as pointed out by Niemiec & Ostrowski (2004), to further the progress, self consistent models taking into account the back reaction and the detailed microphysics has to be made. Recently, Baring & Braby (2004) showed that particle distribution functions (PDFs) inferred from GRB observations are in conflict with those predicted by Fermi theory and diffusive shock acceleration. In this proceeding we report on 3D PIC models, also presented in [Frederiksen et al. 2004, Hededal et al. 2004], of counter streaming plasma shells as a description of the shock interface in GRB afterglows.

2. Numerical Setup

To perform the numerical experiments we use a relativistic 3D PIC code as described in Frederiksen et al. (2004) that works from first principles by solving the full Maxwell equations for the electromagnetic field and move the particles according to the Lorentz force. We set up two counter streaming ion election populations in the rest frame of the densest population. The density jump is 3. The inflow Lorentz boost of the less dense population is $\Gamma = 3$ (Run I) and $\Gamma = 15$ (Run II) in the two experiments, that we report on here. The boundaries are periodic in the x– and y direction, transverse to the flow, and open in the z direction parallel with the flow. The box sizes are $(x, y, z) = (200, 200, 800)$ and $(125, 125, 2000)$ respectively. The electron skin depth is 5 and 3.3 grid zones respectively, and we use a mass ratio of $\frac{m_i}{m_e} = 16$ to resolve both the ion– and the electron dynamics. We use 16 particles per cell and our boxes contained almost 10^9 particles. The plasmas are initially unmagnetised and cold ($v_{th} \simeq 0.01c$).

3. Magnetic Field Generation

In the computer experiments we see how the inter penetrating jets undergo the two–stream instability. First, the electrons, being the lighter particles, collect

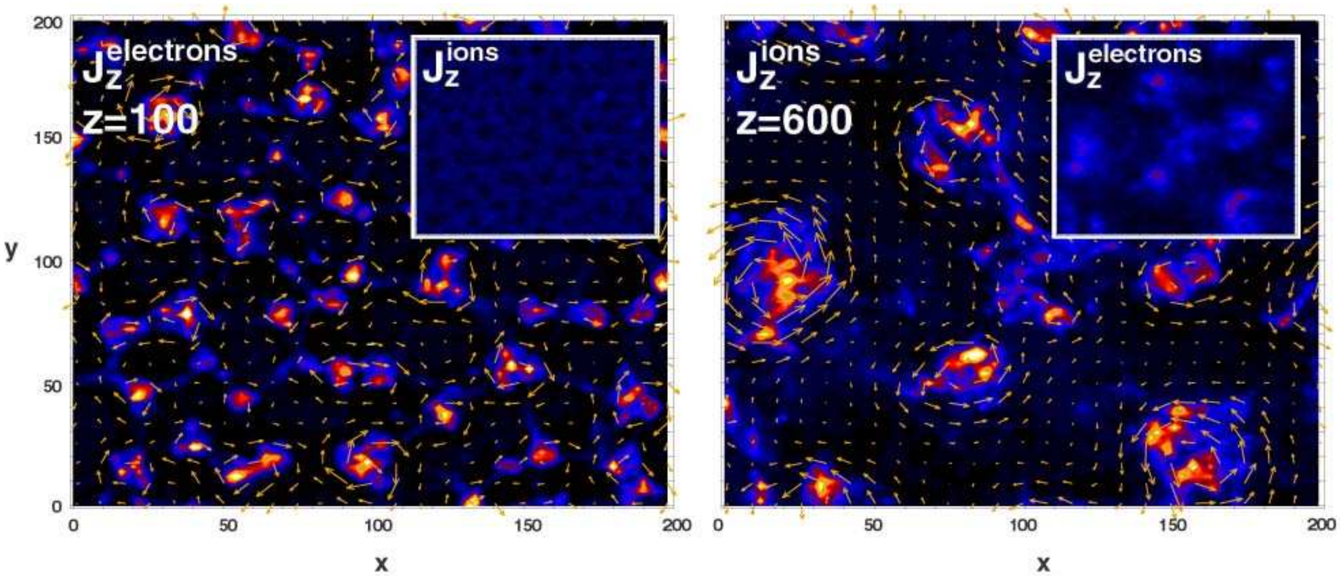

Figure 1: The left hand side panel shows the longitudinal electron current density through a transverse cut at $z = 100$, with a small inset showing the ion current in the same plane. The right hand side panel shows the ion current at $z = 600$, with the small inset now instead showing the electron current. The arrows represent the transverse magnetic field. Both panels are from time $t = 1200$ in Run I.

into caustic surfaces and then current channels; in accordance with the linear theory [Medvedev & Loeb 1999]. Then they reach a non–linear saturation point and the channels simply merge forming thicker and thicker channels. When the magnetic field becomes strong enough the heavier ions are deflected into the magnetic voids between the channels and start undergo the two–stream instability too. Since the ion instability is catalysed by the electron instability the initial growth rate depends on the electron instability growth rate. When the caustic surfaces of the ions collapse into current channels the electrons, being the lighter particles, are heated and scattered by the magnetic field of the ion channels. Attracted by the electric potential of the ion channels the electrons start to Debye shield channels. The Debye shielding quenches the electron channels, while at the same time it supports the ion channels. The large random velocities of the electrons allow the ion channels to keep sustaining strong magnetic fields. This is qualitatively different from the case of a pair plasma, where no shielding mechanism operates. The evolution is illustrated in Fig. 1. To the left we see the initial electron dominated phase, while to the right — further downstream in the shock — the ions dominate the dynamics forming dense ion channels; the more diffuse electrons shielding the channels, and the resulting transverse magnetic field indicated with arrows. The efficiency of conversion of the injected kinetic to magnetic energy, ϵ_B, is around one per cent. The full extent of the plasma dynamics operating in collisionless shocks is still not known, but in Hededal et al. (2004) it was estimated that for a mass ratio $\frac{m_i}{m_e}$ of 16 and inflow Lorentz Boost $\Gamma = 15$ (Run II) the ion channels would survive over 1500 ion skin depths. We speculate that with a more realistic mass ratios the Debye Shielding would be more effective and therefore the ion channels would survive over even larger scales.

4. Particle Acceleration

At distances less than a Debye length from the ion channels electrons are subject to a transverse acceleration towards the ions since the electric field is not fully neutralised. There also exists a strong magnetic

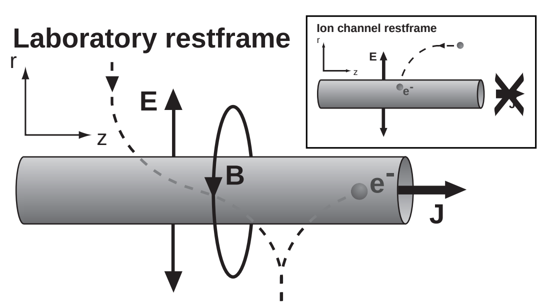

Figure 2: A toy model of the acceleration mechanism: An ion channel surrounded by an electric– and magnetic field. Electrons in the vicinity of the current channel are thus subject to a Lorentz force with both an electric and magnetic component accelerating the electrons.

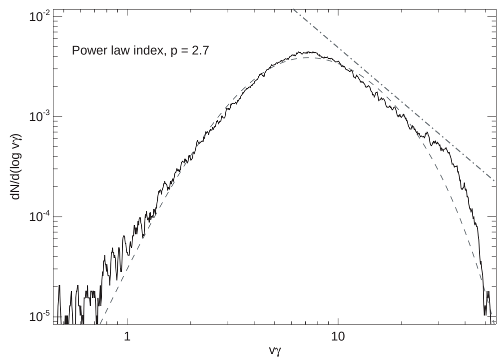

Figure 3: The normalised particle distribution function for the electrons in a slice around $z = 1600$ downstream of the shock in Run II. The dot–dashed line is a power law fit to the non thermal high energy tail. The dashed curve is a Lorentz boosted thermal electron population.

field and in total this translates into a two component transverse oscillation and acceleration along the flow direction. It was shown by Frederiksen et al. (2004) that the ion channels are distributed according to a power law and later Medvedev et al. (2005), showed that this is a consequence of the self similarity in the process of merging ion channels. The acceleration a Debye shielding electron receives depends on the size of the ion channel. As a direct consequence of the power law distributed ion channels the electron PDF obtain a non–thermal energy tail as shown in Fig. 3. This is a local acceleration mechanism, that only depends on the local electromagnetic field. Because the electrons are decelerated when moving away from the channel; the principal energy losses are radiative (e.g. bremsstrahlung, synchrotron– and jitter radiation). It also implies that no high energy electrons are available for recursive acceleration processes through this mechanism. We have confirmed this by an exhaustive search through a representative dataset of 10^7 particles. By tracking back and forth in time we found only ~ 5 possible candidate particles, that had managed to escape retaining their energy. It happened at places where the ion channel made sudden bends and mergers and the electromagnetic fields were not well approximated as static fields. None of them showed any sign of recursive acceleration.

5. Discussion

In this contribution we have presented the results of self consistent PIC computer experiments of collisionless shocks. We have shown how the two–stream instability naturally generates a highly intermittent dominantly transverse magnetic field containing a few per cent of the equipartition energy. The extent of the two stream instability in the case of an ion–electron plasma is unknown; it clearly depends on the inflow Lorentz boost, the density jump and the mass ratio. For $\Gamma = 15$ a density jump of 3 and an electron–ion mass ratio 16 Hededal et al. (2004) estimated the instability to be sustained up to 1500 ion skin depths. For realistic mass ratios this could be closer to 10^5 ion depths. In the neighbourhood of the ion structures electrons are continuously accelerated and decelerated. The mechanism is local and the power law distributed PDF is created is situ. Hence the observed radiation may be tied directly to the local conditions of the plasma. In this experiment with $\Gamma = 15$ we found a power law index of $p = 2.7$. The mechanism does not rule out Fermi acceleration. The lack of evidence in our numerical experiment for any recursive acceleration processes can be due to the limited extent of the simulated region. It may, though, overcome some of the difficulties pointed out by Baring & Braby (2004). ϵ_B, ϵ_e and p should not be understood as free parameters. To unravel the dependence on the outflow velocity and density jump a parameter study or better theoretical understanding of the non–linear evolution is needed. It is also clear that the non–thermal electron acceleration, the ion current channels and the magnetic field generation are beyond an MHD description and techniques respecting the full phase–space description of the plasma is needed to further the understanding of collisionless shocks.

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