MAGNETIC FIELD EVOLUTION IN RELATIVISTIC UNMAGNETIZED COLLISIONLESS SHOCKS

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ABSTRACT

We study relativistic unmagnetized collisionless shocks using unprecedentedly large particle-in-cell simulations of two-dimensional pair plasma. High-energy particles accelerated by the shock are found to drive magnetic field evolution on a timescale $\gtrsim 10^9$ plasma times. Progressively stronger magnetic fields are generated on larger scales in a growing region around the shock. Shock-generated magnetic fields and accelerated particles carry $\gtrsim 1\%$ and $\gtrsim 10\%$ of the downstream energy flux, respectively. Our results suggest limits on the magnetization of relativistic astrophysical flows.

Key words: acceleration of particles – gamma rays: bursts – magnetic fields – shock waves

1. INTRODUCTION

Due to the low plasma densities, shock waves observed in a wide range of astronomical systems are collisionless, i.e., mediated by collective plasma instabilities rather than by binary particle collisions. Such shocks play a central role in, for example, supernova remnants (Blandford & Eichler 1987), jets of radio galaxies (Maraschi 2003), $\gamma$-ray bursts (GRBs; Piran 2005), pulsar wind nebulae (PWN; Kirk et al. 2007), and for example, supernova remnants (Blandford & Eichler 1987), leaving the question of particle acceleration and the resulting magnetic field evolution; the particle acceleration mechanism is discussed separately (Spitkovsky 2008a), and in two-dimensional ion–electron plasma (Spitkovsky 2005, 2008a; Chang et al. 2008), and resolved the formation of shocks in two- and three-dimensional pair plasma (Spitkovsky 2005; Kato 2007; Chang et al. 2008) and in two-dimensional ion–electron plasma (Spitkovsky 2008a). These simulations revealed rapid decay of magnetic fields downstream (Gruzinov 2001; Chang et al. 2008), leaving the question of field survival over scales $\gg l_{\text{sd}}$ open and triggering alternative suggestions for field generation (e.g., Goodman & MacFadyen 2007; Milosavljevic et al. 2007; Sironi & Goodman 2007).

In this Letter, we report new PIC shock simulations performed on unprecedentedly long length and time scales, $(L/l_{\text{sd}})^3(T\omega_p) \approx 4 \times 10^{10}$. These simulations show the growth of magnetic power on progressively longer scales driven by the accelerated particles, and impose lower limits on the efficiencies of particle acceleration and magnetization. Our results suggest that even the most extensive simulations previously reported (Chang et al. 2008) were too small to capture significant particle acceleration and the resulting magnetic field evolution (see Katz et al. 2007 for a discussion of PIC simulation results and limitations). Here we discuss only the main properties of shock evolution; the particle acceleration mechanism is discussed separately (Spitkovsky 2008b), and a detailed analysis of the simulations is deferred to a later publication.

2. SIMULATION SET-UP

For simplicity, we focus here on strong, relativistic shocks in unmagnetized pair plasma. In order to reach long length and time scales, we resort to two dimensions, and comment...
below on expected differences with respect to three-dimensional shocks. We use the electromagnetic PIC code TRISTAN-MP (Spitkovsky 2005), a parallel version of TRISTAN (Buneman 1993) heavily modified to minimize noise and numerical instabilities. A rectangular simulation box is set up in the $x$–$y$ plane, with periodic boundary conditions in the $y$-direction and a conducting wall at $x_{\text{wall}} = 0$. Cold, neutral plasma is continuously injected from $x_{\text{inj}} = ct$ in the $-x$ direction, where $t$ is the simulation time. Reflection off the wall then results in a shock propagating along $+x$. All parameters are measured in the downstream frame, in which the wall is at rest.

Typical simulation parameters are: injected bulk Lorentz factor $\gamma_0 = 15$, thermal spread $\Delta \gamma_0 = 10^{-4}$, and $N_{\text{ppc}} = 8$ particles per species per cell, with spatial and temporal resolutions $\delta x = L_d/10$ and $\delta t = 0.045\omega_p^{-1}$. Here, $\omega_p^2 = 4\pi(n_e + n_i)q^2/\gamma_0 m$, where $m$ and $q$ are the particle mass and charge, and $n$ is the upstream number density. Our largest simulation has $\sim 2 \times 10^{10}$ particles and $(L_x/L_d) \times (L_y/L_d) \times (T_{\text{opp}}) = 6300 \times 1024 \times 6300 \simeq 4 \times 10^{16}$, although smaller simulation boxes have been evolved for as long as $12600\omega_p^{-1}$. The results displayed below mostly refer to a simulation with $L_y = 402L_d$, evolved for $T = 12600\omega_p^{-1}$.

3. SHORT TERM EVOLUTION

At early times, $t \lesssim 1000\omega_p^{-1}$, we recover shock formation as reported previously (Spitkovsky 2005, 2008a; Chang et al. 2008): a transition layer of a few $10L_d$ thickness propagating upstream, in which the plasma isotropizes, thermalizes, and compresses. The simulated shock transition agrees to within a few percent with (magnetic-free) hydrodynamic jump conditions: a shock velocity $v_{sh} = c(\Gamma_d - 1) \times [(1/(\gamma_0 - 1)) - 1]^{1/2}$ and density compression ratio $n_d/n_{\text{sh}} = (\Gamma_d + \gamma_0^{-1})/(\Gamma_d - 1)$. Here, $\Gamma_d \simeq 3/2$ is the downstream adiabatic index, and upstream pressure was neglected (Spitkovsky 2008a).

Upstream, the interaction between the unshocked flow and a counterstream running ahead of the shock leads to the formation of current filaments (in both two and three dimensions) parallel to the flow, surrounded by near-equipartition filamentary magnetic (in the fluid frame) structures. Behind the shock near-equipartition magnetic clumps form and are advected with the downstream flow in two dimensions. At early times (where three-dimensional simulations are possible, $t \lesssim 10^3\omega_p^{-1}$), good agreement is found between these clumps and the two-dimensional projection of extended magnetic loops formed nearly perpendicular to the flow in three-dimensional shocks. When averaged along the transverse direction, $\epsilon_B \equiv (B^2/8\pi\gamma_0)/(\gamma_0 - 1) nmc^2$ (where $B$ is the magnetic field amplitude) peaks at $\sim 7\%$ near the shock transition layer and decays below $0.1\%$ within $1000L_d$ downstream (Chang et al. 2008).

4. LONG TERM EVOLUTION

The above description does not include the effects of high-energy particles accelerated by the shock, negligible at early times. Our present simulations are sufficiently large to reveal the onset of particle acceleration and the slow evolution of shock properties (evident on $\sim 1000\omega_p^{-1}$ timescales) driven by these energetic particles. A small fraction of particles, accelerated to Lorentz factors $\gamma_0 \ll \gamma \ll \gamma_{\text{max}}$ by repeated scatterings near the shock, gradually builds up a flat $(\gamma^2 d\gamma/d\gamma \sim \text{const.})$ power-law energy tail downstream, already containing a fraction $\epsilon_{\text{acc}} \gtrsim 10\%$ of the energy at $t = 10^4\omega_p^{-1}$ (Spitkovsky 2008b).

Here we defined $\epsilon_{\text{acc}}$ as the ratio between the energy density of particles with $\gamma > 5\gamma_0$ behind the shock and the far-upstream kinetic energy density, such that for a thermal distribution of the particles in the downstream $\epsilon_{\text{acc}}(\gamma_0 \gg 1) \simeq 0.3\%$.

The energetic particles running ahead of the shock significantly alter the properties of the counterstream and the resulting current filamentation and magnetization upstream. Figure 1 shows the resulting spatial distribution of magnetic fields at early versus late times, as well as the density and momentum profiles. It reveals an increasing magnetization level, with fields generated on gradually larger scales and extending farther away from the shock, both upstream and downstream. As a result, the shock compression transition layer (defined, say, between $10\%$ and $90\%$ of full shock compression) widens, $n$ and $\epsilon_B$ become more oscillatory with distance behind the shock, the shock slightly accelerates (by $\lesssim 1\%$), and the final compression ratio slightly decreases (by $\lesssim 4\%$). Due to the substantial energy carried by the accelerated particles running ahead of the shock, the average momentum is strongly modified far upstream, $\Delta x \sim -x_{\text{sh}} \gtrsim 1000L_d$, although the incoming flow slows down considerably only at $\Delta x \lesssim 100L_d$. Here $\epsilon_{\text{acc}}$ is the ratio between the energy density of particles with $\gamma > 5\gamma_0$ behind the shock and the far-upstream kinetic energy density, such that for a thermal distribution of the particles in the downstream $\epsilon_{\text{acc}}(\gamma_0 \gg 1) \simeq 0.3\%$.

Noise with power inversely proportional to $N_{\text{ppc}}$, filtered on small scales, and tested not to distort our results.
Figure 1. Plasma evolution within 1000l_{sd} of the shock. Normalized transverse magnetic field sign(B) (color scale stretched in proportion to $\epsilon_B^{1/4}$ to highlight weak features) is shown at (a) early ($t_1 = 225\omega_p^{-1}$) and (b) late ($t_2 = 11925\omega_p^{-1}$) times. Here, $\Delta x \equiv x - x_{sd}$ is the distance from the shock, with $x_{sd}$ (dashed) defined as median density between far upstream and far downstream. Also shown are the transverse averages (at $t_1$, dashed blue, and $t_2$, solid red) of (c) electromagnetic energy normalized to the upstream kinetic energy $\epsilon_{EM} \equiv [(B^2 + E^2)/8\pi]/[(\gamma_0 - 1)n_{mc}^2]$ (with $E$ the electric field amplitude, included because in the simulation frame the induced $E \sim B$ upstream), (d) density normalized to the far upstream, and (e) particle momentum $\gamma \beta_x$ (with $\beta$ the velocity in $c$ units) in the $x$-direction averaged over all particles (higher $\langle \gamma \beta_x \rangle$) and over downstream-headed particles only.

Convergence. Convergence tests were performed with respect to all simulation parameters (around their values given above), with no qualitative changes to the results. Figures 1 and 2 indicate that the simulation box used is sufficiently large to avoid significant boundary effects. However, as $\sim 40\%$ ($5\%$) of the magnetic power is already deposited in $\lambda > 50 l_{sd}$ ($\lambda > 100 l_{sd}$) scales at $t \simeq 10^4 \omega_p^{-1}$, increasingly larger simulation boxes, in both longitudinal and transverse dimensions, will be required in order to properly resolve the shock and the growing coherent structures.

5. CONCLUSIONS

Our analysis shows that collisionless shock configurations simulated previously may represent steady state configurations only as long as particle acceleration remains insignificant. We find that a population of energetic particles is accelerated and drives the generation of progressively stronger fields on gradually larger scales. Our simulations do not reach a steady state; rather, an increasing fraction of shock energy is transferred to energetic particles and magnetic fields throughout the simulation time domain.

Once stochastic acceleration and magnetization ensue, they are unlikely to diminish to a lower energy steady state. Hence, our results suggest lower limits to the efficiencies of magnetization and particle acceleration, $\epsilon_B \gtrsim 1\%$ at distances $|\Delta x| < D = 1000l_{sd}$ downstream of the shock, and $\epsilon_{acc} \gtrsim 10\%$ with no significant cooling identified downstream. We find no evidence for the saturation of $\epsilon_{acc}$, $\epsilon_B$, $D$, or $\gamma_{max}$, although the high-energy particles downstream are already subequipartition at $t \simeq 10^4 \omega_p^{-1}$.

Although our results are obtained for two-dimensional pair plasma, we expect qualitatively similar shock evolution in three-dimensional shocks and in electron–ion plasma. While the nature of upstream current filaments and downstream magnetic loops/clumps may depend on dimensionality, two- and three-dimensional simulations are in good agreement at early times (A. Spitkovsky & J. Arons 2009, in preparation). Also, shocks in ion–electron plasma were found to be similar to pair plasma shocks at early-time two-dimensional simulations due to efficient electron heating (Spitkovsky 2008a). Some level of stochastic particle acceleration is inevitable in all cases, but the generalization of our results to three dimensions or to ion–
electron plasma is yet to be tested at late times and in the presence of a high-energy particle tail.

The major role played by high-energy particles in shock evolution, their flat spectrum, and the apparently flattening magnetic power spectrum are trends consistent with a self-similar plasma configuration (Katz et al. 2007), although the simulated downstream scale growth is more modest than the $\lambda \propto D$ self-similar scaling. At this stage, the simulations are not yet sufficiently advanced to validate or rule out self-similarity.

In summary, we have shown that collisionless shocks in two-dimensional pair plasma evolve on long, $\gtrsim 10^3 \omega_p^{-1}$, timescales, such that the acceleration efficiency, magnetization level, and coherence length scale all increase in time. These trends and the above lower limits on $\varepsilon_{acc}$ and $\varepsilon_B$ indicate that a shock propagating into a cold, homogeneous plasma with $B = 0$ remains a viable model for astronomical shocks, with no need for additional assumptions about magnetic turbulence generation (e.g., Goodman & MacFadyen 2007; Milosavljevic et al. 2007; Sironi & Goodman 2007). Our results confirm that particle acceleration and magnetization are intimately related, with high-energy particles playing a major role in generating the magnetic fields which in turn scatter and accelerate the particles.

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