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Kinetic simulations of mildly relativistic shocks – I. Particle acceleration in high Mach number shocks

P. Crumley, D. Caprioli, S. Markoff and A. Spitkovsky

1Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08554, USA
2Anton Pannekoek Institute for Astronomy, University of Amsterdam & GRAPPA, PO Box 94249, NL-1090 GE Amsterdam, the Netherlands
3Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, USA

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ABSTRACT

We use fully kinetic particle-in-cell simulations with unprecedentedly large transverse box sizes to study particle acceleration in weakly magnetized mildly relativistic shocks travelling at a velocity $\approx 0.75c$ and a Mach number of 15. We examine both subluminal (quasi-parallel) and superluminal (quasi-perpendicular) magnetic field orientations. We find that quasi-parallel shocks are mediated by a filamentary non-resonant (Bell) instability driven by returning ions, producing magnetic fluctuations on scales comparable to the ion gyroradius. In quasi-parallel shocks, both electrons and ions are accelerated into non-thermal power laws whose maximum energy grows linearly with time. The upstream heating of electrons is small, and the two species enter the shock front in rough thermal equilibrium. The shock’s structure is complex; the current of returning non-thermal ions evacuates cavities in the upstream that form filaments of amplified magnetic fields once advected downstream. At late times, 10 per cent of the shock’s energy goes into non-thermal protons and more than 10 per cent into magnetic fields. We find that properly capturing the magnetic turbulence driven by the non-thermal ions is important for properly measuring the energy fraction of non-thermal electrons, $\varepsilon_e$. We find $\varepsilon_e \sim 5 \times 10^{-4}$ for quasi-parallel shocks with $v = 0.75c$, slightly larger than what was measured in simulations of non-relativistic shocks. In quasi-perpendicular shocks, no non-thermal power-law develops in ions or electrons. The ion acceleration efficiency in quasi-parallel shocks suggests that astrophysical objects that could host mildly relativistic quasi-parallel shocks – for example, the jets of active galactic nuclei or microquasars – may be important sources of cosmic rays and their secondaries, such as gamma-rays and neutrinos.

Key words: acceleration of particles – plasmas – radiation mechanism: non-thermal; shock waves.

1 INTRODUCTION

Collisionless shocks are capable of producing non-thermal particles in power laws extending for many orders of magnitude in energy. Krymskii (1977), Axford, Leer & Skadron (1977), Bell (1978), and Blandford & Ostriker (1978) realized that collisionless shocks would be a manifestation of a first-order Fermi/diffusive shock acceleration (DSA) process (Fermi 1949); particles can gain energy from the velocity difference between the upstream and downstream. The particles can reach large energies by being scattered back towards the shock front by magnetic turbulence, thereby crossing the shock front many times. The observed non-thermal radiation from astrophysical systems with strong shocks such as supernova remnants and gamma-ray burst afterglows is strong evidence that shocks in astrophysical systems do indeed accelerate particles. Classic DSA theory has been extremely successful at explaining how non-thermal particles can be accelerated into a power law extending for decades in energy, but it is unable to determine why a particle becomes non-thermal in the first place (see e.g. Drury 1983; Blandford & Eichler 1987; Malkov & Drury 2001 for reviews). That is, a particle may need to be pre-energized before it is ‘injected’ into DSA. Because DSA theory is unable to answer how particles are injected, it cannot predict the fraction of the shock’s energy that is placed into non-thermal particles. Constraining the non-thermal energy fraction of ions ($\varepsilon_p$), electrons ($\varepsilon_e$), and magnetic field ($\varepsilon_B$) requires either modelling multiwavelength observations or numerical simulations. While the values of $\varepsilon_p$, $\varepsilon_e$, and $\varepsilon_B$ depend on several shock parameters (e.g. sonic and Alfvénic Mach numbers, magnetic field inclination), both observation and simulations show...
a striking difference in εe between non-relativistic and relativistic shocks. Relativistic shocks appear to create non-thermal electrons more effectively than non-relativistic ones.

Observational evidence for a changing εe with shock velocity comes from a wide range of astrophysical systems. The values obtained are model dependent, but there is a global trend of increasing εe with shock velocity. The non-relativistic shocks of the young supernova remnant Tycho is an inefficient electron accelerator, with εe ∼ 10−3 e0, or εe ∼ 10−5 e0 if εp = 0.1 (Morlino & Caprioli 2012). A low value of εe/e0 in non-relativistic shocks is supported by observations of cosmic rays at Earth. For every cosmic ray electron with ~30 GeV, several hundred protons are detected (e.g. Aguilar et al. 2015, 2014). On the other hand, the ultra-relativistic shocks that produce gamma-ray burst afterglows are well fit with the much larger εe ∼ 0.1 (Wijers & Galama 1999; Panaitescu & Kumar 2000; Santana, Barniol Duran & Kumar 2014). Particle-in-cell simulations of electron-ion shocks agree with this trend. The simulations of 1D non-relativistic shocks travelling at v = 0.1c in Park, Caprioli & Spitkovsky (2015) show εe of 10−4 and the relativistic electron–ion shocks in Sironi & Spitkovsky (2011) have an εe ∼ 0.1 at γ = 15.

The production of non-thermal particles depends on the magnetic turbulence at the shock front. In collisionless shocks, binary collisions between particles are not capable of isotropizing the upstream bulk motion of the plasma to subsonic speeds. Instead, the shock must be mediated by electric and magnetic fields that are generated by collective motions in the plasma. There are different mediation mechanisms for shocks, but we focus on the two instabilities that mediate mildly relativistic high Alfvenic number shocks: the Weibel instability and the Bell instability. The Weibel instability occurs when initially current-neutral counter-streaming plasma undergoes transverse filamentation into skin-depth wide oppositely directed current filaments, which enhance the transverse magnetic field and eventually isotropize the particles (Weibel 1959). The Weibel instability mediates weakly-magnetized, quasi-parallel, collisionless relativistic shocks (Medvedev & Loeb 1999; Spitkovsky 2008a; Sironi & Spitkovsky 2011). The Bell instability is caused by a current of high-energy ions that are freely streaming through a magnetized plasma. The current in this beam travels along B0 and amplifies transverse waves. The current is balanced by a returning current carried by the background plasma. Because of the different rigidity of energetic ions and compensating electrons, regions experiencing transverse magnetic fluctuations δB lose current balance, and the background plasma feels a J × δB force that pushes it outwards, growing the fluctuation (Bell 2004, 2005). In its non-linear stage, the Bell instability is capable of producing magnetic fluctuations of the size of the ion’s gyroradius, and therefore, it may play an important role in scattering the highest energy particles (Caprioli & Spitkovsky 2014b,c).

Mildly relativistic shocks are a good place to accelerate particles to high energies because both the shock speed (βs) and Lorentz factor (γs) are of order unity. A large βs means the particle gains more energy with each crossing of the shock front; ΔE/E ∝ βs in non-relativistic shocks, and ΔE/E ∝ 1 after the first crossing in relativistic shocks (Bell 1978; Quenby & Lieu 1989; Achterberg et al. 2001). However, in ultra-relativistic shocks, the component of the magnetic field perpendicular to the shock front is magnified by a factor γs due to a Lorentz transformation. Therefore, nearly all magnetized ultra-relativistic shocks will be quasi-perpendicular. The quasi-perpendicular magnetic field geometry may severely suppress particle injection in magnetized relativistic shocks because it is superluminal, i.e. particles confined to background magnetic field lines would need to be travelling faster than the speed of light to return upstream (Begelman & Kirk 1990; Sironi & Spitkovsky 2009; Sironi, Spitkovsky & Arons 2013). Mildly relativistic shocks with γsβs ∼ 1 have an advantage in producing high-energy particles because the acceleration time is short, but the shock is subluminal for a larger range of upstream magnetic field inclinations than ultra-relativistic shocks.

To accelerate the highest energy particles, it is not enough to have the particle gain ΔE/E ∼ 1 at the shock front. The particles also must return to the shock front quickly enough, so they cross the shock many times in a short time-scale. The time it takes to accelerate a particle to energy E in a non-relativistic shock depends on the diffusion coefficient D and is tacc = c^2D(E)/βs^2 (e.g. Drury 1983). If the turbulence has large magnetic field fluctuations at all scales, the diffusion coefficient depends linearly on energy, and the maximum energy grows linearly with time. Previous work has shown that when the magnetic turbulence is at small scales, such as the upstream fluctuations that occur in unmagnetized shocks, the maximum energy increases more slowly as √t (e.g. Sironi et al. 2013). The difference between the two scalings may be the difference in whether an object can be an ultra-high energy cosmic ray progenitor.

This paper is the first in a series of papers that kinetically examines mildly relativistic shocks (γsβs ∼ 1). In this paper, we show the necessary ingredients to properly capture the magnetic field structure at the shock front in a 2D simulation of weakly magnetized, electron–ion shocks, and to measure εe. We examine mildly relativistic shocks travelling at γβ ≈ 1 using self-consistent, fully kinetic, particle-in-cell simulations. Most previous studies of the mildly relativistic shocks have used Monte Carlo and semi-analytical methods that require assumptions about the turbulence and the fraction of non-thermal particles (Kirk et al. 2000; Keshet & Waxman 2005; Morlino, Blasi & Vietri 2007; Summerlin & Baring 2012; Ellison, Warren & Bykov 2013), or full kinetic simulations that were too short to study the late-time evolution of the shock structure (Dieckmann, Shukla & Eliasson 2006; Bohdan et al. 2017; Dieckmann & Bret 2018). We do not vary the shock velocity in this paper, but we plan on using the results of this paper to examine how εe, βs, and εp change in the transition between non-relativistic and relativistic shocks in a future work.

Our paper is organized as follows. First, we describe our simulation set-up in Section 2. In Sections 3 and 4, we analyse the structure of and particle acceleration in a mildly relativistic quasi-parallel shock. In Section 5, we show how resolving the ion gyroradius is important to capture the turbulence at the shock front and measuring εe. In Section 6, we show that superluminal shocks are unable to accelerate particles into a power law. Finally, we conclude by summarizing our results and discussing their astrophysical relevance. Many astrophysical objects host mildly relativistic outflows capable of producing strong shocks. However, the magnetized mildly relativistic shocks studied in this paper are most relevant to the internal shocks in jets with modest Lorentz factors like the jets observed as bright sources of non-thermal radiation in microquasars and low-luminosity active galactic nuclei (AGNs).

2 METHODOLOGY

We use the parallel electromagnetic PIC code TRISTAN-MP (Buneman 1993; Spitkovsky 2005) to simulate mildly relativistic electron–ion shocks (Buneman 1993; Spitkovsky 2005). The computational domain is a 2D Cartesian xy grid, with length Lx and
Particle acceleration in shocks with $\gamma \beta \sim 1$

depth with four cells, with a time-step of $\Delta t = 0.1125 \omega_{pe}^{-1}$. The low
resolution is required to capture the relevant ion length and time-
scales. We use four particles per cell (two ions and two electrons)
and filter particles’ contributions to the current 32 times per time-
step to reduce noise, as is routinely done (e.g. Spitkovsky 2005).
We checked convergence in the number of particles-per-cell (ppc)
and spatial resolution, running smaller simulations with ppc = 64
and $c/\omega_{pe} = 8$ (see Appendix C).

We initialize an upstream magnetic field $B_0$ with inclination $\theta_B$
to the shock normal. A completely parallel shock has $\theta_B = 0$ and a
completely perpendicular shock has $\theta_B = 90^\circ$. We use two different
magnetic field orientations in this paper, one is quasi-parallel ($\theta_B \approx 10^\circ$),
and the other is quasi-perpendicular ($\theta_B \approx 55^\circ$). In
the downstream rest frame the angle, $\theta_B'$, is $15^\circ$ and $65^\circ$, respectively
($\gamma_0 \tan \theta_B = \tan \theta_B'$). We choose a magnetic field orientation such
that perpendicular component of the initialized magnetic field lies
entirely in the $x-y$ plane, i.e. $B_x = 0$.

The strength of the magnetic field is described by $\sigma_0$, the ratio
of the energy density of the upstream magnetic field to the kinetic
energy of the upstream flow as measured in the downstream frame:
$\sigma_0 = v_A^2/(c^2[y_0 - 1])$ where $v_A$ is the Alfvén velocity
as measured in the downstream frame. Re-writing everything in
upstream quantities:

$$\sigma_0 = \frac{B_0^2(y_0^2 \sin^2 \theta_B + \cos^2 \theta_B)}{4\pi \gamma_0 m_i c^2(y_0 - 1)(1 + m_e/m_i)}.$$ (1)

In this paper, we fix $\sigma_0 = 0.007$. The magnetization fixes the
Alfvénic Mach number, which is the shock speed divided by upstream
Alfvénic velocity. Using conservation of particle number $\beta_p = \rho_p/\rho_0(r - 1)$, where $r$ is the compression ratio of the shock, so
the Alfvén Mach number is

$$M_A \approx r \frac{\beta_0 - 1}{\sqrt{\gamma_0(y_0 - 1)}}.$$ (2)

Since our shock is strong, the compression ratio of the shock, $r \sim 4\gamma_0^2$, in the upstream frame and for $\beta_0 = 0.75, \sigma_0 = 0.007$, we find
$\beta_\parallel \approx 0.83$ and $M_A \approx 15$.

Plasma beta, $\beta_\parallel$, is the ratio between the thermal pressure and the
magnetic pressure in the upstream plasma:

$$\beta_\parallel = \frac{4c^2 \Delta \gamma}{v_A^2 \left(1 + \frac{m_e}{m_i}\right)}.$$ (3)

where $v_A$ is the Alfvénic velocity in the upstream frame. Increasing
the plasma beta for a fixed magnetization will decrease the sonic
Mach number of the shock. We assume equilibrium between the magnetic
pressure and thermal pressure of the upstream plasma, that is, $\beta_p = 1$. For $\gamma_0 = 1.5, M_A = 15, m_i/m_e = 64$, and $\theta_B' = 15^\circ$,
$\beta_\parallel = 1$ corresponds to a temperature $\Delta \gamma = 1.27 \times 10^{-3}$ and sonic
Mach number $M_s \approx 15$.

We measure three quantities that capture how much of the
upstream kinetic energy goes into magnetic fields, non-thermal ions,
and non-thermal electrons: $\epsilon_B, \epsilon_p$, and $\epsilon_e$, respectively. To calculate
$\epsilon_B$, we Lorentz boost the total magnetic field $B$ into a frame moving
at $\gamma_B$ in the $+x$-direction and use

$$\epsilon_B = \frac{B^2}{4\pi \gamma_0 m_i c^2(y_0 - 1)}.$$ (4)

Here, $\epsilon_B$ and $\sigma_0$ are the only field quantities we report in the
downstream rest frame. We measure $\epsilon_p$ and $\epsilon_e$ by first Lorentz
boosting the spectra into the downstream rest frame and then
measuring the fraction of energy in the non-thermal particles. This
ratio is converted to $\epsilon_p$ and $\epsilon_e$ by multiplying by the average energy

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1Measuring the distances relative to the moving left wall causes the upstream
to appear to be moving to the left with time even though its velocity is zero in
the simulations.
carried by the respective particle downstream and dividing by the average kinetic energy of an incoming ion. Or more explicitly:

$$\varepsilon_{\text{p,i}} = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} E' \frac{dN}{dE'} \Delta E'}{\int_{E_{\text{min}}}^{E_{\text{max}}} E' \frac{dN}{dE'} \Delta E'} \times \frac{m_{\text{e,i}} ((\gamma_{\text{e,i}}') - 1)}{m_{\text{i}} ((\gamma_{\text{i}}) - 1)}.$$

(5)

The transverse size of our fiducial run is 16 000 cells, equivalent to 4000 electron skin depths or 500 ion skin depths for the reduced mass ratio 64, significantly wider than previous PIC shock simulations (e.g. Sironi & Spitkovsky 2009, 2011; Niemiec et al. 2012; Sironi et al. 2013; Park et al. 2015). For example, while Bohdan et al. (2017) also studied electron acceleration in high Mach number, mildly relativistic shocks, our simulations are ~20 times wider in terms of ion skin depths and were run three times longer in terms of ion gyrofrequency (even when accounting for the different rest frames). The sizes of our simulations are more comparable to hybrid-MHD (kinetic ions-fluid electrons) simulations. We require a large size to resolve the gyroradii of the non-thermal ions. We summarize the simulations run in this work in Table 1.

### Table 1. Summary of simulations. See Section 2 for more information.

<table>
<thead>
<tr>
<th>$B_0$ inclination</th>
<th>$B_0$ orientation</th>
<th>$m_i/m_e$</th>
<th>$L_y$</th>
<th>$c/\omega_{\text{pe}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-para 10.13°</td>
<td>In plane</td>
<td>64</td>
<td>16000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>In plane</td>
<td>64</td>
<td>800</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>In plane</td>
<td>16</td>
<td>3500</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>In plane</td>
<td>160</td>
<td>4000</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Out of plane</td>
<td>64</td>
<td>3220</td>
<td></td>
</tr>
<tr>
<td>Quasi-perp 55°</td>
<td>In plane</td>
<td>64</td>
<td>1600</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Out of plane</td>
<td>64</td>
<td>1600</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: All simulations had $\gamma_0 = 1.5$, $\sigma = 0.007$, and $\beta_p = 1$ ($M_\Lambda \approx M_\Lambda \approx 15$).

In this section, we discuss the structure of a quasi-parallel, electron–ion, magnetized, mildly relativistic shock. With our large simulations, we are able to capture the large-scale structure of magnetic turbulence upstream. For the first time in a PIC simulation, we use a large enough box to resolve the gyroradius of the highest energy ion as the shock transitions between the early times – when the Weibel instability mediates the shock – to late times – when Bell instability is the dominant instability.

The evolution of density and $B_z$ with time is shown in Fig. 2 for a small slice of our simulation. The shock forms because of the Weibel instability, which starts the Fermi process. Once they have escaped upstream, particles are scattered back to the shock front Weibel instability, which starts the Fermi process. Once they have a small slice of our simulation. The shock forms because of the energy particles are not efficiently scattered by Weibel instability, $M_{\text{nr}}$.

In the upstream frame, the growth rate of the Bell waves and the wavenumber of the fastest growing mode is given by equations (16) and (17) of Reville, Kirk & Duffy (2006):

$$\omega_{\text{p,i}} \approx \frac{2}{\xi_{\text{cr}} \beta_{\text{cr}}}; \quad \frac{k_{\text{max}} c}{\omega_{\text{pi}}} = \frac{1}{2} \frac{\xi_{\text{cr}}}{v_{\text{cr}}},$$

(6)

$\xi_{\text{cr}}$ is the number fraction of non-thermal ions in the upstream, and $v_{\text{cr}}$, $\beta_{\text{cr}}$ are the drift velocity of the current carrying ions. Following Caprioli & Spitkovsky (2014b), we measure the drift velocity of the returning ions and find it is equal to the shock speed, $\beta_s \approx 0.83$. We also measure the number density of returning ions and find $\xi_{\text{cr}} \approx 0.029$. For our $M_{\Lambda} \approx 15$ shock, we estimate the fastest growing mode to have a wave number of $\sim 0.22 \omega_{\text{pi}}/c$, which is in good agreement with the peak of the Fourier power spectrum plotted in Fig. 3. The growth time of the fastest growing mode is $\sim 80/\omega_{\text{pi}}$. Transverse waves start to appear around $\omega_{\text{pi}} \sim 560$, and the shock completely transitions to Bell-mediated around $\omega_{\text{pi}} \sim 1500$ or $\sim 20$ times the growth time of the Bell instability. The Bell modes are visible as a striped $B_z$ and $B_y$ pattern upstream, transverse to the shock normal (see Fig. 2). We measured the polarity of the
upstream waves and found they are right hand circularly polarized, as expected for non-resonant ion waves (see Fig. 3).

The ion current $\mathbf{J}$ also drives a filamentary mode. Our simulation shows a similar structure to the one found in hybrid simulation of non-relativistic quasi-parallel shocks (see Caprioli & Spitkovsky 2013). To keep the plasma quasi-neutral, there is a returning negative current in the background plasma that is aligned with $B_0$. Therefore, the background plasma feels $-\mathbf{J} \times \delta \mathbf{B}$ force, which pushes the background plasma away from the regions of strongest current and focuses the current carrying ions, growing the instability further. The size of these upstream cavities grows with time, and they contain a large magnetic field at their walls. The transverse size is limited to be less than the size of gyroradius of the current-carrying ions.

We show the entire simulation domain of our fiducial, magnetized quasi-parallel shock at the final time-step $\omega_{pi}t = 4148$ in Fig. 4. The upper two panels show the ion and electron $x - p_x$ phase diagrams, and lower two panels show $B_z$ and the density. The upstream location where the returning ions start to non-resonantly drive circularly polarized transverse magnetic field fluctuations, $x \sim 650c/\omega_{pi}$, is also visible in structural changes in the top two panels of the phase diagrams. The returning ions transition from being a relatively narrow beam of particles to having a more diffuse structure as a result of the efficient scattering by the magnetic field.

In the electron phase diagram the transition is marked by a minimum momentum required to participate in the particle acceleration. The minimum momentum is visible as a lack of non-thermal electrons with Lorentz factors $\gtrsim \gamma_{\text{mic}}^2 m_i/m_e$ between $350c/\omega_{pi}$ and $650c/\omega_{pi}$. All of the non-thermal electrons have energies comparable to the non-thermal ions. The upstream magnetic field amplification is accompanied by the evacuation of small cavities in the density far upstream that grow to larger worm-like cavities closer to the shock front. The amplified magnetic fields are largest at the walls of these cavities. Downstream, the cavities become long filaments with $\varepsilon_B \gtrsim 0.2$ and small hole of low densities and large $B_z$, $\varepsilon_B \gtrsim 1$.

When swept downstream, the cavity forms two underdense holes that contain large magnetic fields of opposite $B_z$ polarity, and are surrounded by a ring of current. A close-up of a cavity being advected downstream can be seen in Fig. 5. In 3D, the two holes would likely be connected by a flux tube. Some holes merge downstream, and in 3D, the disruption of possible flux tubes may be an important site of magnetic dissipation. Whether the flux tubes do indeed form in 3D simulation, and the importance of any magnetic dissipation during their lifetimes is left to future work.

At the latest times, whistler waves are observed in the ion foot of the shock. Whistler waves are small-scale, dispersive waves that can occur in quasi-perpendicular shocks with low Alfvénic Mach numbers. Whistler waves can grow in non-relativistic quasi-perpendicular shocks when $M_A^2 \lesssim \sqrt{m_e/m_i}$ (e.g. Krasnoselskikh et al. 2002; Riquelme & Spitkovsky 2011). This inequality is satisfied in our simulation when $\delta B_z/B_0 \gtrsim 2$, which is indeed the case in the regions where whistler waves appear in our simulation.
Figure 5. Advection of an evacuated upstream cavity into downstream. The left panels show the density and the right show the out-of-plane magnetic field \( B_z \). Once advected downstream, the upstream cavities forms two holes with opposite \( B_z \) sign filled with a large amount of magnetic field.

Figure 6. The evolution of the \( y \)-averaged \( \varepsilon_B \) with time in the fiducial run. The times correspond to the times shown in Fig. 2. After the shock becomes mediated by the Bell instability (\( \omega_{pi}t \sim 1500 \)), the magnetic field amplification at the shock front increases. In addition, the amplified magnetic field increases further upstream and downstream with time. Note that the increase of \( \varepsilon_B \) at \( x \lesssim 60\omega_{pi} \) is an artefact from the left boundary that initializes the shock.

(see the inset of bottom panels of Fig. 2). Whistler waves are an efficient way to transfer energy from ions to electrons (Riquelme & Spitkovsky 2011). For realistic mass ratios, the condition for the shock to be unstable to whistlers is more easily achieved, and the whistlers may play a role in helping the electrons reach a sizable fraction of the ion temperature. However, we do not see good evidence that this increase in whistler waves increases electron injection into DSA. As increasing the mass ratio does not increase \( \varepsilon_e \) (see Appendix A).

The change in magnetic field amplification with time is best seen in Fig. 6. After the shock becomes Bell-mediated, at \( t \sim 1500\omega_{pi} \), there is significantly larger magnetic field amplification both upstream and downstream compared to earlier times when the shock was Weibel-mediated. The extent of the amplification both upstream and downstream grows with time. The average value of magnetic field amplification saturates at \( \sim 2B_0 \) upstream with a peak value of \( \sim 5B_0 \) inside of the filaments close to the shock front. We note that \( \varepsilon_B \) upstream decreases by \( \sim 33 \) per cent from \( \omega_{pi} = 2812 \) and \( \omega_{pi}t = 4148 \). This decrease may be because the initial beam of ions that triggers the Bell instability is more anisotropic than the later returning ions that are scattered more efficiently. The change from a beam to a diffuse structure in phase space is clearly visible in the ion phase diagram in Fig. 4. At later times, the importance of the organized beam will decrease and the returning particles may be more diffuse.

4 PARTICLE ACCELERATION IN A BELL-MEDIATED SHOCK

In the previous section, we showed that the transition from a Weibel-mediated shock to Bell-mediated shock changes the upstream magnetic field turbulence and shock geometry. In this section, we examine the implications of the Bell turbulence on particle acceleration.

The downstream spectral evolution with time is shown in Fig. 7. Both the ions and electrons show a Maxwellian distribution with significant non-thermal populations. In both the ion and electron spectra, the maximum energy grows with time. The electrons equilibrate with a temperature \( \approx 0.23 \times \text{ion temperature} \). The power law of electron distribution is consistent with \( f(p) \propto p^{-2.2} \) for DSA in ultra-relativistic shocks with \( \gamma_0 \gg 1 \), while \( p^{-4} \) is predicted for non-relativistic shocks (e.g. Achterberg et al. 2001). In the ions, the downstream spectral index appears softer than the electrons, but the spectral index is not well constrained. A proper measurement of the ion spectrum would require a simulation that was run significantly longer with a larger extent of the non-thermal ion power law. In our simulation, \( \varepsilon_p \), the fraction the shock’s energy that is put into non-thermal ions is \( \sim 0.1 \). The downstream electron temperature is 30 per cent of the ion temperature and \( \varepsilon_e \sim 5 \times 10^{-4} \). To measure \( \varepsilon_e \) and \( \varepsilon_p \), we integrate the non-thermal spectrum starting at a momentum \( p_{\text{inj}} = 2\gamma_0\beta_0m_\text{e}c \) as measured in the downstream frame.

The upstream spectral evolution with time is shown in Fig. 8. Both the ions and electrons show two-humped spectra. The lower
energy bump corresponds to the incoming beam of particles, while the higher energy bump is the returning particles. The ions rapidly converge to having a minor amount of pre-heating, as lower bump is well fit by a Maxwellian. In contrast, the electrons show strong heating at times $\omega_{pi} t = 562$ and 1125, which we attribute to the Weibel filaments that transfer a large fraction of the ions’ kinetic energy to the electrons upstream, causing a significant amount of pre-heating of the electrons, increasing the electron gyroradius (e.g. Kumar, Eichler & Gedalin 2015). The initial Weibel filaments are effective at injecting electrons not only due to this pre-heating but also because the perturbations cause the shock to be highly random in magnetic field obliquity, providing locally quasi-perpendicular field orientation that is conducive to electron injection via shock drift acceleration (SDA; Ball & Melrose 2001; Park et al. 2015). At later times, after the shock switches to being Bell-mediated, the upstream magnetic fluctuations grow to larger size scales, and the energy transfer between reflected ions and incoming electrons decreases tremendously. This can be seen by the fact that the lower energy electron hump in Fig. 8 becomes increasingly better fit by a simple Maxwellian.

The two species enter the shock front in approximate thermal equilibrium. Since the momenta of the electrons entering the shock are far less than that of the ions, the scale separation between incoming electrons and ions is preserved. There is a minimum energy electrons must attain to escape far upstream, $E_{min} \sim \gamma^2 \beta m_e c^2$, visible in the hole in the electron phase diagram (see Fig. 4), and in the time evolution of the upstream spectra, see Fig. 8. All of the reflected electrons have energies comparable to the reflected ions. As we argue in Section 5, the Bell instability creates regions of the shock that are locally superluminal. The size of these regions is comparable to the ion gyroradius. Electrons need to attain energies comparable to the ion gyroradius in these regions to escape far upstream, $E \sim \beta m_e c^2$. We find that to properly recover the correct shock structure, and measure $\epsilon_e$, the simulation domain must be wide enough so that the transverse waves cannot fill the entire box. This criterion is satisfied when the size of the box is much larger than the gyroradius of the incoming beam of particles, while the right hump is the returning particles. The spectra shown in the simulation (i.e. upstream) rest frame and extracted from an area $10-20c/\omega_{pi}$ upstream of the shock. Both the ions and electrons show two-humped spectra. The left hump is the incoming beam of particles, while the right hump is the returning particles. In the spectra we show Maxwellian distributions fit by eye, with temperatures in terms of $T_i$, the injected temperature of the plasma. When the shock is Weibel-mediated, the electrons are pre-heated significantly, which can be seen because the left hump is not fit well by a Maxwellian at early times. After Bell instability kicks in at around $t \sim 1500\omega_{pi}$, both the ions and electrons are preheated only by a factor of around a few.

Comparable to the ion gyroradius to escape these regions. We leave a detailed study of the orbits of the non-thermal electrons to future work. However, before electrons escape far upstream, they undergo several cycles of SDA. Once they reach the regions of quasi-parallel fields, they can escape upstream. This hints that the acceleration of electrons in our simulation is likely done through a combination of SDA and then DSA as seen in the simulations of Park et al. (2015).

For both ions and electrons, the highest energy particle in the box for each species has roughly the same kinetic energy. The two species are expected to have the same maximum energy if the rate of energy gain depends only on the rigidity of the particle and not the charge, like in DSA. The maximum energy grows linearly with time and does not saturate, $E_{max} \propto t$ (see Fig. 9). The rate at which the maximum energy particle gains energy is consistent with the Bohm limit in standard DSA theory ($E \propto t$, $D \propto E$, where $D$ is the diffusion coefficient). The linear scaling is much faster than $E_{max} \propto \sqrt{t}$ scaling found from small-angle scattering in relativistic Weibel-mediated shocks (Plotnikov, Pelletier & Lemoine 2011; Sironi et al. 2013), and makes a large difference the potential maximum energy particle produced by an astrophysical system.

### 5 Importance of the Filamentary Mode

We find that to properly recover the correct shock structure, and measure $\epsilon_e$, the simulation domain must be wide enough so that the transverse waves cannot fill the entire box. This criterion is satisfied when the size of the box is much larger than the gyroradius of the incoming beam of particles.
The characteristic angle of the amplified magnetic field, $\theta$, the shock front allows electrons to escape back upstream. The existence of locally quasi-parallel regions of measured in the upstream frame (Begelman & Kirk 1990; Sironi & Bell 2012; Caprioli & Spitkovsky 2013). The maximum size is ultimately limited by the gyroradii of the ions carrying the current. The gyroradius of a typical shock reflected ion ($E \sim \gamma^2 m_e c^2$) is $r_{\text{gyr}} \sim 30 c/\alpha_{\text{ps}}$. Caprioli & Spitkovsky (2013) found that in hybrid simulations of non-relativistic shocks, the size of the filament can grow to be comparable to the gyroradius of the highest energy ion.

To show the importance of the transverse size of simulation for the measurement of $\varepsilon_\theta$, we compare our fiducial run to one that is much wider than the typical ion gyroradius at a width slightly smaller than the ion gyroradius in Fig. 10. At early times, the smaller, $L_z = 25 c/\alpha_{\text{ps}}$, run agrees with the fiducial, $L_z = 500 c/\alpha_{\text{ps}}$ run in terms of magnetic structure (panel a) and particle acceleration (panel c). However, we can see in panel b, failing to resolve the ion gyroradii significantly changes the shock structure, where the fiducial run shows filaments with width $\sim r_{\text{gyr}}$, but the smaller run does not have filaments at the shock front. The filaments in the fiducial run cause the shock front to have regions of subluminal and superluminal magnetic field orientations at the same time. Without filaments, as in the smaller run, alternating strips of subluminal and superluminal fields fill the transverse direction upstream. This difference in structure changes $\varepsilon_\theta$, (see the panel c of Fig. 10). The box must be sufficiently wide to capture the filaments to properly

\[ B_\perp \equiv \frac{\varepsilon_\theta}{\gamma^2 m_e c^2}, \text{ where } \varepsilon_\theta, \text{ is the pressure of the accelerated ions, } \text{Reville & Bell 2012; Caprioli & Spitkovsky 2013}. \]

The size needed to properly resolve Bell cosmic ray current driven instability depends on the size of the evacuated cavities upstream. The cavities grow until they are advected towards the shock. The size of the cavities when they impact the shock front depends on the ratio of the advection time to the growth rate of the cavities ($\Gamma \propto |B_{\perp}/B_{\parallel}|$, where $\xi_{\text{acc}}$ is the pressure of the accelerated ions, Reville & Bell 2012; Caprioli & Spitkovsky 2013). The maximum size is ultimately limited by the gyroradii of the ions carrying the current. The gyroradius of a typical shock reflected ion ($E \sim \gamma^2 m_e c^2$) is $r_{\text{gyr}} \sim 30 c/\alpha_{\text{ps}}$. Caprioli & Spitkovsky (2013) found that in hybrid simulations of non-relativistic shocks, the size of the filament can grow to be comparable to the gyroradius of the highest energy ion.

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Particle acceleration in shocks with $\gamma\beta \sim 1$

6 QUASI-PERPENDICULAR MILDLY RELATIVISTIC SHOCKS

Here, we change the magnetic field orientation to examine a quasi-perpendicular mildly relativistic shock with $\theta_B = 55^\circ$. For $\gamma_0 = 1.5$, the angle at which the shock becomes superluminal is $\theta_{\text{crit}} \approx 34^\circ$. Therefore with $\theta_B = 55^\circ$, particles are unable to escape upstream and drive turbulence far from the shock. The inability of particles to escape far upstream prevents them from being injected into DSA and forming a non-thermal power law.

In Fig. 11, we show an example of a superluminal, quasi-perpendicular shock. Unlike the quasi-parallel shock, there are no reflected ions capable of driving turbulence upstream. The lack of returning ions results in a smaller compression ratio, and in weaker magnetic fields downstream, in good agreement with hybrid simulations of quasi-parallel shocks (Caprioli & Spitkovsky 2014b). We show the averaged 1D profiles of the magnetic field amplification in Fig. 12.

In the quasi-perpendicular shock, a prominent suprathermal bump from SDA is visible in the downstream ion spectra shown in Fig. 13. However, the maximum energy in both species does not grow with time or develop into a power law. The lack of returning upstream particles means that there are no particles to seed magnetic turbulence upstream. Therefore, there is no pre-heating upstream: $T_\parallel = T_\perp = T_0$. Downstream, $T_\parallel \approx 6T_\perp$. The ion temperature is nearly the same in the subluminal and superluminal shocks, but $T_\parallel$ of the superluminal shock is about half of $T_\parallel$ in the quasi-parallel case. The additional turbulence provided by the shock-reflected particles measure the energy in non-thermal electrons in mildly relativistic shocks.

Electron injection into shock acceleration decreases if the transverse size of the waves can grow to the entire box. Decreasing the box size decreases the normalization of the electron power law, but not the extent of the power law in ions nor electrons. We confirmed that the decrease in $\varepsilon_e$ is not just a matter of statistics by running smaller runs with larger ppc (up to 64). We also compared our fiducial, $L_x = 500 c/\omega_{pi}$, run to slightly smaller run that still captured the gyroradius, $L_x = 200 c/\omega_{pi}$. We saw no difference in $\varepsilon_e$ in those runs, suggesting it is sufficient to capture a few patches of a locally quasi-parallel shocks to properly measure $\varepsilon_e$. In Fig. 12, we show an example of a superluminal, mildly relativistic shock with $\theta_B = 55^\circ$. Compare this figure to the subluminal case with $\theta_B \approx 10^\circ$ in Fig. 4. There are no particles escaping upstream and no upstream turbulence, as expected for superluminal magnetized shocks.

Figure 12. A comparison of the magnetic field amplification in mildly relativistic quasi-parallel and quasi-perpendicular shock at the final time-step of each respective simulation. Returning ions amplify the magnetic field upstream in the quasi-parallel shock. The additional turbulence produced by the returning ions also increases the downstream magnetic field beyond shock compression of the unamplified field in the quasi-parallel shock.

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in quasi-parallel shocks drives the downstream species closer to equilibrium.

As we show in Appendix B, when $\theta_B \sim 10^4$, the shock structure and particle acceleration do not depend on the orientation of the magnetic field with respect to the simulation plane. However in quasi-perpendicular shocks, the turbulence right at the shock front and downstream depends strongly on the orientation of the field with respect to the simulation plane. In the out-of-plane configuration, ions gyrate around $B_z$ in the $x$–$y$ plane, reducing the effective adiabatic index, causing downstream magnetic fluctuations, and decreasing the importance of SDA in the ions. But for both in-plane and out-of-plane superluminal magnetic field configurations, particles do not return upstream and a non-thermal power law does not develop.

7 CONCLUSIONS

This paper is the first in a series that examines how particle acceleration in shocks changes when the shock transitions from non-relativistic to relativistic. We used large computational domains and a fully kinetic method. We captured the filamentary behaviour of the Bell instability. In doing so, we have followed the shock from formation to the shock’s later stages, resolving all kinetic ion and electron scales. In this paper, we have shown that properly capturing the non-resonant instability is crucial for measuring the fraction of the shock’s energy that goes into non-thermal electrons, $\varepsilon_e$.

There is observational and theoretical evidence that both relativistic and non-relativistic quasi-parallel shocks are efficient ion accelerators with a $\varepsilon_B \sim 0.1$. We find that the fraction of the shock’s energy in non-thermal electrons, $\varepsilon_e$, to be $\sim 5 \times 10^{-4}$ for a mildly relativistic, magnetized shock with $\theta_B = 10^4$, $\gamma_0 = 1.5$, $\beta_0 \approx 0.75$, and $M_A \approx 15$. Our measurement of $\varepsilon_e$ can be directly compared to other PIC simulations in the literature of shocks with $\sigma \sim 0.01$ or Alfvénic Mach numbers $\sim 10$. Our reported $\varepsilon_e$ is consistent with the 1D measurement of $\varepsilon_e \sim \varepsilon_B$, with a few $\times 10^{-4}$ for non-relativistic shocks with $\beta_0 = 0.1$ by Park et al. (2015), and less than the $\varepsilon_e \sim 0.1$ measured in relativistic shocks by Sironi & Spitkovsky (2011). Our simulations are also consistent with the trend of increasing $\varepsilon_e$ as the shock becomes more relativistic, but a set of directly comparable simulations spanning the non-relativistic to relativistic regime is the goal of a future work.

Our simulations had a moderately large magnetization $\sigma_0 = 0.007$, $M_A \approx M_e \approx 15$: a set-up consistent with possible internal shocks in the jets of microquasars or quasars. We show that magnetized, subluminal, mildly relativistic shocks are capable of producing non-thermal ions and electrons in hard power-laws whose maximum energy grows linearly with time.

The evolution of a quasi-parallel weakly magnetized shock can be summarized as follows: the shock forms via the Weibel instability that starts the Fermi process and reflects particles into the upstream. The Weibel instability efficiently pre-heats incoming electrons to an energy comparable to the ions. Therefore, both electrons and ions are efficiently injected in a Weibel-mediated shock. However, the Weibel instability produces small-scale field fluctuations that only efficiently scatter particles back towards the shock if the gyroradius of the particle is comparable to the size of the fluctuations. A typical filament with a transverse size of 10 ion skin depths will not large-angle-scatter particles who have energies much larger than the shock reflected ions (whose gyroradii are $\sim 30$ ion skin depths). High-energy particles are only deflected by a small angles, and can easily stream far away from the shock due to the quasi-parallel field geometry. The escaping high-energy ions drive a current in the upstream plasma, which grows transverse waves via the Bell cosmic ray filamentary instability. After about $\sim 20$ growth times, the Bell instability becomes the dominant instability that mediates the shock. Once mediated by the Bell filamentary instability, the shock and non-thermal particles change in the following ways:

(i) For $M_A = 15$, there is large magnetic field amplification both upstream and downstream. The $\gamma$-averaged field amplification upstream is as $\sim 2\beta_0$, and close to the shock the most amplified field can be $\gtrsim 5\beta_0$. The largest upstream field amplification occurs at the walls of worm-like cavities evacuated by energetic ions. A $J \times \delta B$ force acts on a current carried by the background plasma, which is balancing the current of high-energy ions that escape far upstream. The force evacuates these worm-like cavities. The transverse size and extent of these structures grows with time. Downstream, $\varepsilon_B$, is both larger and extends further away from the shock than when the shock is Weibel-mediated (see Figs 6 and A4).

(ii) The shock structure is highly turbulent and magnetic field amplification downstream happens in two structures: magnetized filaments with a characteristic $\varepsilon_B \gtrsim 0.1$ and compact underdense holes with a large out-of-plane magnetic field and an $\theta_B \sim 1$, confirming the turbulent structure found by Caprioli & Spitkovsky (2013) using hybrid simulations. When an upstream cavity is advected downstream, it forms two underdense holes of opposite $B_z$. sign. In 3D they would likely form a connected twisted flux tube. The holes last for a long time and even merge in 2D. They may be an important place for magnetic dissipation, but the dynamics needs to be checked in 3D.

(iii) The filamentary nature of the Bell instability plays a vital role in electron injection in mildly relativistic shocks. At early times, the Weibel instability efficiently reflects both ions and electrons at the shock front, as in relativistic shocks (e.g. Sironi et al. 2013). After the shock becomes Bell-mediated, $\varepsilon_B \ell \sim 1500$ in our fiducial run, electron reflection and injection into DSA becomes less effective. If the simulation box is not wide enough to capture the gyroradius of the non-thermal ions, $\varepsilon_e$ will be suppressed significantly in shocks with $\gamma \beta \sim 1$.

(iv) The maximum energy of both the ions and electrons in the quasi-parallel simulation increases linearly after the shock becomes Bell-mediated. The maximum ion and electron energy is the same. The linear increase in energy is consistent with the Bohm scaling, $E_{\text{max}} \propto \ell$, and is much faster than the scaling of $E_{\text{max}} \propto t^{1/2}$ in Weibel-mediated, high-Mach number, ultra-relativistic shocks (Sironi et al. 2013). Because $E_{\text{max}}$ grows much faster in mildly relativistic shocks, sources with mildly relativistic shocks like FRI type AGN may be more likely progenitors of ultra-high energy cosmic rays than the ultra-relativistic unmagnetized shocks in GRBs.

(v) Electrons are not pre-heated to a large fraction of the reflected ion energy in trans-relativistic shocks. In relativistic and mildly relativistic Weibel-mediated shocks, the reflected ions are capable of transferring a sizeable portion of their energy to the electrons upstream, so that the rigidity of the two species is similar at the shock front. We find that once the shock becomes Bell-mediated, ions and electrons are pre-heated by similar amounts; at one ion gyroradius in front of the shock, the two temperatures are $T_e < 3T_0$ and $T_B \sim 4T_0$, where $T_0$ is the initialized temperature of the plasma. Therefore, the two species enter the shock region in approximate thermal equilibrium, with thermal momenta far less than the bulk momentum of an ion. Thus, the large difference between ion and electron rigidity at the shock front is preserved. Downstream and right at the shock front, the ions do transfer their energy...
to the electrons, and the downstream electrons equilibrate with a temperature $\sim 30$ per cent of the ions’ downstream temperature.

(vi) To be reflected upstream, the electrons must have an energy comparable to a shock-reflected ion, meaning electrons must gain a lot of energy close to the shock front, possibly through an SDA process as seen in 1D simulations of Bell-mediated electron–ion shocks (Park et al. 2015), but we did not study the orbits of the non-thermal electrons. We leave that to a future work.

(vii) Magnetized, quasi-parallel shocks are efficient ion accelerators. Approximately, 10 per cent of the shock’s energy goes into non-thermal ions. The power-law index of ions appears to be softer than $f(p) \propto p^{-4.2}$ (dn/dE $\propto E^{-2.5}$). The power law starts at $\sim 2\gamma_0 \beta_0 \gamma_0 m_e c$. For $M_A = 5.0, \theta_B = 10^{\circ}, \gamma_0 = 1.5, \beta_0 \approx 0.75$, the amount of the shock’s energy that is put into the non-thermal electron power law is small, $\varepsilon_e \sim 5 \times 10^{-4}$. This $\varepsilon_e$ corresponds to a number ratio of non-thermal electrons to total electrons of $5 \times 10^{-5}$. However, the value of $\varepsilon_e$ may depend on the magnetic inclination upstream, $\sigma_0$, and the speed of the shock. We will address these trends in a future work.

Finally, we examined particle acceleration in superluminal mildly relativistic shocks, with $\theta_B = 55^{\circ}$. Since particles were unable to escape upstream, neither species was capable of entering DSA. Instead, a fraction of ions gained energy via SDA while crossing the shock front, resulting in a second superthermal bump in the downstream ion spectrum. In mildly relativistic superluminal shocks, the maximum energy of both species did not increase with time. Throughout this paper, we have used a reduced mass ratio of $m_i/m_0 = 64$. We find that $m_i/m_0$ must be fairly large, or else Bell instability will be suppressed. We also find that $64$ is sufficiently large to capture the shock structure and $\varepsilon_e$, as shown in Appendix A.

Our results on acceleration in mildly relativistic shocks have the following implications for simulations of electron–ion shocks: a small-reduced mass ratio, numerical heating, and too short of simulation duration all work in concert to suppress the Bell instability. If Bell does become the main instability, the simulation must have a large transverse size to capture the upstream filaments, and these filaments play a big role in injecting electrons in mildly relativistic shocks. These conclusions are very general and likely apply equally well to non-relativistic and relativistic particle-in-cell simulations of quasi-parallel shocks.

For non-relativistic shocks travelling at $v \ll c$, the filamentary mode of the Bell instability may not be as important for acceleration of electrons because even the amplified magnetic field is subluminal. This may explain the close agreement between $\varepsilon_e$ measured in this work and the 1D simulations of $v = 0.05c$ shocks in Park et al. (2015). A set of directly comparable, 2D simulation of shocks ranging from non-relativistic to relativistic is left to future work.

Since our shocks were mildly relativistic, one needs to account for the cooling of particles with a given energy. This cooling is may be less important because the amplified magnetic field is subluminal. The amplification of magnetic field is subluminal. The amplification of magnetic field is subluminal. The amplification of magnetic field is subluminal.

We will address how electron acceleration efficiency and magnetic amplification depends on $v/c$ and $\sigma_0$, constraining the models that assume equi-partition between $\varepsilon_B$ and $\varepsilon_e$ in future work.

In the future, it will be important to determine if 2D PIC simulations can properly capture the physics of a Bell-mediated shock. The reduced dimensionality of the simulations may allow for structures that do not form in 3D. A 3D simulation will be expensive because to be fully 3D, the $z$-direction should be much larger than that of the typical ion gyroradius and run for a long time. However, we can use the 3D results of prior hybrid simulations to inform how PIC simulations might change if run in 3D. Caprioli & Spitkovsky (2014a) found that in 3D the returning cosmic rays still evacuated cavities upstream, and the magnetic field amplification and ion injection and diffusion was largely the same. Therefore, our general picture of a transition from a Weibel- to a Bell-mediated quasi-parallel shock with an $\varepsilon_e \sim 10$ per cent, $E_{\text{max}} \sim \varepsilon_0 t$ should hold. The characteristic values for the magnetic field amplification upstream and the less-amplified magnetic filaments downstream would likely remain in a 3D PIC simulation as well. However, our simulations have features not capable of being captured in hybrid simulations – the electron heating of a factor of $\sim 3\sigma_0$ and $\varepsilon_e \sim 5 \times 10^{-4}$. A fully 3D PIC simulation would need to be run to answer how our results may change.

In conclusion, we have used fully kinetic particle-in-cell simulations to show that quasi-parallel, magnetized, mildly relativistic electron–ion shocks travelling at velocity $v \sim 0.7c$ are capable of self-consistently generating the necessary magnetic turbulence upstream to accelerate particles to high energies quickly. In addition, these shocks put a large fraction of their energy into hadrons. These characteristics suggest that astrophysical objects that host such shocks may be an important source of high-energy hadronic radiation, cosmogenic neutrinos, and possibly a source of the ultra-high energy cosmic rays. Therefore, objects like low-luminosity AGN like BL Lacs and FRI, as well as micro-quasars, which may have mildly relativistic shocks inside of their jets, are important potential multimessenger sources for the upcoming high-energy gamma-ray telescopes such as the Cherenkov Telescope Array and also existing and forthcoming high-energy neutrino detectors like IceCube and KM3NeT.

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References


Appendix A: Scaling with Mass Ratio

In the main text of paper, we have employed a reduced mass ratio \( m_i/m_e = 64 \approx 1836 \). Here, we examine the consequences of using a smaller mass ratio on the shock structure and particle acceleration. We find that using too small a mass ratio can suppress the cosmic ray filamentation instability with the following implications – there is too little magnetic field amplification upstream and downstream, the maximum particle energy grows too slowly, the energy transfer between electrons and ions is too efficient, and artificially small \( m_i/m_e \) boosts \( e_e \). While our fiducial mass ratio of \( m_i/m_e = 64 \) agrees quantitatively with a higher mass ratio \( m_i/m_e = 160 \) simulation in terms of the magnetic field amplification and maximum particle energy, it only qualitatively agrees in the other respects. Using \( m_i/m_e = 64 \) slightly underpredicts the importance of the cosmic ray filamentation instability, with smaller, weaker filaments in the upstream, more electron heating, and an \( e_e \) that is slightly bigger in the \( m_i/m_e = 64 \) simulation than in \( m_i/m_e = 160 \). In the larger mass ratio simulation, whistler waves may be more important, as they will cross the \( M_A \approx \sqrt{m_i/m_e} \) barrier at smaller values of magnetic field amplification.

To see the effect of our choice of reduced mass ratio, 64, we compare our fiducial run to a simulation with a smaller mass ratio of 16 (the mass ratio used in Sironi & Spitkovsky 2011), and a larger mass ratio of 160 in Figs A1–A4. The higher mass ratio run had the same set-up as the fiducial run except it used a higher resolution of \( c/\omega_{pe} \approx 8 \) cells and a box width of \( \approx 79 c/\omega_{pe} \). The \( m_i/m_e = 16 \) simulation had the same set-up except it used a higher resolution of \( c/\omega_{pe} = 8 \) cells and a box width of \( \approx 109 c/\omega_{pe} \). The higher resolution was required to ensure that the smaller Debye length was resolved \( \lambda_D \propto \sqrt{m_i/m_e} \).

Figs A1 and A2 show the effect of the reduced mass ratio on the downstream and upstream spectral properties, respectively. It is clear that using a mass ratio of 16 is insufficient to correctly capture the spectral properties of a Bell-mediated, electron-ion shock at \( \omega_{pi}t \approx 2000 \), shortly after the time the shock becomes Bell-mediated in the fiducial. \( m_i/m_e = 64 \), simulation. As the mass ratio increases to more realistic values, the energy transfer to electrons from ions decreases, with electrons having a lower temperature downstream. For \( m_i/m_e = 16 \), the cosmic ray filamentary instability is significantly suppressed and \( e_e \) is far too large at \( \omega_{pi}t \approx 2000 \).

\[ \frac{m_i}{m_e} = 16 \]
\[ \frac{m_i}{m_e} = 64 \]
\[ \frac{m_i}{m_e} = 160 \]
Particle acceleration in shocks with $\gamma \beta \sim 1$

Figure A2. Three simulations that illustrate the importance of a large mass ratio. The two panels show the particle spectra in the upstream rest frame extracted 10–20 $c/\omega_{pi}$ upstream of the shock at $\omega_{pi} t \approx 2000$. With a small mass ratio, electrons are heated significantly more upstream before entering the shock.

Figure A3. The effect of varying the mass ratio on the filamentary structures in the upstream. The three panels show $B_z$ near the shock front at time $\omega_{pi} t \approx 2000$. Increasing $m_i/m_e$ increases the importance of the cosmic ray filamentation instability.

The $m_i/m_e = 16$ run predicts an $\varepsilon_e$ that is $\sim 10$ times larger than the runs with larger mass ratios, whereas the $\varepsilon_e$ in the $m_i/m_e = 64$ and 160 runs agree within a factor of 2. There is no sign of an increase in energy transfer in the high-mass run due to whistler waves. As the mass ratio increases, the upstream energy exchange between electrons and ions is less efficient. In all of the runs, the downstream thermal electrons achieve a significant fraction of the ion energy.

The downstream ion spectrum in the $m_i/m_e = 16$ run does not extend to as high of energy as the larger mass ratio runs, so $\varepsilon_p$ is not well-constrained, but it appears similar to the larger mass ratio runs. Note that the non-thermal tail extends to larger energies in both the electrons and ions for the larger mass ratio runs as compared to the $m_i/m_e = 16$. The high-energy particles are scattered back to the shock more efficiently because the larger mass ratio runs show more upstream magnetic field amplification and structures at larger scales (see Figs A3 and A4).

In terms of the overall magnetic field amplification, the $m_i/m_e = 160$ and the fiducial run agree very well both upstream and downstream, the only difference is that the extent of the amplification is larger upstream for $m_i/m_e = 160$. The difference in extent is because the larger mass ratio run transitions from Weibel-mediated to Bell earlier than the fiducial run (in terms of $\omega_{pe}^{-1}$). The smaller mass ratio of $m_i/m_e = 16$ has not yet transitioned to being Bell-mediated.

APPENDIX B: DEPENDENCE ON MAGNETIC FIELD ORIENTATION WITH RESPECT TO SIMULATION PLANE

In this appendix, we show that for both the quasi-parallel and superluminal shocks considered in this paper, the orientation of the magnetic field with respect to the simulation plane does not significantly affect our results.

In the main text of the paper, we used an initial magnetic field $B_0$ that was in the $x-y$ plane. There is a growing body of evidence that 2D simulations initialized with $B_\perp$ along $z$ as opposed to $y$ may be more efficient at accelerating electrons in high Mach number, perpendicular shocks (e.g. Matsumoto, Amano & Hoshino 2012; Sironi et al. 2013; Bohdan et al. 2017). In the quasi-parallel shocks, the out-of-plane configuration initially reflects more electrons, resulting in an $\varepsilon_e$ that is $\sim 2$ times larger than the $5 \times 10^{-4}$ reported in the main paper. However, once the turbulence upstream saturates, the amplified magnetic field is the dominant field at the shock front. Then, the two $B_0$ configurations have approximately the same $\varepsilon_e$. 

Figure A4. The effect of varying the mass ratio on the $y$-averaged $\varepsilon_B$ at time $\omega_{pi} t \approx 2000$. When more realistic mass ratios are used, the cosmic ray filamentation instability becomes more important, increasing the magnetic field amplification both upstream and downstream of the shock front. Note the good quantitative agreement between $m_i/m_e = 64$ and 160 in terms of the magnitude of the magnetic amplification upstream and downstream.
Figure B1. Comparison of upstream and downstream spectra with different initial magnetic field orientations with respect to the simulation plane at time $\omega_{pe} t = 4148$. Solid lines correspond to the fiducial run with an in-plane $B_0$ field (i.e. $B_{0,\perp}$ along $y$). Dotted lines correspond to a smaller run with out-of-plane orientation ($B_{0,\perp}$ along $z$) and a width of $100 \ c/\omega_{pe}$. The upper panel is the particle spectra in the simulation rest frame extracted 20–30 $c/\omega_{pe}$ upstream of the shock, while the lower panel is the spectra in the downstream rest frame extracted 10–80 $c/\omega_{pe}$ downstream of the shock. While the out-of-plane inclination initially reflects more electrons, when turbulence $B$ field upstream grows larger, the difference between the two inclinations electron acceleration efficiency is small.

Figure B2. Comparison of downstream superluminal spectra with different initial magnetic field orientations with respect to the simulation plane at time $\omega_{pe} t \approx 2600$. Solid lines correspond to superluminal shocks with $\theta_B = 55^\circ$ and in-plane $B_0$ field (i.e. $B_{0,\perp}$ along $y$). Dotted lines correspond a superluminal shock with out-of-plane orientation ($B_{0,\perp}$ along $z$). The spectra are extracted 10–80 $c/\omega_{pe}$ downstream of the shock and are calculated in the downstream rest frame. The upstream is not shown as the spectra are simply Maxwellians with $T = T_0$. Neither configurations show non-thermal acceleration. The in-plane configuration has hotter downstream ions and electrons and a larger SDA bump in the ion spectrum due to its larger compression ratio (see Fig. B3).

Figure B3. Comparison of field quantities close to the shock between superluminal in-plane and out-of-plane magnetic field configuration. As can be seen in the top panel, the two configurations have a different compression ratios, and therefore different shock speeds. The lower panels show $\varepsilon_B$ for the in-plane and out-of-plane configuration. The out-of-plane shock takes longer to thermalize the plasma, showing less compression and a more turbulent downstream. The out-of-plane shock front has structures on the scale of the ion gyroradius. The in-plane shock thermalizes the plasma very quickly and has a higher compression ratio.

For the superluminal shocks, the field configuration is more important. The in-plane shock more quickly thermalizes the plasma at the shock front, and therefore has a larger compression ratio. The larger compression ratio results in the ion spectrum having a larger SDA bump, and hotter electrons (see e.g. Caprioli & Spitkovsky 2014a). The out-of-plane configuration does not effectively scatter ions in the $z$ direction decreasing the adiabatic index of the shock. The smaller adiabatic index leads to a smaller compression ratio. However, ions do gyrate efficiently in the $x$–$y$ plane at the shock front, causing more turbulence at the shock front and downstream. In the out-of-plane configuration, the turbulence causes the electrons to be heated far downstream. However, neither configuration is capable of producing upstream magnetic turbulence nor accelerating particles to high energies.

**APPENDIX C: CONVERGENCE IN RESOLUTION AND NUMBER OF PARTICLES**

In this section, we briefly show that our choice of resolution and particles per cell is sufficient to measure $\varepsilon_e$ and $\varepsilon_p$. We compare our fiducial run with $c/\omega_{pe} = 4$ cells, ppc = 4 to a run with twice the resolution $c/\omega_{pe} = 8$ cells, and a different run with 64 particles per cell. The downstream spectra are shown in Fig. C1, $\varepsilon_p$ and $\varepsilon_e$ agree with a factor of 2 for all the runs. The shock structure, magnetic field turbulence, and magnetic amplification were very similar in these runs.
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Figure C1. The figure shows the particle spectra in the downstream rest frame extracted $10^{-50} c/\omega_{pi}$ downstream of the shock at $\omega_{pi} t \approx 1500$, shortly after the time the shock becomes Bell-mediated in the fiducial, $c/\omega_{pe} = 4$, $pcc = 4$, simulation. We compare our fiducial run to a simulation with twice as many cells per skin depth and another simulation with 16 times as many particles per cell. $\epsilon_e$ and $\epsilon_p$ in all the runs agree within a factor of $\sim 2$.

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