Fast electrons at slow shocks

Microphysics of slow collisionless shocks in nonthermal sources of radiation

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In Short

- We conduct kinetic simulations of non-relativistic shocks to study the acceleration of electrons at supernova remnants
- The main question is whether or not our understanding of electron acceleration at perpendicular and quasi-perpendicular shocks also applies to shocks with realistic velocity.
- Our simulations are scientifically important because the unsolved problem of electron injection is the most critical ingredient in the theory of particle acceleration at shocks, and because it determines the level of cosmic-ray feedback and hence the nonlinearity of the system.

Deciphering the acceleration mechanisms of charged particles in space is of great interest and high actuality in astroplasma physics. The interaction of supernova ejecta with the interstellar medium results in shocks which are often associated with radiation in the radio band, in the X-ray band, and in γ rays. Is is commonly assumed that the high energy electrons responsible for this emission are produced through diffusive shock acceleration, a process that relies on particles bouncing between the upstream and downstream side of the shock. A critical ingredient and the main unsolved problem in the model is the particle injection. Particles need to see the shock as a sharp discontinuity in the plasma flow. The shock has a finite width though that is commensurate with the gyroradius of the incoming ions. Electrons have a small mass and consequently a small gyroradius, and so they need to be pre-accelerated with a large energy gain to involve them in this acceleration process.

Energetic charged particles couple to their environment through electromagnetic turbulence that is in part self-produced. We conduct large particle-in-cell (PIC) simulations of collisionless shocks with a view to elucidate the processes that provide electron acceleration. PIC simulations are the appropriate tool to study particle injection into shock acceleration because injection at collisionless shocks is a kinetic problem that cannot be addressed with MHD or other fluid techniques. Only PIC simulations can track the impact of electron-scale fluctuations on the ion dynamics through self-consistent treatment of both electrons and ions. Three-dimensional studies can currently be conducted only with low resolution and for very idealized parameters [1], and so we concentrate on two-dimensional simulations.

We study electron preacceleration for conditions at young-supernova-remnant shock waves, but the results can be used for any high-Mach-number nonrelativistic perpendicular shock, e.g. the bow shock of Saturn [2]. A number of mechanisms are responsible for electron acceleration in the shock transition. Electrons can be accelerated during interaction with electrostatic waves resulting from the Buneman instability. This process is also known as shock-surfing acceleration. Magnetic reconnection in the shock ramp results in acceleration of electrons via a number of channels discussed in [4]. Electrons also undergo stochastic Fermi-like acceleration [5].

We have studied the efficiency of shock-surfing acceleration for a variety of simulation setups and physical parameters before. The energy gain always arises from the electrostatic field of a Buneman wave with which the electron travels for some time.

As the shock-surfing acceleration operates at the front of the shock, the electrons still have to pass through the shock where they might loose energy, and other initially cold electrons might be energized. Figure 1 illustrates which fraction of energetic electrons is provided by shock-surfing acceleration. We follow an ensemble of electrons as they pass through the shock. The energy spectrum of those preaccelerated by shock-surfing acceleration is marked in green, and we see that after passage it is only weakly distinguishable from that of all electrons (in black). Conversely, those that are energetic at the end (red line) are fairly average at the beginning. It appears that the final energy distribution is not dominantly shaped by shock-surfing acceleration [6].

The conclusions described above are valid for nonrelativistic shocks with shock speed that is about a quarter of the speed of light. A realistic shock in a supernova remnant is ten times slower, and it is not at all clear that SSA is unimportant then. We now want to explore electron pre-acceleration at shocks with realistic shock velocity for supernova remnants (SNRs).

The main question is whether or not our understanding of electron acceleration at perpendicular and quasi-perpendicular shocks also applies to shocks with realistic velocity. In detail, our objectives are

- Do we observe modifications of instabilities in

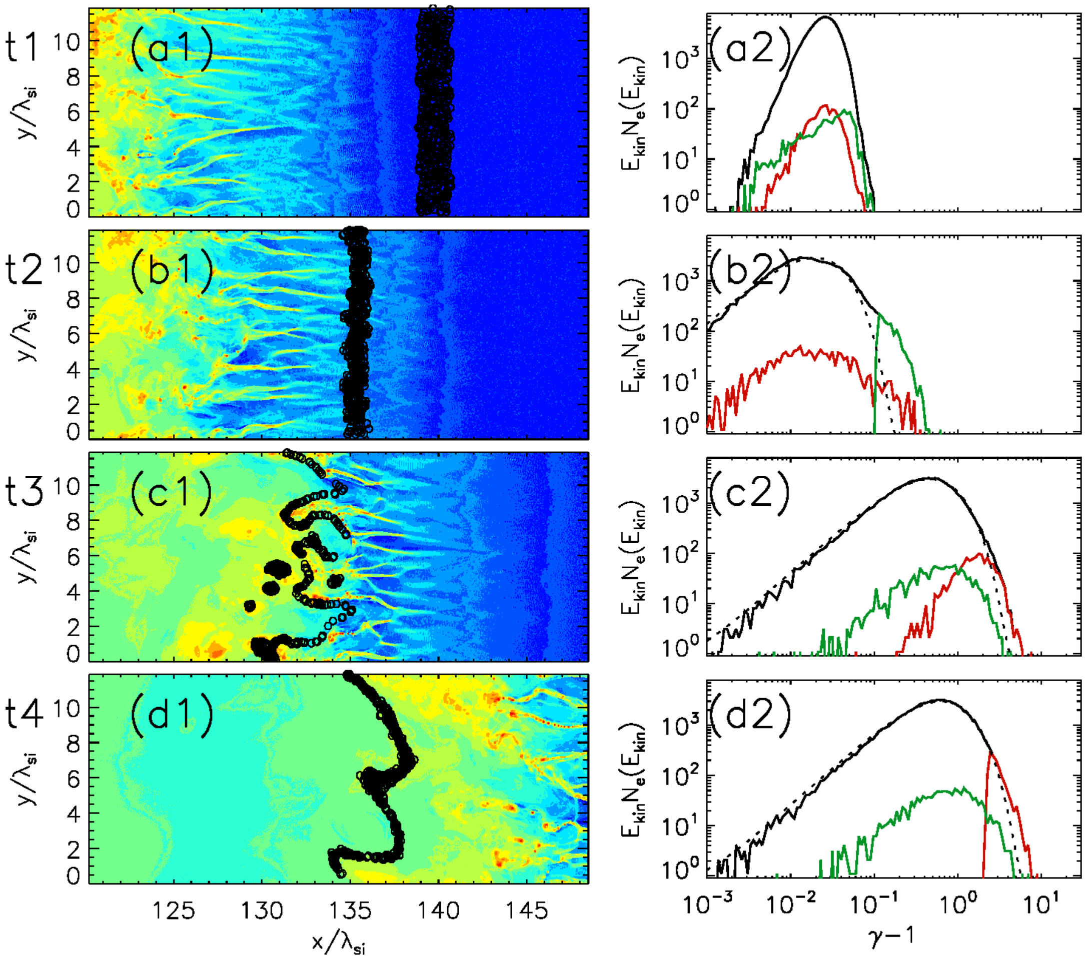

Figure 1: *Spectral evolution of a sample of electrons passing through the shock. Black lines in panels (a2)-(c2) correspond to all traced electrons, green lines indicate electrons energized by SSA in the shock foot, and red lines correspond to electrons that have high energy in the downstream region. The dashed lines represent fits of a Maxwellian.*

the shock transition and the overall shock structure?

- How does the production rate of energetic electrons depend on the shock velocity?
- What is the efficiency of electron acceleration in regions with magnetic reconnection? Do we observe the same number of magnetic reconnection sites as for shocks with high velocity? Are the properties of reconnection sites the same?
- How much of the initial kinetic energy of ion is channeled to magnetic field?
- How do the electron and ion temperatures evolve in the shock transition, i.e. what is the ratio of heating and pre-acceleration at the shock? How does the electron-to-ion temperature ratio depend on the shock velocity?

More Information

[1] Matsumoto, Y., Amano, T., Kato, T. N., et al., 2017, PRL 119, 105101 `doi:10.1103/PhysRevLett.119.105101`

[2] Masters, A., Sulaiman, A. H., Sergis, N., et al. 2016, ApJ, 826, 48. `doi:10.3847/0004-637X/826/1/48`

[3] Bohdan, A., Niemiec, J., Pohl, M., et al. 2019, ApJ, 878, 5 `doi:10.3847/1538-4357/ab1b6d`

[4] Matsumoto, Y., Amano, T., Kato, T. N., et al. 2015, Science, 347, 974 `doi:10.1126/science.1260168`

[5] Bohdan, A., Niemiec, J., Kobzar, O., et al. 2017, ApJ, 847, 71 `doi:10.3847/1538-4357/aa872a`

[6] Bohdan, A., Niemiec, J., Pohl, M., et al. 2019, ApJ in press, arXiv:1909.05294

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