Electrons on the loose

Electron acceleration at collisionless shocks in nonthermal sources of radiation

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Kurzgefasst

We use Particle-in-cell simulations to investigate the kinetic interactions and the pre-acceleration of electrons at shocks in supernova remnants (SNR). More specifically, we simulate particle pre-acceleration at nonrelativistic shocks, concentrating on oblique shocks, at which particles can be reflected and populate a large region ahead of the thermal shock, known as the foreshock. We know from earlier simulations that a number of processes involving localized turbulence in the shock transition can in principle provide electron acceleration in these systems. Equipped with particle-tracking capability, we will explore the interplay and efficacy of these processes under variation of simulation parameters such as the electron-ion mass ratio or the orientation of the large-scale magnetic field. These studies are scientifically interesting because the unsolved problem of injection into the population of nonthermal particles is the most critical ingredient in the theory of particle acceleration at shocks, as 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. Nonrelativistic collisionless shocks have been thought for decades to be efficient particle accelerators, and indeed the observation of nonthermal X rays or high-energy gamma rays from shell-type supernova remnants (SNR) demonstrate the presence of freshly accelerated particles. Of particular interest are electrons, because they are far more radiative than ions, and so a large fraction of the observational evidence for efficient particle acceleration relates to them, albeit their carrying only about 1% of the energy in energetic particles in space. We conduct large particle-in-cell (PIC) simulations of collisionless shocks with a view to elucidating the processes that provide electron acceleration.

Energetic charged particles couple to their environment through electromagnetic turbulence that is in part self-produced. Fermi-type shock acceleration processes at collision shocks are presumably the explanation for the observed nonthermal radiation, as they predict particle spectra that are close to those observed. As the theory involves pre-existing mildly energetic particles, a means of pre-acceleration is required, in particular for electrons [1]. The nature of that pre-acceleration, and its connection to Fermi acceleration, remain an important open question that we address with our simulations.

A critical parameter of collisionless shocks is the orientation of the large-scale magnetic field with respect to the shock surface. In a perpendicular shock the magnetic field lies in the shock plane, and we know that for a considerable range of non-planar orientations the shock are structured in a very similar way as perpendicular shocks. A 3D simulation of such a quasiperpendicular shock has been performed by [2] who demonstrated a substantial acceleration of electrons in the shock region. On account of the extremely high computational expense of 3D simulations the exact influence of the shock obliquity on the individual electron-acceleration processes is still unclear, be it shock-surfing acceleration, magnetic reconnection, shock-drift acceleration, or acceleration by a second-order Fermi process. We were able to study the parameter scaling of these processes in 2D simulations of strictly perpendicular shocks [3].

The shock itself and also the acceleration of particles are shaped by the reflection of particles off the shock. At so-called superluminal shocks the angle between the large-scale magnetic field and the direction of motion of the shock surface, θ_{Bn}, is so large that the charged particles streaming along the magnetic field cannot move far ahead of the shock. In contrast, oblique non-relativistic shocks can be subluminal, meaning a particle moving with close to the speed of light can make it to the far-upstream region where it can drive plasma turbulence that would scatter similar particles.

In the last year we found that such a large foreshock region filled with hot particles is actually established, and that it is the electron population that is most efficiently reflected to the far upstream. Figure 1 displays the structure of such a shock as it appears in the simulation. For the given shock obliquity angle, θ_{Bn}, particles need to be pre-accelerated at the shock upon first contact, otherwise they could not stream to the far-upstream region. A central role in the early energization is played by Buneman waves excited in the shock foot through interaction of reflected ions with cold upstream electrons (At $x \approx (237-240)\lambda_{si}$ in Fig.1 b)). Electrons can be trapped by these electrostatic waves and accelerated by the motional electric field. The efficiency of this so-called shock-surfing acceleration is determined by the Alfvénic Mach number of the shock [4]

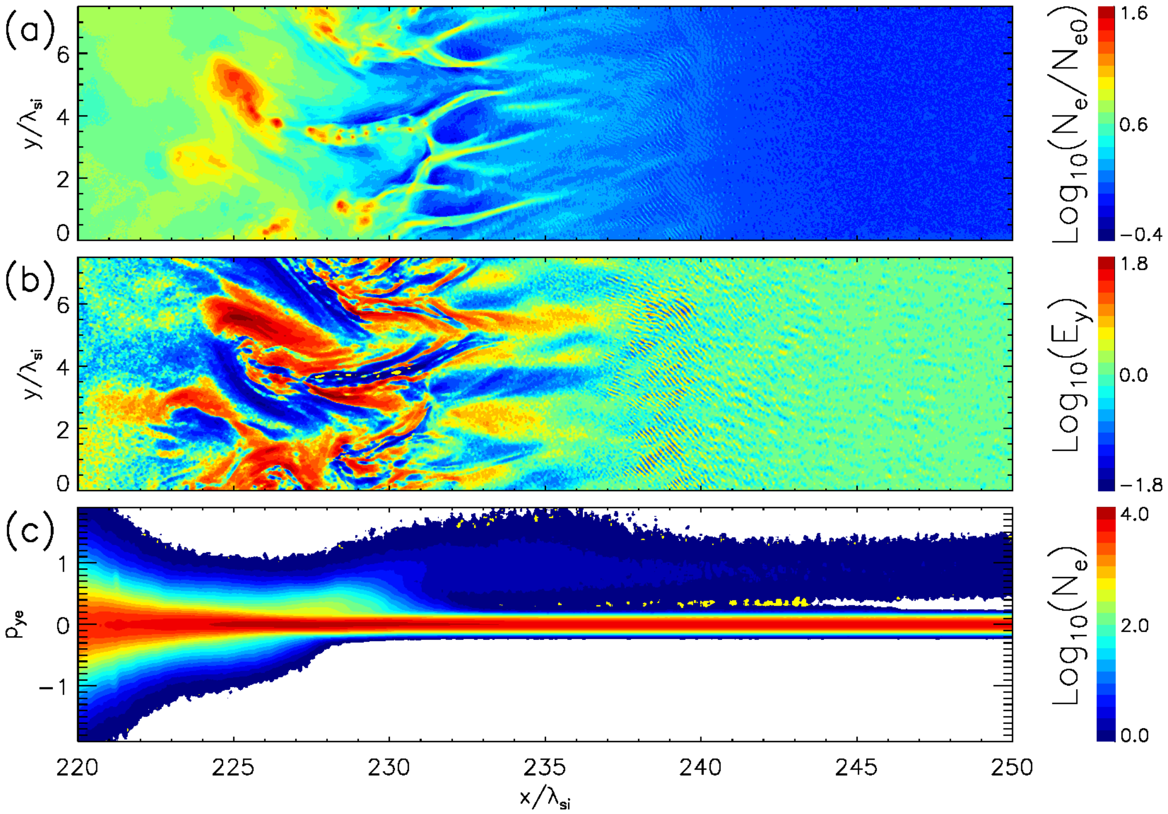

Abbildung 1: *Structure of an oblique shock with $\theta_{Bn} = 63^o$. Panel (a): distribution of the normalized electron density; panel (b): y-component of electric field; panel (c): the phase-space distribution of the y-component of electron momentum.*

and the magnetic-field configuration in 2D runs [3]. The accelerated electrons are fast enough to escape the shock region [5] and drive a bump-on-tail instability in the shock foot that is visible in the electric-field panel of Fig. 1 around $x \approx (240 - 250)\lambda_{si}$.

We now want to explore the parameter scaling for the characteristics of the shocks in 2D simulations, that results from the electron reflection, and for the acceleration processes and final spectrum of energetic electrons. We expect to address the following questions:

- For which magnetic-field orientations relative to the shock normal electrons can be reflected far upstream and produce additional instabilities. How much time do they need to turn back and undergo additional acceleration?
- Does the shock drift acceleration operate in 2D simulations with oblique magnetic-field orientations relative to the shock normal as in the 3D case [2]?
- What is the impact of shock corrugation on injection into shock drift acceleration, and how does it scale with the magnetic-field orientation?
- What is effect of scattering off moving magnetic turbulence?
- What is the efficiency of electron acceleration at magnetic-reconnection structures?
- 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?
- Is there a variation of behaviour depending on the choice of electron/ion mass ratio in the simulation?

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Weitere Informationen

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