Not in a calm sea

Microphysics of collisionless shocks in a turbulent medium

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Kurzgefasst

- We investigate electron pre-acceleration at shocks with realistic shock velocities for supernova remnants (SNRs), where $v_{\rm sh} \approx 10,000\ {\rm km/s}$.
- We have established that shock-reflected particles can drive electrostatic and electromagnetic waves at the shock foot or the foreshock that affect electron dynamics and modify the shocks.
- Whereas all of our earlier studies assumed a homogenous upstream medium of the shock, pre-existing fluctuations are particulary important for, and often decisively shape, the acceleration of particles at quasi-perpendicular shocks.
- It is therefore important to confront our earlier simulations of electron acceleration at shocks in homogeneous media with new studies in which the upstream medium carries turbulent fluctuations.

Where and how cosmic rays are produced in the Galaxy is an important question in modern physics. Observations of nonthermal X-rays and high-energy gamma-rays from shell-type supernova remnants (SNR) imply that nonrelativistic collisionless shocks can efficiently accelerate charged particles. Fermi-type shock acceleration presumably is the explanation for the observed nonthermal radiation, but it involves pre-existing mildly energetic particles, and so a means of pre-acceleration is required, especially for electrons [2]. The nature of that pre-acceleration, and its connection to Fermi acceleration, remain important open questions that we address with our simulations.

Shocks in space are collisionless, meaning that the internal energy distribution is shaped by scattering off electromagnetic turbulence. The shock transition is not sharp but extended and partially shaped by electron dynamics [4]. A number of processes have been proposed for electron pre-acceleration that rely on local structures within the shock.

We use PIC simulations that follow the individual trajectories of charged particles and solve Maxwell's equation for the evolution of the electromagnetic fields on a spatial grid. Previously we performed PIC simulations of non-relativistic plasma collisions with perpendicular or oblique large-scale magnetic field.

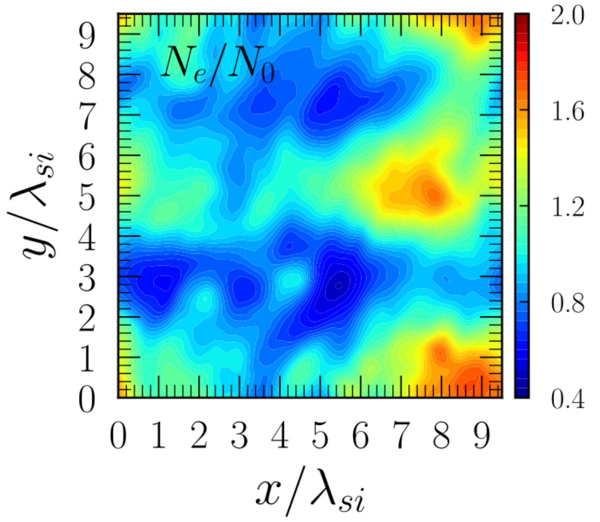

***Abbildung 1:** Normalized electron density map showing well-developed structure of the compressible turbulence.*

All of our earlier studies assumed a homogenous upstream medium of the shock, and so all of the upstream turbulence had to be driven by shock-reflected particles. It is known that this is not a good description of energetic particles at interplanetary shocks. In fact, pre-existing fluctuations are particulary important for, and often decisively shape, the acceleration of particles at quasi-perpendicular shocks [3]. Pre-existing upstream turbulence significantly enhances the trapping near the shock of low-energy charged particles, including near the thermal energy of the incident plasma, even when the shock propagates normal to the average magnetic field. Pre-existing turbulence, always present in space plasmas, is a means for the efficient acceleration of low-energy particles and overcoming the well known injection problem at shocks [1,7]. It is therefore important to confront our earlier simulations of electron acceleration at shocks in homogeneous media with new studies in which the upstream medium carries turbulent fluctuations.

In our shock simulations we continuously add upstream plasma. If that plasma is supposed to carry pre-existing fluctuations, then one needs to separately establish that turbulence. We model turbulence by the evolution of initial perturbations that are represented by the superposition of waves. The first studies have been performed for longitudinal compressive velocity fluctuations. The initial velocity of each particle consists of the bulk component, which describes the large-scale plasma flow, a random thermal component, and the medium-scale velocity

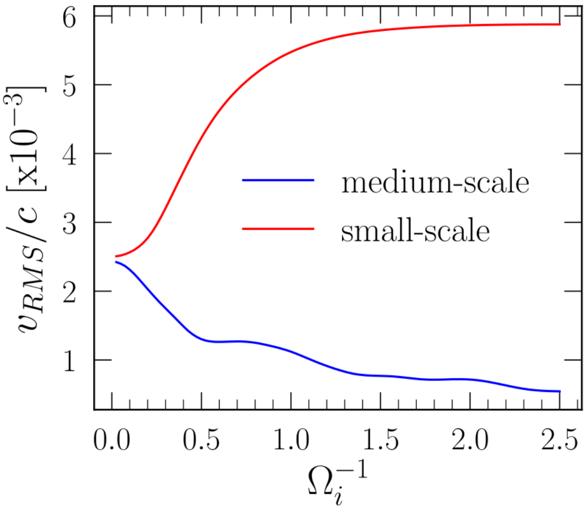

Abbildung 2: *Time evolution of the velocity fluctuation amplitude on medium scale and on microscopic (thermal) scale.*

fluctuations.

The method described above efficiently generates compression-dominated turbulence. Figure 1 presents a well-developed density structure. After swinging in, the evolved fluctuations are sufficiently long-lived to be used in a shock simulation. Figure 2 also shows the level of ion-velocity fluctuations. The medium-scale bulk velocity varies in association with the density fluctuations. As these fluctuations decay, their energy is turned into heat, i.e random motion of the particles relative to the local bulk flow. This is an essential feature of every kind of turbulence.

A separate type of turbulence involves transverse plasma waves that are not necessarily compressive. The most prominent mode is an Alfvén wave, and the Alfvénic nature of turbulence has long been demonstrated in the solar wind, where measurements are possible [6]. It is quite conceivable that similar modes also permeate the circumstellar medium around SNRs. Alfvénic turbulence can be established in PIC simulations with a so-called Langevin antenna [5]. We will use this method to preproduce sections of plasma with Alfvénic turbulence that can be matched to other plasma slabs and added as upstream plasma in a shock simulation in the same manner as is done for compressive turbulence

Using the new setup with turbulent plasma, we shall repeat a selection of the earlier simulations of perpendicular shocks in homogeneous media. The density and velocity fluctuations in the upstream medium will change the local hydrodynamic response at the shock. We are going to explore to what degree that modifies the evolution of the shock, as well as the efficiency of electron pre-acceleration. Our main goal is to understand how our physical understanding of electron acceleration at nonrelativistic shocks is shaped by the competition and interplay of pre-existing turbulence and that driven by reflected particles in the shock foot or the foreshock. We address the following points:

- How do pre-existing turbulence modes affect the upstream electron dynamics? What are possible consequences for scattered electrons?
- Are there modifications in the driving of electrostatic and electromagnetic plasma waves and instabilities by the shock-reflected particles at oblique and perpendicular shocks?
- What properties of the electron distribution function (density, velocity, temperature, reflection rate, etc.) are changed, if any, by the impact of pre-existing turbulence on the shock? How would that depend on the Mach numbers?
- Will the pre-existing turbulence enhance the efficiency of electrons pre-acceleration?

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