Riders in the storm

Microphysics of collisionless shocks in a turbulent medium

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In Short

- Shocks in space are collisionless, meaning that the internal energy distribution is shaped by collective wave–particle interactions with electromagnetic turbulence of various scales. The shock transition layer will be filled with intense and nonlinear plasma waves that are partially shaped by electron dynamics and heat the plasma coming into the shock.
- We conduct large particle-in-cell (PIC) simulations of collisionless shocks with a view to elucidate the processes that provide electron acceleration at shocks with pre-existing turbulence in the upstream medium.
- Compressive turbulence seems to make electron acceleration at shocks more efficient. We will follow individual particles of interest with very high time resolution to infer which specific process is rendered more effective. Our simulations permit finding correlations between energy gain and the interaction with specific turbulence structures.
- Electromagnetic turbulence can be established with a higher amplitude than is possible for compressive turbulence, on account of weaker heating.
- Oblique shocks are affected by such electromagnetic fluctuations, as the region filled with reflected electrons ahead of the shock becomes shorter and hotter.
- Exploring the impact of that for plasma wave instabilities in the foreshock, the structure of the shock itself, and for electrion acceleration is the objective of new simulations in the coming year.

Collisionless shocks, which are mediated by particle-wave interactions instead of binary Coulomb collisions, are known to produce relativistic particles. Diffusive shock acceleration [1] provides the basic description of particle acceleration, but it does not take into account preexisting turbulence ahead of the shock. Turbulence is a common ingredient in various astrophysical environments, but how it affects particle acceleration at collisionless shocks is still poorly understood.

Particle-in-cell (PIC) simulations describe collisionless plasmas from first principles, and are therefore an excellent tool for investigating nonlinear processes at electron kinetic scales. They are widely used to study particle acceleration in astrophysical plasmas [5]. Previous fully kinetic shock simulations assumed a homogeneous upstream medium, so that all turbulence in this region was driven by shock-reflected particles. The influence of initial inhomogeneities ahead of the shock using PIC simulations has been studied at relativistic shocks propagating in pair plasmas [2,3]. We focus on nonrelativistic high-Mach-number shocks, with the sonic and Alfvénic Mach numbers $M_{\rm s}, M_{\rm A} \gtrsim 20$, that are observed in supernova remnants. In our previous work, we performed for the first time PIC simulations of nonrelativistic shocks with a turbulent upstream medium [4]. Our novel method of continuous turbulent plasma injection allows to perform simulations for previously unattainable spatial and temporal scales. At perpendicular shocks that propagate in preexisting compressive turbulence, the behavior of electrons is not significantly different in comparison to the homogeneous upstream medium. Here, we continue our studies of the shock-turbulence interplay in the nonrelativistic high-Mach-number regime, with a focus on oblique shocks.

Generally, shock-reflected ions determine the structure of supercritical shocks. However, at oblique shocks, a significant portion of the incoming electrons can also be reflected by the shock. These particles travel towards the upstream region and form the electron foreshock, resulting in a complex shock structure. In general, the electron foreshock region can be subdivided into the inner foreshock region, dominated by the electromagnetic oblique whistler instability, and the outer foreshock, where the electron-acoustic instability drives electrostatic fluctuations. Both instabilities are driven by the relative drift between the reflected electrons and the background electrons.

Figure 1 compares the results of simulations with an initially turbulent (run T) and a homogeneous (run H) upstream medium. Our focus is on the influence of preexisting turbulence on the global shock structure, the shock velocity, magnetic field amplification, and the properties of the nonlinear structures developed by the oblique whistler instability. The panels cover only the inner part of the electron foreshock, where the whistler waves are present. These waves are stronger closer to the shock front because the energy density of the reflected electrons decreases

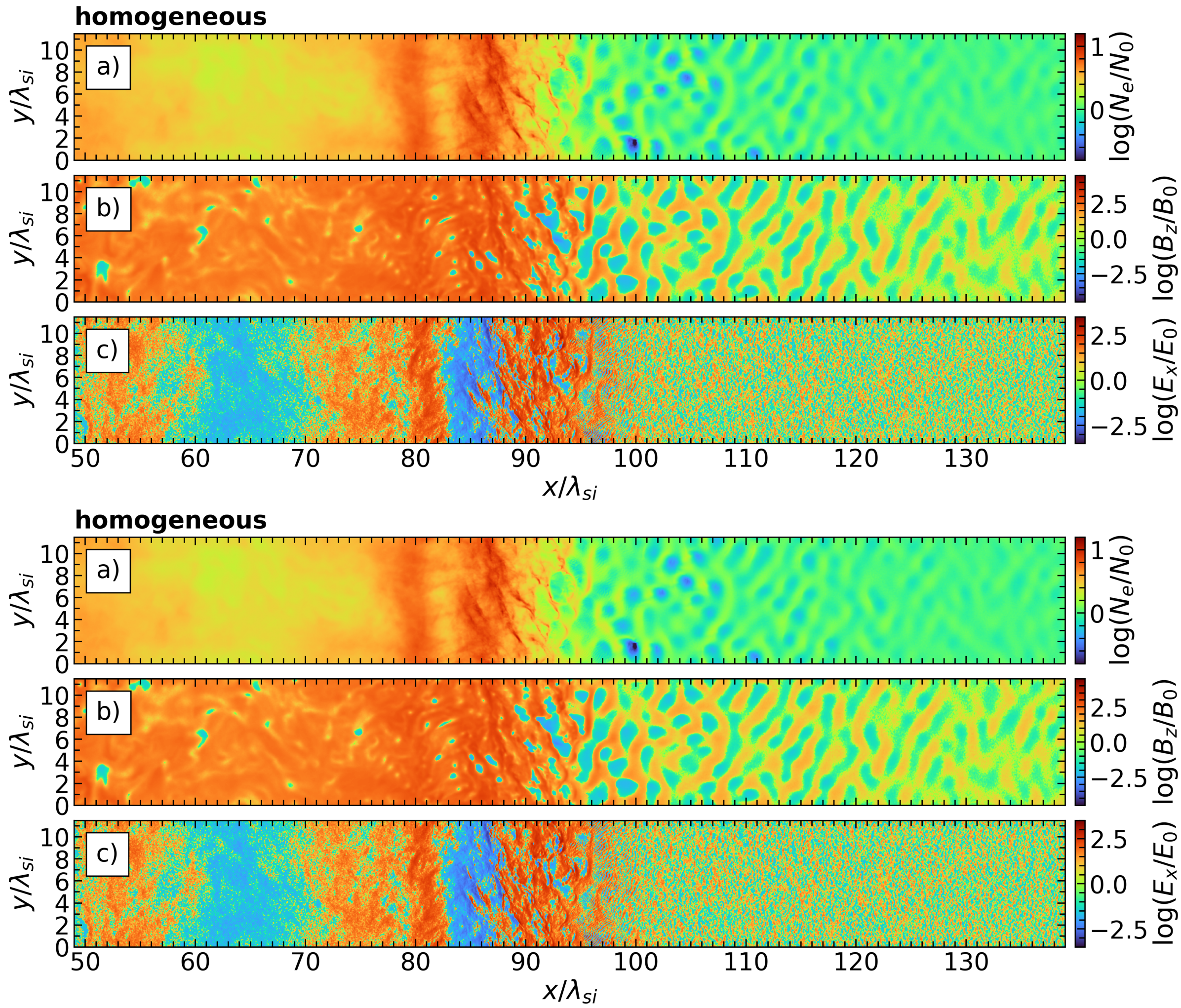

Figure 1: *The spatial distribution of electron density (panels a and d), a component of the magnetic field (b and e), and a component of the electric field (c and f). The top three panels are for a homogeneous environment, the bottom three for a turbulent medium. The shock is located at* $x \approx 90\,\lambda_{\rm si}$ *and moves to the right.*

with distance from the shock. This is best seen in panel (a), since for run T the preexisting fluctuations are more eye-catching that the whistler modes.

Previous work considered compressive turbulence, meaning primarily fluctuations in the plasma density and the bulk velocity. We shall now consider Alfvénic turbulence, in which most of the fluctuations are carried by the electromagnetic fields.

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More Information

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Project Partners

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