Shocks in stormy waters

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 need for the dissipation at the shock indicates that the collisionless 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. The parameters are chosen to be realistic for supernova remnants.
- Our main goal is to understand how 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 at the foreshock.

Where and how the energetic charged particles known as 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. The data indicate the efficient acceleration of electrons, as they are far more radiatively efficient than ions.

Cosmic objects such as the remnants of supernova explosions are a few light-years in size. Their structure and evolution are shaped by non-thermal particles whose acceleration and transport is governed by processes that operate on scales down to a thousand km, or a few light-milliseconds, ten orders of magnitude smaller than the object that is influenced. There is no single technique that permits a simultaneous study of the processes on all scales, and specific methods are employed for smaller ranges of scales. In space particles interact collectively, and the medium is referred to as a plasma, as opposed to an ionized gas. Systematic perturbations in the position and movement of charged particles lead to oscillating electromagnetic fields that can be understood as superposition of waves. The electromagnetic waves interact with charged particles and thus modify their energy distribution.

The structure of the acceleration regions, electron-ion energy equilibration, preacceleration of particles at shocks to permit further energization by diffusive shock acceleration, require knowledge of the distribution function of particles besides the structure and dynamic of electromagnetic fields, and hence a kinetic description is desirable. Particle-in-cell simulations offer an appropriate, if computationally expensive method of essentially conducting numerical experiments that explore kinetic phenomena in collisionless plasma [5].

Previously we performed PIC simulations of nonrelativistic shocks with perpendicular or oblique large-scale magnetic field that propagate through a homogeneous medium. That is a significant simplification, because space plasma is known to be turbulent on all scales. In the last year we performed simulations of perpendicular shocks in a turbulent medium. The turbulence was imposed by fluctuations in the streaming velocity of the plasma that evolved into fluctuations of the plasma density and the magnetic field as well. Step by step, blocks of the so-derived turbulent plasma were appended to the medium ahead of the shock in the simulation. In Figure [1] we see maps of the ion density and the electron density in the vicinity of the shock. The shock moves to the right and is marked by filamentary structures of very high density and is located around $x/\lambda_{\rm si} = 45$. The structure in the right (blue) part of the panels indicates the density fluctuations in the medium that the shock runs into. The reddish filaments in the shock are caused by the so-called Weibel instability that also produces filamentary structure in the magnetic field. Ions will not simply pass through the shock, but perform one orbit around the magnetic-field lines, meaning after a half-circle the move opposite to the incoming ions. That situation drives the Weibel instability. It is through this and other plasma instabilities that nature finds a way to compress, decelerate, and heat the plasma, all of which a shock is known to do. But does it also accelerate some electrons to very high energy? And does pre-existing turbulence facilitate that?

What the earlier simulations tells us is that turbulence makes the Weibel modes stronger, but there is little impact on the energy distribution of electrons behind the shock, at least for perpendicular shocks. Now, what of oblique shocks, meaning shocks that propagate obliquely to a large-scale magnetic field?

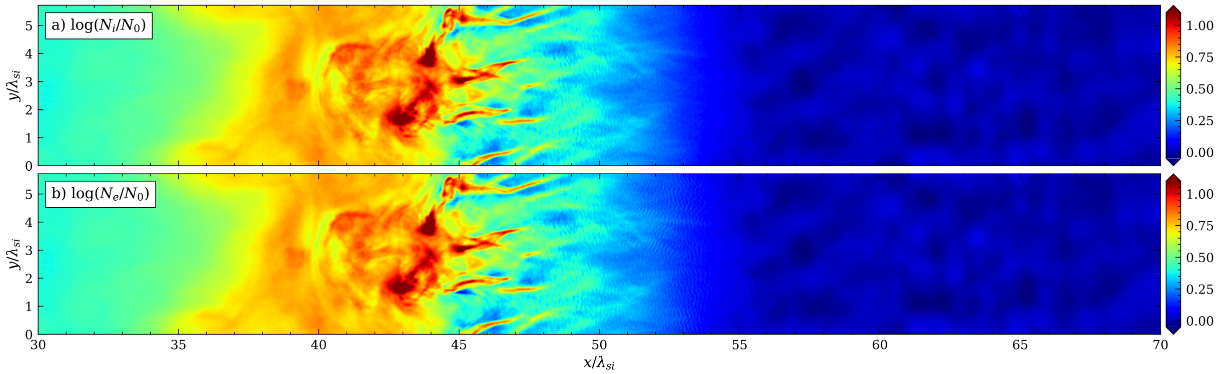

Figure 1: *The density of ions (top panel) and electrons (bottom panel) at a perpendicular collisionless shock.*

At oblique shocks energetic particles may escape back to the region ahead of the shock. Their trajectories are tied to the magnetic field lines, and they may outrun the shock if sufficient energization has taken place. The extended region containing the reflected particles is known as the foreshock where the energy transported upstream by these reflected particles can excite instabilities and generate turbulence which can in turn influence, and possibly pre-accelerate upstream electrons [2–4]. All upstream electrons that eventually encounter the shock must first pass through the foreshock, thus a physical description of these regions is essential.

We will embark on simulations of oblique shocks with pre-existing turbulence. Our main goal is to understand how 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 at the foreshock [1]. 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/instabilities by the shock-reflected particles?
- What properties of the electrons (density, velocity, temperature, reflection rate, etc.) are changed, if any, by the impact of pre-existing turbulence on the shock?
- Will the pre-existing turbulence enhance the efficiency of electron heating and their pre-acceleration?

The electron spectra in the downstream region provide information on the efficiency of electron heating, relevant for understanding electron-ion-equilibration and the interpretation of X-ray line spectra observed from young SNR. What the spectra do not tell, and our particle tracing does provide, is why and how the electrons attained their energy. We select a subset of electrons, for example those with the highest energy in the downstream region, and can trace which structure they encountered in the shock transition and when or where exactly they were energized. We consider the upstream region as well, where the interaction of reflected particles with the incoming flow provide further acceleration.

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More Information

[1] Amano, T., Matsumoto, Y., Bohdan, A., et al. 2022, Reviews of Modern Plasma Physics, 6, 29. doi:10.1007/s41614-022-00093-1

[2] Bohdan, A., Weidl, M. S., Morris, P. J., et al. 2022, Physics of Plasmas, 29, 052301. doi: 10.1063/5.0084544

[3] Morris, P. J., Bohdan, A., Weidl, M. S., et al. 2022, ApJ, 931, 129. doi:10.3847/1538-4357/ac69c7

[4] Morris, P. J., Bohdan, A., Weidl, M. S., et al. 2023, arXiv:2301.00872

[5] Pohl, M., Hoshino, M., & Niemiec, J. 2020, Prog. Part. Nucl. Phys., 111, 103751. doi: 10.1016/j.ppnp.2019.103751

Project Partners

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