Shocking news about shocks

Collisionless shocks and turbulence in nonthermal sources of radiation

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In Short

- We use Particle-in-cell simulations to appropriately describe the kinetic interaction between turbulence and energetic particles at SNR. More specifically, we simulate particle pre-acceleration at nonrelativistic shocks, for which we use a new, clean setup that avoids electromagnetic transients. Clean simulations are particularly important in studies of suprathermal spectral tails, because the artificial electric fields lead to fake acceleration. Simulations performed in 2014 and 2015 suggest a dependence of the behavior in 2D3V runs on the orientation of the large-scale magnetic field with respect to the simulation plane. This is an computational effect that highlights the role of different processes whose real effectiveness is unclear. Equipped with particle-tracking capability, we will explore through a number of 2-D and 3-D simulations why particle acceleration and reconnection appear only for specific configurations and which of them persists in 3D. These studies are scientifically interesting because the unsolved problem of injection 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.

We use PIC simulations that follow the individual trajectories of quasi-particles and solve Maxwell's equation for the electromagnetic fields on a spatial grid. Each quasi-particle represents many real electrons or ions, so it has the same q/m, i.e. it reacts similarly to electromagnetic fields, but its charge q and mass m are much larger than those of real electrons and ions. The fundamental plasma dynamics can then be simulated with parameters not identical to those in the real plasma, but sufficiently similar to them, so one can capture the relevant physics.

Shell-type supernova remnants (SNR) are ideal laboratories for the study of particle acceleration at nonrelativistic collisionless shocks. We explore the micro-physics governing the coupling of energetic charged particles, amplified turbulent magnetic field, and colliding plasma flows, that determines how suprathermal particles can be injected into Fermi-type shock acceleration processes. After studying parallel [1] and strictly perpendicular shocks, for which the large-scale magnetic field is oriented parallel and perpendicular to the flow direction, respectively, in the last year we simulated oblique shocks to investigate the dependence of injection on the magnetic-field orientation.

During the year it became clear that a variation in electron acceleration efficiency with magnetic-field orientation relative to the shock normal was clearly present, but not stronger than that associated with the field orientation with respect to the simulation plane. While the former can be physical and was the focus of our investigation, the latter is a computational effect. Dimensional constraints appear to enable or inhibit certain processes. The real effectiveness must be explored and understood, before we can be certain of the veracity of other simulations. Further simulations are required. Our 3-D code needs to be equipped with particle tracking, though, as that was found indispensible in deciphering where and how particle energization occurs. In

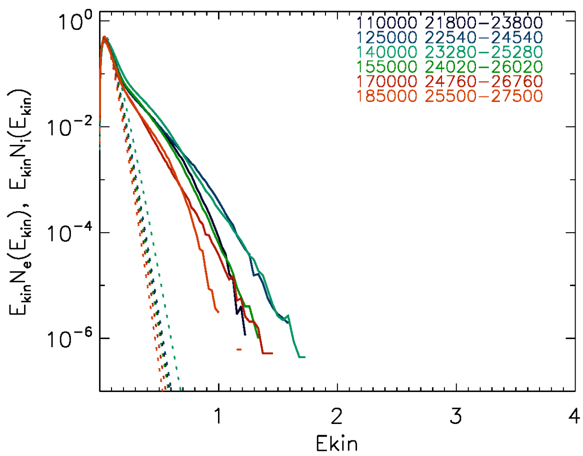

***Figure 1:** Kinetic-energy spectra in the local rest frame of electrons immediately downstream of the overshoot region of a perpendicular shock with large-scale magnetic field oriented strictly out of the simulation plane. The spectra are normalized and expressed in simulation units, in which $m_e c^2 = 0.25$. For comparison, the dotted line indicates a Maxwellian. The color legend refers to the timestamp and the spatial window, for which the spectra were computed.*

the original study of a perpendicular shock we placed the large-scale magnetic field at a 45° angle to the simulation plane ($\theta_{\rm SP} = 45°$). We also measured particle spectra at a safe distance behind the shock to avoid distortions arising from anisotropy and localized structures at the shock overshoot. No significant acceleration was observed. For $\theta_{\rm SP} = 90°$, the electron acceleration reported in the literature [2] very close to the shock can in principle be reproduced, but appears to diminish as the simulation progresses. Figure 1 shows a time sequence of electron spectra in a wandering spatial window for simulation parameters similar to those of Matsumoto et al.; the decay of the high-energy tail at late times (red curves) is evident.

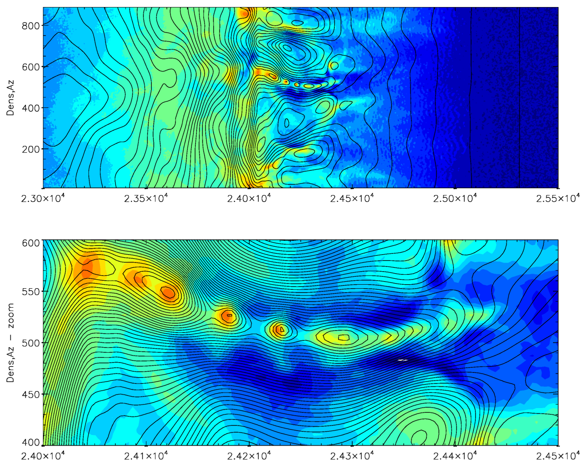

Figure 2: *Distribution of the out-of-plane component of the vector potential, A_z, near the shock front. The lower panel is a blow up of the region harboring magnetic islands, which are indicative of magnetic reconnection.*

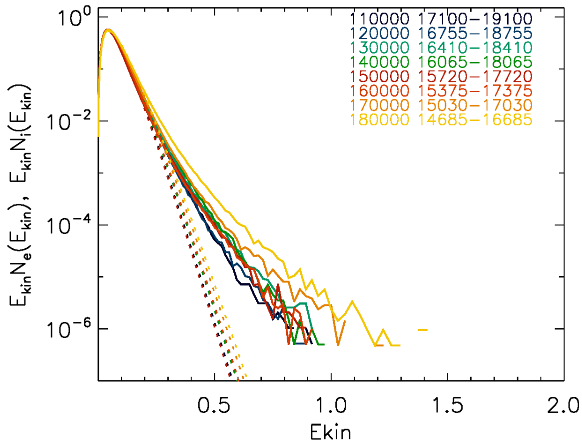

Figure 3: *Kinetic-energy spectra in the local rest frame of electrons immediately downstream of the overshoot region of a perpendicular shock. The left panel is for a large-scale magnetic field in the simulation plane, and the right panel for an orientation strictly out of the simulation plane. The angle between the magnetic field and the shock normal is the same. The spectra are normalized and expressed in simulation units, in which $m_e c^2 = 0.25$. For comparison, the dotted line indicates a Maxwellian. The color legend refers to the timestamp and the spatial window, for which the spectra were computed.*

If we place the large-scale magnetic field strictly in the simulation plane ($\theta_{\rm SP} = 0°$), we confirm the existence of magnetic islands resulting from magnetic reconnection [3] (See Figure 2) and leading to significant high-energy spectral tails as shown in Figure 3. We added particle tracing to our 2-D code and were able to show that efficient electron energization arises from linear acceleration in the out-of-plane electric field, E_z. As by definition the structures are infinitely extended in z-direction of a two-dimensional simulation, their role in a 3-D setting is unclear. The absence of reconnection signatures in simulation with out-of-plane magnetic field suggests that linear acceleration might be less efficient.

We will continue the PIC simulations of oblique and perpendicular magnetic-field configurations. All simulations shall involve particle tracking to investigate exactly where and how high-energy particle were accelerated. Now the emphasis is on understanding why particle acceleration, and certain processes such as reconnection, can be observed only for certain orientations of the large-scale magnetic field relative to the simulation plane. Ideally one would wish to only perform 3-D experiments, but that would limit us to low-resolution experiments that have their own deficiencies. Hence, a mixture of 2-D and 3-D runs is required.

Ours will not be the first PIC simulations of oblique shocks, but they will be particularly clean and devoid of transients, which is particularly beneficial when studying particle preacceleration. The expected impact is high. To our knowledge, the dependence of acceleration on the magnitude of the out-of-plane component of the magnetic field has not been systematically studied to date.

Our simulations are scientifically important because the unsolved problem of injection is the most critical ingredient in the theory of particle acceleration at shocks. 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. Hybrid simulations assuming a mass-less electron fluid may not be appropriate for shocks, because one neglects electron-scale effects that lead to scattering and heating.

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http://www-zeuthen.desy.de/~pohlmadq/

More Information

[1] Niemiec, J., Pohl, M., Bret, A., Wieland, V. 2012, ApJ 759, 73

[2] Matsumoto, Y., Amano, T., & Hoshino, M. 2012, ApJ, 755, 109

[3] Matsumoto, Y., Amano, T., Kato, T. N., & Hoshino, M. 2015, Science, 347, 974

Project Partners

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