Shocking facts about shocks

Collisionless shocks and turbulence in nonthermal sources of radiation

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In Short

- We perform simulations of particle pre-acceleration at nonrelativistic quasi-perpendicular 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. Strictly perpendicular shocks were studied in 2014, and now we are interested in oblique shocks. 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.
- The second subproject involves simulating non-resonant streaming instabilities operating in the cosmic-ray precursor, a.k.a. Bell's instability. In contrast to earlier studies, we will explicitely account for the spatial aspect of the problem: The cosmic-ray precursor continuously meets pristine plasma, implying the instability is pushed back toward its linear regime. Test simulations in 2014 have been successful, in particular concerning stability of the boundaries, and we are ready for production runs. These simulations are important because streaming instabilities of cosmic rays upstream of the shock can not only amplify the turbulent magnetic field, but will also impose heating and hydrodynamical turbulence in the quasithermal plasma, both of which have impact on the shock properties and the particle-acceleration processes.

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 want to 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 shocks [1], in the last year we simulated perpendicular shocks, which we want to extend to oblique shocks to investigate the dependence of injection on the magnetic-field orientation. We also want to study the modifications to the upstream plasma that are imposed by streaming instabilities of cosmic rays. In the last year we found setups that are numerically stable and permit studying non-resonant streaming instabilities both temporally and spatially.

Our simulations are scientifically important because the unsolved problem of injection is the most critical ingredient in the theory of particle acceleration at shocks, and because it determines the level of cosmic-ray feedback and hence the nonlinearity of the system.

Particle-in-cell (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. Only PIC simulations can track the impact of electron-scale fluctuations on the ion dynamics through self-consistent treatment of both electrons and ions.

We have performed 2D3V PIC simulations of non-relativistic plasma collisions with perpendicular large-scale magnetic field. Existing simulations of non-relativistic perpendicular shocks indicate a rapid shock formation and efficient pre-acceleration of particles. However, the simulation setup typically involves large localized gradients in either the electric or the magnetic field, that act as an artificial antenna during the start-up phase.

We devised a new setup using asymmetric plasma flows, i.e., utilizing the collision of plasma slabs of different density, leading to two different shocks and a contact discontinuity (CD) that is self-consistently modeled. Our newly developed setup leads to the creation of a very clean perpendicular shock without artificial transients that may limit the veracity of the simulation. The Alfvénic Mach numbers are too high to permit electron acceleration by Whistler waves, but they are more realistic than the low Mach numbers previously tested. Here, downstream of the shocks the electrons mostly show a thermal distribution or very soft spectral tails. On the other hand, we see clear evidence of pre-acceleration of ions in the form of significant spectral tails.

The aim of the second project is to study the nonlinear development and saturation processes of the nonresonant cosmic-ray-current-driven instability that may be responsible for magnetic-field amplification in the precursors of shocks in young SNRs. Earlier PIC simulations used computational boxes with periodic boundary conditions which do not account for mass conservation in decelerating flows. Our current study uses a more realistic setup with open boundaries that permit inflow of plasma on one side of the simulation box and outflow at the other end. In this way both the temporal and the spatial development of the instability can be investigated. Although the physical parameters are similar to those used in our earlier work, the numerical model is significantly modified to avoid numerical instabilities arising at open boundaries due to plasma injection or removal.

It is interesting to note that the tests have already revealed magnetic-field amplification as expected on the grounds of our earlier results [2]. The plasma beam in its nonlinear evolution stage slows down in bulk from its initial drift velocity of $0.4c$ to about $0.15c$. This limits further growth of the turbulence and leads to its saturation - the effect observed in studies with periodic numerical boxes and re-confirmed in a more realistic setting. The details of the CR backreaction and magnetic-field saturation processes will be studied with our large-scale numerical experiments.

Work program

We now want to extend the PIC simulations to oblique magnetic-field configurations. Again, we use our new setup that permits relatively clean simulations with perpendicular fields, and we add an additional flow-parallel magnetic-field component whose amplitude determines the angle between shock normal and large-scale magnetic field, θ_{Bn}. We will concentrate on 2D3V experiments, although we plan to perform 3D test experiments to verify that we are not missing significant aspects of the physics. It is most important to understand to what degree various features in the simulations depend on the electron-ion mass ratio, and therefore we plan many test simulations to infer the scaling with the assumed mass ratio.

Ours will not be the first PIC simulations of oblique shocks, but they will be particularly clean and devoid of transients and other systematic problems, which is particularly beneficial when studying particle preacceleration. The expected impact is high. A significant advantage of our method is that we model 2 shocks in parallel, because each of the colliding plasmas develops a shock. We can account for different densities and different magnetic-field strength and orientation in the two plasma slabs, something that is impossible with the reflecting-wall method. We shall also implement particle tracking to investigate exactly where and how high-energy particle were accelerated.

For our second project, non-resonant streaming instabilities operating throughout the cosmic-ray precursor of astrophysical shocks, also known as Bell's instabilty, earlier studies suggested that small-scale turbulence builds up that at peak intensity may reach a magnetic-field amplitude a factor of 10 or 20 higher than that of the homogeneous interstellar field. In the nonlinear phase, density fluctuations are imposed in, and bulk momentum is transferred to, the quasi-thermal plasma. All published simulations of this instability employed periodic boundary conditions and thus only solved for the temporal evolution of the instability.

The transfer of bulk momentum implies that neither the density nor the streaming velocity of CRs and background plasma can remain constant. To fully evaluate the nonlinear development of Bell's instability, simulations must be performed that simultaneously solve for both the temporal and the spatial aspect of the problem. Although our initial ideas did not pay off, during the current allocation period we have developed a setup that permits doing so. Now, we want to run large-scale simulations with this setup, whose parameters will be similar to those used in our period-boundary runs to permit a comparison with the earlier simulations. We can use a long, narrow simulation box that employs periodic boundary conditions in the transverse direction. because Bell's instabilitity is parallel to the cosmic-ray streaming.

WWW

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

More Information

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

[2] Stroman, T., Pohl, M., Niemiec, J. 2009, ApJ, 706, 38

Project Partners

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