Using PIC and PIC-MHD to investigate the occurrence of Fermi-1 acceleration in astrophysical shocks

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When charged particles cross an astrophysical shock, they can be accelerated through diffusive shock acceleration (DSA) aka Fermi-1 acceleration. This process involves repeated shock crossings, which occur if the particles are reflected toward the shock by the magnetic field. If the particles reach relativistic speeds, they become known as cosmic rays (CRs).

This process is difficult to simulate, because it involves both large scales (the size of the astrophysical shock, which is typically measured in pc) and microphysics (the interaction between individual particles and the magnetic field).

We investigate these interactions by combining both particle-in-cell (PIC) and combined PIC-MHD simulations. Using a PIC code, we simulate the formation of the shock, which allows us to determine which fraction of the total mass crossing the shock is reflected back upstream. Then, using the combined PIC-MHD method, we continue the simulation on a larger scale in order to follow the interaction between the reflected particles and the thermal gas to determine whether they can trigger the magnetic instabilities that will allow for the particles to be reflected back toward the shock. This would require that the energy of the particle reflected into the upstream plasma has to be about equal to or larger than the local magnetic field energy.

We find that for oblique shocks where the magnetic field makes a large angle with the direction of the flow, the percentage of particles that is reflected upstream is much smaller than for (quasi-)parallel shocks. As a result, the conditions for DSA in oblique shocks can only be satisfied if the upstream magnetic field is weak, with an Alfvénic Mach number of about 50 being required for shocks at 60 degrees. As the angles increases toward the quasi-perpendicular configuration, only extremely strong shocks, with Alfvénic Mach numbers in the hundreds, or even thousands would be able to trigger DSA.