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Numerical models of particle acceleration in low-Mach, high-beta galaxy cluster shocks

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Galaxy cluster shocks are characterized by a low sonic Mach number, combined with a high-Alfvénic Mach number[1,2,3,4]. Initial simulations[5] using a particle-in-cell (PIC) approach demonstrated that, depending on the exact Mach number, these shocks are capable of accelerating ions through the diffusive shock acceleration (DSA) process. By using a combined particle-in-cell and magnetohydrodynamics approach[6,7,8], it is possible to perform large-scale, long-term simulations that model these shocks and follow both the behavior of non-thermal particles and the thermal plasma over time in order to determine how the disturbance of the upstream gas influences the DSA process that creates cosmic rays by accelerating charged particles to relativistic speeds.

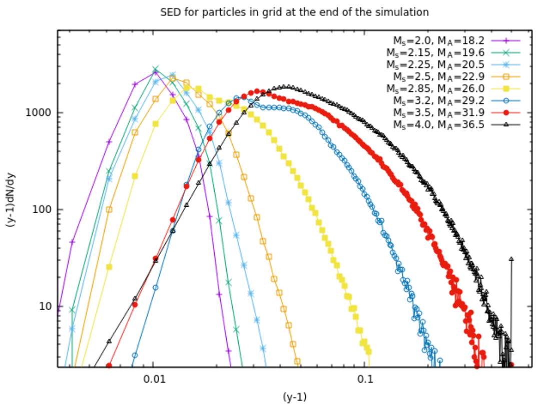

Fig 1 Particle SEDs for shocks between Mach 2 and Mach 4.

These simulations[9,10] allow us to determine whether or not such shocks add a significant contribution to the cosmic ray spectrum, either by accelerating particles as they pass through the shock, or re-accelerating existing high-energy particles that were produced by high-energy shocks in the nearby galaxies. The results are presented in Fig. 1, which shows the particle SEDs for simulations with sonic Mach numbers between 2 and 4. The result clearly demonstrates that at low sonic Mach numbers (<3), the acceleration process becomes increasingly inefficient, to the point where, at shocks lower than M~2.25, the shock loses the capacity to accelerate particles at all, which matches the earlier results obtained with a PIC code[5] as well as analytical estimates[11]. At higher sonic Mach numbers (3+) The shocks are capable of accelerating ions efficiently and will eventually propel them to relativistic speeds(1+ GeV)[12]. However, the presence of the non-thermal particles triggers large-scale instabilities in the upstream medium that change the shock conditions to the point where both the Mach number and the obliquity of the shock become variable in space and time as shown in Fig. 2. Such variations of the shock characteristics will inevitably change the rate at which supra-thermal particles are injected at the shock. Further research will be required to determine how this influences the acceleration process.

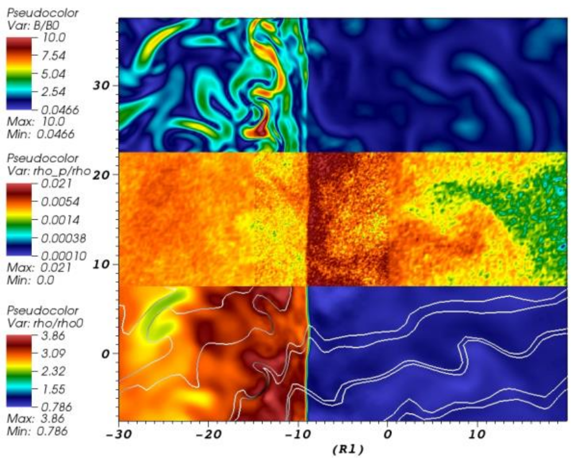

Fig. 2 Magnetic field strength, particle density and thermal gas density with magnetic field lines for a Mach 3.2 shock (Image Credit: van Marle MNRAS, tmp.1891V (2020).)

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