8th Asia-Pacific Conference on Plasma Physics, 3-8 Nov, 2024 at Malacca

Electron injection at galaxy cluster merger shocks

J. Niemiec[1], T. Amano[2], S. Boula[1], K. Fułat[3], O. Kobzar[4], M. Hoshino[2], S. Matsukiyo[5], M. Pohl[3,6]
[1] Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[2] Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan
[3] Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany
[4] Astronomical Observatory, Jagiellonian University, Kraków, Poland
[5] Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan
[6] DESY, Zeuthen, Germany
e-mail (speaker): jacek.niemiec@ifj.edu.pl

Particle pre-acceleration is an important unresolved problem in the diffusive shock acceleration (DSA) theory. This mechanism acting at merger shocks in galaxy clusters is thought to produce relativistic electrons that form the so-called radio relics detected through their radio and X-ray emissions. DSA at merger shocks may also generate high- and ultra-high-energy cosmic rays and associated gamma-ray emission and neutrinos. We report on our recent studies of electron pre-acceleration in low Mach number nonrelativistic quasi-perpendicular shocks that propagate in weakly magnetized and hot intracluster medium with high plasma beta. We use large-scale fully kinetic 2D particle-in-cell (PIC) and hybrid-kinetic 2D and 3D numerical simulations that cover very large spatial and temporal scales, allowing us to investigate the effects of the ion-scale rippling of the shock front and the multi-scale turbulence in the shock transition and downstream.

Based on our 2D PIC simulations for shocks with fiducial sonic Mach number of $M_s=3$, we discuss late-time turbulent structure of cluster shocks and show that electron injection to DSA can be provided through stochastic shock-drift acceleration (SSDA) process, in which electrons are confined in the shock transition by pitch-angle scattering off turbulence and gain energy from the motional electric field. Wide-energy non-thermal electron distributions are formed at the shock and the maximum energy of the electrons is sufficient for their injection into DSA in a range of shock conditions. We demonstrate a crucial role of multi-scale turbulence in the shock, including the shock rippling, in electron acceleration via SSDA.

With hybrid-kinetic simulations we investigate the ion kinetic physics that governs the shock structure and wave turbulence, which in turn influences particle acceleration processes. We demonstrate that the characteristics of ion-driven multi-scale magnetic turbulence in merger shocks align with the ion structures observed in fully-kinetic PIC simulations. In typical shocks with a sonic Mach number $M_s=3$, the magnetic structures and shock front density ripples develop and saturate at wavelengths reaching approximately four ion Larmor radii. Only shocks with $M_s>2.3$ exhibit ripple formation. In contrast, very weak shocks with $M_s<2.3$ generate weak turbulence downstream of the shock. We note a moderate dependence of magnetic field fluctuation strength on the quasi-perpendicular magnetic field obliquity. However, as the obliquity decreases, the shock front ripples exhibit longer wavelengths. Finally, we note that the steady-state structure of $M_s=3$ shocks in high-beta plasmas shows minimal differences between 2D and 3D simulations, with the turbulence near the shock front resembling a 2D-like structure even in 3D simulations.

This work has been supported by Narodowe Centrum Nauki through research projects no. 2019/33/B/ST9/02569 (S.B. and J.N.) and no. 2016/22/E/ST9/00061 (O.K.). We gratefully acknowledge Polish high-performance computing infrastructure PLGrid (HPC Center: ACK Cyfronet AGH) for providing computer facilities and support within computational grant no. PLG/2023/016861. This research was supported by the International Space Science Institute (ISSI) in Bern, through ISSI International Team project #520 (Energy Partition across Collisionless Shocks).

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