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Particle acceleration at weak shocks in high beta ICM plasmas

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Weak shocks with low sonic Mach numbers are induced by mergers and/or supersonic flow motions in the hot tenuous intracluster medium (ICM) of galaxy clusters. High energy cosmic ray (CR) protons are expected to be accelerated at *quasi-parallel* shocks via diffusive shock acceleration (DSA)[1], whereas CR electrons are expected to be accelerated preferentially at *quasi-perpendicular* shocks[2]. One of the key elements in determining the DSA efficiency is the so-called injection process, which energizes thermal particle to supra-thermal energies sufficient to diffuse across the shock transition. Reflection of incoming particles, and ensuing self-excitation of MHD/plasma waves and scattering of backstreaming particles back to the shock by those upstream waves play important roles in the particle injection to DSA. Pre-accelerated particles can participate in the Fermi-I process and be accelerated to relativistic energies.

Using 1D and 2D particle-in-cell (PIC) simulations, we studied the proton injection and early acceleration at weak shocks ($M_s \approx 2.0 - 3.2$) in $\beta \sim 100$ ICM plasma[3]. We found that the protons are reflected efficiently by the overshoot in the shock electric potential only at supercritical quasi-parallel shocks with the sonic Mach number $M_s \geq 2.3$, and that back-streaming protons self-excite upstream waves via both resonant and non-resonant streaming instabilities. Fig. 1 demonstrates the differences between *subcritcal* and *supercritical* shocks. In the case of a $M_s \approx 3.2$ shock, the proton energy spectrum develops a power-lar supra-thermal tail, which is consistent with the DSA prediction. Since a substantial fraction of ICM shocks are subcritical, the CR proton production and the ensuing gamma-ray emission due to the inelastic *p-p* collisions should be less efficient than estimated in the previous studies without the consideration of the shock criticality. The predicted gamma-ray fluxes from simulated galaxy clusters turn out to lie below the observational upper limits of the Fermi LAT telescope[4].

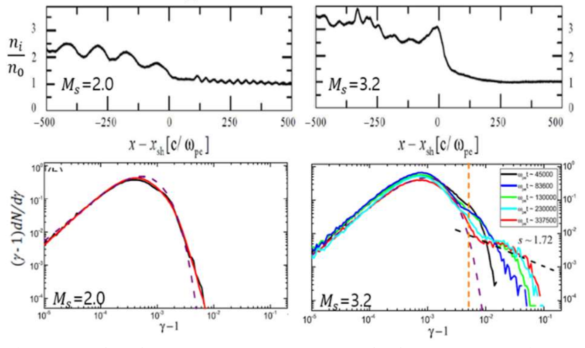

Fig. 1. Shock structures (top) and downstream ion energy spectra (bottom) at weak quasi-parallel shocks with $M_s \approx 2.0$ (left) and 3.2 (right) in β=100 plasma[3].

We showed through 2D PIC simulations that, in contrast, electrons are refelcted by magnetic mirror and gain energies via shock drift acceleration (SDA) at supercritical quasi-perpendiculs shocks with $M_s \geq 2.3$[5]. As shown in Fig. 2, at supercritical shocks, the shock structure develops overshoot-undershoot features and a sufficient amount of incoming electrons are reflected and induce oblique non-propagating waves via the electron firehose instability (EFI)[6]. However, such pre-acceleration is saturated well below the injection momentum due to lack of waves longer than $\sim 20c/\omega_{pe}$. We conclude that a much larger simulation box in 2D is necessary in order to include the effects of the microinstabilities on ion gyro scales, such as Alfven ion cyclrotron instability.

This study also implies that the re-acceleration of pre-existing fossil electrons, deposited in the ICM by radio galaxies, may play significant roles in elucidating the origin of radio relics detected in the outskirts of galaxy clusters. Since the shocks associated with some of observed radio relics are inferred to have low Mach numbers below 2.3, further investigation is necessary to examine whether subcritical shocks can re-accelerate fossil electrons in the ICM.

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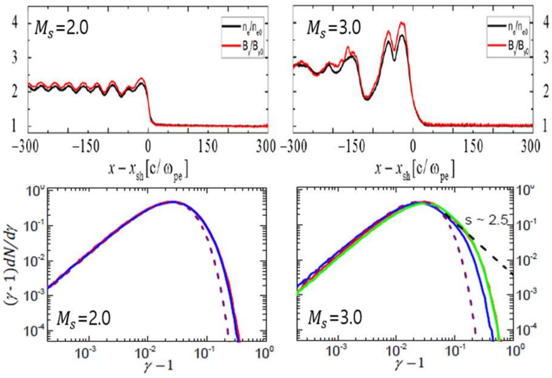

Fig. 2. Shock structures (top) and upstream electron energy spectra (bottom) at weak quasi-perpendicular shocks with $M_s \approx 2.0$ (left) and 3.0 (right) in β=100 plasma[5].

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