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Particle acceleration by relativistic shocks induced by density fluctuations

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Cosmic rays (CRs) are high-energy charged particles ($10^9 \sim 10^{20}$ eV) originating from the universe, yet their exact sources remain unknown. CRs are categorized into Galactic CRs (lower energy,
$lesssim 10^{15}$ eV) and extragalactic CRs (highest energy, $\sim 10^{20}$ eV). As their names imply, Galactic CRs are accelerated within our Galaxy, while extragalactic CRs originate from beyond it. High-energy objects like gamma-ray bursts and active galactic nuclei, where they emit relativistic jets, are considered potential sources of extragalactic CRs. These jets generate relativistic shocks that can accelerate CRs through a process known as 1st-order Fermi acceleration.
However, a significant challenge exists: in relativistic shocks, due to the no velocity difference between the shock and particles, they cannot be accelerated efficiently. Consequently, particles struggle to achieve energies up to 10^{20} eV within the propagation of the relativistic shocks. To overcome this, strong turbulence ($\delta B/B_0$
$gtrsim 1$) near the shock front must be considered (Lemoine et al., 2006, ApJL; Niemiec et al., 2006, ApJ). However, the origin of this turbulence remains unknown.
In our talk, we propose that such strong turbulence is generated by the interaction between relativistic shocks and shock-upstream density fluctuations. This interaction leads to a corrugated shock front and drives turbulence in the downstream region. This process is well studied in the context of non-relativistic shocks, and it is confirmed that the turbulent structure is generated in the downstream region. On the other hand, in the case of relativistic shocks, it is pointed out that the turbulence generation is suppressed by the relativistic effects. To investigate whether turbulence is sufficiently amplified for particle scattering and acceleration, we conducted large-scale simulations.
First, we performed the interaction between relativistic shocks and upstream density fluctuations by magnetohydrodynamic simulations to obtain a large-scale electromagnetic field. Then, we calculated the particle motions by test-particle simulations, enabling us to study large-scale particle acceleration, particularly for particles like extragalactic CRs with large gyroradii.
Our results reveal that particles are efficiently accelerated by repeatedly crossing the shock front, with energy evolution following $E \propto t$, demonstrating higher efficiency than previous studies. The important thing is that the particles are not scattered isotropically just behind the shock front because the turbulence is not amplified well. Additionally, we found that particles are accelerated only through shock-driven turbulence. This additional acceleration can lead to the injection into the relativistic shock acceleration (Morikawa et al., 2024 ApJL). This injection depends on the size and amplitude of the density fluctuations. This should be significant for the connection between the small-scale acceleration by the Weibel instability or for the CR acceleration scenarios.
In our presentation, we will detail the characteristics of the turbulence and the mechanisms of particle acceleration observed in our simulations.

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