

# Persistence of Precursor Waves in Two-dimensional Relativistic Shocks

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The origin of high energy cosmic rays ( $>10^{15.5}$  eV) has not been fully understood, and the acceleration mechanism is still controversial. Recently Chen et al. (PRL, 2002) proposed the particle acceleration by the large-amplitude Alfvén waves at gamma-ray bursts as a model of the generation of ultra-high energy cosmic rays ( $>10^{18}$  eV), based on the wakefield acceleration mechanism which was initially proposed by Tajima and Dawson (PRL, 1979) in the context of laser-plasma interactions in the laboratory. The wakefield acceleration in laboratory is induced by an intense laser pulse (or transverse electromagnetic waves) propagating in a plasma. The mechanism may also operate in relativistic shocks in nature because it is known that large-amplitude electromagnetic precursor waves are excited by synchrotron maser instability driven by the particles reflected off the shock-compressed magnetic field in relativistic shocks (Hoshino and Arons, PoP, 1991). In fact, Hoshino (ApJ, 2008) demonstrated the generation of the non-thermal electrons by the wakefield induced by the ponderomotive force of the electromagnetic precursor waves in relativistic magnetized shocks by means of one-dimensional Particle-In-Cell (PIC) simulation.

The wakefield acceleration has been discussed only in one-dimensional shocks so far. It is not known very well whether or not the same mechanism can operate in more realistic multi-dimensional systems. In multi-dimensional shocks, the inhomogeneity may appear in the transverse direction of the shock, and the waves emitted from different positions at the shock may overlap with each other. Consequently, the wave coherency which is essential for the ponderomotive force may be broken and the wakefield acceleration may not occur. Another possible problem is the competition between the synchrotron maser and Weibel instability. The Weibel instability occurs near the shock front due to effective temperature anisotropy generated by the reflected particles in the shock transition region. Since both the instabilities are excited from the same free energy source, the efficiency of the precursor wave emission may be affected or even completely shut off.

To solve these subjects, we investigated in this study the properties of the precursor wave emission in relativistic shocks by using the two-dimensional PIC simulation. Since the growth rate of the synchrotron maser instability at high harmonics are significantly large, the precursor waves are high-frequency electromagnetic waves and thus may easily be damped. Therefore, our simulations were performed with high spatial resolution to resolve the precursor waves well. We observed that large-amplitude, coherent precursor waves were excited in two-dimensional shocks, and found that the amplitude of the precursor waves was large enough to induce the wakefield acceleration even if the Weibel instability occurs. In addition, the amplitude of the precursor wave remains finite and has reached a quasi-steady state by the end of the simulation. In this presentation, we quantitatively evaluate the efficiency of the precursor wave emission in both one-dimensional and two-dimensional shocks, and then discuss the possibility of the wakefield acceleration model for the production of non-thermal electrons in an astrophysical shock.

Keywords: acceleration of particles, collisionless shock, cosmic rays