4th Asia-Pacific Conference on Plasma Physics, 26-31Oct, 2020, Remote e-conference

Wakefield Excitation by Synchrotron Maser Emission and Associated Particle Acceleration in Relativistic Shocks

Masanori Iwamoto[1], Takanobu Amano[2], Masahiro Hoshino[2], Yosuke Matsumoto[3]
[1]Department of Earth System Science and Technology, Kyushu University, [2]Department of Earth and Planetary Science, The University of Tokyo, [3]Department of Physics, Chiba University
e-mail (speaker): iwamoto@esst.kyushu-u.ac.jp

Relativistic shocks are ubiquitous in the Universe as a consequence of interaction between relativistic plasma outflow and interstellar medium, in which synchrotron maser instability produces intense electromagnetic precursor waves [1]. Particles are reflected off the shock-compressed magnetic field and start gyrating. A ring-like momentum distribution of electrons is naturally formed at the shock front and induce the instability. Recent one-dimensional particle-in-cell (PIC) simulations of relativistic shocks show that longitudinal electrostatic waves, which are called wakefields, are induced in the wake of the large-amplitude electromagnetic waves via parametric decay instability and that nonthermal particles are generated during the nonlinear collapse of the wakefields [2, 3]. This particle acceleration mechanism is similar to the laser wakefield acceleration which has been widely studied in laboratory plasma [4] and may explain the origin of ultra-high-energy cosmic rays, which is a long-standing problem in astrophysics [5].

Although the synchrotron maser instability in the context of relativistic shocks are important for the coherent emission from astrophysical sources and cosmic ray acceleration, it has so far been discussed solely with one-dimensional simulations [5, 6]. In multidimensional systems, inhomogeneity such as Weibel instability can appear in the transverse direction of the shock and disturb the ring distribution of electrons in the shock transition. Consequently, the wave emission may be inefficient or completely shut off. In addition, the wakefield amplitude may not be sufficiently large to affect the incoming particles because the ponderomotive force exerted by the large-amplitude electromagnetic precursor waves may decrease due to the oblique propagation. Earlier two-dimensional simulations of relativistic shocks indeed demonstrated that the precursor waves were seen only in the initial phase and that the nonthermal particles are not generated. These results are in clear contrast to the previous one-dimensional simulations.

However, according to our numerical convergence study, the spatial resolution used in the earlier two-dimensional simulations is insufficient for an accurate estimate of the synchrotron maser emission because the precursor waves are high-frequency electromagnetic waves. In addition, the application of digital filtering used to suppress the numerical Cherenkov instability may filter both physical and unphysical electromagnetic waves and underestimate the wave emission efficiency. Therefore, the previous two-dimensional simulations are numerically inadequate to treat the synchrotron maser emission and the particle acceleration in multidimensional relativistic shocks.

Our high-resolution two-dimensional PIC simulations showed that the wave emission continues with substantial amplitude for the first time [8, 9]. We confirmed that the large-amplitude electromagnetic precursor waves continue to persist and that the wakefields are indeed excited by the intense electromagnetic waves [10]. The wakefields collapse during the nonlinear process of the parametric decay instability in the near-upstream region, where both ions and electrons are accelerated by the motional electric field in the upstream and produce clear nonthermal tails in the particle energy spectra measured in the upstream rest frame. In this talk, we discuss this particle acceleration and wave-plasma interaction for more details.

References

1. Hoshino, M., & Arons, J. 1991, PhFlB, 3, 818
2. Lyubarsky, Y. 2006, ApJ, 652, 1297
3. Hoshino, M. 2008, ApJ, 672, 940
4. Tajima, T., & Dawson, J. M. 1979, PhRvL, 43, 267
5. Chen, P., Tajima, T., & Takahashi, Y. 2002, PhRvL, 89, 161101
6. Langdon, A. B., Arons, J., & Max, C. E. 1988, PhRvL, 61, 779
7. Gallant, Y. A., Hoshino, M., Langdon, A. B., Arons, J., & Max, C. E. 1992, ApJ, 391, 73
8. Iwamoto, M., Amano, T., Hoshino, M., & Matsumoto, Y. 2017, The Astrophysical Journal, 840, 1, 52
9. Iwamoto, M., Amano, T., Hoshino, M., & Matsumoto, Y. 2018, The Astrophysical Journal, 858, 2, 93
10. Iwamoto, M., Amano, T., Hoshino, M., Matsumoto, Y., Niemiec, J., Ligorini, A., Kobzar, O., & Pohl, M., 2019, The Astrophysical Journal Letters, 883, 2, L35