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

Origin of the first cosmic rays

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Cosmic rays (CRs) and the magnetic field are ubiquitous in the current universe and plays various roles in different environments. The energy densities of CRs and the magnetic field are about 0.1 - 1eV/cm^3 in our Galaxy, which is comparable to that of thermal particles. Therefore, CRs and the magnetic field are thought to have important roles in galaxies. It is widely accepted that collisionless shocks of supernova remnants accelerate CRs with energies up to 10^{15} eV and the standard acceleration mechanism is diffusive shock acceleration [1]. However, it has not been studied when, where, and how the first CRs are accelerated since the Big Bang. In this talk, we are going to talk about our recent works for the origin of the first CRs [2] and the magnetic field generation by the first CRs [3].

In early universe, there are two energetic shocks that could accelerate the first population of CRs, supernova blast waves of the first stars and accretion shocks of the large-scale structure formation in the universe. We considered particle accelerations by the two types of shocks, showing that the first CRs are provided by Weibel mediated nonrelativistic collisionless shocks driven by the first star explosion at the redshift of $z \sim 20$ [2].

A two component (electrons and ions) plasma has been often assumed in the early studies for the generation of the magnetic field. However, astrophysical plasmas have the propagating CRs in addition to the electron-ion plasma after the first CRs are generated. We found a new generation mechanism of the magnetic field in three-component plasma with CRs.

We consider a simple example where propagating CRs are uniform, but the electron-ion plasma has a steady-state incompressible flow before the beam plasma appears. After the CRs appear, the ion and electron densities and the ion velocity field are approximately still steady state, but the electron velocity field deviates from the steady flow because a new electron flow is induced to satisfy the current neutrality. If the electron-ion plasma initially has some inhomogeneities, the electron-return current to satisfy the current neutrality makes the vorticity of the electron plasma. As a result, the magnetic field and the electric current are generated.

To verify our idea, we perform two-dimensional particle-in-cell (PIC) simulations with the periodic boundary condition in both directions using the public code, pCANS [4]. The PIC simulation solves the full Maxwell equations and the equation of motion for many particles, that is, the generalized Ohm's law is not assumed. The simulation results are almost consistent with the analytical solutions. Therefore, the PIC simulations confirmed that the magnetic field is generated in a nonuniform plasma with a CR component.

In the standard picture, CRs are thought to be accelerated after the magnetic field with a sufficiently large scale is generated and amplified. However, recently, we proposed that CRs are first accelerated at the redshift of $z \sim 20$ by supernova remnants of first stars without the large-scale magnetic field [2], and the first CRs generate the large-scale magnetic field [3]. The magnetic field with a small scale is generated by the Weibel instability in the first supernova remnants at $z{\sim}20$; the small scale magnetic field and the supernova remnant shock accelerate the first CRs by the diffusive shock acceleration; the first CRs generate the magnetic field with a large scale while propagating to the intergalactic space.

The software used in this work was in part developed in pCANS at Chiba University. Numerical computations were carried out on the XC50 system at the Center for Computational Astrophysics (CfCA) of the National Astronomical Observatory of Japan. This work is supported by JSPS KAKENHI Grant Number JP16K17702 and JP19H01893, and by Leading Initiative for Excellent Young Researchers, MEXT, Japan.

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