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Can Supernova Shock Wave be Accelerator of 1PeV Particles?

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Supernova remnants (SNRs) are believed to be the accelerators of cosmic-rays up to 1 PeV (10^{15} eV) or even more. However, in order to accelerate the cosmic-rays to 1 PeV by the diffusive shock acceleration mechanism (Blandford & Ostriker 1978), magnetic field amplification is necessary. The Bell's cosmic-ray streaming instability (Bell 2004) has been regarded as the most promising mechanism for the magnetic field amplification. However, due to a huge scale gap between the Bell instability scale and the SNR size, it has been very difficult to study particle acceleration under realistic conditions by numerical simulations.

In this paper, using a novel method developed by Inoue (2009), we examine the Bell instability mediate cosmic-ray acceleration at the supernova shock wave under real environmental parameters such as Mach number, cosmic-ray injection rate, and initial level of magnetization. We find that the Bell instability can successfully amplify magnetic field around the shock wave (see Figure 1), and cosmic-rays are energized more than the maximum energy estimated under initial background magnetic field strength. In addition, we show that the maximum energy of cosmic-rays can be more than 1 PeV at the supernova shock propagating in a dense circum stellar medium created by a red super giant stellar wind (Figure 2), while it is difficult to accelerate particles more than 1 PeV at a typical young SNR shock with age ~500 years, which is consistent with recent gamma-ray observations.

Based on the non-linear growth mechanism of the Bell instability, we discuss why the young SNRs do not show clear 1 PeV acceleration. Our study predicts that very young SNRs of a few weeks after the explosion can be observed as PeVatrons. We also discuss effect of inelastic p-p collisions on cut-off feature of the cosmic-ray spectrum, which could be an important feature for probing our theory by future gamma-ray observations.

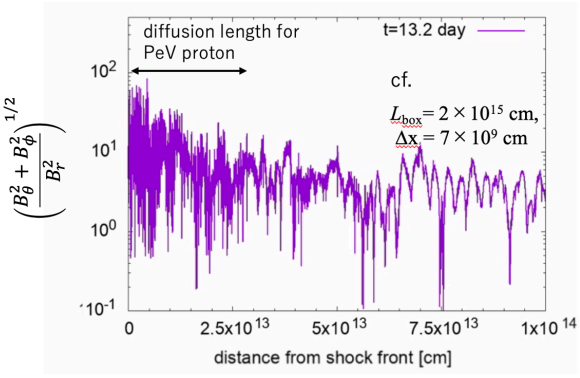

Figure 1: Structure of magnetic field in upstream region of the shock wave propagating in a dense circum stellar medium created by a red super giant stellar wind. The horizontal axis shows distance from shock front toward upstream. The vertical axis indicates amplification level of magnetic field from initial strength.

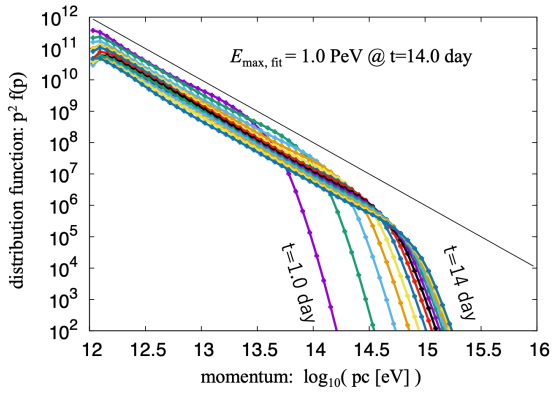

Figure 2: Cosmic-ray spectrum at the shock wave propagating in a dense circum stellar medium. We can observe that the maximum energy exceeds 1 PeV at t ~ 10 days after shock generation by a core-collapse supernova.

References
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