Nonthermal Electron Acceleration at Supernova Shocks: Relativistic Shock Surfing Mechanism

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Abstract

A nonthermal electron acceleration mechanism in high Mach number shocks is studied. We find that the relativistic shock surfing/surfatron acceleration occurs in the shock transition region, where a series of large amplitude electrostatic soliton-like waves (ESWs) are excited by Buneman instability under the interaction between the reflected ions and the incoming electrons. It is shown that the electrons are likely to be trapped by ESWs, and during the trapping phase they can be effectively accelerated by the shock motional/convection electric field. When Alfven Mach number exceeds several tens, the nonthermal electrons are efficiently produced, and their maximum energy reaches up to the shock potential energy determined by the global shock size.

1. Introduction

Several mechanism have been proposed to account for the observed nonthermal electrons radiating in astrophysical synchrotron source such as supernova remnants (SNRs) and extragalactic radio sources by jets, etc. [1]. Shock acceleration has been discussed as one of the important mechanisms producing the high-energy particles. Fermi acceleration in shock waves is believed to be the most successful modeling to explain for the observed power-law energy spectrum [2]. This process utilizes the upstream and downstream Alfvenic turbulence as the particles' scatterers, and a wide acceleration region across the shock front is required. Another important acceleration mechanism is shock surfing/surfatron acceleration that occurs at a thin shock front region through the action of shock electric potential. Among various mechanisms, however, there are many outstanding questions regarding effectiveness of particle acceleration that motivate continuing research on the field. We discuss that electron shock surfing/surfatron acceleration as an efficient particle accelerator where they are continuously accelerated along a the shock motional electric field through the action of a series of large amplitude electrostatic fields [3]. We also demonstrate the electron shock surging acceleration can produce a nonthermal high energy electrons.

pp. 2047–2050

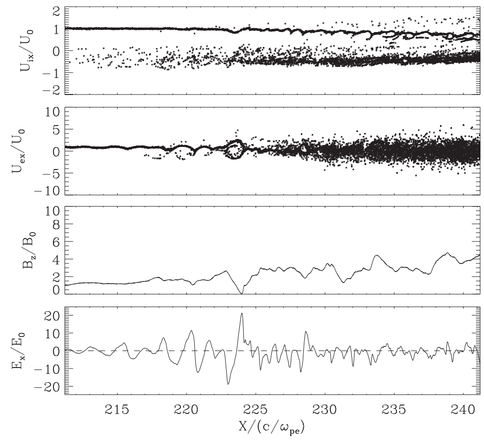

Fig. 1. High Mach Number Shock Front Structure with Electron Phase Space Holes.

2. Electron Shock Surfing Acceleration

Figure 1 shows a snapshot of the enlarged shock front structure obtained by using a relativistic particle-in-cell simulation. The leftward and rightward regions are the shock upstream and the downstream, respectively. In our simulation, a low entropy, high-speed plasma consisting of electrons and ions is injected from the left boundary at $x = 0$, which travels toward positive x. At the injection boundary at $x = 0$, the plasma carries a uniform magnetic field B_z, polarized transverse to the flow. The downstream right boundary condition at $x = 300$ is a wall where particles and waves are reflected.

Top two panels show the ion phase space diagram in (X, U_{ix}) and the electron phase space in (X, U_{ex}), and the plasma four velocity is normalized by the upstream flow velocity $U_0 = v_0\sqrt{1-(v_0/c)^2}$. The bottom two panels are the perpendicular magnetic field and the electric field, normalized by the upstream magnetic field B_0 and the upstream motional electric field $E_0 = v_0 B_0/c$, respectively. The spatial scale is normalized by the electron inertia length c/ω_{pe} in upstream.

It is well known that a high Mach number shock forms the multi-stream ions in the shock transition layer [4], and we can find that the reflected ions coexist with the incident ions and electrons in Figure 1. Also it is seen that the electron phase space holes associated with a large amplitude electric field E_x are formed by nonlinear Buneman instability excited by the interaction between the incident electrons and the reflected ions [5]. Hoshino and Shimada [6] discussed that the electron shock surfing acceleration is occurring around the large amplitude electric field, i.e., electrostatic soliton-like waves (ESW), and the nonthermal electrons are efficiently produced in a thin shock front layer.

The mechanism of the electron's shock surfing can be summarized in Figure

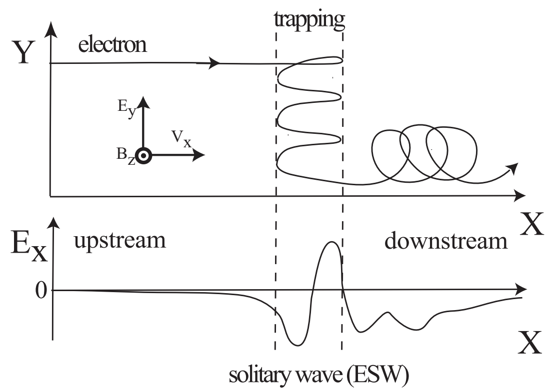

Fig. 2. Mechanism of the electron shock surfing acceleration under the action of ESW.

2. Top panel shows a typical electrons orbit in the (x, y) plane. The magnetic field is polarized perpendicular to the $x-y$ plane, and both ions and electrons are convecting toward positive x. The shock upstream is the left-hand side, while the downstream is the right-hand side. The bottom panel show the electric field E_x, and an ESW in association with the electron phase space hole is depicted. Because of the nature of the electron hole, the electron charge density is slightly lower than the ion one, and the ESW has a bipolar signature with diverging electric field. If an electron convecting toward the ESW structure is reflected by both the Lorentz force and the electric field E_x and is trapped inside the ESW, it is successively accelerated toward the negative E_y direction. However, as the electron's velocity v_y is increased by the shock surfing acceleration, it can be detrapped from the ESW structure when the Lorentz force ev_yB_z/c becomes larger than the electric force eE_x, and then it is convecting toward downstream and quickly becomes an isotropic and gyrotropic distribution.

Based on the above picture, the maximum energy of electron can be estimated as follows: the amplitude of ESW excited in the shock transition layer can be estimated as $E_{ESW}/E_0 = 2(c/V_A)\sqrt{\alpha m_e/M_i}$, where $\alpha = 1/4 \sim (m_e/M_i)^{1/3}$ is the energy conversion coefficient. Since the trapping condition can be estimated by equating the electric force eE_{ESW} to the Lorentz force ev_yB_0, one can easily obtain that if the Alfven Mach number $M_A > (1/2)\sqrt{M_i/(m_e\alpha)} = 43 \sim 75$, electrons cannot escape from the acceleration region, and they will be unlimitedly accelerated until they reach the edge of a global shock structure.

3. Nonthermal Energy Acceleration

It is interesting to study whether or not the electron shock surfing acceleration can offer an efficient electron energization to explain for observed non-thermal

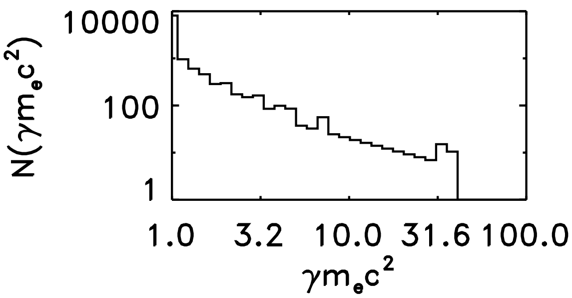

Fig. 3. Electron Energy Spectrum by Shock Surfing Acceleration.

energy spectrum. It is simplest to investigate the individual particle orbits for a prescribed electromagnetic shock structure which include an electrostatic soliton-like wave in the shock transition region. We assume a linearly increasing magnetic field B_z with a $tanh(x)$ functional form and a bipoar electric field with an $exp(-x^2)tanh(x)$. As a simple treatment, we inject an isotropic electron with its energy of $m_e v_0^2$ from the center of ESW and assume the mirginal elelectric field amplitude of ESW for $M_A = (1/2)\sqrt{M_i/(m_e \alpha)}$. Then we calculate the electron energy spectrum in downstream. The energy spectrum is shown in Figure 3, and we can find that the electron shock surfing can produce the nonthermal electron energy spectrum.

4. Concluding Remarks

Our shock surfing acceleration is based on the assumption that ESWs stably exist during the acceleration phase, but it is known that the shock front is not stable and periodically breaks. Further more, the ESWs would have a finite structure along the shock front. Therefore, it is very important to know the interaction of shock surfing electrons with the ESWs in a turbulent state.

1. *e.g.*, Koyama K. et al., 1995, Nature 378, 255
2. *e.g.*, Axford W.I. et al., 1977, Proc. 15th ICRC 11, 132
3. Hoshino M. 2001, Prog. Theor. Phys. Suppl. 143, 149
4. Leroy M. et al., 1982, Geophys. Res. Lett. 87, 5081
5. Shimada N. and Hoshino M. 2000, ApJ 543, L67
6. Hoshino M. and Shimada N. 2002, ApJ 572, 880