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Particle Acceleration in Cosmic Plasmas: Relativistic Surfing Acceleration
宇宙プラズマ中での粒子加速：相対論的波乗り加速

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The production of energetic particles is explored for collisionless shocks and magnetic reconnection by using full particle simulations and analytic study, and it is argued that “surfing acceleration” can provide the quick and strong energiztion than that believed before.　Large amplitude and small scale electrostatic field, which is a necessary condition for the strong surfing acceleration, can be easily generated in cosmic plasmas.　Therefore, non-adiabatic particles trapped by the potential well of the large amplitude wave are capable of reaching relativistic energies.

1. Introduction

The origin of high energy particles is a long-standing problem in cosmic plasmas.　One of the most widely applied acceleration processes is the diffusive shock acceleration, and it is well known that electric and magnetic field turbulence acts to scatter the high energy particles in both shock upstream and downstream, and gain energies from the converging turbulent waves.

In contrast to this acceleration mechanism under turbulence, the modern satellites observed the coherent, small-scale, large-amplitude electric field waves embedded in turbulence in many key regions of terrestrial magnetosphere, and it is now discussed that the coherent waves may be also responsible to the plasma thermalization and acceleration.　The scale of the small-scale wave is of several tens of Debye length, but the amplitude of the wave is 10 to 100 times that of the motional electric field induced in the MHD scale.　Then it is proposed that the micro-scale processes appear to control the global dynamics.　This kind of multi-scale coupling process is beginning to shed light on not only the space plasma phenomena but also the high-energy astroplasma physics.

In particularly, the so-called “surfing acceleration” discussed first by Sagdeev and Shapiro [1], is now believed to be widely applied in many cosmic plasma settings.　The surfing acceleration is one of “direct” acceleration mechanisms, in which the particles trapped by a small-scale, large amplitude wave can resonate with the electric field normal to the wave structure.　In this paper, we discuss that the surfing acceleration mechanism plays a significant role on relativistic particle acceleration in magnetosonic shocks and in magnetic reconnection.

2. Surfing Acceleration

In spite of enormous progress in understanding of surfing acceleration, there still remain fundamental questions: how the non-thermal acceleration efficiency is controlled by the plasma parameters, whether or not the energy spectrum is approximated by a power-law spectrum that is often observed for cosmic ray sources.　The maximum energy that the surfing acceleration can provide is another important question.　Effect of plasma turbulence on the surfing acceleration is probably an important quest to understand the relationship between the conventional stochastic acceleration and the direct acceleration.

The basic mechanism of the surfing acceleration can be simply described by the balance between the electric field force (eE) and the Lorentz force eVxB/c) in the Lorentz equation.　Let us assume a large amplitude electric field (Ex) imposed in the x-direction, the normal, ambient magnetic field (Bz) in the z-direction.　Also assume the electric field (Ey) in the y-direction.　In this geometry, if a particle moving toward the y-direction with the velocity (Vy) satisfy the force balance condition of Ex + Vy Bz/c = 0, and are trapped by a wave potential well, the particle can gain energy from Ey electric field.　If the amplitude of Ex becomes the order of the ambient magnetic field Bz, the particle can be accelerated up to relativistic energy.

Recently several people discussed that the strong electric field can be easily excited in many situations such as shock front regions and magnetic diffusion region of reconnection where the ion inertia effect dominates.

3. Magnetosonic Shocks Case

Let us start from the case of magnetosonic shocks.　Among a various high energy particle acceleration sites in astrophysical plasmas, the most strong particle acceleration is believed to occur in collisionless shocks. Interplanetary shocks induced by solar flares, supernova shocks, and extragalactic radio sources by jets are those examples. The shock surfing acceleration has been extensively discussed since 1970's. In early investigation, the shock surfing are studied for acceleration for ions by utilizing the ambipolar electric field induced by inertia difference between ions and electrons at the shock front [2], and relativistic ions may be generated when the Alfven velocity becomes close to the speed of light.

Since the conventional surfing acceleration utilize the electric field excited at the shock front, it is discussed that only ions can be trapped at the shock front, and electrons are not the case. But recently, several people discussed that not only ions but also electrons can be effectively trapped in the shock front region by large amplitude waves generated by two-stream instabilities [3]. Also shown that the amplitude of electrostatic field can becomes larger than the magnetic field when the Alfven Mach number exceeds several tens, and the electrons are accelerated into relativistic energies.

In addition to the surfing accelerations in the form of electrostatic potential, Hoshino [4] also suggested that the surfing acceleration of particles trapped by the magnetic potential is possible, and both positrons and electrons are shown to be surfing-accelerated in relativistic, magnetosonic shocks by using relativistic particle simulation.

From the above studies, it is now believed that the surfing acceleration is very important mechanism for producing high energy particles in a various different shock situations.

4. Magnetic Reconnection Case

Next we will show that magnetic reconnection also involve the surfing acceleration for generation of non-thermal particles. Many plasma states in universe have magnetic fields whose structure contains the neutral sheet where the magnetic field polarity changes its direction, and magnetic reconnection also plays a crucial role on the magnetic energy release and the resultant plasma heating/acceleration. Reconnection is believed to be particularly important in celestial magnetospheres such as terrestrial magnetosphere, solar atmosphere, pulsar magnetosphere, and accretion disks in X-ray binaries and active galactic nuclei etc.

The energization of charged particles in reconnection is basically provided by the interaction of the charged particles with an electric field around the X-type region. In the earliest exploration of particle acceleration during reconnection, the test particle calculations based on the magnetic and electric fields structure obtained by the resistive MHD model demonstrated the production of supra-thermal particles by moving in the direction of the electric field over a substantial distance. Hoshino et al. [5] noted that large amplitude turbulence can be generated in collisionless reconnection, because the plasma sheet becomes as thin as ion inertia scale, and because kinetic instabilities such as beam instabilities are easily switched-on. They explored electron acceleration by using full particle simulations and showed that electrons accelerated around the X-type region are further accelerated under electromagnetic turbulent fields around the magnetic field pile-up region formed by the reconnection jets.

In addition to the above acceleration, Drake et al. [6] also demonstrated that large amplitude, bipolar electric field can be generated in and around the X-type region, and found that the electrostatic fields parallel to the magnetic fields plays an important role on acceleration. During this nonlinear stage, Hoshino [7] found that the ambipolar electric field normal to the magnetic field can be excited around the X-type region, and the electric field grows up to almost same amplitude as the local magnetic field. Therefore, the shock surfing can be switched-on around the X-type region, and high energy particles are generated in reconnection.

We have only begun to investigate the potentially rich multi-scale structuring phenomena that result from the coupling of the MHD scale to the scale of electron kinetics. Further studies should help to elucidate how particle acceleration are provided in cosmic plasmas.

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