Electron dynamics surrounding the X-line in magnetopause-type asymmetric reconnection

*Seiji Zenitani[1], Hiroshi Hasegawa[2], Tsugunobu Nagai[3]

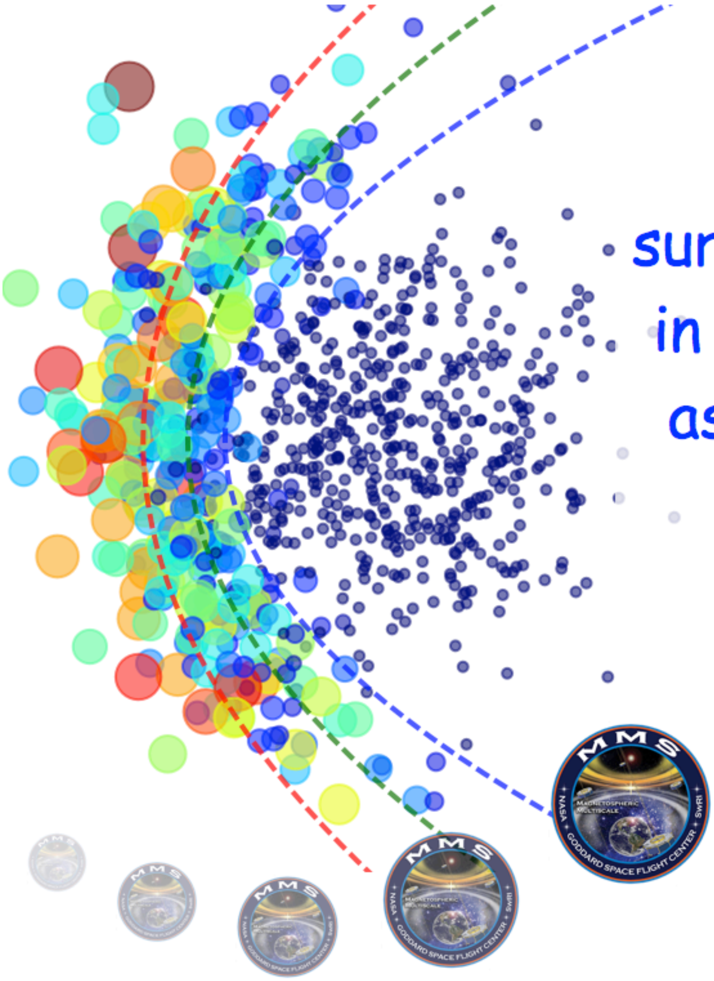
1. NAOJ National Astronomical Observatory of Japan, 2. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3. Department of Earth and Planetary Sciences, Tokyo Institute of Technology

Electron dynamics surrounding the X-line in magnetopause-type asymmetric reconnection is investigated using a two-dimensional particle-in-cell (PIC) simulation. We study electron properties of three characteristic regions in the vicinity of the X-line. The fluid properties, velocity distribution functions (VDFs), and orbits are studied and cross-compared. In the low-beta side of the X-line, the normal electric field enhances the electron meandering motion from the high-beta side. The motion leads to a crescent-shaped component in the electron VDF, in agreement with recent studies. In the high-beta side of the X-line, the magnetic field line is highly stretched in the third dimension. As a result, its curvature radius is comparable with a typical electron Larmor radius. The electron motion becomes chaotic, and therefore the electron idealness is no longer expected to hold. Around the middle of the outflow regions, the electron nonidealness is coincident with the region of the nonadiabatic motion.

Reference:

- Zenitani, S., H. Hasegawa, and T. Nagai, submitted to *J. Geophys. Res.* (MMS special issue)

Keywords: magnetic reconnection, magnetopause, particle dynamics



Electron dynamics surrounding the X-line in magnetopause-type asymmetric magnetic reconnection

Seiji ZENITANI

with H. Hasegawa, T. Nagai

Triggering fast tearing: from MHD to kinetic effects

*Marco C M Velli[1], Fulvia Pucci[2], Anna Tenerani[1]

1. University of California Los Angeles, 2. NIFS-Princeton

One of the main questions about magnetic reconnection concerns how this mechanism may account for fast magnetic energy conversion to kinetic and thermal energies, resulting in explosive events in astrophysical and laboratory plasmas. Over the past decade progress has been made on the initiation of fast reconnection via the plasmoid instability and what has been called ``ideal" tearing, which sets in once current sheets thin to a critical aspect ratio: as shown by Pucci and Velli (2014) once the thickness reaches a scaling a/L ~ S^-1/3, the time scale for the instability to develop becomes of the order of the Alfvén time and independent of the Lundquist number. However, given the large values of the Lundquist number in natural plasmas, this transition might occur for thicknesses of the inner, singular layer, approaching the ion inertial length. When this occurs, Hall currents produce a three-dimensional quadrupole structure of magnetic field, and the dispersive waves introduced by the Hall effect accelerate the instability. Here we present a linear study showing how an "ideal tearing mode" is achieved when Hall effects are taken into account, including scaling laws for sheet aspect ratios and growth rates. We show that for an appropriate scaling of the aspect ratio in the parameter space (S, d_i/L), the instability develops on ideal timescales and the associated growth rate does not depend on the parameters, suggesting a revision of the phase diagrams describing different regimes for magnetic reconnection in space and laboratory plasmas.

Keywords: Plasma, Magnetic Reconnection, Heliosphere

Macroscopic quasilinear kinetic model for electrons and protons instabilities in homogeneous and in inhomogeneous solar wind plasmas

*Muhammad Sarfraz[1], Peter H. Yoon[2,3]

1. Department of Physics, GC University Lahore, Katchery Road, Lahore 54000, Pakistan, 2. University of Maryland, College Park, Maryland 20742, USA, 3. School of Space Research, Kyung Hee University, Yongin, Gyeonggi 446-701, Korea

Solar wind species like electrons, protons and alpha particles are detected to possess temperature anisotropies with respect to ambient magnetic field. Microinstabilities driven by these anisotropies are responsible for an upper check of higher values of temperatures at different radial distances of solar wind. For a homogeneous and non-collisional medium, we employed a macroscopic quasilinear kinetic model to display asymptotic variations and saturations of temperature anisotropies and wave energy densities for electromagnetic electron cyclotron (EMEC) and electron firehose (EFH) instabilities. A bi-Maxwellian form of particles distribution adopted all the time except that temperatures may vary in time t. We showed that, in ($\beta_{\parallel}$, $T_{\perp}/T_{\parallel}$) phase space, the saturations stages of anisotropies associated with core and halo electrons lined up on their marginal stability curves for EMEC instability. For case of EFH instability, the electrons and protons dynamics saturated at firehose and proton cyclotron marginal stability curves, respectively. Next, we interpreted the outstanding issue that most of observed proton data resides in nearly isotropic state in phase space. Here, in quasilinear frame-work of inhomogeneous solar wind system, we formulated a set of self-consistent quasilinear equations to show a dynamical variations of temperatures with spatial distributions. On choice of different initial parameters, we showed that, interplay of electron and proton instabilities provided an counter-balancing force to slow down the protons away from marginal stability states. Our present approach may eventually be incorporated in global-kinetic models of the solar wind electrons and ions.

Keywords: solar wind, instabilities

Propertime Path Integral for Relativistic Diffusion

*Tadas Nakamura[1]

1. Fukui Prefectural University

It is well known that there exist infinite speed components in a solution of a simple diffusion equation with the first order time derivative. This does not cause serious problems if that part is small enough in non-relativistic regime, however, it may cause spurious growing solution in relativity. The reason is that propagation faster than the speed of light means backward propagation in time in some reference frame, and time reversal diffusion equations may have growing component.

This difficulty is inevitable for equations with first order time derivative, and hence, equations with second order have been proposed by Israel and Stewart (1970) for relativistic thermodynamics. Theories in this line are called "causal thermodynamics" and have been extensively studied since then. Second or higher order time derivative can make the propagation speed under a certain finite value to avoid the non-causal propagation. However, these higher order terms are not based on some physical reasoning of underlying mechanism; they are mathematical device to avoid infinite speed. Solutions of these equations do not violate causality, but it does not mean they are physically reasonable. For example, when we apply the theory of Israel and Stewart to thermal diffusion, we obtain so called telegraph equation. A telegraph equation is reduced to wave equation in high speed (highly relativistic) limit; it does not violate causality but wave equation does not represent diffusion.

A method proposed here is to solve the evolution of the particle distribution function, which is defined on the spacetime (x,t), along the proper time. The evolution cannot be formulated in the form of diffusion equation along propertime because the direction of time is forward only. To avoid this problem the method of path integrals with the constraint of energy shell is introduced in the present study.

Keywords: Relativistic Diffusion, Path Integral, Proper time

Cyclic self-reformation of perpendicular shocks in two-dimensional particle-in-cell simulation

*Takayuki Umeda[1], Yuki Daicho[1]

1. Institute for Space-Earth Environmental Research, Nagoya University

The cyclic self-reformation of perpendicular collisionless shocks was first identified in one-dimensional (1D) kinetic particle-in-cell simulations. In early studies, the reformation was defined as the cyclic accumulation and release of ions. The release ions toward upstream (ion reflection) takes place periodically at the ion gyro period of the downstream, which forms the shock foot region. Later, the cyclic self-reformation of perpendicular shocks was also identified in two-dimensional (2D) full particle-in-cell simulations with a simulation domain shorter than the ion inertial length in the shock tangential direction. However, some of recent 2D full particle-in-cell simulations with a large simulation domain argued against the evidence of the cyclic self-reformation of perpendicular shocks due to rippled structures at the shock front. In the previous studies, the cyclic self-reformation was identified from the cyclic oscillation of the magnetic field at overshoot, since the magnetic field and the ion density are well correlated in 1D simulations and 2D simulations with a small simulation domain. In the present study, we analyze ion particle data obtained from large-scale 2D full particle-in-cell simulations with different ion-to-electron mass ratio, and discuss the effect of the mass ratio to the evidence of the cyclic self-reformation of perpendicular shocks.

Keywords: collisonless shock wave, particle-in-cell simulation

Anomalous convection diffusion model of cosmic rays

*Tohru Hada[1]

1. Earth System Science and Technology, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Transport of cosmic rays (energetic particles) in a turbulence field remains to be an important issue, both from astrophysical and nonlinear science points of view. In particular, it is known that the transport in a plasma with large amplitude MHD turbulence can exhibit properties of non-gaussian statistics. A natural formalism to model such anomalous transport processes is the fractional diffusion equation, in which the time and/or spatial derivative contain fractional differentiation operators. After briefly introducing the idea of the fractional differentiation/integration operators and numerical methods, we discuss the diffusive shock acceleration process by solving numerically the fractional convection diffusion equation. The results will be compared with those obtained by test particle simulations using sub- and super- diffusive particles. Possible applications of the present model to other high-energy astrophysical phenomena will be discussed as well.

Keywords: cosmic rays, diffusion

MHD relaxation with flow inside a sphere

*Kohei Yamamoto[1], Akira Kageyama[1]

1. Kobe University

We have studied MHD (magnetohydrodynamics) relaxation processes inside a spherical vessel with a perfectly conducting boundary. According to the classical theory of the MHD relaxation--Woltjer-Taylor theory--the relaxed state is force-free and its magnetic field configuration is called spheromak. The formation and stability of spheromaks were not only confirmed by plasma experiments, but also used in various experiments such as magnetic reconnections. The Woltjer-Taylor theory assumes, however, that the flow energy in the relaxed state is negligibly small. Here in this study, we investigate MHD relaxations with flow in a ball region by computer simulation. We have numerically solved compressible MHD equations in all ball region including the origin ($r=0$) by making use of recently developed Yin-Yang-Zhong grid [Hayashi & Kageyama, JCP, 2016]. Since we can perform high resolution simulations, incorporated viscosity is much lower than those in previous MHD relaxation simulations. Since general spheromak solutions are composed of the spherical bessel function (in the radial direction r) and the spherical harmonics (in the latitude θ and longitude ϕ directions), they are characterized by eigenvalue n (in r) and l and m (in θ and ϕ). As for the initial conditions, we employed higher modes $l,m>1$ with weak perturbations. Pressure and mass density were uniform. The flow velocity is zero. Due to the instability of the spheromaks with higher modes, flows are driven when simulations start. After some transient time, the flows arrives at quasi-stationary states that retain in the dissipation time (i.e., long) scale, because the simulated viscosity is low enough. Although the flow energies E_K in the quasi-steady states are relatively small compared with the magnetic energies E_M ($E_K/E_M=O(10^{-3})$), the existence of the flow is not negligible. We have found, in particular, the quasi-steady states are not force-free; the electric current and the magnetic field are not in parallel.

Keywords: magnetohydrodynamics, plasma relaxation, Yin-Yang-Zhong grid

Simulation study of transition from steady Petschek reconnection to dynamical Petschek reconnection

*yonaha hiroyasu[1], Kanya Kusano[1], Takuya Shibayama[1]

1. Institute for Space-Earth Environmental Research

Magnetic reconnection is a process of converting magnetic energy into thermal energy and kinetic energy. However, classical steady reconnection model (Sweet-Parker model) cannot explain the high speed of reconnection (reconnection rate) observed in the solar corona. Fast magnetic reconnection model has developed to solve this problem. Although the steady Petschek model reconnection can explain the fast reconnection, it requires the localized anomalous resistivity in current sheet. On the other hand, when the resistivity is uniform in space, so-called plasmoid reconnection occurs as the result of instability of a thin current sheet, and reconnection is accelerated. Recently, Shibayama et al. (2015) showed that the plasmoid-type reconnection in uniform resistivity can produce a new-type of fast reconnection with non-steady slow mode shocks, called "dynamical Petschek reconnection." In this study we have performed two-dimensional magnetohydrodynamics (MHD) simulation to investigate a holistic picture from the steady Petschek reconnection to the dynamic Petschek reconnection. We focused on the dependency of reconnection on the intensity of anomalous resistivity localized in space. As a result of that, we found that there is an oscillating Petschek-type reconnection between the steady Petschek reconnection and the Dynamical Petschek reconnection. We analyze magnetic field in the oscillating Petschek reconnection by decomposing two components of the different parities for mirror symmetry with respective to the current sheet, and discuss the picture of transition from the steady Petschek reconnection to the dynamical Petschek reconnection.

Keywords: magnetic reconnection, Petschek reconnection, simulation, slow shock

Persistence of Precursor Waves in Two-dimensional Relativistic Shocks

*Masanori Iwamoto[1], Takanobu Amano[1], Masahiro Hoshino[1], Yosuke Matsumoto[2]

1. Graduate School of Science, The University of Tokyo, 2. Graduate School of Science, Chiba University

The origin of high energy cosmic rays (>$10^{15.5}$eV) has not been fully understood, and the acceleration mechanism is still controversial. Recently Chen et al. (PRL, 2002) proposed the particle acceleration by the large-amplitude Alfvén waves at gamma-ray bursts as a model of the generation of ultra-high energy cosmic rays (>10^{18}eV), based on the wakefield acceleration mechanism which was initially proposed by Tajima and Dowson (PRL, 1979) in the context of laser-plasma interactions in the laboratory. The wakefield acceleration in laboratory is induced by an intense laser pulse (or transverse electromagnetic waves) propagating in a plasma. The mechanism may also operate in relativistic shocks in nature because it is known that large-amplitude electromagnetic precursor waves are excited by synchrotron maser instability driven by the particles reflected off the shock-compressed magnetic field in relativistic shocks (Hoshino and Arons, PoP, 1991). In fact, Hoshino (ApJ, 2008) demonstrated the generation of the non-thermal electrons by the wakefield induced by the ponderomotive force of the electromagnetic precursor waves in relativistic magnetized shocks by means of one-dimensional Particle-In-Cell (PIC) simulation.

The wakefield acceleration has been discussed only in one-dimensional shocks so far. It is not known very well whether or not the same mechanism can operate in more realistic multi-dimensional systems. In multi-dimensional shocks, the inhomogeneity may appear in the transverse direction of the shock, and the waves emitted from different positions at the shock may overlap with each other. Consequently, the wave coherency which is essential for the ponderomotive force may be broken and the wakefield acceleration may not occur. Another possible problem is the competition between the synchrotron maser and Weibel instability. The Weibel instability occurs near the shock front due to effective temperature anisotropy generated by the reflected particles in the shock transition region. Since both the instabilities are excited from the same free energy source, the efficiency of the precursor wave emission may be affected or even completely shut off.

To solve these subjects, we investigated in this study the properties of the precursor wave emission in relativistic shocks by using the two-dimensional PIC simulation. Since the growth rate of the synchrotron maser instability at high harmonics are significantly large, the precursor waves are high-frequency electromagnetic waves and thus may easily be damped. Therefore, our simulations were performed with high spatial resolution to resolve the precursor waves well. We observed that large-amplitude, coherent precursor waves were excited in two-dimensional shocks, and found that the amplitude of the precursor waves was large enough to induce the wakefield acceleration even if the Weibel instability occurs. In addition, the amplitude of the precursor wave remains finite and has reached a quasi-steady state by the end of the simulation. In this presentation, we quantitatively evaluate the efficiency of the precursor wave emission in both one-dimensional and two-dimensional shocks, and then discuss the possibility of the wakefield acceleration model for the production of non-thermal electrons in an astrophysical shock.

Keywords: acceleration of particles, collisionless shock, cosmic rays

Verification of Super Massive Black Hole Binaries Discovered at the Center of Our Galaxy by Observations of Decameter Radio Wave Pulses

*Hiroshi Oya[1]

1. Department of Geophysics Graduate School for Science Tohoku University

1. Introduction Based on the observations of decameter radio wave pulses from the center part of our Galaxy by using ,mainly, decameter radio wave interferometer at Tohoku University, search for super massive black holes has currently been carried out starting from 1984. In 1999, it had tentatively reported that there were at least 23 black holes which could be origins of the decameter radio wave pulses. From 2016, new observations to verify the proposed black hole hypothesis were started and further development of the observations had been realized by introducing digital system to obtain the interferometer data. New analyses provide evolutional progress correcting the previous results of the present study.

2. Observations In 2016, observations of the decameter radio wave pulses had been made from February 2 to February 28, for non Galaxy center condition, and from March 15 to June 30 aiming at the Galaxy center. The utilized decameter long baseline interferometer at Tohoku University consist of three observation stations at Kawatabi, Zao and Yoneyama which provide three interferometer base lines with the length ranges from 44km to 83km. At each station, signals at 21.860MHz were observed and converted down to 1kHz with bandwidth of 500Hz which were sent to the Sendai station ,through the telemeter system. The signals at the backend of the telemetry system were converted into digital signals by AD converter with sampling rate of 3000 data points per sec.

3. FFT analyses and Confirmation by Simulation For the obtained digital data from each observation point of the interferometer system, interferometry correlation functions were calculated by digital computer to find interferometry fringe function to which the template fringe to detect the arrival directions of the signal were applied culculating the correlation. To these direction correlated data, FFT analyses are carried out so as to pick up the source signals of a few percent level compared with large background noises by averaging 6000 times trial of independent FFT operations. The results had definitely indicated that the purposing spectra are arriving from the center part of our Galaxy with allowance angle range of +-0.5 degree. The resulted spectra are characterized by two fundamental periods at 156.6sec corresponding to the source Gaa and 130.8 sec corresponding to Gab. These two fundamental spectra are associated with 2nd and 3ird harmonics; furthermore all spectra are associated with 3 to 5 sideband spectra both in the upper side and lower side of the principal spectra. All sidebands have a frequency gap of 1/2200 Hz :that is, all spectra are manifestation of the frequency modulation caused by orbital motions of Gaa and Gab with orbiting period of 2200sec.

4. Confirmation by FFT simulation Based on the characteristic parameters deduced by the FFT analyses, possible signals from spinning Gaa and Gab which are moving along two orbits with a common period of 2200sec with speeds respectively of 0.16c and 0.19c are constructed as simulation function to understand the observed FFT results: it is concluded that FFT results for this constructed function revealed coincidence with observation case. That is, current results in which 5 set of black hole binary have been proposed should be corrected so as to be one set of principal black hole binary consisting of

Gaa and Gab .

5. Box Car Analyses Accurate feature of the Gaa and Gab black hole binary system has been investigated applying period correlation analyses (Box Car analyses) to find pulse forms with search of the orbit period and orbiting speeds together. The results has indicated that orbiting period of Gaa and Gab is 2205 sec ; two black holes have two separated visible sources of radio wave as manifestation of curving effect of the ray paths due to the space rotation of the ergo-sphere.

Keywords: Black Hole Binary, Galaxy Center, Decameter Radio Wave

