S-R2-2

Solar Observations of Various Plasmoid Ejections and Particle Acceleration
太陽観測で見た多様なプラズモイド放出と粒子加速

Naoto Nishizuka
西塚 直人

Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency
3-1-1, Yoshinodai, Chuo-ku,Sagamihara, Kanagawa 252-5210, Japan
独立行政法人宇宙航空研究開発機構・宇宙科学研究所 〒252-5210 神奈川県相模原市中央区由野台3-1-1

Magnetic reconnection in the solar atmosphere is ubiquitous and fractal and associated multi-scale plasma ejections, called plasmoid ejections, have been discovered by recent observations. Multiple plasmoid ejections, as a result of unsteady reconnection, play a role in enhancing fast inflows and driving fast reconnection. They also have a role in constructing fractal-like or turbulent current sheet which connects microscopic and macroscopic plasma phenomena. Such a dynamic structure is favorable to the efficient particle acceleration. In this presentation, I will introduce recent observation results of multiple ejections in the solar atmosphere and compare with the simulation results.

1. Introduction

Recent space observations of the Sun with Yohkoh, SOHO, TRACE, and RHESSI revealed that magnetic reconnection is ubiquitous in the solar corona, ranging from small scale reconnection (nanoflares) to large scale one (coronal mass ejection (CME) related flares). These reconnection events are often associated with mass ejections with various sizes, from small scale jets to large scale plasmoid ejections and CMEs: for example, small scale impulsive flares (with order of 10^9 cm), long duration event (LDE) flares (with order of 10^{10} cm), and large scale giant arcades associated with CMEs (with order of 10^{11} cm) [1-3].

Recent Hinode satellite has also revealed that magnetic reconnection is ubiquitous in the solar chromosphere, and that even smaller reconnection events occur in the solar chromosphere, which are associated with tiny jets [4-5]. These observations indicate that the solar atmosphere consists of self-similar structure, i.e., fractal structure, which is consistent with basic magnetohydrodynamics (MHD) theory, since MHD does not contain any characteristic length and time scale. It is natural that MHD reconnection tends to become fractal in ideal MHD plasmas with large magnetic Reynolds number such as in the solar atmosphere, and it is proposed that even current sheet might have a fractal structure, which is favorable for particle acceleration.

There remain fundamental puzzles on flares:

(1) What is the energy storage mechanism?
(2) What is the triggering mechanism?
(3) What determines the reconnection rate?
(4) What fraction of energy goes to nonthermal particles?
(5) Is there any relation to coronal and chromospheric heating?
(6) The scale gap between microscopic plasma scale (10-100 cm) and macroscopic plasma scale (i.e. flare loop: 10^9-10^{10} cm)

Hence even if the micro-scale plasma physics has been solved, there still remains the fundamental puzzle how to connect micro and macro scale plasma physics to explain solar flares.

2. Plasmoid-induced-reconnection in a Fractal Current Sheet

On the basis of the solar observations, Shibata (1999) proposed the unified model of flares, in which plasmoid ejections play an essential role to induce fast reconnection, and called this mechanism the *plasmoid-induced-reconnection* mechanism [6].

There are two roles of plasmoid (flux rope) in reconnection: (1) to store energy in a current sheet, (2) to induce inflow into reconnection region. When a plasmoid (or flux rope in 3D) is situated in a current sheet, the anti-parallel magnetic field cannot touch, so cannot reconnect. Only when the plasmoid is ejected out of the current sheet, reconnection becomes possible. If larger plasmoid is in a current sheet, larger energy is stored, and larger energy release would occur eventually after its ejection. Furthermore, to solve the fundamental question on scale-gap in solar flares, Tajima and Shibata (1997) have suggested the idea of *fractal current sheet* [7], which was developed by Shibata and Tanuma (2001) [8].

Observations of solar flares in hard X-rays (HXRs) and microwaves often show the fractal-like time variability, i.e., power spectral analysis of the time variability show power-law distribution [9]. This fractal-like time variability may be evidence of particle acceleration in an impulsive reconnection associated with plasmoid ejections with various sizes (i.e., fractal current sheet).

On the other hand, Asai et al. (2004) discovered that downflows occurred in association with HXR bursts during impulsive phase of the flare, in soft X-ray images of a flare observed with Yohkoh [10]. These downflows seem to correspond to downwardly ejected plasmoids, because their velocity and other properties are similar to those of upwardly ejected plasmoid seen in soft X-rays. More recently, using soft X-ray images taken with Yohkoh, Nishizuka et al. (2010) discovered that multiple plasmoid ejections occurred from a single flare on 24 Nov. 2000 and that they are all associated with HXR bursts [11-12]. Hence these observations may indicate plasmoid-induced reconnection and the relationship between plasmoid ejections (or downflows) and particle acceleration.

3. A Model of Particle Acceleration in a Fractal Current Sheet

The particle acceleration is naturally explained in the interaction of multiple plasmoids with various sizes and fast mode shock generated by the reconnection outflow at the loop-top of a flare [13].

Here we propose that nonthermal electrons are efficiently accelerated by Fermi process at the fast shock, coupled with the dynamics of multiple plasmoid ejections. Multiple plasmoids are ejected upward and downward with trapped particles inside and collide with the fast shock, which is naturally formed below the reconnection site. Trapped particles inside a plasmoid are reflected by the magnetic mirror force to conserve magnetic momentum upstream the fast shock. As a plasmoid passing through the shock front, the distance between the two reflection points becomes smaller and smaller, during which particles gain momentum energy parallel to the upstream magnetic field by each collision, leading to the first order Fermi acceleration. Finally when the trapping distance becomes comparable to ion Larmor radius, particles escape from the trapping in a plasmoid.

With 2.5D resistive MHD simulation and test particle simulation, we showed that particles can be accelerated more efficiently during the plasmoid ejections. Some particles are accelerated in a current sheet by enhanced electric field, while others are at the fast shock during the interaction between plasmoids and the shock front. This tendency can be seen even in 3D MHD simulation. The current sheet becomes turbulent in 3D direction, and intermittent reconnections eject plasmoids and locally enhance electric field, as shown in 2D case. It is also shown that global flux rope (plasmoid) ejection also increases inflow and electric field in a global current sheet, driving faster reconnection and efficient particle acceleration. Here we note that when we consider fractal plasmoid ejections, we can naturally explain the power-law distributions of hard X-ray observations.

The purpose of this paper is to introduce recent observation results of multiple plasmoid ejections and the comparison with theoretical studies of plasmoid-induced-reconnection and fractal reconnection, including application to the particle acceleration.

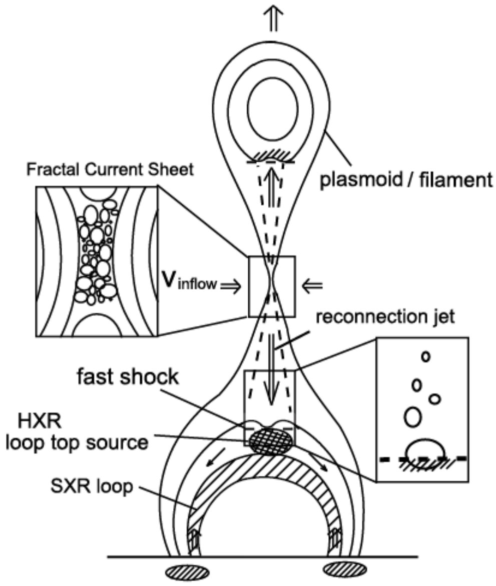

Fig.1. Fractal current sheet and fast shock in a solar flare.

References

[1] K. Shibata et al.: ApJ **451** (1995) L83.
[2] S. Tsuneta et al.: ApJ **483** (1997) 507.
[3] M. Ohyama and K. Shibata: PASJ **49** (1997) 249.
[4] K. Shibata et al.: Science **318** (2007) 1591.
[5] N. Nishizuka et al.: ApJ **683** (2008) L83.
[6] K. Shibata: Ap&SS **264** (1999) 129.
[7] T. Tajima and K. Shibata: Plasma Astrophysics (Reading, MA: Addison-Wesley) 1997.
[8] K. Shibata and S. Tanuma: Earth Planets Space **53** (2001) 473.
[9] M. Aschwanden: Particle acceleration and kinematics in solar flares (Kluwer Academic Publishers) 2002.
[10] A. Asai, T. Yokoyama, M. Shimojo and K. Shibata: ApJ **605** (2004) L77.
[11] N. Nishizuka, H. Takasaki, A. Asai and K. Shibata: ApJ **711** (2010) 1062.
[12] H. Takasaki: PhD thesis, Kyoto Univ. (2006).
[13] N. Nishizuka and K. Shibata: in 38th COSPAR Scientific Assembly (2010) 1959