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Particle Transport and Acceleration in a Chaotic Magnetic Field: Implications for Seed Population to Solar Flare and CME

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Abstract. In large Solar Energetic Particle (SEP) events, ions and electrons are accelerated to GeV/nucleon and keV in energy. These very high energetic particles are likely accelerated at fast coronal shocks. Observations have shown that the seed population (the particles that participate in the shock acceleration process) is not the bulk solar wind, but the suprathermal population. In this work, we propose to investigate a novel pre-acceleration mechanism that may provide the needed seed population for the subsequent shock acceleration in large SEP events. We examine the transport and acceleration of charged particles by chaotic electric and magnetic fields during the pre-eruptive period. It is demonstrated that a realistic chaotic magnetic field can be produced by any asymmetric current configurations - one such configuration is an asymmetric current wire loop system (CWLS). Observational studies have established the existence of current loops and current filaments at the solar surface and simple configurations as CWLSs inevitably exist in solar active regions. This suggests that the magnetic field at an active region is very much chaotic and time variation of these current configurations induces time-varying electric fields. Therefore, charged particles can be naturally accelerated. We outline an approximate model to study the pre-acceleration process of seed particles in a solar active region prior to eruptions by considering the transport and acceleration of charged particles in a time-dependent chaotic magnetic field.

Keywords: Chaotic magnetic field, Particle energzation, Solar energetic particles, Seed population
PACS: 95.10Fh, 96.25Ln, 96.50Pw,05.45a

INTRODUCTION

Particles upto 1 GeV are accelerated at the Sun through either solar flares or coronal mass ejections (CMEs). In large Solar Energetic Particle (SEP) events, flares and CMEs often co-exist, making the identification of the acceleration site difficult. Nevertheless, it is believed that, at least in large gradual SEP events, particles are efficiently accelerated at the CME-driven shock. Recent studies (Mason et al. 1999, Cohen et al., 2003, Desai et al 2006, Ho et al. 2004) have shown that it is the suprathermal population that is preferentially accelerated in SEP events. The pertinent questions such as where do these suprathermal ions come from, and whether there is some mechanism that can accelerate, for example, thermal ions with $T \sim 10^6$ K (the typical coronal temperature) to become the seed population which is later accelerated at the CME-driven shock, should be addressed to determine the physics of generation of large SEP events.

We propose a transient acceleration process which can be caused by a chaotic electric field which results from a time dependent pre-eruptive magnetic field in and around an

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active region. As we will see, the essence of the acceleration is closely related to the fact that prior to the eruption process, the magnetic field becomes very non-force-free due to strong shear motions near the neutral line.

MODELING PRE-ERUPTIVE SCENARIO

We approximate the pre-eruptive magnetic field and its evolution by an ensemble of time dependent current wire loop systems (CWLS), and these are the fundamental building blocks in our system. No doubts that approximating the magnetic field in an active region by some CWLSs is a simplification of the realistic magnetic field, however, using CWLSs gives us, although crude, an *analytical*, thus tangible model of the active region magnetic field.

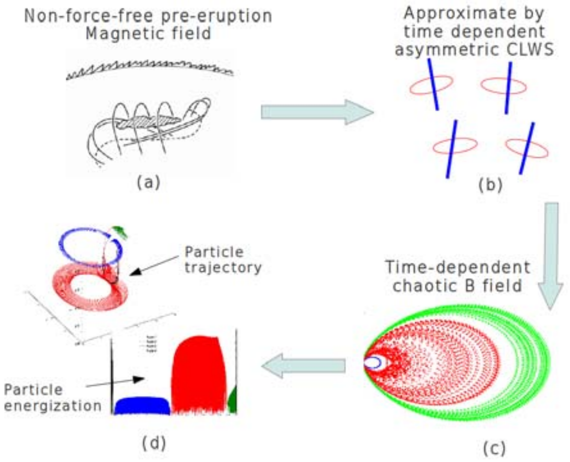

FIGURE 1. Modeling Pre-eruptive Scenario: (a): the very non-force free pre-eruption magnetic field configuration adapted from Moore et al. (2001). (b): we approximate the B field in (a) by an ensemble of time-dependent asymmetric CLWSs. (c): a time dependent chaotic magnetic field develops. (d): particle trajectory and energization in time-dependent chaotic magnetic field.

Furthermore, as we will show, the symmetry property of the CWLSs is closely related to the force-free or non-force-free nature of the active region magnetic field. In our model a force-free field corresponds to a symmetric wire-loop system and a non-force-free field corresponds to an asymmetric wire-loop system. In the latter case, the magnetic field is inevitably chaotic. If such a chaotic magnetic field is time dependent, then a chaotic electric field will develop. Consequently, charged particles will be accelerated.

Figure 1 illustrates our model. Panel (a) represents the pre-eruption magnetic field configuration (adapted from Moore et al. (2001)). Prior to the eruption, very non-force-free field develops (see e.g. Aulanier et al. 2010, Démoulin et al. 1996). This can be seen from panel (a), where close to the neutral line, strong shear motion along the neutral line twists the loops from an almost-perpendicular orientation to an almostparallel orientation (with respect to the neutral line). While the pre-eruption magnetic field is very complicated, we approximate such a field by an ensemble of time-dependent asymmetric CLWSs. It is important we have asymmetric CLWSs, which ensures the non-force-free nature of the magnetic field. Such an asymmetric configuration of the CLWS, will develop, as shown in panel (c), a time dependent chaotic magnetic field, and through Farady's law, a chaotic electric field will be induced. The particle trajectory and energy as a function of time, in the time-dependent chaotic magnetic and electric field, are depicted in panel (d). Although our approximation of the pre-eruption magnetic field by an ensemble of CLWSs (i.e. approximating (a) by (b)) is essentially a simplification yet the motivation of doing so is to allow us to perform a focused study on a well-defined problem which is the abstraction of the very much complex reality.

Structure of the magnetic field in the active region in Sun

The wealth of observational data gathered by various solar missions (GOES, SOHO, Yohkoh, RHESSI, Hinode, etc.) reveals the structure of solar magnetic fields in general, and active region magnetic field in particular, which is extremely complex and variable in time. However, out of the complex labyrinth and entanglement, we can identify (and focus our attention to) some basic building blocks which fabricate these colossal cosmic complex structures- these are current loops, current-sheets and linear elements. Measurements of sunspots with the imaging vector magnetograph at Mees Observatory show that magnetic fields that emerge at the solar surface already carry electric currents at a large scale. Later studies established the existence of current loops and current filaments at the solar surface. In large SEP events, active regions undergo explosive eruptions, from which big flares and fast CMEs are observed. Prior to the eruption, the core field across the neutral line is strongly sheared and twisted in the shape of a sigmoid and the magnetic field configuration in the source active region is such that it is very non force-free and contains a lot of magnetic energy, through, e.g., strong shear motion near the neutral line [Moore et al. 2001]. Sakai [1987], Tajima et al.[1987] discussed the signature of current loop coalescence in solar flares. In coronal loops, the random shuffling of the photospheric flux tubes causes twisting and braiding of the coronal magnetic field generating field-aligned electric currents. Parker [1972, 1983] proposed that these random motions lead to the formation of tangential discontinuities - corresponding to thin current sheets. All of these works imply that chaotic magnetic field commonly occur at solar surface and are likely the cause of various observations ranging from remote-sensing to in-situ.

While a chaotic magnetic field has been noted in many early work, it has been introduced into these works, cited above, in a somewhat ad hoc manner. Indeed, none of these previous work have shown that how a chaotic field can be generated in a self consistent way. This situation is changed when recently, Ram and Dasgupta, (2006, 2007, 2008, 2010); Li et al., (2009); and Dasgupta and Ram, (2007) first demonstrated that chaotic magnetic fields can arise in very simple configurations. Indeed, it is so basic, that it is guaranteed to exist at the solar surface. As such, it represents a fundamental problem in plasma physics that deserves a systematic investigation. We discuss the chaotic magnetic field generated by asymmetric current configuration in the next section.

PARTICLE DYNAMICS IN A CHAOTIC MAGNETIC FIELD

We now demonstrate that chaotic magnetic fields can be generated by a simple asymmetric current configuration consisting of a current loop combined with a straight current wire(CWLS). The geometrical setup is as follows. A reference current loop is assumed to be lying in the *x*-*y* plane with the center of the loop located at the origin of the coordinate system. A straight current carrying wire is added to the reference current loop. In the symmetric configuration, the straight current carrying wire passes through the center of the current loop and is perpendicular to the plane of current loop. Asymmetry can be introduced either (i) by a parallel translation of the central wire, or (ii) by inclining the wire relative to the plane of the current loop.

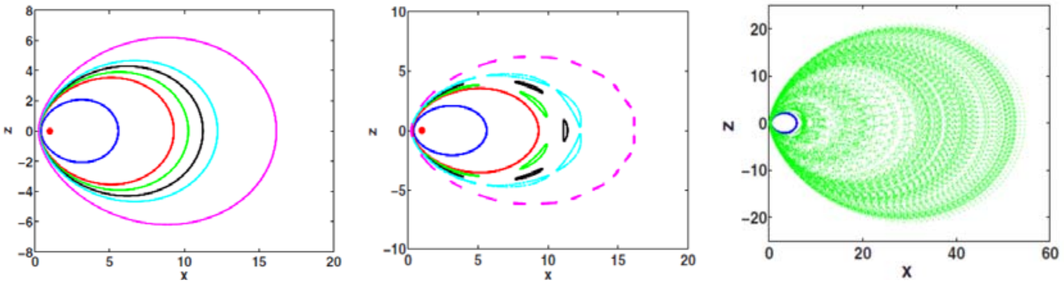

FIGURE 2. Generation of chaotic magnetic field lines by asymmetric wire-loop configuration illustrated by Poincaré section as explained in the text. Δr is the displacement of the central wire in a normalized unit. Left : Poincaré section of six magnetic field lines, for the symmetric wire-loop system ($\Delta r = 0$). Closed curves indicate existence of magnetic surface and non-chaotic magnetic field lines. Middle: Poincaré section of the same field lines when the central wire is displaced by $\Delta r = 0.001$. Appearances of “islands" indicate chaotic transition. Right: For a displacement $\Delta r = 0.01$ of the central wire leads to complete destruction of magnetic surfaces (except for the innermost one) indicating magnetic field lines are chaotic.

To trace the magnetic field lines of this configuration, we integrate the field line equations (in spherical coordinates) along the path of magnetic field lines. To exhibit the nature of the magnetic field , we have plotted the Poincaré surface-of-section in the *x*-*z* plane for the symmetric and asymmetric configurations. The plots are shown in Figure 2. The left panel shows the results for the symmetric configuration, where the translation of the central wire is 0. The continuous lines in the the Poincaré surface-of-section plot indicate unbroken flux surfaces. For the middle panel, the translation of the central wire, measured in units of the radius of the circular loop, is $\Delta r = 0.001$. In this case, the Poincaré surface-of-section plot shows the appearance of island structures for the outer flux surfaces (a classical route to chaos). Finally, for the translation of the central wire is $\Delta r = 0.001$ (the right panel), the Poincaré surface-of-section plot shows complete destruction of all the flux surfaces, except the innermost one.

Motion of a charged particle in chaotic magnetic field: For the particle motion, we numerically integrate the Lorentz equation in the presence of the chaotic magnetic fields generated by the asymmetric current configurations. The Poincaré surface-of-section plot is shown in Figure 3. It is found that the particle motion is chaotic only when the value of a parameter α (ratio of the parallel kinetic energy of the particle to its total energy) is greater than a critical value. For the magnetic field corresponding to that described in the left panel of Figure 2, three sets of particle motions are illustrated in Figure 3. Characteristics of particle motion are described in the figure caption.

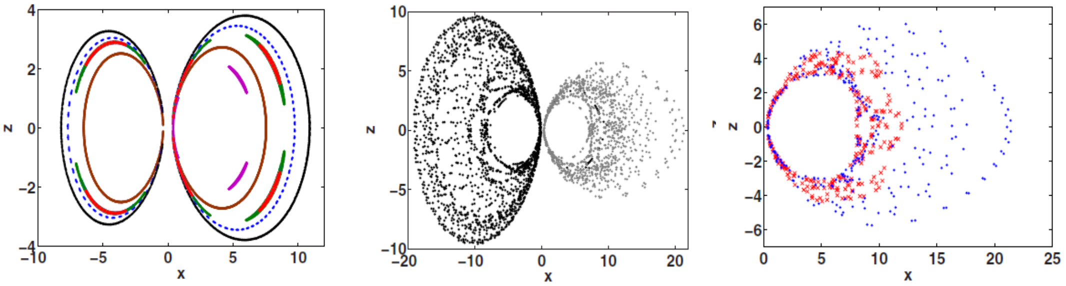

FIGURE 3. Poincaré sections of particle orbits and magnetic field lines. Left: Intersection points of points of four particle orbits in x-z plane for $\alpha = 0.989$ Middle: Intersection points of two particle orbits in x-z plane for $\alpha = 0.990625$ For this case, the ratio of particle larmor radius to the magnetic scale length is $\ll 1$.Appearances of dark dots $x > 0$ region indicate trapped particles. Right: The blue dots are the intersection points of a single particle orbit for $\alpha = 1$ in x-z plane. The red crosses are the intersection points of field lines. The much broader spatial extent of the particle orbit indicate that the particle does not follow the magnetic field line, - it diffuses across the magnetic field line. More detailed descriptions of particle motion is given in Ram & Dasgupta (2010).

Particle Diffusion: In many astrophysical problems, the motion of (charged) particles are assumed to be diffusive in nature. For example, Parker's [Parker, 1965] cosmic ray transport equation implicitly assumes that cosmic ray's motion in the solar system is diffusive. In a collisionless plasma such as the solar wind, this diffusion is due to the interaction between the charged particle and the irregular turbulent magnetic field δB of the solar wind [Jokipii 1966, 1971]. This interaction leads to a diffusion coefficient $D_{\mu\mu}$ which is a function of the power spectrum $I(k)$ of the turbulent field δB.

In a chaotic magnetic field, Poincaré map is not closed as no magnetic surface can exist, therefore it is conceivable that one may still obtain a diffusion along the perpendicular direction to B_0 without explicitly introducing either a 2D component of the turbulence or current sheet. In order to examine the diffusive nature of the particle trajectory, one has to follow many individual particles that start at different locations. This is because, as we have seen, depending on the initial location of the particles, the particle trajectory can be vastly different. Therefor the diffusion process is location-dependent. In a future work we will examine how the diffusion will depend on the initial location of particles.

Particle Energization by a Chaotic Magnetic Field Particle acceleration is an outstanding problem in Space Plasma physics. Two widely accepted mechanisms of particle acceleration in space plasma are shock acceleration and stochastic acceleration. Shock acceleration is also known as "first order" Fermi acceleration, while stochastic acceleration is sometimes referred to as "second order" Fermi acceleration. The main difference between the "first order" Fermi acceleration and the "second order" Fermi acceleration is that the collisions in the "first order" Fermi acceleration are coherent while that in the "second order" Fermi acceleration are random. In the context of solar flare, both mechanisms have been explored [Mann et al. 1999, Miller, 1998]. In both these mechanisms, electric field is not invoked explicitly, one can understand the acceleration process by changing reference frames and assuming the “collisions” conserve particle’s energy in an instantaneous “local frame”. Electric field can also be invoked explicitly, as shown by Litvinenko, (1996), Matthaeus et al, (1984). At solar flare site, currents and magnetic fields are all time dependent, so electric fields are ever present. Indeed, various electromagnetic waves are the agent of these electric fields. Of course, because of non-linear interactions among these plasma waves, turbulence is often a better description — yielding a spectrum of the turbulence (i.e. a continuous wave number k)

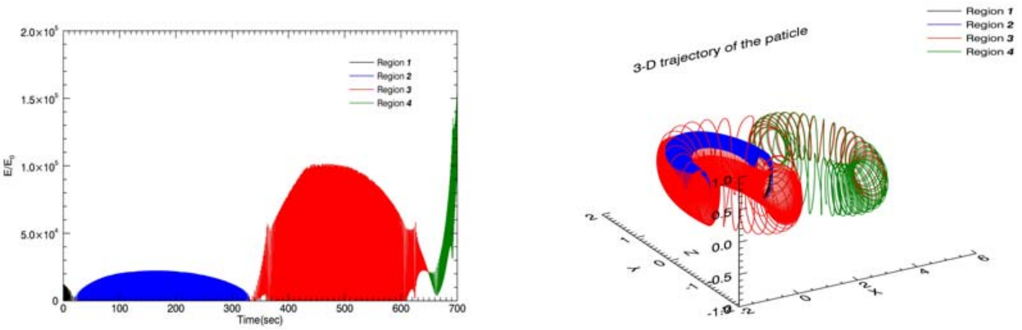

FIGURE 4. Left panel: A 3-D view of the chaotic nature of particle trajectory moving in a time-varying chaotic magnetic field. The trajectory is split in 4 different parts, (in temporal sequence, shown in different colors) indicating that the particle enters into different region of chaotic magnetic field. Right panel: Showing the particle energy changing with time, with a particular color matching the color of the region of particle trajectory. It is seen that the ranges maximum energy gain of the particle are different for different regions of the chaotic magnetic field. The normalization factor E_0 is 50 kev, and the maximum particle energy is $\sim$ 5 Mev.

To study particle energization, we consider the current, as a first approximation, the current varying sinusoidally in time, which is the "basic time-varying configuration“. The time-dependent (retarded) vector potential is from the equation for Green’s function, and explicit expressions for magnetic field and electric field are calculated. Particle acceleration is studied by following particle’s trajectory in these fields.

To illustrate our approach, we show in figure 4 some preliminary results from a CWLS that consists of two one-loop-one-wire configuration. The straight wires intersect with the x-y plane at (0,0) and (3,0) with a unit length of $L_0 = 6.96 * 10^8$ cm. The two loops have the same radius $r = L_0$ and both loops are in the x-y plane with center of two loops locate at (0.01,0), (3.01,0). The currents in the wires are set to be $I_0 = 4 * 10^7$ Ampere and the currents in the loops are 5 times larger. The current in the loop is assumed to be time-independent and the current in the wire vary sinusoidally with a frequency of 0.01 Hz. Protons are injected to the system at (1.4,0,0) with an initial energy to be 50 keV. The left panel of figure 4 shows an example particle trajectory and the right panel of figure 4 shows the particle energy as a function of time. It is interesting to note that the trajectory can be splitted into 4 different parts, which are color-coded. The range of particle energy in each of these 4 periods differ. The maximum particle energy is found to occur in the third period, where the proton can reach $\sim$ 5 MeV in energy (Note, however, the particle energy oscillate very quickly).

CONCLUSION

We have demonstrated that a charged particle is energized by a chaotic magnetic field, which can be produced by an asymmetric current configuration. Considering the structures of solar photospheric magnetic fields during a pre-eruptive period, we conclude that such chaotic magnetic fields could be ubiquitous in solar environment, so these chaotic magnetic fields play an important role in particle energization. We have discussed a possible model for generating the seed population for the production of solar energetic particles during solar flares and coronal mass ejections.

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