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A two-step scenario for both solar flares and magnetospheric substorms: Short duration energy storage

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The basic observations for magnetic storms and substorms at Earth and for flares at the Sun are reviewed for background. We present a common scenario of double magnetic reconnection for both substorms and flares based on previous interplanetary observations and substorm-triggering results. Central to the scenario is that the first magnetic reconnection phase is the source of energy loading for possible substorms and flares. The energy placed in the magnetotail or magnetosphere/at the sun lasts for only a short duration of time however. The energy gets dissipates away rapidly (in some less dramatic form). This scenario predicts that if the initial reconnection process is sufficiently intense and rapid, concomitant substorms and flares occur soon thereafter. If the energy input is less rapid, there may be lengthy delays for the onset of substorms and flares. If external influences (shocks, etc.) occur during the latter energy buildup, the "trigger" will cause a sudden release of this energy. The model also explains reconnection without subsequent substorms and flares. The model addresses the question why strong triggering events are sometimes ineffective.

Key words: Solar flares, substorms, magnetic storms, magnetic reconnection.

1. Introduction

It has been well established that major geomagnetic storms do not occur at Earth unless the upstream interplanetary magnetic field (IMF) is southward for durations of hours (Gonzalez and Tsurutani, 1987; Gonzalez *et al.*, 1994, 2007). There have been no exceptions to this rule found to date. On the other hand, if the upstream IMF is northward, the magnetosphere and auroras becomes very quiet (Tsurutani and Gonzalez, 1995). It can be assumed that the energy input into the magnetosphere/magnetotail does not occur during such intervals (or takes place at a much lower rate). The implication of both of these observations is that magnetic reconnection (Dungey, 1961) is the major mechanism for solar wind energy input into the magnetosphere (Echer *et al.*, 2008) and is a direct or indirect source of the energy powering magnetic storms.

Substorms are much smaller intensity geomagnetic events, and there the situation is less clear. Tsurutani and Meng (1972) and Meng *et al.* (1973) found that southward IMFs preceded substorms by ∼10 to 40 min, and concluded that southward IMFs are both the ultimate energy source and trigger for the substorms that follow. Alternatively Lyons *et al.* (1997) have suggested that some substorms are "triggered" by northward IMF turnings due to braking of the magnetospheric convection process. Freeman and Morley (2004) have demonstated that substorms may occur spontaneously and may not be triggered at all. We will argue that all of these positions are correct and are not contradictory to each other.

The strongest external impact on the magnetosphere and potential substorm triggers are interplanetary fast forward shocks (Kennel *et al.*, 1985) impinging on the dayside magnetopause. The solar wind ram pressure can increase by an order of magnitude across a shock. Such pressure pulses will compress the magnetosphere in a dramatic fashion such that magnetic increases (sudden impulses or SIs) are detected on the ground (Araki, 1994). As the shock propagates further downstream, it will compress the magnetotail and thereby increase currents within and bounding the tail (Tsurutani *et al.*, 1986; Tsurutani and Zhou, 2003). Shock compression will also enhance field-aligned currents from the magnetosphere to the ionosphere (Araki, 1994). These shocks can immediately trigger substorms with little or no delay (Heppner, 1955; Kawasaki *et al.*, 1971; Kokubun *et al.*, 1977). However there are also times when they do not trigger substorms. What does this mean?

Zhou and Tsurutani (2001) and Tsurutani and Zhou (2003) have found that if the IMF is southward or ∼zero nT a few hrs prior to shock impingement, a substorm will occur. If the IMF is northward, one will not. These observations have been somewhat of a mystery. The Earth's magnetotail has enough stored magnetic energy to supply a dozen or more substorms. Why don't shocks trigger substorms irrespective of preceding IMF directionality? A similar question can be asked about solar flares. The energy stored in the coronal loops is sufficient for many solar flares. Why

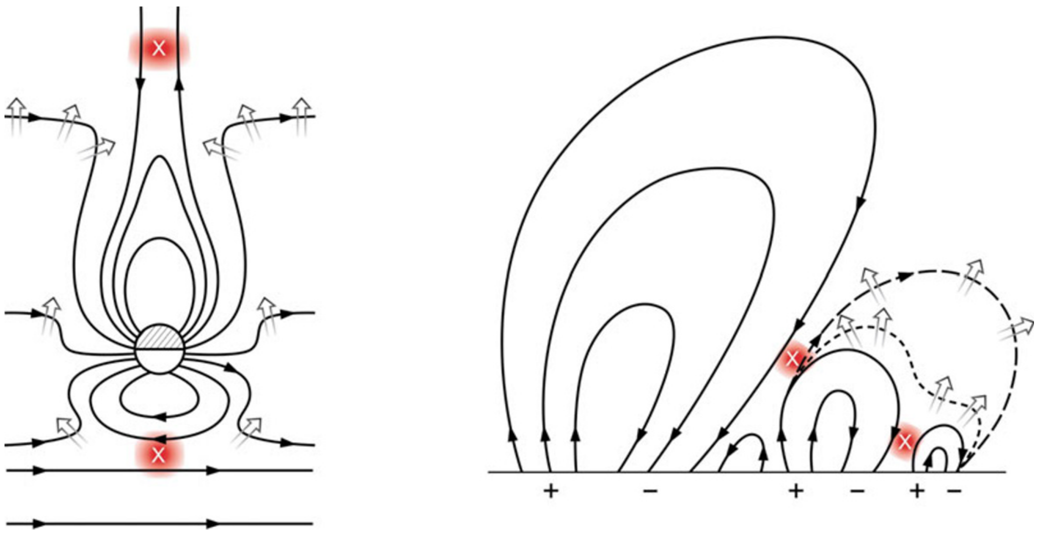

Fig. 1. A schematic of two-step reconnection at Earth (on left) and at the sun (on right). For the Earth's case the solar wind from the sun (at bottom out of the figure) convects interplanetary magnetic fields to the Earth. Magnetic reconnection at the magnetopause (indicated in red at the bottom) allows the transfer of solar wind energy to the ionosphere/magnetosphere/magnetotail. If this first reconnection process is intense enough, a substorm will occur. Magnetic reconnection in the tail (indicated in red at the top) may either drive the substorm or be a consequence of the substorm. This is currently being debated in the literature. An analogous solar flare schematic is shown on the right. An emerging flux region occurs on the far right of the figure. Magnetic reconnection between it and the neighboring (central) loop leads to an increase of magnetic stress between the central loop and the large loop at the left. Release of this stress occurs in the form of a solar flare.

don't flares occur continuously until the loop energy is exhausted? The loop configuration often looks remarkably similar before and after the flare.

We present a scenario of double magnetic reconnection for substorms and solar flares. Our scenario follows the above empirical findings that magnetic reconnection is the major process transferring solar wind energy into the magnetosphere. That is a standard, well-accepted concept (see Terasawa *et al.*, 2000 for a discussion of the similarities and differences between substorms and flares). However we also follow the Zhou and Tsurutani (2001) and Tsurutani and Zhou (2003) result that the energy stored in some form in the magnetosphere/magnetotail/ionosphere is being dissipated rapidly. If the energy is not released in the form of a substorm within several hrs, it gets released in a less dramatic manner. In this scenario, the quiet-time tail lobe energy does not play a prominent role. In this paper we explore the consequences of this idea, assuming that the same processes occur at the sun. We will hypothesize under what condition solar flares occur and when they do not.

2. Results

2.1 Substorms

Substorms were first identified and described by Akasofu (1964) (see also Akasofu and Chapman, 1972) by all sky images measured from the ground. Substorms are isolated midnight sector auroral zone (∼60° to 65° magnetic latitude) events. Akasofu (1964) found that a substorm was found to consist of the following sequence: 1) a brightening of the equatorward arc (the arc width typically is ∼1 km), 2) a breakup of the arc, and then poleward, eastward and westward expansions of auroral forms. This sequence takes between ∼10 and ∼30 min to complete, with no definite time interval identified.

Auroral light is created by ∼1–10 keV electrons precipitating into the upper atmosphere colliding with neutral atoms and molecules. The electrons lose their kinetic energies through electron-electron collisions resulting in the excitation of the atoms and molecules. The excited atoms and molecules relax to emit visible and UV photons. To a much lesser extent (∼1 to 2% of the total radiated energy), the incoming energetic electrons are accelerated by interactions with atmospheric nuclei to form bremsstrahlung X-rays.

The processes accelerating the electrons to 1–10 keV occurs above the ionosphere. Electric fields with components aligned along the geomagnetic field (so called "parallel electric fields") have been detected at low altitudes by satellites such as FAST (Carlson *et al.*, 1998). These electric fields accelerate thermal electrons to monoenergetic beams of ∼keV kinetic energies (Evans, 1968). The causes of these electric fields are due to processes occurring in the magnetosphere, at higher altitudes still. The lack of sufficient current carrier densities is the cause of the parallel electric fields generated above the ionosphere (Carlson *et al.*, 1998).

Large scale convection of magnetotail (plasmasheet) plasma also occurs simultaneous with auroral substorms. The plasmasheet is convected inward towards the Earth, compressing (heating) the plasmasheet plasma. Due to curvature and gradients in the magnetospheric magnetic field, the electrons drift from the midnight sector towards dawn and the ions from the midnight sector to dusk. The energies of these particles are ∼10 to 100 keV. Through plasma instabilities and plasma wave growth, these magnetospheric particles are pitch-angle scattered and some precipitate into the ionosphere. This is the "diffuse" component of the aurora.

It is well documented that the energy for substorms ultimately comes from the solar wind Poynting flux (discussed previously). The magnetic field directionality serves as an energy gate. If the interplanetary magnetic fields are oriented in a southward direction, opposite in direction to the magnetopause magnetic fields, reconnection will take place. A second site of reconnection occurs in the magnetotail. A schematic of this model is shown on the left-hand side of Fig. 1.

Although sufficient energy may be transferred into the magnetosphere/magnetotail system by the first reconnection process, substorms may not take place immediately or even at all. Our scenario is that if energy is supplied at a rapid enough rate, e.g., if the IMF is intensely southward, substorms will result (Tsurutani and Meng, 1972). If sufficient energy has recently been put into the magnetosphere and the IMF turns northward, this current disruption can cause a substorm (Lyons *et al.*, 1997). Or if there is energy being put into the magnetosphere/magnetotail continuously, substorms will occur sporadically (Freeman and Morley, 2004). However if the IMF is northwardly directed for hours prior to the "trigger" arriving at the magnetopause, neither IMF southward turnings, northward turnings nor shocks will trigger substorms. In our scenario, the important feature is the rate of energy input into the magnetosphere/magnetotail system. The "triggers" are less important.

In the above substorm scenario, there is less emphasis on the second reconnection event. It may occur as a byproduct of the substorm or may lead to the substorm. There are many ongoing debates of the timing of the events. In our point of view, it is the first reconnection event that is the important one. This leads to energy input from the solar wind to the ionosphere/magnetosphere/magnetotail.

2.2 Solar flares

Solar flares were first observed (1859) and reported independently by R. C. Carrington (1860) and R. Hodgson (1860) as localized brightenings in a sunspot group. The brightening lasted only ~5 min. No changes in the sunspot orientation or intensity was noted after the flare had occurred. This is similar to the case of substorms, viewed from a great distance. Differences in the magnetosphere before and after substorms would be difficult to discern from a viewing distance of 10^8 km.

Since the above 1859 observations, numerous flare events have been recorded by ground-based, balloon-borne and spacecraft telescopes. Today, a solar flare is defined as "a transient phenomenon showing a rapid increase followed by either a rapid or gradual decay" (Tajima and Shibata, 1997). The "rapid" time scale normally corresponds to 10 sec to 10 min, although it varies largely from event-to-event. It is often accompanied by quasi-periodic variations, or pulsations, with the time-scale as small as 20 msec. These observations are similar to those of substorms.

The wavelength of the electromagnetic emission covers radio wavelengths at the low end to γ- rays at the upper end. The γ-rays are produced by precipitating high energy ions, a feature far more energetic than that in substorms. The low end includes Hα photons, a feature often used in flare diagnostics. Recent progress has come from spectral and imaging observations of X-rays (e.g., Svestka, 1976). Soft X-rays (SXR) are thought to be thermal emission from plasmas of 10^7 K temperature whereas hard X-rays are "non-thermal". The latter are bremsstrahlung emissions created by 10 keV to 1 MeV electron collisions with ions.

The whole duration of a flare depends on the type of flare. Long duration event (LDE) flares typically last more than 1 hr while impulsive flares are short-lived ones that last far less. The latter is characterized by impulsive hard X-ray emission whereas the former shows a softer X-ray spectrum.

Generally, the LDE flares have larger characteristic scale sizes of $\sim 10^5$ km. SXR observations show cusp-type loops associated with their rise and expansion motion (e.g., Tsuneta *et al.*, 1992). The temperature was found to be systematically higher in the outer loops. The loops gradually shrink with time (Forbes and Acton, 1996). Some other phenomenon such as plasmoid ejections (Hudson, 1994), downflows (McKenzie and Hudson, 1999; Asai *et al.*, 2004), and inflows (Yokoyama *et al.*, 2001) were also observed.

Impulsive flares, on the other hand, are relatively small with characteristic scales of $\sim 10^4$ km but occur much more frequently than LDE flares. A notable feature of these events is that they do not show clear cusp-shaped loop structures, so some researchers considered the two types of flares to be different phenomena. From the mid-1990s, however, many features similar to LDE flares were found in impulsive flares (e.g., see a review by Shibata, 1999). In 1994, a careful comparison between SXR and HXR images revealed an above-the-looptop HXR source so-called Masuda-type source (Masuda *et al.*, 1994). It was soon discovered, from the time-of-flight (TOF) analysis, that the acceleration site of energetic electrons is situated high above the Masuda type sources (Aschwanden *et al.*, 1996). Other important findings in impulsive flares are plasmoid ejections (Shibata *et al.*, 1995; Ohyama and Shibata, 1998), temperature distributions, upward and shrinking motions of SXR loops, and increasing footpoint/double-ribbon separation (Sakao, 1994; Fletcher and Hudson, 2001; Asai *et al.*, 2002). A detailed analysis of spatial distribution of the coronal sources has provided evidence of a large scale current sheet (Sui and Holman, 2003). It is only recently that the γ-ray line observations revitalized the discussion of the differences between ions and electrons in acceleration and/or propagation (Lin *et al.*, 2003).

In both types of flares, plasma heating and particle acceleration are primary processes of solar flares that take place in the solar corona (very recent observations by Hinode clarified many small-size flares not only in the solar corona but also in the chromosphere (e.g., Shibata *et al.*, 2007). The impact of such ubiquitous presence of flares, caused by reconnection, should be discussed in the future literature. During the peak time of flares, the accelerated particles and thermal conduction fronts propagate to and heat the chromosphere. The heated chromospheric plasma results in an upward flow or 'chromospheric evaporation'. It is this phase that the highest energy emission such as HXR and γ-rays are prominently observed. In the later phase of flares, a cooling process dominates heating. The typical temporal variation of energy spectra shows the "soft-hard-soft" sequence (e.g. Fletcher and Hudson, 2002).

The magnetic field configuration for our solar flare model is shown on the right-hand side of Fig. 1. Our model is a double reconnection event, similar to the process of reconnection at Earth (reconnection occurs first at the magnetopause and then in the tail). We note that double reconnection models for solar flares have been previously proposed by Wang and Shi (1993), Aulanier *et al.* (2000), Kusano *et al.* (2004) and Zhang *et al.* (2006). We include the tether cutting model (Moore and Roumeliotis, 1992) and the breakout model (Antiochos *et al.*, 1999) because in a broader sense, they are double reconnection models too (see review by Shibata, 2005). In this paper we build on this model to draw a schematic for solar flares that is similar to the magnetospheric case. The initial condition is two magnetic loops adjacent to each other. These are the large loops on the left and center. The source of the loops and their intrinsic magnetic energy is magnetic buoyancy.

The emergence of a new loop on the far right leads to energy transfer to the system (e.g., Chen and Shibata, 2000). This loop has a polarity that is conducive to magnetic reconnection (indicated by an "x") between the emerging loop and the right-hand initial loop. This reconnection corresponds to the dayside reconnection in the Earth's case. Reconnection between the small emerging loop and the central loop enlarges the initial right-hand loop and increases the magnetic stress between it and the left-hand loop. If significant stress builds up between the two loops, magnetic reconnection will take place between them and the energy will be abruptly released in the form of a flare. If on the other hand the stress build up is slow such that the magnetic stress is being dissipated more rapidly than increased, no sudden release of energy will occur.

If the rate of energy input (reconnection between the new loop and central loop) is rapid enough, a flare will occur with short delay. If the energy input is less rapid but the amount of accumulated energy is sufficient for a flare, coronal disturbances may "trigger" it. As one example, coronal shocks propagating from distant regions of the sun can trigger "sympathetic" flares, much in the way an interplanetary shock can trigger a substorm at Earth. If however the energy input is at a relatively low rate or there is no energy being added, even strong triggers may be ineffective.

3. Summary

We have developed a scenario for double reconnection involving three coronal loops at the sun which has an analog to the case of interplanetary magnetic reconnection at the Earth's magnetosphere and reconnection in the magnetotail. Our scenario emphasizes short duration energy storage time scales in both the magnetosphere/ionosphere and at the sun. If the energy input is rapid, flares/substorms occur. This scenario is based on detailed observations made for storms and substorms at Earth.

At this time, the authors do not speculate on what specific form the resultant energy from the (first) magnetic reconnection process is stored at Earth and at the Sun. For the Earth's case, energy storage in the magnetotail, magnetosphere and in the ionosphere have been suggested. The literature is extensive. For the solar case, Zirin and Tanaka (1973), Neidig (1979), Hagyard *et al.* (1983) and Moore *et al.* (2001) have suggested that shear in the magnetic field is one mechanism. This may be the case for our model between the central and left-hand loop of Fig. 1. Kusano *et al.* (2002) have suggested flux emergence was an important feature for a November 1997 interval. Similarly Schrijver *et al.* (2008) have indicated that electrical currents associated with the emerging flux is important. In our model, the existence of the right-hand side emerging loop is such a feature.

All of the energy storage mechanisms mentioned above (and more) may occur to varying degrees, depending on the particular solar preconditions. It is possible that the path of energy storage and release may be different for different events.

4. Final Comments

We have proposed a double reconnection model that can be applied to both substorms at Earth and to solar flares. We emphasize that the rate of the first reconnection process is important to determine if the substorm/flare: 1) will occur immediately, 2) will occur with some delay, 3) could occur if there is an external "trigger" and 4) may not occur at all. Key to this scenario is that the energy input leaks away from the storage site (as implied from magnetospheric results) and the preexisting magnetotail/loop energy is not the main source for the substorm/flare. The ideas presented in this paper are readily testable.

One can envision obvious simple variations to this double reconnection model. Flux emergence enhancing the central loop will eliminate the need for the emergence of the small right-hand loop. Otherwise, the scenario is the same. Again, the rate of free energy input into the system will be critical for the occurrence/lack of occurrence of a flare.

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