Small-scale Magnetic Reconnection in the Quiet Sun

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Abstract. Recent observations indicate that small-scale magnetic reconnection ubiquitously occurs in the quiet Sun as well as in active regions. Particularly interesting is the latest finding of close associations among (1) magnetic flux cancellation seen from photospheric magnetograms, (2) chromospheric upflow events seen in the Hα line and (3) transition region explosive events seen in UV lines. I present a brief review of this finding, and propose a schematic two-step magnetic reconnection model to explain it. The essence of the model is in the formation of magnetic islands as a result of slow magnetic reconnection occurring in the low atmosphere. Magnetic islands are ejected and accelerated upward by the so-called diamagnetic melon seed mechanism, and are eventually annihilated by overlying magnetic field lines through fast magnetic reconnection. I consider photospheric flux cancellation as a direct result of the first magnetic reconnection, and identify chromospheric upflow events with upward moving magnetic islands, and explosive events with the hotter material ejected from the second magnetic reconnection.

1. Introduction

A typical deep magnetogram shows that magnetic fields exist everywhere in the quiet Sun —i.e., both in supergranulation boundaries and in cells. Therefore it appears that the chromosphere and corona in the quiet Sun as well as in active regions is dominated by magnetic fields. Furthermore, the small-scale and mixed-polarity nature of the quiet Sun magnetic fields implies that small-scale magnetic reconnection should ubiquitously occur in the quiet Sun and may be important in the dynamics and energetics of the upper atmosphere. In the present paper, I give a brief review of some of recent observations which support small-scale magnetic reconnection in the quiet Sun, and propose a two-step magnetic reconnection model as an attempt to explain them in a self-consistent way.

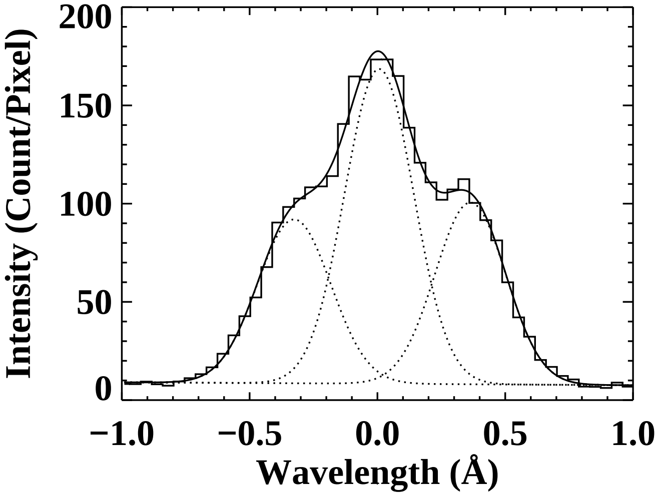

Figure 1. A typical explosive event seen in the Si IV $\lambda1402$ line profile observed by SOHO/SUMER. The profile consists of three components, one stationary and two high velocity components (Paper II).

2. UV Explosive Events, Flux Cancellation, and Hα Upflow Events

UV explosive events which were first discovered from the High Resolution Telescope and Spectrograph (HRTS) experiments (Brueckner & Bartoe 1983; Dere, Bartoe & Brueckner 1989) are small-scale dynamic features which can be barely resolved at a spatial resolution of about $1''$. They ubiquitously occur in the quiet Sun as well as in active regions. Explosive events are characterized by very broad UV line profiles, and therefore have been considered to be a manifestation of small-scale magnetic reconnection (Porter & Dere 1991; Dere et al. 1991; Dere 1994). Recent observations performed by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) on board the Solar and Heliospheric Observatory (SOHO) confirm the magnetic reconnection origin of explosive events in a couple of ways. Firstly, the structure of the explosive events evolves in the manner predicted by theoretical models of magnetic reconnection (Innes et al. 1997). Figure 1 shows a typical explosive event seen in the Si IV $\lambda1402$ line profile. Note that the broad line profile is mainly due to the existence of the two high-velocity components: one blue-shifted and the other red-shifted. The velocities of these components are comparable to the local Alfvén speed, demonstrating the bi-directional jet nature of the explosive event. It was also found from SOHO/SUMER that explosive events preferentially occur at the regions with weak and mixed polarity fluxes, and the majority of explosive events occur as bursts during magnetic flux cancellation which usually lasts longer than 1 hour (Paper I). Since flux cancellation is usually considered to be a result of magnetic reconnection (e.g., Wang & Shi 1993), the observed association be-

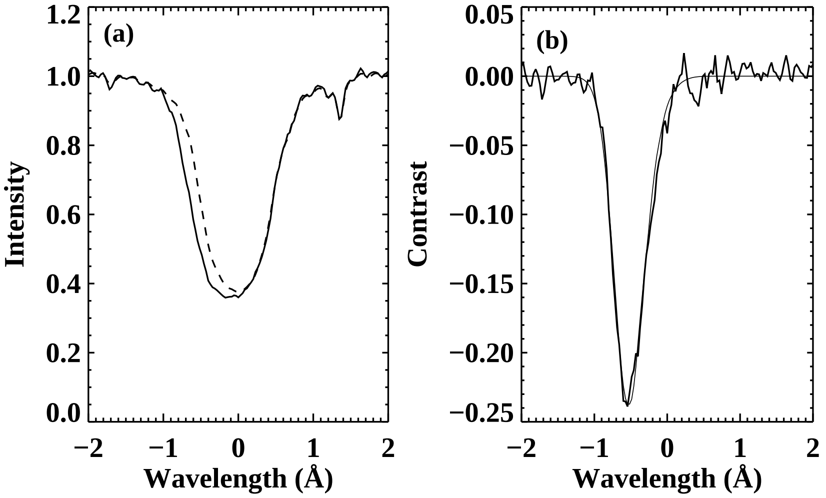

Figure 2. (a) Hα profiles of the average Sun (dashed curves) and a chromospheric upflow event (solid curve). (b) The Hα contrast profile (thick curve) and its cloud model fit (thin curve) (Paper II).

tween flux cancellation and explosive events is further evidence of the magnetic reconnection origin of explosive events.

Chromospheric upflow events are short-lived events which display blueshifts in Hα which were first discovered by Wang et al. (1998). A typical upflow event seen in the Hα line is presented in Figure 2. As seen from the contrast profile, the event appears dark and highly visible at the wavelength Hα-0.6 Å , but is not easily visible at the line center and the red wing. This characteristic can be well explained by the existence of an upward-moving cloud which can either absorb or scatter the Hα light incident from below (Wang et al. 1998; Chae et al. 1998b, hereafter, Paper II). Hα upflow events appear physically distinct from spicules in that they have a round and compact shape, are visible only in the blue wing, display only blueshifts, and are found in both network (Wang et al. 1998) and intranetwork areas (Paper II). That upflow events are related with magnetic reconnection was inferred from the finding of the association between upflow events and converging magnetic dipoles (Wang et al. 98), and was supported by the later finding of the associations among upflow events, flux cancellation and explosive events (Paper II). It was found that chromospheric upflow events are similar to explosive events in size, lifetime, and mass density (see Table 1), and in that both the kinds are recurrent at the same place. But they have different temperatures and velocities so that they may represent different kinds of plasma ejection.

What are the physical relationships among photospheric flux cancellation, Hα upflow events, and UV explosive events, which appear to be associated with one another? Answering this question requires a self-consistent picture of small-

Table 1. Typical Parameters of Transition Region Explosive Events and Chromospheric Upflow Events (Ref. (1) Dere 1994; (2) Paper II).

Parameter	Explosive event	Upflow event
Size	1500 km (1)	1500 km (2)
Lifetime (FWHM)	60 s (1)	60 s (2)
Bulk motion	100 km s^{-1} (1)	20 km s^{-1} (2)
Nonthermal motion (ξ)	35 km s^{-1} (2)	$<$ 10 km s^{-1} (2)
Temperature	10^5 K (1)	10^4 K (2)
Electron density	7×10^{10} cm^{-3} (1)	3×10^{10} cm^{-3} (2)
Mass density	$1{\times}10^{-13}$ g cm^{-3} (1)	$1{\times}10^{-13}$ g cm^{-3} (2)
Global birthrate	600 s^{-1} (1)	?

scale magnetic reconnection occurring in the quiet Sun, including the driving source of the magnetic reconnection. Paper II proposed that chromospheric upflow events represent the cool plasma material flowing into regions of magnetic diffusion whereas explosive events are a manifestation of the hot plasma material flowing out of the regions. This proposition can explain at least two important observational facts about explosive events: their lifetime and why explosive events are not seen in lines cooler than 4×10^4 K. But the origin of the upflow events was not explained in Paper II. In the next section, I propose a two-step magnetic reconnection which attributes the upflow events to the dynamical development of magnetic islands formed by slow magnetic reconnection occurring in the low atmosphere.

3. A Two-Step Magnetic Reconnection Model

Our two-step magnetic reconnection model is schematically drawn in Figure 3. According to this picture, there are two kinds of magnetic reconnection: the first step magnetic reconnection occurring in the lower atmosphere and the second step magnetic reconnection occurring in the upper atmosphere. The first step magnetic reconnection is driven by the converging motion of two flux systems of opposite polarities like network-intranetwork and intranetwork-intranetwork collisions due to supergranular flow. The converging motion slowly develops a current sheet in the interface of two flux systems, which contains two Y-type neutral points and one O-type neutral points. The reconnected field lines above the upper Y point float upward and eventually form the overlying field lines in the upper atmosphere whereas the reconnected field lines below the lower Y point sink and eventually disappear from the photospheric level, which we identify with photospheric flux cancellation. On the other hand, the O-type neutral point forms a magnetic island which grows with flux pile-up due to the converging motion. After reaching a critical value of magnetic flux, the magnetic

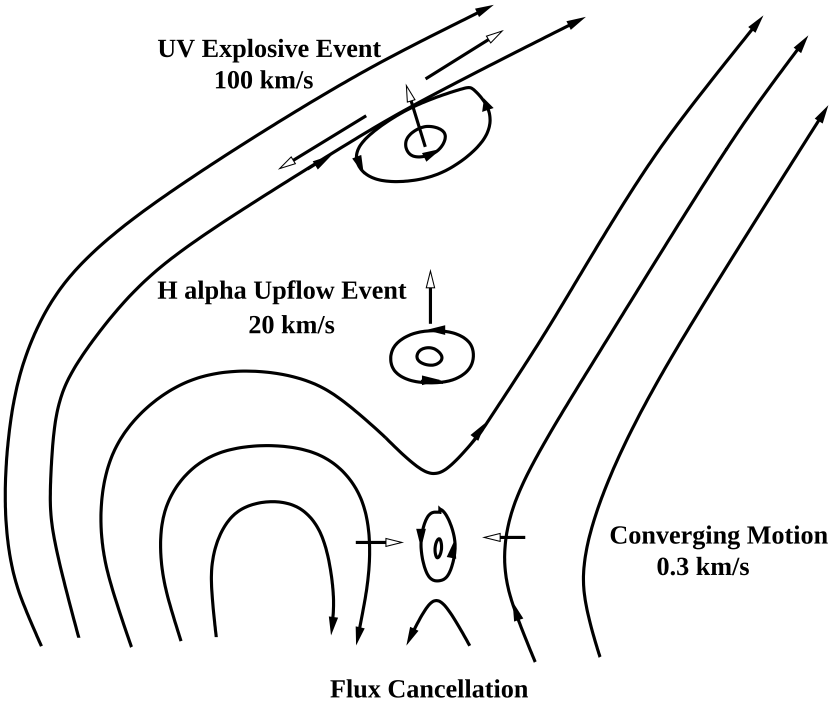

Figure 3. A schematic drawing of the two-step magnetic reconnection model.

island may become dynamically unstable and begins to move either upward or downward. These processes in the low atmosphere proceed slowly and steadily, forming and ejecting magnetic islands continually.

The second step magnetic reconnection is driven by an upward moving magnetic island. As the magnetic island moves upward, it expands and is accelerated to have a size and a velocity large enough to be observable in the Hα line, which we identify with chromospheric upflow events. The magnetic island collides with the overlying field lines, forms current sheet in the interface, and eventually drives the second magnetic reconnection. During the magnetic reconnection, the cool material carried by the magnetic island is injected into the overlying field lines to be heated and accelerated, leading to explosive events. Since the magnetic island carries a finite amount of mass and magnetic flux, this process lasts for only a short period. A series of magnetic islands successively colliding with the overlying field lines cause this process to happen recurrently in the same region.

In this two-step reconnection model, the origin of chromospheric upflow events is attributed to the development of magnetic islands produced by the first magnetic reconnection in the lower atmosphere. For this idea to be physically plausible, we should be able to answer the following questions: 1) Can a magnetic island be formed during the first magnetic reconnection in the low atmosphere?

2) Is the magnetic island large enough to carry sufficient mass for an upflow event? 3) What accelerates the magnetic island to produce the upflow event? We address to these questions one by one below.

The structure of a magnetically non-neutral reconnection current sheet was studied in detail by Somov (1992) based on a two-dimensional steady flow assumption. One of the important results is that a slow magnetic reconnection has an O-type magnetic configuration at the central zone of the current sheet whereas a fast magnetic reconnection has a X-type magnetic field configuration which is consistent with the Petschek model. The speed of magnetic reconnection is characterized by the dimensionless parameter $\alpha = \frac{w}{h}\frac{v_{\rm A}}{v_{\rm in}}$ where w, h, v_{rmA}, and $v_{\rm in}$ are the thickness and the length (height) of the current sheet, the local Alfv'en speed, and the inflow speed. Somov(1992) showed that if α is greater than a critical value α_c — i.e., if the magnetic reconnection is slow enough —, magnetic islands are formed inside the current sheet. He estimated α_c to be about 1.28. Recently, Oreshina & Somov (1998) found that α_c can be as low as 0.1 if radiative losses are taken into account. The thickness of the current sheet, w, is determined by the electrical conductivity, σ, and the inflow speed, and is roughly given by $w = \frac{c^2}{4\pi\sigma v_{\rm in}}$. Thus we see that the conditions of magnetic island formation are a small electrical conductivity and a small inflow speed if the length of the current sheet and the Alfvén speed are taken to be constant.

The first magnetic reconnection occurring in the low atmosphere in our schematic model is likely to be a slow magnetic reconnection and thus form magnetic islands. First of all, it is driven by a small converging motion due to the supergranular flow, which is typically 0.3 km $\rm s^{-1}$ (e.g., Wang et al. 1996; Zhang et al. 1998). Secondly, there is observational evidence that there exist very cool regions in the low atmosphere, especially around the temperature minimum region (e.g., Ayres & Rabin, 1996), so that those regions should have a very low value of electrical conductivity, as asserted by Feldman (1993). The electrical conductivity at the temperature minimum can be as low as 1×10^{10} $\rm s^{-1}$ according to Wang's (1993) calculation, which is about 10^{-6} times the coronal value. The small inflow speed and electrical conductivity produces a fairly large estimate of the current sheet thickness, 2.4 km. The mass density at the temperature minimum is about 5×10^{-9} g $\rm cm^{-3}$ (e.g., Vernazza et al. 1981). The magnetic field field strength at the same level of flux cancelling region may be smaller than 500 G which is known as a typical intrinsic field strength of the intranetwork magnetic element (Keller et al. 1994). Choosing 200 G as an estimate of the field strength at the temperature minimum, leads to an estimate of $v_{\rm A}$, 8 km $\rm s^{-1}$ at the same height. Thus the first magnetic reconnection must be slow and have the O-type magnetic field configuration if h is smaller than 50 km (no radiative loss) or 640 km (radiative loss). It appears that these values are physically plausible since they are roughly of the same order as an estimate of the intranetwork magnetic element diameter, 100-200 km (e.g., Wang et al. 1995). On the other hand, the second magnetic reconnection occurring in the upper atmosphere is not likely to be a slow magnetic reconnection. The electrical conductivity at 10^5

K is as high as 10^{14} s^{-1}, and the inflow speed is 20 km s^{-1} which is equal to the typical velocity of Hα upflow events. The thickness of the current sheet is then estimated to be 3.6×10^{-6} km. The Alfvén speed is about 100 km s^{-1}. Thus we see that the second magnetic reconnection could be slow if h is smaller than 1.3×10^{-5} km (no radiative loss) or 1.8×10^{-4} km (radiative loss). It appears that these values are physically unrealistic since they are extremely small compared with the size of the explosive events, 1500 km. This means that the second magnetic reconnection should be a fast magnetic reconnection which displays an X-point magnetic configuration.

Now let's examine whether the mass in a magnetic island formed during the first magnetic reconnection can account for the mass carried by an upflow event. The mass of an upflow event is estimated to be about $L^3\rho = 3 \times 10^{11}$ g if we use $L = 1500$ km and $\rho = 1 \times 10^{-13}$ g cm^{-3}. On the other hand, the mass of the magnetic island is of the order of $M = whl\rho$ where l is the length of the current sheet in the direction of invariance. The length l can inferred from the flux loss rate, $l = \frac{d\Phi/dt}{v_{\rm in}B}$ and is estimated to be 100 km if we use $d\Phi/dt = 6\times10^{13}$ Mx s^{-1} (Paper I). Thus M is estimated to be in the range between 6×10^{10}–8×10^{11} g depending on the choice of h. This range is comparable to the mass of an upflow event, 3×10^{11} g.

It is quite likely that the so-called *diamagnetic melon seed* mechanism (e.g., Pneuman 1983) will eject and accelerate the magnetic island. The magnetic island is carrying a current whose direction is opposite to the directions of the currents that create the ambient quadrupolar magnetic fields so that the island must be expelled from the current sheet either upward or downward. Once the magnetic island is accelerated, its speed is soon as large as the Alfvén speed unless the effect of gravity is large. Thus a magnetic island ejected upward may have a velocity greater than the Alfvén speed at the temperature minimum, 8 km s^{-1}, since the Alfvén speed usually increases with height. This will explain the typical observed velocity of upflow events, 20 km s^{-1}. That a magnetic island can be formed in the current sheet of a quadrupolar magnetic field geometry and is ejected at a local Alfvén speed was also demonstrated by numerical simulations (e.g., Karpen et al. 1995).

4. Conclusion

I have proposed a two-step magnetic reconnection model to explain in a self-consistent way the three kinds of observed phenomena – photospheric flux cancellation, Hα upflow events, and UV explosive events which are closely associated with one another. This model chooses the temperature minimum region as a preferential height for the slow magnetic reconnection which is directly responsible for flux cancellation. In particular, it is demonstrated that this model can explain the physical origin of the mass and velocity of Hα upflow events. High spatial and high temporal resolution observations of flux cancelling features which can cover simultaneously photosphere, temperature minimum region, chromosphere and transition region may be able to provide further evidence either for or against the proposed model.

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