OBSERVATIONAL SIGNATURES OF SIMULATED RECONNECTION EVENTS IN THE SOLAR CHROMOSPHERE AND TRANSITION REGION

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ABSTRACT

We present the results of numerical simulations of wave-induced magnetic reconnection in a model of the solar atmosphere. In the magnetic field geometry we study in this paper, the waves, driven by a monochromatic piston and a driver taken from Hinode observations, induce periodic reconnection of the magnetic field, and this reconnection appears to help drive long-period chromospheric jets. By synthesizing spectra for a variety of wavelengths that are sensitive to a wide range of temperatures, we shed light on the often confusing relationship between the plethora of jet-like phenomena in the solar atmosphere, e.g., explosive events, spicules, and other phenomena thought to be caused by reconnection. Our simulations produce spicule-like jets with lengths and lifetimes that match observations, and the spectral signatures of several reconnection events are similar to observations of explosive events. We also find that in some cases, absorption from overlying neutral hydrogen can hide emission from matter at coronal temperatures.

Key words: magnetic fields – MHD – Sun: chromosphere – Sun: transition region

Online-only material: mpeg animations

1. INTRODUCTION

The Sun displays a bewildering array of jet-like phenomena that can be observed at many different wavelengths and in many different regions. At the limb, we find spicules, protrusions of cool gas that can reach heights of 6–10 Mm and have lifetimes of several minutes (e.g., Beckers 1968), and that are observed in chromospheric lines such as Hα and Ca ii H. There are also larger and longer-lasting jets such as surges and macrospicules. Recently, faster and shorter-lived jets, called type II spicules, have been found (De Pontieu et al. 2007b), many lasting less than 100 s before fading from view. Hinode observations were instrumental in finding these, but have also shown a large amount of other jet activity in Ca H and other lines (e.g., Katsukawa et al. 2007; Shibata et al. 2007).

On the disk, mottles show much of the same behavior as spicules, and we can also observe shorter-lived dynamic fibrils in the same lines. In higher-temperature ultraviolet (UV) lines such as C iv, Si iv, and O vi, we observe short-lived explosive events and longer-lasting blinkers. The former, in particular, have very wide line profiles indicating strong bidirectional jets (Brueckner & Bartoe 1983; Dere et al. 1991; Innes et al. 1997).

There have been investigations into whether some of these terms simply describe different aspects of the same basic phenomena, e.g., spicules and mottles (Grossmann-Doerth & Schmidt 1992; Tsiroupana et al. 1994), blinkers and explosive events (Chae et al. 2000), spicules and explosive events (Wilhelm 2000), spicules, blinkers, and explosive events (Madjarska & Doyle 2003), or spicules, macrospicules, and surges (Blake & Sturrock 1985). Different authors often conclude differently, and the matter cannot be considered settled. Part of the problem is that we usually lack cotemporal, cospatial observations across several wavelength bands, so that we most often cannot trace events across different temperatures and with enough spatial and temporal resolution to elucidate the relationship between the various features. Another complication is that we cannot observe the exact same phenomenon both on the disk and at the limb, for simple geometric reasons. Simulations can be very helpful here in letting us change our vantage point at will.

The driving mechanism of the various jets is in general not well established. The main candidates have been waves (magnetoacoustic or Alfvén) and magnetic reconnection. There are strong indications that acoustic shock waves cause dynamic fibrils (Hansteen et al. 2006; De Pontie et al. 2007a; Heggland et al. 2007) and that reconnection causes explosive events (Dere et al. 1991; Innes et al. 1997; Chae et al. 1998; Muglach 2008), but the case is more open for the other types of jets. It has been noted by, e.g., Chae et al. (1998), Ning et al. (2004), and Doyle et al. (2006) that many explosive events occur in bursts, often with intervals of 3–5 minutes. These periods correspond to the dominant wave modes produced by the solar granulation, suggesting that such waves may induce or modulate reconnection events.

A review of various spicule models can be found in Sterling (2000). Most models so far are in one dimension, assuming a rigid magnetic flux tube either with or without expansion. Some use a piston driver, either at a given frequency or randomized, while others use a sudden increase in pressure and temperature as a trigger mechanism for setting up shocks. This pressure increase is often assumed to be in the photosphere, but Shibata et al. (1982) and Sterling et al. (1993) have investigated the effects of energy input in the upper chromosphere as well, producing different types of jets that have similar properties to spicules or surges. The source of the energy input is usually not specified, though reconnection could be a natural candidate, as speculated by Sterling et al. (1993).

Two-dimensional simulations containing an actual magnetic field (as opposed to treating it merely as a given rigid flux tube) have been performed by Takeuchi & Shibata (2001a, 2001b). They studied photospheric reconnection which they claim produces a large enough wave energy flux to drive spicules, but their actual simulation box does not extend past the lower chromosphere.
Explosive events have been modeled in one dimension by Erdélyi et al. (1999) and Sarro et al. (1999). Two-dimensional simulations of explosive events have been performed by Karpen et al. (1995), Innes & Tóth (1999), Roussev et al. (2001a, 2001b, 2001c), and Chen & Priest (2006). Again, the one-dimensional simulations generally assume a rigid flux tube geometry, and treat the magnetic reconnection not explicitly, but as a sudden deposition of energy at a specified height. The two-dimensional simulations often assume a simplified magnetic geometry with vertical antiparallel field lines. Karpen et al. (1995) use a more complicated magnetic field geometry with some similarities to the one used in this paper, as well as three-dimensional magnetic field and velocity components, but do not include radiative losses or heat conduction in their simulations.

In this paper, we present the results of two-dimensional simulations that include the effects of radiation and heat conduction, and that involve a complex magnetic field geometry in which reconnection events are induced by waves propagating upward from the photosphere/convection zone. We do not attempt to match the results to specific observations, but show the signatures of these events in several chromospheric, transition region and lower coronal spectral lines, and viewed both on the disk and at the limb of the Sun.

2. SIMULATIONS

The model atmosphere is similar to the one used by Heggland et al. (2007), but now the lower boundary of the domain reaches down to the upper photosphere, as opposed to the chromosphere. The simulation box extends about 11 Mm in height, going from the photosphere through the chromosphere, transition region and lower corona. The lower boundary, \( z = 0 \), corresponds to a height of 150 km in the VAL3C model (Vernazza et al. 1981). The simulation box contains 201 \times 191 grid cells, using a uniform spacing of 50 km in the horizontal direction and a non-uniform spacing in the vertical direction, starting at 16 km in the chromosphere and transition region and increasing exponentially in the corona, reaching 220 km at the upper boundary. In Figure 1, we have plotted the initial temperature distribution with magnetic field lines and curves of equal plasma \( \beta \), the latter defined as the ratio between the thermal and the magnetic pressure.

The magnetic field configuration is a potential field, with a central flux tube which progressively widens with height and ends up dominating the field in the corona. However, there are also two inclined flux tubes, one on each side of the center. These tubes both end up in magnetic null points, located at transition region heights (\( z = 1.75 \) Mm, \( x = 2.6 \) Mm, and \( x = 7.4 \) Mm). The null points can be seen in Figure 1 as \( \beta \) maxima that are very small in spatial extent. It is near these null points that the reconnection events we study in this paper occur. Finally, there are two outer flux tubes that open into the corona.

It should be noted that this null point configuration is somewhat peculiar to the two-dimensional geometry, and would be difficult to reproduce exactly in a three-dimensional model, or indeed on the real Sun. We have chosen it as a configuration that is conducive to reconnection, while being reasonably representative of field conditions in a network environment with weak field nearby.

The code we use is the same three-dimensional MHD code that was used in, e.g., Heggland et al. (2007) and Martínez-Sykora et al. (2008), and is described in more detail in the

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**Figure 1.** Initial temperature structure, with overplotted \( \beta \) contours (white) and magnetic field lines (green). The red line between \( x = 4 \) and \( x = 5 \) Mm marks the location of the piston. The magnetic null points show up as local maxima of the \( \beta \) at \( z = 1.75 \) Mm and \( x = \{2.6, 7.4\} \) Mm.
latter paper and by Rosenthal et al. (2002), Hansteen (2005),
and Hansteen et al. (2007). It should be noted that it contains a
realistic radiative loss function based on collisional excitation
of hydrogen, carbon, oxygen, neon, and iron, as well as thermal
conduction along the magnetic field. Martínez-Sykora et al.
(2008) contains an explanation of the methods and equations
used. Since our simulation box does not include the convective
layers and lower photosphere included in that paper, we include
only the optically thin part of the radiative loss function, i.e.,
Equation (5) from Martínez-Sykora et al. (2008) is not included.

The upper coronal boundary is maintained at 1 MK, while
radiation and heat conduction set the temperature structure in
the rest of the domain. There is a heating term preventing the
temperature in the lower atmosphere from falling much be-
low 2000 K, and in addition, the upper boundary acts as a
heat reservoir to balance the radiative losses. It is a trans-
mitting boundary based on characteristic extrapolation of the
hydrodynamic variables. At the lower boundary, we set the
velocity field directly based on the properties of the driver.
It is therefore closed and reflecting, but as there are no ex-
ternal sources of downward propagating waves, any that are
present will be due to refraction or reflection within the box,
E.g., from the transition region. Such waves and their potential
re-reflections appear to have little effect on the dynamics of the
system.

In the models presented here, we operate with a magnetic
diffusivity \( \eta \) many orders of magnitude larger than that on
the Sun, and dissipation starts at much smaller magnetic field
gradients. The dissipated energy is

\[
Q_{\text{diss}} = E \cdot J.
\]

where \( J = \nabla \times B \) is the current density and the resistive part of
the electric field is given by

\[
E_{i} = \left\{ \frac{1}{2} (\eta_{x}^{(1)} + \eta_{z}^{(1)} \sim + \frac{1}{2} (\eta_{x}^{(2)} + \eta_{z}^{(2)}) J_{i}, \right. \)

and similar for \( E_{y} \) and \( E_{z} \).

The numerical diffusivities we use are split into two parts;
the first takes care of truncation errors in advection and in wave
motions, the second deals with magnetic “shock” diffusion.
As the wavelength of a sound or magnetoacoustic wave
approaches the grid size, the numerical propagation speed
decreases rapidly and phase errors occur; the propagation
of small-scale disturbances does not occur at the relevant
characteristic speed for the wave. To counter this effect, the
amplitude of short-wavelength waves must be damped at a rate
that is comparable to the growth of the phase error; likewise for
the error introduced by advection at the fluid velocity \( u \). Thus,
our diffusion coefficient in the \( j \) direction is constructed as

\[
\eta_{j}^{(1)} = \Delta x_{i} (k_{1} c_{f} + k_{2} |u_{j}|),
\]

where \( j \) takes the values \( x, y, \) and \( z \); \( k_{1,2} \) are dimensionless
diffusion coefficients of order unity and \( c_{f} \) is the fast mode
speed.

In analogy with Equation (3), we adopt a weak magnetic
diffusivity

\[
\eta_{j}^{(2)} = \frac{\Delta x_{i}^{2}}{Pr_{M}} k_{1} |\nabla_{\perp} \cdot u_{j}|.
\]

The expression for the magnetic shock diffusion accounts
for the fact that the magnetic field is only influenced by the
perpendicular part of the velocity field. We adopt a magnetic
shock diffusivity that is proportional to the local convergence of
the perpendicular velocity field;

\[
\eta_{j}^{(2)} = \frac{\Delta x_{i}^{2}}{Pr_{M}} \eta_{i} \nabla_{\perp} \cdot u_{j}.
\]

This term prevents the collapse of a magnetic flux tube that is
nearing the limit of numerical resolution. As long as resistive
effects are small, the magnetic field lines are carried passively
by the flow; however, when a patch of magnetic field becomes
highly concentrated to a few grid points diffusion rises enough
to balance the convergence.

In order to have as little diffusion as possible in regions where
it is not needed, we use a third-order derivative to concentrate
diffusion to high gradient locations. Thus, our diffusion operator
in one dimension is of the form

\[
\frac{\partial f}{\partial t} = \ldots + v \frac{\partial f}{\partial x} \left( \frac{\partial f}{\partial x} \right),
\]

where

\[
Q (g) = \frac{\partial}{\partial x} \left( \left| \frac{\partial f}{\partial x} \right| \right) \frac{|g|}{|g| + \frac{1}{\alpha} \frac{\partial f}{\partial x} \left( \frac{\partial f}{\partial x} \right)}. \]

The “hyper-diffusivity” thus defined makes it possible to run the
code with a global diffusivity that is at least a factor 10 lower than
without it. (The use of hyper-diffusivity also makes it impossible
to give a single value of the Reynolds and magnetic Reynolds
numbers for a simulation.) The choices made here are discussed
at much greater length by Nordlund & Galsgaard (1995).

In the simulations, we investigate the effects of different
locations and methods of driving, and how the produced waves
can trigger reconnection. In one case, we use a monochromatic
localized piston with 300 s period and 1.1 km s\(^{-1}\) amplitude,
representing values typical of solar granulation, driving the
lower boundary in the vertical direction at \( z = 0 \) Mm between
\( x = 4 \) Mm and \( x = 5 \) Mm (marked with a red line in Figure 1).
In another, we use a driver taken from observations with
Hinode/ SP (B. Lites 2009, private communication), producing waves at
all locations along the lower boundary and in a more realistic
range of periods. The data were obtained on 2007 October
22 and contain the line-of-sight velocities in a slice across a
network element. The detailed composition of this time series is
plotted in Figure 2. The series has a 1 minute cadence, and linear
interpolation between these points is performed in the code.

We also experiment with putting the null points at different
heights in the atmosphere. In one case, they are located in the
transition region at a height of about 1.75 Mm above the
lower boundary, as in Figure 1; in another, they are in the upper
chromosphere, some 450 km lower.

3. ANALYSIS

3.1. Transition Region Null Points, Piston Driver

3.1.1. General Description of Events

We first look at the case with null points in the transition
region and the localized piston driver as described above. Due
to the varying magnetic inclination in the region of the piston, it
will generate a mixture of fast and slow mode waves. In low-\( \beta \)
regions, which include the piston location as well as most of the simulation box, the fast modes can propagate everywhere, though they tend to be refracted into regions of low Alfvén velocity (e.g., Osterbrock 1961), such as null points. The slow modes are mainly restricted to propagation along the magnetic field.

The waves disturb the field as they travel, and once the disturbance reaches the null points, reconnection is triggered as lines of opposite polarity are pushed together and meet. This process releases a significant amount of energy in a short time and leads to very rapid heating of the plasma; in the stronger events, the plasma around the null points reaches coronal temperatures of roughly 1 MK. In addition, a bidirectional jet is formed, as plasma is rapidly accelerated away from the reconnection region.

Since the lines of opposing polarity are located quite close to each other around the null point, only a small disturbance is required to start off the reconnection process the first time. This happens soon after the start of the simulation, as fast mode waves generated by the piston in the central flux tube propagate upward and reach the transition region in as little as 10–12 s. There, they are refracted away from the high Alfvén speed region in the center of the box (see Figure 3) and move instead toward the sides, where they reach the magnetic null points and push the field lines together, triggering reconnection.

The piston, driving generally along the field in a magnetically dominated (i.e., low-β) plasma, is more efficient at generating slow mode than fast mode waves, so these initial fast disturbances have low amplitude—around 1 km s$^{-1}$ just before reaching the transition region—but this is enough to push the field lines above and below the null point into each other and trigger a weak reconnection event. This leads to moderate heating of the reconnecting region and the formation of a bidirectional jet, with high velocities upward to the left and downward to the right (Figure 4, left panel). The jets reach maximum velocities of around 70 km s$^{-1}$ toward the left and 35 km s$^{-1}$ toward the right, an asymmetry that is mainly a consequence of the different densities in the regions the jets propagate into. The null point geometry means that the Alfvén speed varies significantly in the surrounding region, so direct comparisons between the jet and Alfvén speeds are of limited value; that said, the jet speeds are superalfvenic in a few grid zones near the null point but only around one quarter of the Alfvén speed at the velocity maxima.

After some 160 s, or half a driver period later, the piston driven disturbance changes sign, and starts pulling the field lines above and below the null point away from each other. Instead, the lines to the left and right of the null point are pushed together, and reconnection occurs again, this time in a direction perpendicular to the original reconnection event. Another bidirectional jet is formed, this time being mostly vertical, and the region around the null point (now embedded entirely in cooler chromospheric gas) is heated to coronal temperatures. This heated region spreads out along the jets and the magnetic field, and creates a butterfly-shaped region of heated plasma (Figure 4, left center panel).

The orientation of the upward-moving jet changes as the reconnection continues, and it rotates from being directed upward to the right (mainly across the field lines) to being directed somewhat to the left (mainly along the field lines). The latter orientation allows the gas to move much more freely, and the hot plasma is soon accelerated upward along the field lines with great speed (Figure 4, right center panel). As it passes the now mainly sideways moving cool jet generated by the first reconnection, it pushes some of that cool gas upward as well and greatly extends the length of the cool jet, which reaches a maximum height of $z = 8 \text{ Mm}$.

This pattern then repeats itself, with reconnection being triggered every 150 s (i.e., every half period), alternating...
between vertical and horizontal orientation, and propelling both cool and hot jets upward. The later events are not as strong as the first one, and are quite similar to each other. An example of a later horizontally oriented reconnection jet is shown in the right panel of Figure 4.

### 3.1.2. Synthesized Limb Observations

In order to get an impression of how these jets would look if observed at the solar limb, we have used the non-LTE radiative transfer code MULTI (Carlsson 1986) to calculate the population densities of the different excitation levels of Ca\textsc{ii} ions in our simulations. In the side views, we have chosen to concentrate on the Ca\textsc{ii} H line at 3968 Å. In a two-dimensional model, it is not possible to do a full radiative transfer calculation along a line perpendicular to the plane of the computational box, but the population density of the upper level of this transition serves as a rough approximation of the actual intensity.

In Figure 5, we show plots of the logarithm of the calculated Ca\textsc{ii} H upper level density (upper left, henceforth and in the figure captions referred to as the Ca signal), the logarithm of the mass density from the MHD simulation data (upper right), the velocity along the magnetic field (lower left), and the plasma temperature with overplotted magnetic field lines (lower right), after 226 s. At this time, reconnection with vertically oriented jets is happening near the left-hand null point, while a horizontally oriented event is happening near the right-hand null point—though the jet on the right-hand side of it is field-aligned and has turned upward quite sharply. The cooler jets show up in Ca\textsc{ii} as rather thin, elongated features, similar to spicules or fibrils. In contrast, the hotter jets, and the reconnection regions themselves, show no Ca\textsc{ii} signal. The hot jet on the right does have a density enhancement (upper right panel), but it and the regions around the null points are heated to temperatures of about 1 MK, far above the temperature where calcium gets multiply ionized, which explains the lack of Ca\textsc{ii} emission. The high velocities of the reconnection jets are clearly visible in the lower left panel.

The cooler jets are seen to rise and fall; in Figure 6, we show the situation after 364 s, when the cool jet seen on the left in Figure 5 has reached its maximum extent, after being pushed upward by the hot jet from the reconnection event at 200–240 s (see Figure 4). It reaches a height of nearly 8 Mm.

In Figure 7, we see a later, thinner cool jet on the left, which shows up only weakly in Ca\textsc{ii}. The density plot (upper right) tells us why: its density appears to be too low, even though it is in about the right temperature range.

The typical lifetimes of the cool jets are 200–300 s, and they reach maximum lengths of 6–8 Mm above the photosphere. Their thickness varies a lot with time, but is typically slightly less than 1 Mm. These figures are roughly within the ranges reported for spicules (Beckers 1968). However, it is important to look at the whole range of spectral, spatial, and temporal data available before trying to establish correspondence between simulations and observations.

### 3.1.3. Synthesized Disk Observations

In producing synthesized disk observations, we look into the simulation box directly from above, in the plane of the box. A proper radiative transfer treatment is then possible, and has been carried out for the Ca\textsc{ii} IR line at 8542 Å, widely used in spectroscopic studies. The calculations have been made column by column, i.e., neglecting any radiative interaction in the x-direction. A simplified treatment based only on collisional excitation has been carried out for the optically thin lines of C iv (1548 Å), O vi (1032 Å), and Fe xii (195 Å). These latter lines will typically be formed in the transition region or lower corona, whereas the Ca IR line is formed in the chromosphere. In the treatment of the Fe line, which has a wavelength shorter than the Lyman threshold at 912 Å, we have included the effects of absorption by neutral hydrogen and neutral and singly ionized helium.

λ–τ plots of these lines, looking directly down on the center of the reconnection region at \( \lambda = 2.6 \) Mm, are shown in Figure 8. The C, O, and Fe lines have had their resolution and cadence downgraded to typical instrumental values of 650 km (about 1”) and 20 s, and are plotted using logarithmic scaling to bring out details in the weaker later events. Ca is plotted at 150 km resolution and 2 s cadence, using linear scaling.

In the transition region lines, there is a sudden onset of a very bright, very broad feature, with upflows of 80–90 km s\(^{-1}\) and downflows of 60–80 km s\(^{-1}\). This happens first in C iv, the lowest temperature line, at 160 s, then in O vi at 180 s (with a weaker signal at 160 s). This feature is caused by the sudden heating and the powerful bidirectional jet generated by the reconnection. These spectra show significant similarities to observations of explosive events (Brueckner & Bartoe 1983; Dere et al. 1991; Innes et al. 1997; Chae et al. 2000; Muglach 2008), which are believed to be caused by reconnection. Dere (1994) finds that explosive events have typical lifetimes of 60 s, spatial extents of about 1.5 Mm, and typical Doppler shifts of 100 km s\(^{-1}\), though both higher and lower durations and Doppler shifts have been reported. The figures match up well.
Figure 5. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with transition region null points and piston driver. The elapsed time is 226 s. Reconnection is producing a butterfly-shaped, vertically oriented heated region and jet on the left, and a hot TR jet on the right.

(An mpeg animation of this figure is available in the online journal.)

Figure 6. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with transition region null points and piston driver. The elapsed time is 364 s. The spicule-like cool jet on the left has reached its greatest length, extending nearly 8 Mm above the photosphere.
with our results; the main parts of the brightenings fade away after 60 s and the spatial extent is roughly in the quoted range (see Figures 4 and 5). Observations also often show redshift and blueshift in different positions along the slit. This phenomenon is present to some degree in our simulations as well, and is a natural consequence of the inclination of the bidirectional jets—the more the inclination deviates from the vertical, the greater the separation between the red- and blueshifted component.

The profiles are asymmetric, with larger blueshifts than redshifts, and in particular the C and O lines have a short-lived blueshift of 140–150 km s\(^{-1}\) at 220 s. On the other hand, the intensity maximum is redshifted. This behavior can be readily understood in terms of the density stratification. The reconnection outflow jets are expected to propagate outward at the Alfvén speed, which is inversely proportional to the square root of the density. Hence, the jets propagating upward in a stratified medium should be faster than those propagating downward, leading to an asymmetry like the one we find. The blueshift maximum between 220 and 240 s happens when the heated jet, which is initially embedded in material at chromospheric temperatures (Figure 5), enters the corona where the Alfvén speed increases markedly. Meanwhile, the compression effect of the jet should be stronger for the part propagating downward into denser material, leading to higher emission at slight redshifts.

The temperature in the reconnection region gets high enough to produce significant emission also in the Fe \text{XII} line, but it is quite strongly affected by neutral hydrogen absorption. The first powerful event is completely absorbed because the reconnection region at that time is located under a small jet with at least 1 Mm of chromospheric material above it. The first horizontal jet reconnection event shows up weakly at around 400 s, but strong blue- and redshifts are not seen until the vertical jet at 500 s. The intensity maximum is in a horizontal jet at around 680 s, at which time there is hardly any chromospheric material above the reconnection region.

The chromospheric Ca \text{II IR} line shows signs of activity before any of the higher-temperature lines. A relatively strong upflow (15 km s\(^{-1}\)) is caused after less than 100 s by the first weak reconnection episode. This upflow is soon reversed, and after 150 s the first major reconnection happens, changing the line center from a redshift of 20 km s\(^{-1}\) to 0 almost instantly, while also yielding a significant blueshifted component with speeds up to 30 km s\(^{-1}\).

After this violent first event, several periodic weaker reconnection events follow. In these, the line only undergoes significant redshifts, with very little evidence of blueshifts. This indicates that the line’s main formation height is below the reconnection region. The other lines show periodic weaker brightenings, though still with quite high velocity. In every other event, the main jets are oriented horizontally, leading to smaller Doppler shifts. The intensity decrease is mainly due to reduced density in the reconnection region; the reconnection jets cause a large outflow of material, and because the inflow (amplified by the waves) soon triggers another reconnection event, the area never recovers its initial density. This is also responsible for the slight core darkening seen in later C \text{IV} events—with the reduced density, the emission mainly comes from the compressed upward- and downward-moving shock fronts while the tenuous matter in the center of the reconnection region quickly gets heated out of the passband. This effect is less pronounced for the higher-temperature O \text{IV} line.
3.2. Chromospheric Null Points, Piston Driver

3.2.1. General Description

These simulations use a piston driver of the same period (300 s) and amplitude (1.1 km s\(^{-1}\)) as in the previous section. However, here the magnetic null points are located around 450 km lower in the atmosphere, putting them in the upper chromosphere rather than in the lower transition region. The basic geometry of the magnetic field is not changed, as we can see in Figure 9; the only difference is a translation of the whole geometry to lower heights.

3.2.2. Synthesized Limb Observations

Figure 9 shows the simulation, viewed from the side, at the time when the first and most powerful reconnection event has reached its maximum, at around 260 s elapsed time. Once more, we have plotted the Ca H signal (upper left), the logarithm of the mass density (upper right), the field-aligned velocity (lower left), and the temperature (lower right). We clearly see the butterfly-shaped region of higher temperature (lower right) and the fast bidirectional jet (lower left), although the latter is now going upward much faster than downward due to the plasma being able to more easily propagate along the magnetic field. The beginnings of a jet can be seen in Ca H (upper left), although the heated region is too hot (and to some extent too evacuated) to show any Ca signal.

In Figure 10, we show the situation as the cool jet reaches its maximum extent, 90 s later. As could be expected, the velocity signal is weak at this point, and the region around the null point is no longer heated to coronal temperatures. The jet shows up clearly in Ca, but reaches a maximum height of only about 4.5 Mm, as compared to 8 Mm when the null points are located in the transition region. The general pattern described above repeats itself periodically every 300 s, with progressively slower and shorter jets.

Overall, this case is quite similar to the case with higher null points described in the previous section. The jets are slower and shorter because of the higher density surrounding the null points, resulting in lower acceleration for similar force.

3.2.3. Synthesized Disk Observations

Figure 11 shows \(\lambda-t\) diagrams of C IV, O VI, Fe XII, and Ca II IR as they would appear looking straight down at the center of the reconnection region (\(x = 2.6\) Mm), as for the high null point case in Section 3.1. The resolution is also the same as used previously. In C IV and O VI, we get bidirectional signals spaced 300 s apart, with Doppler shifts of 40–60 km s\(^{-1}\), but little other signal. In Fe XII, the events give no visible signal, and we just see the background emission. The reason for the low Fe emission is
Figure 9. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with chromospheric null points and piston driver. The elapsed time is 260 s. The outflow speed from the reconnection region on the left is at its maximum.
(An mpeg animation of this figure is available in the online journal.)

Figure 10. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with chromospheric null points and piston driver. The elapsed time is 354 s. The extent of the cool jet is at its maximum, 4 Mm above the photosphere.
Figure 11. Spectra of the chromospheric null point piston driver case, centered at $x = 2.6$ Mm and using logarithmic scaling for the UV lines and linear scaling for Ca. C and O show largely symmetric profiles with maxima on each reconnection event with vertical jets. Fe shows only the background emission. Ca has a complex line profile with multiple components.

Figure 12. Ca spectrum with Doppler shifts (grayscale) in the chromospheric null point piston driver case, with velocities at $z = 0.93$ Mm (solid line) and $z = 1.37$ Mm (dashed line) superimposed. The former fits well with the line center position, while the latter is a reasonable match for the blueshifted spikes and their following redshifts.

...a combination of the relatively lower temperature reached in the region heated by reconnection and greater absorption by neutral hydrogen due to the deeper location of the reconnection region. The UV lines are in general more symmetric in this simulation, because the hot jet does not reach the perturbed transition region and corona before being cooled.

The Ca line, though, appears highly complex in this simulation. It exhibits both absorption and emission, as well as strong Doppler shifts into both red and blue. In observations, such a spectrum would be difficult to make sense of. However, we have the full simulation data to work with, including the velocity at all heights. In fact, at least two different velocity components can be identified as being responsible for the appearance of the spectrum, as shown in Figure 12. The line center closely follows the vertical velocity at a height of 0.92 Mm, below the magnetic null point, as marked with a solid white line in the figure. The strongest blueshifted signal, which later passes through the line center and becomes redshifted, corresponds reasonably well to the vertical velocity at a height of 1.37 Mm (dashed line), just above the null point, which is located at 1.30 Mm. These two velocity components are in counterphase as a result of the bidirectional jet produced by the reconnection.

This nicely illustrates the fact that spectral lines are formed over a range of heights, rather than at one specific height, and that care must be taken when using them as probes of atmospheric conditions. But it also illustrates that such a multi-component signal could be used as evidence of reconnection via the characteristic bidirectional velocity pattern, as long as the reconnection happens in the height range where the line is formed. By contrast, in our simulation with null points in the transition region, we observe only downflows in the Ca line...
because it is then primarily formed below the null points and reconnection region.

3.3. Transition Region Null Points, Hinode Driver

3.3.1. General Description

In this simulation, we go back to the magnetic configuration of the first simulation studied (Section 3.1), where the null points are located in the transition region. However, instead of using a localized, monochromatic piston driver, we use velocity data obtained with Hinode/SP (as described in Section 1) to drive the whole lower boundary. As before, we will not attempt to match the simulation to specific observations; the data simply serve as a more random and realistic velocity driver with a wider range of frequencies than our monochromatic piston.

3.3.2. Synthesized Limb Observations

Using the Hinode driver changes a number of things. In general, the velocity field in the atmosphere becomes much more complex. On the left-hand side, the first reconnection has its jet oriented vertically, as opposed to the horizontal orientation we get in the runs with a piston driver. This is a result of the different phase of the first waves to reach the null point. In this case, as the reconnection happens in the transition region, only the hotter material above the null point is ejected upward, and there is little cool material above the null point to be accelerated by later reconnection events. As a result, only few and short cool jets are formed at all.

At the right-hand side null point, no significant reconnection happens until 130 s, but then a quite major event occurs, with its jet oriented vertically. This leads to the ejection of a powerful hot jet, as seen in Figure 13. The jet is too hot to show up in Ca. This latter reconnection event is actually quite long lasting, the flow direction only being reversed at 290 s, and then only for 90 s before another 170 s period of vertically oriented recon-
Figure 15. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with transition region null points and Hinode driver. The elapsed time is 326 s. This figure shows the longest of the cool jets that appear in this simulation.

The sustained event releases quite a bit of energy from the magnetic field and changes its structure fairly significantly; among other things, the null point is moved down into the chromosphere by 3–400 km (Figure 14). Later jets are fairly weak, the cool ones reaching only around 1 Mm above the transition region (Figure 15).

The long duration of the event is likely a result of the specifics of the driver. On the right-hand side of the box, the input velocity only rarely changes sign, leading to a fairly continuous flow in one direction, rather than the periodic reversals of the piston driver.

3.3.3. Synthesized Disk Observations

Because the null point in this simulation displays significant movement, both horizontally and vertically, and because the jets tend to follow the magnetic field, which is slightly inclined even in the lower corona, we can find interesting phenomena at several different locations when looking down as we would do if the events happened on the solar disk. We calculate the same C, O, Fe, and Ca lines as above, and use the same spatial resolution and exposure times.

In Figure 16, we show λ–t plots of the different spectra centered at x = 7.6 Mm. This is the place where the transition region and coronal lines have their highest intensities, looking straight down on the reconnection region. The C IV line shows little bidirectionality in this case, having its maximum at redshifts of around 25 km s^{-1}. The O VI line is bidirectional, but has much higher intensity in the red. The Fe XII line is more extended, but also has its maximum at the same redshift. This line not only includes emission from the region immediately surrounding the null point, but also from the upward propagating fast hot jet between x = 8 and x = 9 Mm. A spectrum centered at x = 8.45 Mm showing this jet in more detail is shown in Figure 17. We can see the strong signature of the fast hot jet and its deceleration between 160 and 340 s. It reaches an impressive blueshift of roughly 160 km s^{-1}, matching the maximum field-aligned velocity from the simulation data.

The Ca II IR line shows only redshifts for this event (130–200 s), some of them rather powerful (up to 20 km s^{-1}), and exhibits strong central reversal at around 140 s, when the plasma is significantly heated by the reconnection. The later Ca spectrum is more complex, likely showing several overlapping velocity components as in the low null point piston driver case in Section 3.2, as well as the effects of the movement of the null point itself. Of course, the velocity input from the Hinode driver includes a wide spectrum of frequencies rather than the single one of the piston, which serves to further complicate the simulated Ca spectrum.

The effects of having the null point move several hundred km downward are visible in the Ca signal in some locations. In Figure 18, we show a portion of the spectrum at x = 7.9 Mm. Between 680 and 780 s, there is a clear blueshifted excursion, similar to what we saw in the spectra of the simulations with chromospheric null points (Figures 11 and 12). By the time of this event, the right-hand null point in this simulation is at a height of 1.4 Mm (Figure 14), very close to the height of the null points in the other simulation.

3.4. Chromospheric Null Points, Hinode Driver

3.4.1. General Description

In this simulation, we again use the magnetic configuration that puts the magnetic null points in the chromosphere,
use the same Hinode driver as in the previous section. Once again this leads to extensive reconnection near the right-hand null point, but because that is now embedded in chromospheric plasma, it produces a major cool jet rather than the hot one produced when the null points are in the transition region. Again, the reconnection changes the field and pushes the null point lower in the atmosphere after about 500 s (Figure 19). Later jets are fairly weak and do not extend far above the transition region; neither do the jets produced by the weaker events at the left-hand null point. Some jets are also produced by shock waves propagating from the lower boundary, especially in the magnetic channel connecting to \( x = 2 \) Mm—the shock fronts are clearly visible in movies of the field-aligned velocity. This process is similar to the one that produces dynamic fibrils (Hansteen et al. 2006), but the jets produced this way tend to reach heights of no more than 0.5 Mm above the transition region in this simulation.

3.4.2. Synthesized Limb Observations

In Figure 20, we show the Ca H signal, density, temperature, and field-aligned velocity at 216 s elapsed time, when the region heated by the first powerful reconnection event has reached its maximum extent. We see that the upper part of that region follows the field lines upward; the total length of the heated region is more than 2 Mm. We also see the high velocity of the jet. Note that the heated region gets too hot to show up in the Ca signal.

Figure 16. Spectra of the high null point Hinode driver case, centered at \( x = 7.6 \) Mm. The UV lines use logarithmic scaling and the Ca line uses linear scaling. The C and O lines show mainly redshifts because the matter moving upward is heated out of their passbands. Fe shows not only the signal of the heated area around the reconnection point, but also of the fast hot jet to the side of it, shown in more detail in Figure 17.

Figure 17. Fe XII spectrum of the high null point Hinode driver case, centered at \( x = 8.45 \) Mm and using logarithmic scaling. This spectrum shows the very fast hot jet and its considerable blueshift of 160 km s\(^{-1}\).
In Figure 21, we show the situation at 350 s, when the cool jet has reached its maximum extent. As we see, it reaches a height of nearly 8 Mm above the lower boundary, or 6 Mm above the transition region. This cool jet shows up quite strongly in Ca, and has a notable density enhancement compared to the surrounding corona. The velocity, as one would expect, is close to zero at this time.

This jet does not form a perfect parabola in a \( z-t \) diagram (it ascends slightly faster than it descends), but the best parabolic fit, using the method of De Pontieu et al. (2007a) and Heggland et al. (2007), yields a maximum velocity \( v_{\text{max}} \) of 52 km s\(^{-1}\), a deceleration \( d \) of 250 m s\(^{-2}\), and a duration \( P \) of roughly 430 s. Although these values fall outside the range studied by Heggland et al. (2007) in their study of shock-wave-driven dynamic fibrils—in particular, the maximum velocity is much higher than would reasonably develop through steepening of acoustic waves alone—they are a pretty good fit to the formula predicted and found in that paper, namely,

\[
d = \frac{v_{\text{max}}}{P/2};
\]

not too surprisingly since the jet is driven by a shock, albeit one generated by reconnection rather than directly by photospheric motions. The shock front can be traced back to the reconnection region in movies.

3.4.3. Synthesized Disk Observations

In Figure 22, we show the simulated \( \text{C} \text{iv}, \text{O vi}, \text{Fe xii}, \) and \( \text{Ca ii} \) spectra looking down on \( x = 7.65 \) Mm. As in the other cases, the TR lines are plotted at 650 km and 20 s resolution, and the Ca spectrum at 150 km and 2 s.

C, O, and Fe all have huge maxima in connection with the first reconnection event, centered at 180–200 s—even with a lower intensity cutoff of \( 10^{-4} \) times the maximum intensity, as in all the UV spectral plots, only Fe shows any part of the background signal. The event shows up as a clear bidirectional jet in all three,

![Figure 18. Ca ii IR spectrum of the high null point Hinode driver case.](image)

with 50–70 km s\(^{-1}\) velocities, even up to 90 km s\(^{-1}\) in O vi. C and O have some of the same asymmetry as in the TR null point piston driver case (Section 3.1), with slightly higher blueshifts than redshifts and slightly redshifted intensity maxima.

In Ca, we get strong emission and a redshift of 17 km s\(^{-1}\) for this event. Later on, the spectrum gets more complex, as usual with the \( \text{Hinode} \) driver. However, it is notable that after the null point moves down at around 500 s, the Ca spectrum, although largely symmetric, mainly shows excursions into the blue wing, since the primary formation height is now above the reconnection region. This makes a nice contrast with the mainly redshifted excursions of the high null point piston driver case (Figure 8), where the null point is located almost 900 km higher up.

3.5. Energy Release Estimates

In Figure 23, we have plotted the energy release rate in the form of joule heating (\( j^2/\sigma \), where \( j \) is the current density and \( \sigma \) is the conductivity) in our four simulations. The energy release is calculated over the reconnection region, in this case defined as the region around the null point where the joule heating is above 5% of the value at the null point. The results are not very sensitive to the particular value of the threshold, and changing it from 1% to 10% changes the calculated energy release by less than 10%. In the piston driver cases, we include the region around the right-hand null point, while we use the right-hand one in the \( \text{Hinode} \) driver cases.

As we would expect from the side views and spectra, the greatest peaks in the energy release occur in the transition region null point piston driver case (upper panel, solid line) and the chromospheric null point \( \text{Hinode} \) driver case (lower panel, dashed line). The two piston driver cases are more regular, with double peaks (horizontal, then vertical jets) appearing every 300 s. The \( \text{Hinode} \) driver cases have second peaks appearing between 600 and 800 s, and the energy release is actually greater in these events than in the first one at around 200 s, but the later events show only weak observational signatures. This is because the jets of these events are horizontally oriented, giving no Doppler shifts in the simulated spectra and not very tall
Figure 20. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with chromospheric null points and Hinode driver. The elapsed time is 216 s. A powerful reconnection event is happening at the right-hand null point, heating a large area and propelling a cool jet upward at great speed.

(An mpeg animation of this figure is available in the online journal.)

Figure 21. Plots of the Ca signal (upper left), density (upper right), field-aligned velocity (lower left), and temperature with magnetic field lines (lower right) in the case with chromospheric null points and Hinode driver. The elapsed time is 350 s. The cool jet has reached its maximum extent, 8 Mm above the photosphere.
Figure 22. Spectra of the chromospheric null point Hinode driver case, centered at $x = 7.65$ Mm. The UV lines use logarithmic scaling and the Ca line linear scaling. All lines have huge maxima when the first major reconnection event happens. Fe is largely symmetric while the C and O lines have asymmetries similar to those in Figure 8. Ca, formed at the lowest height, is redshifted, but the later signal is shifted more toward the blue after the null point moves to lower heights.

4. DISCUSSION AND SUMMARY

These simulations have been able to produce a number of jet phenomena through the same basic mechanism of wave-induced magnetic reconnection; in the Hinode driver cases reconnection is also induced by less periodic flows. In particular, these appear to be the first two-dimensional simulations to show the formation of spicule-like jets as a result of reconnection, while including most important physics; the main omission is time-dependent ionization. The simulated spicules match observed lifetimes and lengths.

In this model of spicule formation, we also expect a brightening and broadening of UV lines at the footpoint of the spicule at the start of its lifetime; the heated plasma causing this is in general cooled down on a shorter timescale than the lifetime of the spicule. This UV bright point is a property our model shares with most earlier models that assume a sudden energy/pressure deposition as the source of spicules, rather than a velocity perturbation at photospheric heights. Although UV bright points are frequently observed in connection with spicules, some observations (e.g., Suematsu et al. 1995) indicate that this brightening happens after the ascending phase of the spicule, rather than at the beginning. This timing problem is not resolved by our model.

The UV brightenings that are produced in the reconnection regions have many of the same properties as observed explosive events, which could point toward a possible connection between jets, and also because the energy release happens over a longer period of time than at the first peak, at least in the case with chromospheric null points.

The energy release rate is given in J m$^{-1}$ s$^{-1}$ because the total energy release will be dependent on the size of the reconnection region in the third dimension. In order to calculate the total energy release, we must assume an extent, and this value will necessarily be somewhat arbitrary. Observations report an average length along the slit of about $2''$; we have used the slightly lower value of 1 Mm in Table 1 since the strength of real three-dimensional events would not be constant across their whole extent. The released energy per event is comparable to the generally assumed values for nanoflares, though not all the energy released in these events will be in the form of joule heating.

### Table 1
Energy Release Per Reconnection Event

| Case               | First Event | Strongest Later Event |
|--------------------|-------------|-----------------------|
|                    | Energy (J)  | Duration (s)          | Energy (J)  | Duration (s) |
| TR np/piston       | $2.46 \times 10^{18}$ | 280                  | $1.08 \times 10^{18}$ | 280 |
| Ch. np/piston      | $1.10 \times 10^{18}$ | 280                  | $8.38 \times 10^{17}$ | 280 |
| TR np/Hinode       | $1.00 \times 10^{18}$ | 240                  | $1.43 \times 10^{18}$ | 260 |
| Ch. np/Hinode      | $6.62 \times 10^{17}$ | 100                  | $1.44 \times 10^{18}$ | 280 |
some spicules and explosive events, as suggested by Wilhelm (2000). One of the plasma acceleration mechanisms suggested in that paper, a slingshot effect Wilhelm 2000; Figure 8) may be happening at times in our model; see, for example, the left center panel of Figure 4, where the mass flow is perpendicular to the field lines and chromospheric matter is propelled upward by several hundred km. On the other hand, flow along the field proves much more effective in lifting chromospheric material in our simulations (right center panel of Figure 4 and lower two panels of Figure 5); different field geometries could give different results. If there is such a connection, it is in only likely to apply to a subset of spicules, since the two phenomena are only sometimes seen in the same region, and there are far more spicules than explosive events.

Although our UV brightenings match many of the properties of explosive events, there are also some differences. Our events are generally very bright, with maximum intensities 50–100 times higher than the “quiet” profiles—in some cases, even 1000 times for the most powerful initial events. Although some explosive events have strong brightenings, the majority are not particularly bright—Innes (2001) quotes typical brightening factors of 2–5. Also, we get significant signal in the lower coronal Fe xii 195 Å line, while explosive events rarely show up in coronal lines (e.g., Muglach 2008). Erdelyi et al. (1999) show one example of an explosive event brightening in TRACE 171 Å, but since it does not show up in the lower-temperature Mg x 625 Å line, they interpret it as a brightening of a transition region O vi line within the passband rather than the coronal Fe x line.

In one of our cases (Figure 11), we also find only very weak Fe xii emission. Since the heating is quite strongly localized to the reconnection region, it becomes a blob of coronal plasma surrounded by low-temperature chromospheric material. In the low-temperature region, neutral hydrogen is present in significant proportions, and this leads to strong Lyman absorption of all lines with shorter wavelengths than 912 Å. This, combined with the heating events themselves being relatively weak, explains the lack of Fe emission in this case, and could also do the same for observed explosive events if in fact they occur relatively deep in the chromosphere. However, the C and O lines will be unaffected by this absorption, and are still stronger than observed. Also, the high velocities observed in many explosive events indicate a quite high formation height. One possible explanation for the discrepancy may be that our reconnection events are simply more energetic than those responsible for most explosive events. The temperatures reached are high enough (>1 MK) that they might even have an X-ray signal. Another, perhaps more likely, explanation is that geometric effects play a significant role which these two-dimensional simulations cannot fully simulate. A three-dimensional flux system could be less confining and therefore drive cooler, less energetic events.

It should be noted that even the very strong first event in the TR null point piston driver case is completely absorbed by the neutral hydrogen above it. Therefore, the absence of observed signal in high-temperature lines does not necessarily mean that the plasma is not heated to such temperatures, as the emission could be absorbed by overlying cool matter. In observations, one could check this with coronal lines at longer wavelengths than the Lyman threshold at 912 Å.

Finally, wave-induced reconnection offers a natural explanation for the repetitive behavior sometimes observed in explo-
sive events (e.g., Chae et al. 1998; Ning et al. 2004). If these events are caused by reconnection induced by waves, we would naturally expect repetition at timescales of 3–5 minutes, corresponding to the dominant periods in the solar chromosphere and photosphere.

We have found a number of striking similarities between our simulation results and observations. However, the complexity of the signals in our synthetic spectra and images shows that it is not surprising that the many different jet-like phenomena are observed in the solar atmosphere have been, and remain to some extent, such a puzzle. For example, in the same simulations, with similar magnetic field geometry and driver, we find at different times jets that show significant chromospheric signal without transition region or coronal counterparts, jets that show only blueshifts in the chromosphere, jets that show only redshifts in the chromosphere, jets that do not show chromospheric signatures but are dominated by bidirectional flows in the transition region, and jets in the transition region lines that do not show any coronal counterpart. This is a natural consequence of the complex mix of magnetic field geometry, the history of the plasma motions, the narrow height/temperature range in which the observables are formed, and the varying mix of heating and acceleration in reconnection events. As a result, establishing the relationship between various types of events in the solar atmosphere is a challenging task that can only be solved through statistical comparisons of spatiotemporal data of high quality with advanced radiative MHD models.

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