ORIGIN OF MACROSPICULE AND JET IN POLAR CORONA BY A SMALL-SCALE KINKED FLUX TUBE

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ABSTRACT

We report an observation of a small-scale flux tube that undergoes kinking and triggers the macrospicule and a jet on 2010 November 11 in the north polar corona. The small-scale flux tube emerged well before the triggering of the macrospicule and as time progresses the two opposite halves of this omega-shaped flux tube bent transversely and approach each other. After ~2 minutes, the two approaching halves of the kinked flux tube touch each other and an internal reconnection as well as an energy release takes place at the adjoining location and a macrospicule was launched which goes up to a height of 12 Mm. Plasma begins to move horizontally as well as vertically upward along with the onset of the macrospicule and thereafter converts into a large-scale jet in which the core denser plasma reaches up to ~40 Mm in the solar atmosphere with a projected speed of ~95 km s⁻¹. The fainter and decelerating plasma chunks of this jet were also seen up to ~60 Mm. We perform a two-dimensional numerical simulation by considering the VAL-C initial atmospheric conditions to understand the physical scenario of the observed macrospicule and associated jet. The simulation results show that reconnection-generated velocity pulse in the lower solar atmosphere steepens into slow shock and the cool plasma is driven behind it in the form of macrospicule. The horizontal surface waves also appeared with shock fronts at different heights, which most likely drove and spread the large-scale jet associated with the macrospicule.

Key words: magnetohydrodynamics (MHD) – Sun: chromosphere – Sun: corona

Online-only material: color figures, animations

1. INTRODUCTION

Macrospicules are giant spicules, mostly observed in polar coronal holes, reaching heights up to between 7 and 45 Mm above the solar limb with lifetimes of 3–45 minutes (e.g., Bohlin et al. 1975; Sterling 2000; Wilhelm 2000). A number of mechanisms have been proposed for the formation of such plasma ejecta, e.g., gas pressure pulse (Hollweg 1982) and velocity pulse (Suematsu et al. 1982; Murawski et al. 2011). Shibata (1982) suggested that if reconnection takes place in the upper chromosphere/lower corona (lower chromosphere/photosphere), the macrospicule can be triggered due to magnetic reconnection (the evolution of slow shocks). Alternative mechanisms have also been reported for the formation of such plasma ejecta (e.g., Moore at al. 1977; Habbal & Gonzalez 1991; Mustsevoi & Solovev 1997; De Pontieu et al. 2004; Kamio et al. 2010 and references therein).

Besides the spicules and macrospicules in the lower solar atmosphere, the large-scale jets have a significant role in mass and energy transport up to the higher corona, as well as in destabilizing large-scale coronal magnetic fields leading to the eruptions (e.g., Innes et al. 1997; Isobe & Tripathi 2006; Chifor et al. 2006, 2007; Culhane et al. 2007; Filippov et al. 2009; Tripathi et al. 2009; De Pontieu et al. 2009, 2011; Judge et al. 2012). Using STEREO/EUVI (Kaiser et al. 2008), a variety of solar jets on the basis of their sizes and lifetimes have been reported (Nisticò et al. 2009). The magnetic reconnection was found to be one of the drivers of coronal jets (Yokoyama & Shibata 1995; Innes et al. 1997; Culhane et al. 2007; Chifor et al. 2008; Filippov et al. 2009; Nishizuka et al. 2008). Pariat et al. (2009) have shown that reconnection-generated nonlinear Alfvén waves can produce polar coronal jets. Alternatively, the MHD pulse-driven models are also employed for triggering various large-scale solar jets (e.g., Srivastava & Murawski 2011; Srivastava et al. 2012; Kayshap et al. 2013 and references therein), and are supported by recent observations (Morton et al. 2012).

The interrelationship of spicules and jets is also important for understanding their formation processes. Kamio et al. (2010) have shown the association of the jet with the macrospicule, which was triggered by a twisted magnetic flux rope. Close association of the polar surges with macrospicules is also reported by Georgakilas et al. (2001). Moore et al. (2011) have suggested that granule-size emerging bipoles (EBs) can trigger the longer spicules and associated Alfvén waves, while larger EBs can form X-ray jets. In this Letter, we report the first evidence of the activation of a small-scale bipolar twisted flux tube in the lower polar corona, which undergoes internal reconnection and triggers a macrospicule and associated coronal jet. We study the relationship between the formation of a macrospicule and its associated jet, as well as their most likely triggering mechanism using Solar Dynamic Observatory (SDO)/Atmospheric Imaging Assembly (AIA) observations and numerical simulations. In Section 2, we discuss the observations of a macrospicule and its associated jet. In Section 3, we present the results of our numerical simulations. We outline our discussion and conclusions in the final section.

2. OBSERVATIONS OF THE MACROSPICULE AND ASSOCIATED JET

High-resolution observations (0′.6 pixel⁻¹ with cadence 12 s) from the AIA on board SDO, using its various filters sensitive to the plasma at different temperatures (Cheimets et al. 2009; Del Zanna et al. 2011; Lemen et al. 2012; O’Dwyer et al. 2010), recorded the origin of a macrospicule and its associated polar jet on 2010 November 11 (cf. Figure 1 and MS-Jet-304.mpeg).
For this study, we have used a 304 Å image sequence to study the triggering of the macrospicule and jet that occurred at the north pole of the Sun.

Figure 1 (top panel) displays some selected snapshots of SDO/AIA 304 Å during the evolution of the macrospicule and its associated jet. A bipolar, omega-shaped, small-scale flux tube emerges at the polar cap around 00:58:08 UT (top left panel). During the evolution of this flux tube between 00:58:08 and 00:59:44 UT (~96 s), the flux tube shows some transverse bending of magnetic surfaces on both of its halves that may be a signature of the evolution of kink perturbations (cf. blue arrows in the snapshot 00:58:44–00:58:56 UT and schematic in the bottom panel). The combined effect of the apparent rotation and transverse bending generates a kinked flux tube at smaller spatial scales, which undergoes internal reconnection and further leads the macrospicule and jet (cf. MS-Jet-304.mpeg). To the best of our knowledge, this is the first direct observation of the evolution of kink perturbations in a small-scale flux tube, which further enables internal reconnection and leads to the formation of the macrospicule and its associated jet that move along ambient open field lines (cf. Figure 2 and the schematic in Figure 1). The two halves and legs of the flux tube come closer to each other and merge to produce a brightening (cf. snapshot on 00:59:44 UT), which is very likely a signature of internal magnetic reconnection between the two opposite halves of a small-scale flux tube. A macrospicule is triggered at the same time (cf. 01:00:56 UT snapshot in Figure 2 and the schematic in Figure 1). The macrospicule reaches up to a height of ~12 Mm with a speed of about 80 km s\(^{-1}\) and fades within ~4 minutes. During this time, a jet-like feature evolved which grew in vertical as well as horizontal directions (cf. 01:00:56–01:02:08 UT snapshots in Figure 2). The detailed plasma dynamics can be seen in the online animation associated with Figure 2. We also investigated other high-temperature filters of AIA (e.g., 171, 211, 193 Å) where jet plasma fronts are clearly evident; however, the macrospicule material is only visible in the 304 Å channel (cf. the online animations). Figure 3 displays a slit position along the macrospicule and jet (left panel) and the corresponding height–time diagram (right panel). The two paths represented by pink and yellow colors, respectively, show the ejecting and downflowing jet material. The denser core of the large-scale jet plasma reaches a height of ~40 Mm with a speed of ~95 km s\(^{-1}\), while some fainter traces of it are evident up to ~50–60 Mm. In the first ~10 minutes, the large-scale jet plasma material was seen to be moving upward and later it began to fall back toward the surface within a total lifetime of ~24 minutes. The average outflow speed and acceleration in the fast rising phase of the jet were ~95 km s\(^{-1}\) and 89.015 m s\(^{-2}\), thereafter plasma shows some deceleration over the parabolic path. While the average downflow speed and downward acceleration in the rapid inflowing phase of the jet are, respectively, 154 km s\(^{-1}\) and −649.99 m s\(^{-2}\).

The small-scale flux tube in the polar corona, which is most likely imposed by the kink perturbations due to the asymmetric bending of magnetic surfaces on both of its halves, creates a reconnection diffusion region on the temporal scale of ~96 s. This region has a length of \((2L) \sim 12\) Mm, which is the height of the emerged flux tube at 00:58:08 UT. The width \((2S) \sim 3.6\) Mm, which is the separation between the two opposite halves of the kinked flux tube (cf. snapshot on 00:58:08 UT in Figure 1). The two opposite halves of the small-scale flux tube approach each other with a supersonic speed of ~37 km s\(^{-1}\) (sound speed in chromosphere is 15 km s\(^{-1}\)) and reconnect. The height of the reconnection site is ~3.0 Mm from the anchored footprint of the tube, suggesting chromospheric/TR reconnection which may trigger the evolution of slow shocks excited by the velocity pulse (Shibata 1982; Murawski et al. 2011; Kayshap et al. 2013) and the observed plasma dynamics. Considering this as a basic scenario, we numerically simulate the observed macrospicule and jet dynamics.
Figure 2. Macrospicule triggers on 00:59:44 UT due to the reconnection between the opposite halves of flux tube, as shown in Figure 1, and finally converts into a jet (cf. 01:02:08–01:06:08 UT snapshot). The comprehensive dynamics of the macrospicule and jet are shown in the online movie. The schematic in Figure 1 also depicts the scenario of the formation of macrospicule and jet along ambient open field lines.

(Animations and a color version of this figure are available in the online journal.)
3. NUMERICAL MODEL OF THE MACROSPICULE AND JET

We perform a two-dimensional MHD numerical simulation to understand the physics of the observed macrospicule and jet using the FLASH code (Lee & Deane 2009) with an assumption that the polar corona is gravitationally stratified. The set of equations solved using the FLASH code are as follows:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \]  \hspace{1cm} (1)

\[ \frac{\partial \mathbf{V}}{\partial t} + \rho (\mathbf{V} \cdot \nabla) \mathbf{V} = -\nabla p + \frac{1}{\mu} (\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \mathbf{g}, \]  \hspace{1cm} (2)

\[ \frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{V}) = (1 - \gamma) p \nabla \cdot \mathbf{V}, \]  \hspace{1cm} (3)

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}), \quad \nabla \cdot \mathbf{B} = 0. \]  \hspace{1cm} (4)

Here \( \rho, \mathbf{V}, \mathbf{B}, p = (k_B/m)T, T, \gamma = 5/3, \mathbf{g} = (0, -g), \) with its value \( g = 274 \text{ m s}^{-2}, m, k_B, \) are, respectively, the mass density, flow velocity, magnetic field, gas pressure, temperature, adiabatic index, solar gravitational acceleration, mean particle mass, and Boltzmann’s constant. Radiative cooling and thermal conduction are not included in our model, as we are only interested in the dynamics at this instance.

3.1. Equilibrium Configuration

We assume that the solar atmosphere is in the static equilibrium \( (\mathbf{V}_e = 0) \) with a force-free magnetic field,

\[ (\nabla \times \mathbf{B}_e) \times \mathbf{B}_e = 0, \]  \hspace{1cm} (5)

such that it satisfies the current free condition, \( \nabla \times \mathbf{B}_e = 0, \) and it is specified by the magnetic flux function, \( A, \) as

\[ \mathbf{B}_e = \nabla \times (A \hat{z}). \]  \hspace{1cm} (6)

Here the subscript “e” corresponds to equilibrium quantities.

We set a weakly curved arcade type magnetic field configuration by choosing

\[ A(x, y) = B_0 \Lambda_B \cos (x/\Lambda_B) \exp \left[-(y - y_e)/\Lambda_B \right]. \]  \hspace{1cm} (7)

Here, \( B_0 \) is the magnetic field at the reference level, which is the initial location of the pulse \( y = y_e, \) and the magnetic scale height is

\[ \Lambda_B = 2L/\pi. \]  \hspace{1cm} (8)

We set and hold fixed \( L = 200 \text{ Mm} \) and \( y_e = 10 \text{ Mm}. \)

As a result of Equation (5), the pressure gradient is balanced by the gravity force:

\[ -\nabla p_e = \rho_e \mathbf{g} = 0. \]  \hspace{1cm} (9)

With the ideal gas law and the \( y \)-component of Equation (9), we arrive at

\[ p_e(y) = p_0 \exp \left[ -\int_{y_t}^{y} \frac{dy'}{\Lambda(y')} \right], \quad \rho_e(y) = \frac{p_e(y)}{g \Lambda(y)}, \]  \hspace{1cm} (10)

where

\[ \Lambda(y) = k_B T_e(y)/(mg) \]  \hspace{1cm} (11)

is the pressure scale height, and \( p_0 \) denotes the gas pressure at the reference level that we choose in the solar corona at \( y_t = 10 \text{ Mm}. \)

We take an equilibrium temperature profile \( T_e(z) \) (cf. bottom left panel in Figure 4) for the solar atmosphere that consists of the VAL-C atmospheric model of Vernazza et al. (1981) and obtain the corresponding gas pressure and mass density (not shown) using Equation (10). In our simulation, the transition region is located at \( y \simeq 2.7 \text{ Mm}. \) An extended corona and a chromosphere are considered, respectively, above and below this with the requirement of a minimum temperature at \( y \simeq 0.9 \text{ Mm}. \)
3.2. Perturbations

We impulsively perturb the system in equilibrium by a Gaussian velocity pulse $V$ that is nearly parallel to the ambient magnetic field lines, viz.,

$$V_t(x, y, t = 0) = A_v \exp\left[-\frac{(x-x_0)^2 + (y-y_0)^2}{w^2}\right].$$

Here $A_v$ is the amplitude of the pulse, $(x_0, y_0)$ is its initial position, and $w$ is its width. We set and hold fixed $A_v = 7.5$ km s$^{-1}$, $x_0 = 0$ Mm, $y_0 = 0.9$ Mm, and $w = 0.2$ Mm.

3.3. Results of the Numerical Simulation

We set the simulation box as $(-10, 10)$ Mm $\times (0, 40)$ Mm and impose boundary conditions by fixing all plasma quantities to their equilibrium values in time for the $x$- and $y$-directions, while all plasma quantities remain invariant along the $z$-direction. In the study, we use an adaptive mesh refinement (AMR) grid with a minimum (maximum) level of refinement set to 3(8) (cf. top left panel in Figure 4). We launch the velocity pulse in the lower solar atmosphere, which is considered to be excited by the chromospheric/TR reconnection-generated energy between the opposite halves of the omega-shaped bipolar flux tube (cf. Equation (12)). As the pulse propagates in gravitationally stratified atmosphere, it converts into a slow shock at higher altitudes. As a result, a low-pressure region develops behind it and drives the cool chromospheric plasma upward. This lagging plasma exhibits the properties of the observed macrospicule.

Figure 5 displays key snapshots of the simulation results as the temperature map (color) and velocity (arrows) of the plasma. At 100 s (first image), the shock front of the initially launched pulse reaches up to $\sim 6$ Mm. The chromospheric plasma, however, lags behind the shock front and reaches up to a height of $\sim 4$ Mm. This lag is primarily due to the rarefaction of the plasma behind the shock front. Rarefaction is the low-pressure region behind the shock front and is due to the surrounding plasma falling back into the low-pressure region. The material falling back pushed back due to the larger photospheric density, which is basically lagging plasma. By the time the chromospheric plasma reaches a height of $\sim 10$ Mm at 250 s (see the right-top panel), the shock front has reached a height of more than 30 Mm. Our observational finding shows that the macrospicule reaches up to $\sim 12$ Mm with a width of $\sim 4$ Mm and a lifetime of $\sim 4$ minutes. The simulation results presented here approximately mimic the observed dynamics of the macrospicule, which is the propagation of cool plasma.
At \( t = 400 \) s, there are two bumps present on each side of the main macrospicule, which are very likely created by the secondary shocks. Due to these shocks, the base of the spicule becomes wider, i.e., the surrounding material is moving upward along with the macrospicule, which is most likely the plasma spreading as observed in the form of the initiation of the jet. At this moment, the central material is suppressed compared to the bumps due to the dominance of the downflowing material.
at the center. The bumps on each side of the central part reach up to $\sim 11$ Mm while that of the central part is suppressed up to $\sim 8$ Mm. The next snapshot ($t = 450$ s) again shows that the material in the central region continuously falls back toward the solar surface suppressing it while the sideways plasmas move upward in the solar atmosphere and most likely form the core of the jet. According to observations, the macrospicule fades, and the large-scale jet plasma evolves around it, which may have a striking similarity with this model result. This quasi-periodic rise and fall with a minimum timescale of 200 s of the cool chromospheric material is clearly visible over the longer duration in simulation due to the arrival of wave trains of slow shocks (cf. bottom right panel of Figure 4; Figure 5 and its online animation). This timescale, though, depends upon pulse strength, steepening of slow shocks, and their reflection from the transition region creating downflows. Moreover, the simulated plasma ejection creates horizontal surface waves at higher altitudes, which are clearly visible with comparatively high temperature shock fronts at different heights (cf. Figure 5 and the online animation). These surface waves may interact with various layers of the upper atmosphere up to 40 Mm (cf. Fedun et al. 2011) and most likely trigger the horizontal and vertical spread of the multitemperature jet (cf. the online animations). Quasi-periodic rise and fall of a comparatively cooler (cf. the online animation) macrospicule and its jet may not be evident in the observational baseline as the upcoming pulse trains may be absorbed by downfalling material (Srivastava & Murawski 2011).

4. DISCUSSION AND CONCLUSIONS

Using the high-resolution observations of SDO/AIA at 304 Å, we studied the detailed evolution of a macrospicule and its associated jet recorded on 2010 November 11. In addition, we performed numerical simulations to qualitatively match the observed macrospicule and jet using the VAL-C model of the solar atmosphere and the FLASH code. To the best of our knowledge, this is the first direct evidence of the formation of a macrospicule and associated jet due to the magnetic reconnection between two opposite halves of an emerging small-scale, kinked bipolar loop at a lower altitude in the solar corona. The observed kinked small-scale flux tube may also be a rotating helical structure that undergoes internal reconnection to trigger the jet (e.g., Patsourakos et al. 2008; Nisticò et al. 2009; Pariat et al. 2009). The triggering of the macrospicule was followed by the evolution of a large-scale jet. These types of kinked flux rope, internal reconnection, and related plasma dynamics were only observed in large-scale active regions, sometimes leading to large-scale coronal eruptions, e.g., prominences, coronal mass ejections, etc. (e.g., Török & Kliem 2004; Tripathi et al. 2007, 2009; Srivastava et al. 2010, 2013a, 2013b; Kliem et al. 2010 and references therein). However, the analogous conditions of the evolution of the kinked bipolar loop at a small spatio-temporal scale in the solar corona are observed for the first time as episodic mechanism for the triggering of the macrospicule and jet. The macrospicule reaches up to $\sim 12$ Mm with a projected speed of $\sim 80$ km s$^{-1}$ and had a lifetime of $\sim 4$ minutes. The brightened and core plasma of the large-scale jet reaches up to $\sim 40$ Mm in the solar atmosphere with a projected speed of $\sim 95$ km s$^{-1}$, and its lifetime was $\sim 24$ minutes. The standard jet models deal with the direct-reconnection-driven forces ($j \times B$) between the open and closed field lines in the corona leading to the jet plasma propulsion (Yokoyama & Shibata 1995; Nishizuka et al. 2008; Pariat et al. 2009). However, the present new episodic mechanism suggests that the internal reconnection in a small-scale loop in the lower chromosphere further generates a velocity pulse that steepens in slow-shock wave trains propagating through ambient open field lines and triggering the dynamics of macrospicule and jet.

Depending upon the height of the reconnection site inside the chromosphere/TR and the amount of energy release during reconnection within the small-scale flux tube (e.g., Shibata 1982; Murawski et al. 2011; Kayshap et al. 2013 and references therein), it most likely generates the velocity pulse that further converts into a slow shock and exhibits the features of macrospicule and associated jet. The excitation of surface waves and the motion of the shock fronts and associated plasma may be responsible for the formation of the observed solar jet. Our numerical results, therefore, approximately and qualitatively match the observed plasma dynamics. We conclude that the kinking and chromospheric reconnection in the small-scale flux tube can be an episodic mechanism to drive the observed macrospicule and associated jet via secondary consequences in the form of the evolution of the velocity pulse and its associated slow shocks.

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