JETS IN CORONAL HOLES: HINODE OBSERVATIONS AND THREE-DIMENSIONAL COMPUTER MODELING
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ABSTRACT

Recent observations of coronal hole areas with the XRT and EIS instruments on board the Hinode satellite have shown with unprecedented detail the launching of fast, hot jets away from the solar surface. In some cases these events coincide with episodes of flux emergence from beneath the photosphere. In this Letter we show results of a three-dimensional numerical experiment of flux emergence from the solar interior into a coronal hole and compare them with simultaneous XRT and EIS observations of a jet-launching event that accompanied the appearance of a bipolar region in MDI magnetograms. The magnetic skeleton and topology that result in the experiment bear a strong resemblance to linear force-free extrapolations of the SOHO/MDI magnetograms. A thin current sheet is formed at the boundary of the emerging plasma. A jet is launched upward along the open reconnected field lines with values of temperature, density, and velocity in agreement with the XRT and EIS observations. Below the jet, a split-vault structure results with two chambers: a shrinking one containing the emerged field loops and a growing one with loops produced by the reconnection. The ongoing reconnection leads to a horizontal drift of the vault-and-jet structure. The timescales, velocities, and other plasma properties in the experiment are consistent with recent statistical studies of this type of event made with Hinode data.

Subject headings: MHD — Sun: corona — Sun: flares — Sun: magnetic fields — Sun: X-rays, gamma rays

1. INTRODUCTION

X-ray jets in coronal holes are being observed with unprecedented quality by the instruments on board the Hinode satellite, in particular the X-Ray Telescope (XRT) (Golub et al. 2007) and the Extreme UV Imaging Spectrometer (EIS) (Culhane et al. 2007). With their enhanced sensitivity and spatial resolution, those instruments have revealed that the frequency of jet formation is at least an order of magnitude greater than was thought previously (Cirtain et al. 2007). The new observations are leading to an in-depth revision of the statistics of jet properties (Shimojo et al. 1996; Savcheva et al. 2007). Sometimes, the formation of the jet is seen to occur simultaneously with an episode of flux emergence from the solar interior (e.g., Canfield et al. 1996; Jiang et al. 2007). In many XRT events, a brightening close to the surface is followed by enhanced emission in a region with an inverted-Y shape above the former (Fig. 1). The tail of the inverted Y coincides with a fast jet.

This kind of jet is most probably a consequence of the field line reconnection between the upcoming magnetic system and the open ambient field in the coronal hole, as originally suggested by theory and two-dimensional (2D) numerical experiments (Heyvaerts et al. 1977; Yokoyama & Shibata 1996). In this Letter, we analyze XRT and EIS observations of a jet in a coronal hole coplanar with a simultaneous flux emergence event observed with SOHO/Michelson Doppler Imager (MDI; § 2). We study the magnetic topology using linear force-free extrapolations from the MDI data. We then present the results of a three-dimensional (3D) experiment of flux emergence into a region in the atmosphere with temperature, density, and magnetic field values akin to those in a coronal hole (§ 3). We explain the resulting three-dimensional structure (geometry, topology, dynamics) and show the excellent overall agreement with the observations.

2. OBSERVATIONS

A large coronal hole was observed near disk center on 2007 March 10 by the Hinode satellite (Kosugi et al. 2007). We present EIS and XRT observations of a jet that appeared at 06:20 UTC at solar coordinates (−25°, −115°) within the equatorial hole, at the same time as a magnetic bipole emerged at the photosphere (Fig. 2). A low-latitude event was chosen to facilitate the extrapolation and radial velocity measurement. The evolution of the jet was inspected using XRT 512 × 512 pixel images taken in the Open/Ti_poly filter combination at a cadence of 70 s. Spatial sampling is 1′′ per pixel. The EIS observations consisted of 30 s exposures in sit-and-stare mode with the 1′ × 512′′ slit. Standard routines were used in the data processing. The alignment between both instruments was done via cross-correlation of north-south cross sections of the X-ray images with the Fe xii emission along the EIS slit. Accuracy is down to between 1″ and 2″ in the north-south direction and less than 5″ in the east-west. For the analysis of the magnetic flux density we used full-disk magnetograms from SOHO/MDI (Scherrer et al. 1995). Only magnetograms with a 96 minute cadence were available at the time of the jet. The closest one in time (06:27 UTC) shows a newly emerged bipole under the location where the jet is formed. The magnetic flux density of the emerged polarities is in the range (−70, 88) Mx cm−2 [i.e., (−7, 8.8) × 1019 Wb m−2] with total fluxes of ≈ 1 × 1019 Mx = 1 × 1014 Wb. The magnetic topology was determined with a linear force-free extrapolation method (see details in Ugarte-Urra et al. 2007) and reveals the existence of a coronal null point and a separatrix dome that encloses the connectivity domain of the newly emerged flux.

In the XRT images (as, e.g., in the top left panel of Fig. 2), we first see the appearance of small coronal loops that connect the preexisting dominant ambient positive flux to the newly emerged negative polarity. This is followed immediately by the formation of the jet, oppositely oriented and rooted in the positive flux, with the footpoints most likely located where the separatrix
surface intersects the photosphere. The top right panel of the figure shows the relationship of the loops and jet to the magnetic topology from the extrapolation. The bottom right panel shows a side view of the topology with four labeled connectivity domains. In region 1 lie the magnetic connections between the two newly emerged polarities. The loops on the XRT image correspond to region 3. A natural explanation for this configuration is that the emerging flux (region 1) is merging with flux from region 2, yielding two reconnected-line regions (3 and 4). The jet must be in an open-field region, so it must be in region 4, and close to the separatrix (dark blue field lines). This is consistent with what the projected extrapolation and the XRT image suggest and is also in agreement with the results of the numerical simulation presented in § 3. At least two consecutive jet events can be identified in the XRT movie before the loops grow and finally populate the whole enclosed domain. The initial and most impulsive phase lasts around 12 minutes.

The EIS slit crosses the jet structure at about 15° to the east side of its origin. EIS’s unique combination of high spatial, spectral, and temporal resolution can provide diagnostics for the density and velocity (for an in-depth discussion of previous EUV spectroscopic observations of jets, see Wilhelm et al. 2002; Ko et al. 2005; Pike & Harrison 1997 and references therein). On the jet we measured (Fig. 2, bottom left panel) a line-of-sight blueshifted velocity of up to 240 km s\(^{-1}\) in the Fe\(^{xii}\) 195.12 Å line. The zero value is given by an average profile in the quiet coronal hole. After averaging 2 pixels along the slit and two exposures, to increase the signal-to-noise ratio, we also obtained an estimate for the electron density through the line ratio Fe\(^{xii}/H\(_{1}\) 1002 with a filling factor of \(\approx 0.2\) for the Fe\(^{xii}\) 195.1 column\(\AA\) (Mazzotta et al. 1998), and a column depth of 4.7 Mm, equal to the jet’s measured width. We used CHIANTI v5.2 (Landi et al. 2006) for the calculations.

3. NUMERICAL EXPERIMENT

The numerical results were obtained for a 3D domain of size 34 Mm \(\times\) 38 Mm in the horizontal directions and 33 Mm in the vertical direction, z, 29 Mm of which are above the photosphere. For the unmagnetized hydrostatic background at time \(t = 0\) we chose an adiabatic stratification in the solar interior and a domain at photospheric temperature in the first 2 Mm above the surface; above it, we have a steep temperature gradient mimicking the transition region and, finally, an isothermal corona \((T = 1.1 \times 10^6 \text{ K})\) in the topmost 25 Mm (as in Fig. 1 of Archontis et al. 2004, but with a much larger vertical domain). In the main experiment described here, \(\rho_{\text{top}}\), the initial coronal density at the top of the box, was \(5 \times 10^{-16} \text{ g cm}^{-3}\), equivalent to an atom number density of \(\approx 2 \times 10^{18} \text{ cm}^{-3}\). The domain is endowed at time \(t = 0\) with a uniform magnetic field contained in the \(xz\) plane of strength \(B_{\text{amb}} = 10 \text{ G} = 10 \text{ mT}\) and pointing 25° away from the vertical. This field is dynamically dominant in the corona \((\beta \approx O(10^{-3}))\), whereas it is very weak \((\beta \gg 1)\) in the solar interior. Density and field strength are adequate to simulate coronal holes (see Wilhelm 2006; Harvey & Recely 2002). To explore the parameter space, experiments have also been carried out for \(B_{\text{amb}}\) equal to 25 G and 5 G, for \(\rho_{\text{top}} = 1.5 \times 10^{-15} \text{ g cm}^{-3}\), and for inclinations of 15° and 0° to the vertical. We solve the MHD equations and assume an ideal gas law, no radiation cooling, and no heat conduction. The system is solved using the staggered-grid MHD code of our previous experiments (Nordlund & Galsgaard 1997; see Archontis et al. 2004). The numerical grid is nonuniform in the vertical direction, with minimum resolution of 5.3 points per scale height (pps) in the photosphere (65 pps in the corona), and has 350 \(\times\) 322 \(\times\) 320 nodes in the \((x, y, z)\) directions.

The emergence process is initiated by including a twisted magnetic flux tube with axis along the y-coordinate direction located 1.7 Mm below the photosphere and with maximum field strength 3.8 kG. The tube is endowed with buoyancy in its central part so that it rises and reaches the surface in about 15 minutes. The main features of these initial phases are as described in our previous experiments (e.g., Archontis et al. 2004, 2005). Once in the atmosphere, the rising plasma has a
Fig. 3.—Three-dimensional view of the emerged region, the reconnection site, and the jet at the time of peak reconnection activity (top: side view; bottom: view from below). The isosurface of $j/B$ (in blue) delineates the collapsed current sheet on the side of the emerged volume. The temperature isosurface ($T = 6.5 \times 10^6$ K; in red) encompasses both the reconnection site and the jet volume. Underlying the jet and current sheet, a double set of current loops (emerged and reconnected, with field lines in orange and green, respectively) is visible, giving a “double-chambered” vault shape to the region below the jet.

Fig. 4.—Vertical cuts at different stages of the evolution. Top: $j/B$ distribution and field line projection at an early stage. A thin current sheet is situated to the top right of the emerged coronal loops. The diffuse, elongated current perturbations to the top and left of the emerged volume correspond to previously reconnected field lines. Center: Total velocity map and field line projection at the peak activity phase of the jet, occurring about 7 minutes later than the top panel. The double-chambered structure below the jet is clearly visible. Bottom: Temperature distribution for the same snapshot as the central panel. An inverted-Y structure appears prominently, with $T \approx 3 \times 10^7$ K (reconnection site) and $\approx 10^7$ K (upward-pointing jet).

considerable magnetic pressure excess and expands in all directions, albeit preferentially horizontally, whereby it adopts a helmet shape protruding from the solar interior. The pressure of the ambient coronal field opposes the expansion and the emerged volume reaches a maximum size of about 8 Mm in height, 11 Mm in the $x$-direction (i.e., transverse to the original tube axis), and 17 Mm in the $y$-direction.

The expansion just described firmly presses the magnetic field in the emerged volume and the ambient corona against each other. The field in the rising plasma is twisted around the tube axis; hence, it is almost counteraligned with the coronal field on one of the sides of the emerging volume. A thin, elongated current sheet is thereby formed (blue isosurface in Fig. 3) that embraces that side of the volume, resembling those obtained by Archontis et al. (2005). Seen in a vertical cut, the sheet appears as a thin stripe (in red in Fig. 4, top panel) of
Syrovatskii type. Reconnection takes place across the current sheet: the archlike loops next to it inside the helmet merge with the open loops coming in from the other side of the sheet. Two regions of reconnected field result; at the thin edge at the top of the current sheet, a set of open field lines are ejected: that region is visible in Fig. 4 (top panel) as a vertical band of diffuse current perturbations. At the lower edge, closed coronal loops ensue.

High-velocity outflows are ejected from the upper and lower edges of the current sheet. The outflow at the upper edge (Fig. 4, center) is roughly horizontal and reaches peak speeds around 400 km s⁻¹ (of order the local Alfvén speed). Shortly after leaving the reconnection site, it is deflected into two secondary jets propagating upward and downward along the field lines, basically as described in 2D by Yokoyama & Shibata (1996). The upgoing branch attains vertical velocities above 200 km s⁻¹ (Fig. 4, center). High temperature values are reached in the jets and in the reconnection site itself. At the peak of activity (Figs. 3 and 4), the 6.5 \× 10⁴ K isosurface (in pink in Fig. 3) extends over the current sheet and into the jet. Values as high as 3 \× 10⁷ K (reconnection site) and slightly above 10⁷ K (jet) are reached (Fig. 4, bottom). The high-T regions have the shape of an inverted Y on top of the emerged material (Figs. 3 and 4), not unlike those observed by Hinode (Fig. 1). The density of the jet at the peak of activity is about 10 times the density of the unperturbed corona.

As reconnection proceeds, a double-chambered vault structure of closed loops develops below the jet, visible below the blue stripe in Figure 3 and in Figure 4 (center and bottom panels): in one of the chambers (the emerged chamber), coronal loops with the original connectivity are still present; in the other (the reconnected chamber), the new set of closed, high-T coronal loops are being stored. The whole system strongly resembles the topology obtained in § 2 through extrapolation from MDI data. As time proceeds, the emerged chamber decreases in transverse size while the reconnected chamber grows to a size similar to the original emerged volume. There results an apparent sideways drift of the vault and of the jet in the direction toward the reconnected loops, with roughly 10 km s⁻¹ drift speed. This may correspond to the drift discussed by Savcheva et al. (2007).

The main phase of reconnection with jet speeds above 100 km s⁻¹ lasts around 7 minutes, followed by an extended phase with lower temperature and jet velocities, for a total duration of some 20 minutes. In the early stages of reconnection, in turn, we observe cool and dense plasma being ejected from the reconnection site. At that stage, the high-density shell that covers the emerging plasma is being merged with the ambient coronal field. The resulting reconnect domain of open field lines becomes loaded with high-density \( \rho \approx O(10^3 \rho_{\text{up}}) \), low-T \( O(10^3) \) K material (visible to the left of the hot jet in Fig. 4, bottom panel).

4. DISCUSSION

In this Letter we have shown that the inverted-Y–shaped jets recently observed by Hinode/XRT in coronal holes are a natural consequence of the emergence of magnetic flux from below the surface and its interaction with the preexisting open field in the coronal hole. Flux emergence is a prime candidate to trigger reconnection and the consequent launching of jets along field lines in the corona, as proposed through theoretical or 2D numerical results (Heyvaerts et al. 1977; Yokoyama & Shibata 1996) and through 3D experiments of jet formation in a horizontally magnetized atmosphere (Archontis et al. 2005; Galsgaard et al. 2007). Our present 3D experiments had a field configuration and stratification parameters akin to those in a coronal hole. The match we obtain between the X-ray, EUV, and magnetogram data and the numerical results is highly satisfactory concerning overall geometry, topology of the magnetic field, and density, temperature, and velocity of the plasma. Various basic features obtained through 2D vertical cuts in our experiments agree qualitatively with the results of Yokoyama & Shibata (1996) in spite of the differences in parameter values. Beyond all that, our experiments permit discerning for the first time the 3D geometry of this type of event.

A number of refinements must be implemented for a better test of the match of the present numerical results with the observations, such as heat conduction or radiative cooling. Those improvements are being incorporated into this research at present.

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