A Solar Blowout Jet Caused by the Eruption of a Magnetic Flux Rope

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Abstract

We investigate the three-dimensional (3D) magnetic structure of a blowout jet originating in the western edge of NOAA active region (AR) 11513 on 2012 July 2 by means of recently developed forced field extrapolation model. The results show that the blowout jet was caused by the eruption of the magnetic flux rope (MFR) consisting of twisted field lines. We further calculate the twist number $T_w$ and squashing factor $Q$ of the reconstructed magnetic field and find that (1) the MFR corresponds well with the high $T_w$ region, and (2) the MFR outer boundary corresponds well with the high $Q$ region, probably interpreting the bright structure at the base of the jet. The twist number of the MFR is estimated to be $T_w = -1.54 \pm 0.67$. Thus, the kink instability is regarded as the initiation mechanism of the blowout jet as $T_w$ reaches or even exceeds the threshold value of the kink instability. Our results also indicate that the bright point at the decaying phase is actually composed of some small loops that are heated by the reconnection occurring above. In summary, the blowout jet is mostly consistent with the scenario proposed by Moore et al., except that the kink instability is found to be a possible trigger.

Key words: Sun: activity – Sun: chromosphere – Sun: corona – Sun: magnetic fields

Supporting material: animation

1. Introduction

The concept of “blowout jet” was first introduced by Moore et al. (2010) based on the morphological description of the X-ray jet in the Hinode/X-ray Telescope movie. The broad spire and bright base arch of the “blowout jet” distinguish from the thin spire and relatively dim base arch of standard jet. In the widely accepted scenario of a blowout jet (Moore et al. 2010; Raouafi et al. 2016), the sheared or twisted arch field is supposed to emerge from below the photosphere, forming a current sheet at the interface between the arch field and ambient open field. The onset of magnetic reconnection at the current sheet shows a similar feature as the standard jet, then the sheared or twisted arch field is erupted outward as the key structure of a coronal mass ejection (CME; Chen 2011). Among the total number of 109 jets examined in Moore et al. (2010, 2013), 50 are blowout, 53 are standard, and 6 are ambiguous.

A filament whose magnetic structure is argued to be a helical magnetic flux rope (MFR) is often observed at the base of the blowout jet (Hong et al. 2011, 2013; Shen et al. 2012; Adams et al. 2014; Sterling et al. 2015). The existence of MFR is supported by the helical structure in the spire during the untwisting motion of the erupting mass (e.g., Patsourakos et al. 2008; Nistic et al. 2009; Shen et al. 2011; Chen et al. 2012; Curdt et al. 2012; Morton et al. 2012; Shen et al. 2012; Lee et al. 2013; Liu et al. 2014; Zhang & Ji 2014; Cheung et al. 2015). In addition, 3D magnetohydrodynamic (MHD) jet models (Pariat et al. 2009, 2010, 2015; Rachmeler et al. 2010; Cheung et al. 2015; Karpen et al. 2017) according to the eruption of the twisted magnetic field also show the same helical motion as the observations.

Magnetic structures of the source regions of the blowout jets have been modeled using potential (Liu et al. 2011; Zhang et al. 2012), linear (Moreno-Insertis et al. 2008), and nonlinear force-free modelings (Guo et al. 2013a; Schmieder et al. 2013). The previous works only unveiled the weakly sheared core fields and opened ambient fields. The twisted MFRs in which more magnetic free energy is stored to power the blowout jets, however, have never been disclosed.

In this Letter, we report an MFR at the base of a blowout jet. The MFR is successfully reconstructed by a recently developed forced field extrapolation (FFE) model (Zhu et al. 2013, 2016). To study the change of the magnetic field, we make a time series of extrapolations using Helioseismic and Magnetic Imager (HMI; Schou et al. 2012; Hoeksema et al. 2014) vector magnetograms. We further calculate the twist number (Berger & Prior 2006) and squashing factor (Démoulin et al. 1996; Titov et al. 2002; Pariat & Démoulin 2012) to study the properties of the MFR. The observational data sets are described in Section 2, the evolution of the blowout jet is presented in Section 3, and the extrapolation results are analyzed in Section 4, which is followed by the discussions and conclusions in Section 5.

2. Observational Data

Recurrent jets were observed at the boundary between the AR 11513 and the neighboring coronal hole on 2012 July 2 (see the white box in Figure 1). We focused on the blowout jet occurring at 21:12 UT.

HMI on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) provides 45 s line of sight (LOS) magnetograms and 12 minute vector magnetograms. They both have a pixel size of 0.05. The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), also on board SDO, provides full-disk images of the solar corona at multiple EUV passbands with a cadence of 12 s and a pixel size of 0.6. We also used the Hα data observed at Big Bear Solar Observatories (BBSO) to study the evolution of the jet in the chromosphere.
3. Evolution of the Blowout Jet

Figure 2 and the corresponding movie show the blowout jet in different passbands. Here, the evolution is divided into three stages.

**First stage:** before 21:11, the jet’s base appeared as a circular shape (Figures 2(a1), (b1), (c1), and (d1)), which could be the combination of several dipoles, and the loops connect, which may be heated. The plasma is observed to intermittently move...

Figure 1. SDO/AIA 193 Å (a) and 304 Å (b) images, and line of sight (LOS) magnetogram of AR 11513 (c). The white box shows the location of the jet.

Figure 2. SDO/AIA 211 Å (a1–a4), 193 Å (b1–b4), 171 Å (c1–c4), and BBSO Hα (d1–d4) show the evolution of the blowout jet. The arrows show the bright tube (b2, c2) and the helical structure (a3, b3, c3). (e) Distance–time plot of black line in (a2).

(An animation of this figure is available.)
out along the open field lines even though the whole structure is stable.

Second stage: at 21:11, a bright point at the southern flanks of the circular area appeared and then quickly extended to the north to form a bent tube (pointed to by the white arrows in Figures 2 (b2) and (c2)). The tube increasingly got brightened, followed by a slow upward motion (lower dotted line in Figure 2(e)) and a fast ejection motion (upper dotted line in Figure 2(e)).

The strong brightening of the jet’s base suggests that the internal reconnection occurs between the opposite-polarity stretched legs of the erupting structure. Meanwhile, the jet’s spire shows a multi-stranded curtain structure with rotating motion in the broadened spire (pointed to by the yellow arrows in Figures 2 (a3), (b3), and (c3)). All these are typical morphological characteristics of a blowout jet.

Third stage: at 21:18, the jet’s base and spire started to decay. All bright structures faded away, except a dimming bright point (Figures 2(a4), (b4), (c4), and (d4)).

4. 3D Magnetic Structure of the Blowout Jet

To understand the magnetic structure and evolution of the jet, we use the FFE model that utilizes the MHD relaxation method (full MHD equations are solved) to build the equilibrium state of the system that approximates the solar atmosphere. The HMI vector magnetograms are taken as the bottom boundary condition. The FFE model is particularly suited to compute the magnetic field in the chromosphere, transition region, and low corona because of the relatively high plasma β there. It has been successfully used to reproduce the magnetic structure of Hα fibrils (Zhu et al. 2016), small filaments (Wang et al. 2016), and bright arcades in the chromosphere or low corona (Zhao et al. 2017). In the work, the extrapolation is performed in the cubic box resolved by 480416128 grid points with Δx = Δy = Δz = 0.75. The photosphere boundary field of view for extrapolation is shown in Figure 1.

4.1. The Evolution of the Magnetic Structure

Figure 3(d) shows that an MFR (yellow lines) appears at the source region of the jet. The MFR corresponds well with the observed bright tube (Figure 3(a)) as seen in AIA images. With the jet eruption, most of the twisted lines are released, only leaving some untwisted and open field lines in place (Figure 3(e)). The small loops (white field lines in panel (e)) at the bright point (Figure 3(b)) are possibly the reconnected field lines. Although we can not see the dynamic process of the jet by extrapolation, the change of the magnetic field clearly displays that the MFR is ejected during the jet.

The arrows in Figure 3(g) show the transverse field that is aligned with the MFR. After the jet, the transverse field decreases and becomes disordered (Figures 3(h) and (i)). This is consistent with the fact that the eruption of the jet takes away most of twisted field and just leaves some small closed field lines and a large-scale open field.

4.2. The Structure of the MFR

Berger & Prior (2006) defined the twist of the neighboring magnetic field lines, which is related to the parallel electric current (J), as follows:

\[ T_w = \int_s \frac{\mu_0 J \parallel}{4\pi |\mathbf{B}|} ds = \int_s \frac{(\nabla \times \mathbf{B}) \cdot \mathbf{B}}{4\pi B^2} ds, \]

where the integration is carried out along the specific field line.

Démoulin et al. (1996) introduced the quasi-separatrix layers (QSLs) as the generalized topological structure. The QSLs are defined by high squashing factor Q regions where the connection of the magnetic field varies strongly. Q is defined by mapping the field line (Titov et al. 2002):

\[ Q = \frac{a^2 + b^2 + c^2 + d^2}{|B_n(x_1, y_1)/B_n(x_2, y_2)|}, \]

where \((x_1, y_1)\) and \((x_2, y_2)\) are the two footpoints of a field line.

The code we used to calculate the twist number \(T_w\) and squashing factor \(Q\) is developed by Liu et al. (2016). To save computation resources, we select the subdomains \(x \in [130.0, 160.3], y \in [231.0, 240.3]\) and \(z \in [0.0, 10.1]\), where \(x\) (+x toward west) and \(y\) (+y toward north) are the heliocentric coordinate and \(z\) is the height. The subdomain was resolved by 960880320 grids when computing \(T_w\) and \(Q\). Therefore, the grids are refined 16 times after extrapolation.

Figure 4(a) shows the extrapolated 3D field lines of the MFR. The contour of \(T_w = -1.5\) (see panel (b)) marks the MFR accurately. Figures 4(e) and (f) show a 2D plane of \(T_w\) and \(Q\) perpendicular to the axis of the MFR. We can see that the \(T_w\) has a sharp edge that is consistent with the regions of high \(Q\) value. In an MFR, field lines winding around an axis have similar connectivity. QSLs separate the twisted field lines from ambient field lines, which are typical features of an active-region-scaled MFR (e.g., Titov et al. 2002; Guo et al. 2013b; Cheng et al. 2014; Liu et al. 2016). Assuming \(T_w = -0.5\) as the boundary, field lines inside have a twist number of \(T_w = -1.54 \pm 0.67\). The twist at the center of the MFR exceeds 2.0 turns, while decreasing to 0.5 toward the edge. Török & Kliem (2003) show that the Titov & Démoulin (1999) MFR is kink unstable for \(|T_n| > 1.75\) with an aspect ratio of \(R/r = 5\) (\(R\) and \(r\) are the major and minor radius of the MFR, respectively). The instability threshold decreases with a decreasing aspect ratio (Török & Kliem 2003). Assuming the length (21 arcsec) and width (5.5 arcsec; see Figure 4(g)) of the extrapolated MFR approximates the major and minor diameters, respectively. The aspect ratio is estimated to be 3.8, implying a smaller kink-instability threshold than 1.75 turns. Therefore, the small-scale MFR may be marginally kink unstable. The decay index of the magnetic field above the MFR is about 0.3, which means that the MFR is far below the height where torus instability will occur (the critical decay index is required to be 1.5; Kliem & Török 2006).
4.3. Noise and Change of the Magnetic Field on the Photosphere

The noise of the transverse magnetic field is large in the weak field region because of the nonlinear dependence between the linear polarization and field strength. This leads to unreliable vector magnetic field inversion in solar-quiet regions. The jet we analyzed occurred at the boundary of an AR and a coronal hole, which is the interface area of the strong and weak magnetic fields. Therefore, it is necessary to assess the noise of the transverse magnetic field at the jet source region. The SDO/HMI provides the standard deviation of the inverted magnetic field with data segments_ERR. For example, FIELD_ERR and INCLINATION_ERR are the standard deviation of field strength and inclination angle relative to the LOS. Hence, it is convenient to compute the uncertainty of the transverse field. The temporal profile of the magnetic field is shown in Figure 5. Typically, at 21:12 UT, the average LOS field, average transverse field, average noise of the transverse field, and the
Figure 4. Extrapolated 3D magnetic structure (a) and 3D contour of $T_w = -1.5$ (b) of the MFR. (c) The twist number in the cutting plane (denoted by the yellow line in panel (a)). (d) The MFR inside the boundary of $T_w = -0.5$. (e, f) $T_w$ and $Q$ in the magnified cutting plane. (g, h) $T_w$ distribution along the horizontal and vertical direction. "x" and "o" in panels (e), (g), and (h) indicate the boundary of the MFR. The length and height of the MFR are about 5.5 arcsec and 0.9 arcsec, respectively.
average signal to noise of region “R” (surrounded by black curves in Figure 5, left) are 28 G, 160 G, 32 G, and 5.4, respectively. The transverse field on the photosphere is about 5.7 times larger than the LOS field under the MFR, which indicates that the field lines in this area are nearly horizontal. This results in the relatively small noise of the transverse field. The uncertainty of the transverse field is about 18%, 20%, and 36% at 21:00:00, 21:12:00, and 21:24:00, respectively (see the error bar in Figure 5, right). The high signal to noise of the data denotes it could be used in extrapolation.

The largely different field configuration mainly results from the change of the transverse magnetic field on the photosphere after the jet took place. The region “R” has a pronounced, 30% decrease of the transverse field (the solid line in Figure 5, right) from 160 G at 21:12:00 before the jet to 112 G at 21:24:00 after the jet in 12 minutes. Figures 3(f)–(i) also show the decreased and less sheared transverse field after the jet. The decrease of the positive, negative, and unsigned LOS field (Figure 5, right) suggests that the flux cancelation took place at the jet’s source region.

5. Discussion and Conclusion

A blowout jet was observed on 2012 July 2 at the western edge of AR 11513. In a previous paper, Chen et al. (2015) suggested that the rotation and shear motion of the magnetic field built up the free energy to make the jet blowout. In this work, we further study the 3D magnetic structure of the jet’s source region by the recently developed FFE model. The twist number and squashing factor are calculated to analyze the magnetic property of this jet. We have the following findings:

First, the transverse magnetic field decreased during the jet. The originally twisted and closed field lines are released, manifesting as the bright base and broadened helical spire, finally just leaving some untwisted and opened field lines in place.

Second, an MFR, reconstructed by the FEE method and being cospatial with the bright tube, is found to exist before the jet and then to disappear after the jet blows out. A sharp boundary of the MFR can be seen at the 2D cutting plane of the $T_\nu$ distribution. This boundary also corresponds well with the layer with the very high $Q$ value that distinguishes the twisted field lines of the MFR from the outside.

Third, the twist number of the MFR is $T_w = -1.54 \pm 0.67$ with a small aspect ratio of $R/r = 3.8$, which indicates that the blowout jet is likely triggered by kink instability. The low decay index prevents eruption from torus instability.

Combining the observed features with reconstructed 3D magnetic structures, we can argue that before the onset of the blowout jet, a highly twisted MFR exists at the source region of the jet. The twist of the MFR may continuously increase because of the plasma motion or magnetic cancelation at the photosphere. Homologous jets that erupted before the blowout one removed the restraining overlaid field lines. When the twist exceeds a critical value, kink instability takes place and leads to the MFR being ejected. As the MFR moves upward, the internal reconnection occurs between the stretched field lines below. The reconnection outflows may take on a bright core of the jet. Meanwhile, the eruption of the heated MFR in the partly opened ambient field shows a multi-strand curtain structure. The helical motion observed in the spire indicates the untwisting process of the erupting MFR. Finally, the jet’s base gradually fades away with a weak bright point. This bright point may denote small loops that are heated by the reconnection above. In short, the process of the blowout jet is mostly consistent with the scenario proposed by Moore et al. (2010), except that the kink instability is considered to be its initiation mechanism. It has to be pointed out that the direct observation of the twist, for example, the twist between fine structures of a filament (Wang et al. 2015), is a stronger and direct piece of evidence for the MFR existence. In the future, more case studies, even a statistical study, of 3D magnetic structures of blowout jets will be presented.
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