TWISTED MAGNETIC FLUX TUBES IN THE SOLAR WIND

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ABSTRACT

Magnetic flux tubes in the solar wind can be twisted as they are transported from the solar surface, where the tubes are twisted due to photospheric motions. It is suggested that the twisted magnetic tubes can be detected as the variation of total (thermal+magnetic) pressure during their passage through the observing satellite. We show that the total pressure of several observed twisted tubes resembles the theoretically expected profile. The twist of the isolated magnetic tube may explain the observed abrupt changes of magnetic field direction at tube walls. We have also found some evidence that the flux tube walls can be associated with local heating of the plasma and elevated proton and electron temperatures. For the tubes aligned with the Parker spiral, the twist angle can be estimated from the change of magnetic field direction. Stability analysis of twisted tubes shows that the critical twist angle of the tube with a homogeneous twist is 70°, but the angle can further decrease due to the motion of the tube with respect to the solar wind stream. The tubes with a stronger twist are unstable to the kink instability, therefore they probably cannot reach 1 AU.

Key words: magnetohydrodynamics (MHD) – methods: data analysis – solar wind

Online-only material: color figures

1. INTRODUCTION

Turbulent fluctuations in the solar wind, which can be partly associated with advected flux tubes (Bruno et al. 2007), are increasingly dominated by magnetic energy at large heliospheric distances. This idea is further supported by recent results about magnetic coherent structures (current sheets) which have been found to be locally associated not only with intermittency but also with temperature enhancements in the solar wind (Osman et al. 2012). Current sheets in the solar wind can arise due to nonlinear turbulent interactions (Chang et al. 2004; Servidio et al. 2009) or steepening of outwardly propagating Alfvén waves (Malara et al. 1996) or they can be flux tube walls (Borovsky 2008). It is crucial to understand the contribution of all these physical processes to intermittency or heating of solar wind plasma. In particular, dynamical evolution of flux tubes in the solar wind may be important for better understanding of turbulence and heating.

Each magnetic flux tube may contain a distinct plasma and may lead to the distinct feature of magnetohydrodynamic (MHD) turbulence. If the magnetic flux tubes are “fossil structures” (i.e., they are carried from the solar atmosphere), then they may keep the magnetic topology typical for tubes near the solar surface. The solar magnetic field has a complicated topology throughout the whole solar atmosphere. Photospheric motions may stretch and twist anchored magnetic fields, which may lead to the consequent changes of topology at higher regions. The observed rotation of sunspots (Brown et al. 2003; Zhang et al. 2007) may lead to twisting of the magnetic tubes above active regions, which can be observed in chromospheric and coronal spectral lines (Srivastava et al. 2010). Recent observations of magnetic tornados (Wedemeyer-Böhm et al. 2012; Li et al. 2012) also strongly support the existence of twisted magnetic flux tubes on the Sun. On the other hand, newly emerged magnetic tubes in the solar photosphere are supposed to be twisted during the rising phase through the convection zone (Moreno-Insertis & Emonet 1996; Archontis et al. 2004). Consequently, magnetic flux tubes in the solar wind could also be twisted if they originated in the solar atmosphere. The twisted tubes can be unstable to Kelvin–Helmholtz instability when they move with respect to the solar wind stream (Zaqarashvili et al. 2014). The Kelvin–Helmholtz vortices may eventually lead to enhanced turbulence and plasma heating; therefore the twisted tubes may significantly contribute to solar wind turbulence.

Twisted magnetic tubes can be observed by in situ vector magnetic field measurements in the solar wind (Moldwin et al. 2000; Feng et al. 2007; Cartwright & Moldwin 2010), but this method establishes limitations on real magnetic field structure by considering a force-free field model. In this Letter, we propose a new method for in situ observation of twisted magnetic flux tubes and study their stability assuming that the solar wind plasma is composed of individual magnetic flux tubes which are carried from the solar surface by wind (Bruno et al. 2001; Borovsky 2008) or are locally generated (Telloni et al. 2012). We show that the twisted magnetic tubes can be observed in situ through observation of total (thermal+magnetic) pressure and this method removes the necessity of a force-free field assumption consideration. In the next section, we calculate the total pressure of a simple model of a twisted tube and compare it to real observations.

2. OBSERVATION OF TWISTED TUBES THROUGH TOTAL PRESSURE VARIATION

We consider an isolated twisted magnetic flux tube of radius $a$ with a magnetic field of $(0, B_\phi(r), B_z(r))$ and thermal pressure of $P_0(r)$ in the cylindrical coordinate system $(r, \phi, z)$, where $r$ is the distance from the tube axis. Integration of pressure balance condition inside the tube gives the expression for the total pressure as

$$P_{T0}(r) = P_{T0}(0) - \frac{1}{4\pi} \int_0^r \frac{B_\phi^2(s)}{s} ds, \quad (1)$$
Figure 1. Structure of total pressure inside twisted (red solid line) and untwisted (red dashed straight line) model magnetic flux tubes. The total pressure is normalized by its value at the tube axis \((r = 0)\) and the distance from the tube axis is normalized by the tube radius \(a\). Here the magnetic pressure of the \(\phi\) component at the tube surface is 0.4 of the total pressure at the tube axis. The black solid line shows the radial structure of the total pressure in the magnetic flux tube first detected by Feng et al. (2007) using WIND observations (see also Figure 2). The blue, green, purple, and cyan dashed curves correspond to the total pressure profiles of flux ropes analyzed by Moldwin et al. (2000). (A color version of this figure is available in the online journal.)

which shows that the total pressure \(P_{T0} = P_0 + (B_0^2 + B_z^2)/8\pi\) is not constant inside the twisted magnetic flux tubes and its radial structure depends on the type of twist.

Figure 1 shows the radial structure of the normalized total pressure (red solid line) inside the tube with the simple homogeneous twist of \(B_\phi = Ar\), where \(A\) is a constant. It is seen that the total pressure is maximum at the tube axis and decreases toward the surface. Therefore, the variation of total pressure observed in situ by satellite may indicate the passage of an isolated twisted tube. Untwisted tubes yield no variation in the total pressure (see red dashed line in Figure 1); therefore, it is easy to identify the passage of twisted and untwisted tubes. The type of twist can be deduced from Equation (1) using the observed profile of the total pressure. In order to test this method, we consider already known observations of twisted magnetic flux tubes in the solar wind. WIND spacecraft magnetic field (Lepping et al. 1995) and plasma data (Lin et al. 1995; Ogilvie et al. 1995) are used. For demonstration purposes, Figure 2 shows an event in detail, which was first spotted by Feng et al. (2007) and carefully analyzed by Telloni et al. (2012). It was found that this event was embedded between regions with different solar wind speeds. The analysis of the magnetic helicity and hodogram revealed a twisted structure with a clockwise rotation of the magnetic field within the structure (Telloni et al. 2012). The \(z\)-component of the magnetic field in the GSE system also shows recognizable bipolar turning (Figure 2(c)), which according to Moldwin et al. (2000) is the classic flux rope signature (note that here \(B_z\) is in the geocentric solar ecliptic (GSE) system). The walls of the flux tube structure indicated by the vertical boxes before 22:30 UT on 1998 March 28 (leading edge) and at 02:15 UT on 1998 March 29 (trailing edge) are readily recognizable as jumps in the values of physical quantities. At the trailing edge, a sudden increase of \(T_p\) and a slight decrease of \(T_e\) can be observed, with steady values afterward. The temperature change, the increase of density, and the single peaked jump in \(\Delta\Theta\) indicate that the probe crosses the flux tube discontinuity and enters a different plasma. However, at the leading edge, the density before and after the wall is the same; one can see a simultaneous increase of both \(T_p\) and \(T_e\) and several rapid fluctuations in the orientation of the magnetic field vector (\(\Delta\Theta\)). Since before and after the leading edge (first vertical box in Figure 2) the temperatures are smaller and \(\Delta\Theta\) fluctuates less, we interpret these observations as signatures of local heating at the unstable flux tube wall. We plot the total pressure \(\left(P_T; \text{Figure 2(d)}\right)\),

Figure 2. WIND observations of a twisted flux tube: (a) proton \((T_p)\) temperature, electron \((T_e)\) temperature, and proton density \((N)\); (b) magnetic field vector directional change \(\Delta\Theta\) over a timescale of two minutes; (c) total magnetic field \((B)\), the magnetic field \(z\)-component in GSE system \(\left(B_z\right)\), and plasma \(\beta\); (d) total pressure \(\left(P_T\right)\) as a sum of magnetic, proton, and electron pressures.

(A color version of this figure is available in the online journal.)
Twisted magnetic flux tube

External magnetic field

Figure 3. Twisted magnetic flux tube in the solar wind. The tube axis is supposed to be directed along the mean external magnetic field, which can be the Parker spiral. $\phi$ is the angle between the internal twisted magnetic field and the Parker spiral. Tangential discontinuity of magnetic field strength and direction can be detected when the tube passes through a satellite.

(A color version of this figure is available in the online journal.)

which is the sum of the electron and proton thermal pressure and magnetic pressure. The enhanced $P_T$ at the center of the interval indicates a twisted magnetic field structure. Converting the temporal observations of the advected structures to spatial observations using the solar wind speed, we can compare our data with the theoretical total pressure profile for twisted flux tubes. The observed smoothed profile of the total pressure (black solid line) is plotted over the theoretical profile of the twisted tube (see Figure 1). It is seen that the theoretical curve describes the observed profile rather well. This means that the observed flux tube may have a homogeneous twist of $B = 5\rho$. The double peaked structure, which mainly resembles the evolution of $B$ (Figures 2(c) and (d)), can appear as a result of periodic kinking motions of the flux tube or internal inhomogeneities via turbulence or waves. As a consequence of the kinking motion $P_T$ can gradually increase, then decrease, before the subsequent increase near the center of the flux tube. Since the changes are rather smooth in time with a quasi-period $>1$ hr (Figure 2(d)) we can suppose that the resulting double peaked structure is associated with kink motions rather than multi-scale turbulence.

The other total pressure curves in Figure 1 correspond to associated with kink motions rather than multi-scale turbulence. As a consequence of the kinking motion $P_T$ can gradually increase, then decrease, before the subsequent increase near the center of the flux tube. Since the changes are rather smooth in time with a quasi-period $>1$ hr (Figure 2(d)) we can suppose that the resulting double peaked structure is associated with kink motions rather than multi-scale turbulence.

The twist angle near the tube surface for the pressure profile model (red solid line on Figure 1) is estimated to be $\sim 55^\circ$. Then the flux tube of Feng et al. (2007) and some tubes of Moldwin et al. (2000) are twisted with angles of $50^\circ \text{--} 55^\circ$, while the other tubes of Moldwin et al. (2000) are less twisted.

The abrupt change of the magnetic field direction $\Delta \Theta$ may indicate that the wall of the twisted tube is crossed by a satellite if the tube axis is aligned with the Parker spiral (Figure 3). Then the angle of the abrupt magnetic field direction change may show the twist angle at the tube wall, which could be significantly scattered from the direction of the Parker spiral. Indeed, in a statistical study, Borovsky (2008) found that the tube axes are aligned with the Parker spiral with significant scatter (Borovsky considered only untwisted tubes, and therefore the direction of the magnetic field inside the tube was considered as the tube axis). The observational scatter of the average direction of the tubes magnetic field with respect to the Parker spiral can be explained by the simultaneous existence of untwisted and twisted magnetic tubes in the solar wind plasma: untwisted tubes on average are aligned with the Parker spiral and the scatter is caused by the twisted tubes. However, the hypothesis is too simplified and some spread in the results is expected due to the complexity of solar wind plasma. Borovsky (2008) also found that the mean angle between the tubes magnetic field and the Parker spiral is $\sim 42^\circ$, while the mean angle between the wall normal and the Parker spiral peaks toward $90^\circ$. If the magnetic tube axes are aligned with the Parker spiral, then the result of Borovsky (2008) means that the mean twist angle of the tubes is $\sim 42^\circ$. On the other hand, the twisted tubes are subject to kink instability when the twist exceeds a critical value. Therefore it is important to estimate whether the angle is less than the critical one.

3. STABILITY OF TWISTED MAGNETIC FLUX TUBES

Normal mode analysis (Dungey & Loughhead 1954) and the energy consideration method (Lundquist 1951) show similar thresholds of the kink instability in twisted magnetic tubes. The instability condition for the homogeneous twist $B = Ar$ and $B_z = \text{const}$ is $B_{z}(a) > 2B_{z}$. This leads to the critical twist angle of $\sim 65^\circ$. Therefore, the mean twist angle of $\sim 42^\circ$ indicates that the majority of tubes are stable to kink instability. The external magnetic field may increase the threshold and thus stabilize the instability (Bennett et al. 1999). On the other hand, a flow along the twisted magnetic tube may decrease the threshold (Zaqarashvili et al. 2010). Magnetic flux tubes in the solar wind may move with respect to the main stream of solar wind particles, and therefore it is important to study the competitive effects of the external magnetic field and the motion of tube (or external medium). Note that the consideration is simplified compared to turbulent solar wind plasma.

In order to study the instability criterion of moving twisted magnetic flux tube in the external magnetized medium, we use normal mode analysis. We consider a tube with homogeneous twist, $B = Ar$, homogeneous axial magnetic field $B_z$, and uniform density $\rho_0$. The external medium with homogeneous magnetic field $0, 0, B_z$ directed along the z-axis and uniform density $\rho_e$ is moving with homogeneous speed $U$ along the tube axis, i.e., along the z-axis. It is equivalent to the consideration of a moving magnetic tube with speed $-U$ in a static external medium. In order to obtain the dispersion equation governing the dynamics of the tube, one should find solutions of perturbations inside and outside the tube and then merge them at the tube surface through boundary conditions. After Fourier analysis of linearized MHD equations with $\exp[i(m\phi + kz - \omega t)]$, where $k$ is the longitudinal wavenumber and $\omega$ is the frequency, incompressible perturbations of the total pressure, $p_t$, inside the tube are governed by the Bessel equation (Dungey & Loughhead 1954; Bennett et al. 1999; Zaqarashvili et al. 2010; Zhelyazkov & Zaqarashvili 2012):

$$\frac{d^2 p_t}{dr^2} + \frac{1}{r} \frac{dp_t}{dr} - \left( \frac{m^2}{r^2} + m_0^2 \right) p_t = 0, \quad (2)$$

where

$$m_0^2 = k^2 \left( 1 - \frac{4A^2 \omega_A^2}{4\pi \rho \omega^2 - \omega_A^2} \right), \quad \omega_A = \frac{mA + kB_z}{\sqrt{4\pi \rho_0}}.$$
at infinity is $p_t = a_\theta K_m(kr)$, where $a_\theta$ is a constant. The boundary conditions at the tube surface are the continuity of the Lagrangian displacement $[\xi_i]_0 = 0$ and total Lagrangian pressure $[p_t - B^2/2\xi_i / (4\pi r)]_0 = 0$ (Dungey & Loughhead 1954; Bennett et al. 1999; Zaqarashvili et al. 2010), which after straightforward calculations give the transcendental dispersion equation

$$\frac{(\omega^2 - \omega^2_A)F_m(m_o a) - 2m\omega_A A/\sqrt{4\pi\rho_0}}{(\omega^2 - \omega^2_A)^2 - 4\omega_A^2 A^2/(4\pi\rho_0)} = \frac{P_m(ka)}{[(\omega - kU)^2 - \omega^2_A](\rho_e/\rho_0) + P_m(ka)A^2/(4\pi\rho_0)},$$

where

$$F_m(m_o a) = \frac{m_o a f_m(m_o a)}{I_m(m_o a)}, \quad P_m(ka) = \frac{kaK'_m(ka)}{K_m(ka)},$$

and $\omega_A = kB_z/\sqrt{4\pi\rho_e}$. A prime (') denotes the derivative of a Bessel function with respect to its dimensionless argument. The imaginary part of $\omega$ in the dispersion equation (Equation (3)) indicates the instability of the tube. The threshold for the kink instability ($\rho = 1$) can be found analytically through marginal stability analysis, i.e., considering $\omega = 0$ (Chandrasekhar 1961). Using the thin flux tube approximation, $ka \ll 1$ (yielding $F_1(m_o a) \approx 1 + m_o a^2/4 + \cdots$ and $P_1(ka) \approx -1$), after some algebra we obtain the following criterion for the kink instability from Equation (3):

$$B_\phi(a) > 2B_z \left(1 + \frac{kB_z}{A}\right) \sqrt{1 - \frac{\rho_e}{\rho_0}M_A^2 + \mu^2},$$

where $M_A = U\sqrt{4\pi\rho_0}/B_z = U/V_{\phi0}$ is the Alfvén Mach number and $\mu = B_z/B_A$ (here $U$ is the relative speed of tube with regards to the mean solar wind stream and could be much less than the wind speed itself). For a static tube with a field-free environment the criterion leads to the Lundquist criterion (see also Dungey & Loughhead 1954). For $B_z = 0$ it leads to the instability condition of twisted tube moving in a field-free environment (Zaqarashvili et al. 2010). The critical twist angle for the kink instability can be approximated as

$$\theta_c = \arctan \left(\frac{B_\phi(a)}{B_z}\right) \approx \arctan \left(\frac{2}{\sqrt{1 - \frac{\rho_e}{\rho_0}M_A^2 + \mu^2}}\right).$$

It is seen that the critical twist angle depends on the Alfvén Mach number, the ratio of the external to internal axial magnetic field strength $\mu$, and the ratio of external to internal densities. A twist angle larger than the critical angle leads to kink instability. Figure 4 shows that the critical twist angle decreases when $\mu$ decreases and $M_A$ increases. Denser tubes are more stable. Maximum critical twist angle $\sim 70^\circ$ occurs for static tubes $M_A = 0$ and $\mu = 1$. It means that the tubes twisted with an angle of $\geq 70^\circ$ are always unstable to kink instability.

Kink instability may lead to magnetic reconnection, which may either destroy the tube (Feng et al. 2011) or remove additional twist from the tube, keeping only a stable configuration. Therefore, the tubes twisted with an angle of $\geq 70^\circ$ probably cannot reach the distance of 1 AU. The motion of the tube with Alfvén speed with respect to the solar wind stream may reduce the critical twist angle to $45^\circ$ for $B_z > B_A$ and $\rho_e = 0.8 \rho_0$. This is close to the statistically mean value of the angle between tube magnetic field and the Parker spiral obtained by Borovsky (2008). Three of the five tubes analyzed in this Letter have a twist angle of $50^\circ$–$55^\circ$, which is less than the critical angle for the kink instability of the tubes with $M_A < 0.5$, but can be larger for tubes with $M_A > 0.5$. Suppose a magnetic flux tube is twisted with a sub-critical angle near the Sun. The Alfvén Mach number could be increased toward the Earth due to the decrease of the Alfvén speed. Consequently, an initially stable flux tube may become unstable to kink instability at some distance from the Sun. Two other tubes are below the threshold of kink instability for any $M_A$.

4. DISCUSSION AND CONCLUSIONS

It is shown in this Letter that twisted magnetic tubes in the solar wind can be detected by in situ observations as a variation of the total pressure during the passage of the tubes through a satellite. This method allows us to obtain the radial structure of the twist and it can be used for any configuration of the magnetic field including a non-force-free field. We tested the method using several already known cases of observed twisted tubes, which shows that the total pressure in observed events resemble the theoretically expected profile. Therefore, the total pressure variation can be used to estimate the value of the twist and its radial structure in the tubes embedded in the solar wind. The method can be also used to estimate the twist in coronal mass ejections in addition to the Grad–Shafranov Reconstruction method (Möstl et al. 2009).

We suggest that the twist of an isolated magnetic tube may explain the observed abrupt changes of the magnetic field direction at tube walls in the solar wind (Borovsky 2008). The mean statistical angle of the abrupt change, which was estimated by Borovsky (2008) to be $\sim 42^\circ$, can be considered as the mean twist angle of the magnetic flux tubes. The significant scatter of the average direction of the tubes magnetic field observed with respect to the Parker spiral can be explained by untwisted and twisted magnetic tubes: untwisted tubes are aligned with the Parker spiral and the twisted tubes cause the scatter.

Using stability analysis of twisted magnetic tubes, we obtain the theoretical criterion of kink instability, which shows that the maximum twist angle is $\sim 70^\circ$ in the case of static tubes, while it decreases to $45^\circ$ for tubes moving with Alfvén speed with.
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respect to the solar wind. It may explain the observed mean statistical angle of 42° because the tubes twisted with a larger angle are unstable to the kink instability, and therefore they probably cannot reach 1 AU.

Tangential velocity discontinuity due to the motion of magnetic flux tubes with respect to the solar wind stream may lead to Kelvin–Helmholtz instability (Drazin & Reid 1981). A flow-aligned magnetic field may stabilize sub-Alfvénic flows (Chandrasekhar 1961). However, the twisted tubes can be unstable for any sub-Alfvénic motion if they move with an angle to the Parker spiral (Zaqarashvili et al. 2014). Then the Kelvin–Helmholtz vortices may lead to enhanced MHD turbulence and plasma heating near the walls of twisted magnetic tubes.

A statistical fraction of twisted tubes in the solar may correspond to the fraction of twisted tubes near the solar surface. Therefore, in situ observations of twisted tubes in the wind may allow us to estimate their fraction in the lower solar atmosphere.

In conclusion, twisted magnetic flux tubes could be essential components in the solar wind structure and they may play significant role in the turbulence and heating of the solar wind plasma.

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