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THE EVOLUTION OF AN ISOLATED RECONNECTED FLUX TUBE

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Abstract—The detailed structure of a reconnected flux tube is examined in an effort to explain the twisted magnetic field that is commonly observed within Flux Transfer Events (FTEs). We begin by clarifying the definition of a twisted flux tube. From the observed direction of the twist on both sides of the magnetopause we argue that the twist is unlikely to be introduced after the tube formation, and so must be already present in the tube when reconnection stops. On purely topological grounds, it is evident that a Flux Transfer Event produced by single or multiple *X*-line reconnection will exhibit a twist. The evolution of such a tube is complicated, but by considering the forces inherent in such a structure we show that there will be a torque acting upon the flux tubes that leave the reconnection site. The torque will propagate torsional Alfvén waves along reconnected flux tubes. We predict the sense of twist and pitch length of these torsional Alfvén waves and find excellent agreement with observations obtained at the Earth's dayside magnetopause.

1. INTRODUCTION

It was first suggested by Dungey (1961) that reconnection is an important mechanism for driving convection within the Earth's magnetosphere. The effect of reconnecting a solar wind magnetic flux tube to a terrestrial one is to produce two open flux tubes. Open flux tubes have one end on the Earth and the other end in the solar wind (see Fig. 1). The boundary between the terrestrial (magnetospheric) field and the solar wind (magnetosheath) field is called the magnetopause, and the resulting open flux tubes can efficiently transfer momentum from the solar wind to the magnetosphere via Alfvén waves. When the reconnection rate is sporadic, discrete flux tubes are formed and these were termed Flux Transfer Events (FTEs) by Russell and Elphic (1978). There is also evidence that reconnection can occur in a quasi-steady fashion (Paschmann *et al.*, 1979, 1985; Sonnerup *et al.*, 1981).

The evolution of a FTE is complicated because the two plasmas on either side of the magnetopause are different; they have different densities, Alfvén speeds, plasma velocities and plasma temperatures. In addition the magnetic fields in the magnetosphere and the magnetosheath will be skewed relative to one another in general. Satellite observations of FTEs are invaluable when trying to determine the way in which FTEs evolve. Hence we shall now review the main signatures of FTEs that are found in satellite data.

2. PROPERTIES OF FTEs

FTEs produce easily identifiable signatures in satellite magnetometer data; namely a bipolar B_N signature (B_N is the magnetic field component normal to the magnetopause). This signature was initially attributed to the draping of the background magnetic field over the reconnected flux tube (see Fig. 1) as the tube

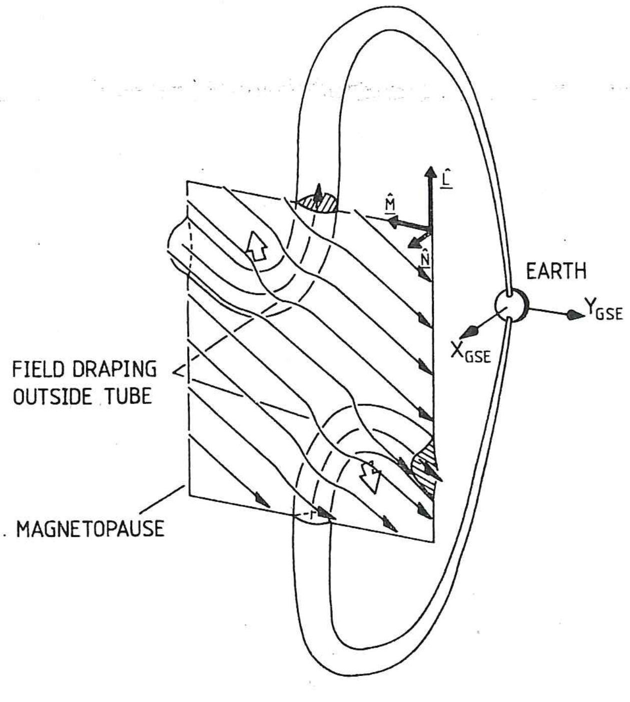

FIG. 1. THE RECONNECTION OF A SOLAR WIND MAGNETIC FLUX TUBE TO A TERRESTRIAL ONE PRODUCES TWO OPEN FLUX TUBES. The end of the flux tube that is in the solar wind is blown antisunward past the Earth. This motion is communicated down the flux tube to the Earth by Alfvén waves that transfer momentum from the solar wind to the Earth's magnetosphere and drive magnetospheric convection. The motion of a reconnected flux tube along the magnetopause causes the background fields to drape over it and produces an oscillatory B_N signature. This feature is commonly used to identify FTEs.

moves past the satellite (Russell and Elphic, 1978). If the satellite enters the flux tube it may be expected that the B_N signature would fall discontinuously to zero. The fact that this behaviour was not observed prompted both Paschmann *et al.* (1982) and Cowley (1982) to independently suggest an internal twist of the flux tube that would give a more continuous character to the signature. Paschmann *et al.* (1982) also showed that the tension due to the twisted internal field was necessary to balance plasma and field pressure inside the tube. This must be satisfied if the tube is to remain stable.

The requirement that the internal field tension be balanced by the plasma and field pressure does not define the direction, or sense, of the twist. Cowley (1982) noted that the observed behaviour of B_N does define a sense of twist. However, why there should be a preferred direction was not explained. We discuss this point in the next section.

Satellite observations of the interior of FTEs show that the direction of twist in both the magnetosheath and magnetospheric half have the same sense for a single FTE, the actual orientation being determined by the Interplanetary Magnetic Field (IMF). If IMF $B_y > 0$ the field twist is clockwise when viewed along the magnetic field direction and anticlockwise if IMF $B_y < 0$. Saunders *et al.* (1984) used dual-satellite data to study FTEs. Such data can provide more compelling evidence that the interior of reconnected flux tubes is twisted than one-satellite data can. Saunders *et al.* (1984) analysed the magnetic field and plasma flow perturbations of the twisted interior and concluded that for the cases they studied the twist was an Alfvén wave propagating away from the site of reconnection. Haerendel *et al.* (1985) have also examined the twist inside reconnected flux tubes and found that the field and flow perturbations satisfy those of an Alfvén wave propagating away from the magnetopause to a very high degree. Both the Saunders *et al.* and Haerendel *et al.* studies were for magnetosheath FTEs. Although we know that the magnetospheric half of the FTE is twisted, it has not been determined whether the flow inside the tube is that of an Alfvén wave. Further analysis of data is required.

3. TWISTED FLUX TUBES

Before we discuss the twisting mechanism it is useful to define what we mean by a twisted flux tube. The reconnected flux tubes shown in Figs 1 and 2(a) are actually twisted as well as kinked. As we shall see, this is due to the background fields being skew and lying on opposite sides of the magnetopause. This is easier to understand by first considering the tube that would be formed by reconnection in antiparallel magnetosheath and magnetospheric magnetic fields. In this case both halves of the flux tube would lie next to one another and be separated by the magnetopause. Such a tube is not twisted but merely kinked. By introducing some skewness into the background magnetic fields we produce tubes that have a twist in addition to a kink. The concept of twist requires a definition. For the purpose of this paper we shall term a flux tube "not twisted" if every magnetic field line is independently confined to a plane (not necessarily the same plane for every field line). Thus a flux tube that consists of self-coplanar magnetic field lines is not twisted—it is either kinked (cf. antiparallel fields) or straight (if the field lines are linear).

It is useful to introduce the concepts of global and local twist. Local twist is the twist within a small volume or section of a flux tube. Global twist is the twist over a large section of flux tube—possibly an infinite length of tube, or a closed loop of magnetic flux. For example, consider moving the "ends" of a flux tube, produced by reconnection in antiparallel fields, in opposite directions along the magnetopause. The tube is stretched out through a configuration similar to that in Fig. 2(a) until the tube axis is straight; however, the flux tube (from our definition) is twisted. We have introduced a one-half twist into an initially untwisted section of tube. By considering the properties of a magnetic field it is evident that we have introduced an opposite amount of twist into the part of the tube beyond the "ends" that we moved.

The difference between global and local twist can be appreciated by considering a long straight flux tube that has been twisted over a certain section and twisted by an opposite amount over another section. The magnetic field structure of the flux tube is straight field lines in the untwisted regions and helical field lines in the twisted sections. In this case the local twist is zero when the small volume under consideration lies in the straight (i.e. self-coplanar) magnetic field region and is non-zero when we consider a small volume within the helical (not self-coplanar) field line region. Within our working definition of a twisted flux tube, the flux tube described above is twisted; however, there is no net (global) twist over the entire flux tube. The global twist is zero because there exist sections of equal and opposite local twist, not because the local twist is everywhere equal to zero.

A field configuration that can be produced by more than one reconnection line is shown in Fig. 3. Note how the field lines are not self-coplanar and so we describe the tube as being twisted. Although it is fairly evident that the structure in Fig. 3 is twisted, it is not obvious, at first sight, that the flux tube in 2(a) is also

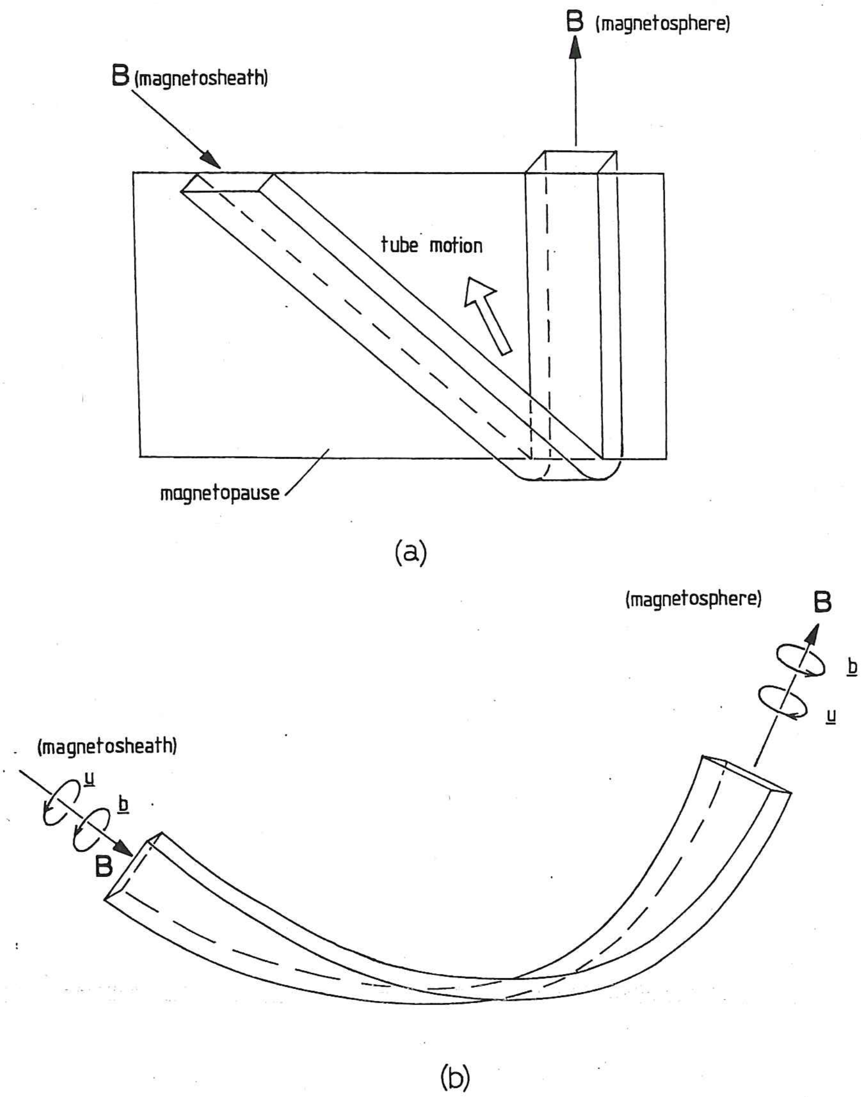

FIG. 2. THE GEOMETRY OF A SLAB OF MAGNETOSHEATH PLASMA AND FIELD THAT HAS BEEN RECONNECTED TO THE MAGNETOSPHERE IS SHOWN IN (a) IMMEDIATELY AFTER RECONNECTION HAS STOPPED FOR IMF $B_y > 0$. (Only the northern half is shown.) The sequence in which magnetic field lines reconnect is important. First of all, field lines lying on the magnetopause will reconnect to one another, thereafter we begin to reconnect field lines that lie on top of the newly reconnected field lines. This results in the last field lines that are reconnected lying on the front side of the magnetosheath slab and on the back-side of the magnetospheric slab. The strong kink in this field configuration is released into plasma energy by acceleration of the flux tube in the direction indicated in the figure. The details of the evolution of this motion are complicated. However, by examining the Maxwell stresses inherent in such a field configuration it is possible to show that there is a torque acting upon the tube. The torque will cause a torsional Alfvén wave to propagate away from the reconnection site and along the flux tube. The torsional Alfvén wave will twist the magnetic field inside the tube as it travels through it and the directions of the magnetic field perturbations (b) and the flow perturbations (u) are also shown for this wave mode in figure (b).

twisted. It is because of this difficulty that a criteria has been introduced that defines a twisted magnetic field.

The definition of twist attributes the following properties to twisted and untwisted flux tubes. An untwisted flux tube (all magnetic field lines self-coplanar) has zero local twist everywhere and thus zero global twist. A twisted flux tube (not all field lines self-coplanar) will have regions where the local twist is non-zero; however, the global twist may or may not be zero. These definitions are adequate for our discussion and we shall not attempt to define a quantitative measure of twist. Using this classification of twisted and kinked flux tubes we shall now consider the forces and torques that act upon such structures.

4. TWISTING MECHANISM

To produce a twisted field structure we must either introduce twist by applying some rotational motion at one or several positions on a flux tube, or we must form the (composite) flux tube with a twist implicit in its structure. Let us consider the first mechanism to begin with. If we were to turn (azimuthally) a portion of a long, straight tube we would introduce oppositely directed field twists on either side of the section that we turn. The fact that in any one FTE the direction of field twists on either side of the magnetopause is the same means that if the twist is produced by rolling a portion of the tube, this portion must be beyond the range of our satellite, i.e. we only see data from one side of the turning region. Thus the region being turned must either be out in the solar wind or within the magnetosphere. The Saunders *et al.* (1984) examples were of Alfvén waves propagating away from the magnetopause and into the solar wind. Therefore the rolling region cannot be out in the solar wind. Unfortunately it has not been shown to date whether the twist in the magnetospheric portion of the tube is propagating to or from the magnetopause, so we cannot definitively say if the twist is produced within the magnetosphere or at the magnetopause. The bulk motion of a flux tube past a satellite is accomplished by a shear Alfvén wave whose propagation speed is the same as the torsional Alfvén wave. If the source of twist is within the magnetosphere it is likely that some of the magnetosheath halves of the FTEs we observe will sometimes have no twist because of the extra distance that the twist has to travel. This is not

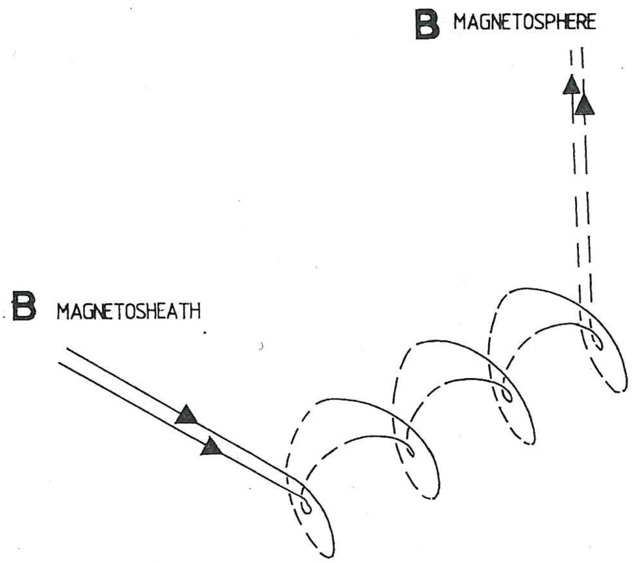

FIG. 3. THE PRESENCE OF MORE THAN ONE RECONNECTION LINE MAY SIGNIFICANTLY INCREASE THE AMOUNT OF TWIST IN A FLUX TUBE.

Heavy lines represent the magnetosheath field lying in front of the magnetopause, and the dashed lines are magnetospheric field lines that lie behind the magnetopause. This structure is like the field configurations envisaged by Lee and Fu (1985).

observed and so it is unlikely, but not impossible, that FTEs are twisted by a rolling motion within the magnetosphere.

The remaining twisting mechanism is to form a reconnected tube that has a twist inherent in its structure. As the tube relaxes it will distribute the twist along its length and and the twist will propagate as a torsional Alfvén wave. Since the torsional Alfvén wave and the bulk motion of the tube (a shear Alfvén wave) both propagate at the same speed and originate from the same region we would always expect to see a tube twisted if it moved over the spacecraft. This mechanism appears to be more consistent with the data and we shall now investigate it in more detail.

The reconnection process that is responsible for creating open flux tubes is a source of the three magnetohydrodynamic wave modes. A full modeling of the propagation waves, their interaction with one another and the resulting magnetic field structure is a formidable problem and will not be attempted here. The intermediate, or Alfvén, mode gives rise to the bulk motion of a flux tube and is also the mode that Saunders *et al.* (1984) observed as the twist inside the tube (a torsional Alfvén wave). We shall restrict our analysis to this wave mode only.

The structure of the reconnection site is, of course, very important. The flux tube in Fig. 2(a) has been formed by a single reconnection line. In contrast to this, multiple reconnection lines have been suggested by Lee and Fu (1985) and Sato *et al.* (1986). The effect of increasing the number of reconnection lines is to increase the amount of twist possible within the flux tube. In fact the structure can be simply visualized as a wound-up tube lying in the magnetopause that is connected to terrestrial or solar wind flux at either end.The resulting tube will move according to the forces acting upon it. In the wound-up portion the magnetic force will cause the tube to collapse until balanced by plasma pressure. There is no net force taken over the cross-section of this part of the tube and hence no bulk motion. However, where the background field joins the wound-up section there will be unbalanced forces which will give rise to flux tube motion. There is also a component of this force which acts as a torque and twists the tubes running into the reconnection region. This will transmit the twist inherent in the reconnected field geometry along the untwisted portions as torsional Alfvén waves. As we have stated, the forces and torques that excite Alfvén waves (i.e. tube motion) will only be significant where the background field enters the reconnection site. For this reason it is sufficient to consider the configuration in Fig. 2(a) only. (The effect of having a more twisted field in the reconnection region is to merely increase the number of twists that can be propagated away as torsional Alfvén waves.)

Figure 2(a) schematically depicts a northern open field line immediately after reconnection [for Interplanetary Magnetic Field (IMF) $B_y > 0$; GSE coordinates]. Initially there is a strong kink in the new tube. This kink corresponds to a current ($\mu_0 J = \nabla \wedge B$) and gives rise to a force ($J \wedge B$, or Maxwell stresses). The result is a slingshot motion in the direction of the arrow. The propagation of this disturbance and the associated tube motion is not well understood, but is crucial in understanding the features observed in satellite data.

From the discussion in the previous section we know that the tube in Fig. 2(a) is twisted. This is because it is impossible for a field line in the magnetosheath half to be coplanar with its continuation in the magnetospheric half (due to their relative displacement normal to the magnetopause). By considering the topology of field lines it can be seen that as the tube relaxes we must produce a structure like that in Fig. 2(b). On solely topological grounds we can anticipate that a twisted flux tube will evolve with the field twist shown in the figure. To understand how the tube can evolve in this fashion we need to discuss the torque acting upon each half of the open flux tube. It is possible to quantify the torque, but first consider the linear force that gives rise to it. We shall only treat the case of similar magnetosheath and magnetospheric plasmas and magnetic field strengths. Since the Alfvén mode does not give rise to changes in magnetic field strength, only the "field line tension" part of the Maxwell stresses will be considered. (If a magnetic field line has a local radius of curvature $\mathbf{R}$, the field line tension force is $B^2/\mu_0 R$ per unit volume and is directed antiparallel to $\mathbf{R}$.) Consider a reconnected flux tube of radius r that is produced in antiparallel fields. The mean radius of curvature at the kink that straddles the magnetopause is also r. If there is a shear between the two background field directions this curvature will be reduced since the turning region in the kink is no longer produced by semicircular magnetic field lines but by helically-shaped ones. If the supplementary angle between the two field directions is θ ($\theta = 0°$ for antiparallel magnetic fields), the mean radius of curvature at the reconnection site will now be a function of θ. It can be shown that the mean radius of curvature of magnetic field lines in the turning region is in fact $r/\cos^2(\theta/2)$, and so the associated force per unit volume is

$$F = (B^2/\mu_0 r) \cdot \cos(\theta/2).$$

The net force on the kinked region is along the direction of motion shown in Fig. 2(a). At the centre of this region (in the plane of the magnetopause) the field line tension force is confined to the plane of the magnetopause and bisects the flux tube axes by $\theta/2$. The force on elements within the kinked region that lie outside the plane of the magnetopause has only a component tangential to the magnetopause that reduces to zero at the ends of the kinked regions. On each half of the flux tube near the reconnection site this will produce a strong force along the magnetopause on the part of the flux tube lying next to the magnetopause. The part of the tube furthest from the magnetopause experiences a force that is largely normal to the magnetopause, and the shear in the background fields means that this will act as a couple on the kinked region. The non-uniform magnitude of the force distributed throughout the turning region produces a torque whose magnitude is determined by the component of the force that is orthogonal to the tube axis and the radial direction. The torque (per unit volume) experienced by both halves of the tube is approximately

$$T = F \sin(\theta/2) \cdot r = (B^2/2\mu_0) \cos(\theta/2) \sin(\theta).$$

It is directed in a clockwise sense about the magnetosheath field and an anticlockwise sense about the magnetospheric field (viewed parallel to the field). Note how in antiparallel fields ($\theta = 0°$) the torque is zero and from the previous section the tube is not twisted. In this limit the force acts solely to produce bulk motion of the tube along the field directions and only a shear Alfvén wave is excited. It is the propagation of this wave mode that manifests itself as the tube motion. If $\theta \neq 0°$ there will be a non-zero torque in addition to the linear force. This will excite both torsional and shear Alfvén waves. The torsional Alfvén wave will propagate along the tube as a twist in the magnetic and velocity fields. The evolving tube is shown in Fig. 2(b). The directions of the magnetic field and plasma flow perturbations are also shown. (These are in the opposite senses for the southern open tube.) If IMF $B_y < 0$ all these directions are reversed, as is the sense of the torque.

It should be remembered that the above argument is highly idealized. In particular, the background plasma and field are assumed to be static. If there is some magnetosheath plasma flow perpendicular to the magnetospheric field direction (as is normally the case) the two halves of the tube will spatially separate. This will cause the flux tube to twist even in antiparallel fields as it evolves.

5. DISCUSSION

The current structure for the torsional Alfvén wave shown in Fig. 2(b) will correspond to an earthward core-aligned current (on both sides of the magnetopause). On the outside of the flux tube will be a return current that closes the core-aligned current via perpendicular currents ($J_\perp$) at the front and back of the wave packet. It is these perpendicular currents that change the untwisted tube outside the Alfvén wave packet to a twisted structure inside the wave packet. It is easy to envisage how the $J_\perp \wedge gB$ force will give rise to an azimuthal momentum within the tube. (These currents will, of course, be in the opposite direction for the southern tube and all perturbations change sign if IMF $B_y < 0$.). It is interesting to note that the forces acting upon the tube will always act to shorten the field lines. As a result of this the interior field is always expected to have a direction that is intermediate of the two background directions.

If we identify these torsional Alfvén waves with those observed by Saunders *et al.* (1984), we find that the directions of all field and flow perturbations agree with their data. Furthermore, it is possible to estimate the pitch length of the magnetic field twist within the torsional Alfvén wave. The mean angular acceleration can be equated to the mean torque ($T/2$)

$$r\rho\frac{u}{\tau} = \frac{B^2}{4\mu_0}\cos(\theta/2)\sin(\theta)$$

where τ is the timescale that a one-half twist is released in, u is the azimuthal velocity and ρ is the plasma density. Recalling that the azimuthal magnetic field and velocity in an Alfvén wave are related to one another by $b/B = \pm u/V_A$ and that the Alfvén velocity is $V_A = B/(\mu_0\rho)^{1/2}$, we can calculate the pitch length (L) from

$$\frac{2\pi r}{L} = \frac{b}{B} = \frac{u}{V_A} = (V_A\tau)\cdot\cos(\theta/2)\sin(\theta)/4r.$$

The maximum twist that single x-line reconnection can impart is one-half twist. Assuming that each half of the tube is twisted equally, $V_A\tau = L/4$. Thus the pitch length is

$$L = 4r\left[\frac{2\pi}{\cos(\theta/2)\sin(\theta)}\right]^{1/2}.$$

Saunders *et al.* estimated the tube radius and pitch length to be 0.5 R_E and $6R_E$, respectively. (1 R_E = one Earth radius.) Using their value for r and estimating $\theta = 90°$ from their magnetometer data we anticipate $L = 6R_E$. This is in excellent agreement with their value in view of the crudeness of our model.

6. CONCLUSION

The properties of twisted flux tubes have been discussed and a criterion given for deciding whether or not a magnetic field structure is twisted. We term a magnetic field "twisted" if the field lines are not self-coplanar. By considering the effect of twisting a section of flux tube we conclude that the twist seen inside FTEs originates within the magnetosphere, or that the reconnected flux tube is formed with an inherent twist. If further data analysis can show in which direction the twist in the magnetospheric half is propagating it will be possible to decide between these two alternatives. At present we cannot definitely say which mechanism is responsible; however, in view of the twist (torsional Alfvén wave) and the tube motions (shear Alfvén wave) always being observed together it is likely that they have a common source. This favours the tube being formed with a twist implicit in the reconnection geometry.

The evolution of the reconnected flux tube is discussed and we show how torsional Alfvén waves will be propagated away from the reconnection site. The pitch length of the wave is estimated and the directions of field and flow perturbations are given. We find excellent agreement with observations obtained at the Earth's dayside magnetopause.

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