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RESEARCH ARTICLE

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Magnetospheric Physics

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Key Points:

- Plasma filaments entering the magnetosphere get rotation by crossing velocity shear at magnetopause
- Filaments propagate in magnetosphere even if their magnetic field is not in-line with ambient field
- It is possible when filaments' axes are oriented along or close to ambient magnetic field

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Penetration of magnetosheath plasma into dayside magnetosphere: 2. Magnetic field in plasma filaments

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Abstract In this paper, we examined plasma structures (filaments), observed in the dayside magnetosphere but containing magnetosheath plasma. These filaments show the stable antisunward motion (while the ambient magnetospheric plasma moved in the opposite direction) and the existence of a strip of magnetospheric plasma, separating these filaments from the magnetosheath. These results, however, contradict both theoretical studies and simulations by Schindler (1979), Ma et al. (1991), Dai and Woodward (1994, 1998), and other researchers, who reported that the motion of such filaments through the magnetosphere is possible only when their magnetic field is directed very close to the ambient magnetic field, which is not the situation that is observed. In this study, we show that this seeming contradiction may be related to different events as the theoretical studies and simulations are related to the case when the filament magnetic field is about aligned with filament orientation, whereas the observations show that the magnetic field in these filaments may be rotating. In this case, the rotating magnetic field, changing incessantly its direction, drastically affects the penetration of plasma filaments into the magnetosphere. In this case, the filaments with rotating magnetic field, even if in each moment it is significantly inclined to the ambient magnetic field, may propagate through the magnetosphere, if their average (for the rotation period) magnetic field is aligned with the ambient magnetic field. This shows that neglecting the rotation of magnetic field in these filaments may lead to wrong results.

1. Introduction

In this study, we examined the magnetic field of plasma structures (filaments), comprising magnetosheath plasma but observed in dayside magnetosphere. The penetration of magnetosheath plasma into the magnetosphere, which is observed also as a significant increase of plasma density in the low-latitude boundary layer [Newell and Meng, 2003], is an important problem since it affects significantly the plasma density in Earth's magnetosphere.

Despite many previous studies [e.g., Lemaire, 1977; Lemaire and Roth, 1978; Heikkila, 1982; Lemaire, 1985; Lundin and Dubinin, 1984; Lundin, 1997; Echim and Lemaire, 2000; Lundin et al., 2003; Gunell et al., 2012, 2014], the mechanism of penetration of this plasma into the magnetosphere is not clear. The main problem impeding understanding of this phenomenon is how these plasma filaments propagate across the Earth's magnetic field. To resolve this problem, in paper 1 we examined the structure of these plasma filaments, their velocity, and other factors to verify their penetration into the magnetosphere. In this study, we examine the magnetic field inside these filaments and compare the observation results with the results of theoretical studies and modeling. For this purpose, we examined events measured on Cluster during 2 years, 2007–2008, when spacecraft orbits were appropriate for this analysis.

The mechanism, responsible for penetration of magnetosheath plasma into the magnetosphere in the form of plasma filaments (or blobs), was proposed by Lemaire [1977], Lemaire and Roth [1978], Heikkila [1982], Lemaire [1985], Lundin and Dubinin [1984], Lundin [1997], Echim and Lemaire [2000], Lundin et al. [2003], and Gunell et al. [2012, 2014].

They suggested that penetration of the plasma filaments into the magnetosphere may occur in the case of an enhanced momentum of these filaments. This mechanism, however, lacked a convincing explanation of how these plasma structures (within which the magnetic field may be considerably inclined to Earth's magnetic field) can penetrate into the magnetosphere and move earthward in contrast to the results of the theoretical studies

by Schindler [1979] and numerical simulations by Ma *et al.* [1991], Dai and Woodward [1994, 1998], Savoini *et al.* [1994], and Savoini and Scholer [1995], which showed that even an insignificant (a few degrees) inclination of these filaments to the ambient magnetic field prevents their penetration into the magnetosphere.

This contradiction between observations and theory is the main problem that motivated researchers to examine other explanations, such as back and forth magnetopause motions and surface waves propagating along the magnetopause. Nevertheless, the idea of the direct penetration of plasma filaments into the magnetosphere continues to evolve and obtained significant support from the Cluster observations [e.g., Lundin *et al.*, 2003; Hultqvist *et al.*, 2005; Gunell *et al.*, 2012, 2014, and references therein]. In particular, Lundin *et al.* [2003] showed that the penetration of magnetosheath plasma is observed not only on the dawn and dusk magnetospheric boundaries (where it is supported by the Kelvin-Helmholtz instability) or near the cusps but in any sector in dayside magnetosphere and that the penetration of magnetosheath plasma into the magnetosphere is observed during different directions of the interplanetary magnetic field (IMF) but more frequently during the northern IMF B_z , when the traditional reconnection is weak.

However, as mentioned above, these results contradict both theory and simulations (see also the review by Echim and Lemaire [2000]). Theoretical studies of the penetration of two-dimensional magnetosheath plasma filaments into Earth's magnetosphere by Schindler [1979] showed that, in the case of the ideal MHD, the penetration is possible only when the magnetic field in the filament is aligned with the magnetic field in the ambient magnetospheric plasma. This was confirmed by Ma *et al.* [1991], Dai and Woodward [1994, 1998], Savoini *et al.* [1994], and Savoini and Scholer [1995], who used different models of numerical simulations and also showed that such plasma filaments cannot move through the magnetosphere in the cases when their magnetic field is inclined to the ambient magnetic field by more than 5° . Thus, both theoretical study and simulations show that the penetration of magnetosheath plasma filaments into the magnetosphere is possible only when very restrictive conditions are met. Consequently, Schindler [1979] reported that under conditions of ideal MHD, the "penetration of an irregularity (filament) is possible if the magnetic fields inside the filament and in the magnetosphere are aligned" since (if they are not aligned) "there is a repelling force due to piling up of magnetic flux in front of the filament." This statement was repeated by Ma *et al.* [1991], Dai and Woodward [1998], Savoini *et al.* [1994], and Savoini and Scholer [1995], who used the 2-D hybrid simulation with particle ions and fluid electrons. Thus, these results show that the impulsive penetration is possible when the magnetic field in filaments is strongly parallel or insignificantly inclined to the ambient magnetic field. This, however, is totally inconsistent with observation results, mentioned above, which show that the penetration of the plasma filaments into the magnetosphere is observed even when the magnetic field inside these filaments is significantly inclined to the ambient magnetic field.

In this study, we have shown that the reason for this discrepancy may be due to the fact that the theoretical studies and observations may be related to different events. Indeed, both theoretical studies and simulations, mentioned above, have been related to the simple cases of the straight magnetic field inside plasma filaments, whereas the observation results may be related to a rotating magnetic field inside these filaments. In this case, the direction of the rotating magnetic field is variable inside the filaments, and as a result, the mandatory condition for penetration of such filaments into the magnetosphere is related not to the direction of their magnetic field (varying in time and space) but to the filament elongation (which, however, is more difficult to determine than the magnetic field direction). Testing this possibility is explored below.

In this study, we use the term "impulsive penetration," proposed by Lemaire [1977], who suggested that some filaments may penetrate from the magnetosheath into the magnetosphere, if their momentum exceeds the momentum of surrounding magnetosheath plasma. Later this mechanism was used by Lemaire and Roth [1978], Heikkilä [1982], Lemaire [1985], Lundin and Dubinin [1984], Lundin [1997], Echim and Lemaire [2000], Lundin *et al.* [2003], Gunell *et al.* [2012, 2014], and others. In this study, we use this term as proposed by Lemaire: as a third penetration mechanism of magnetosheath plasma into the magnetosphere, being "an alternative to the Dungey and Axford-Hines models" (see, e.g., http://csrsrv1.fynu.ucl.ac.be/csr_web/seminars/Lemaire/Abs_Daejeon_modMME.pdf). This definition admits different ways to implement this mechanism in the frames of the model of impulsive penetration, including the MHD, kinetic approach, or other models. This manuscript is a continuation of our previous study [Lyatsky *et al.*, 2016] (part 1), where we investigated the plasma density, velocity, and rotation of these plasma filaments; in this study we investigate the magnetic field in these filaments.

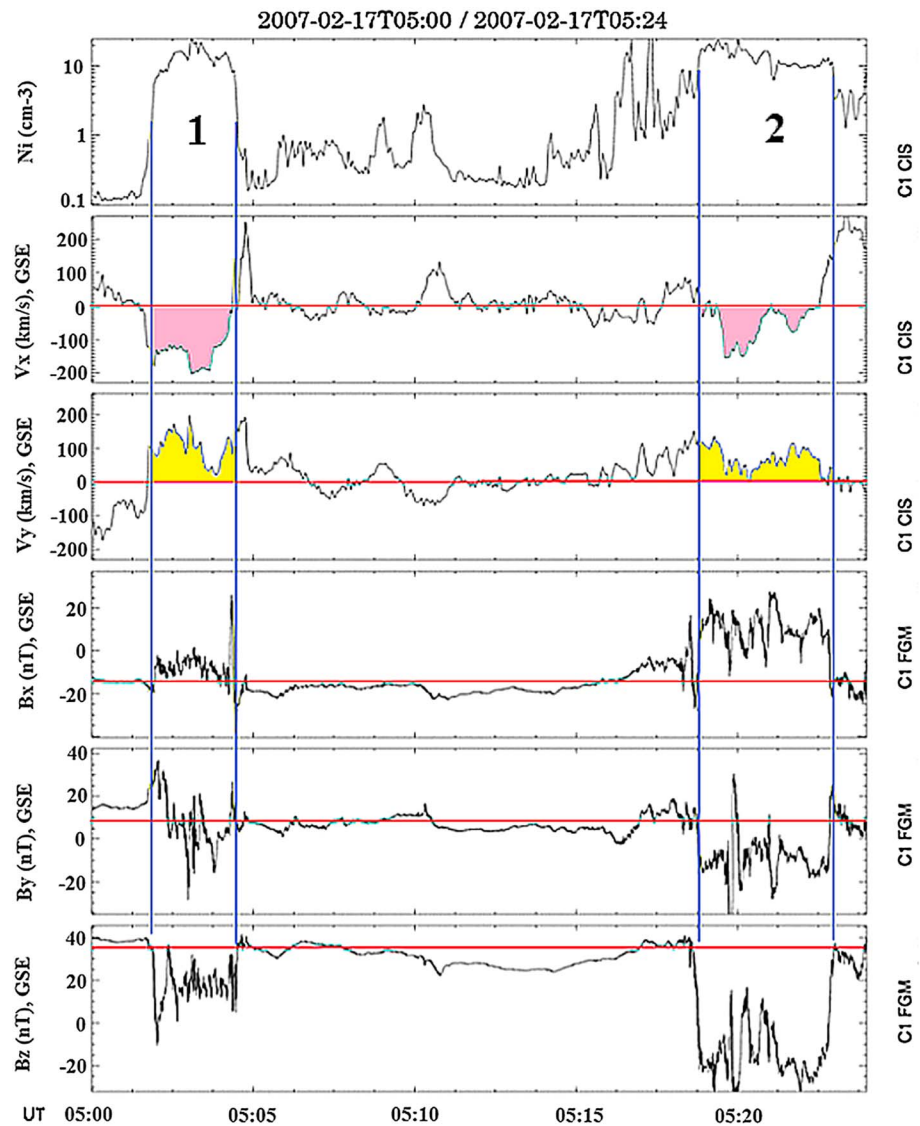


Figure 1. Examples of the magnetic field inside and in the vicinity of the plasma filaments in noon-dusk sector. Both filaments (marked by 1 and 2) move antisunward at the velocity $V_x \approx 150$ km/s and duskward at the velocity $V_y \approx 100$ km/s. The red horizontal lines for the magnetic field show the average magnitudes of the ambient magnetic field for all three components. The magnetic field shows the strong variations and may even change its direction. The vertical B_z magnetic field component in both cases decreases, but in case 1, it remains positive, while in case 2, it changes its sign and becomes negative, which usually coincides with the direction of the magnetic field in the magnetosheath.

2. Analysis Method

In this paper, we consider the events in dayside magnetosphere predominantly within a narrow cone ($\leq 30^\circ$) about the subsolar point. Among the possible causes of penetrating magnetosheath plasma into dayside magnetosphere, we mention the magnetic reconnection during the northern IMF appearing simultaneously in two polar cusps or the multiple reconnection at the magnetopause, leading to the isolated “plasma islands” [e.g., Lyatsky and Goldstein, 2013, and references therein], and the penetration of plasma filaments from the magnetosheath into the magnetosphere as a result of their excess momentum, which was discussed above.

The reconnection of the magnetosheath magnetic field with Earth’s magnetic field in both polar cusps basically might result in linking the reconnected elements of magnetosheath magnetic field lines with Earth’s magnetic field in two polar cusps, allowing them to move earthward. However, since the magnetosheath

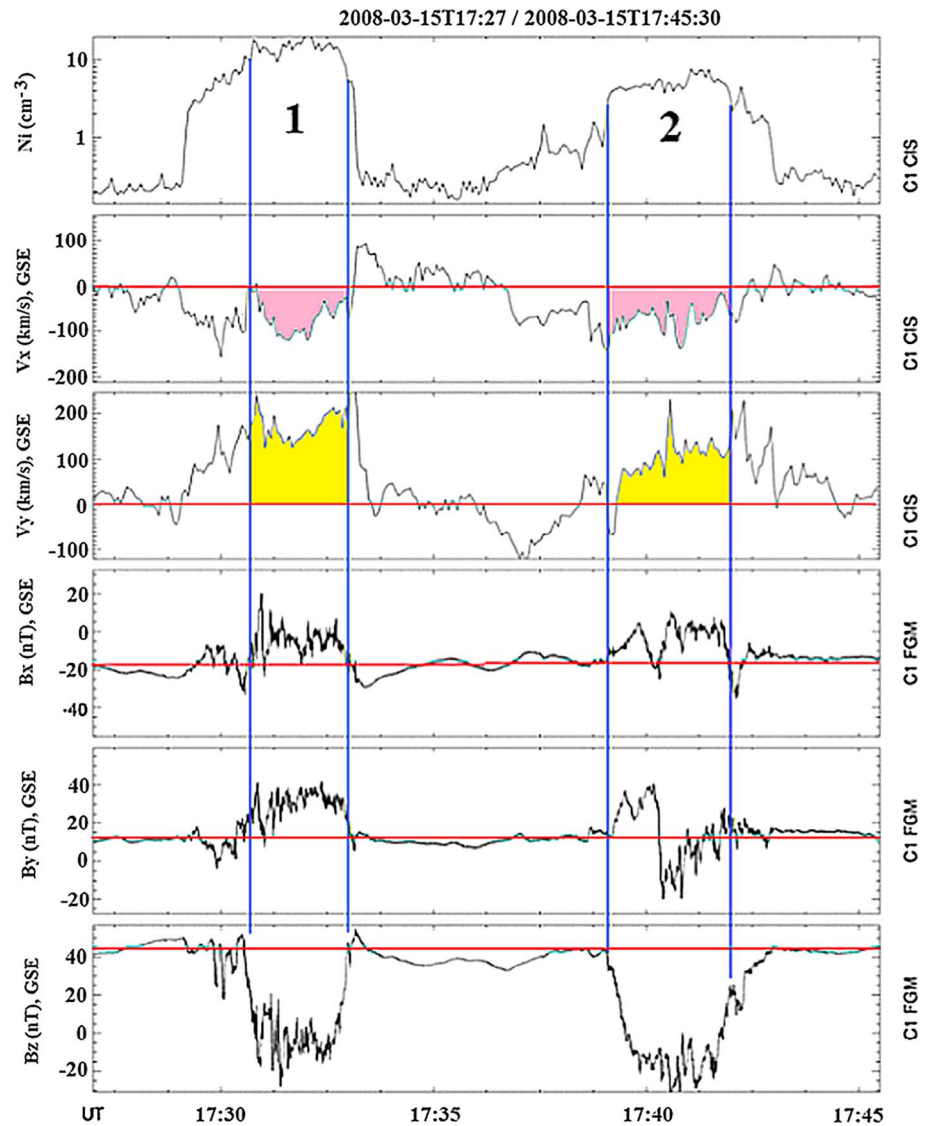


Figure 2. The same as in Figure 1 but in the near-noon sector. Both filaments, the same as in Figure 1a, move antisunward at the velocity $V_x \approx 100$ km/s and duskward at the velocity $V_y \approx 100$ –150 km/s. The magnetic field also shows strong variations. The vertical B_z magnetic field component in both cases decreases and may change its sign.

magnetic field is very variable and its orientation may significantly differ from that of Earth's magnetic field, the "two-point" reconnection may occur very rarely, and unlikely, it may explain the large number of plasma filaments observed in the magnetosphere. Therefore, in this study as a main cause of the penetration of plasma filaments into the magnetosphere, we consider the excess momentum of these plasma filaments, proposed by Lemaire [1977], Lemaire and Roth [1978], Lemaire, [1985], Lundin and Dubinin [1984], Lundin [1997], Echim and Lemaire [2000], Lundin et al. [2003], and other researchers, which is more realistic. Some cases of "imaginary filaments" (which may be a result of back and forth motions of the magnetopause or the surface waves propagated along the magnetopause) sometimes also may be seen, but these events are easily separated from the filaments, detached from the magnetosheath and containing magnetosheath plasma.

The examples of plasma filaments moving antisunward (approximately earthward) are shown in Figures 1 and 2. Figure 1 shows the events in the noon-dusk sector, moving stably earthward and identified as plasma filaments, detached probably from the magnetosheath, while Figure 2 shows the similar events in the near-noon sector. These events observed on C1 are marked by the numbers 1 and 2 (all events here and later are

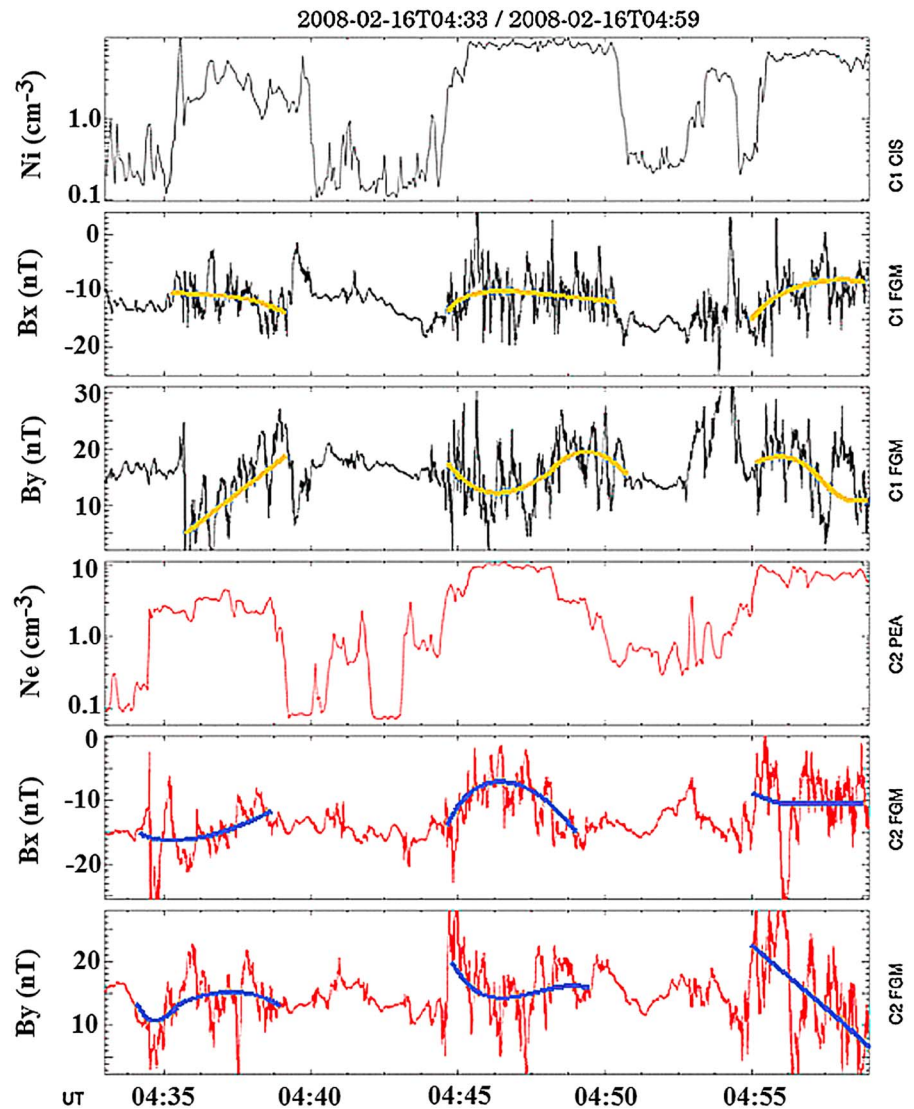


Figure 3. Shown are the ion (N_i) and electron (N_e) plasma densities observed on C1 and C2, respectively, and the magnetic field B_x and B_y components in noon-dusk sector on 16 February 2008. The phase shift between the B_x and B_y magnetic field components shows the rotation of the magnetic field vectors in the x - y plane, although the intermittent character of the magnetic field complicates this rotation. The black lines are related to C1, while the red lines to C2. The yellow and blue lines show the average values of the B_x and B_y components on both spacecraft.

presented in the GSE coordinate system). Both Figures 1 and 2 show the antisunward V_x component of plasma velocity, the dusk-down (V_y) component of plasma velocity, and three (B_x , B_y , and B_z) components of the magnetic field.

Although the behaviors of the magnetic field in the filaments in Figures 1 and 2 are alike (e.g., the magnitude of the magnetic field B_z component inside the filaments decreases as a result of diamagnetic currents on filament boundary), in other cases they may significantly differ: in some cases, the currents inside the filaments may be not diamagnetic but paramagnetic (when the plasma pressure inside the filaments is lower than that in ambient plasma; although the ambient plasma has low density, its temperature sometimes may exceed that in the dense but colder filaments). Note also the frequently observed increases of the magnetic field on filament boundaries (well seen in Figures 1 and 2), appearing as a result of compression of the ambient plasma and its magnetic field by these moving filaments. Another feature is a strong variability of the magnetic field inside the filaments, which is a result of the presence of subfilaments inside the main filament. However, the most

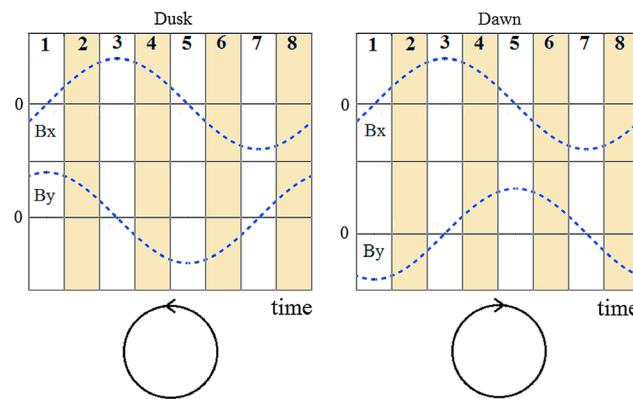


Figure 4. Magnetic field B_x and B_y components in the case of a rotating magnetic field. (left) The magnetic field vector in the x - y plane is rotating counterclockwise. (right) It is rotating clockwise, as shown by circles with arrows. Since the plasma filaments (or subfilaments) cross the spacecraft position over time intervals shorter than the rotation period of the field, we see only short intervals of filament rotation. Each plot in this figure is separated into eight intervals, which facilitates determination of magnetic field rotation.

worth noting: (i) the filaments with a twisted magnetic field, rotating about the filament axis, may propagate across the ambient magnetic field in the same way as the filaments with the magnetic field directed along the filament, and (ii) the twisted magnetic field inside plasma filaments may remain stable even when they consist of several twisted and interwoven subfilaments.

For better understanding the effect of the magnetic field in plasma filaments on their penetration into the magnetosphere, let us consider a case, when a plasma filament moves through the magnetosphere. For simplicity, we suggest that this filament is a cylindrical form and is oriented along the ambient magnetic field. In this case, this filament can move earthward in between the ambient field lines and penetrates a significant distance in the magnetosphere.

The situation, however, is different in the case when the filament and its magnetic field are inclined to the ambient magnetic field in the plane, perpendicular to filament motion (say, along the y axis). In this case, the filament, while moving earthward (against the direction of the x axis) and perpendicularly to its elongation, compresses the ambient magnetic field in a wide longitude sector. As a result, the compressed ambient magnetic field pushes this filament back, making impossible its penetration into the magnetosphere contrary to the observations [e.g., Lemaire, 1977; Lemaire and Roth, 1978; Lundin et al., 2003]. The question of how the plasma filaments with a significantly inclined magnetic field can penetrate into the magnetosphere and move earthward is the main problem to be addressed here. We will show that the motion of the filaments through the magnetosphere is possible in the case of the rotating magnetic field inside the filaments.

Note that the rotation of the filaments and their magnetic field is a natural result of their crossing the velocity shear in the vicinity of the magnetopause. This effect is especially significant on magnetosphere flanks, where the velocity of magnetosheath plasma along the magnetopause is very high that may be a result of the Kelvin-Helmholtz instability [e.g., Hasegawa et al., 2004]. However, the velocity shear exists also in dayside magnetosphere, where it is not as strong as on flanks but may be sufficient for rotation of plasma filaments and their magnetic field.

Note also that the rotation of any fraction of filament length leads to the generation of the rotating Alfvén waves, propagating along the magnetic field (the Alfvén waves inside the filaments were observed, e.g., by Gunell et al. [2014]). These Alfvén waves transport the rotation of the plasma and magnetic field along the filament that produces twisting the magnetic field within the filament about its axis. This twisted magnetic field inside the filament in some cases allows it to move through the magnetosphere. Note that the observation results not always let us to identify the twisted magnetic field inside the filaments, consisting of several subfilaments, which hinders to examine the wave rotation. Nevertheless, the rotating magnetic field inside the filaments in many cases is well seen, as shown in the next section.

important feature of these filaments is their rotating magnetic field (see later), which is critical for better understanding of the nature of these events.

3. Effect of Twisted Magnetic Field Inside Plasma Filaments

Rotating (twisted) magnetic fields are well known on the Sun [e.g., Bennett et al., 1999; Klimchuk et al., 2000; Longcope and Welsch, 2000; Mackay et al., 2010], where plasma filaments, observed around solar spots, show frequently the twisted structures. Among many features of the twisted magnetic field inside plasma filaments, two are especially

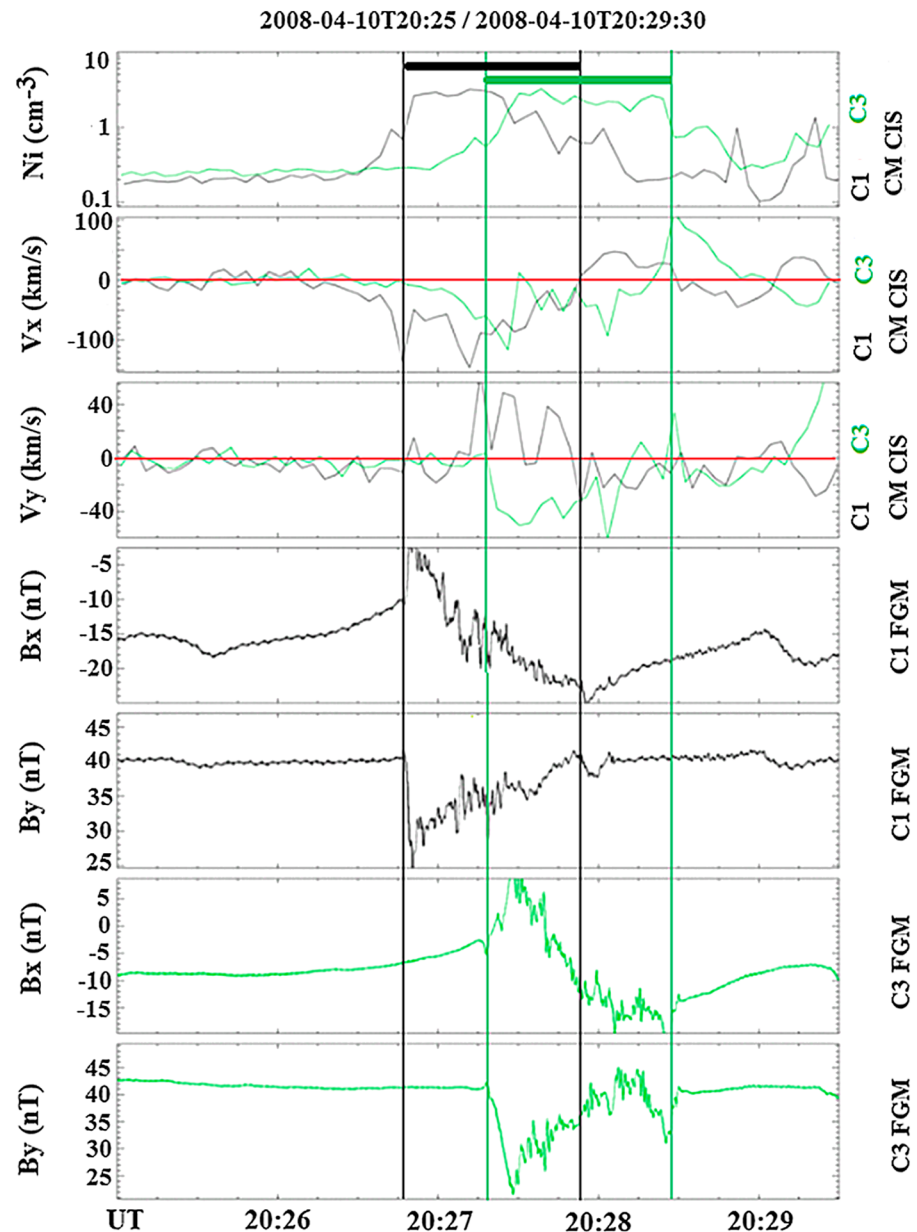


Figure 5. An example of rotating magnetic field inside a plasma filament, observed on C1 and C3 in the noon-dawn sector on 10 April 2008. Shown are the ion (N_i) density, two components (V_x and V_y) of plasma velocity, and two components (B_x and B_y) of the magnetic field in the x - y plane as observed on the C1 (in black) and C3 (in green), respectively.

4. Rotating Magnetic Field from Observations

Thus, the complicated structure of plasma filaments, consisting of subfilaments, leads to an intermittent magnetic field inside the filaments, which impedes their study. Nevertheless, the rotating magnetic field inside the filaments in many cases is seen rather clearly; several such cases are shown below. Figure 3 shows the magnetic field on C1 and C2 Cluster spacecraft, moving at a considerable distance ($\sim 10,000$ km) from each other. There are significant variations in the magnetic field B_x and B_y components (which are approximately normal to the ambient magnetic field) as well as a significant difference in variations of average values of these components, which shows the rotation of the magnetic field vector in the x - y plane. Note that rotation of the magnetic field is well observed (although it is not always the same) on both spacecraft.

Although the rotation of the magnetic field in Figure 3 is well seen on both C1 and C2, sometimes it is obscure by the intermittent structure of the magnetic field inside the filaments by the fact that the short transit time of

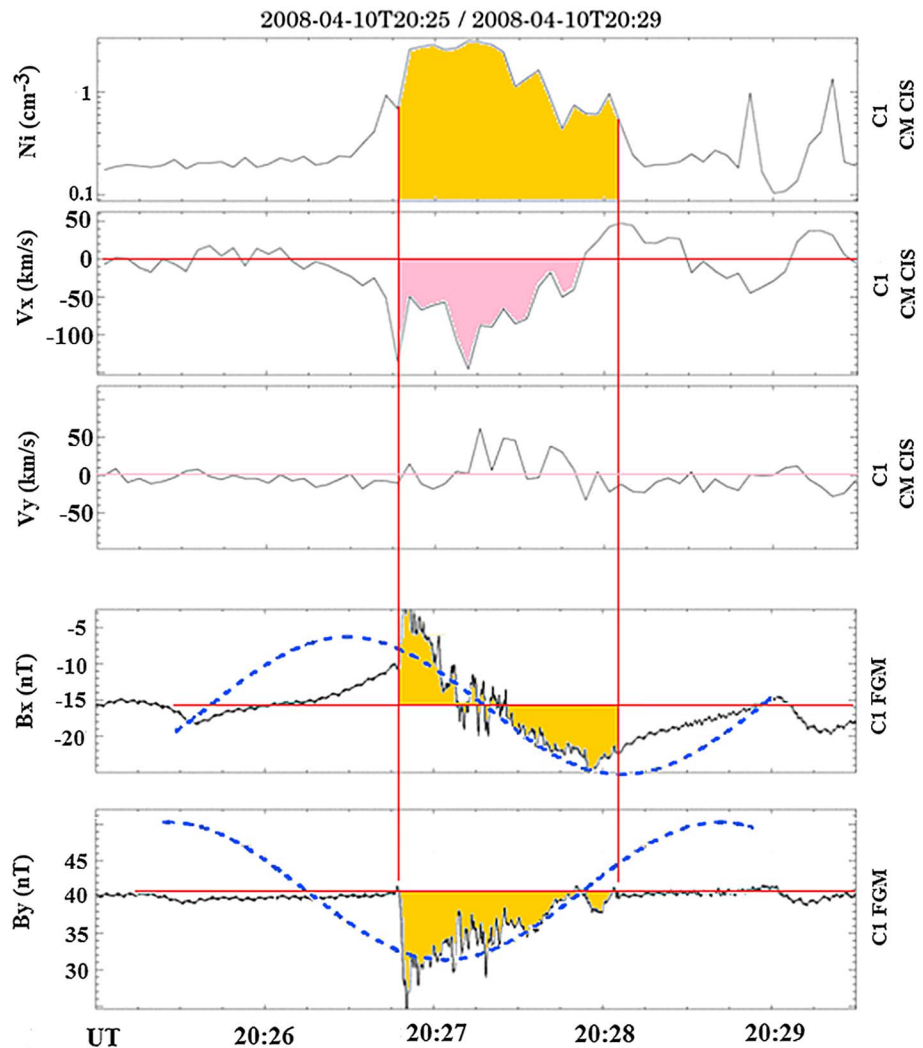


Figure 6. The same as in Figure 5 but for C1 in the noon-dawn sector. The filament and its magnetic field are shown in orange; the earthward (V_x) plasma velocity within the filament is shown in pink. The horizontal red lines show the velocities and average values of the magnetic field components in the ambient plasma, while two sinusoidal curves depict approximately B_x and B_y within the filament. One can see the $\sim 90^\circ$ phase shift between B_x and B_y .

filament crossing may be shorter (~ 1 – 2 min) than the period of the magnetic field rotation. To examine better the rotating magnetic field, we compared the observed fragments of variations in the B_x and B_y magnetic field components with similar fragments of expected variations of the rotating magnetic field in Figure 4. The expected variations of the B_x and B_y magnetic field components in this figure are shown for noon-dusk and noon-dawn sectors, where these variations have the opposite rotation directions.

Another case of a rotating magnetic field observed on C1 and C3 is shown in Figure 5. The two spacecraft in this case were located at a considerable distance from each other; therefore, this filament is significantly shifted in time on the two satellites.

A phase shift between B_x and B_y in Figure 5 shows the rotations of magnetic field vectors in the x - y plane. Another case of the rotating magnetic field is shown in Figure 6.

Two more cases of rotating magnetic field are shown in Figures 7 and 8, which also show a significant phase shift between B_x and B_y .

Figure 8 shows a complicated structure of the magnetic field within the filaments which consists of several subfilaments of different density and different magnetic field strength. The rotating magnetic field in this and other figures is convenient to see using the diagram in Figure 4.

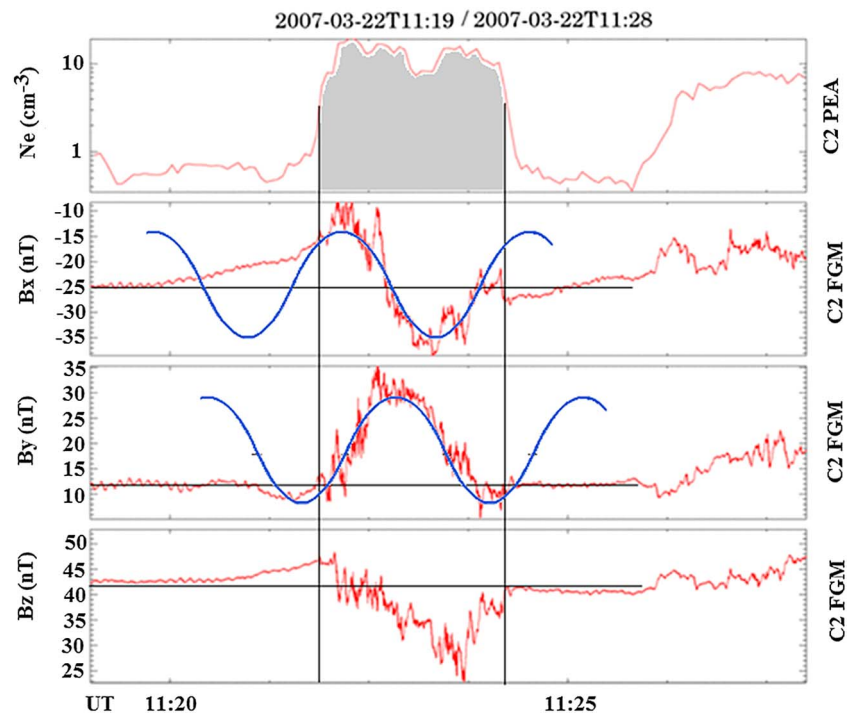


Figure 7. An example of a rotating magnetic field inside the plasma filament observed in the near-noon sector on the C2 on 10 April 2008. Shown are the electron (N_e) density and B_x , B_y , and B_z , where the B_z component is approximately along the ambient magnetic field. The blue curves show roughly the sinusoidal approximations to the magnetic field B_x and B_y variations inside the filament, which show the rotating magnetic field.

5. A Simple Model of Plasma Filaments with Twisted Magnetic Field

In the previous section, we mentioned that plasma rotation inside filaments leads to the generation of Alfvén waves, which transport the rotation of plasma and (frozen-in) magnetic field along the filament, resulting in a twisted magnetic field. A model of rotating plasma filaments and twisted magnetic field in noon-dawn and noon-dusk sectors is shown in Figure 9.

Figure 10a shows a similar model, including subfilaments, which has a more complicated geometry of the magnetic field; note that curling subfilaments, shown in different colors, may rotate not only about the axis of the complex filament but also about the axes of these subfilaments. Figure 10b accounts for the different Alfvén velocities inside subfilaments, which results in a more complicated structure of the magnetic field, so that the focal filament (consisting of several intertwining subfilaments) becomes similar to a tangled rope. This structure is accompanied by strong variations in the amplitude and direction of the magnetic field.

6. Some Estimates

Thus, the rotation of plasma filaments, penetrating from the magnetosheath into the magnetosphere, may be a result of their crossing velocity shears in the vicinity of the magnetopause. In the noon sector, this velocity shear is not as strong as it is at on the magnetosphere flanks, but it may be sufficient for the rotation of the filaments while they are crossing the magnetopause (the azimuthal velocity of magnetosheath plasma in the near-noon sector may reach 100–200 km/s and more). While moving across the velocity shear, the filaments, penetrating into the strong magnetospheric magnetic field, lose their velocity and translational energy (which is partially converted into the rotation energy). An example of a reducing velocity of several filaments, moving earthward inside the magnetosphere, is shown in Figure 11.

Thus, while crossing the velocity shear at the magnetopause, the filaments continue to move earthward but their translational velocity decreases, being partly converted into the rotational velocity. Here we present

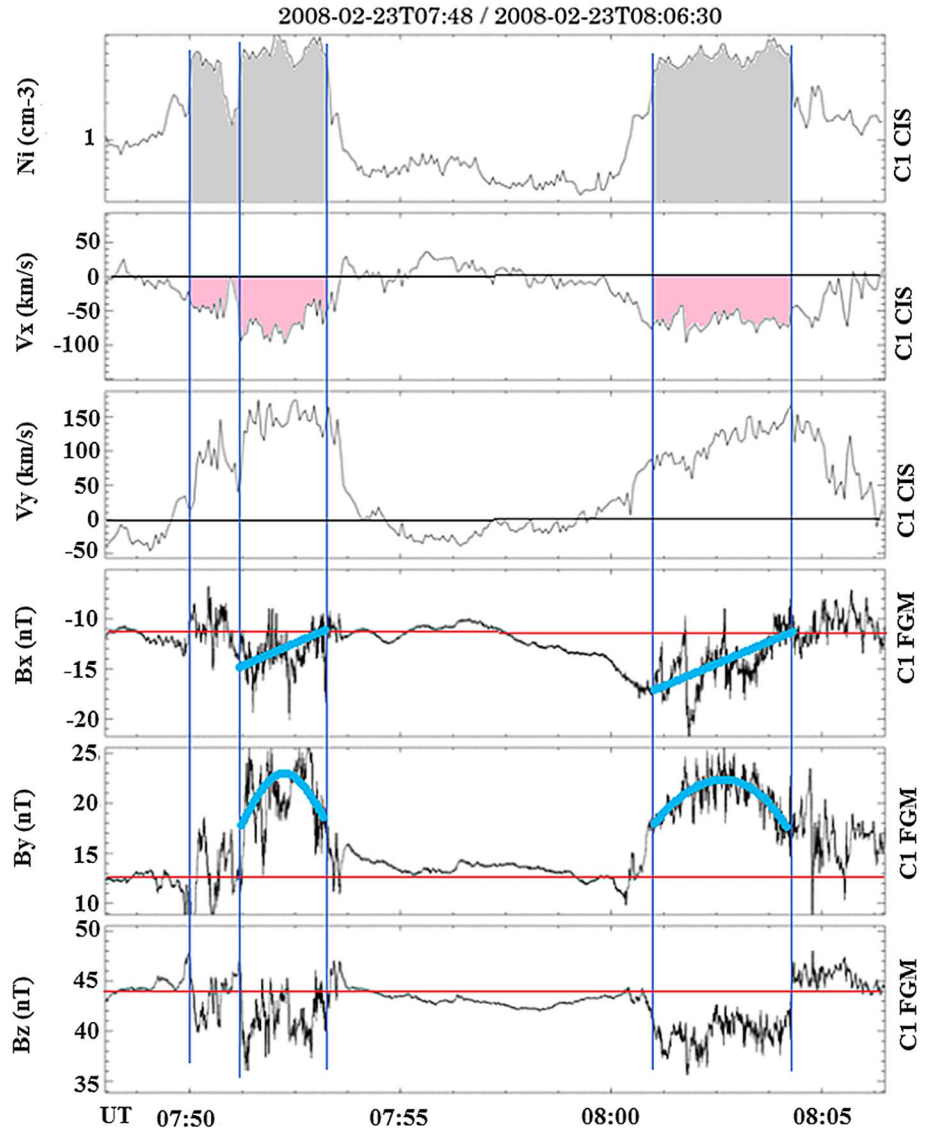


Figure 8. Magnetic field B_x and B_y components measured on C1, showing the rotating magnetic field in the x - y plane in the noon-dusk sector. Shown also is the ion (N_i) density. One can see a phase shift between the B_x and B_y , which shows the rotating magnetic field in the x - y plane. The blue lines show the average values of B_x and B_y within the filaments. The thin red lines show the average values of the ambient magnetic field.

some estimates. For simplicity, we consider a uniform plasma cylinder moving across its axis at a translational velocity, V_T , and rotating at an angular frequency, ω . The translational energy of the cylinder is

$$W_T = (1/2)MV_T^2 \quad (1)$$

where M is the cylinder mass. The rotational energy, W_R , of this cylinder is

$$W_R = (1/2)I\omega^2 = (1/4)MV_R^2 \quad (2)$$

Here $I = (1/2)MR^2$ is the moment of inertia of this cylinder, R is the cylinder radius, and V_R is its rotational velocity at the cylinder boundary. Then the total kinetic energy of this cylinder is

$$W_{\text{sum}} = (1/2)M[V_T^2 + (1/2)V_R^2] \quad (3)$$

The ratio of the rotating energy to the total energy, $W_{\text{sum}} = (W_R + W_T)$, in this case is

$$\frac{W_R}{W_{\text{sum}}} = \frac{1}{1 + 2V_T^2/V_R^2} \quad (4)$$

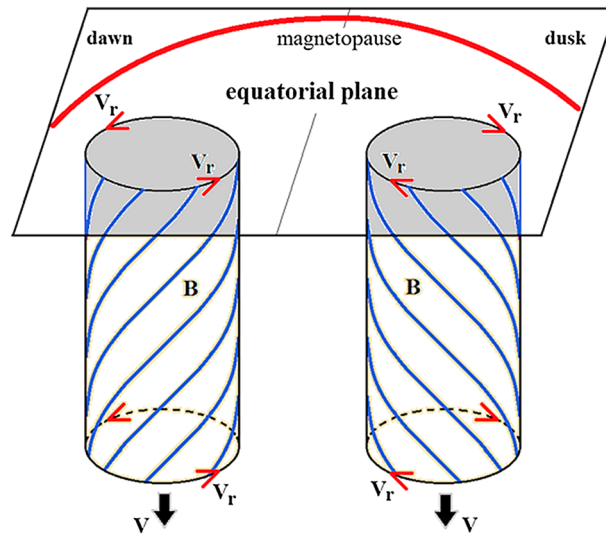


Figure 9. A simple model of twisted magnetic field on boundaries of rotating plasma filaments in noon-dusk (on left) and noon-dawn (on right) sectors, where V_R is the rotation velocity of plasma filaments. On filament sunward boundaries, the plasma is rotating in the direction of plasma motion in the magnetosheath. The rotating plasma results in the rotating magnetic field, B , inside the filaments. The propagation of rotating magnetic field along the filament results in a spiral (twisted) structure of the magnetic field, rotating in opposite directions in dawn and dusk sectors. The twisted magnetic field propagates along the filaments approximately at the Alfvén velocity (or slower due to twisted field lines). The black arrows show the propagation of the rotation along the filaments.

In the limiting case when the initial translational energy, W_{sum} , of the cylindrical filament during its crossing the velocity shear is totally converted to filament rotation, the rotational velocity (which decreases toward the filament axis) at the filament boundary may exceed the initial translational velocity of magnetosheath plasma. However, in a more realistic case, the translational velocity (V_T) of the filaments within the magnetosphere is frequently approximately equal to the rotational (V_R) velocity at the filament boundary. In this case, from equation (4) we obtain

$$W_R = (1/3)W_{\text{sum}} \quad (5)$$

which shows that at least one third of initial energy of the filament may be converted into its rotational energy.

Note also that the summary velocity vector of filament plasma is derived not only by the rotational and translational velocities of filament plasma but also by spacecraft position within this filament. Figure 12 shows schematically the vectors of the rotational (V_R), translational (V_T), and summary (V_T) plasma velocities at the filament boundary, when V_R and V_T velocities are equal in magnitude, but whereas the translational velocity (V_T) remains

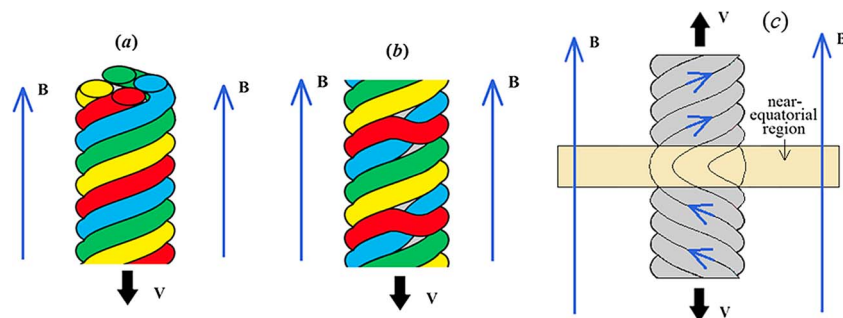


Figure 10. Twisted filaments in the cases of the (a) identical and (b) different subfilaments. (c) Two Alfvén waves propagating in two directions (above and below the equatorial region) on the dawn side are shown. The black arrows show the propagation of the rotation along the filaments. V is the propagation velocity of the magnetic field and plasma rotation along the filament. B is the ambient magnetic field.

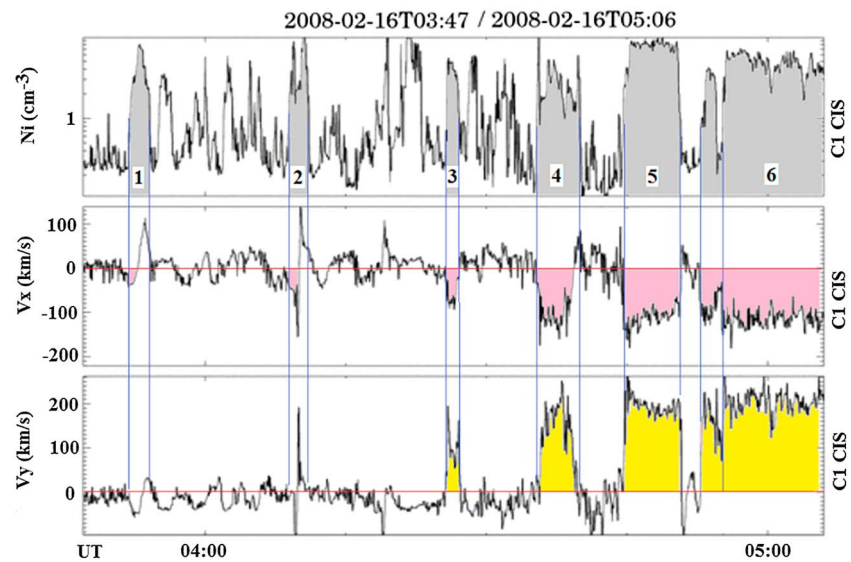


Figure 11. Shown are several filaments, observed on C1 in the noon-dusk sector at different distances from the magnetopause. The spacecraft moves sunward (toward the magnetopause shown by number 6). The filaments, moving antisunward, retain their high density ($\sim 10 \text{ cm}^{-3}$) but lose their velocity in both components (the strong decrease in filament velocity occurs within a time interval of $\sim 15\text{--}20$ min). The filaments 1 and 2, observed in the deeper magnetosphere, lost their initial antisunward velocity (contrast filaments 3, 4, and 5) and show only some back and forth oscillations.

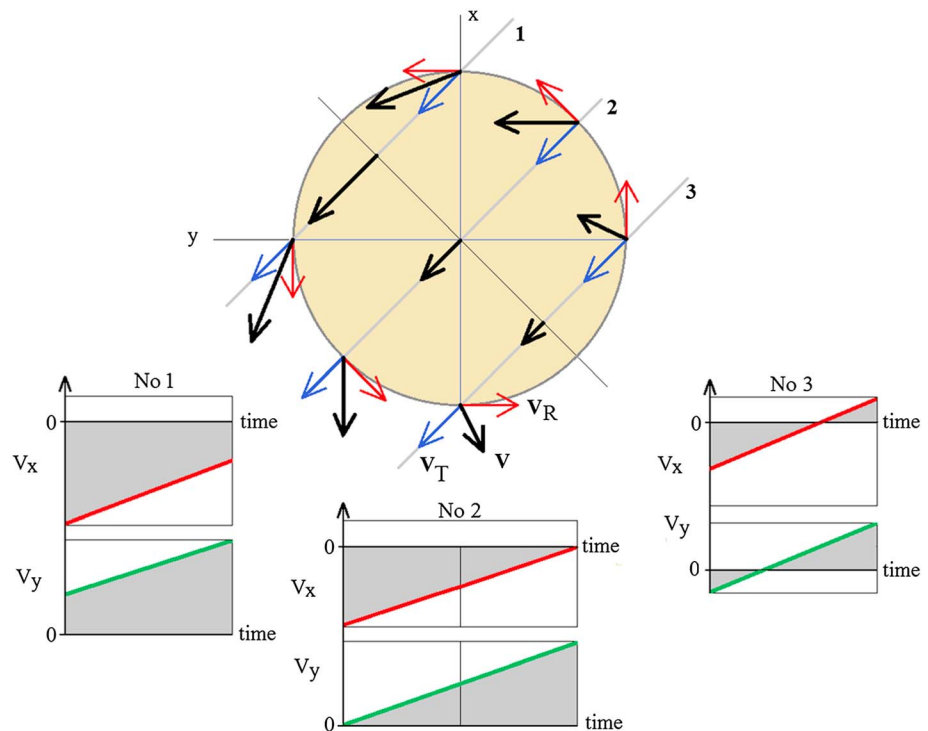


Figure 12. Shown are the translational (V_T), rotational (V_R), and summary ($V = V_T + V_R$) vectors of plasma velocities (shown in blue, red, and black, respectively) within a plasma filament for three cases of spacecraft intersection: when the dusk (1), central (2), or dawn (3) sections of this filament were going through Cluster. The dependence of the V_x and V_y velocity components for each trajectory is shown below as a function of time; the velocities and time are in relative units. The V_R and V_T velocities at the filament boundary are assumed to be equal in magnitude. This figure is related to a filament moving in the noon-dusk magnetosphere sector.

constant, the rotational velocity (V_R) changes its direction in different points of filament boundary. This figure shows the cases, when the (1) dusk, (2) central, or (3) dawn sections of this filament intersect Cluster location.

Figure 12 shows a large difference in magnitude and direction of plasma velocity inside the filament. In the case (1), the magnitudes of V_x and V_y velocity components are maximal, but the antisunward V_x velocity is negative and decreases in magnitude in time, while the azimuthal V_y velocity is positive and increases in magnitude in time. In the case (2), both velocity components are reduced in magnitude so that the negative (earthward) V_x velocity decreases up to zero, while the positive V_y velocity increases from zero. In the case (3), both velocity components are minimal in magnitude and may change their directions. The expected behavior of plasma velocity inside the filaments in many cases is approximately consistent with observation results. Thus, Figure 12 shows a complicated behavior of plasma velocity inside rotating filaments even in the case of uniform plasma; the existence of subfilaments makes the velocity behavior even more complicated.

The propagation of plasma rotation along the filaments results in a twisted magnetic field within the filaments. The magnetic field, twisted in the filament like a spiral, is a result of the generation of the Alfvén waves, transporting this twisted magnetic field along the filament. For simplicity, let us consider an Alfvén wave propagating along a magnetic flux tube and rotating about the tube axis (such waves are well known in plasma physics). Due to relatively high plasma density and reduced magnetic field within the filament, the Alfvén velocity, V_A , within the filament is much less than it is in surrounding magnetosphere. The velocity of the Alfvén wave along the filament in this case may be written as

$$V_{||} = V_A \cos \alpha \quad (6)$$

where α is the angle between the rotating magnetic field within the filament and the filament axis and $V_A = B/(4\pi\rho)^{1/2}$ is the Alfvén velocity inside the filament, where B and ρ are the magnetic field and plasma density in this filament, respectively. By neglecting the angle, α , the Alfvén velocity inside the filament for reasonable values of filament plasma density $n \approx 10 \text{ cm}^{-3}$ and the magnetic field $B \approx 10 \text{ nT}$ is $V_A \approx 70 \text{ km/s}$ (that is about 15 times less than the typical Alfvén velocity ($\sim 1000 \text{ km/s}$) in the magnetosphere), and this magnitude may increase or decrease while plasma is moving along this filament. The existence of subfilaments may also significantly affect the propagation velocity of these waves (and related magnetic disturbances) within the filament.

Note also that magnetic perturbations may be transported along the filament not only by the Alfvén waves but also by the surface magnetosonic waves (which are a combination of two magnetosonic waves inside and outside the filament). The magnetic perturbation of these waves propagates along the filament at the velocity [e.g., Maltsev and Lyatsky, 1981]

$$V_{MS} = \frac{\omega}{k_z} = 1.4 \frac{V_{A1} V_{A2}}{\sqrt{(V_{A1}^2 + V_{A2}^2)}} \quad (7)$$

where ω and k_z are the wave frequency and the wave vector along the filament, while V_{A1} and V_{A2} are the Alfvén velocities inside and outside the filament, respectively. Although these waves usually are not as significant as the Alfvén waves, in some cases they also may be important.

7. Discussion and Conclusions

Thus, the study of plasma filaments containing magnetosheath plasma, which density exceeds plasma density in ambient magnetosphere by 10 and more times, shows that these events are frequently observed not only on the magnetospheric flanks and the cusp regions but also in subsolar magnetosphere. These filaments are moving predominantly earthward at the velocity of about 50–200 km/s and more, which significantly exceeds the velocity of ambient plasma, moving usually in the opposite (sunward) direction. These filaments may also move duskward or dawnward dependently on in which (noon or dusk) MLT sector they are observed. These results in general are consistent with those obtained by Lundin *et al.* [2003] and other researchers, mentioned above.

The observation results also show that these filaments almost continuously move antisunward (earthward) even when their magnetic field is significantly inclined to the ambient magnetic field that contradicts to the theoretical studies by Schindler [1979] and numerical simulations [e.g., Ma *et al.*, 1991; Dai and Woodward,

1994, 1998; Savoini and Scholer, 1995], who reported that even insignificant inclination of these filaments to the ambient magnetic field makes impossible their penetration into the magnetosphere (since in these cases these filaments compress the Earth's magnetic field in a wide MLT sector and, as a result, are pushed back from the magnetosphere). However, we showed that this contradiction between the observation results and theoretical studies may be a result of incorrect comparison of these theoretical studies (based on simple cases when a straight magnetic field inside the filaments is directed along these filaments) with the observation results (which show that plasma and magnetic field inside the filaments may be not straight but rotating).

So since the theoretical studies (including simulations) and observation results are related to different geometry of the magnetic field inside these filaments, this contradiction between the theory and observations is apparent. In the case, when the magnetic field inside a filament is directed along this filament, any significant inclination of this filament magnetic field to the ambient magnetic field, indeed, may make impossible the propagation of this filament through the surrounding magnetic field. However, in the case of a rotating and twisted magnetic field inside the filament, this filament may propagate across the ambient magnetic field the same way as if its magnetic field is aligned with this filament. It means that the correct mandatory condition for penetration of such filaments into the magnetosphere is dependent not on the local orientation of the twisted magnetic field inside the filaments but first of all on the filament elongation (which, however, is not easy to determine).

Note that since the filaments usually consist of subfilaments, having different plasma density and different magnetic field, these subfilaments also affect the structure and magnetic field inside the filament. In particular, the subfilaments may lead to an intermittent magnetic field inside the complex filament, which significantly hampers its scrutiny. Nevertheless, the rotating magnetic field inside the filaments in many cases is seen rather clearly, and although the rotation of each subfilament is difficult to identify, the rotation of a complex filament may be well seen from the behavior of the B_x and B_y magnetic field components (the phase shift between the B_x and B_y components clearly shows the rotation of the magnetic field vector in the x - y plane).

So in this paper we examined the plasma density, velocities, and magnetic field of the plasma filaments, observed in dayside magnetosphere but containing magnetosheath plasma. The results of that study show (i) the stable antisunward motion of these filaments in the near-noon magnetosphere (while ambient magnetospheric plasma moves slowly in the opposite, sunward direction) and (ii) the existence of a strip of magnetospheric plasma, separating these filaments from the magnetosheath and frequently observed on all four Cluster spacecraft. These results, showing that these plasma filaments may be detached from the magnetosheath, support the previous results by Lemaire [1977], Lemaire and Roth [1978], Heikkila [1982], Lundin *et al.* [2003], Gunell *et al.* [2012, 2014], and other researchers, and they also show that these plasma filaments may be rotating in the x - y plane, which may be a result of their crossing the velocity shear at the magnetopause.

The study of the magnetic field inside these filaments showed that the observed rotation of this magnetic field in the plasma filaments may play a crucial role in their propagation inside the magnetosphere. The main results of this study may be summarized as the following:

1. The rotation of these filaments (shown in Figures 3 and 5–8 and resulting in the rotation of their magnetic field) basically affects the motion of these filaments.
2. The rotation of both filament plasma and frozen-in magnetic field leads to the generation of rotating Alfvén waves, transmitting the rotation along the filament; the rotating field lines in this case become twisted and inclined to filament elongation as shown in Figures 9 and 10.
3. The filament magnetic field, rotating and twisted about the filament axis, does not prevent the motion of this filament through the ambient magnetic field (unlike the straight magnetic field, but inclined to the ambient magnetic field). The motion of the filament through the magnetosphere in this case depends not on varying orientation of its rotating magnetic field but only on the orientation of this filament. That is, the rotating magnetic field within the filaments does not prevent their propagation in the magnetosphere even when their rotating magnetic field is significantly inclined to filament elongation (until the filament is aligned with the ambient magnetic field). Therefore, the results of theoretical studies and simulations by Schindler [1979], Ma *et al.*, [1991], Dai and Woodward [1994, 1998], and other authors, who did not account for the rotation of the magnetic field within the filaments, are not applicable to the case of the rotating magnetic field.

4. Thus, in the case of rotating and twisted magnetic fields within the filaments, the propagation of these filaments in the magnetosphere does not depend on a varying direction of their rotating magnetic field: the filaments with rotating magnetic field are propagated the same way as if their rotating magnetic field is elongated along these filaments. The only condition for penetration of these filaments into the magnetosphere is their orientation: if the filament is aligned with the ambient magnetic field, it may propagate in the magnetosphere independently on a varying direction of its magnetic field. This simple but important consequence of the rotating magnetic field resolves the seeming contradiction between the results of observations and theoretical studies, mentioned above.

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