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RESEARCH ARTICLE

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Key Points:

- In dayside magnetosphere frequently observed filaments containing magnetosheath plasma
- The filaments move stably antisunward, while ambient plasma moves in the opposite direction
- The observed rotation of these filaments makes possible their penetration into magnetosphere

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Penetration of magnetosheath plasma into dayside magnetosphere: 1. Density, velocity, and rotation

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Abstract In this study, we examine a large number of plasma structures (filaments), observed with the Cluster spacecraft during 2 years (2007–2008) in the dayside magnetosphere but consisting of magnetosheath plasma. To reduce the effects observed in the cusp regions and on magnetosphere flanks, we consider these events predominantly inside the narrow cone $\leq 30^\circ$ about the subsolar point. Two important features of these filaments are (i) their stable antisunward (earthward) motion inside the magnetosphere, whereas the ambient magnetospheric plasma moves usually in the opposite direction (sunward), and (ii) between these filaments and the magnetopause, there is a region of magnetospheric plasma, which separates these filaments from the magnetosheath. The stable earthward motion of these filaments and the presence of a region of magnetospheric plasma between these filaments and the magnetopause show the possible disconnection of these filaments from the magnetosheath, as suggested earlier by many researchers. The results also show that these events cannot be a result of back-and-forth motions of magnetopause position or surface waves propagating on the magnetopause. Another important feature of these filaments is their rotation about the filament axis, which might be a result of their passage through the velocity shear on magnetopause boundary. After crossing the velocity shear, the filaments get a rotational velocity, which has opposite directions in the noon-dusk and noon-dawn sectors. This rotation velocity may be an important factor, supporting the stability of these filaments and providing their motion into the magnetosphere.

1. Introduction

The penetration of magnetosheath plasma into the magnetosphere is an important problem not only for the Earth but also for other planets having an intrinsic magnetic field. For years, it was generally suggested that the main causes for the penetration of solar wind plasma into Earth's magnetosphere are the magnetic reconnection (especially during the northward interplanetary magnetic field [e.g., see *Sibeck et al.*, 1999]), the transport of magnetosheath plasma into Earth's magnetosphere through the cusps [e.g., *Heikkila and Winningham*, 1971], the Kelvin-Helmholtz instability at magnetospheric flanks [e.g., *Hasegawa et al.*, 2004], and diffusion of solar wind plasma into the magnetosphere [*Axford and Hines*, 1961] (which may be significant on the magnetospheric flanks).

Another possible mechanisms are the direct penetration into the magnetosphere of plasma filaments with the enhanced momentum (known also as "plasma blobs") [*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, and others]. This mechanism, however, was met with a skepticism based on the lack of convincing explanation of how these plasma structures (we will call them the filaments) with the magnetic field, which may be significantly inclined to the ambient (Earth's) magnetic field, may penetrate into the magnetosphere and move earthward. Moreover, both theoretical studies [e.g., *Schindler*, 1979] and numerical simulations [e.g., *Ma et al.*, 1991; *Dai and Woodward*, 1994, 1998; *Savoini et al.*, 1994; *Savoini and Scholer*, 1995] show that even an insignificant inclination of these filaments to the ambient magnetic field prevents their penetrating into the magnetosphere. Nevertheless, a large number of observations (including the results, obtained with the Cluster spacecraft and reported here) gives grounds to suggest that the magnetosheath plasma, indeed, may penetrate into the magnetosphere. For instance, *Hultqvist et al.* [2005] emphasize that the Cluster mission identified "detached solar wind plasma blobs inside the magnetopause." They also mentioned that "doubts have been raised about the existence of such plasma blobs, whether they can retain an excess momentum and whether they can penetrate the magnetopause."

Nevertheless, some recent Cluster observations indicate that blobs of solar wind plasma do penetrate the magnetopause and become detached."

Previous observations on the Cluster spacecraft [e.g., *Lundin et al.*, 2003] have shown that (1) the penetration of magnetosheath plasma is observed not only on the dawn and dusk magnetospheric boundaries (where the penetration of this plasma may be supported by the Kelvin-Helmholtz instability) and near the cusps (where magnetosheath plasma penetrates deep into the magnetosphere) but also practically in any local time sector in the dayside magnetosphere and (2) that the penetration is observed during different directions of the interplanetary magnetic field (IMF) but more frequently during the northward IMF B_z , when the traditional reconnection, responsible for magnetospheric substorms and supplies solar wind energy into the magnetosphere, is weak or does not work. The penetration of magnetosheath plasma into the magnetosphere is also supported by observations of a significant increase in plasma density in the low-latitude boundary layer inside the magnetosphere [e.g., *Newell and Meng*, 2003, and references therein]. However, despite the large number of observations, showing the possible penetration of solar wind plasma into the magnetosphere, the theoretical studies by *Schindler* [1979] as well as the simulation results by *Ma et al.* [1991], *Dai and Woodward* [1994, 1998], *Savoini et al.* [1994], and *Savoini and Scholer* [1995], as mentioned above, do not support these observations. Note that some penetration of plasma filaments into the magnetosphere was reported in an earlier paper by *Schmidt* [1960], as a result of the appearance of the polarization electric field (in a case of an earthward velocity of these filaments). However, in that paper the author does not account for any inclination of the filament magnetic field to the ambient field (that is usually observed), which drastically reduces the penetration of the filaments into the magnetosphere.

The first theoretical studies of penetration of two-dimensional magnetosheath plasma filaments into the Earth's magnetosphere by *Schindler* [1979] showed that in the case of the ideal magnetohydrodynamics (MHDs), the penetration is possible only when the magnetic fields in the filament and in the ambient magnetospheric plasma are aligned. This result was supported by numerical simulations of *Ma et al.* [1991], *Dai and Woodward* [1994, 1998], *Savoini et al.* [1994], and *Savoini and Scholer* [1995]. *Ma et al.* [1991] and *Dai and Woodward* [1998] showed that the conditions for filament penetration into the magnetosphere may be slightly softened in the case of the resistive MHD. So *Ma et al.* [1991] reported that for typical parameters of plasma and magnetic fields in the dayside magnetosphere, the plasma filaments may penetrate from the magnetopause into the magnetosphere if their magnetic field is inclined to the ambient geomagnetic field by an angle of not more than 5°; a more detailed review of these results is given, for instance, by *Echim and Lemaire* [2000].

Thus, the numerical simulations support the earlier results by *Schindler* [1979], which require a stringent condition for penetration of magnetosheath plasma filaments into the magnetosphere. So *Schindler* [1979], while summarizing the results of his study, wrote that under conditions of ideal MHD, "penetration of an irregularity (filament) is possible if the magnetic fields inside the filament and in the magnetosphere are aligned," while as 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] and *Dai and Woodward* [1998] (who used a resistive MHD model) and *Savoini et al.* [1994] and *Savoini and Scholer* [1995] (who used 2-D hybrid simulation with particle ions and fluid electrons), who also concluded that any plasma filament with its magnetic field inclined to the ambient geomagnetic field at an angle larger than few degrees cannot penetrate into the magnetosphere. For instance, *Savoini et al.* [1994] wrote that "the cases either exactly parallel or exactly antiparallel magnetic fields... are the only ones from the ideal MHD point of view that allow a filamentary plasma element to penetrate into a closed magnetosphere."

Thus, simulations provided by many researchers confirm the earlier results by *Schindler* [1979] that the impulsive penetration takes place when the magnetic fields in the filaments and ambient magnetospheric plasma are strongly parallel (in the case of ideal MHD) or insignificantly inclined (not more than few degrees in the case of nonideal MHD and/or hybrid simulations). These results, however, are totally inconsistent with observational results, which demonstrate many cases of penetration of magnetosheath plasma filaments into the magnetosphere even when the magnetic field inside the filaments is significantly inclined to the local geomagnetic field. In this study, we show that this discrepancy can occur because of the theory and observation results may be related to different events. Indeed, the theoretical studies and simulations, mentioned above,

are related to a simple case of a straight magnetic field inside plasma filaments, whereas the observation results, as shown below, may be related to the rotating magnetic field inside these filaments. In this case, the direction of this rotating magnetic field varies continuously; however, if their *average (for the rotation period)* magnetic field is elongated close to the ambient magnetic field, these filaments may penetrate a significant distance inside the magnetosphere. The rotation of plasma filaments and their magnetic field is considered in the following sections as well as in our next study under review (W. Lyatsky et al., Penetration of magnetosheath plasma into dayside magnetosphere: (2) Magnetic field in plasma filaments, submitted to *Geophysical Research Letters*, 2016).

2. Method Used for Analysis

In this study, we consider the events in dayside magnetosphere inside the 30° cone around the subsolar point. Two main mechanisms, discussed in the literature as possible causes of penetrating magnetosheath plasma into the magnetosphere in this region, are (1) so-called “component magnetic reconnection” (which may occur when the solar wind and Earth’s magnetic fields are directed at some angle to one another) [e.g., Fuselier et al., 2011]; (2) multiple reconnection at the magnetopause [e.g., Lyatsky and Goldstein, 2013, and references therein]; and (3) the penetration of plasma filaments from the magnetosheath into the magnetosphere as a result of their excess momentum or other processes, as discussed above.

It is well known that the magnetic reconnection in the case of the southward IMF B_z plays a very important role in the penetration of the electric field and energy into the magnetosphere. In the case of northward IMF B_z , the reconnection theoretically may happen simultaneously in two symmetric points at dayside magnetopause poleward of both cusps; in this case, both ends of the magnetosheath magnetic tube become connected to Earth’s magnetic field. However, since the IMF as a rule has also significant B_x and B_y components, reconnection of the same magnetic tube simultaneously in two cusps is very unlikely, while the one-end reconnection unlikely is able to explain the observed penetration of plasma filaments into the magnetosphere. Therefore, we consider other possible mechanisms for penetration of magnetosheath plasma into the magnetosphere, particularly, the direct penetration of plasma filaments into the dayside magnetosphere due to their excess momentum, as proposed by Lemaire [1977], Lundin et al. [2003], and other researchers.

In this study, we examined approximately 200 events, observed during 38 day when Cluster was close to the subsolar point (inside the cone of $\sim 30^\circ$) in 2 years (2007–2008). We did not consider events near the cusps and on magnetopause flanks, where the formation of plasma filaments and their properties may be significantly different from those in the subsolar region. We also did not separate events related to differing IMF orientations as the duration of these events is usually very short (a few minutes), and their appearance is a result rather of local magnetic field variations in the magnetosheath than IMF variations at the ACE orbit [e.g., Tkachenko et al., 2011], although statistically, they may be observed more frequently during periods of northward IMF [e.g., Lundin et al., 2003]. However, we carefully analyzed the main plasma parameters inside and outside these filaments, such as the plasma density and velocity, magnetic field, and filament location. Three main criteria identifying the filaments are (1) they contain magnetosheath plasma with ion density of about 10 ions/cm^{-3} and more (which significantly exceeds the ion density of ambient magnetospheric plasma); (2) they move stably earthward, whereas the ambient magnetosphere plasma moves in the opposite (sunward) direction or nearly immobile; and (3) there is a strip of magnetospheric plasma observed between these filaments and the magnetopause. In the subsolar region, these filaments move earthward usually at the velocity from $\sim 50 \text{ km/s}$ up to 300 km/s and more.

Note that the filaments, containing magnetosheath plasma but probably detached from the magnetosheath, are easily separated from transient spacecraft excursions into the magnetosheath as a result of magnetopause motions, since the detached filaments are moving in the magnetosphere steadily antisunward (earthward), while such transient excursions into the magnetosheath would show the back-and-forth motions. These “false filaments,” observed occasionally, were removed from consideration.

Examples of both types of events are shown in Figures 1 and 2. Figure 1 shows the events, moving stably antisunward and identified as plasma filaments probably detached from the magnetosheath, while the events in Figure 2 show the back-and-forth motions, which may be identified as the magnetopause motions

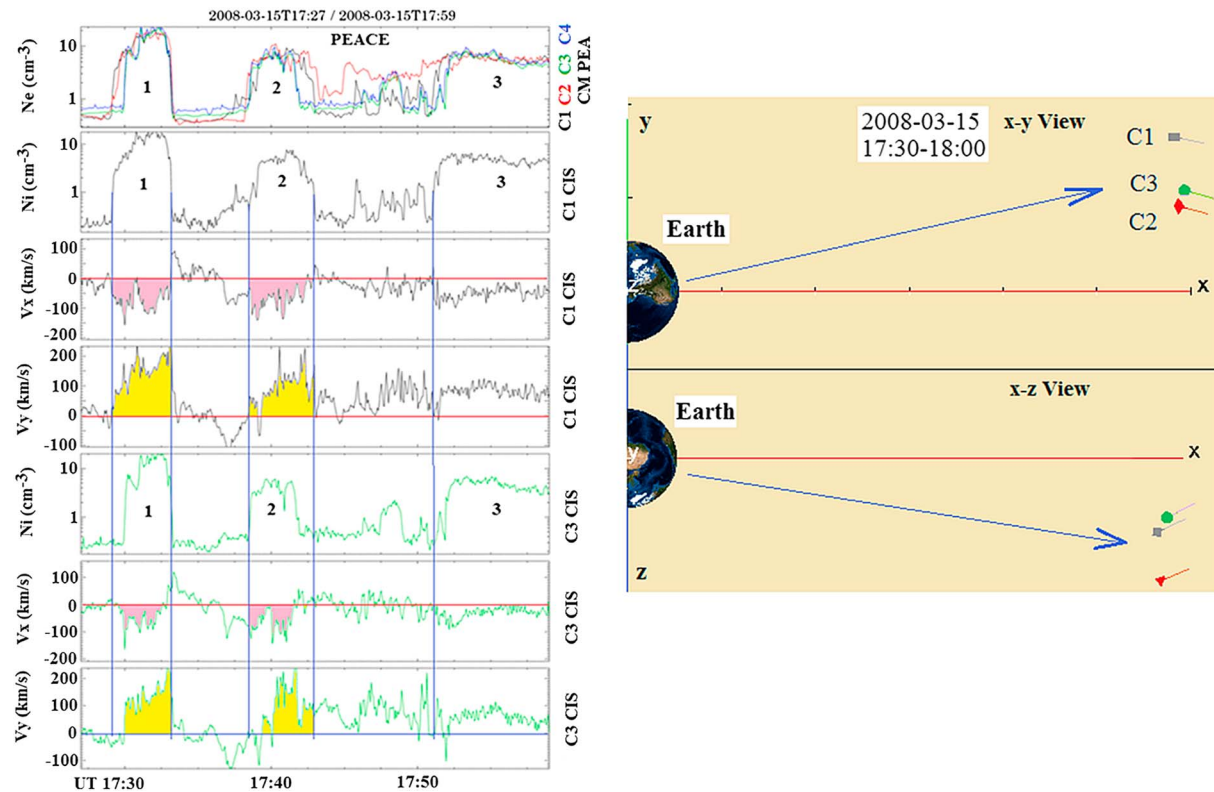


Figure 1. Typical examples of plasma filaments, probably detached from the magnetosheath and moving stably antisunward as observed in near-noon magnetosphere on the Cluster C1 and C3 S/C during the time interval shown above the figure. (left, first panel) The electron density of all four (C1, C2, C3, and C4) S/C as measured with the PEACE instrument. (left, second to seventh panels) The ion density and V_x (sunward) and V_y (duskward) ion velocities measured with the CIS instruments on the C1 and C3 S/C. (right) The related trajectories of three (C1, C2, and C3) S/C in the x-y and x-z planes from the 4-D orbit viewer at <http://sscweb.gsfc.nasa.gov/WebServices/tipsod/launch.html> (the trajectory of C4 S/C is very close to that of C3 S/C). All trajectories are located inside a narrow cone about the subsolar point; the blue arrows show the average direction from the Earth to the Cluster S/C.

(similar events are observed rarely, and as mentioned above, they have been excluded from consideration). The events in Figure 1, measured simultaneously on the Cluster C1 and C3 spacecraft, are marked by the numbers 1 and 2; the events marked by numbers 3 are related to the magnetosheath. All events in these and other figures are presented in the GSE coordinate system. Note that in this study we consider mainly the data from two (C1 and C3) spacecraft; the data from the C2 and C4 spacecraft (S/C) we used less often

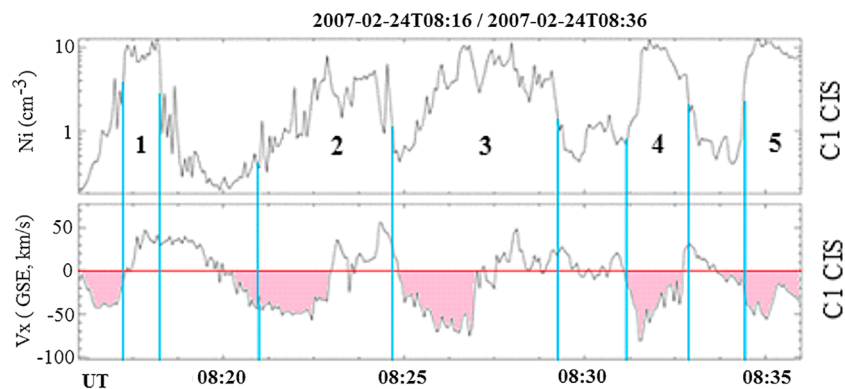


Figure 2. Examples of “false filaments” (the first three events) which can be identified as the result of the back-and-forth motions of magnetopause position. The last two events, marked by the numbers 4 and 5, move stably earthward and may be related to the detached plasma filaments.

as the C2 S/C did not show correctly the plasma velocity, while the C4 S/C was located at a small distance from the C3 S/C and the data from these spacecraft were practically indistinguishable.

Figure 1 shows the two typical plasma filaments (marked with 1 and 2) crossing the positions of these four S/C approximately at the same time, which show the large sizes of these filaments across the ambient magnetic field, exceeding the distance between the S/C ($\sim 10,000$ km). This figure shows two important features of these filaments. First, these filaments, moving as a rule antisunward (earthward) in the near-noon sector, are following by interval(s) of rarefied magnetospheric plasma in a wide zone (including all four S/C) between these filaments and the magnetopause, which suggests that these filaments indeed may be detached from the magnetopause). And second, this figure shows the stable antisunward motion (the negative V_x) of plasma filaments observed on both C1 and C3 S/C (the plasma velocity measured by the Plasma Electron And Current Experiment (PEACE) instrument on C2 S/C shows the strong variations and is not presented), whereas the V_x velocity of ambient magnetospheric plasma between the filaments is strongly reduced and (on average) moves slowly in opposite (sunward) direction. The well-seen separation from the magnetopause and stable antisunward motion of these plasma filaments are two important features, observed clearly in most cases. Note that the azimuthal, V_y , velocity of these filaments may have different directions and usually coincides with the velocity of magnetosheath plasma in the same magnetic local time sector.

So the filaments in Figure 1, moving antisunward in the near-noon sector and following by a strip of rarefied magnetospheric plasma, observed in a wide zone between these filaments and the magnetopause on all four S/C, allow us to suggest that these filaments indeed may be detached from the magnetopause. Thus, both stable earthward motion of these filaments, containing magnetosheath plasma, and the existence of a region (strip) of magnetospheric plasma between these filaments and the magnetopause show the probable disconnection of these filaments from the magnetosheath. One more feature of these filaments is that they usually consist of several subfilaments, having different plasma density but moving as a single unit (as seen in Figure 1). The typical plasma density in both magnetosheath and these plasma filaments is about 10 cm^{-3} or more, which significantly exceeds the density of surrounding magnetospheric plasma, which usually is $\sim 1 \text{ cm}^{-3}$ or less. An enhanced density remains also in plasma filaments penetrating deeper into the magnetosphere, although this density declines while the filaments move to the Earth, which is consistent with the results by Lundin *et al.* [2003].

Figure 2 shows the events, which may be identified as a result of back-and-forth motions of the magnetopause. Such events are observed relatively rarely and, as mentioned above, are not considered in this study.

3. Antisunward Motion of Plasma Filaments

As mentioned above, the important feature of these filaments is their stable antisunward motion. The plasma velocity inside the filaments in these cases may reach up to 100–200 km/s and more. In some cases, however, the plasma velocity (both inside and in the vicinity of these filaments) shows more complicated behavior. In some cases, the antisunward velocity may be observed in ambient plasma just before an antisunward moving filament crosses the spacecraft (which may be a result of pushing the ambient plasma by the antisunward moving filament). The velocity of ambient plasma may increase also near the filament sunward boundary, where the ambient plasma, moving about the filament, tends to occupy the space, abandoned by the antisunward moving filament; another explanation may be related to the rotation of this filament, which will be discussed later. One more important feature of these filaments, as mentioned above, is that they usually consist of several subfilaments, which may have different densities and velocities; despite that, these filaments usually show surprising stability and move as a single body. Examples of such events are shown in Figures 3–5.

As seen in Figure 4, despite the large distance of $\sim 10,000$ km between C1, C2, and C3 (the distance between C3 and C4 is small), these filaments intersect all spacecraft almost simultaneously. Figure 4 (left), showing the energy spectra of electrons, shows also energetic electrons of the ring current with energy higher than several keV, which are observed inside the magnetosphere; however, after $\sim 18:10$ UT these energetic electrons disappear, which shows that the spacecraft have entered the magnetosheath. One can see also a strip (strips) of magnetospheric plasma between the filaments, observed almost simultaneously on all S/C, which

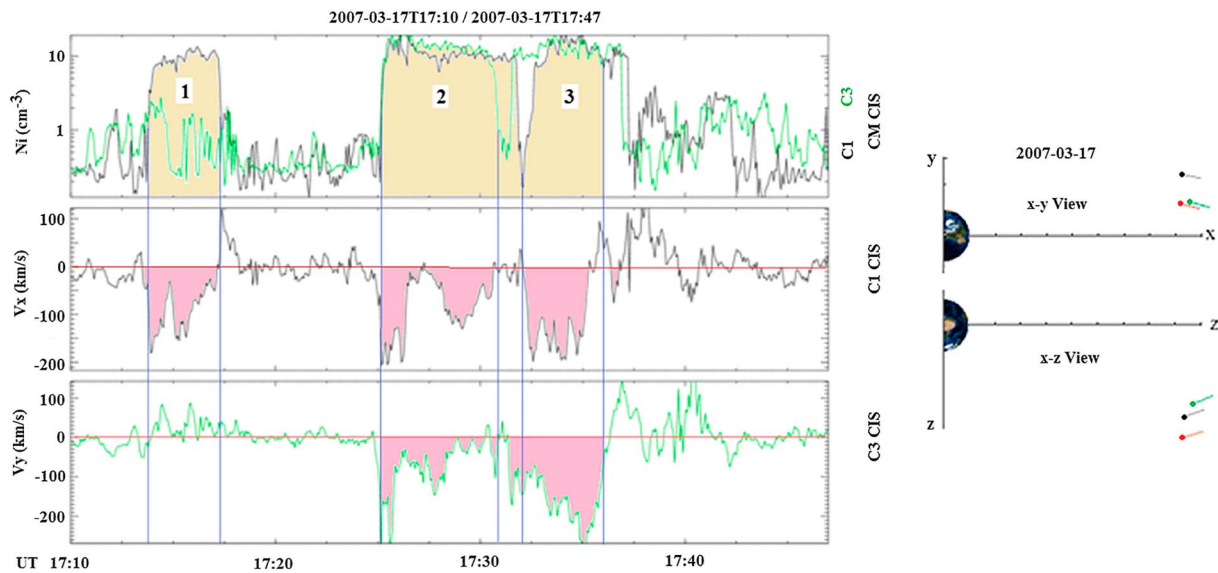


Figure 3. An example of filaments, observed near noon on Cluster C1 (black lines) and C3 (green lines). One can see predominantly antisunward (earthward) motions of magnetosheath plasma inside the filaments. The filament velocities are up to about 200 km/s, which is much larger than the velocity of ambient plasma. Note the strong variations of the velocity inside the filaments, which usually are related to the existence of subfilaments. Note also that the filament no. 1 is well seen on C1 but is not well seen on C3 S/C, and it is not accompanied by antisunward velocity on C3. However, the filaments 2 and 3 are seen clearly on both C1 and C3. (right) The trajectories of these three Cluster S/C in the x-y and x-z planes, obtained from the 4-D orbit viewer (for more details, see the description of Figure 1); these trajectories are inside a narrow cone about the subsolar point.

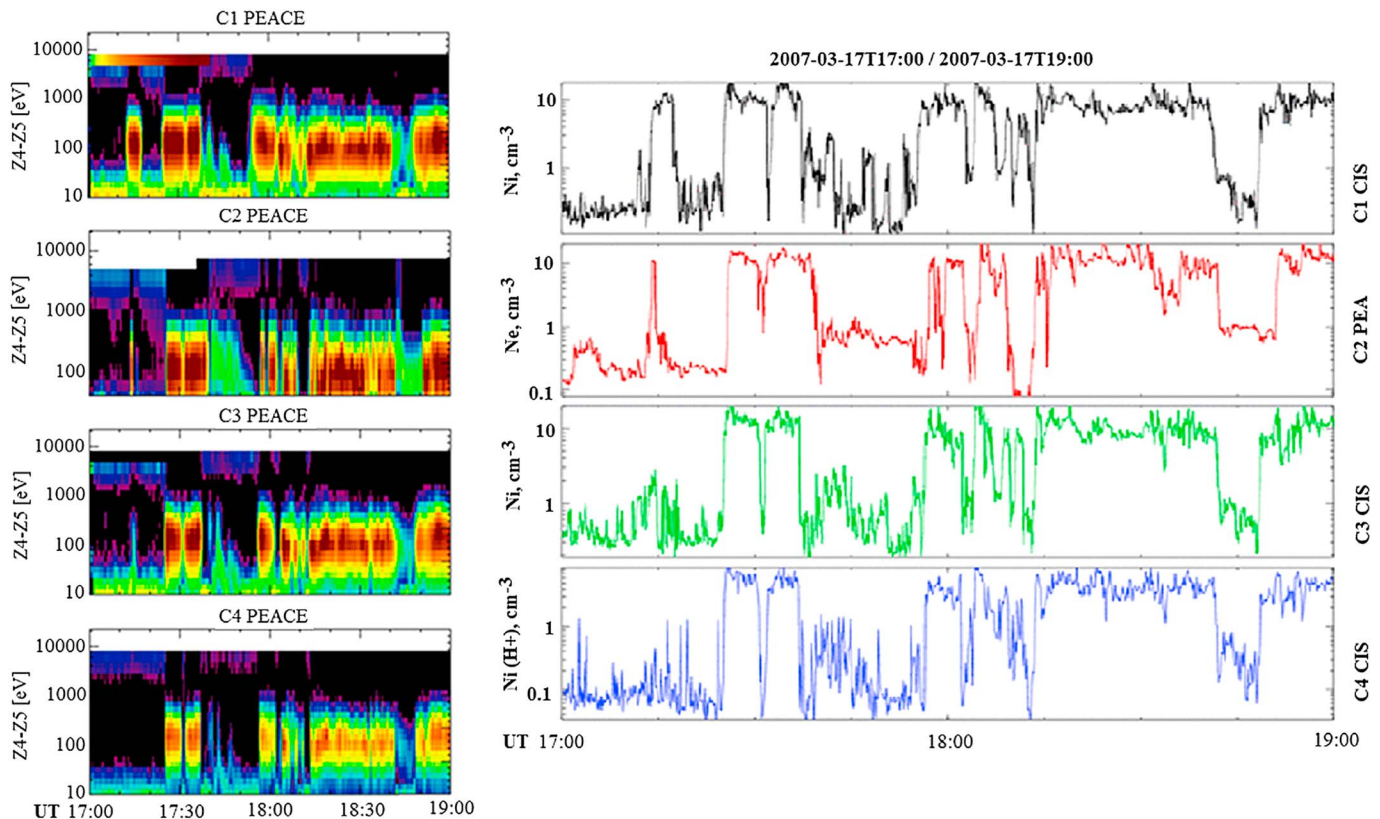


Figure 4. The same case as in Figure 3 but shown inside a longer time interval from 17:00 to 19:00 UT. Shown are the (left) energy spectra and (right) plasma densities, measured on all (C1, C2, C3, and C4) S/C from Cluster PEACE instrument; the trajectories of the S/C are shown in Figure 3.

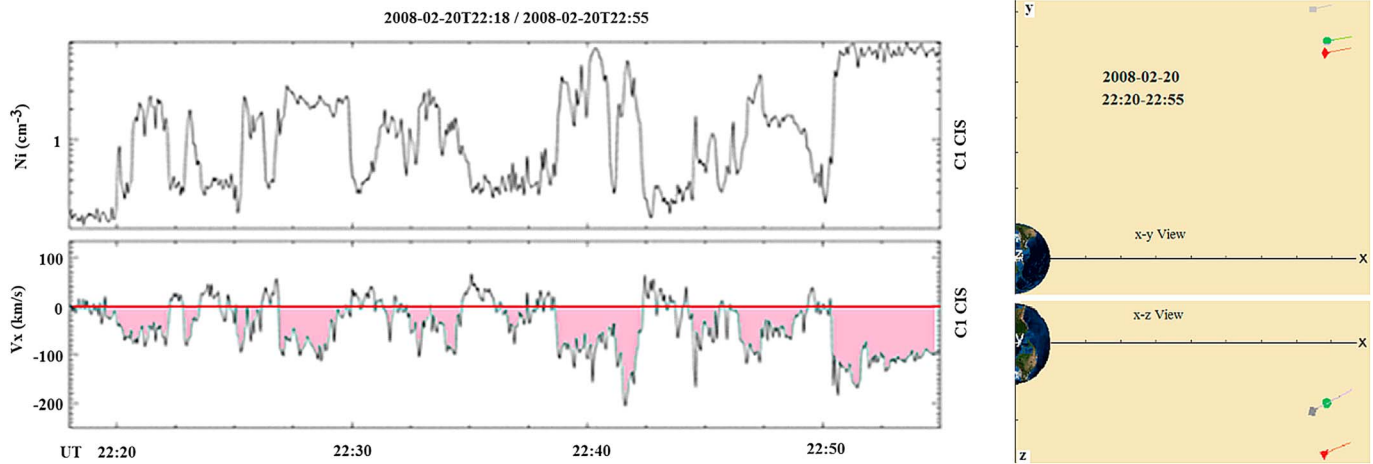


Figure 5. The same as in Figure 3, but in this case, the C1 spacecraft is located in a wider, dusk sector (as shown on the right). There is a remarkable antisunward plasma velocity inside all filaments. The filament plasma density and velocity also show strong variations, which (the same as in Figure 3) may be caused by the existence of a large number of subfilaments. (right) The trajectories of the Cluster S/C in the x-y and x-z planes from the 4-D orbit viewer (see above).

suggests the possible disconnection of these filaments from the magnetosheath. Note that the first filament in this figure is well seen only on C1.

For comparison, Figure 5 shows a series of plasma filaments in the dusk sector. The plasma density of these filaments is somewhat lower than that in Figures 3–5, but these filaments also show antisunward plasma velocity (V_x), whereas the plasma velocity in ambient plasma (between the filaments) is significantly reduced and may change its direction.

Thus, these figures show that the plasma filaments have a clear tendency to move antisunward at velocities that may reach up to 200 km/s, which is well consistent with results by Lundin *et al.* [2003] and other authors. These figures also show that these plasma filaments as a rule consist of several subfilaments, which may have different sizes, densities, and velocities, which might lead to fast separation of these filaments into smaller substructures. Indeed, sometimes such separation may be observed, but the difference in the density and other parameters of subfilaments may also lead to their strong interweaving that may stabilize these filaments.

4. Azimuthal Velocity and Rotation of Plasma Filaments

Another feature of these filaments is their azimuthal velocity, V_y . This velocity on average is comparable in magnitude with the V_x velocity, but (in contrast to the stable antisunward V_x velocity) the direction of the V_y velocity depends on filament location: in the noon-dusk sector, it is directed predominantly duskward while in the noon-dawn sector predominantly dawnward, following the direction of plasma velocity in the magnetosheath. Examples of the V_x and V_y components of plasma velocity in these filaments are shown in Figures 6–9.

Figure 7 shows the plasma filaments observed in a wider noon-dusk sector. The same as in Figure 6, all filaments show antisunward (V_x) plasma velocity.

Figures 8 and 9 show the V_x and V_y plasma velocities in the filaments in the opposite, noon-dawn sector (where the V_y velocity has the opposite direction than that in Figures 6 and 7).

Figures 6–9 (related to the noon-dusk and noon-dawn sectors, respectively) show the opposite directions of the V_y velocity, which is consistent with the motion of magnetosheath plasma in these sectors. The V_y plasma velocity in these cases is comparable with or exceeds the antisunward V_x velocity; however (as shown later), near the subsolar point, where magnetosheath plasma changes its direction, the antisunward V_x velocity may significantly exceed the azimuthal velocity. Figures 8 and 9 show also the vertical (V_z) component of plasma velocity, which usually is varying variable and may depend on spacecraft location with respect to the equatorial plane, the geometry of the filaments, and other factors.

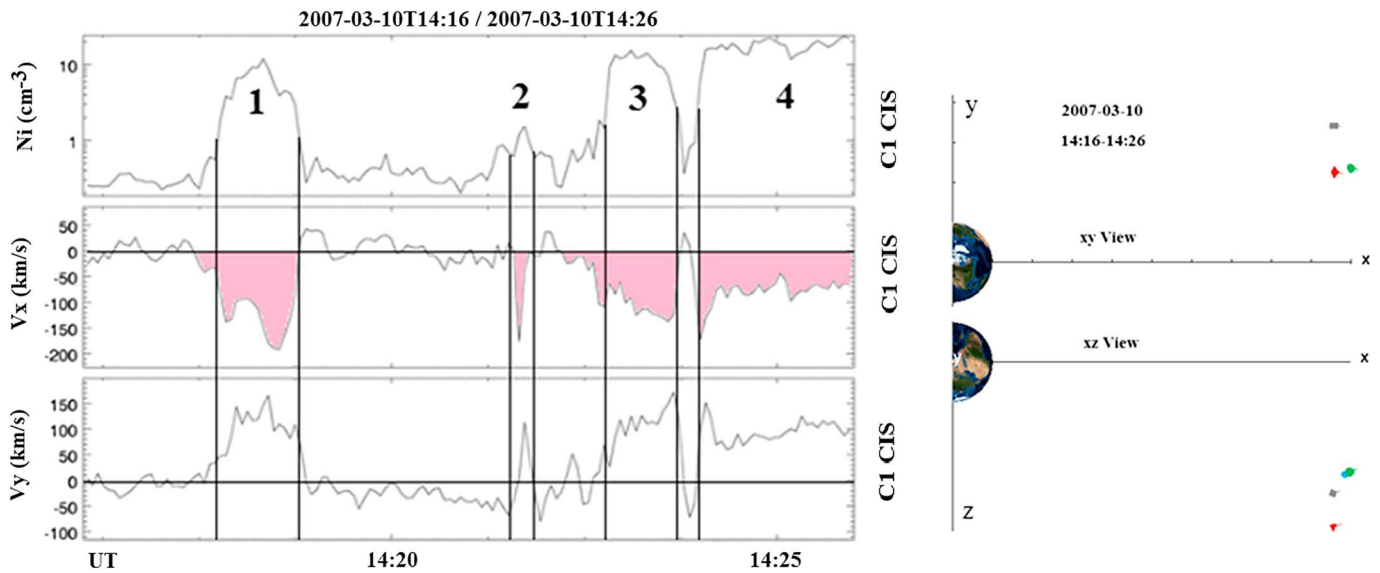


Figure 6. Shown are several filaments (1, 2, and 3), containing magnetosheath plasma and moving both antisunward and duskward as measured on C1 Cluster in the noon-dusk sector. The V_x velocity of plasma filaments, as usual, is directed antisunward, while the V_y velocity is positive, which shows that the filament plasma is moving in the same direction as the magnetosheath plasma near the magnetopause moves. The average azimuthal velocity of the filament plasma (equal approximately to the azimuthal velocity of the filaments) is about 150 km/s. (right) Shown are the trajectories of three Cluster spacecraft in the x-y and x-z planes from the 4-D orbit viewer (see above).

Another important feature of these filaments is their rotation. The filament rotation in the x-y plane (which coincides with its plasma rotation) may be derived from the phase shift between the V_x and V_y velocity components (although sometimes it may be difficult to determine because of a strong intermittency in the velocity due to an inhomogeneous, subfilamentary structure of these filaments). The phase shift between the V_x and V_y velocity components is well seen, for instance, in Figures 1, 7, and 8, and other cases. The velocity rotation is also well seen in Figure 10 (in filaments 1 and 2), which demonstrates asynchronous behavior and a significant phase shift between the V_x and V_y velocity components.

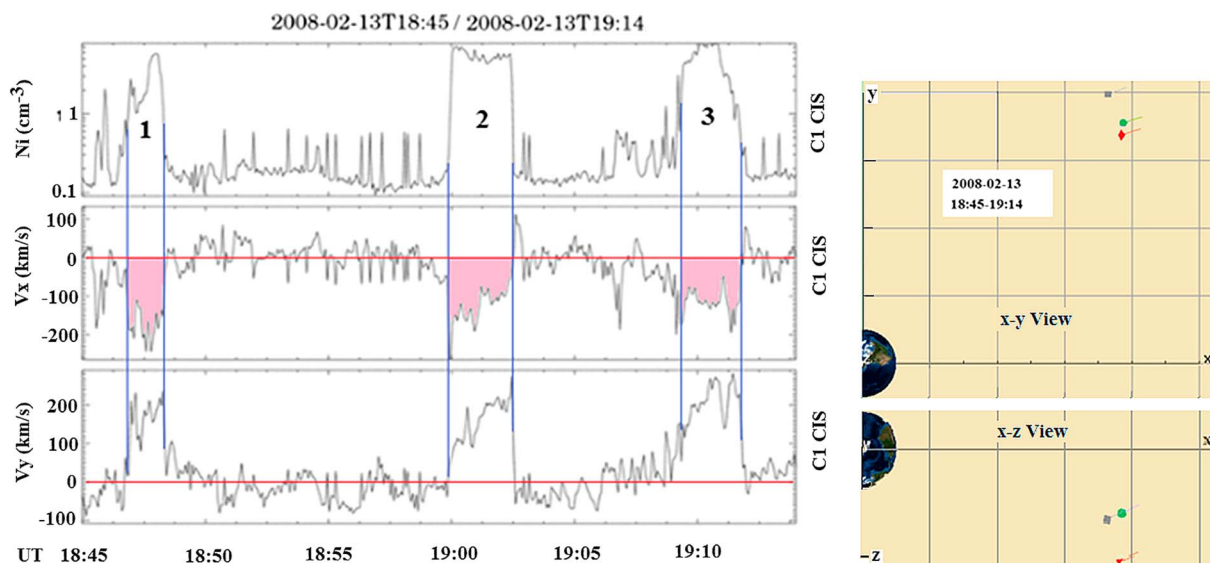


Figure 7. The same as in Figure 6 measured on C1 S/C but in a wider noon-dusk sector. The azimuthal (V_y) plasma velocity in the filaments in this figure slightly exceeds their antisunward (V_x) velocity. (right) Shown are the trajectories of three Cluster spacecraft in the x-y and x-z planes from the 4-D orbit viewer.

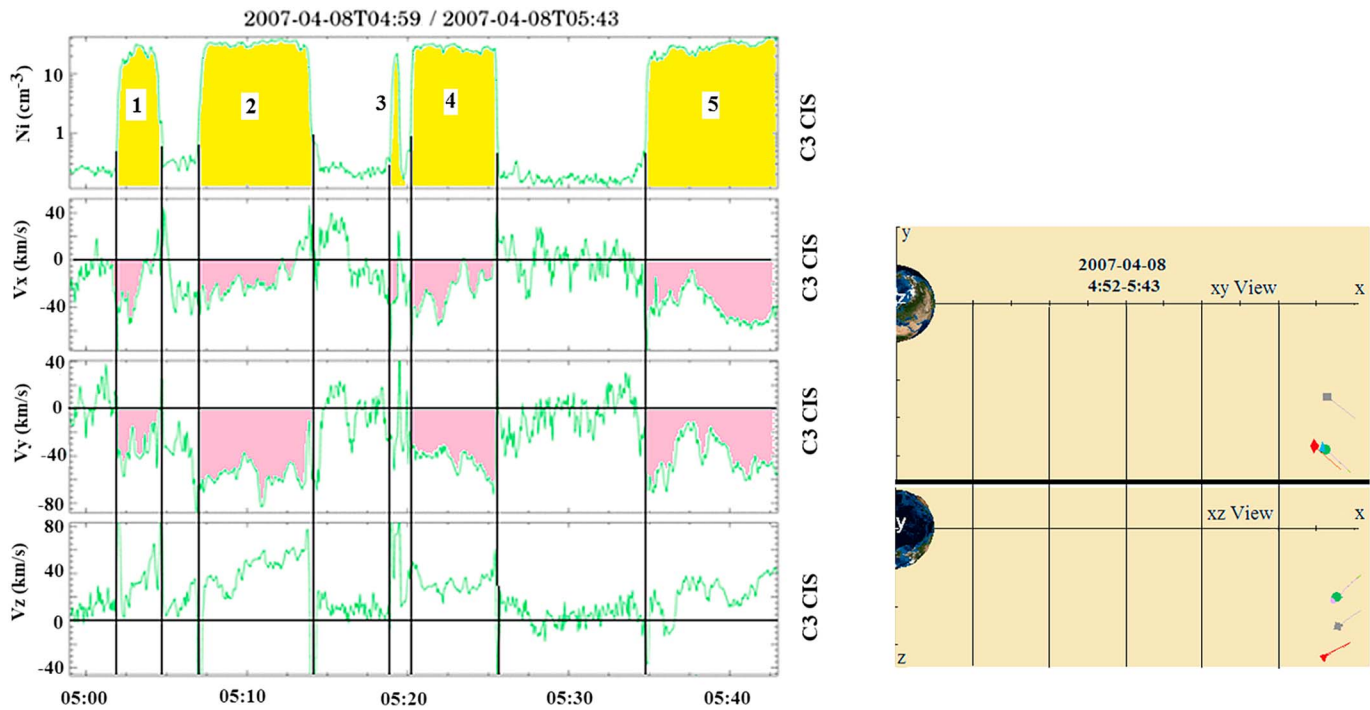


Figure 8. Three components of plasma velocity are shown in the filaments in noon-dawn sector as observed on C3 S/C. Note that the V_y velocity in this case is negative (downward); the regions of antisunward V_x and downward V_y velocities inside the filaments are shown in pink. Shown also is the V_z velocity. (right) The trajectories of all four spacecraft in the x-y and x-z planes from the 4-D orbit viewer.

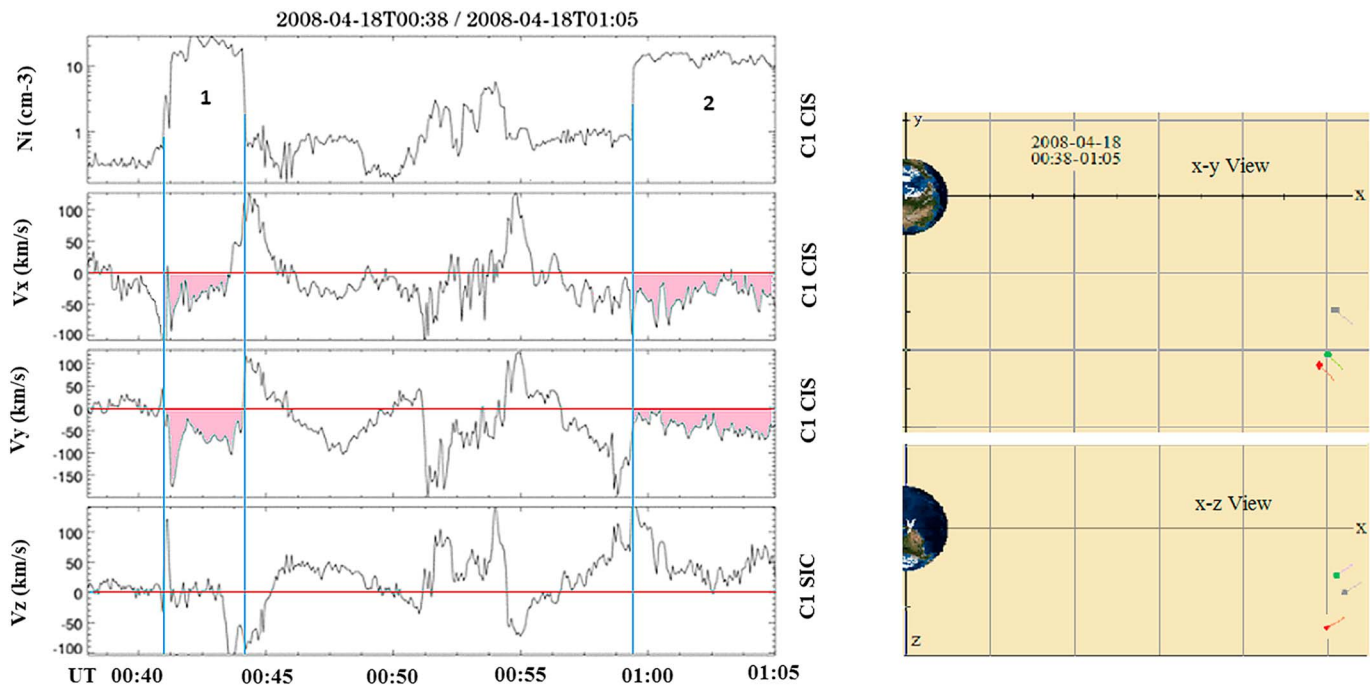


Figure 9. The same as in Figure 8 also in the noon-dawn sector but for another day as observed on C1 S/C. The V_y velocity of filament plasma in this case is also negative (downward); the regions of antisunward V_x and negative (downward) V_y velocities inside the filaments are shown in pink. (right) The trajectories of Cluster S/C in the x-y and x-z planes from the 4-D orbit viewer. Note the sharp increases in plasma velocity, observed on the boundaries of the filaments.

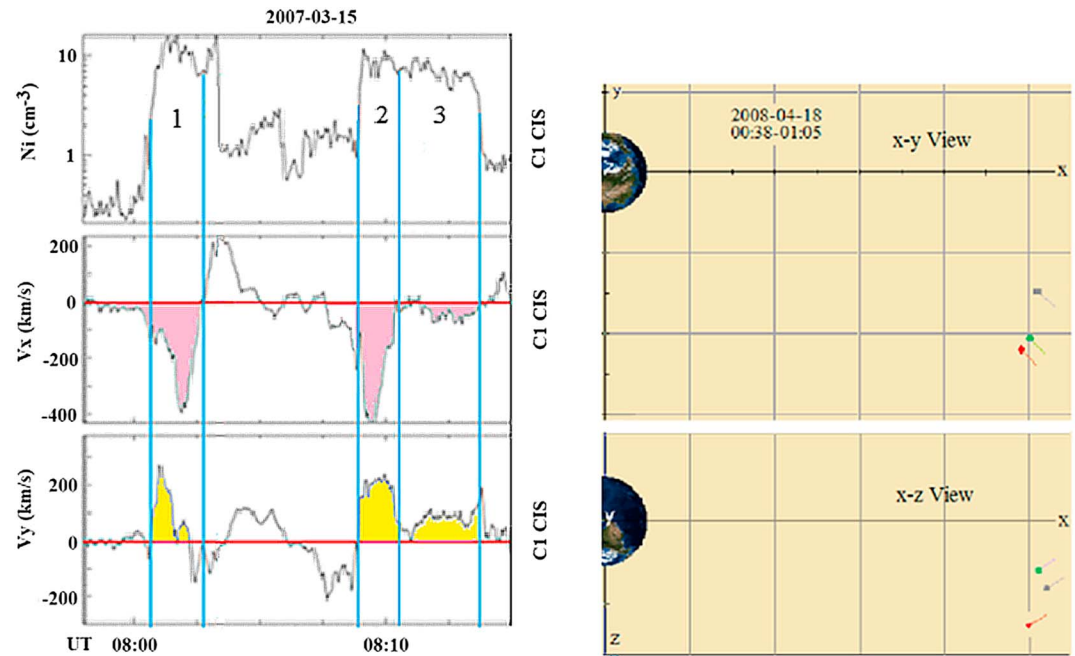


Figure 10. An example of rotating plasma velocity inside the filaments in the x - y plane (which is approximately perpendicular to the ambient magnetic field) in the near-noon sector as observed on C1 S/C. One can see a significant phase shift between the V_x and V_y velocity components in filaments 1 and 2, which shows the velocity rotation. (right) The trajectories of three Cluster spacecraft in the x - y and x - z planes from the 4-D orbit viewer.

The examples of rotating filaments, presented above, show that this rotation is a common feature of these events, which (as shown in our next study (W. Lyatsky et al., submitted manuscript, 2016)) may play an important role in the penetration of these filaments into the magnetosphere. Note that the theoretical studies (mentioned in the Introduction) consider the cases, when the filament magnetic field is aligned along the filament, which is correct in the case of a straight magnetic field. However, it is incorrect in the case of a rotating magnetic field. The filaments with the rotating magnetic field (even when it is significantly inclined to the ambient magnetic field) may penetrate deep into the magnetosphere, if their rotation magnetic field, *averaged for the rotation period*, is elongated along the ambient magnetic field. In this case, the filaments occupy a narrow sector along the ambient magnetic field, which significantly reduces pulling out these filaments from the magnetosphere and allows them to penetrate rather deep into the magnetosphere.

5. Discussion and Conclusions

Thus, in this study we investigated a large number of plasma filaments, observed in dayside magnetosphere but containing magnetosheath plasma. In order to reduce the effects of the polar cusps and the Kelvin-Helmholtz instability on magnetospheric flanks, we examined these events predominantly in a narrow cone ($\leq 30^\circ$) about the subsolar point. The important features of these events are (1) they contain magnetosheath plasma with ion density of about 10 ions/cm^{-3} and more (which significantly exceeds the density of ambient magnetospheric plasma); (2) they move stably earthward inside the magnetosphere, whereas the ambient magnetosphere plasma moves in the opposite direction or nearly immobile; and (3) the presence of a strip of magnetospheric plasma between these filaments and the magnetopause frequently observed on all Cluster spacecraft and showing the separation of these filaments from the magnetosheath.

A simple model of two rotating filaments after their crossing the magnetopause and penetration into the magnetosphere in the noon-dawn and noon-dusk sectors in the magnetospheric equatorial plane is shown in Figure 11. The filaments get rotation during their crossing the magnetopause and are rotating in opposite directions in noon-dawn and noon-dusk sectors (although the point of altering their rotation direction may

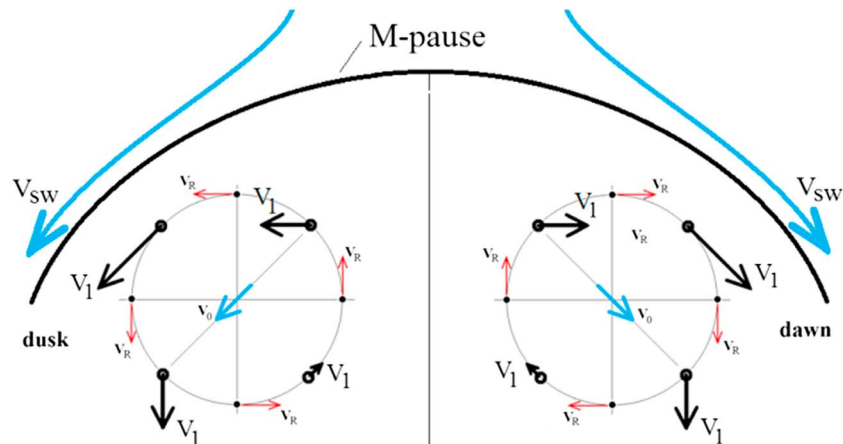


Figure 11. A schematic of two rotating filaments in the magnetosphere equatorial plane (not to scale) in the noon-dawn and noon-dusk sectors. The filaments are assumed to be rotating at a rotation velocity, V_R , and moving along the magnetopause at a translational velocity, V_0 ; the directions of these velocities, however, are significantly different in the dawn and dusk sectors. The summary velocity of the filament plasma, $V_1 = (V_R + V_0)$, also is shown. All velocities are shown in the spacecraft frame (which is suggested to be immobile as the spacecraft velocity is much less than the plasma velocity). The total velocity, V_1 , is maximal near the magnetopause and is reduced earthward (where this velocity may change its direction (in the case when the rotation velocity, V_1 , exceeds the translational velocity, V_0 , as shown in this figure).

be shifted duskward due to an inclination of solar wind magnetic field from the Earth-Sun line as a result of the Parker spiral effect). Note that this model does not account for subfilaments.

Although similar plasma filaments were observed by many researchers (see above), a significant progress in their study was started after the launch of Cluster, which made possible the resolution of many questions. Nevertheless, the main questions, whether are these events really detached from the magnetopause, and if yes, how can they propagate through the magnetosphere, remain unanswered. A chance that these events may be a result of magnetic reconnection in the case of the northern IMF B_z is very low: as mentioned in the Introduction, in this case, the magnetosheath magnetic field lines should be reconnected with Earth's magnetic field simultaneously in two points poleward of two polar cusps, which may occur only in some exceptional cases, when the magnetosheath magnetic field is aligned with Earth's magnetic field.

Two other possible explanations of these events may be the back-and-forth motions of the magnetopause and the surface waves propagated along the magnetopause. The results of this study, however, show (i) a stable earthward motion of these filaments in the magnetosphere and (ii) the existence of a region of magnetospheric plasma, separating these filaments from the magnetopause, which are not consistent with both back-and-forth motions of the magnetopause and surface waves on the magnetopause; note that such events potentially can be observed but only in the case when the B_y magnetic field component in the magnetosheath is much less than the positive B_z component, which occurs very rarely, whereas these filaments are observed very often. Note also that in the cases of compression and decompression of the magnetosphere, both magnetosheath plasma and ambient magnetospheric plasma are moving together toward or out from the Earth, following the magnetopause motion. However, in most cases, these two plasmas usually move in opposite directions: while the plasma filaments move antisunward, the ambient magnetospheric plasma remains relatively stable or moves in the opposite (sunward) direction, which also shows that the stable antisunward motion of plasma filaments cannot be explained by magnetopause motions (at least, in the vicinity of the subsolar point).

Another possible explanation of these events as a result of surface waves on the magnetopause is appearing because of the Kelvin-Helmholtz instability (although it is unlikely developing near subsolar region) or the Rayleigh-Taylor instability (which during some cases may be a more likely mechanism for generation of surface waves at dayside magnetopause [e.g., Gratton *et al.*, 1996; Lyatsky and Sibeck, 1997a, 1997b]). However, this explanation is also inconsistent with observation results showing the separation of these plasma filaments from the magnetosheath.

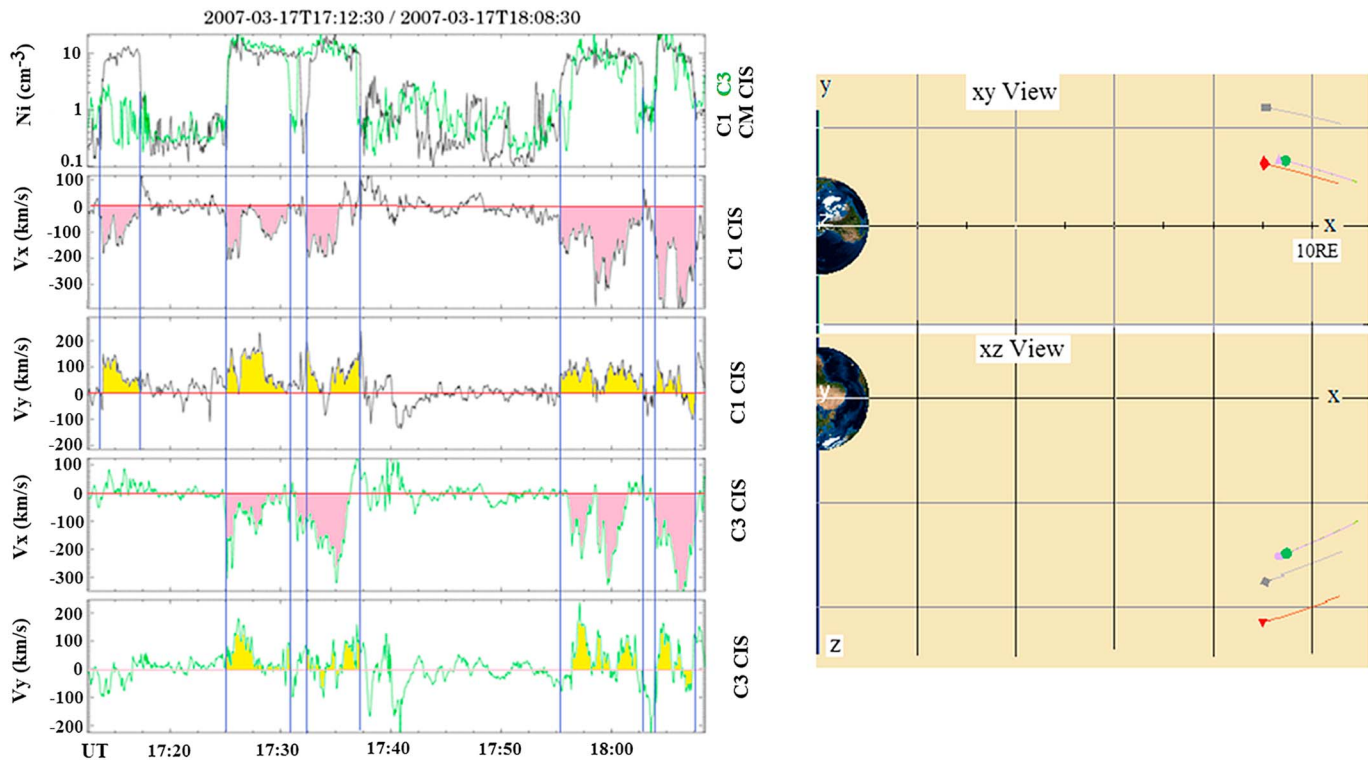


Figure 12. Ion densities and velocities of plasma filaments, observed on 03 March 2007, on the C1 (black lines) and C3 (green lines) in the near-noon sector, where the solar wind plasma is separated into two streams going downward and duskward around the magnetopause. In this sector, the antisunward V_x velocity may significantly exceed the V_y velocity, as seen especially clearly on C3 (note that the weak positive V_x observed on C3 near 17:12 UT is not related to a filament as the plasma density in this time interval is too low). The stable antisunward V_x velocity of these filaments shows the penetration of magnetosheath plasma into the magnetosphere. (right) Shown are the Cluster trajectories in the x-y and x-z planes, obtained from the 4-D orbit viewer.

Therefore, our results of observations of plasma filaments in a narrow cone near the subsolar point seem to be more consistent with the third possibility that these filaments have been detached from the magnetosheath and penetrate into the magnetosphere, as was earlier proposed by many researchers mentioned above. In this case, these detached plasma filaments may propagate in the magnetosphere until they will be pushed out by the compressed ambient magnetic field or dissipated in ambient plasma. In the next paper (W. Lyatsky et al., submitted manuscript, 2016), we show that the rotation of these filaments may be an important factor, which significantly facilitates the motion of these filaments through the magnetosphere even in the case when their local rotating magnetic field is significantly inclined to the ambient magnetic field.

In conclusion, in Figure 12 we present one more example of these filaments, observed on C1 and C3 S/C near the noon meridian, where the antisunward V_x velocity mainly significantly exceed the V_y velocity (that is especially clear on C3 S/C). This figure shows the typical antisunward (about earthward) motion of the filaments; the plasma velocity in these filaments may be as large as about 300–400 km/s, which in most cases significantly exceeds the magnitude of the azimuthal (V_y) velocity. Note also significant time intervals between these filaments, well seen on both spacecraft. Figure 13 shows the schematically three possible events related to these plasma filaments.

The main results of this study may be summarized as follows:

1. In this study, we examined a large number of plasma structures (filaments), observed with the Cluster spacecraft during 2 years (2007–2008) in the dayside magnetosphere but consisting of magnetosheath plasma. To reduce the effects observed in the cusp regions and on magnetosphere flanks, we consider these events predominantly inside the narrow cone $\leq 30^\circ$ about the subsolar point. The obtained results show the existence in the subsolar magnetosphere of plasma filaments, containing magnetosheath plasma. These results support earlier results by Lemaire [1977], Lemaire and Roth [1978], Lundin and

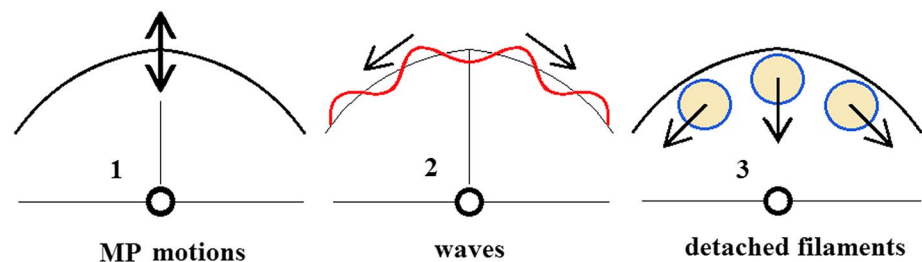


Figure 13. Schematics showing three phenomena in the equatorial plane, considered above: no. 1 shows the back-and-forth magnetopause (MP) motions; no. 2 shows the dusk-dawn propagation of surface waves on the magnetopause; and no. 3 shows the plasma filaments, detached from the magnetosheath and propagating antisunward by virtue of their inertia. Two first events do not explain the stable antisunward motion of the plasma filaments and unlikely related to plasma filaments, considered in this study, while the event 3 basically explains these filaments. The black arrows show the velocities of these structures.

Dubinin [1984], Echim and Lemaire [2000, 2005], Lundin *et al.* [2003], Gunell *et al.* [2012, 2014], and other researchers, who suggested that these plasma filaments may be detached from the magnetosheath and enter the magnetosphere probably due to their excess momentum.

2. Two important features of these filaments are (i) their stable antisunward (about earthward) motion inside the magnetosphere, whereas the ambient magnetosphere plasma usually moves in the opposite, sunward direction, and (ii) between these filaments and the magnetopause a strip of magnetospheric plasma is observed, frequently seen on all Cluster spacecraft and separating these filaments from the magnetopause. Note that these features are observed even near the subsolar point, where the antisunward velocity of these filaments may significantly exceed their azimuthal (V_y) velocity.
3. The stable earthward motion of these filaments in the near-noon sector as well as the presence of a notable strip of magnetospheric plasma between these filaments and the magnetopause position shows the possible disconnection of these filaments from the magnetosheath that was suggested earlier by many researchers, mentioned above. The obtained results also show that these filaments unlikely can be a result of motions of magnetopause position or the surface waves propagated on the magnetopause.
4. The antisunward motion of these filaments is usually accompanied by their azimuthal motion (duskward in the noon-dusk sector or dawnward in the noon-dawn sector) that is consistent with their penetration into the magnetosphere from the magnetosheath.
5. An important feature of these filaments is their rotation about the filament axis, which may be a result of their passage through the velocity shear on the magnetopause boundary. Although the velocity shear in dayside near-noon magnetosphere is not as large as it is on magnetospheric flanks, it is sufficient to induce rotation of plasma filaments crossing the magnetopause. While crossing the velocity shear, the filaments and their magnetic field get a rotation, which supports the penetration of these filaments into the magnetosphere even in the case of strong deviations of this rotating magnetic field, if this magnetic field, averaged over their rotation period, is oriented close to the ambient magnetic field.

Thus, the stable antisunward motion of the plasma filaments in the near-noon sector of the magnetosphere (whereas the ambient magnetospheric plasma usually is about immobile or moving in the opposite direction) as well as the existence of a significant region of magnetospheric plasma separating these filaments from the magnetosheath show that these filaments unlikely may be a result of magnetopause motions or the surface waves propagated along the magnetopause. At the same time, the observed rotation of these filaments about the filament axes (which may be a result of their passage through the velocity shear on the magnetopause boundary) may support both the motion of these filaments in the magnetosphere and their stability as shown in our next study (W. Lyatsky *et al.*, submitted manuscript, 2016).

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