Survey of flux transfer events observed with the ISEE 1 spacecraft: Dependence on the interplanetary magnetic field

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Abstract. We have surveyed the interplanetary magnetic field (IMF) dependence of isolated bipolar perturbations of the magnetic field component normal to the magnetopause, identifiable as flux transfer events (FTEs), from nine seasons during which the ISEE 1 spacecraft completely traversed through the dayside magnetopause and magnetosheath. The majority of substorm FTEs are associated with southward IMF, consistent with previous studies. The ratio of the number of FTEs during spiral IMF orientation to that during ortho-spiral IMF is roughly the same at any MLT, an unfavourable finding for the foreshock being the source of our FTEs. The curvature force controlled by IMF $B_z$ tends to affect significantly the motion of FTEs near noon, causing sunward moving FTEs. This behavior is consistent with reconnection betwee the source of our events. The totality of these results suggest that the foreshock is not the source of the dayside magnetopause but that reconnection at the magnetopause is the source.

1. Introduction

This paper studies the IMF dependence of flux transfer events (FTEs) by using the largest database of FTEs presently available. FTEs are observed in the magnetosheath and magnetosphere and are characterized by a prominent isolated bipolar (positive-then-negative or vice versa) perturbation in the component normal to the magnetopause ($B_z$). Russell and Elphic (1978) first reported FTEs and interpreted them as the manifestation of transient and patchy reconnection at the dayside magnetopause. This interpretation naturally led to an expectation that FTEs would arise during southward interplanetary magnetic field (IMF) conditions and the consequent southward magnetosheath magnetic field conditions.

Later papers supported the expected correlation of FTEs with the southward IMF (e.g., Rigby et al., 1984; Berchem and Russell, 1984; Le et al., 1995; Kuo et al., 1995).

More recently, there has been a suggestion that FTEs are caused by pressure pulses generated in the foreshock (e.g., Sibeck, 1994). If this conjecture is true, then FTEs should occur for both northward and southward IMF. Sibeck and Newell (1995) applied three methods to estimate the magnetosheath magnetic field at times of 24 magnetospheric FTEs: (1) the average magnetosheath magnetic field orientation in the 30-min period adjacent to the nearest magnetopause crossing, (2) the magnetosheath magnetic field orientation observed just outside the magnetopause, and (3) the lagged IMF orientation at the time of the transient event. They obtained a southward bias for method 2 but no apparent de-

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conditions, and we average them to obtain an average IMF condition. The conditions are (1) the data points include both the magnetic field data and the plasma ion bulk velocity data, and (2) when data time, $t_{SW}$, is corrected for the propagation time lag of the solar wind by $t_{SW} = t_{SW} + (X B_x - Y B_y) / (V_x B_y + V_y B_x)$, then $|t_{SW} - t_{PFE}| < 13$ min.

Here, $X$ and $Y$ are GSE components of the spacecraft position in the solar wind, $B_x$ and $B_y$ are GSE components of the IMF, $V_x$ and $V_y$ are GSE components of the solar wind ion bulk velocity, and $t_{PFE}$ is the time when the FTE is observed. The above lag correction equation is a simplified version of an equation used by Lockwood et al. [1989]. The assumptions used in the equation are that the solar wind plasma is rather uniform along the magnetic field line, that the field line is straight, and that planes of constant magnetic field orientation are perpendicular to the ecliptic plane containing the magnetic field direction. Thus there is no $Z_{eq}$ dependence of the time delay. The second term of the right-hand side of the above equation exhibits the time lag for the straight field line to connect from the spacecraft position in the solar wind to the position of the center of the Earth (in case there is no magnetoplasma obstacle) with the velocity ($V_y$, $V_x$). The threshold of 15 min for $|t_{SW} - t_{PFE}|$ means all data in the time interval 15 min before and after $t_{PFE}$ are used to calculate a 30-min average IMF condition for each FTE.

Here we note that in the above lag calculation we ignored the distance from SEE 1 (observing FTEs) to the center of the Earth and, consequently, the time for the solar wind to travel the distance. The lag time calculated by using the above equation could therefore be an overestimate for events with position $X > 0$ and an underestimate for events with $X < 0$. However, the time for the solar wind to travel the distance between SEE 1 and Earth is usually much smaller than the 30-min interval. For example, with nominal solar wind speed of 440 km/s and the spacecraft distance 11 R$_{E}$, the lag time is $< 3$ min. Thus the ignorance of the distance between SEE 1 and Earth does not affect much the average IMF condition corresponding to an FTE.

As an additional constraint we require that more than three data points of the solar wind exist in the 30-min interval for an FTE to be selected for the IMF correlation study below. As a result of these calculations we have obtained 340 FTEs that have corresponding IMF data. The spatial distribution of the 340 FTEs is shown in Figure 1.

3. Data Analysis

3.1. IMF Dependence of FTE Occurrence

Figure 2 shows the distribution of IMF $B_z$ (in GSM coordinates) for the 340 FTEs. Unshaded portions are symmetric with regard to $B_z = 0$. The shaded portions show that the overall IMF dependence of the FTEs is biased toward southward, consistent with previous results and consistent with the interpretation in terms of reconnection.

Figure 1. Spatial distributions of 340 FTEs used in this study, in GSM (top) YZ plane and (bottom) XZ plane. Note in the bottom panel the positive X axis is directed toward the bottom of the panel.

In Figure 3 the 340 FTEs are divided into three groups according to the MELT: 1000~1400 (top), 1400~1800 (middle), and 1800~2200 (bottom). That is, the top panel shows subsolar FTEs, the bottom panel shows postterminator FTEs, and the middle panel shows FTEs in the dayside region near the dusk or dawn. For each group a histogram of corresponding IMF $B_z$ is shown in the same format as Figure 2. The figure shows that the FTEs in the subsolar region (top panel) are predominantly associated with southward IMF, but the FTEs in the postterminator region are associated with both northward and southward IMF. The bias of the subsolar FTEs toward southward IMF is statistically significant: The number of events with IMF $B_z < 0$ ($B_z > 0$) is 45 (16), and from these numbers the fractional ratio of the events with IMF $B_z < 0$ is calculated,
with standard error, to be 0.74±0.07. The majority of subso- 
lar events is probably generated by equatorial reconnection. 
The post-terminator FTEs are briefly discussed in section 4. 
Next we test the possibility that our FTEs are generated 
by foreshock pressure pulses. Figure 4 is a cartoon show- 
ing where one expects to observe foreshock pressure pulse- 
driven events. The top panel is for the Parker-spiral IMF 
case, and the bottom panel is for the ortho-spiral IMF case. 
The shaded area indicates where one expects the events. In 
the spiral case the foreshock is located on the dawnside, 
thus the pressure pulse-driven events are also expected to be fre- 
quent on the dawnside, and vice versa for the ortho-spiral 
case (bottom panel). Then, if one divides data into MLT bins 
and calculates the ratio of number of events during spiral IMF 
orientation to that during ortho-spiral IMF, the ratio should 
be asymmetric around the noon meridian. That is, the ratio 
should be larger in the dawnside than in the duskside.

Figure 5 shows the result of the above described calcula-
tion. The data are divided into 3-hour MLT bins. The number 
of events in each bin is given in Table 1. For each MLT bin 
the total number of events is normalized to unity to show 
the above mentioned ratio. Error bars are calculated by us-
ing the bootstrap method [e.g., Kawano and Higuchi, 1995]. 
The figure shows that there is no MLT dependence of the 
ratio, as opposed to the model expectation of the foreshock 
pressure pulse (dashed superposed line).

3.2. IMF \( B_z \) Dependence of FTE Motion

From the above results, reconconnection is likely as the 
generation mechanism of dayside FTEs. To further confirm this 
possibility, we have surveyed the IMF \( B_z \) dependence of FTE 
motion. As Kawano and Russell [1996] have shown, the mo-
tion of each FTE can be estimated from the rotational polarity 
of the magnetic field perturbation in the (roughly) equato-
rial plane. That is, the rotational polarity (right-handed or 
left-handed) in the MN plane of the LMF coordinates has 
one-to-one relationship with the direction of azimuthal mo-
tion (downward or duskward) (see Figure 10 of Kawano and 
Russell [1996]). The LMF coordinate system was first intro-
duced by Russell and Elphic [1978]. It is a local coordinate 
system with its origin at the spacecraft position. The \( N \) axis 
is normal to the magnetopause and pointed downward. The \( L \) axis is the projection of the GSM \( Z \) axis to the plane tangent to the 
magnetopause. The above mentioned study of Kawano and 
Russell [1996] on the rotational polarity showed that the mo-
tion of FTEs is mainly antisunward everywhere. However, 
the database also includes some sunward moving events, and 
their occurrence is highest near the noon meridian (see their
Figure 10. It is possible that the sunward moving events near the noon meridian are caused by the \( B_y \) effect of the reconnected PTE flux tube. That is, the reconnected field lines have a kink at the magnetopause, according to the \( B_y \) component of the IMF, and the kink causes tangential stress along the boundary in the direction of the asymptotic field.

Figure 6 is a cartoon showing where one expects to observe sunward motion of FTEs. The top panel corresponds to the IMF \( B_y < 0 \) case, and the bottom panel corresponds to the opposite case. The shaded area indicates where one expects sunward motion. For \( B_y > 0 \), sunward motion is expected in the dawnside and north of the reconnection line ("RL") and in the duskside and south of the reconnection line. For \( B_y > 0 \), sunward motion is expected in the dawnside and south of the reconnection line (RL) and in the duskside and north of the reconnection line.

If we look at only events north of the reconnection line when IMF \( B_y < 0 \) plus those south of the reconnection line when IMF \( B_y > 0 \) (noted as group A below), we can expect to see sunward motion on the duskside of the noon meridian. On the other hand, if we look only at events south of the reconnection line when IMF \( B_y < 0 \) plus those north of the reconnection line when IMF \( B_y > 0 \) (noted as group B below), we can expect to see sunward motion on the duskside of the noon meridian. To estimate whether each FTE is located north or south of the reconnection line, we use the bi-polar \( B_y \) perturbation of the FTE, it is widely acknowledged that the positive-then-negative (\( + \rightarrow - \)) perturbation of \( B_y \) (\( B_y \)) is prominent in the region north of the reconnection line, and vice versa [e.g., Reisenbichler et al., 1984; Reisenbichler and Russell, 1984]. The FTEs in our database also agree with these previous studies (not shown). If we define the polarity of \( B_y \) \( \left( \text{pol}(B_y) \right) \) in the figure to be plus for positive-then-negative perturbation, then group A events correspond to IMF \( \text{pol}(B_y) = \text{pol}(B_y) > 0 \) and group B events correspond to IMF \( \text{pol}(B_y) = \text{pol}(B_y) < 0 \). Thus we use this quantity to classify our FTEs into group A or B.

The top panel of Figure 7 shows group A, for which sunward motion is expected on the duskside of the noon meridian. In contrast, if the bars above (below) the zero line correspond to the downstream moving (duskward moving) events, as determined from the rotation polarity of the magnetic field perturbation [Kawano and Higashi, 1995]. In each 3-hour MLT bin, the total number of events is normalized to unity. The number of events in each bar is listed in Table 2. Error bars are calculated by using the bootstrap method [see Kawano and Higashi, 1995, and references therein]. The superposed solid curve in each panel is obtained by fitting a logistic curve to the center points of the bars (in addition to the six bars shown, bins of 1000-2000, 2000-3000, 3000-4000, 4000-5000, and 5000-6000, and so on, are also used (not shown) to constitute 16 data points in total, to which the logistic curve is fitted). The logistic curve is defined as

\[
y = \frac{a}{1 + \exp\left(\frac{x - c}{d}\right)} + b,
\]

where \( y \) is a function of \( x \) (MLT in our case), and \( a, b, c, d \) are fitting parameters. Dashed curves above and below the solid curves show the range of the standard error of the curve, or, in other words, the 68% confidence interval calculated by using the bootstrap method.

We note for the pentoon bins of the top panel of Figure 7 the number of events is so small (see the long error bars, and also see Table 2) that it is difficult to obtain a significant conclusion from the bars. However, the curves in the panel show that with 68% confidence we could say the change at the rotation point (the curves cross the zero line) takes place before \( \sim 1100 \) MLT (or duskward motion for all MLTs). That is, the sunward motion is observed in the duskside sector, an expected consistency with the top panel of Figure 6. For the bottom panel the numbers of events...
Table 1. Number of Events in Bins of Figure 5

<table>
<thead>
<tr>
<th>MLT hour</th>
<th>&lt;6</th>
<th>6-9</th>
<th>9-12</th>
<th>12-15</th>
<th>15-18</th>
<th>&gt;18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral IMF</td>
<td>47</td>
<td>27</td>
<td>27</td>
<td>38</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>Ortho-spiral IMF</td>
<td>13</td>
<td>9</td>
<td>7</td>
<td>12</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

in the bins are larger. Thus the MLT dependence is more reliable in the bottom panel than in the top panel. This panel shows again that the sunward motion is observed just as expected, in the duskside sector (from 1200 to ~1400 MLT).

A further test of the IMF $B_z$ dependence of the FTE motion is to see whether the large [$B_z$] would increase the occurrence of sunward moving events far from the noon meridian. That is, a large [$B_z$] would cause a large tangential stress of reconnected field lines, and if it is directed sunward, it would overcome the drag force of the tailward magnetosheath flow far from the noon meridian. A way to do that is to divide group A into two subgroups, according to the magnitude of IMF $B_z$, and do the same study as was done in Figure 7, and do the same for the group B. However, if we divide the database into four subgroups, the number of data in each subgroup becomes too small to draw significant inforation.

Thus we first merge group A with group B by reversing the direction of azimuthal motion and mirroring the position with regard to the noon meridian. For example, if an event in group A is observed at 1330 MLT and moving duskward, then it will be treated as if it is a group B event observed at 1030 MLT and moving downward. A rough way to understand this procedure graphically is to rotate the upper panel of Figure 7 by 180° and add to the bottom panel: by this, the duskward asymmetry in the fractional occurrence is conserved correctly. Second, the merged data set is divided into two groups according to the magnitude of IMF $B_z$.

Figure 6. Expected regions of sunward moving FTEs (shaded areas) for (top) IMF $B_y < 0$ and (bottom) IMF $B_y > 0$. See text for details.

Figure 7. Fractional occurrence of downward moving FTEs and duskward moving FTEs. (top) Events in group A, for which sunward motion is expected (From Figure 6) on the duskside of the noon meridian. (bottom) Events in group B, for which sunward motion is expected on the duskside of noon. Superposed solid curve in each panel shows a logistic curve fitted to the center points of the bars, and dashed curves show its 68% confidence interval. See text for details.
threshold is set to 4.505 nT so that the two groups have the same amount of data for statistical sake. Finally, the same analysis as in Figure 7 is applied to the two groups.

Figure 8 shows the results. Table 3 shows the number of events in each bar. The top panel shows the group with IMF $|B_z| < 4.505$ nT, and the bottom panel shows the group with IMF $|B_z| \geq 4.505$ nT. The median $|B_z|$ for these two groups is 2.7 and 6.2 nT, respectively. As is explained above, for both group the sunward moving events are expected diskside of the noon meridian. The figure indicates that the region of sunward motion, diskside of the noon meridian, is widened for large IMF $|B_z|$ just as expected. We note that the posterior simulator bins show some deviations from the trend shown by the solid curves, but their error bars are large, and if we look at the edges of the error bars, the deviations are acceptable as statistical errors.

**Table 3. Number of Events in Bins of Figure 7**

<table>
<thead>
<tr>
<th>Group A, downward motion</th>
<th>Group B, downward motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>

**Figure 8.** Similar to Figure 7, but group A is merged with group B, so that the IMF $|B_z|$ effect is conserved correctly, and the merged data set is divided into (top) a group with IMF $|B_z| < 4.505$ nT and (bottom) a group with IMF $|B_z| \geq 4.505$ nT. Thus the same analysis as in Figure 7 is applied to the two groups. See text for details.

4. Discussion

The above results demonstrate that most daily PTIIs use in fact generated by reconnection near the equatorial magnetopause, not by the foremost pressure pulses. As we stated in the introduction, Silbereisen and Neubert [1995] suggested that PTIIs are not necessarily associated with southward IMF. We are tempted to assume that the instability to their much smaller database than ours (24340). We also stated in the introduction that Kawanami et al. [1992], Baumjohann et al. [1993], and Sany et al. [1990] reported that long-duration large-amplitude compressions in the magnetic field observed deep in the magnetosphere showed little or any dependence on the north-south component of the IMF. For these compressions we refer to the discussion of Kawanami and Russell [1961]. They can be distinguished from PTIIs by the appearance of the waveform of the magnetic field perturbation. That is, the compression events deep within the magnetosphere appear to be quasi-periodic waveforms perturbations, while PTIIs in the vicinity of the magnetopause are highly isolated. Because our selection criteria of PTIIs, described by Kawanami and Russell [1996], reject wave-like perturbations, it is possible our database includes few pressure pulse-associated events.

We also note that Sany et al. [1990] studied the IMF $B_z$ dependence on the azimuthal motion of 59 transient compressions observed deep within the magnetosphere. They found that the events appear to be better governed by the sunward-to-south motion of IMF events than by IMF $B_z$. Following the preceding discussion in this section, we can say their result shows a feature of pressure pulse-driven long-duration wave-like events, and we do not have to worry about their mimicking PTIIs at least on a statistical basis.

As to the posterior simulator PTIIIs, Figure 8 suggests they are not caused by long-term pressure pulses. However, the posterior simulator PTIIs during IMF $B_z > 0$ do not seem to fit well with the picture of reconnection at first sight. We have four possible explanations for these PTIIs:

1. Because the magnetosheath magnetic field is draped around the magnetopause, it can happen that the draped magnetosheath field has a negative $B_z$ (in IMF) component in the postshock magnetosphere causes a local reconnection, even when IMF $B_z > 0$.

2. Because of the dragging effect of the magnetosheath plasma and because of the current sheet in the tail, the magnetic field in the postshock magnetosphere is tilted. If the postshock PTIIIs are locally generated there via reconnection, the amplification condition is different from that in the nonshock region, and thus the IMF $B_z$ is not a good indicator of the efficiency of postshock reconnection.
3. They are generated near the polar cap during northward IMF and move both antitoward and toward the equator, to reach the equatorial region in the postnoon sector. It is widely believed that during northward IMF the reconnection takes place near the polar cap region [e.g., Macewcu, 1976; Kessell et al., 1996]. The IMF and the lobe field are reconnected there. Considering that the reconnection in the dayside equator region exhibits a transient nature (as FTEs), the lobe reconnection is also likely to exhibit a transient nature.

4. Even if the IMF is northward directed, reconnection could take place around the subsolar region; Nichihashi [1989] suggests that reconnection takes place randomly, and the reconnected flux lines are often re-reconnected and result in closed field lines. In this case the antitoward motion of reconnected flux tubes can only start from the edge of the reconnection area. That is, near the subsolar region, reconnection stops the motion of the reconnected flux tube, and thus there is no clear observation of them, but in the postnoon region there are flux tubes coming from the edge of the reconnection area.

Determining the validity of these four possibilities requires further tests, which will be the subject of future research.

5. Summary
We have studied the IMF dependence of FTEs, characterized by their isolated bipolar Bz perturbations, from nine months of ISEE 1 data. The ratio of the number of FTEs during spiral IMF to that during orthogonal IMF is roughly the same at all MLT. This observation suggests that the FTEs cannot be explained in terms of the forelock pressure pulses at any MLT. The subsolar FTEs mainly take place during northward IMF, and this finding favors the equatorial reconnection as their generation mechanism. We have also found that the east-west motion of the dayside FTEs is controlled by IMF By, just as we expected from the tangential stress of the reconnected magnetic field lines. This result also supports reconnection as the generation mechanism of dayside FTEs. In the postnoon region, FTEs are associated with both northward and northward IMF. The cause of this behavior is the subject of future research.

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