Abstract. We present observations in a distant magnetotail between October 2003 and January 2004. During this time, the Wind spacecraft voyaged behind \( \approx -200 \) \( R_E \) and recorded the magnetotail dynamics as a response of many solar wind disturbances, which also affected the magnetosheath, magnetosphere and surface of the Earth. We investigate two cases of interplanetary shocks, which were observed by the spacecraft in the solar wind (ACE, SOHO, Cluster, Geotail) and in the far magnetotail (Wind). The IP shock passages through the far magnetotail were connected with observations of complex structure tail movement including possible fast plasma tailward flow bursts.

Introduction

Processes in the distant magnetotail up to the Lagrangian point L2 in the Sun-Earth system behind of the Earth began to be studied in the second half of the 20\textsuperscript{th} century. Dungey [1965] required for his reconnection-based models of the magnetosphere long, around 1000 \( R_E \) (Earth radii) magnetotail. Slavin et al. [1985] studied the excursion of the spacecraft ISEE-3 deep into the geomagnetic tail between December 25, 1982 and April 20, 1983. They determined a low-latitude Earth’s magnetotail with diameter of 60 \( \pm \) 5 \( R_E \) at distances \( |X| = 130 \div 225 \) \( R_E \) and examined the tail aberration angle to be about \( \pm 3^\circ \), which corresponds for the tail variation about \( \pm 10 \) \( R_E \) along the Y axis. This research showed correlations between \( V_x \), \( B_y \) and the Auroral Electrojet (AE) index [Kamei et al., 1983] in the plasmasheet with respect to reconnection (dynamics in this region is associated with substorms).

A passing very similar to ISEE-3 around the L2 point was made by the Wind spacecraft between October 10, 2003 and February 25, 2004. Figure 1a shows its trajectory in the XY plane in the Geocentric Solar Ecliptic (GSE) coordinate system. As we can see from Figure 1b, which depicts plasma and magnetic field measurements by Wind, through this time, there exist at least three strong geomagnetic storms (according to the Disturbance Storm Time (\( D_ST \)) Index), including the largest storm of the previous solar cycle [Farrugia et al., 2009]. During this event, one of the largest abrupt dynamic pressure drops was observed.

The goal of the present study is to analyze an interplanetary shock propagation through the solar wind to the Earth’s magnetosphere and to the far magnetotail. We present the example of evolution of two interplanetary shocks and their response in the magnetotail.

Observations

In our study, we demonstrate a propagation of two interplanetary (IP) shocks encountered in December 7, 2003 (Case 1) and January 22, 2004 (Case 2). In Figure 1b, we note these events as black squares in the \( X_{GSE} \) coordinate. The both cases were observed successively in the solar wind near the Lagrangian L1 point by two spacecraft (ACE,SOHO), in/near the magnetosheath by five spacecraft (Cluster 1–4, Geotail), on the Earth’s surface as changes of geomagnetic indices, and finally, in the far magnetotail (Wind).

Our analysis is based on calculation of local normals and velocities using the full set of the Rankine-Hugoniot (R-H) system of equations [Grib, 1982; Zhuang et al., 1981] and parameters
calculated from the locations and times of multipoint observations in the solar wind (so-called four-spacecraft method [Russell et al., 1983], further 4 s/c). The times of the shock arrivals in each region are determined by e.g. sharp changes of the magnetic field magnitude, plasma density, and solar wind velocity.

Response on the Earth’s surface can be evaluated through geomagnetic indices: from the AE index in the auroral zone to the equatorial region using the $D_{st}$ index. The ACE and Wind spacecraft were separated around 400 $R_E$ along the X-axis at this time. We calculated parameters of both shocks using R-H relations for ACE data, and using these results, we estimated the approximate time of the shock arrivals at Wind. We shifted data from Wind relatively to the ACE time of the IP shock arrival, in both cases to compare modifications of plasma parameters.

Case 1

On December 7, 2003 at 1341:27 UT, the ACE spacecraft, which was located near the L1 point, registered a fast forward IP shock. Later, this IP shock was registered by SOHO at 1401:15 UT at $(198.5, -79.6, 8.9)_{GSE} R_E$. Geotail orbiting tailward near the bow shock observed a relatively strong change of the solar wind parameters in comparison to ACE (Figure 2a). The shock arrival is marked by the vertical solid line. The four Cluster spacecraft located in the magnetosheath, in consequence of the IP shock arrival, crossed the bow shock (Figure 2b) temporarily. In this figure, we noted by vertical lines the shock time and the solar wind interval (which is bounded by two bow shock crossings). The locations of all spacecraft and shock arrival times are shown in Table 1.

Further, at 1417:18 UT, enhancements in geomagnetic indices were detected (last four panels in Figure 2a). The latest spacecraft observing this event was Wind in the magnetotail. The shock needed around 80 minutes to pass the distance between the L1 and L2 points. Data from Wind were shifted for this time to compare modifications of plasma flow, as it depicted in Figure 3 (in (a), these data are represented in high resolution in comparison to (b)). Here, we noted main regions in the tail using the vertical line (BL-boundary layer, MSH-magnetosheath),
Figure 2. (a) Geotail spacecraft measurements, from top to middle: \(V_x\) component of the solar wind velocity, proton density, thermal speed, magnitude of the magnetic field in the GSE coordinate system; response on surface of the Earth through geomagnetic indices: from middle to bottom: AE, SYM-H, ASY-H and \(D_s\) indices. (b) Cluster spacecraft data, from top to bottom: \(V_x\) component of the velocity and proton density at Cluster-4 and the magnetic field magnitude at Cluster-1/2/3/4.

determined similarly as by Slavin et al. [1985].

As we can see, all spacecraft saw clearly signatures of the IP shock, consequently these data were used to calculate the shock orientation and velocity. Table 2 shows obtained parameters of the event using R-H equations and the 4 s/c timing method. Prediction times of the shock arrival to Wind are shown in the last column.

Case 2

The second case shows a stronger fast forward IP shock observed on January 22, 2004. The event was first registered at 0102:37 UT at \((229.1, -40.3, 22.1)_{GSE} R_E\) by ACE and at 0110:15 UT, by SOHO near the L1 point. Further, it was observed more than half an hour later in

Table 1. Observation times of the IP discontinuity of the December 7, 2003 indicated by the spacecraft in the solar wind, magnetosphere, Earth’s surface and in far magnetotail (in the GSE coordinate system).

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Time of shock, [UT]</th>
<th>(X_{GSE}[R_E])</th>
<th>(Y_{GSE}[R_E])</th>
<th>(Z_{GSE}[R_E])</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>13:41:27</td>
<td>242.1</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>SOHO</td>
<td>14:01:15</td>
<td>198.5</td>
<td>-79.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Cluster 4</td>
<td>14:16:02</td>
<td>0.81</td>
<td>18.75</td>
<td>-1.15</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>14:16:04</td>
<td>0.80</td>
<td>18.75</td>
<td>-1.11</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>14:16:05</td>
<td>0.83</td>
<td>18.74</td>
<td>-1.12</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>14:16:05</td>
<td>0.83</td>
<td>18.76</td>
<td>-1.11</td>
</tr>
<tr>
<td>Ground</td>
<td>14:17:18</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Geotail</td>
<td>14:22:40</td>
<td>3.7</td>
<td>-24.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Wind</td>
<td>14:59:18</td>
<td>-232.8</td>
<td>-20.6</td>
<td>-17.5</td>
</tr>
</tbody>
</table>
the solar wind by the four Cluster spacecraft (first three panels in Figure 4a) and by Geotail in the plasmasheet (Figure 4b). We can assume (by magnetic field and plasma velocity data), that Geotail crossed probably the whole magnetosheath (MSH), twice the bow shock and spent in the solar wind (SW) around two minutes. We also see clear signatures of sudden impulse (the last three panels in Figure 4a) in geomagnetic indices. Finally, a strong disturbance in the distant magnetotail was observed by Wind at 0207:45 UT at (−210.2, 41.8, −2.4)\textsubscript{GSE} \textit{RE}.

The locations of all spacecraft and shock arrival times are shown in Table 3. Figure 5 presents parameters of plasma obtained by ACE (solid thin line in all panels) and Wind (bolded line). Here, as in the Case 1, we tried to identify some tail regions in far magnetotail. Further, we also, as in the Case 1, calculate the local and 4 s/c shock normals. Results are summarized in Table 4.

**Conclusion and Discussion**

In the paper, we present two observations of the IP shock propagating from the solar wind through the magnetosphere and distant magnetotail. These events were selected from the list

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**Table 2.** Parameters of the December 7, 2003 IP shock, calculated locally and using the 4 s/c method.

<table>
<thead>
<tr>
<th>December 7, 2003</th>
<th>n_x</th>
<th>n_y</th>
<th>n_z</th>
<th>V_x, km/s</th>
<th>Prediction shock time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>−0.406</td>
<td>−0.493</td>
<td>0.771</td>
<td>334</td>
<td>14:41:35</td>
</tr>
<tr>
<td>Geotail</td>
<td>−0.851</td>
<td>−0.526</td>
<td>−0.028</td>
<td>492</td>
<td>15:05:49</td>
</tr>
<tr>
<td>Wind</td>
<td>−0.178</td>
<td>0.657</td>
<td>0.732</td>
<td>173</td>
<td>14:59:18 (arrival time)</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Geotail/Wind)</td>
<td>−0.692</td>
<td>−0.708</td>
<td>−0.135</td>
<td>478</td>
<td>—</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Cluster-3/Wind)</td>
<td>−0.639</td>
<td>−0.684</td>
<td>−0.349</td>
<td>448</td>
<td>—</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Cluster-4/Geotail)</td>
<td>−0.637</td>
<td>−0.613</td>
<td>0.467</td>
<td>439</td>
<td>14:56:01</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Cluster-3/Geotail)</td>
<td>−0.653</td>
<td>−0.632</td>
<td>0.416</td>
<td>450</td>
<td>14:56:23</td>
</tr>
</tbody>
</table>
Figure 4. (a) Cluster-4 data (magnitude of the magnetic field, proton density, \(V_x\) component of the solar wind velocity) and geomagnetic indices (AE, SYM-H, ASY-H). (b) Geotail measurements, from top to bottom: \(V_x\) component of the solar wind velocity, proton density, thermal speed, magnitude and all components of the magnetic field.

We have shown propagation and modification of these IP shocks in each region, calculated shock normals by a single spacecraft and 4 s/c methods. For both events we have compare of

Table 3. Observation times of interplanetary discontinuities of the December 7, 2003 indicated by the spacecraft in the solar wind, magnetosphere, Earth’s surface and in far magnetotail (in the GSE coordinate system).

<table>
<thead>
<tr>
<th>Spacene</th>
<th>Time of shock, [UT]</th>
<th>(X_{GSE}[R_E] )</th>
<th>(Y_{GSE}[R_E] )</th>
<th>(Z_{GSE}[R_E] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>1:02:37</td>
<td>229.14</td>
<td>-40.27</td>
<td>22.09</td>
</tr>
<tr>
<td>SOHO</td>
<td>1:10:15</td>
<td>199</td>
<td>76.70</td>
<td>9.9</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>1:34:39</td>
<td>14.97</td>
<td>11.09</td>
<td>-5.22</td>
</tr>
<tr>
<td>Cluster 4</td>
<td>1:34:40</td>
<td>14.99</td>
<td>11.09</td>
<td>-5.25</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>1:34:41</td>
<td>14.99</td>
<td>11.07</td>
<td>-5.23</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>1:34:42</td>
<td>15.01</td>
<td>11.09</td>
<td>-5.21</td>
</tr>
<tr>
<td>Geotail</td>
<td>1:35:58</td>
<td>6.85</td>
<td>7.16</td>
<td>-2.17</td>
</tr>
<tr>
<td>Ground</td>
<td>1:36:18</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Wind</td>
<td>2:07:45</td>
<td>-210.23</td>
<td>41.76</td>
<td>-2.35</td>
</tr>
</tbody>
</table>

Table 4. Parameters of the January 22, 2004 IP shock calculated locally and using 4 s/c method.

<table>
<thead>
<tr>
<th>January 22, 2004</th>
<th>(n_x)</th>
<th>(n_y)</th>
<th>(n_z)</th>
<th>(\text{V}_{sh} ) km/s</th>
<th>Prediction shock time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>-0.936</td>
<td>0.183</td>
<td>0.3</td>
<td>717</td>
<td>2:04:44</td>
</tr>
<tr>
<td>Geotail</td>
<td>-0.939</td>
<td>-0.296</td>
<td>0.176</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Wind</td>
<td>-0.439</td>
<td>0.07</td>
<td>0.896</td>
<td>403</td>
<td>2:07:45(arrival time)</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Geotail/Wind)</td>
<td>-0.966</td>
<td>0.230</td>
<td>-0.114</td>
<td>728</td>
<td>—</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Cluster-4/Geotail)</td>
<td>-0.859</td>
<td>0.236</td>
<td>0.452</td>
<td>610</td>
<td>2:09:55</td>
</tr>
<tr>
<td>4 s/c (ACE/SOHO/Cluster-3/Geotail)</td>
<td>-0.88</td>
<td>0.239</td>
<td>0.409</td>
<td>628</td>
<td>2:09:41</td>
</tr>
</tbody>
</table>
Wind data with measurements by ACE to understand changes of plasma parameters at large distance of the tail region. In our two cases, we can conclude that the IP shock leads to compress of the Earth’s magnetotail (see several crossings of the tail regions after IP shock arrivals), and causes the whole geomagnetic tail tilt in accord with Owen et al. [1995] (changes the values and sign in the downstream magnetic field and velocity components).

In the event of January 22, 2004, we clearly see the strong shock (at 0103 UT in Figure 5) with a sharp enhancement of all parameters of the flow in each region. Prior to the shock arrival to Wind, we can distinguish some boundary layer (by drop density and thermal speed). \( V_y \) and \( V_z \) components of the plasma velocity in the plasmasheet abruptly changed its sign. Upstream and downstream \( V_y \) had similar values for both spacecraft and \( V_z \) changes from predominantly southward in upstream to northward in downstream. Prior to the IP shock arrival between 0101:40 UT and 0103 UT (Figure 5), we see an increase in the \( V_z \) component up to \(-800\) km/s. After the IP shock at 0103 UT, the Wind spacecraft passed again through a boundary layer (by increasing proton density and total magnetic field, thermal speed drop). We computed the time prediction of the shock arrival for the Wind spacecraft (see Table 4). Its time is in a good agreement with experimental data. We can conclude that shock normals, which were calculated using the ACE/SOHO/Cluster/Geotail spacecraft can take place and the shock can be considered planar on this scale.

The IP shock on December 7, 2003 was weak in comparison to one described above in each region. Therefore, the value of AE indices at the Earth’s surface rises up to 900 nT for Case 1 (Figure 2a) but to 1400 nT for Case 2 (Figure 4a). Here, as for the previous event, we also can separate the upstream region plasma sheet (by increased proton density, thermal velocity, boundary layer (by decreased density, enhancement total magnetic field). In the downstream region, the Wind spacecraft crossed some boundary layer region (in which IP shock occurred at 1339:24 UT in Figure 3) and passed to the magnetosheath (as we can see by well correlated ACE/Wind plasma data in this time). The plasma velocity components in the
whole upstream region were duskward ($V_y$), southward ($V_z$). In the downstream region, they changed to dawnward and northward, respectively. The time prediction of the shock for the Wind spacecraft (Table 2) is in a good agreement with experimental data. In the boundary layer region indicated, the $V_x$ velocity component rises to $-850$ km/s suggesting a strong anti-earthward burst flow of plasma (started at 1337:25 UT and ended at 1338:48 UT in Figure 3), which could be caused by the IP shock traveling through the magnetotail and the reconnection process taken place. A similar burst was observed in far tail also by Farrugia et al. [2009]. This tailward flow burst was associated with negative variations in the magnetic field ($B_x \simeq 20$ nT and $B_z \simeq 10$ nT). The shock normals, which were calculated using the 4 s/c method including the Wind spacecraft differ in the sign of the Z-coordinate to comparison to the shock normals obtained from ACE/SOHO/Cluster/Geotail in both events. Due to the small $\Delta Z_{GSE}$ differences in positions of the spacecraft (in comparison to the $\Delta X_{GSE}$ difference), this normal coordinate cannot be determined reliably, but fortunately, the IP shock normals were lying near the ecliptic plane.

So, we can conclude that:

- Parameters of the plasma flow (density and velocity of the solar wind) are well correlated in upstream/downstream region near the L1 point by the ACE to Wind spacecraft near the L2 point (see Figure 3b and Figure 5b) in a wide range of times.
- In both cases, the plasma velocity at the Wind spacecraft abruptly increased at 1–2 minutes before the IP shock arrival. Probably this effect is associated with the tailward flow burst or some other phenomena in the far magnetotail.
- During the IP shock, propagation at long distance can save its nearly planar structure.
- Disturbance in the solar wind or magnetotail flow (e.g., IP shock) can significantly affect boundaries of the magnetotail at distances more than $-200$ RE and can change the flow directions in the YZ plane. Possible tailward plasma flow burst can be triggered by the IP shock passage through the far tail.

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**References**


