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Key Points:
- Under low solar wind Mach number conditions, the Chapman-Ferraro current does not exert a force on the solar wind
- The bow shock always exerts a force on the solar wind, and sometimes, this force is the dominant force in the system

Correspondence to:
R. E. Lopez,
relopez@uta.edu

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Magnetospheric balance of solar wind dynamic pressure

Ramon E. Lopez[1] and Walter D. Gonzalez[2]

[1]Department of Physics, University of Texas at Arlington, Arlington, Texas, USA, [2]National Institute of Space Research, São José dos Campos, Brazil

Abstract The magnetopause is the boundary established by pressure balance between the solar wind flow in the magnetosheath and the magnetosphere. Generally, this pressure balance is represented to be between the solar wind, the dynamic pressure, and the magnetic pressure of Earth's dipole field. The plasma actually in contact with the magnetosphere is the slowed, compressed, and heated solar wind downstream of the shock. The force exerted on the magnetosheath plasma is the $\boldsymbol{J} \times \boldsymbol{B}$ force produced by the Chapman-Ferraro current that flows on the magnetopause. Under typical solar wind conditions of relatively high magnetosonic Mach number flow (>6), this simple picture is a reasonable description of the situation. However, under conditions of low solar wind magnetosonic Mach number flow (~2) the force on the solar wind plasma is not exerted at the magnetopause and must be exerted at the bow shock by currents that connect to the Region 1 currents. In this paper we present observations from two magnetopause crossings observed by the Time History of Events and Macroscale Interactions during Substorms spacecraft to compare and contrast the force balance with the solar wind for two situations with very different solar wind magnetosonic Mach numbers.

Plain Language Summary When the solar wind hits Earth's magnetic field, the magnetic field pushes back on the solar wind. Typically, this force is exerted at the boundary between Earth's magnetic field and the solar wind. However, when the supersonic solar wind has a low Mach number (about 2, as opposed to the typical value of >6), the place where the force is exerted on the solar wind is at the bow shock wave in front of Earth. This force is produced by an electric current that flows on the bow shock and which connects to currents that flow directly into Earth's ionosphere in the polar regions. This paper presents spacecraft observations documenting this unusual situation.

1. Introduction

The location of the magnetopause is determined by the pressure balance between the solar wind and the magnetosphere, and the topic is a fairly basic issue that is addressed in textbooks and reviews [e.g., *Kivelson and Russell*, 1995; *Gonzalez and Parker*, 2015]. It is generally represented as a balance between the external solar wind dynamic pressure and the magnetic pressure inside the magnetosphere, since typically, the magnetospheric plasma pressure is small, and given a typical Alfvén Mach number of 8 in the solar wind, the flow energy density is 64 times the solar wind magnetic energy density. In this picture, the force on the shocked solar wind in the magnetosheath is basically the $\boldsymbol{J} \times \boldsymbol{B}$ force produced by the Chapman-Ferraro current that confines the geomagnetic field inside the magnetosphere. In the simplest conceptual model for the magnetospheric cavity there is no interplanetary magnetic field (IMF), outside the magnetopause the geomagnetic field is excluded, inside the magnetopause the field is compressed relative to the dipole field, and the Chapman-Ferraro current flows just inside the magnetopause, closing on itself.

This simple picture provides a good estimate for the magnetopause position, though the presence of a southward IMF complicates the picture. The merging interaction and the Region 1 current result in a weakening of the dayside field. The magnetopause then moves in to a point where pressure balance with the solar wind is restored [e.g., *Wiltberger et al.*, 2003]. This IMF-induced inward motion of the magnetopause is called magnetopause erosion, and the amount of erosion depends on the magnitude of the southward IMF [*Sibeck et al.*, 1991].

As the solar wind moves across the bow shock, it is compressed and heated, and a current flows along the shock consistent with the compression of the field across the shock. This current is always a generator current that exerts an outward force on the solar wind [*Siebert and Siscoe*, 2002; *Lopez et al.*, 2010] and converts some of the solar wind mechanical energy into electromagnetic energy as the solar wind flows across the shock.

Part of this electromagnetic energy generated at the shock is dissipated in reconnection at the dayside [*Siebert and Siscoe*, 2002] and in the magnetotail [*Tang et al*., 2009], as well as by ionospheric Joule heating [*Lopez et al*., 2011]. The bow shock current closes in part through the Region 1 and magnetopause boundary currents, and these currents flow across the magnetosheath to connect to the shock [*Lopez et al*., 2008, 2011]. The $\boldsymbol{J} \times \boldsymbol{B}$ force in the magnetosheath, along with the pressure gradient force, accelerates the magnetosheath flow back to solar wind speeds, so that the bulk of the kinetic energy in the solar wind extracted at the shock is returned to the magnetosheath flow as it rejoins the solar wind [*Lopez et al*., 2010, 2011].

Consider a case of solar wind flow with purely southward IMF. As the magnitude of the negative B_z component of the IMF becomes larger, the solar wind Mach number can become very low, and under these conditions the magnetosphere enters a different state [*Lavraud and Borovsky*, 2008; *Borovsky et al*., 2009; *Lopez et al*., 2010] in which convection and the amount of open flux saturate [*Siscoe et al*., 2002, 2004; *Lopez et al*., 2009, 2010]. Simulations [*Siscoe et al*., 2002; *Lopez et al*., 2010] and observations [*Lopez et al*., 2008; *Tang et al*., 2012] indicate that a substantial amount of the Region 1 current flows on open field lines, where it can connect directly to the bow shock current [*Lopez et al*., 2011]. The bow shock current becomes the primary generator current in the system [*Lopez et al*., 2011], and it has been proposed that the Region 1 current exerts the primary force to stand off the solar wind [*Siscoe et al*., 2002; 2004; *Siscoe*, 2006]. In fact, it has been argued that the Chapman-Ferraro current disappears as its role in force balance with the solar wind is completely usurped by the Region 1 current [*Siscoe*, 2006].

In this paper, we examine two magnetopause crossings observed by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft. In one case, the solar wind magnetosonic Mach number was 5.3, which is smaller than typical but large enough that the magnetosheath flow is still dominated by the plasma pressure gradients and that most of the solar wind kinetic energy is converted into plasma thermal energy at the shock. In the second case we have a very low magnetosonic Mach number situation (approximately 2) in which the electromagnetic forces are dominant at the shock and throughout the magnetosheath, and in this case most of the solar wind kinetic energy is converted into magnetic energy. These observations will allow us to determine the nature of the force balance at the magnetopause for low Mach number solar wind as contrasted with a high Mach number solar wind.

2. The 13 January 2013—A Typical Case

The OMNI data for the magnetopause crossing on 13 January 2013 are presented in Figure 1. From 1300 UT to 1400 UT the solar wind was in a typical state, with moderate values of the plasma and magnetic field. The solar wind magnetosonic Mach number was a bit on the lower side, around 5.3, but this means that the solar wind flow energy density was still more that 25 times the sum of the thermal and magnetic energy densities. Moreover, the bulk of the solar wind energy density was converted to plasma thermal energy at the shock, and the plasma pressure gradient was the dominant force on the magnetosheath flow. From the discussion in section 1, we would expect this case to fall into the typical situation in which the Chapman-Ferraro current balances the solar wind pressure, compressing the dayside magnetic field.

Figure 2 presents magnetic field data from THEMIS E, which was on the dayside near noon from 1300 to 1400 UT, during which time the dipole tilt angle was about 14°. The spacecraft was outbound but near apogee and moving slowly. From 1340 UT to 1400 UT it only moved in radial distance from 9.92 R_E to 10.15 R_E. Throughout most of the hour, the field at THEMIS E was northward and steady, with B_z about 65 nT, indicating that THEMIS E remained in the magnetosphere. The value for B_x was about −20 nT, consistent with the spacecraft GSM Z coordinate of about 3 R_E. The dipole field value at the THEMIS E position for B_z was 31 nT; thus, the observed field was roughly double the dipole field value, as expected from the classical Chapman-Ferraro interaction scenario. At 1352:13 UT the spacecraft crossed the magnetopause at SM coordinates (9.73, −2.47, and 0.69) in R_E, so it was close to the geomagnetic equator at 1104 magnetic local time (MLT). The B_z value in the magnetosheath was −30 nT, which is roughly consistent with the compression of the −5 nT value in the IMF at that time. The transition from the magnetospheric B_z of 62.17 nT at 13:51:58.702 UT to the magnetosheath B_z of −28.86 nT at 13:52:16.767 UT took about 18 s.

Inspecting the solar wind data in Figure 1, since the solar wind dynamic pressure was fairly constant, it is likely that the inward motion of the magnetopause was driven by enhanced erosion [e.g., *Wiltberger et al*., 2003]

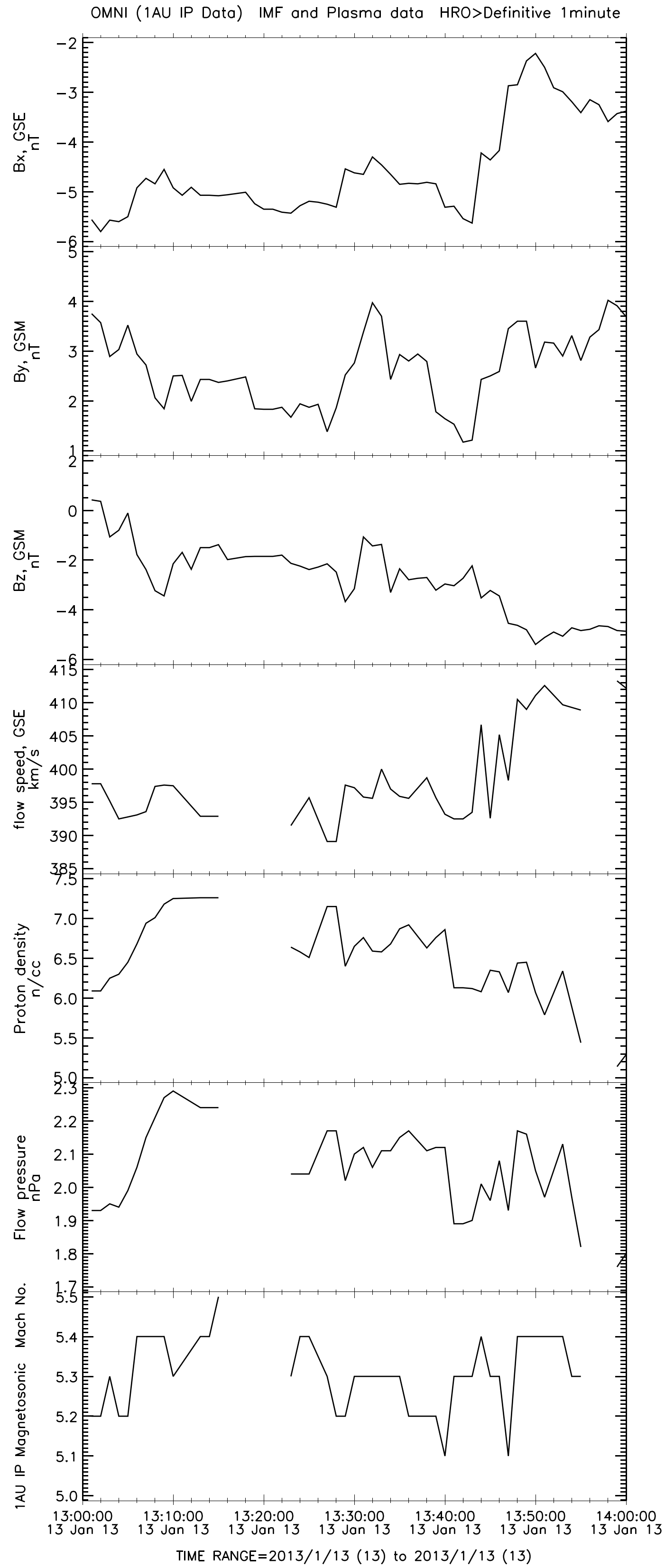

Figure 1. OMNI data for 13 January 2013. After 1330 UT the plasma pressure was roughly constant, but the magnitude of the negative B_z increased.

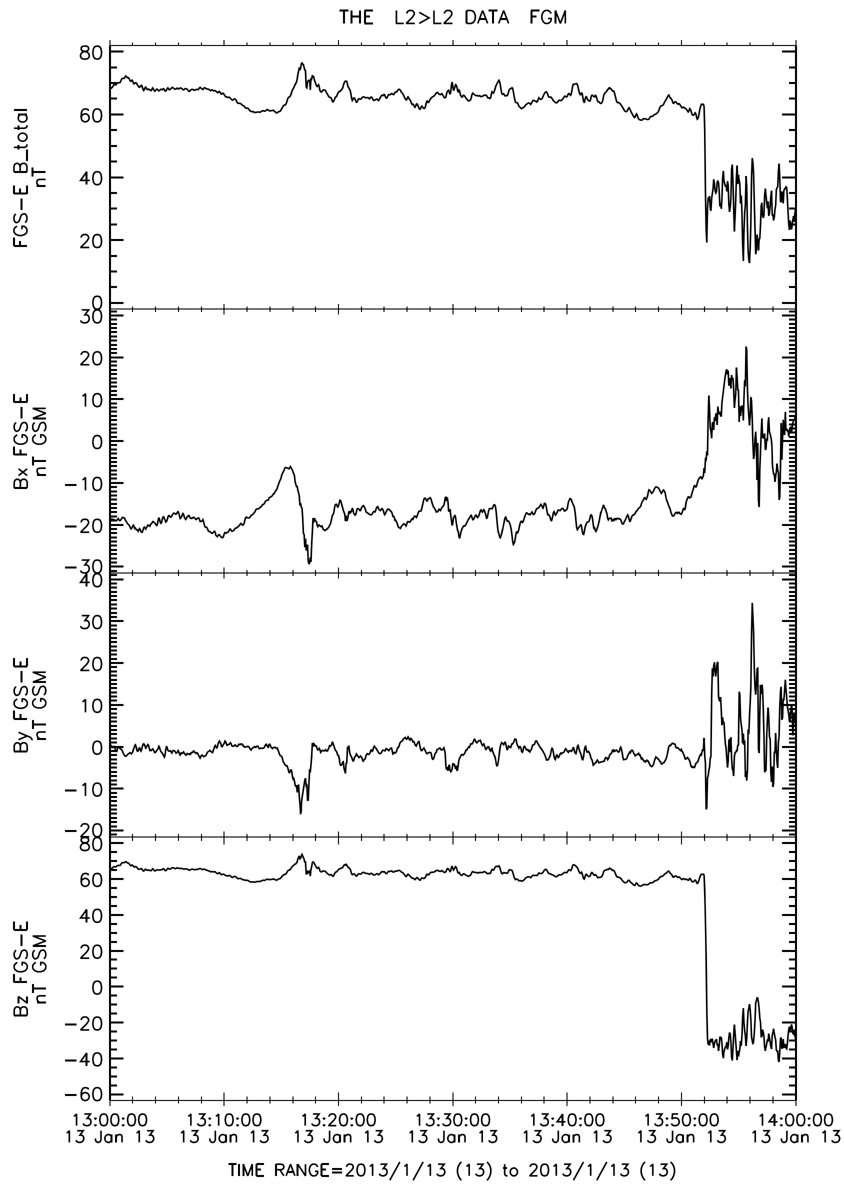

Figure 2. Magnetic field data from THEMIS E on 13 January 2013. The crossing of the magnetopause is evident around 1352 UT.

due to the larger southward IMF after 1345 UT. In fact, the average magnetic field magnitude from 1342 to 1344 UT was 66 nT compared to the average of 62.7 nT from 1349 to 1351 UT. We can directly compare the plasma pressures inside and outside the magnetosphere using the onboard moments calculated from the electrostatic analyzer and solid-state telescope data (available at the CDAWeb along with the THEMIS magnetic field data).

The plasma pressure (ion + electron) measured by THEMIS E in the magnetosphere just before the crossing (averaged over 1347:58.803 UT to 1349:25.517 UT) was 0.16 nPa, while in the magnetosheath just after the crossing (averaged over 1355:05.147 UT to 1356:39.087 UT) the plasma pressure was 1.52 nPa. The corresponding average values of the magnetic field magnitude for essentially the same time periods were 63.97 nT (1.63 nPa) and 33.2 nT (0.44 nPa). The slightly larger total magnetosheath pressure (1.96 nPa) as compared to the magnetosphere pressure (1.79 nPa) is consistent with the inward motion of the magnetopause. The magnetosheath pressure is consistent with the approximately 2 nPa dynamic pressure of the solar wind in the OMNI data.

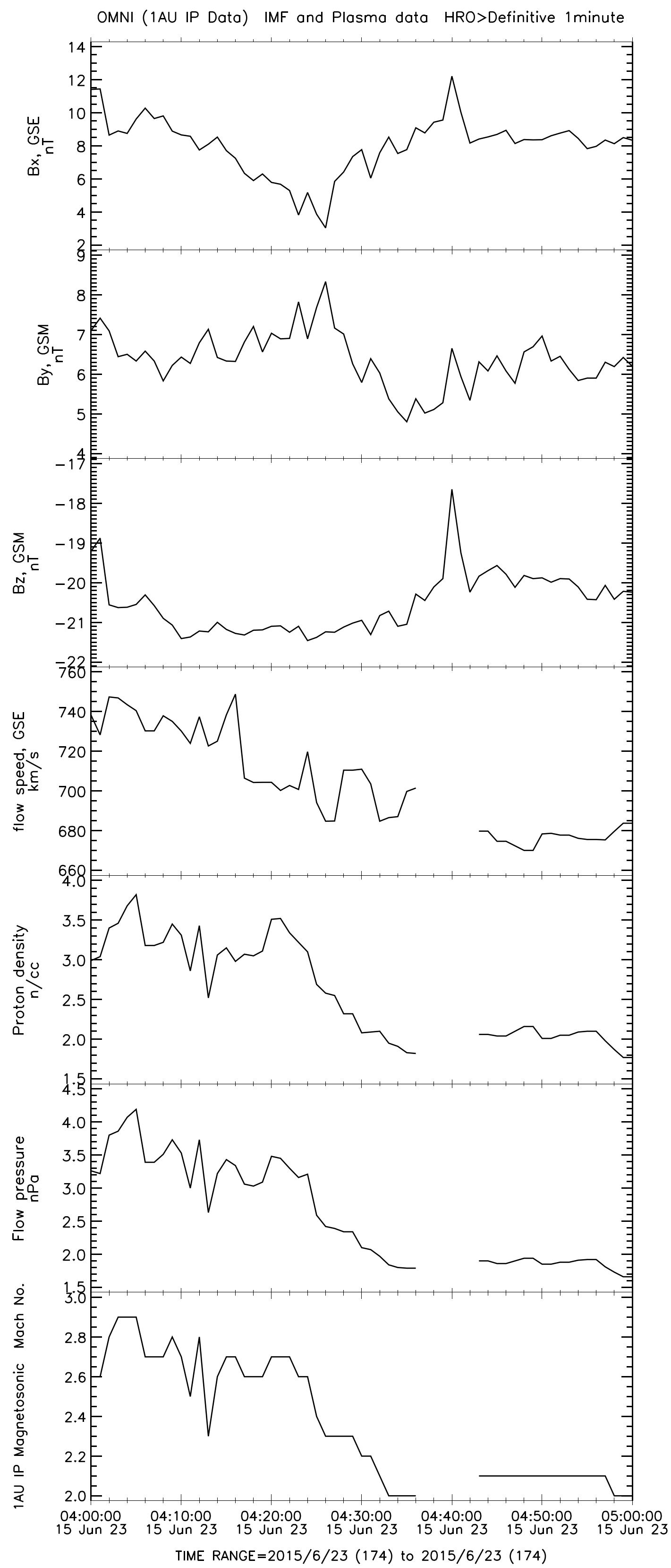

Figure 3. OMNI data for 23 June 2015. After 0422 UT, the solar wind dynamic pressure decreased and continued to do so until 0436 UT (at least).

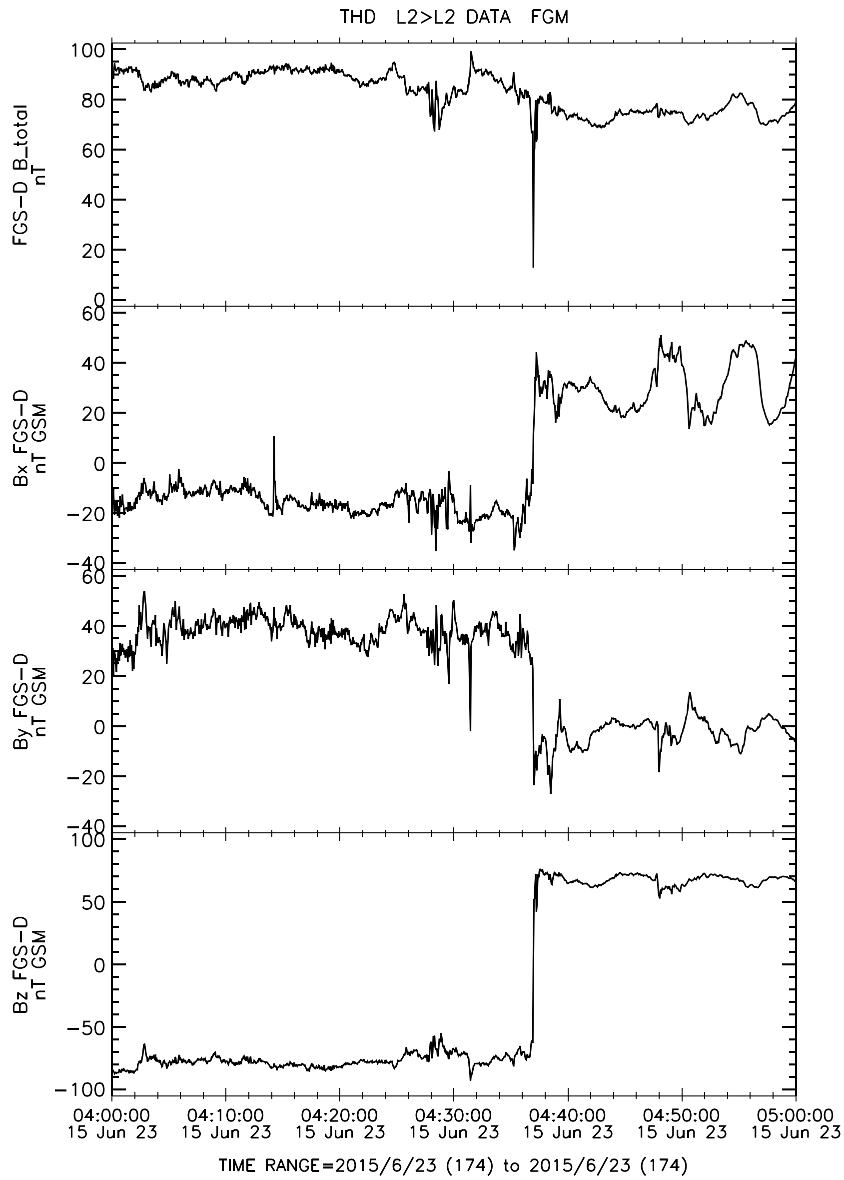

Figure 4. Magnetic field data from THEMIS D on 23 June 2015. The crossing of the magnetopause is evident around 0437 UT.

3. The 23 June 2015—A Low Solar Wind Mach Number Case

The OMNI data for the magnetopause crossing on 23 June 2015 are presented in Figure 3. From 0400 UT to 0500 UT the IMF was strongly southward (and had been since 0200 UT), and as in the previous case the solar wind dynamic pressure was moderate, beginning at around 3.5 nPa and decreasing to about 2 nPa for the last half of the hour. At 0430 UT the magnetosonic Mach number went to about 2 (or below) and stayed there the rest of the hour. Such a low Mach number solar wind state was observed only 0.3% of the time from 1 January 2013 to 1 January 2016. During such a situation, the bulk of the solar wind kinetic energy is converted into magnetic energy at the shock and the $\boldsymbol{J} \times \boldsymbol{B}$ force is the dominant force on the magnetosheath flow [*Lopez et al.*, 2010].

THEMIS D was inbound on the dayside near noon during this hour moving 0.19 R_E (from 7.94 R_E to 7.75 R_E) in the time period from 0430 UT to 0440 UT. The magnetosphere expanded due to the decreasing solar wind pressure in the middle of the hour, which produced the magnetopause crossing at THEMIS D.

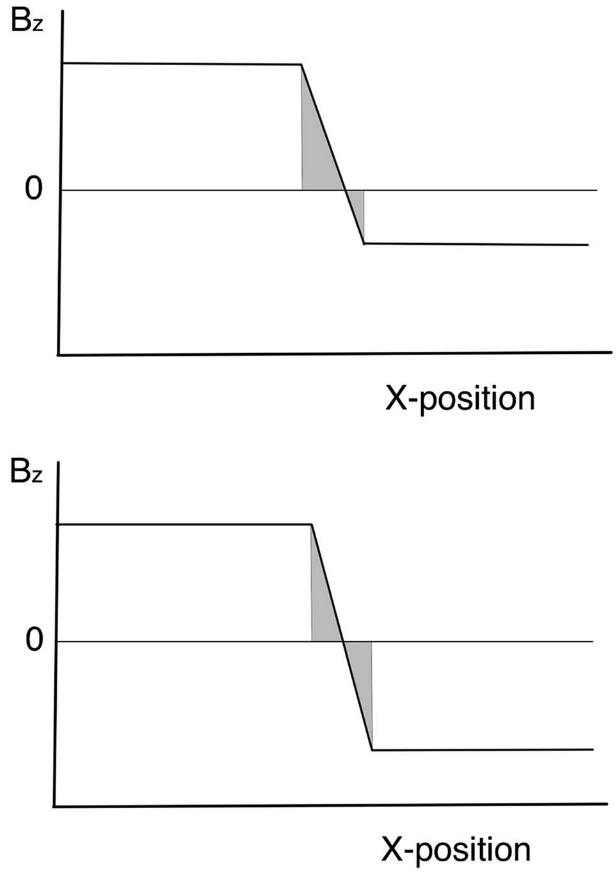

Figure 5. A schematic showing the value of B_Z at noon in the equatorial plane along the X axis (toward the Sun to the right). The point where B_Z goes through zero is the magnetopause. The shaded grey region shows the distribution of a uniform Chapman-Ferraro current across the magnetopause in the positive Y direction. (top) The conditions on 13 January 2013, during which the Chapman-Ferraro current was mostly flowing inside the magnetosphere. (bottom) The conditions on 23 June 2015, during which the current was centered on the transition from magnetospheric field to magnetosheath field.

Figure 4 shows the magnetometer data with the magnetopause crossing at 0436:58 UT, at which time all three components of the field reversed direction. At the crossing of the magnetopause the magnetic field magnitude dropped to 12.89 nT for a single point spike in the 3 s, spin-averaged magnetometer data (higher temporal resolution data were not available). The brief excursion in |**B**| is easily understood. If we take a simple case of purely negative B_z in the magnetosheath and purely positive B_z in the magnetosphere, as you cross from one region to the other, the field magnitude at some point B_z will go to zero. Of course, in this case the magnetic field was more complicated with components in the Y and Z directions as well. However, those components of the field also reverse direction around the same point, so with all of the components of the field going through zero at nearly the same point, there is for one data point a sharp drop in the magnitude of the field. It appears that THEMIS D crossed the magnetopause very close to a real neutral point.

At 0437 UT, THEMIS D was at SM coordinates (7.74, −0.96, and −0.62), so the spacecraft was close to the magnetic equator and near noon at 1131 MLT. The dipole-L value of 7.8 indicates that the B_z component in the magnetosphere should be about 62 nT. The observed average value of B_z from 0439:04 to 0440:30 UT was 67.97 nT, indicating that there was almost no compression of the dayside field. Moreover, the B_z just outside the magnetosphere (from 0434:33 UT to 0435:52 UT) was −72.51 nT. From 0430 UT to 0433 UT it had been −76.7 nT, and this steady decrease in the magnetosheath field is consistent with the reduction of the solar wind flow pressure and the outward motion of the magnetopause.

The plasma pressure played essentially no role in establishing the magnetopause position since the average total plasma pressure in the magnetosheath (from 0434:33 UT to 0435:52 UT) was only 0.36 nPa, and the magnetosheath was dominated by the magnetic pressure of 2.09 nPa. Inside the magnetosphere (from 0439:04 to 0440:30 UT) the magnetic pressure was 1.84 nPa and the plasma pressure was 0.34 nPa, almost the same as in the magnetosheath. This lower magnetosphere total pressure is consistent with a reduction in the solar wind dynamic pressure in the OMNI data. One final point is that in the 3 s interval in the plasma data nearest to that at 0436:58 when the magnetic field magnitude dropped to 12.89 nT (0.07 nPa), the sum of the ion and electron pressures spiked up to 1.64 nPa for a total pressure of 1.71 nPa. The integration times do not line up exactly, so there is some time aliasing in the total pressure calculation; however, these numbers are consistent with a current sheet centered on the field reversal region.

4. Discussion and Conclusion

In the two cases presented in this paper we see very different situations of pressure balance across the magnetopause. In both cases the spacecraft were moving slowly, and if the satellites had cross a stationary magnetopause, it would mean that the current would be 22 km thick on 13 January 2013 and 12.8 km thick on 23 June 2015. Since the observed thickness of the magnetopause current is 400–1000 km [*Berchem and Russell*, 1982], the rapid change in the magnetic topology means that the magnetopause moved over the spacecraft, consistent with the expected magnetopause motion given the changing solar wind conditions in each case. The 13 January 2013 magnetopause crossing showed a typical case in which the plasma pressure in the magnetosheath was roughly balanced by the magnetic pressure of the magnetosphere, and the magnetospheric field was compressed by the Chapman-Ferraro current. Since the magnetosonic Mach number was moderate (5.3), the magnetic pressure in the magnetosheath played a role, though the plasma pressure was still dominant. In contrast, the magnetosheath during the 23 June 2015 event was completely dominated by the magnetic pressure and the magnetospheric field was not much compressed relative to the undisturbed dipole field.

A Chapman-Ferraro current existed in both events, though the dynamics involved were different. If we consider the field to be uniform on either side of the magnetopause (as it was essentially observed to be), the current can be simply modeled as a uniform current sheet of finite thickness over which the field change occurs. This situation is illustrated in Figure 5 for a situation in which we only consider B_z and neglect the other components (the same arguments would apply to any IMF orientation). The current in each case is flowing perpendicular to the magnetic field in the positive Y direction in both the magnetosphere and magnetosheath. The portion of the current in the magnetosheath closes on the bow shock, along with part of the Region 1 current [*Siebert and Siscoe*, 2002; *Lopez et al*., 2011], and it was referred to by *Vasyliūnas* [2011] as the "exterior Chapman-Ferraro current." The magnitude of the uniform current density $\boldsymbol{J}$ depends on the thickness of the current sheet and the change in the field across it. The outward force per unit area produced by the $\boldsymbol{J}\times\boldsymbol{B}$ force is just the integral across the layer of a constant value of current times the value of B_z; hence, it is the sum of the areas shaded in grey, where positive and negative areas cancel. It is this outward pressure that ultimately balances the dynamic pressure of the solar wind in the classic picture.

In the case of the 13 January 2013 event, the bulk of the Chapman-Ferraro current was flowing in the magnetosphere where the field is northward so that there is a net outward pressure from the $\boldsymbol{J}\times\boldsymbol{B}$ force. Using the observed values, we estimate that this outward pressure at the THEMIS E position was 1.1 nPa, about 50% of the solar wind dynamic pressure. For the 23 June 2015, the current was evenly distributed, with half on the magnetospheric side and half on the magnetopause side and the center of the current sheet was at the point at which the field reversed direction. Thus, in this case the Chapman-Ferraro current did not produce any net force. However, this does not mean that the Chapman-Ferraro current vanished [e.g., *Siscoe*, 2006] since the curl of **B** was not zero across the magnetopause. The Chapman-Ferraro current was still there, but it provided no net force on the magnetosheath plasma.

If the Chapman-Ferraro current exerts roughly half of the required force to balance the solar wind pressure as in the 13 January 2013 case, or essentially no force at all as in the 23 June 2015 case, then where and how is the force on the solar wind exerted? It must be at the bow shock, where there is always an outward $\boldsymbol{J}\times\boldsymbol{B}$ force [e.g., *Lopez et al*., 2010]. In the case of high Mach number solar wind, the pressure gradient is the dominant force in the magnetosheath and most of the solar wind kinetic energy goes into the thermal energy of the plasma. But in the case of low Mach number solar wind, irrespective of the orientation of the solar wind [e.g., *Mitchell et al*., 2010; *Bhattarai et al*., 2012], the dominant force is the $\boldsymbol{J}\times\boldsymbol{B}$ force and the solar wind flow does work against this force, converting most of the solar wind kinetic energy into magnetic energy, producing a low beta magnetosheath. In the 23 June 2015 case, the magnetic energy density of the magnetosheath just outside of the magnetopause was essentially the same as in the magnetosphere just inside of the magnetopause, and the plasma pressures on either side of the magnetopause were negligible. This led to a situation where almost all of the force balance against the solar wind dynamic pressure had to be affected at the bow shock by the bow shock current.

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References

Berchem, J., and C. T. Russell (1982), The thickness of the magnetopause current layer: ISEE 1 and 2 observations, *J. Geophys. Res.*, *87*(A4), 2108–2114.

Bhattarai, S. K., R. E. Lopez, R. Bruntz, J. G. Lyon, and M. Wiltberger (2012), Simulation of the polar cap potential during periods with northward interplanetary magnetic field, *J. Geophys. Res.*, *117*, A04219, doi:10.1029/2011JA017143.

Borovsky, J. E., B. Lavraud, and M. M. Kuznetsova (2009), Polar cap potential saturation, dayside reconnection, and changes to the magnetosphere, *J. Geophys. Res.*, *114*, A03224, doi:10.1029/2009JA014058.

Gonzalez, W. D., and E. N. Parker (2015), *Magnetic Reconnection: Concepts and Applications*, Springer, New York.

Kivelson, M. G., and C. T. Russell (Eds.) (1995), *Introduction to Space Physics*, Cambridge Univ. Press, Cambrige.

Lavraud, B., and J. E. Borovsky (2008), Altered solar wind-magnetosphere interaction at low Mach numbers: Coronal mass ejections, *J. Geophys. Res.*, *113*, A00B08, doi:10.1029/2008JA013192.

Lopez, R. E., S. Hernandez, K. Hallman, R. Valenzuela, J. Seiler, P. Anderson, and M. Hairston (2008), Field-aligned currents in the polar cap during saturation of the polar cap potential, *J. Atmos. Sol. Terr. Phys.*, *70*, 555–563, doi:10.1016/j.jastp.2007.08.072.

Lopez, R. E., J. G. Lyon, E. Mitchell, R. Bruntz, V. G. Merkin, S. Brogl, F. Toffoletto, and M. Wiltberger (2009), Why doesn't the ring current injection rate saturate?, *J. Geophys. Res.*, *114*, A02204, doi:10.1029/2008JA013141.

Lopez, R. E., R. Bruntz, E. J. Mitchell, M. Wiltberger, J. G. Lyon, and V. G. Merkin (2010), The role of magnetosheath force balance in regulating the dayside reconnection potential, *J. Geophys. Res.*, *115*, A12216, doi:10.1029/2009JA014597.

Lopez, R. E., V. G. Merkin, and J. G. Lyon (2011), The role of the bow shock in solar wind-magnetosphere coupling, *Ann. Geophys.*, *29*, 1129–1135, doi:10.5194/angeo-29-1129-2011.

Mitchell, E. J., R. E. Lopez, R. Bruntz, M. Wiltberger, J. G. Lyon, R. C. Allen, S. J. Cockrell, and P. L. Whittlesey (2010), Saturation of transpolar potential for large *Y* component interplanetary magnetic field, *J. Geophys. Res.*, *115*, A06201, doi:10.1029/2009JA015119.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof (1991), Solar wind control of magnetopause shape, location, and motion, *J. Geophys. Res.*, *96*, 5489–5495, doi:10.1029/90JA02464.

Siebert, K. D., and G. L. Siscoe (2002), Dynamo circuits for magnetopause reconnection, *J. Geophys. Res.*, *107*(A7), 1095, doi:10.1029/2001JA000237.

Siscoe, G. L. (2006), Global force balance of region 1 current system, *J. Atmos. Solar-Terr. Phys.*, *68*(18), 2119–2126.

Siscoe, G. L., N. U. Crooker, and K. D. Siebert (2002), Transpolar potential saturation: Roles of Region 1 current system and solar wind ram pressure, *J. Geophys. Res.*, *107*(A10), 1321, doi:10.1029/2001JA009176.

Siscoe, G., J. Raeder, and A. J. Ridley (2004), Transpolar potential saturation models compared, *J. Geophys. Res.*, *109*, A09203, doi:10.1029/2003JA010318.

Tang, B. B., X. C. Guo, C. Wang, Y. Q. Hu, and J. R. Kan (2009), Bow shock and magnetopause contributions to the cross-tail current from global MHD simulations, *J. Geophys. Res.*, *114*, A08203, doi:10.1029/2009JA014325.

Tang, B. B., C. Wang, and X. C. Guo (2012), Bow shock and magnetopause contributions to the magnetospheric current system: Hints from the Cluster observations, *J. Geophys. Res.*, *117*, A01214, doi:10.1029/2011JA016681.

Vasyliūnas, V. M. (2011), Physics of magnetospheric variability, *Space Sci. Rev.*, *158*(1), 91–118.

Wiltberger, M., R. E. Lopez, and J. G. Lyon (2003), Magnetopause erosion: A global view from MHD simulations, *J. Geophys. Res.*, *108*(A6), 1235, doi:10.1029/2002JA009564.