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Global Magnetospheric Response to an Interplanetary Shock: THEMIS Observations

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Abstract.

We investigate the global response of geospace plasma environment to an interplanetary shock at ∼0224 UT on May 28, 2008 from multiple THEMIS spacecraft observations in the magnetosheath (THEMIS B and C) and the mid-afternoon (THEMIS A) and dusk magnetosphere (THEMIS D and E). The interaction of the transmitted interplanetary shock with the magnetosphere has global effects. Consequently, it can affect geospace plasma significantly. After interacting with the bow shock, the interplanetary shock transmitted a fast shock and a discontinuity which propagated through the magnetosheath toward the Earth at speeds of 300 km/s and 137 km/s respectively. THEMIS A observations indicate that the plasmaspheric plume changed significantly by the interplanetary shock impact. The plasmaspheric plume density increased rapidly from 10 to 100 cm^{-3} in 4 min and the ion distribution changed from isotropic to strongly anisotropic distribution. Electromagnetic ion cyclotron (EMIC) waves observed by THEMIS A are most likely excited by the anisotropic ion distributions caused by the interplanetary shock impact. To our best knowledge, this is the first direct observation of the plasmaspheric plume response to an interplanetary shock's impact. THEMIS A, but not D or E, observed a plasmaspheric plume in the dayside magnetosphere. Multiple spacecraft observations indicate that the dawn-side edge of the plasmaspheric plume was located between THEMIS A and D (or E).

Keywords. Interplanetary shock, magnetospheric response to shocks, sudden impulses, EMIC wave, plasmaspheric plume

1 Introduction

The interaction of interplanetary shocks (usually fast forward shocks) with the magnetosphere includes several phases, including interaction with the bow shock, transmission through the magnetosheath, interaction with the magnetopause, transmission into the magnetosphere as fast and intermediate mode waves, modifications of the field-aligned and ionospheric current systems, and perturbations in ground magnetograms (Samsonov et al., 2007). The interaction of interplanetary shocks with the bow shock has been extensively studied (e.g., Shen and Dryer, 1972; Grib et al., 1979; Zhuang et al., 1981; Samsonov et al., 2006, 2007; Zhang et al., 2009). In MHD simulations, the interaction of an interplanetary shock with the bow shock launches a fast shock into the magnetosheath and creates a new discontinuity (Zhuang et al., 1981) where the magnetic field strength and density increase, the temperature decreases and the velocity remains unchanged (Samsonov et al., 2006). The transmitted fast shock and new discontinuity have been observed (Šafránková et al., 2007; Přech et al., 2008).

Past work has predicted that the interaction of an interplanetary shock marked by a pressure increase with the bow shock results in earthward then sunward motion of the bow shock. By analyzing the Rankine-Hugoniot conditions, Grib et al. (1979) and Völk and Auer (1974) predicted that the bow shock moves towards the magnetosphere after interaction with the interplanetary shock. Then the interaction of the transmitted fast shock and the magnetopause (considered a tangential discontinuity) results in a fast rarefaction wave propagating toward the bow shock. This rarefaction wave could result in outward bow shock motion. In MHD simulations, the bow shock begins moving earthward immediately after an encounter with an interplanetary shock at velocities of $\sim$100 km/s (Samsonov et al., 2006). Results from a three-dimensional magnetosheath numerical model show that both a fast reverse shock and a fast expansion wave (rarefaction wave) may result from the interaction of the interplanetary shock with the magnetopause depending on boundary conditions of the model (Samsonov et al., 2006). The existence of the rarefaction wave reflected from the magnetopause due to the shock-magnetopause interaction was confirmed by a case study employing observations made by Cluster spacecraft in the magnetosheath (Maynard et al., 2008). Based on results from global MHD simulations, Samsonov et al. (2007) suggested that the dayside ionosphere reflects the transmitted fast shock and that the bow shock and the magnetopause move sunward when the reflected fast shock passes. Earthward then sunward bow shock motion due to the interaction of an interplanetary shock with the bow shock has been observed (e.g., Šafránková et al., 2007). Šafránková et al. (2007) concluded that the observed bow shock crossings result from the interplanetary shock-magnetosphere interactions because there are no further changes in the upstream dynamic pressure or IMF that could cause them.

Enhanced solar wind pressure behind a shock front compresses the magnetopause, resulting an enhancement of the Chapman-Ferraro current at the magnetopause. This interaction launches a fast magnetosonic wave that propagates to the ionosphere. Typically, low-latitude magnetometers record rapid increase in the northward magnetic field, called sudden impulses (SI), or storm sudden commencements (SSC) if a geomagnetic storm follows (Tamao, 1975; Araki, 1977; Huttunen et al., 2005). In addition to the inward propagation there is a field-aligned propagation of Alfvén waves due to the shock impact, changing the ionospheric currents, and causing auroral activity (Zhou and Tsurutani, 1999).

Electromagnetic ion cyclotron (EMIC) waves are generated by the ion temperature anisotropy ($T_\perp > T_\|$) (e.g., Cornwall, 1965). The frequencies of EMIC waves are below the local proton gyrofrequency. In the magnetosphere, the frequency of the EMIC waves ranges from 0.1 to 5 Hz. There is a strong emission below the helium gyrofrequency (Young et al., 1981; Roux et al., 1982; Anderson et al., 1992). EMIC waves are often observed in the outer magnetosphere beyond L = 7 (Anderson et al., 1990, 1992). EMIC waves have been found to be often associated with compressions (Anderson and Hamilton, 1993; Engebretson et al., 2002; Usanova et al., 2008).

The plasmasphere is a region located in the dipolar portions of the Earth's magnetosphere and populated by cold ($\sim$eV) and dense plasma of ionospheric origin (Lemaire and Gringauz, 1998). Plasmaspheric plumes are large-scale density structures that are usually connected to the main body of the plasmasphere, and extend outward (e.g., Elphic et al., 1996; Ober et al., 1997; Sandel et al., 2001). Plasmaspheric plumes have been detected by in-situ and ground-based instruments (e.g., Chappell et al., 1970; Carpenter et al., 1992; Foster et al., 2002; Moldwin et al., 2004; Goldstein et al., 2004). More recently, dense ($> 10\ cm^{-3}$) plasmaspheric plumes extending to the magnetopause have been observed by the THEMIS spacecraft (McFadden et al., 2008a). Darrouzet et al. (2008) did a statistical analysis of the plasmaspheric plumes observed by the Cluster spacecraft. They found that plasmaspheric plumes were observed mostly for moderate Kp and not for small Dst. They also showed that plumes are mainly located in the afternoon and pre-midnight MLT sectors. Plasmaspheric plumes have been suggested as a major cause of EMIC waves (Fuselier et al., 2004).

Most of the previous studies on EMIC waves and plasmaspheric plumes were during magnetic storms or substorms. In this paper, we investigate the global response of geospace plasma environment to an interplanetary shock from multiple THEMIS spacecraft observations in the magnetosheath (THEMIS B and C) and the mid-afternoon (THEMIS A) and dusk magnetosphere (THEMIS D and E). THEMIS A observed accelerated plasmaspheric plume population in the mid-afternoon magnetosphere when the plasma flow was $\sim$50 km/s. Meanwhile, THEMIS D and E did not observed plasmaspheric plume population in the dusk magnetosphere. These observations indicate that dawn-side edge of the plasmaspheric plume was located between THEMIS A and D (or E). The plume properties changed significantly after the shock arrival. The density increased from 10 to 30 cm^{-3} and the ion distribution changed from isotropic to strongly anisotropic. THEMIS A also observed EMIC waves which were most likely excited by the anisotropic ion distributions caused by the interplanetary shock impact.

2 Spacecraft Observations

The plasma observations reported in this paper were obtained with Electrostatic Analyzer (ESA) (McFadden et al., 2008b) on the THEMIS spacecraft (Angelopoulos, 2008). In one 3-s spin, ESA measures the 3-D ion and electron distributions over the energy range from a few eV up to 30 keV for electrons and 25 keV for ions. The magnetic field observations presented herein are obtained by the Fluxgate Magnetometer (FGM) (Auster et al., 2008) which measures the DC magnetic field up to 128 Hz.

Figure 1 shows an interplanetary shock observed by the WIND spacecraft located at (x,y,z)= (257, 52, 23) GSE R_E. The top three panels show plasma moments measured by SWE (Ogilvie et al., 1995). The fourth panel shows the calculated dynamic pressure. The bottom two panels show magnetic fields measured by MFI (Lepping et al., 1995). The IMF was southward from 0100 to 0112 UT and from 0118 to 0125 UT, mainly northward from 0112 to 0118 UT and after 0125 UT. The vertical dashed red line at 01:17:38 UT marks the interplanetary shock crossing. The interplanetary shock is a fast forward shock which is characterized by increases in the solar wind density, thermal temperature, bulk velocity, dynamic pressure (nmv^2) and magnetic field strength.

Figure 2 shows the trajectories of the THEMIS spacecraft from 0200 UT to 0300 UT on May 28, 2008. Five different symbols in Figure 2 mark the positions of 5 THEMIS probes at 0300 UT. THEMIS B and C were in the magnetosheath and THEMIS D, E, and A were inside the magnetosphere at 0200 UT. THEMIS D and E were very close to each other on the dusk flank.

The IP shock observed by WIND (shown in Figure 1) propagated toward the Earth and was observed by the THEMIS spacecraft. The top four panels in Figure 3 show THEMIS B observations, the following four panels show THEMIS C observations. The bottom six panels show observations by THEMIS D, E and A. The IP shock first reached THEMIS B in the magnetosheath. The first panel shows the plasma flow V_x component. The second panel shows the ion density. The third panel shows the ion temperature. The fourth panel shows the ESA plasma ion spectrum. The bow shock moved inward past THEMIS B at ∼0225 UT, as indicated by the transition to low solar wind densities and temperatures but high velocities. The black dashed line at 0223:47 UT marks the transmitted shock which can be identified by increases in the plasma flow speed, density and temperature. This shock was followed by a discontinuity at 0224:04 UT which is characterized by a density increase and a temperature decrease. This is the new discontinuity predicted by MHD theory (Samsonov et al., 2006). Both discontinuities propagated Earthward towards THEMIS C. The separation between the shock and discontinuity observed by THEMIS C at 0224:16 UT and 0225:42 UT is larger than that observed by THEMIS B at 0223:47 UT and 0224:04 UT due to the greater propagation speed of the shock than the discontinuity. The speed of the shock is 300 km/s and the speed of the discontinuity is 137 km/s (from R-H conditions and the timing method). The dynamic pressure increases associated with both discontinuities then compressed the magnetosphere. THEMIS D, E and A inside the magnetosphere observed antisunward-moving plasmas beginning at almost the

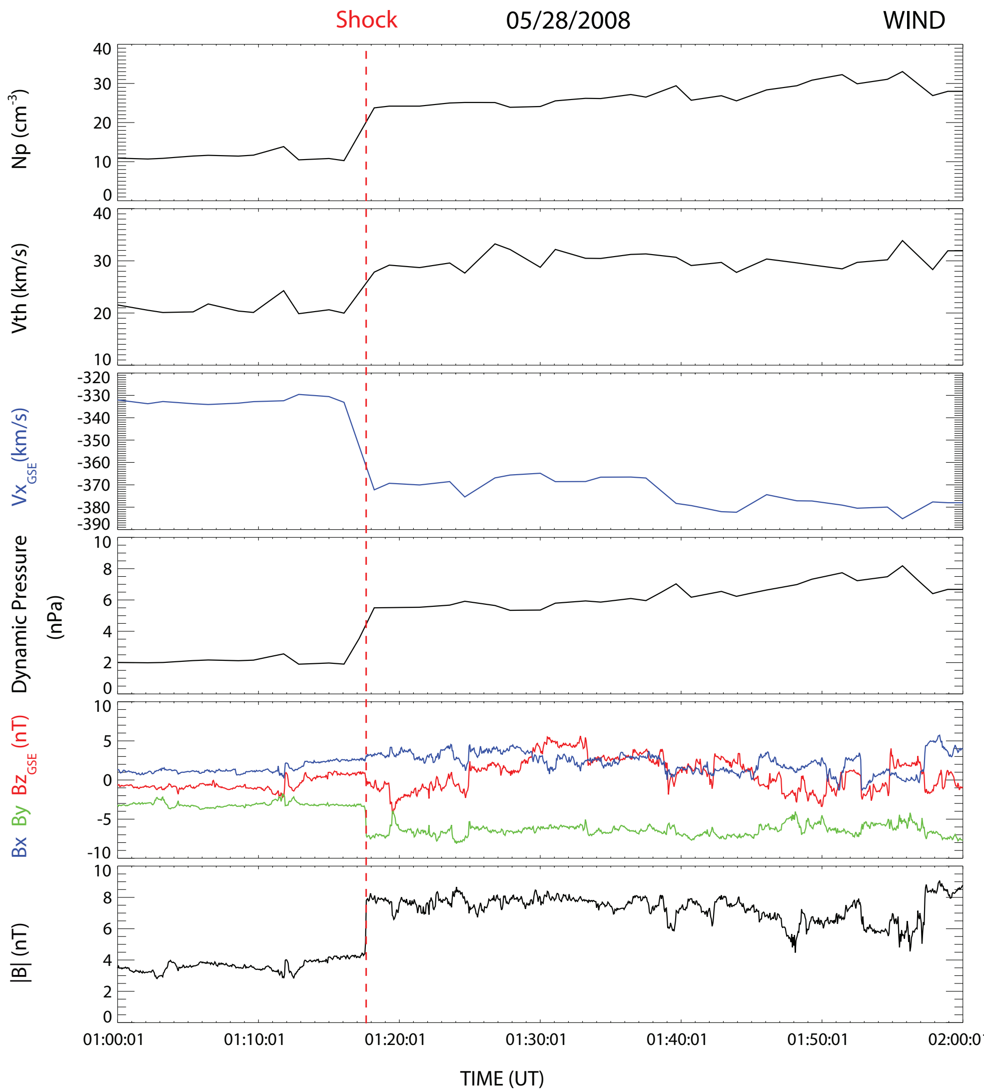

Fig. 1. An interplanetary shock observed by the WIND spacecraft upstream at (257, 52, 23) R_E. From top to bottom: ion density, thermal velocity, component of the flow velocity V_x along the Sun-Earrth line, dynamic pressure, components of the magnetic fields in GSE coordinates, and the magnetic field strength. The vertical dashed red line at 01:17:38 UT marked the interplanetary shock crossing.

same times (marked by black dashed lines in the bottom 6 panels), and lasting for at least 2 minutes.

Figure 4 shows THEMIS A observations from 0220 to 0310 UT, May 28, 2008. The first panel shows three components of the magnetic field in GSM coordinates with 0.25 s time resolution. The magnetic field strength (second panel) increased sharply from 60 nT to 75 nT at ~0225 UT due to the pressure enhancement associated with the IP shock. Then the magnetic field strength decreased slowly to 68 nT at 0234 UT. The magnetic field strength showed a few more compressions and relax-

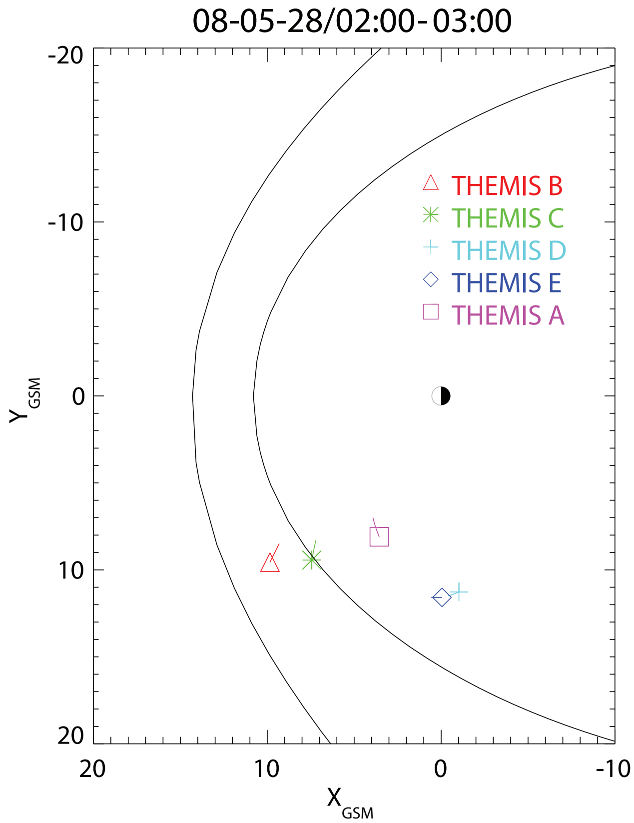

Fig. 2. THEMIS trajectory projected in GSM $X - Y$ plane from 0200 to 0300 UT on May 28, 2008. The positions of 5 THEMIS probes at 0300 UT are marked by 5 different symbols. THEMIS B and C were in the magnetosheath and THEMIS D, E, and A were inside the magnetosphere at 0200 UT. THEMIS D and E were very close to each other on the dusk flank. At 0225 UT, THEMIS A was located at (3.8, 7.5, -1.1) GSM R_E, THEMIS D and E were located at (-0.7, 11.4, 0.6) GSM R_E and (0.3, 11.6, 0.2) GSM R_E respectively.

ations with a ∼5 minutes period from 0243 to 0257 UT. The third panel shows the x component of the plasma flow velocity in GSM coordinates. After the IP shock arrival (at ∼0224 UT), the V_x component turned antisunward and then oscillated around 0 with an amplitude of ∼50 km/s from 0224 to 0310 UT. The amplitude of the oscillating electric field E_y measured by EFI was 5 mV/m (not shown). The fourth panel shows the wavelet analysis result for the B_y component of the magnetic field. The black (magenta) line at around 0.25 Hz (0.03 Hz) shows the gyrofrequency of Helium (Oxygen) ions. The strong emissions with frequencies between the gyrofrequencies of the Helium and Oxygen ions are EMIC waves. The fifth panel shows the ESA ion spectrum. An interesting feature is the sporadic measurement of a very cold plasma (∼10 eV). The cold ions appear when there is substantial plasma flow V_x component. The cold ions are accelerated plasmaspheric plume population. The sixth panel shows the plasma density derived from the spacecraft potential. Before

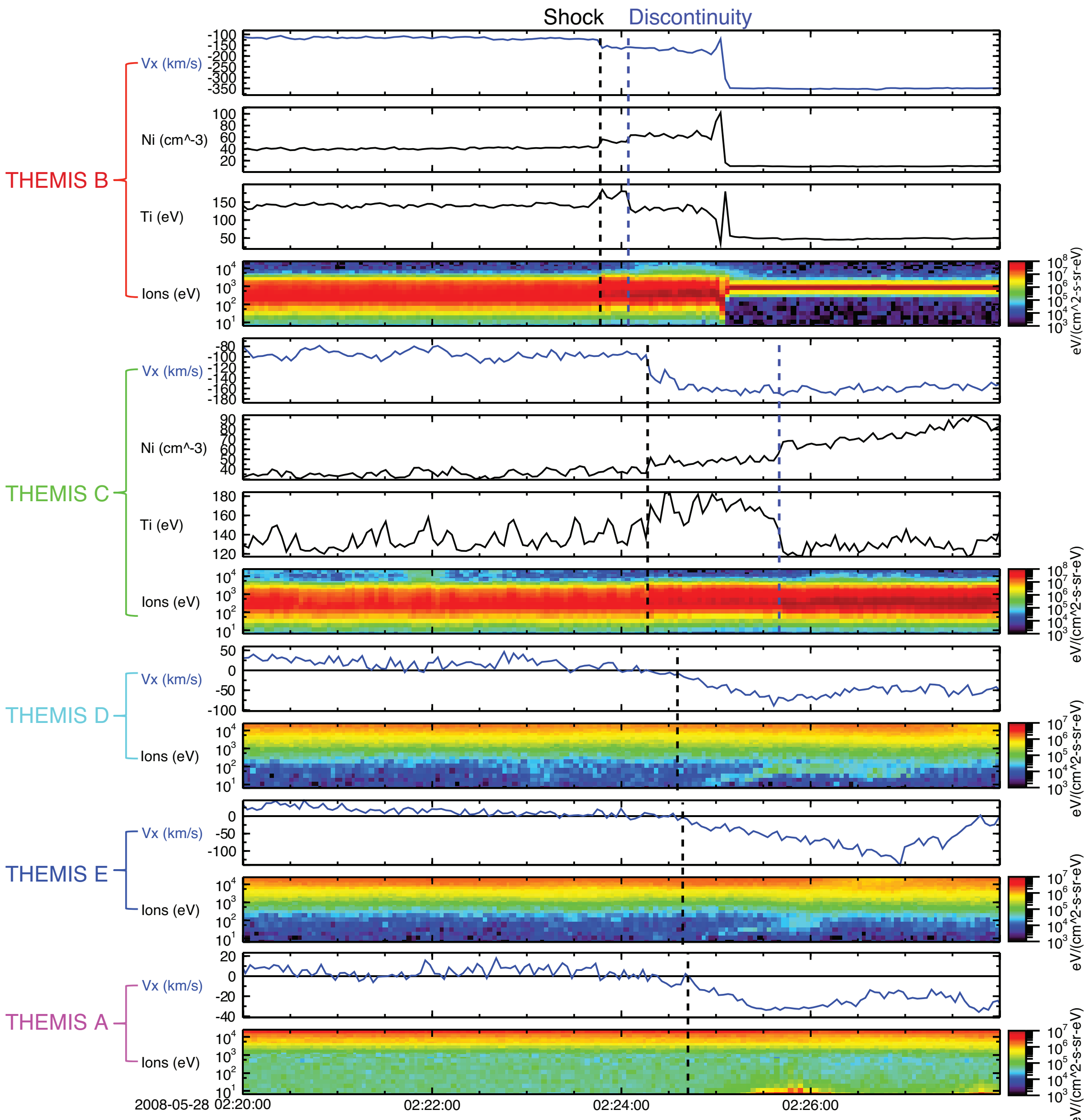

Fig. 3. The propagation of the interplanetary shock through the magnetosheath and in the magnetosphere. From top to bottom: THEMIS B plasma flow V_x component, ESA ion density, temperature, spectrum, THEMIS C plasma flow V_x component, ESA ion density, temperature, spectrum, THEMIS D plasma flow V_x component, ESA ion spectrum, THEMIS E plasma flow V_x component, ESA ion spectrum, THEMIS A plasma flow V_x component, ESA ion spectrum. The bow shock crossing was observed by THEMIS B near 0225 UT. The vertical black dashed lines mark the transmitted shock (top 8 panels) or the time when the plasma inside the magnetosphere started to move earthward (bottom 6 panels). The vertical blue dashed lines in the top 8 panels mark the discontinuity produced by the interaction of the IP shock and the bow shock.

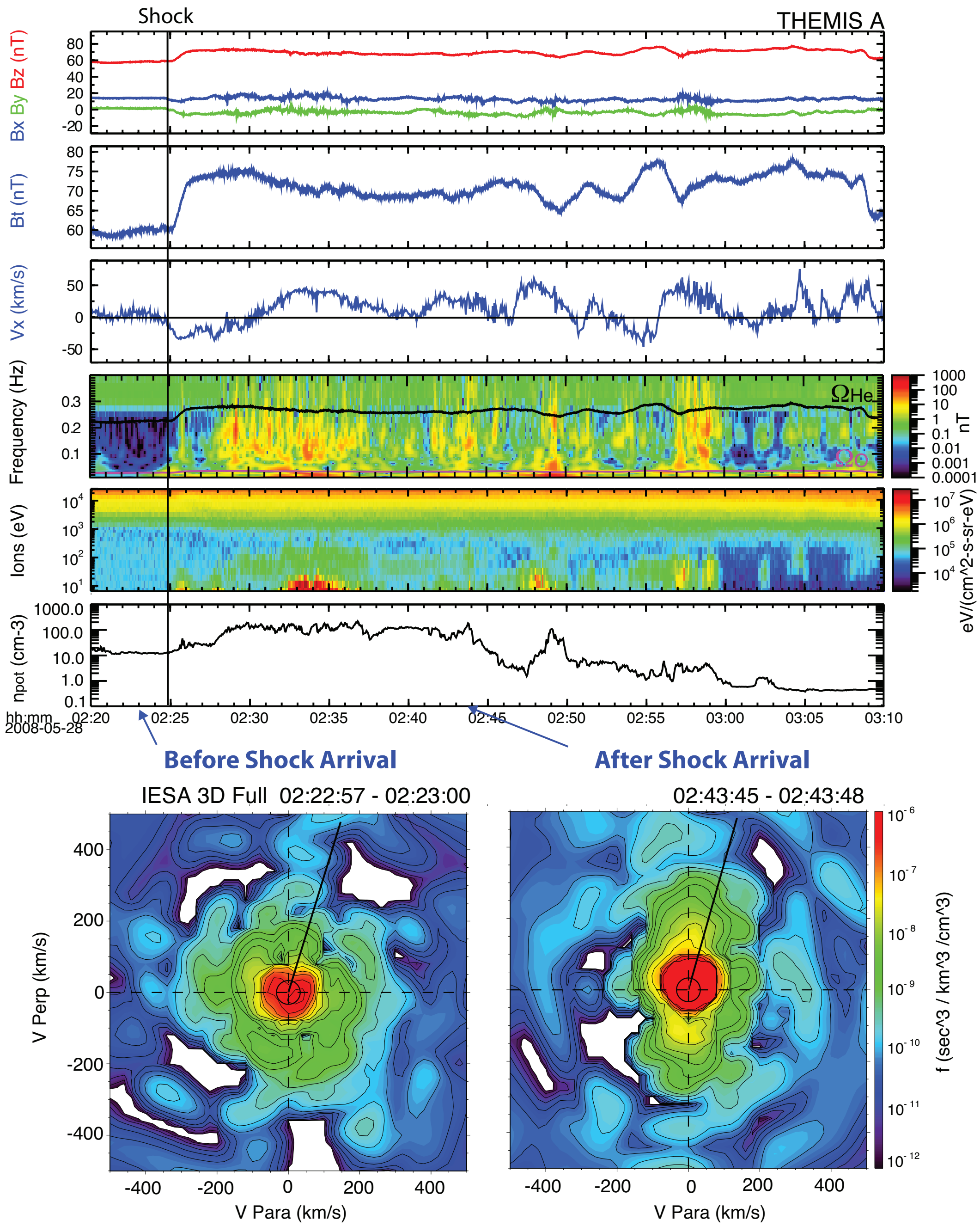

Fig. 4. THEMIS A (in the magnetosphere) observations of the EMIC wave activity and plasmaspheric plumes. From top to bottom: three components of the magnetic field in GSM coordinates, the magnetic field strength, the x component of the plasma flow velocity in GSM coordinates, wavelet analysis result for the B_y component of the magnetic field, ESA ion spectrum, plasma density derived from the spacecraft potential, and ion distributions for 3 s time intervals before (left) and after (right) the shock arrival. The thick black lines point toward the sun.

the shock passage at 0225 UT, the density was 10 cm^{-3}, indicating that THEMIS A observed a plasmaspheric plume. The density increased to 30 cm^{-3} at 0226 UT and 100 cm^{-3} at 0229 UT. We expect the arrival of an interplanetary shock to result in a significant brightening in emissions in the outer magnetosphere which can be detected by EUV imagers. The density drop from 5 to 0.5 cm^{-3} observed by THEMIS A at (3.6, 8.1, -1.3) GSM R_E indicates the dusk-side edge of the plume at 0300 UT.

The EMIC wave activity seems to be closely related to the accelerated plasmaspheric plume population from the fourth and fifth panels of Figure 4. Ion temperature anisotropy can stimulate EMIC waves in frequency $\omega/\Omega_i < A_i/(1+A_i)$ (Horne and Thorne, 1993), where Ω_i is the ion gyrofrequency, A_i is the ion temperature anisotropy which is defined by $A_i = \mathrm{T}_\perp/T_\| - 1$. The bottom two panels of Figure 4 present ion distributions for 3 s time intervals before (left) and after (right) the shock arrival. The ion distribution before the shock arrival was nearly isotropic, while it was strongly anisotropic towards perpendicular temperatures above 50 eV after the shock passage. The displacement towards positive $V_\perp$ in the right panel is evidence for accelerated flows. The anisotropy A_i is $\sim$ 1 at 0243:45 UT, and the EMIC wave frequency should be less than 0.5 Hz which is consistent with the wave frequency shown in the fourth panel of Figure 4. Therefore, the observed EMIC waves were most likely excited by the anisotropic ion distributions caused by the interplanetary shock impact. To our best knowledge, this is the first direct observation of the plasmaspheric plume response to an interplanetary shock's impact. The magnetic field strength compression ratio of this IP shock is 2 which is close to the average compression ratio of interplanetary shocks for both solar maximum (1.97) and solar minimum (1.93) (Echer et al., 2004), therefore, this event is common.

With multiple THEMIS spacecraft, the spatial distribution of plasmaspheric plumes can be estimated. The bottom six panels in Figure 3 show that while THEMIS A observed accelerated plasmaspheric plume population at (3.8, 7.5, -1.1) GSM R_E (16 MLT, $L \approx 8.5$) from 0225 to 0226 UT, THEMIS D and E at (-0.7, 11.4, 0.6) GSM R_E and (0.3, 11.6, 0.2) GSM R_E (18 MLT, $L \approx 11.6$) did not observed plasmaspheric plume population during this time interval. This indicates that the dawn-side edge of the plasmaspheric plume was located between THEMIS A and D (or E) as illustrated in Figure 5. THEMIS A (D, E) was located in the L-MLT bin where there is a high (low) probability to observe a plasmaspheric plume as shown in Figure 8 of Darrouzet et al. (2008). The Kp index was 3 during this time interval which is consistent with Darrouzet et al. (2008) that plumes were mostly observed during moderate Kp (3-6). However, the Dst was only -5 which is inconsistent with Darrouzet et al. (2008) that plasmaspheric plumes were never observed for small Dst.

3 Conclusions

The global magnetospheric response to an interplanetary shock has been investigated using the THEMIS spacecraft observations. With THEMIS B and C in the magnetosheath, THEMIS A in

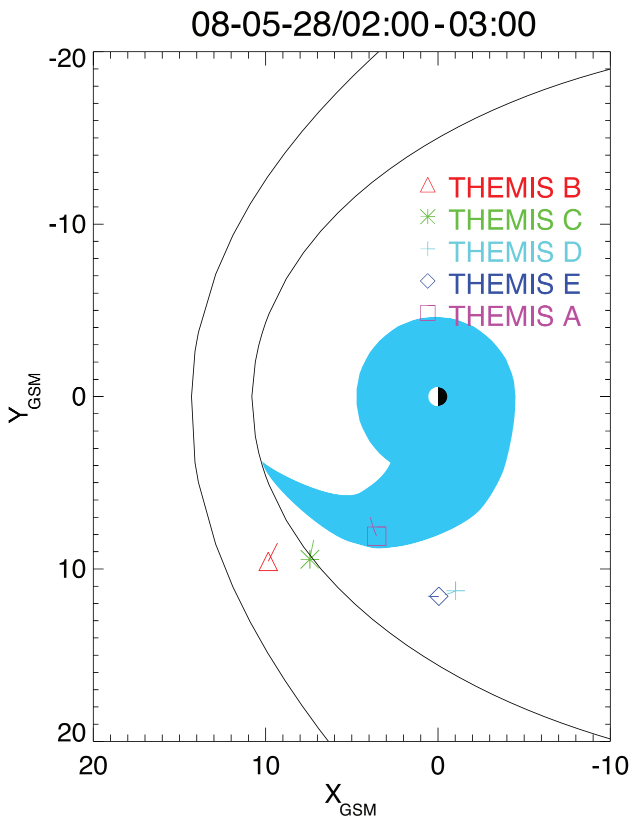

Fig. 5. A cartoon illustrates a plasmaspheric plume observed by THEMIS A (but not observed by THEMIS D and E) in the mid-afternoon magnetosphere.

the mid-afternoon magnetosphere, and THEMIS D and E in the dusk magnetosphere, the THEMIS spacecraft offer a remarkable opportunity to track the propagation of the shock and the magnetospheric response. The interaction of the transmitted interplanetary shock with the magnetosphere has global effects. Consequently, it can affect geospace plasma significantly.

The main conclusions of this paper can be summarized as follows:

1. The interaction of an interplanetary shock with the bow shock launched a fast shock and a discontinuity which propagated toward the Earth at speeds of 300 km/s and 137 km/s respectively.

2. THEMIS A, but not D or E, observed a plasmaspheric plume in the dayside magnetosphere. Multiple spacecraft observations indicate that the dawn-side edge of the plasmaspheric plume was located between THEMIS A and D (or E) as illustrated in Figure 5.

3. The plume properties changed significantly by the interplanetary shock impact. The density increased from 10 to 100 cm^{-3} in 4 min and the ion distribution changed from isotropic to strongly anisotropic distribution.

4. THEMIS A also observed EMIC waves which were most likely excited by the anisotropic ion

distributions caused by the interplanetary shock impact. To our best knowledge, this is the first direct observation of the plasmaspheric plume response to an interplanetary shock's impact.

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References

Anderson, B. J. and Hamilton, D. C.: Electromagnetic ion cyclotron waves stimulated by modest magnetospheric compressions, J. Geophys. Res., 98, 11,369–11,382, doi:10.1029/93JA00605, 1993.

Anderson, B. J., Takahashi, K., Erlandson, R. E., and Zanetti, L. J.: Pc1 pulsations observed by AMPTE/CCE in the earth's outer magnetosphere, Geophys. Res. Lett., 17, 1853–1856, doi:10.1029/GL017i011p01853, 1990.

Anderson, B. J., Erlandson, R. E., and Zanetti, L. J.: A statistical study of Pc 1-2 magnetic pulsations in the equatorial magnetosphere. I - Equatorial occurrence distributions. II - Wave properties, J. Geophys. Res., 97, 3075–3101, doi:10.1029/91JA02706, 1992.

Angelopoulos, V.: The THEMIS Mission, Space Sci. Rev., 141, 5–34, doi:10.1007/s11214-008-9336-1, 2008.

Araki, T.: Global structure of geomagnetic sudden commencements, Planet. Space Sci., 25, 373–384, doi:10.1016/0032-0633(77)90053-8, 1977.

Auster, H. U., Glassmeier, K. H., Magnes, W., Aydogar, O., Baumjohann, W., Constantinescu, D., Fischer, D., Fornacon, K. H., Georgescu, E., Harvey, P., Hillenmaier, O., Kroth, R., Ludlam, M., Narita, Y., Nakamura, R., Okrafka, K., Plaschke, F., Richter, I., Schwarzl, H., Stoll, B., Valavanoglou, A., and Wiedemann, M.: The THEMIS Fluxgate Magnetometer, Space Sci. Rev., 141, 235–264, doi:10.1007/s11214-008-9365-9, 2008.

Carpenter, D. L., Smith, A. J., Giles, B. L., Chappell, C. R., and Décréau, P. M. E.: A case study of plasma structure in the dusk sector associated with enhanced magnetospheric convection, J. Geophys. Res., 97, 1157–1166, doi:10.1029/91JA01546, 1992.

Chappell, C. R., Harris, K. K., and Sharp, G. W.: The morphology of the bulge region of the plasmasphere., J. Geophys. Res., 75, 3848–3861, doi:10.1029/JA075i019p03848, 1970.

Cornwall, J. M.: Cyclotron Instabilities and Electromagnetic Emission in the Ultra Low Frequency and Very Low Frequency Ranges, J. Geophys. Res., 70, 61–69, doi:10.1029/JZ070i001p00061, 1965.

Darrouzet, F., de Keyser, J., Décréau, P. M. E., El Lemdani-Mazouz, F., and Vallières, X.: Statistical analysis of plasmaspheric plumes with Cluster/WHISPER observations, Annales Geophysicae, 26, 2403–2417, doi:10.5194/angeo-26-2403-2008, 2008.

Echer, E., Alves, M. V., and Gonzalez, W. D.: Geoeffectiveness of interplanetary shocks during solar minimum (1995 1996) and solar maximum (2000), Solar Physics, 221, 361–380, doi:10.1023/B:SOLA.0000035045.65224.f3, 2004.

Elphic, R. C., Weiss, L. A., Thomsen, M. F., McComas, D. J., and Moldwin, M. B.: Evolution of plasmaspheric ions at geosynchronous orbit during times of high geomagnetic activity, Geophys. Res. Lett., 23, 2189–2192, doi:10.1029/96GL02085, 1996.

Engebretson, M. J., Peterson, W. K., Posch, J. L., Klatt, M. R., Anderson, B. J., Russell, C. T., Singer, H. J., Arnoldy, R. L., and Fukunishi, H.: Observations of two types of Pc 1-2 pulsations in the outer dayside magnetosphere, J. Geophys. Res., 107, 1451, doi:10.1029/2001JA000198, 2002.

Foster, J. C., Erickson, P. J., Coster, A. J., Goldstein, J., and Rich, F. J.: Ionospheric signatures of plasmaspheric tails, Geophys. Res. Lett., 29, 1623, doi:10.1029/2002GL015067, 2002.

Fuselier, S. A., Gary, S. P., Thomsen, M. F., Claflin, E. S., Hubert, B., Sandel, B. R., and Immel, T.: Generation of transient dayside subauroral proton precipitation, J. Geophys. Res., 109, A12 227, doi:10.1029/2004JA010393, 2004.

Goldstein, J., Sandel, B. R., Thomsen, M. F., Spasojević, M., and Reiff, P. H.: Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes, J. Geophys. Res., 109, A03 202, doi:10.1029/2003JA010281, 2004.

Grib, S. A., Briunelli, B. E., Dryer, M., and Shen, W.-W.: Interaction of interplanetary shock waves with the bow shock-magnetopause system, J. Geophys. Res., 84, 5907–5921, 1979.

Horne, R. B. and Thorne, R. M.: On the preferred source location for the convective amplification of ion cyclotron waves, J. Geophys. Res., 98, 9233–9247, doi:10.1029/92JA02972, 1993.

Huttunen, K. E. J., Slavin, J., Collier, M., Koskinen, H. E. J., Szabo, A., Tanskanen, E., Balogh, A., Lucek, E., and Rème, H.: Cluster observations of sudden impulses in the magnetotail caused by interplanetary shocks and pressure increases, Ann. Geophys., 23, 609–624, 2005.

Lemaire, J. F. and Gringauz, K. I.: The Earth's Plasmasphere, Cambridge University Press, 1998.

Lepping, R. P., Acũna, M. H., Burlaga, L. F., Farrell, W. M., Slavin, J. A., Schatten, K. H., Mariani, F., Ness, N. F., Neubauer, F. M., Whang, Y. C., Byrnes, J. B., Kennon, R. S., Panetta, P. V., Scheifele, J., and Worley, E. M.: The Wind Magnetic Field Investigation, Space Sci. Rev., 71, 207–229, doi:10.1007/BF00751330, 1995.

Maynard, N. C., Farrugia, C. J., Ober, D. M., Burke, W. J., Dunlop, M., Mozer, F. S., Rème, H., Décréau, P., and Siebert, K. D.: Cluster observations of fast shocks in the magnetosheath launched as a tangential discontinuity with a pressure increase crossed the bow shock, J. Geophys. Res., 113, A10 212, doi:10.1029/2008JA013121, 2008.

McFadden, J. P., Carlson, C. W., Larson, D., Bonnell, J., Mozer, F. S., Angelopoulos, V., Glassmeier, K.-H., and Auster, U.: Structure of plasmaspheric plumes and their participation in magnetopause reconnection: First results from THEMIS, Geophys. Res. Lett., 35, L17S10, doi:10.1029/2008GL033677, 2008a.

McFadden, J. P., Carlson, C. W., Larson, D., Ludlam, M., Abiad, R., Elliott, B., Turin, P., Marckwordt, M., and Angelopoulos, V.: The THEMIS ESA Plasma Instrument and In-flight Calibration, Space Sci. Rev., 141, 277–302, doi:10.1007/s11214-008-9440-2, 2008b.

Moldwin, M. B., Howard, J., Sanny, J., Bocchicchio, J. D., Rassoul, H. K., and Anderson, R. R.: Plasmaspheric plumes: CRRES observations of enhanced density beyond the plasmapause, J. Geophys. Res., 109, A05 202, doi:10.1029/2003JA010320, 2004.

Ober, D. M., Horwitz, J. L., Thomsen, M. F., Elphic, R. C., McComas, D. J., Belian, R. D., and Moldwin, M. B.: Premidnight plasmaspheric "plumes", J. Geophys. Res., 102, 11 325–11 334, doi:10.1029/97JA00562, 1997.

Ogilvie, K. W., Chornay, D. J., Fritzenreiter, R. J., Hunsaker, F., Keller, J., Lobell, J., Miller, G., Scudder, J. D., Sittler, Jr., E. C., Torbert, R. B., Bodet, D., Needell, G., Lazarus, A. J., Steinberg, J. T., Tappan, J. H., Mavretic, A., and Gergin, E.: SWE, A Comprehensive Plasma Instrument for the Wind Spacecraft, Space Sci. Rev., 71, 55–77, doi:10.1007/BF00751326, 1995.

Přech, L., Němeček, Z., and Šafránková, J.: Response of magnetospheric boundaries to the interplanetary shock: Themis contribution, Geophys. Res. Lett., 35, L17S02, doi:10.1029/2008GL033593, 2008.

Roux, A., Perraut, S., Rauch, J. L., de Villedary, C., Kremser, G., Korth, A., and Young, D. T.: Wave-particle interactions near omega He/plus/ observed on board GEOS 1 and 2. II - Generation of ion cyclotron waves and heating of He/plus/ ions, J. Geophys. Res., 87, 8174–8190, doi:10.1029/JA087iA10p08174, 1982.

Šafránková, J., Němeček, Z., Přech, L., Samsonov, A. A., Koval, A., and Andréeová, K.: Modification of interplanetary shocks near the bow shock and through the magnetosheath, J. Geophys. Res., 112, A08 212, doi:10.1029/2007JA012503, 2007.

Samsonov, A. A., Němeček, Z., and Šafránková, J.: Numerical MHD modeling of propagation of interplanetary shock through the magnetosheath, J. Geophys. Res., 111, A08 210, doi:10.1029/2005JA011537, 2006.

Samsonov, A. A., Sibeck, D. G., and Imber, J.: MHD simulation for the interaction of an interplanetary shock with the Earth's magnetosphere, J. Geophys. Res., 112, A12 220, doi:10.1029/2007JA012627, 2007.

Sandel, B. R., King, R. A., Forrester, W. T., Gallagher, D. L., Broadfoot, A. L., and Curtis, C. C.: Initial results from the IMAGE extreme ultraviolet imager, Geophys. Res. Lett., 28, 1439–1442, doi: 10.1029/2001GL012885, 2001.

Shen, W.-W. and Dryer, M.: Magnetohydrodynamic theory for the interaction of an interplanetary double-shock ensemble with the earth's bow shock., J. Geophys. Res., 77, 4627–4644, 1972.

Tamao, T.: Unsteady interactions of solar wind disturbances with the magnetosphere, J. Geophys. Res., 80, 4230–4236, doi:10.1029/JA080i031p04230, 1975.

Usanova, M. E., Mann, I. R., Rae, I. J., Kale, Z. C., Angelopoulos, V., Bonnell, J. W., Glassmeier, K., Auster, H. U., and Singer, H. J.: Multipoint observations of magnetospheric compression-related EMIC Pc1 waves by THEMIS and CARISMA, Geophys. Res. Lett., 35, L17S25, doi:10.1029/2008GL034458, 2008.

Völk, H. J. and Auer, R.-D.: Motions of the bow shock induced by interplanetary disturbances., J. Geophys. Res., 79, 40–48, 1974.

Young, D. T., Perraut, S., Roux, A., de Villedary, C., Gendrin, R., Korth, A., Kremser, G., and Jones, D.: Wave-particle interactions near Omega/He plus/ observed on GEOS 1 and 2. I - Propagation of ion cyclotron waves in He/plus/-rich plasma, J. Geophys. Res., 86, 6755–6772, doi:10.1029/JA086iA08p06755, 1981.

Zhang, H., Zong, Q., Sibeck, D. G., Fritz, T. A., McFadden, J. P., Glassmeier, K., and Larson, D.: Dynamic motion of the bow shock and the magnetopause observed by THEMIS spacecraft, J. Geophys. Res., 114, A00C12, doi:10.1029/2008JA013488, 2009.

Zhou, X. and Tsurutani, B. T.: Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks), Geophys. Res. Lett., 26, 1097–1100, doi:10.1029/1999GL900173, 1999.

Zhuang, H. C., Russell, C. T., Smith, E. J., and Gosling, J. T.: Three-dimensional interaction of interplanetary shock waves with the bow shock and magnetopause - A comparison of theory with ISEE observations, J. Geophys. Res., 86, 5590–5600, 1981.