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Multisatellite observations of the magnetosphere response to changes in the solar wind and interplanetary magnetic field

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Abstract

We employ multipoint observations of the magnetosphere to present case and statistical studies of the electromagnetic field and plasma response to interplanetary (IP) shocks. On February 27, 2014 the initial encounter of an IP shock with the magnetopause occurred on the early postnoon magnetosphere, consistent with the observed alignment of the shock with the spiral IMF. The dayside equatorial magnetosphere exhibited a dusk-dawn oscillatory electrical field with a period of ~ 330 s and peak to peak amplitudes of ~ 15 mV/m for a period of 30 min. The intensity of electrons in the energy range from 31.5 to 342 KeV responded with periods corresponding to the shock induced ULF electric field waves.The initial electric field perturbation was directed dawnward for this case study. We then perform a statistical study of Ey variations of the electric field and associated plasma drift Vx and Vy flow velocities for 30 magnetospheric events during the passage of interplanetary shocks. The direction of the initial Vx component of plasma flow is tailward at all local times except the nightside magnetosphere, where flows are sunward near the sun-Earth line but antisunward towards dawn and dusk. The observed directions of the azimuthal velocity Vy predominately agree with those expected for the given spiral or orthospiral shock normal orientation.

Introduction

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Sudden increases in the solar wind dynamic pressure accompanying interplanetary (IP) shocks cause earthward motion of the bow shock and the magnetopause and launch fast and intermediate mode waves into the magnetosphere [Tamao, 1964]. The fast mode waves propagate both radially inward and azimuthally around the Earth [Araki et al., 1997] whereas the intermediate mode waves propagate along magnetic field lines to produce transient perturbations in the high-latitude dayside ionosphere [Southwood and Kivelson, 1990; Glaßmeier and Heppner, 1992]. Using multipoint observations Wilken et al. [1982] estimated the propagation speeds to be about 600 km/s in the radial direction from geostationary orbit to the ground and about 910 km/s in the azimuthal direction in the equatorial plane. Nopper et al. [1982] estimated an impulse disturbance speed of about 1500 km/s at geostationary orbit. Schmidt and Pedersen [1988] derived a propagation velocity for the radially inward travelling compressive wave of 950 km/s and for the azimuthal wave in the outer magnetosphere of 1100 km/s. Samsonov et al. [2007] used a magnetohydrodynamic code to simulate the interaction of a moderately strong interplanetary shock propagating along the Sun-Earth line and obtained the average speed of the primary and reflected fast shocks in the magnetosphere to be about 700 km/s, in agreement with their assumptions concerning the mean Alfvén velocity in the outer dayside magnetosphere (1000 km/s) and in the plasmasphere (500 km/s).

The IP shock orientation plays an important role in determining the associated geophysical effects [e.g., Oliveira and Raeder, 2015]. Guo et al. [2005] showed that system evolution times are much longer for shocks with normals oblique to the Sun–Earth line. The pressure pulse model of Sibeck et al. [1990] predicts dawnward moving transient events near local noon when shock normals point perpendicular to the nominal spiral interplanetary magnetic field (IMF) direction, but duskward moving events occur near local noon for events when shock normals point perpendicular to the orthospiral IMF orientation. The direction of the plasma flow within the magnetosphere is expected to be consistent with the orientation of the shock. That is to say dawnward flow for spiral IMF shocks and duskward flow for orthospiral IMF shocks. Here orthospiral refers to IMF longitudes ($0^{\circ} < \Lambda < 90^{\circ}$ and $180^{\circ} < \Lambda < 270^{\circ}$), spiral refers to IMF longitudes ($90^{\circ} < \Lambda < 180^{\circ}$ and $270^{\circ} < \Lambda < 360^{\circ}$), where longitude $\Lambda = 0^{\circ}$ points sunward, and $\Lambda = 90^{\circ}$ duskward.

The magnetic and electric fields are key parameters for understanding of the response of the Earth's space environment to IP shocks. The propagation and evolution of electric fields in the magnetosphere-ionosphere system in response to IP shocks have been studied for several decades but signatures of the shock related electric field perturbations are still not fully understood. Knott et al. [1985] reported that the electric field observed by the GEOS-2 satellite showed a transient signature of about 7 mV/m in the dayside magnetosphere associated with the onset of a Sudden Commencement (SC). These signatures were followed by Pc4-5 oscillations. Schmidt and Pedersen [1988] performed a statistical investigation of the GEOS2 electric field signatures associated with SC that showed a clear tailward flow pattern near local noon. Close to the flanks or in the nightside of the magnetosphere the corresponding flows also exhibited a radially inward component. Shinbory et al [2004] investigated the detailed signatures of the Akebono electric and magnetic fields associated with SCs inside the plasmasphere ($L < 5$). The initial excursion of the electric field associated with SCs was almost directed westward at all local times. The amplitude did not show a clear dependence on magnetic local time and the intensity of the Ey field gradually increased by 0.5-2.0 mV/m about 1-2 minutes after the onset of the initial electric field impulse. The propagation velocity of SCs disturbances derived from the amplitude ratio of the electric field to magnetic field was about 360 km/s in the equatorial plasmasphere. Kim et al. [2009] used an MHD simulation to examine the electric field and suggested that the SC associated electric field seen by Shinbory et al. [2004] was the convection electric field. Takahashi et al. [2017] investigated the spatial and temporal evolution of large-scale electric fields in the magnetosphere and ionosphere associated with SCs using multipoint equatorial magnetospheric and ionospheric satellites together with ground radars and showed that the propagation characteristics of electric fields in the equatorial plane depend on magnetic local time. They showed that the initial variation of the electric field (negative Ey) lasted about one minute and was directed westward throughout the inner magnetosphere. Positive Ey became dominant 2 min after SCs propagated to pre-midnight or post-midnight region with near costant amplitude.

Observations and MHD simulations [e.g., Li et al., 1993; Zong et al., 2009; Halford et al., 2014; Schiller et al., 2016] show that the electric fields generated by sudden compressions can resonantly interact with trapped charged particle populations within the Earth magnetosphere,

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energizing and injecting them deep into the magnetosphere. During the well-known shock event in March 1991, the CRESS satellite observed injected electrons energized to extremely high energies, up to 5 MeV [Blake et al., 1992]. Wygant et al. [1994] showed that the shock related electric and magnetic field perturbations observed by the CRRES satellite in the nightside inner magnetosphere exhibited a bipolar waveform with amplitude of about 80 mV/m and 140 nT, respectively, and energized the energetic electrons to energies up to 15 MeV. Foster et al. [2015] found that a shock with an azimuthal electric field impulse of 10 mV/m observed by the Van Allen Probes was responsible for accelerating 1.5-4.5 MeV electrons by 400 KeV in the radial region of L= 3.5-4.

This paper focuses on two major issues. We will inspect multispacecraft electric and magnetic field and particles and plasma observations to study their response to an IP shock on February 27, 2014. We will time the occurrence of magnetic field disturbances associated with the shock in space and the magnetosphere and will determine the direction of their propagation. Then we will perform a statistical study of the Van Allen Probes electric field disturbances in the magnetosphere and associated plasma drift Vx and Vy velocities in response to IP shocks. We will investigate how the electric field perturbations deviate from the preceding undisturbed period during shock-induced compressions and whether the signatures of the shock electric field perturbations have a clear dependence on magnetic local time. We will study whether the direction of the shock normal has any effect on the propagation of the shock induced magnetic and plasma disturbances. We will compare our statistical results to the results of MHD simulations.

Data sets

The extensive Van Allen Probes, THEMIS, Cluster and GOES multi-instrument data sets provide numerous opportunities to observe the magnetospheric response to the changes in the solar wind and interplanetary magnetic field monitored by Wind. The five THEMIS spacecraft were launched in 2007 and carry identical instruments and operated in highly elliptical, near-equatorial, orbits that precess about the Earth with apogees of 12, 20, and 30 RE and orbital periods of 1, 2, and 4 days. With the outermost two spacecraft ARTEMIS now at the Moon, three THEMIS spacecraft remain on the innermost orbits. We use magnetic field data with 3 s

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time resolution data from the THEMIS FGM triaxial fluxgate magnetometers [Auster et al., 2008]. The ESA electrostatic analyzer on the THEMIS spacecraft measures the distribution functions of 0.005 to 25 keV ions and 0.005 to 30 keV electrons over 4ˇ-str and provides accurate 3 s time resolution plasma moments, pitch angle and gyrophase particle distributions [McFadden et al., 2008].

The two Van Allen Probes were launched in August 2012 into nearly identical equatorial and low inclination (~10°) orbits with perigee altitudes of 605 and 625 km and apogee altitudes of 30410 and 30540 km [Mauk et al., 2012]. Both satellites carry identical sets of instruments to measure charged particle populations, fields, and waves in the inner magnetosphere. In this paper, we employ observations from the Energetic Particle, Composition, and Thermal Plasma Suite (ECT: MagEIS**,** 20-4000 keV for electrons) [Spence et al., 2013; Blake et al., 2013]. Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) [Kletzing et al., 2013], and the Electric Field and Waves Suite (EFW) [Wygant et al., 2013]. In particular, we inspect electric and magnetic field observations with 11 and 4 s time resolution, respectively, and differential particle flux measurements with ~ 11 s (spin period) time resolution. The electric field data were obtained from sites http://www.space.umn.edu/rbspefw-data and CDAWEB where they are presented in an MGSE (modified GSE) coordinate system. They provide two components Y and Z of the electric field. Both components are in the spin plane of the spaceraft and are measured with the 50 m long booms. The spin axis X is oriented within 37 degrees of the Earth-Sun line. The spin axis component of the electric field can be obtained from the **E** dot **B** = 0 assumption. For this to succeed the magnetic field should be at least 15 degrees out of the spin plane. To calculate Van Allen Probes plasma flow velocities we converted the electric field data from modified MGSE coordinates into GSE coordinates. Additionally we used magnetic field data from GOES 13 and 15 with 0.5 s time resolution [Singer et al., 1966] and Cluster with 4 s time resolution [Balogh et al., 1997]. We use Wind solar wind magnetic field and SWE plasma data with 3 s [Lepping et al., 1995] and 1 min, respectively [Ogilvie et al., 1995].

Observations

Figure 1 presents Wind magnetic and plasma data from 15:30 to 16:10 UT on February 27, 2014. The arrival of the shock at Wind at 15:50 UT (X, Y, Z GSM = (220.9, 93.9, 30,7 Re)) is revealed by an enhancement in the interplanetary magnetic field strength from 6 to 16 nT and

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total plasma velocity from 350 to 420 km/s. The IMF had positive Bx and negative By components during the whole interval that both increased the shock arrived. The solar wind density increased from 18 to 45 cm-3, and the dynamic pressure increased from 3 to 13 nPa. This fast forward (FF) shock was oblique. Its normal was calculated using magnetic field coplanarity and pointed in the GSM coordinates directions of [nx, ny, nz] = [0.72, 0.39, 0.56], i.e., it was aligned with the spiral shock orientation. We will use the direction of the shock normal to interpret the timing results for the IP shock arrival observed by THEMIS, GOES, Cluster and the Van Allen Probes spacecraft for this event.

Figure 2 shows the GSM locations of The THEMIS, Cluster, Van Allen Probes and GOES spacecraft at ~ 16:50 UT (Their coordinates are given in Table 1). All the spacecraft located in the solar wind observed the enhanced the magnetic field strength, densities, velocities and temperatures associated with the IP shock. The shock induced disturbances were seen just upstream from the bow shock by Cluster 2 and 1 at 16:48:44 UT and 16:48:46 UT, respectively .

Figures 3 (a, b) show the THEMIS D and A observations of the magnetic field, plasma and energy spectra of ion fluxes from 16:40 to 17:20 UT. The spacecraft were initially located in the magnetosheath. At 16:49:01 UT the IP shock hit THEMIS D as indicated by enhanced densities, magnetic field strength and velocities. Particles from low to high energies showed the increase of energy and enhanced fluxes. The shock produced compression caused the bow shock to move inward at 16:49:36 UT, past the spacecraft as indicated by the decrease in the magnetic field strength and, decrease in density and temperature and spectra expected for its entry into the solar wind. THEMIS A observed the IP shock at 16:49:12 UT and in about 1 min and 34 s later its magnetic field, density and temperature traces indicate that the bow shock moved inward past THEMIS A.

Figures 4 (a, b) show GOES 13 and 15 observations of the magnetic field from 16:40 to 17:20 UT. Following the arrival of the transmitted IP shock at GOES 13 near local noon at 16:50:07 UT there was a sharp increase of magnetic field variations with amplitudes of ~70 nT in the H component. The shock induced compression was so strong that at 17:02 UT GOES 13 briefly entered the sheath. The shock front was then detected at GOES 15 in the morning local hours 33 sec later at 16:50:40 UT, where it caused a gradual increase of the magnetic field amplitudes by ~ 20 nT followed by compressional pulsations that fall in the category of Pc5 pulsations.

The upper and middle panels of Figures 5 (a, b) present the Van Allen Probes A and B magnetic field and electric observations from 16:40 to 17:20 UT. The arrival of the shock characterized by a strong (~ 50 nT) increase in the total magnetic field strength and bipolar variations in all three components of the electric field at ~ 16:50:26 UT at Probe B and 7 sec later at Probe A. The initial electric field perturbations in the azimuthal component Ey observed by Van Allen Probes A and B were directed dawnward with amplitudes of -9.4 and - 8.2 mV/m, respectively, but ~ 4 minutes later the sense changed direction towards dusk (with amplitudes of 5.3 and 5.8 mV/m). We interpret these variations as due to a compression of the magnetosphere followed by a reflection [Samsonov et al., 2007]. The Ez and Ex components show variations with amplitudes that are a factor of 1.5-2 smaller than those of the Ey component. The bipolar electric field waveforms are followed by geomagnetic pulsations with periods of ~ 330 s that damp within ~ 30 min.

Figures 6 (a, b) present Van Allen Probes A and B observations of the azimuthal component of the electric field and pitch angle distributions of electron fluxes for energies at 31.5, 53.8, 108.3, 183.4, 231.8, and 342 KeV as measured by MagEIS instrument. The particles exhibit enhanced fluxes of electrons at all energies but most intense at pitch angles ~ 90^o, immediately after the arrival of the IP shock. Kanekal et al. [2016] suggested that the shock-injection mechanism can be effective for energizing particles over substantional range of pitch angles. One of the interesting features in Figures 6 is that the intensity of electrons in the energy range of 31.5-342 KeV exhibits a regular periodicity with periods corresponding to the ULF electric field waves. The oscillations in electron fluxes are in quadrature with the Ey component. This component is of special interest because some charged particles that drift azimuthally as a consequence of the gradient and curvature drifts in the Earth magnetic field can traverse this electric field acquiring significant amount of energy. The initial flux enhancement is more pronounced by comparison with the following pulses. We interpret these observations as evidence for prompt energization of electrons due to shock induced ULF electric fields with an additional contribution for the initial acceleration from the compressional effect of the shock [Zong et al., 2009]. It should be noted that electrons can be accelerated most significantly

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through a process known as drift resonance [Southwood and Kivelson, 1981] when resonant particles drift with the same velocity as the wave front. Claudepierre et al. [2013] showed Van Allen Probes observations of the energy dependence of the amplitude and phase of the electron flux modulations which were consequences of drift resonance between ~ 60 keV electrons and fundamental poloidal Pc5 waves. Hao et al. [2014] presented Van Allen Probes observations of electron injections caused by the IP shock and showed that the injected electrons with energies between 150 KeV and 230 KeV were in drift resonance with the excited poloidal ULF waves. Considering the process for energizing drift resonant electrons, the value for the **E**X**B** drift velocities of the particles in the wavefields provides important information. We calculated the radial (Vx) and azimuthal (Vy) drift velocities at Van Allen Probes A and B for the interval from 16:40 to 17:20 UT and present them in the two bottom panels of Figures 5 (a, b). The Vx and Vy components associated with the minimum peak of the Ey electric field are about -40 km/s and -15 km/s for Van Allen Probe B and -35 km/s and -6 km/s for Van Allen Probe A, i. e., the initial direction of the plasma flow is tailward and dawnward consistent with expectation for the spiral orientation of the IP shock.

Knowing the distances between the satellites and the lag times for the propagation of shock induced disturbances we calculated the shock propagation velocities. Table 1 summarizes the onset times of the shock driven encounters at different spacecraft. In the solar wind Cluster 2 observed the shock earlier then and Cluster 1, respectively, that is the shock moved dawnward. The shock perturbations occurred almost simultaneously in the magnetosheath at Themis A and D **(**delta t < 12 s**)** so we suppose that it hit the magnetopause somewhere between the two spacecraft. The shock induced impulse propagated both dawnward and duskward (thick arrows in Figure 2) from the point of origin on the magnetopause (depicted as an oval in Figure 2) that is consistent with spiral orientation of the IP shock. In the outer magnetosphere the propagation velocity for the disturbance was about 1348 km/s between Goes 13 and 15 but only about 390 km/s between Van Allen Probes B and A. We believe that the shock induced pulse propagated with the velocity of fast mode waves. The local fast mode speed can be evaluated from Van Allen Probe measurements of the magnetic field and density. At the time of the shock encounter Van Allen Probes A and B were in the high-density plasmasphere at L = 5.5 and L = 5.1, respectively. For a measured local magnetic field of 255 nT for Probe A and 220 nT for

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Probe B and density of ~ 200 cm-3 derived from the potential of both spacecraft, the fast-mode speeds will be ~ 395 km/s and 337 km/s, respectively, which are consistent with our estimates of the propagation velocity derived from the time difference of shock arrivals at the spacecraft. The decrease of the fast mode wave speed in the plasmasphere relative to that in the outer magnetosphere agrees well with earlier studies [e.g., Wilken, 1982; Foster et al., 2016].

Statistical study of shock-initiated signatures of the electric field

In view of the importance of the electric field energizing particles we performed a statistical study of Ey variations of the electric field and associated plasma drift Vx and Vy velocities during the passage of interplanetary shocks. The list of IP shocks used in this study was obtained from Heliospheric Shock Database mantained and generated by the University of Helsinki [http://ipshocks.fi]. They identify shocks by visual inspection and an automated shock detection algorithm. To be included in the database a shock should satisfy the following upstream to downstream jump conditions: Bdown/Bup > 1.2, Ndown/Nup > 1.2, Tdown/ Tup > 1/1.2, for FF Vup-Vdown >20 km/s. The normal vector of the shock (n) was calculated from the magnetic field data and velocities using the mixed mode method [Abraham-Shrauner and Yun, 1976]. When there is data gap in the velocity components the normal was calculated using magnetic field coplanarity [Colburn and Sonett, 1966]. We identified more than 80 events observed by Vann Allen Probes A and B associated with FF IP shocks for the period from 2013 to 2015.

The passage of a shock causes both electric and magnetic field perturbations and their amplitudes to increase with the intensity of IP shocks. The initial peak to peak amplitudes of the shock induced electric field variations ranged mostly from 0.8 mV/m to 6 mV/m and lasted from 1.5 to 6 minutes. We classified their signatures into four different groups according to the initial Ey electric field response to IP shocks. Figure 7 presents examples of observed Ey variation, including a negative pulse, a negative-positive waveform, a positive pulse and pulsations (upper panels) and the corresponding magnetic field response (bottom panels). Figure 8 shows the GSM locations where event in each of these four groups were observed in the X-Y plane. It provides evidence that they are local time dependent. The direction of the initial Ey impulse is predominantly from the dusk-to-dawn direction in the dayside

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magnetosphere, but in the dawn to dusk direction in the nightside magnetosphere within an L-shell range of 3-5.

We used the formula **V = EXB/B^2** to analyze the Vx and Vy flow velocities for the 30 events under the study for which the spin component Ex could be obtained from the **E** dot **B** = 0 assumption. Figure 9 presents the magnitude and direction of the plasma drift velocities Vx observed by Probes A and B in response to interplanetary shocks (red- sunward and blue – tailward directions). The direction of the Vx component of plasma flow is antisunward at all local times except the nightside magnetosphere, where flows are sunward near the sun-Earth line but antisunward towards dawn and dusk. Numbers show that the magnitudes of the flow velocities Vx are a factor of 5 to 10 times stronger near noon (could reach 40 km/s) as this region is fully exposed to compression that are shielded on the nightside.

Our results are consistent with the results of global 3D MHD code simulation for the geosynchronous magnetic field response in the nightside magnetosphere to IP shocks by Wang et al., [2010] presented in Figure 10. The figure shows contours of delta |Bz| and velocity vectors in the equatorial plane (blue regions - Bz negative, red regions - Bz positive). Their model revealed that when a IP shock sweeps over the magnetosphere there are mainly two regions in the nightside magnetosphere, a positive response region in Bz caused by the compressive effect of the shock and a negative response region (blue) which is associated with the temporary enhancement of earthward convection. They believe that the displacement of the nightside magnetopause caused by the IP shock launches a flow in the magnetosphere near the magnetopause that has a significant y-component, and converges toward the X axis. In the vicinity of the Sun-Earth line at ~ -5, -6 Re the flow diverges, producing both an earthward flow (consistent with the sunward direction of plasma flow in the nightside magnetosphere presented in Figure 9) and a tailward flows.

As the direction of the shock normal should determine the direction of propagation of transient perturbations and expected flow direction in the magnetosphere initiated by an IP shock we categorize the events into two groups for spiral and orthospiral orientation of the shock normal. Figure 11 presents the magnitude and direction of the plasma drift velocities Vy observed by Van Allen Probes A and B in response to IP shocks (red- sunward Vx and blue – tailward Vx directions) for spiral and orthospiral orientations of IP shocks. We excluded several

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events from the list of shocks that lacked well defined shock normal. As anticipated, the shock orientation controls the sense of dawn/dusk flows in magnetosphere. The observed directions of azimuthal velocity Vy predominately agree with those expected for the given shock normal orientation: dawnward for shocks that sweeps dawnward across the magnetosphere, diskward for shocks that sweep duskward.

Conclusions

We studied multipoint observations of the electric, magnetic fields, plasma and particles in response to an IP shock on February 27, 2014. We found that the initial encounter of the IP shock with the magnetopause occurred on the early postnoon magnetosphere and the shock induced impulse propagated as fast mode wave both dawnward and duskward from the point of origin, that is consistent with spiral orientation of the IP shock. In the outer magnetosphere the propagation velocity of disturbances was about 1348 km/s between Goes 13 and 15 in the outer magnetosphere, but only about 390 km/s between Van Allen Probes B and A in the inner magnetosphere. The multipoint measurements give evidence that the dayside equatorial magnetosphere exhibited a dusk-dawn oscillatory electrical field with peak to peak amplitudes of ~ 15 mV/m for a period of 30 min. The intensity of electrons in the energy range of 31.5 - 342 KeV shows a regular periodicity with periods corresponding to the shock induced ULF electric field waves. The initial plasma flow velocity in the magnetosphere was directed tailward and dawnward.

Then we performed a statistical study of Ey variations of the electric field and associated plasma drift Vx and Vy flow velocities for 30 events during the passage of interplanetary shocks. The initial peak to peak amplitudes of the transient electric field variations ranged mostly from 0.8 mV/m to 6 mV/m and lasted from 1.5 to 6 minutes. As expected, flow velocity is greatest near the local noon. We classified the shock-induced electric field signatures into four different groups according to the initial Ey electric field response and provided evidence that they are local time dependent. The direction of the Vx component of plasma flow is tailward at all local times except the nightside magnetosphere, where flows are sunward near the Sun-Earth line but antisunward towards dawn and dusk. The observed directions of azimuthal velocity Vy predominately agree with those expected for the given spiral or orthospiral shock normal

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orientation. Our results are consistent with the results of global 3D MHD code simulation of the geosynchronous nightside magnetic field response to IP shock by Wang et al. [2010].

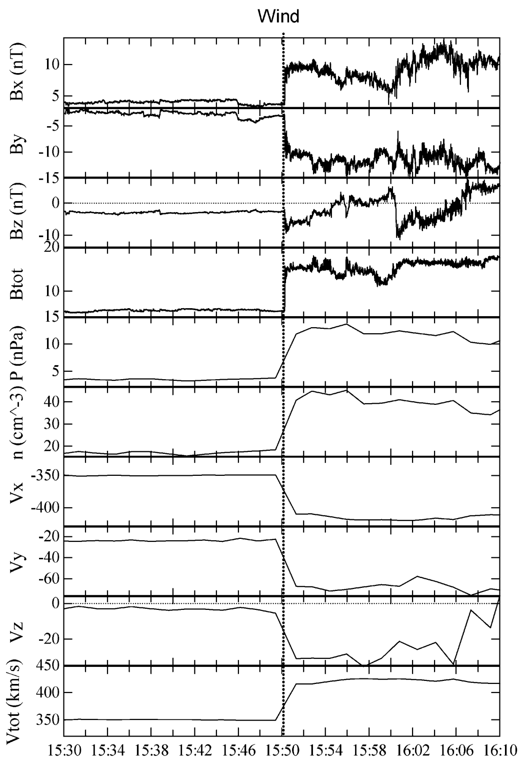


Figure 1. Wind observations of magnetic field and plasma in GSM coordinates from 15:30 UT to 16:10 UT on February 27, 2014. Dashed line shows the time of arrival of an interplanetary shock.

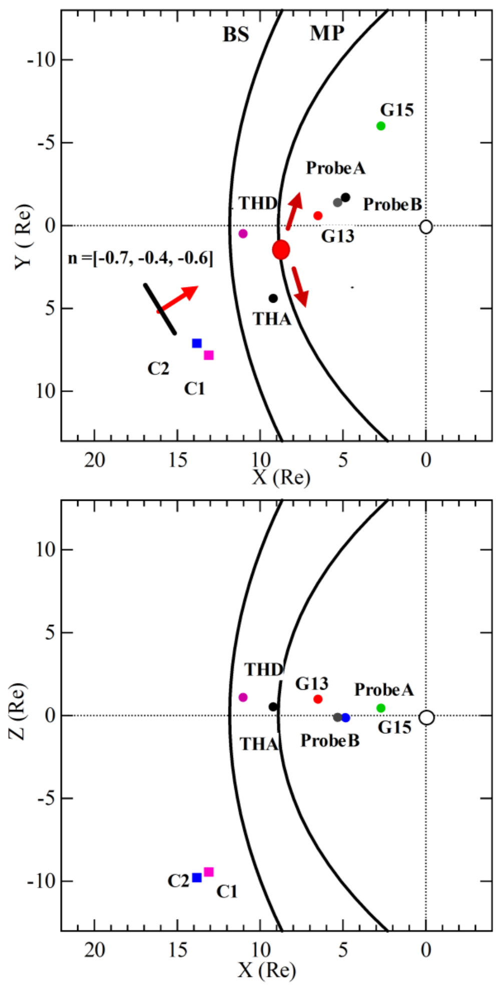
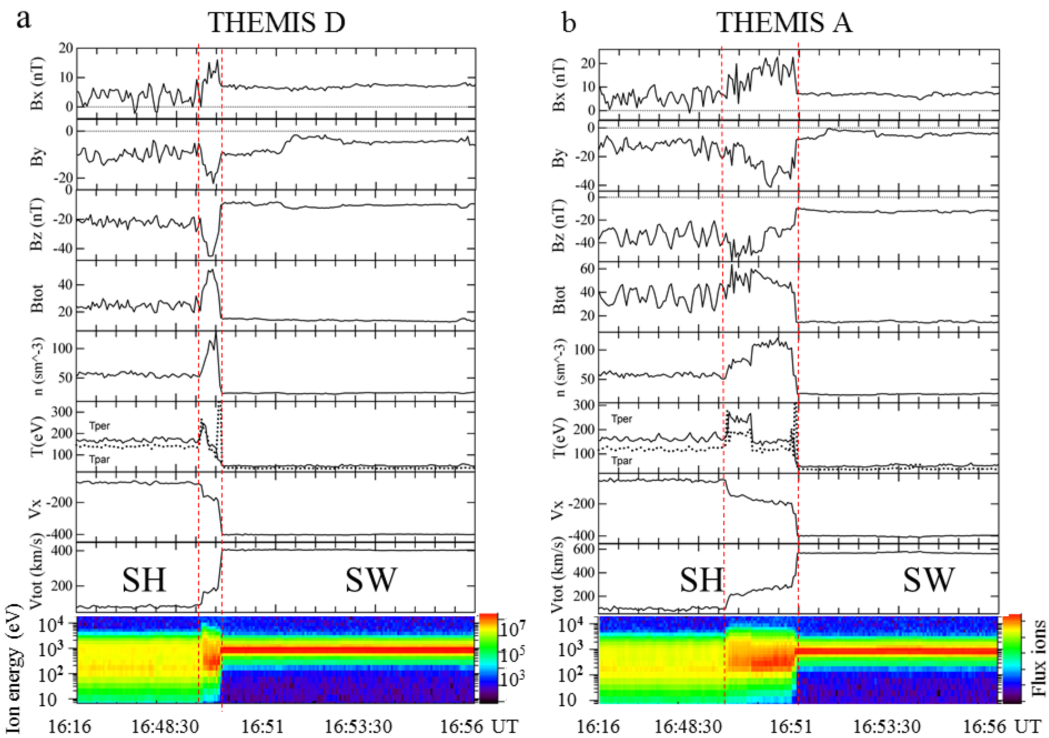


Figure 2. GSM locations of Cluster 1 and 2, THEMIS A, D, Van Allen Probes A and B and GOES 13 and 15 in the X-Y and Z-Y planes at ~ 1650 UT on February 27, 2014. The meaning of the solid oval and thick arrows will be discussed in the text later.



Figures 3 (a, b). THEMIS A (a) and THEMIS D (b) observations of magnetic field in GSM coordinates plasma and energy spectra of ion fluxes from 16:16 UT to 16:56 UT on February 27, 2014.

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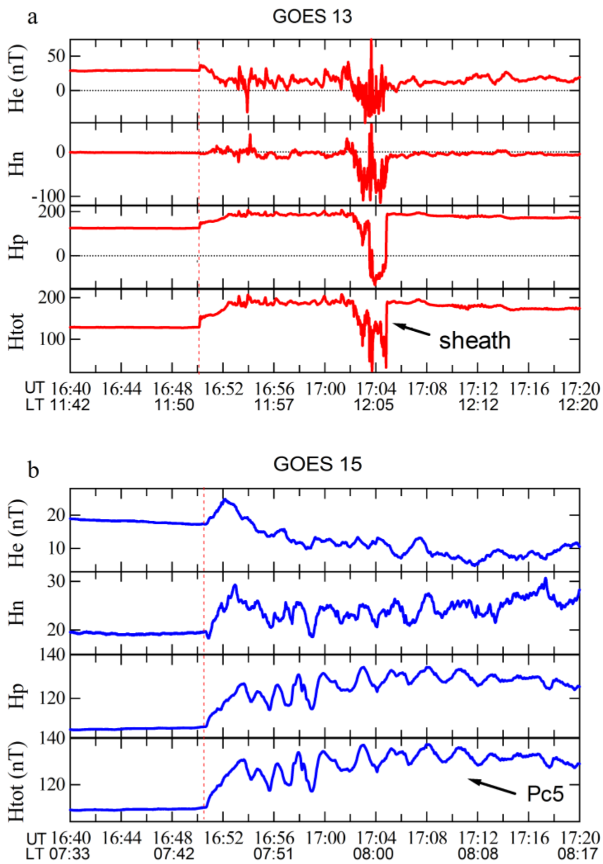

Figures 4 (a, b). GOES 13 (a) and GOES 15 (b) magnetic fields observations in PEN coordinate from 16:40 UT to 17:20 UT on February 27, 2014. Hp is perpendicular to the satellite's orbital plane, He pointing earthward parallel to the satellite-Earth center line, and Hn is perpendicular to both Hp and He and pointing eastward.

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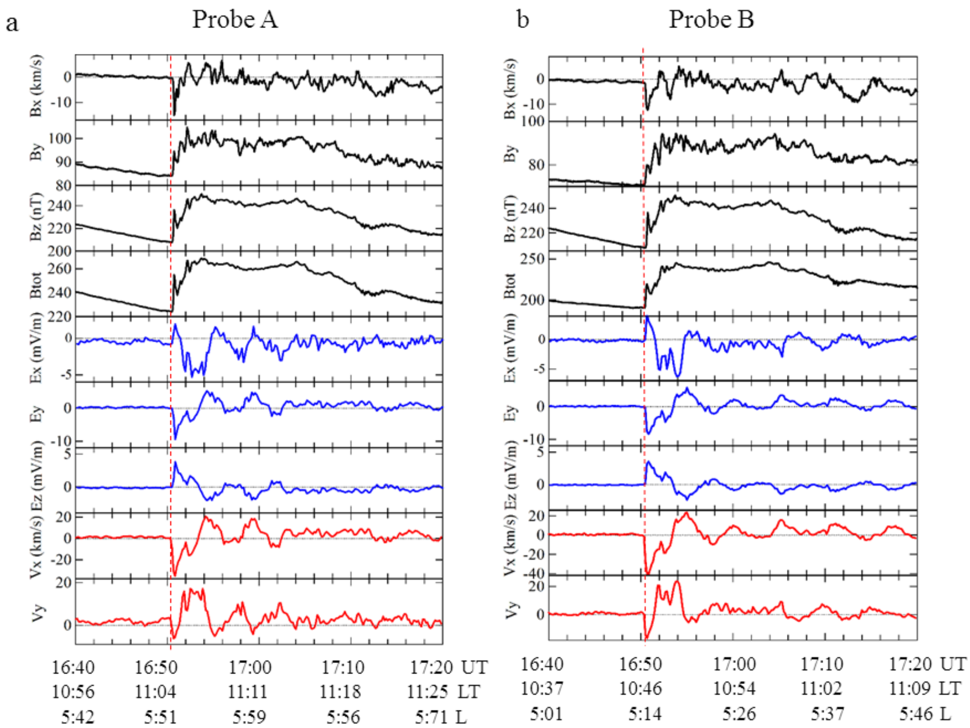

Figures 5 (a, b). Van Allen Probes A (a) and B (b) magnetic and spin-fit electric field observations and the Vx and Vy plasma flow velocities in GSE coordinates from 16:40 UT to 17:20 UT on February 27, 2014.

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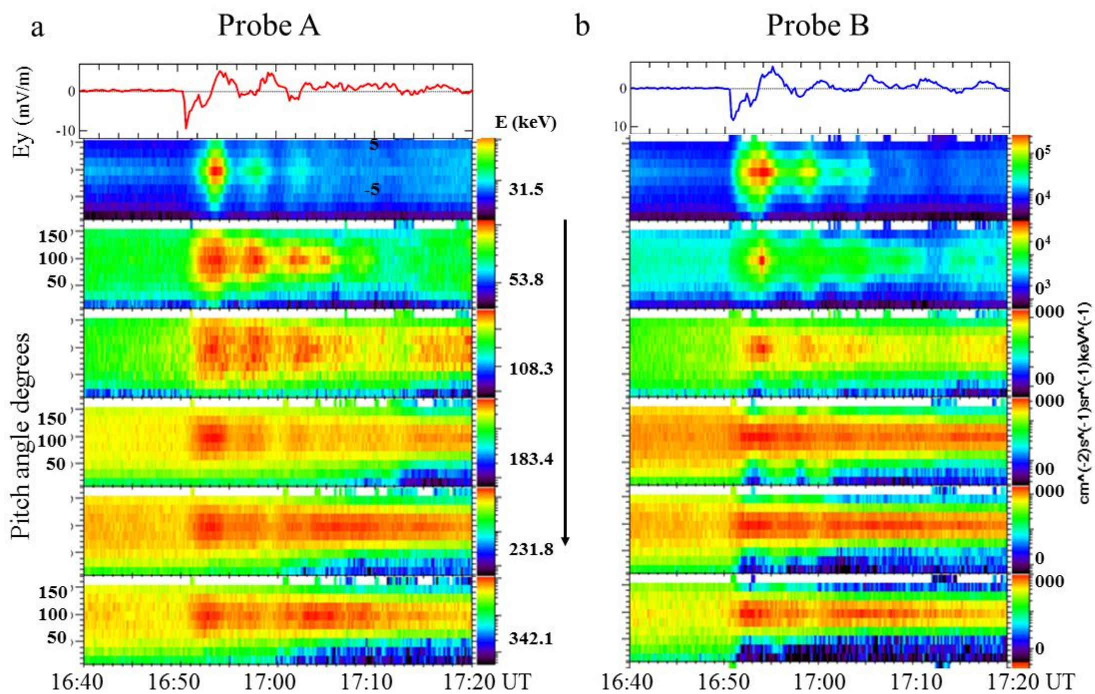

Figures 6 (a, b). Van Allen Probes A (a) and B (b) azimuthal component of the electric field and pitch angle distributions of electron fluxes in the range of energies from 31.5 to 342 KeV, measured by MagEIS instrument from 16:40 UT to 17:20 UT on February 27, 2014. The log fluxes are color coded according to the color bar shown in the right panel.

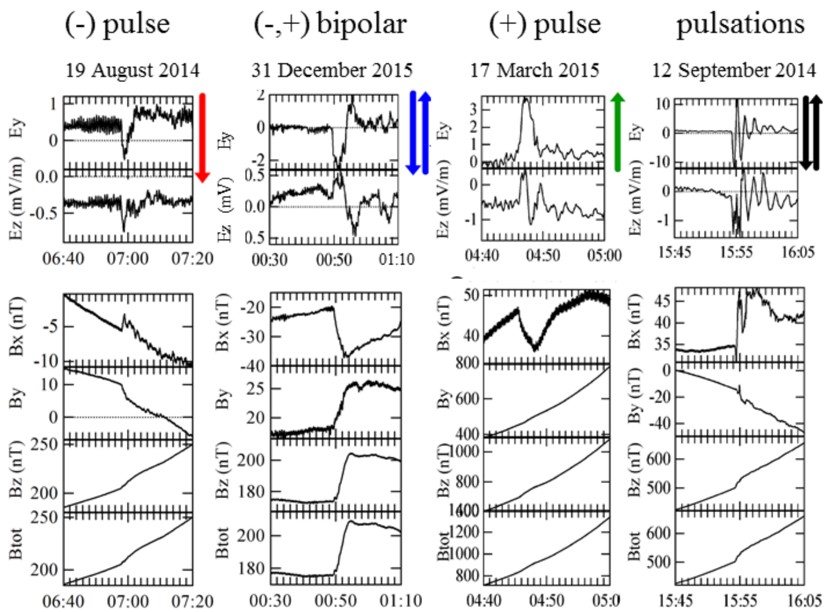

Figure 7. Examples of observed Ey initial variation, including a negative pulse, a negative-positive waveform, a positive pulse and pulsations (upper panels) and the corresponding magnetic field response (bottom panels).

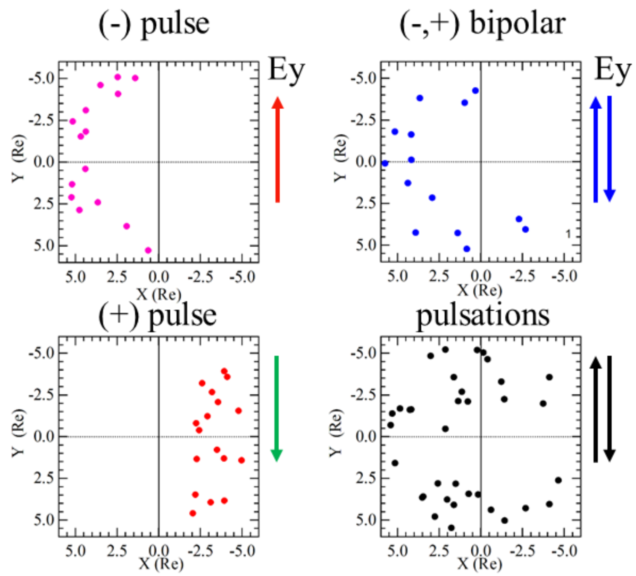

Figure 8. GSM locations where event in each of the four groups were observed in the X-Y plane.

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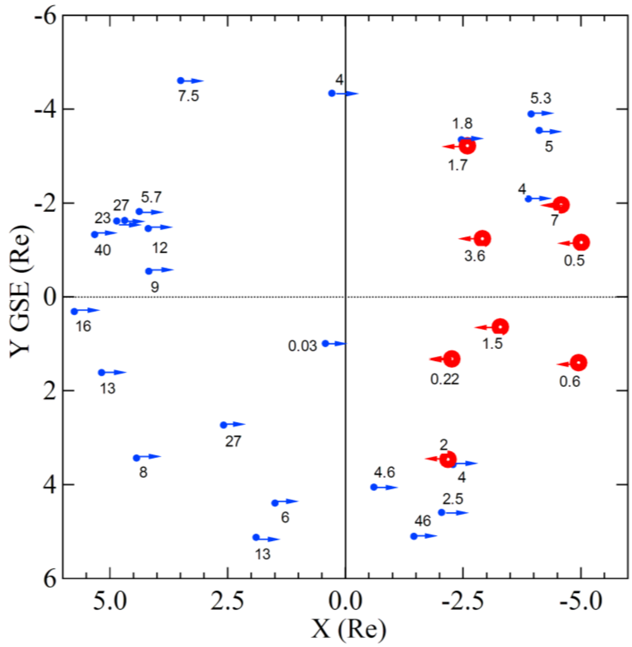

Figure 9. The magnitude and direction of the plasma drift velocities Vx observed by Van Allen Probes A and B in response to interplanetary shocks (red - sunward and blue – tailward directions). Numbers show their magnitudes.

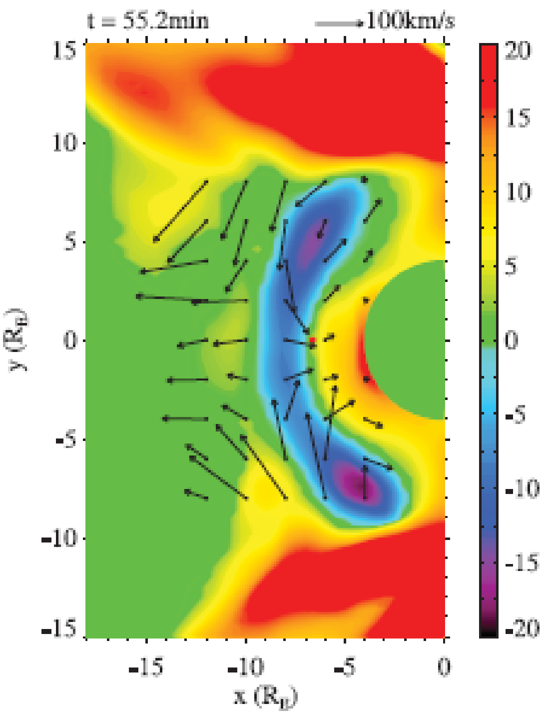

Figure 10. Results of nightside geosynchronous magnetic field response from the global MHD code simulation of IP shock [Wang et al., 2010]. The arrows represent velocity vectors on the equatorial plane.

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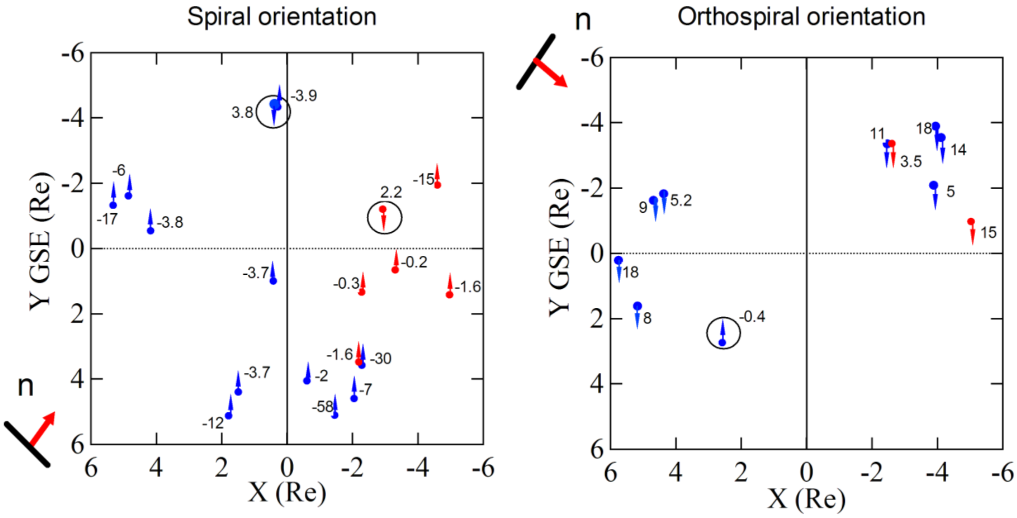

Figure 11. The magnitude and direction of Vy plasma drift velocities observed by Van Allen Probes A and B in response to interplanetary shocks for spiral and orthospiral orientations (red - sunward and blue – tailward Vx directions).

Table 1. Times of encounter of the IP shock with the spacecraft and their locations in GSM coordinates

S/C	Time	Position GSM [X, Y, Z] Re		
Wind	15:50:12	220.90	93.92	31.49
Cluster 1	16:48:46	13.10	7.82	-9.44
Cluster 2	16:48:44	13.83	7.10	-9.78
THEMIS D	16:49:01	11.03	0.48	1.10
THEMIS A	16:49:12	9.22	4.39	0.53
Probe A	16:50:33	4.86	-1.69	0.12
Probe B	16:50:26	5.33	-1.39	-0.10
GOES 13	16:50:07	6.51	-0.60	0.99
GOES 15	16:50:40	2.71	-6.02	0.45

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