The response of the inner magnetosphere to the trailing edges of high-speed solar-wind streams

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ABSTRACT

The effects of the leading edge stream-interface of High-speed Solar-wind Streams (HSSs) upon the Earth's magnetosphere have been extensively documented. The arrival of HSSs leads to significant changes in the plasmasphere, plasma sheet, ring current and radiation belts, during the evolution from slow solar wind to persistent fast solar wind. Studies have also documented effects in the lower ionosphere and the neutral atmosphere. However, only cursory attention has been paid to the trailing-edge stream interface during the transition back from fast solar wind to slow solar wind. Here, we report on the statistical changes that occur in the plasmasphere, plasma sheet, ring current and electron radiation belts during the passage of the trailing-edge stream interface of HSSs, when the magnetosphere is in most respects in an extremely quiescent state. Counter-intuitively, the peak flux of ~1 MeV electrons is observed to occur at this interface. In contrast, other regions of the magnetosphere demonstrate extremely quiet conditions. As with the leading-edge stream-interface, the occurrence of the trailing-edge stream-interface has a periodicity of 27 days, and hence understanding the changes that occur in the magnetosphere during the passage of trailing edges of HSSs can lead to improved forecasting and predictability of the magnetosphere as a system.

1. Introduction

Since the first explanations for geomagnetic storms associated with so-called M-Regions on the Sun (e.g. *Bartels* [1939]; *Parker* [1964]; *Billings and Roberts* [1964]), there have been numerous studies of fast solar wind, its interaction with slow solar wind, and subsequent effects in the magnetosphere. The repeatability of these effects, with a 27 day period, allows some level of predictability and forecasting to take place. Attention has focused on the *onset* of storms and their effects, but not on the *duration* or time of *cessation* of the storm period. Since attention has focused on the leading edge of HSSs, there has been little-to-no work in determining possibilities of predicting and forecasting the effects of trailing edges.

High-speed Solar-wind Streams are features in the solar wind that contain plasma originating from coronal holes (e.g. *Burlaga* [1974], *Gosling et al.* [1978], *Geiss et al.* [1995]). The speed of the plasma within these regions ('fast' solar wind) is typically greater than the speed of the plasma that originated from other regions of the Sun ('slow solar wind'). As a result of this difference in speed two distinct boundaries arise: (i) the 'leading edge' of HSSs, where fast solar wind catches up with preceding slow solar wind, resulting in compression of the plasma and the formation of a Corotation Interaction Region (CIR), and (ii) the 'trailing edge' of HSSs where the fast solar wind outpaces the slow solar wind following it, leading to a region of rarefaction. The effects of the leading-edge interaction region and HSS upon the Earth's magnetosphere have been studied in detail in numerous previous studies since such structures are known to cause geomagnetic storms (e.g. *Tsurutani et al.*, 2006; *Denton and*

Borovsky [2006]; *Borovsky and Denton* [2006], *McPherron and Weygand* [2006], and references therein). In contrast there have only been a few limited studies of trailing edges of HSSs (e.g. *Burlaga et al.* [1990], *Burton et al.* [1999], *Simunac et al.* [2010]) since the arrival of this region of solar wind has not been directly linked to repeatable changes in the state of the magnetosphere.

A recent study used both data analysis and simulations to comprehensively describe the solar-wind properties of trailing edges of HSSs [*Borovsky and Denton*, 2016]. The study contrasted the leading edge and the trailing-edgo of HSSs. It was shown that critical locations within trailing edges of HSSs can be readily identified using a combination of solar-wind parameters, including the solar-wind velocity, heavy-ion charge states, and solar-wind entropy. One conclusion to be drawn from the study is that the magnetosphere is bathed in a distinct type of solar wind before, during, and after the arrival of a trailing edge. And since such structures are repeatable with a period of 27 days (as with the leading edge of a HSS), understanding the effects of the trailing edges on the magnetosphere will enhance our ability to predict and hence forecast the likely state of the magnetospheric system in advance. Predictions are of particular interest since the peak fluxes of the electron radiation belt occur during the passage of trailing edges of HSSs.

The work carried out in this current study is aimed towards extending the work of *Borovsky and Denton* [2016] by considering the effects of trailing edges in the solar wind upon the plasmas and particle populations within the Earth's magnetosphere. Changes in the Earth's magnetic field are examined during the passage of trailing edges, along with changes in the plasmas of the magnetotail, the plasmasphere, the plasma sheet, the ring-current, and the radiation belts. A combination of case-studies and superposed epoch analyses are performed to explore the properties of the magnetosphere before, during, and after the arrival of trailing edges. Our findings document some of the effects of trailing edges of HSSs upon the magnetosphere and demonstrate that understanding these phenomena is important for developing a system-science view of the magnetosphere.

2. The Solar-Wind Properties of Trailing Edges of HSSs

Figure 1 contains a schematic diagram of the solar wind velocity during the passage of a single HSSs, including the location of the compression region (CIR) on its leading edge and rarefaction region on its trailing edge (see also Figures 1, 2, and 5 from *Borovsky and Denton* [2016]). The precise location of the interface between fast plasma that is of coronal-hole origin and slow plasma that originates in the streamer belt is generally straight-forward to identify on the leading edge of a HSS (e.g. the east-west flow deflection in the solar wind velocity), and challenging to identify on the trailing edge of a HSS. As outlined in *Borovsky and Denton* [2016] a combination of parameters including the magnetic field strength, the intensity of the electron strahl, the orientation of current sheets, the intensity of the vorticity, the heavy-ion charge states, the proton specific entropy, and the solar wind velocity profile all show distinct signatures in the trailing edge rarefaction region. The authors in that study identified an inflection point in the solar-wind velocity as the best indicator of the fast-to-slow-wind stream interface. Fluid simulations supported this parameter as marking the fast-to-slow transition based on pressure balance; see *Borovsky and Denton* [2016] Figure 11 and Figure 12 for a detailed description of the fluid simulations. Based on the findings from that study, it is clear that during (and after) the arrival of trailing edges of HSSs in the vicinity of Earth, the magnetosphere will be bathed in a different type of solar-wind, with different plasma parameters, than those which are encountered on the leading edge of HSSs.

3. Case Study: 2-22 October 2005

The solar wind conditions during 10 days around the passage of a HSS in October 2005 are shown in Figure 2, along with the AE index. Clear signatures of the leading edge of the HSS are evident with an increase in solar wind density occurring prior to the arrival of fast wind (V_{sw}>600 km s^{-1}) - the density (and the magnetic-field strength) increases due to fast wind catching up with preceding slow wind and generating a compression region. Non-compressive density structures also play a role in the pressure increase. The combination of high density, high solar wind speed, and increased magnetic field, all apparent in Figure 2, combine to drive activity in the magnetosphere before, during, and after the leading edge of a HSS. Such activity is particularly strong when the interplanetary magnetic field (IMF) has a strong southwards component [cf. *McPherron et al.*, 2009]. The transition from slow wind to fast wind on the leading edge of the HSS can be clearly identified by the east-to-west deflection in the flow velocity [*McPherron and Weygand*, 2006].

The particular event shown in Figure 2 is chosen as a case-study due to the presence of a clear reverse west-to-east flow deflection in the y-component of the velocity that occurs on the trailing edge of the HSS. It is noted that such west-to-east signatures are not always clearly evident for all trailing edges. However, also co-located with the reverse velocity deflection is an inflection in the solar wind velocity gradient. It is this signature (in many cases much easier to identify than changes in other parameters) that marks the fast-to-slow stream interface in the trailing edge of a HSS.

4. Data and Statistical Analyses

The data used in the current study are taken from a variety of sources. Changes in the bulk parameters of the solar wind are explored using the OMNI2 database of solar-wind observations [*King and Papitashvili*, 2005] at one-hour resolution. Solar wind composition during the passage of trailing edges is determined using measurements from the SWICS instrument onboard the ACE satellite [*Gloeckler et al.*, 1998]. Changes in the magnetic field in the magnetosphere are determined from 1-minute resolution magnetometer observations from the GOES spacecraft orbiting at geosynchronous orbit (GEO) [*Dunham et al.*, 1996; *Singer et al.*, 1996]. Plasma parameters (from ~1 eV to ~2 MeV) are provided by measurements from Los Alamos National Laboratory (LANL) spacecraft, also on orbit at GEO.

In order to reveal features that are common to the trailing edges of HSSs we first perform a statistical superposed-epoch analysis of a number of solar wind and plasma parameters from the inner magnetosphere during a collection of trailing-edge events. The events used are sub-selected from the original list of 54 trailing-edge events (1998-2008) given in Table 1 of *Borovsky and Denton* [2016]. A subset of 43 events are identified where there was no arrival of a second HSS for at least 36 hours after the time of the zero epoch. The time of the bend in the solar wind speed (change in gradient) is the zero epoch for the study [*Ilie et al.*, 2008]., since, after consideration of a variety of other parameters, it was identified as the clearest boundary (stream-interface) between the fast and slow solar winds [*Borovsky and Denton*, 2016]. It is intended that the statistical analysis of these 43 events will reveal the reaction of the magnetosphere to the arrival and progression of a trailing-edge alone, and the results will be uncontaminated by the subsequent arrival of known-storm drivers in the solar wind.

4.1 Solar Wind

Figure 3 contains plots of eight superposed parameters for the list of 43 trailing edges used in this study, at one-hour resolution. Four solar wind parameters are plotted in the left column (solar wind velocity, v_{sw}; solar wind density, N_{sw}; solar wind ram pressure, P_{ram}; solar wind proton temperature, T_{sw}) and four geomagnetic indices are plotted in the right column (auroral electrojet index, AE; planetary Kp index; pressure-corrected disturbance storm-time index, Dst*; polar cap index, PCI), with values for seven of the parameters taken from the OMNI2 database. The pressure-corrected Dst* index is calculated based on the formula given in *Borovsky and Denton* [2013]. The mean and the median of each superposition are shown in black and blue with the upper and lower quartiles shown in red and purple, respectively. The grey shading indicates the standard deviation of the superpositions.

With regard to solar wind parameters plotted in the left column, the superposition of the solar-wind velocity over this fortnight shows that prior to zero epoch the velocity was elevated above ~550 km s^{-1} for ~6 days. At zero epoch a bend is evident in the velocity after which the velocity fall to between ~300-400 km s^{-1} for ~2-3 days. The solar wind number density prior to the zero epoch fluctuates around 3 cm^{-3} and then commences a gradual rise over the following 2-3 days. As a result of these density and velocity changes, the ram pressure of the solar wind is minimized (and reasonably symmetric) around zero epoch. The solar wind temperature is highest in the fast wind prior to zero epoch, falls approaching the stream interface, and continues falling over the following two days before commencing a gradual increase.

With regard to the terrestrial indices plotted in the right column, the AE index is elevated during the fast wind and then falls to a minimum at zero epoch, before rising slowly over the following days. The Kp index shows a similar trend with the highest activity occurring in the days prior to zero epoch, and the minimum activity occurring very close to the trailing-edge stream interface. Activity remains at very low levels for ~2-3 days after zero epoch. The pressure-corrected Dst* index fluctuates around zero close to zero epoch and also remains at this level for ~2-3 days after zero epoch. The level of the PCI is very similar with the minimum occurring in the trailing-edge transition region. All geomagnetic indices demonstrate that while activity is elevated in the fast solar wind prior to the zero epoch, the passage of the stream-interface marks the commencement of a period when geomagnetic activity falls to very low levels (and remains at very low levels for in excess of 48 hours). With the arrival of a trailing edge stream interface the magnetosphere enters a calm state, with low solar wind driving.

In order to explore the precise nature of the solar wind bathing the magnetosphere at this time we perform a superposed epoch analysis of the solar-wind categorization scheme developed by *Xu and Borovsky* [2015]. This scheme assigns a category to the origin of the solar wind with a one hour time cadence. The four categories of solar-wind origin are: (1) Ejecta, (2) Coronal Hole, (3) Sector Reversal, and (4) Streamer Belt. Figure 4 contains a plot of this superposition for the 43 events considered in Figure 3 (top panel). Also shown in Figure 4 are charge-state ratios of the solar wind, the C^{6+}/C^{4+} ratio (middle panel) and the O^{7+}/O^{6+} ratio (bottom panel), from the SWICS instruement on-board the ACE spacecraft [*Gloeckler et al.*, 1998] previously examined in *Borovsky and Denton* [2016]. The plots cover four days with the zero epoch being the time of the trailing edge of a HSS (bend in velocity). This plot demonstrates that the solar wind two days prior to zero epoch almost all originated in coronal holes (fast solar wind, as expected). The assigned origin of the solar wind then shifts in 24 hours prior to the trailing edge to being streamer belt with some admixture of current-sheet origin solar wind. This categorization persists for the two days following the trailing edge.

The charge state ratios plotted in Figure 4 demonstrate similar gradients, showing a steady increase during the passage of the trailing edge. Since the charge state of the ions in the solar wind is a good marker for their origin on the Sun, these plots both demonstrate that the solar wind bathing the magnetosphere 48 hours prior to the trailing edge is substantially different from the solar wind bathing the magnetosphere 48 hours after the trailing edge has passed. Figure 3 also helps confirm that the events within the superpositions shown in Figure 3 are largely uncontaminated by known storm-drivers (e.g. ejecta and fast solar wind from coronal holes) following zero epoch.

Taken together, the plots in Figure 3 and Figure 4 demonstrate that the magnetosphere passes through a repeatable set of conditions during the passage of a HSS trailing edge. Examinations of the indices leads to the conclusion the system is entering a period that would be considered very clam by most observers. However, it is unclear how this low driving manifests itself with regard to magnetospheric plasmas. Are the magnetic field and the plasmas of the magnetosphere also in a quiescent state?

4.2 Magnetospheric Magnetic Field

The changes in magnetic field observed at GEO during the passage of the leading-edge of a HSS have been investigated in detail by *Borovsky and Denton* [2010a] using magnetometer observations from the GOES spacecraft [*Dunham et al.*, 1996; *Singer et al.*, 1996]. Fluctuations in the magnetospheric magnetic field may drive radial diffusion of electrons in the outer radiation belt (e.g. *Fälthammar* [1965], *Shprits et al.* [2008a; 2008b]) and/or energize these electrons [*Rostoker et al.*, 1998; *Mathie and Mann*, 2000; *Elkington et al.*, 2003]. On the leading edge of the HSS the increased density in the solar wind leads to compression of the magnetosphere and a sharp increase in the magnitude of the dayside field strength |**B**| and also a rapid increase in the field fluctuations [*Borovsky and Denton*, 2010a; 2016b]. Around 24 hours after the passage of the leading edge of the HSS, the field magnitude declines but the field fluctuations continue while-ever fast solar wind impinges on the magnetosphere. To investigate how the magnetospheric magnetic field at GEO changes during the trailing-edges of HSSs, superposed parameters of the field magnitude, |**B**|, and the 1 minute change in the field magnitude (defined as $\Delta B(t) = B(t + 1\text{ min}) - B(t)$) are plotted in Figure 5 [*Dunham et al.*, 1996; *Singer et al.*, 1996]. It is apparent that the magnitude of the field around noon is, on average, reduced for ~24-48 hours prior to the arrival of the trailing edge stream interface (~105 nT) compared with the usual noon field magnitude (~120 nT). The field magnitude increases back to this level at the same time as the arrival of the trailing edge, close to zero epoch. In contrast, fluctuations in the field magnitude cease more than 24 hours prior to the arrival of the trailing edge stream interface and remain minimized until at least 24 hours after the stream interface has passed - this roughly corresponds to the period of rarefaction in the solar wind within the trailing edge. Given the cessation in field fluctuations, it is logical to assume that only minimal acceleration and/or diffusion of electrons in the outer belt could take place via field fluctuations during this period.

4.4 Plasmasphere and Plasma Sheet

The effects of the trailing edges on the plasmasphere and plasma sheet can be evaluated by examining plasma data measured at GEO by the Magnetospheric Plasma Analyzer (MPA) instruments onboard multiple LANL satellites [*Bame et at.*, 1993]. MPA measures the distributions of ions and electrons from ~1 eV to ~40 keV [*Thomsen et al.*, 1999]. Calculation of moments of the distribution yield the density and temperature of the hot electron population (plasma sheet) and the hot and cold ion populations (plasma sheet and plasmasphere) [*Thomson et al.*, 1999]. The flow velocity of the cold ion population is also obtained. The plasma sheet is known to respond strongly to the leading edge of HSSs and these changes have been studied in detail (e.g. *Denton and Borovsky* [2006; 2009]) with an increase in particle precipitation also demonstrated statistically and during case-studies (e.g. *Longden et al.* [2008]; *Sandanger et al.* [2009] *Kavanagh et al.* [2012]; *Clilverd et al.* [2013]; *Rodger et al.* [2007; 2010]). Prior to the arrival of the leading edge of the HSS an elevated region of solar wind density is encountered. Approximately 2 hours later elevated densities are encountered in the electron and ion plasma sheet around local midnight at GEO [*Denton and Borovsky*, 2007].

In the plasmasphere the increase in magnetospheric convection close to the leading edge of the HSS leads to the erosion of the outer regions and the formation of a plasmaspheric drainage plume (e.g. *Moldwin et al.* [1994]; *Goldstein and Sandel* [2005]; *Borovsky and Denton* [2006; 2008]; *Goldstein et al.* [2014]). Changes in particle populations closer to Earth, that are know to have close links to the plasmasphere (e.g. the ionosphere [*Denton et al.*, 2007; *Pokhotelov et al.*, 2010], the lower atmosphere (e.g. *Mlynczak et al.*, [2008, 2010a, 2010b]; *McGranaghan et al.*, [2014]) have also been identified.

In order to examine some aspects of the reaction of the plasma sheet and the plasmasphere to the arrival and passage of trailing edges, hot ion data from MPA instruments at GEO are again utilized. Figure 6 contains plots of the hot ion density and temperature as a function of local time and epoch time (for the 43 events from Figure 3), along with the cold ion density and the cold ion flow speed in the equatorial plane. The hot ion density decreases over ~48 h prior to the passage of the trailing edge stream interface as the level of convection decreases (the ion and electron plasma sheet densities and temperatures are very closely correlated with the level of convection). Prior to zero epoch convection has fallen to a very low levels on average (cf. Figure 3) and the ion plasma sheet at this time has likely retreated radially outwards beyond GEO. However, in the 24 hours following zero epoch the plasma sheet is again detected at GEO with low density and low temperature. With respect to the cold ions of the plasmasphere, it is clear that during the ~4-5 day period of elevated solar wind speed during the HSS, and the concurrent high levels of convection, a high density plasmaspheric drainage plume is detected at GEO (at ~18 LT). Flow speeds in the plume are typically sunwards (cf. *Borovsky and Denton* [2008]) with a magnitude of ~12-16 km s^{-1}. Prior to the trailing edge arrival, the density in the plume decreases and around zero epoch the flow speeds indicate a return to corotation of the plasma (flow speeds of ~ 8 km s^{-1}) maximized at dawn and dusk.

For comparison, the superposed hot electron density and temperature are shown in Figure 7, along with the measured (negative) spacecraft surface potential - a quantity known to be strongly correlated with the electron plasma sheet temperature [*Thomsen et al.*, 1999; *Denton et al.*, 2016]. Similar to the ion plasma sheet, the electron plasma sheet density and temperature decreases in the days prior to the arrival of the trailing edge stream interface as magnetospheric convection falls to very low levels at this time. Around 24 hours prior to zero epoch it is clear that the electron plasma sheet has retreated radially outwards to beyond GEO and the density and temperature remain very low until ~24 hours after zero epoch. It is apparent that the magnitude of the spacecraft potential measured by MPA is maximized during the passage of the HSS prior to the trailing edge when the electron temperature is high and the surface potential may reach 1000s of Volts (negative). For the 48 hour period centered on zero epoch, the electron plasma sheet is outside of GEO and the measured surface potential is, on average, at very low levels.

4.5 Outer Radiation Belt

The leading edge of a HSS is known to frequently lead to dropouts in the outer electron radiation belt flux (e.g. *Freeman* [1964], *Onsager et al.* [2002; 2007], *Green et al.* [2004], *Borovsky and Denton* [2009b], *Morley et al.* [2010]) and phase-space density (e.g. *Hartley et al.* [2013]) and explanations of the dropout typically invoke some combination of magnetopause shadowing, outwards radial diffusion, and particle precipitation (e.g. *Elkington et al.* [2003], *Shprits et al.* [2008a; 2008b], *Borovsky and Denton* [2009a; 2009b], *Clilverd et al.* [2013], *Turner et al*. [2012], *Hartley and Denton* [2014], *Rodger et al.* [2016] and references therein). Following the initial dropout, which occurs in close proximity in time to the leading edge of the HSS, the outer radiation belt recovers and electrons appear to be energized during the period of fast solar wind that follows the leading edge [*Borovsky and Denton,* 2010b]. Here, we examine how the outer electron radiation belt measured at GEO responds during the passage of the trailing edge of a HSSs. Figure 8 contains plots of the normalized superposed electron flux measured by the LANL Synchronous Orbit Particle Analyzer (SOPA) instrument, also on orbit at GEO [*Belian et al.*, 1992; *Cayton and Belian*, 2007] for the same 43 events discussed above. The top panel shows the normalized electron flux as a function of energy for pitch angles between 45-55°, averaged over all local times. The flux plotted here is normalized by the mean flux observed during the 35 days prior to zero epoch (cf. Figure 10). It is clear that the electron flux at the highest energies (MeV) is substantially increased in the days prior to zero epoch (when the fast solar wind in the HSS is passing the Earth). However, it is also apparent that the flux for the highest energies reaches a maximum very close to or just after the passage of the stream interface, before decreasing and then falling to lower levels over the following few days. The highest electron flux levels measured between 1.3 and 1.7 MeV occur in the 48 hours centered on the trailing edge, when almost all measures of geomagnetic and solar activity are at their lowest levels. Interestingly, a recent study by *Hendry et al.* [2013] identified the same recovery-from-HSS storm period as the peak time for measured electron precipitation from the radiation belts into the atmosphere.

The second and third panels in Figure 8 show the variation of the density and temperature of the electrons when relativistic bi-Maxwellian fits are made to the counts from the SOPA instrument. Previous results using this technique applied to the leading edge of HSSs demonstrated that important insights can be derived regarding the relativistic electron flux dropout and recovery [*Denton et al.*, [2010], *Borovsky and Cayton* [2011], *Denton and Borovsky* [2012], *Hartley et al.*, 2014]. Close to the leading edge of a HSS the flux at relativistic energies decreases sharply over a very short timescale (minutes). During the recovery from dropout the temperature and density behave differently from the flux. The density recovers first in the hours following the dropout and the temperature recovers slowly

[*Borovsky and Denton*, 2010; *Denton et al.*, 2010] - the radiation belt recovery from dropout on the leading edge of a HSS can be described as the return of a high-density lower-energy population that is energized slowly (the temperature increases) over a period of days following the leading edge of the HSS. The plots shown in Figure 8 also reveal important differences between the flux behavior and the density-temperature behavior. The middle panel of Figure 8 demonstrates that the density is elevated in the days prior to the trailing edge. The density then begins to decrease around zero epoch and this decrease continues for ~48 h. The temperature shown in the bottom panel of Figure 8, is elevated prior to zero epoch and remains elevated through the passage of the trailing edge stream interface - the peak temperature at ~1 MeV occurs ~24 hours after the trailing edge interface. In contrast to the density, the temperature does not begin to fall significantly until ~48 hours after the passage of the trailing edge. A summary schematic of these changes is provided in Figure 9 where the gross behavior of the relativistic electron flux, F, density, N, and temperature, T in the outer radiation belt encountered at GEO, around the passage of a trailing edge, are summarized.

5. Repeatability of Trailing Edges and Their Effects on the Magnetosphere

In Figure 10 a superposition of the MPB index [*Chu et al.*, 2015] is plotted for 35 days prior to the trailing edge and 35 days after the trailing edge. The MPB index is being developed to identify periods of substorm activity. However, here we use the index as a general measure of magnetospheric activity and also a proxy for the likelihood of a 'seed population' of the electron radiation belt. The variation of the MPB index shows a clear 27 day periodicity centered on the time of zero epoch. The index peaks during the passage of HSSs, highlighting the frequent and recurrent substorms that occur during these solar wind drivers. The index is minimized very close to the passage of the trailing edge when the occurrence of substorms is infrequent. The second panel shows the superposition of the 1.1-1.5 MeV flux from the LANL/SOPA instrument (cf. *Borovsky and Denton* [2009b; 2010b], *Denton et al.* [2010]). Again, there is a 27 day periodicity to the fluxes - however, in contrast to the MPB index, the peak in the SOPA flux is centered on the time of the trailing edge, very close to zero epoch. The third panel shows the superposition of the spacecraft surface charging measured by LANL/MPA instruments within one hour of local midnight [cf. *DeForest* [1972], *Thomsen et al.* [2013]; *Denton et al.,* 2016]. Again, a clear 27-day periodicity is evident. The time of most elevated (and potentially dangerous) charging is in the period of fast wind prior to the trailing edge). The time when the spacecraft charging is at its lowest level (most benign) is precisely centered on the passage of the trailing edge stream interface at zero epoch. Both the radiation belt electron flux and the level of spacecraft charging are potential hazards to the operation of orbital assets. However, it is clear that for HSSs and HSS-driven storms, the peak in the radiation belt flux is maximized (and potentially most dangerous) at the trailing edge stream interface whilst the level of surface charging is minimized (and most benign).

6. Discussion and Conclusions

It has previously been demonstrated that a 'calm-before-the-storm' in the magnetosphere occurs prior to the arrival of HSSs [*Borovsky and Steinberg*, 2006; *Borovsky and Denton*, 2009a, etc] and such calms-before-storms have also been noted in activity within the Earth's ionosphere [*Clilverd et al.*, 1993]).

The transition from fast solar wind to slow solar wind that clearly occurs at the trailing edge stream interface of HSSs certainly marks the onset of a calm in geomagnetic (and solar) activity. However, whilst the magnetospheric magnetic field, the plasma sheet, and the plasmasphere evince little activity that could be considered 'storm-like', the flux of relativistic electrons in the outer radiation belt reaches a peak. The hardness of the radiation belt spectra (temperature) as measured at GEO remains elevated actually continues to increase for ~48 hours after the passage of the trailing edge. At a time when all geomagnetic and solar indices point to quiescent conditions, fluxes in the radiation belt are at a highly elevated level.

We conclude this study with a summary by enumerating the following points.

1. The solar wind impinging on the magnetosphere during the passage of trailing edges of HSSs is different to that during the leading edges of HSSs (see *Borovsky and Denton* [2016]). The effects of the trailing edge on magnetospheric plasmas has received little attention to date. This study has addressed this issue statistically and detailed some of the effects occuring during the passage of trailing edges.

2. The occurrence of trailing edges repeats with a 27 day period. Hence, understanding the changes in magnetospheric plasmas and related quantities provides some level of forecasting and predictability of the state of the magnetosphere 27 days after the passage of a trailing edge, and also some knowledge of

the likely future state ~27 days in advance.

3. Solar wind and geomagnetic indices indicate that the magnetosphere is in many ways in a very quiescent state during the passage of a trailing edge. The trailing edge stream interface marks the beginning of a calm period of geomagnetic activity. Global magnetospheric convection, substorm activity, plasma sheet density, etc., are all at very low levels and have been quantified as a function of time relative to the passage of the trailing edge stream interface.

4. The plasma sheet electron temperature, as measured at GEO, is very low during the passage of the trailing edge. This results in minimal spacecraft surface charging, even in the region close to local midnight when the satellite is in darkness. Spacecraft anomalies related to surface charging will be less likely to occur under such conditions.

5. In contrast to other magnetospheric parameters investigated, the flux in the electron radiation belt reaches its peak very close to the time the trailing edge stream interface. The temperature (spectral hardness) in the outer radiation belt measured at GEO remains at an elevated level for more than 48 hours after the passage of the stream interface. Such conditions may pose a risk to orbiting spacecraft.

6 Due to the connection between trailing edges measured at Earth, and their origin on the Sun, the physical behavior of the magnetosphere during the passage of trailing edges is repeatable with a 27 day

periodicity, and hence predictable to some degree.

7. Since solar wind structures impinge on the planets situated radially inwards and outwards from Earth, the results from this study may have applications for understanding solar-wind/planetary coupling in other locations within the Solar System.

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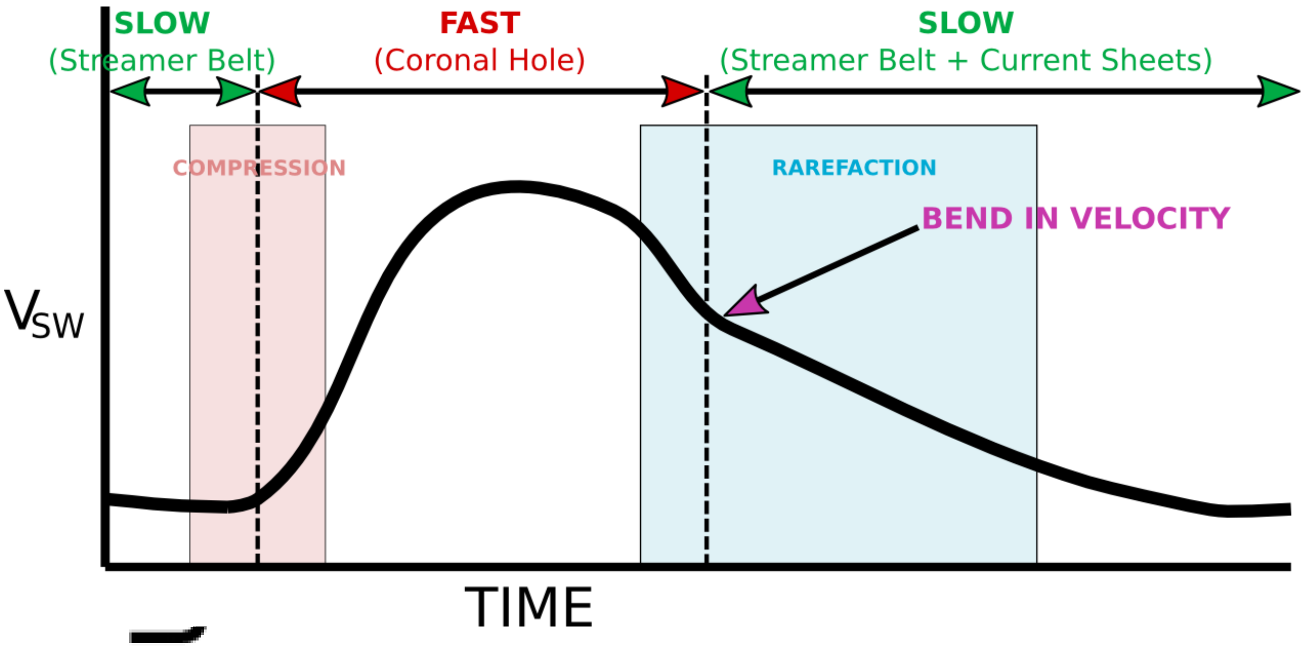


Figure 1. Schematic diagram of the leading edge and trailing edge of a high-speed solar wind stream. As fast solar wind catches up with the preceding slow wind it forms a compression region on the leading edge. The transition of the velocity back to slow solar wind results in a rarefaction region and a bend in the gradient of the velocity (also see *Borovsky and Denton* [2016]). Changes in the state of the magnetosphere during the passage of the trailing edge have received little attention to date.

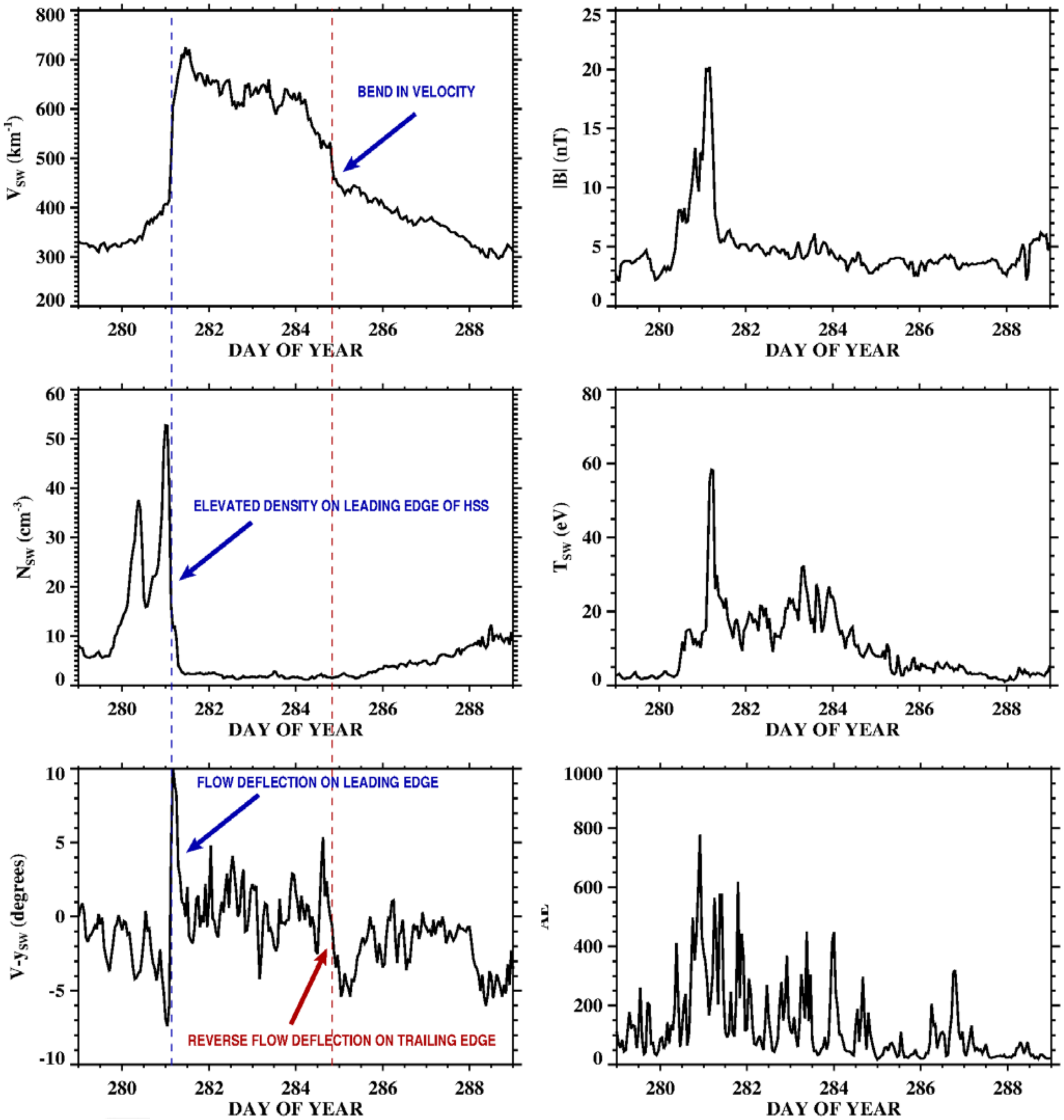


Figure 2. Assorted solar-wind parameters and the AE index, taken from the OMNI2 database during a 10 day period containing the passage of a HSSs between 6-16th October 2005.

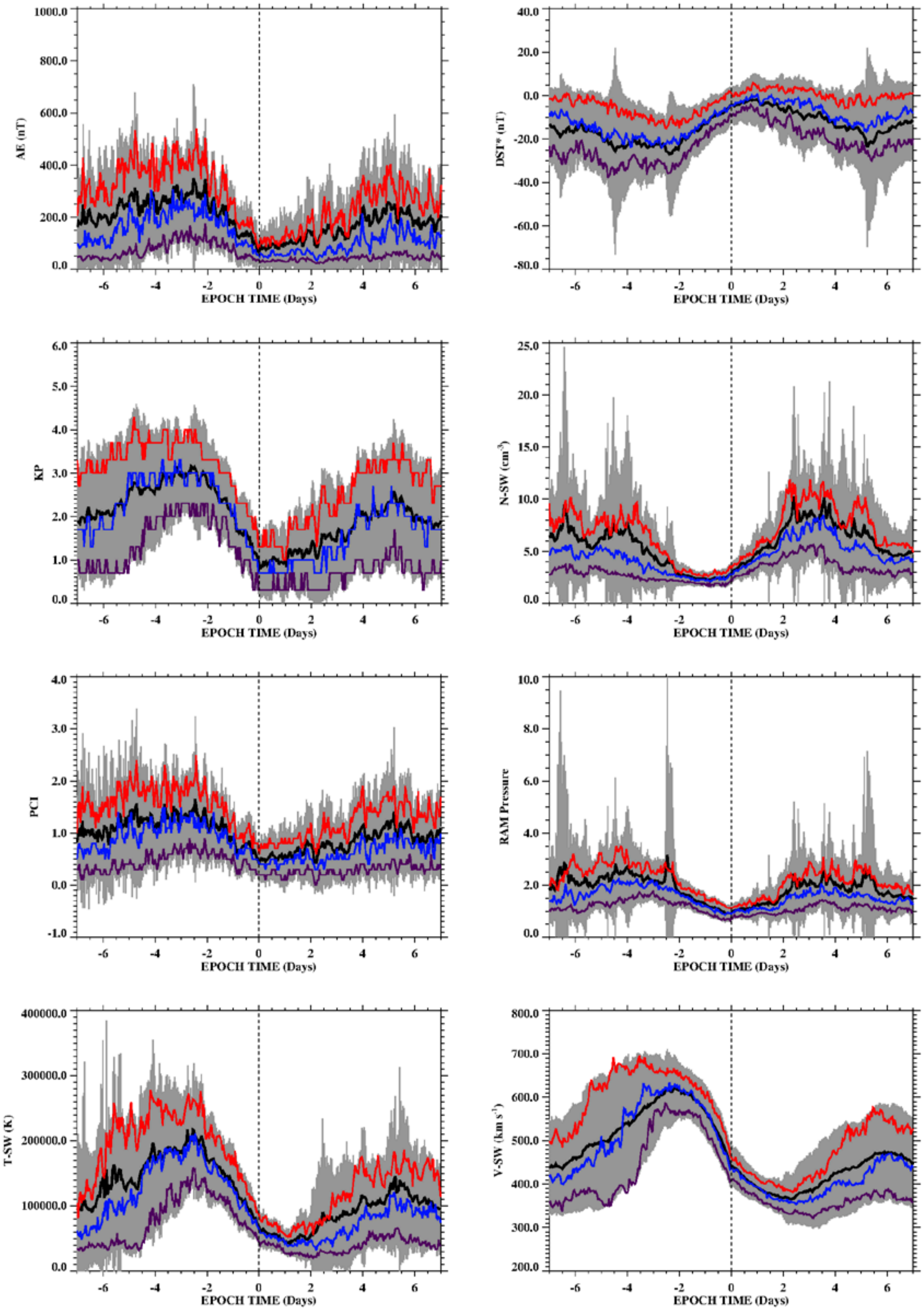

AE (nT)
1000.0
800.0
600.0
400.0
200.0
0.0
DST* (nT)
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
KP
6.0
5.0
4.0
3.0
2.0
1.0
0.0
N-SW (cm-3)
25.0
20.0
15.0
10.0
5.0
0.0
PCI
4.0
3.0
2.0
1.0
0.0
-1.0
RAM Pressure
10.0
8.0
6.0
4.0
2.0
0.0
T-SW (K)
400000.0
300000.0
200000.0
100000.0
0.0
V-SW (km s-1)
800.0
700.0
600.0
500.0
400.0
300.0
200.0
-6
-4
-2
0
2
4
6
EPOCH TIME (Days)

Figure 3. Superpositions of solar wind and magnetospheric parameters for 43 trailing edges of HSSs. The zero epoch for these events is the time of a **clear change** in the slope of solar wind speed as detailed in Table 1 of *Borovsky and Denton* [2016].

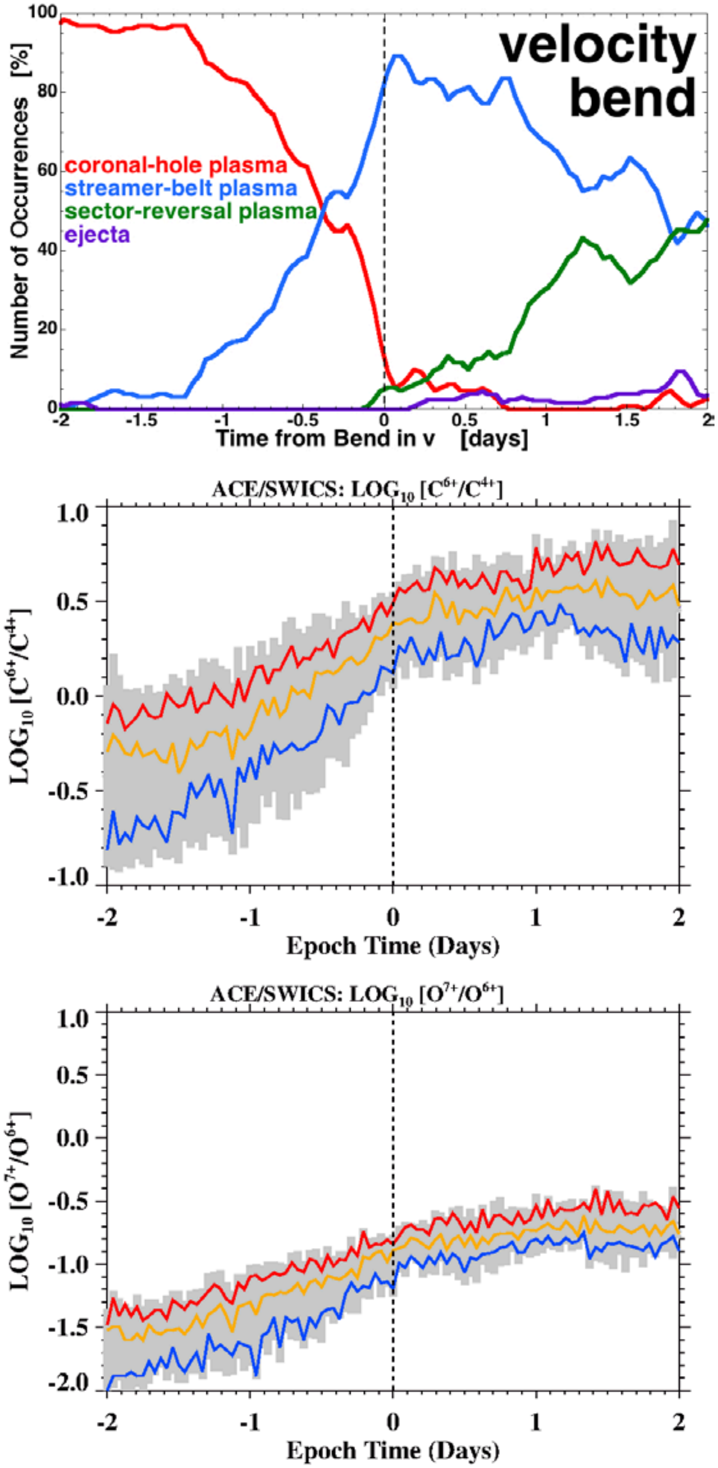
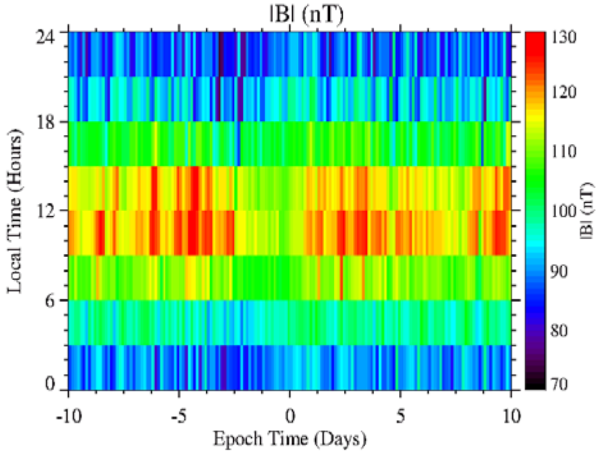
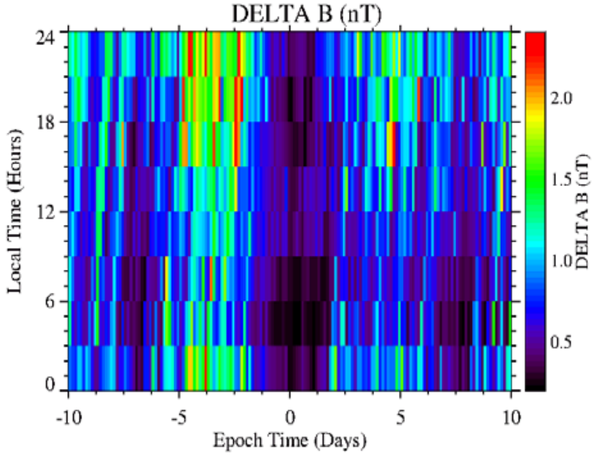


Figure 4. Showing a superposition of the solar-wind categorization scheme of *Xu and Borovsky*

[2015] applied to the 43 trailing edges of HSSs used examined in this study (top panel). Also shown are superpositions of heavy-ion charge-state ratios from the ACE/SWICS instrument. The middle panel shows the C^{6+}/C^{4+} ratio and the bottom panel shows the O^{7+}/O^{6+} ratio. The solar wind bathing the magnetosphere during trailing edges is much different than that bathing the magnetosphere during leading edges of HSSs.


|B| (nT)


DELTA B (nT)

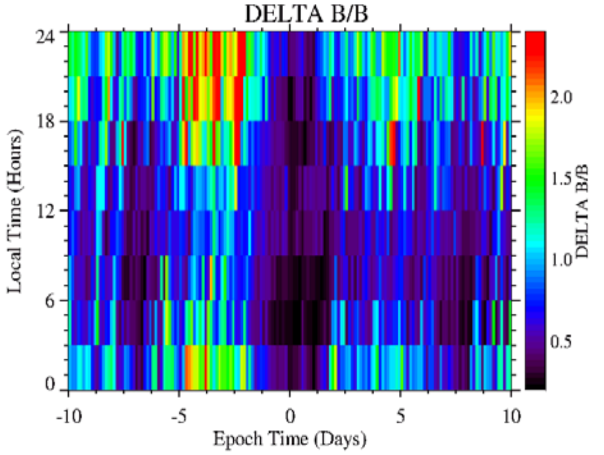

DELTA B/B

Figure 5. Showing superpositions of the measured magnetic field at GEO calculated from observations by GOES spacecraft during the passage of 43 trailing edges of HSSs. The magnitude of the field (top panel), the 1-minute change in the field (middle panel) and the normalized change in the field (bottom panel) are plotted.

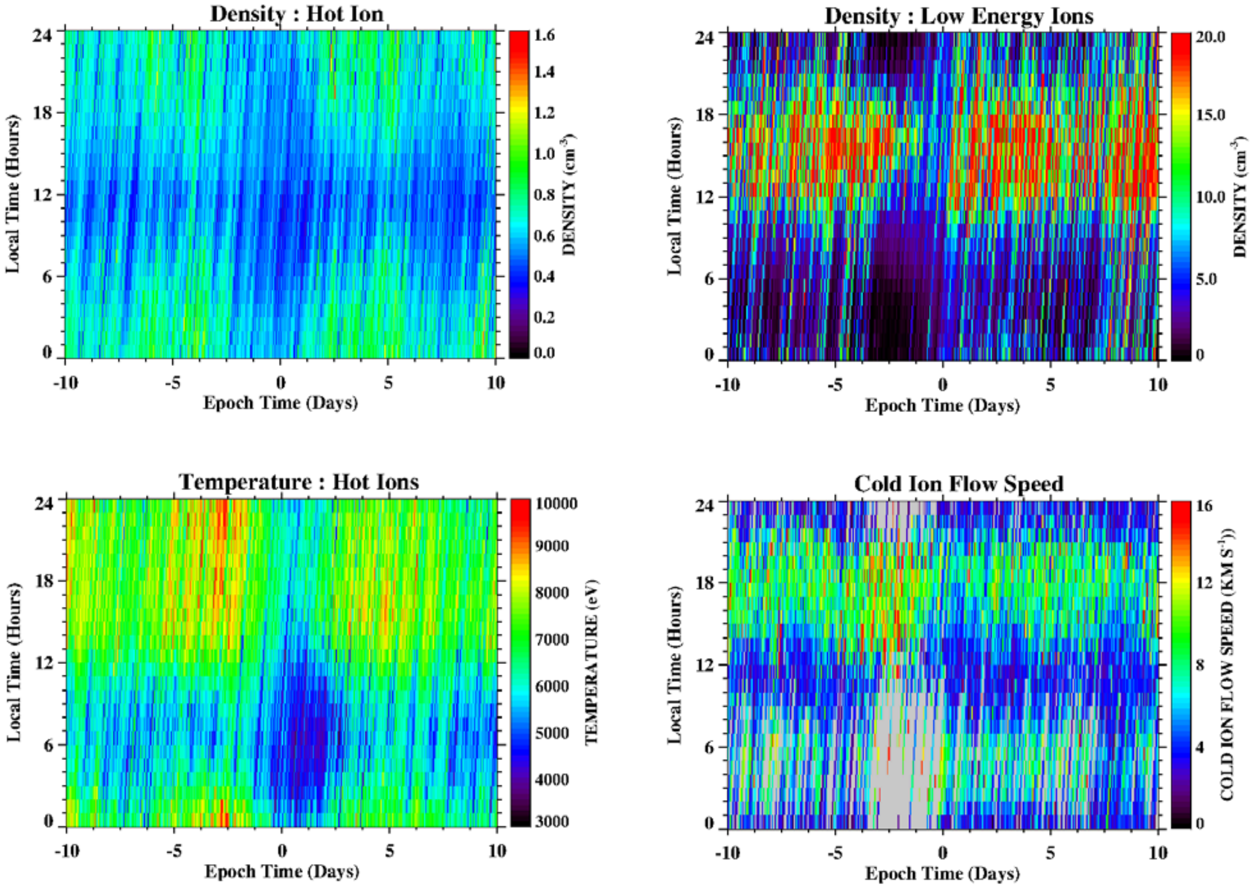
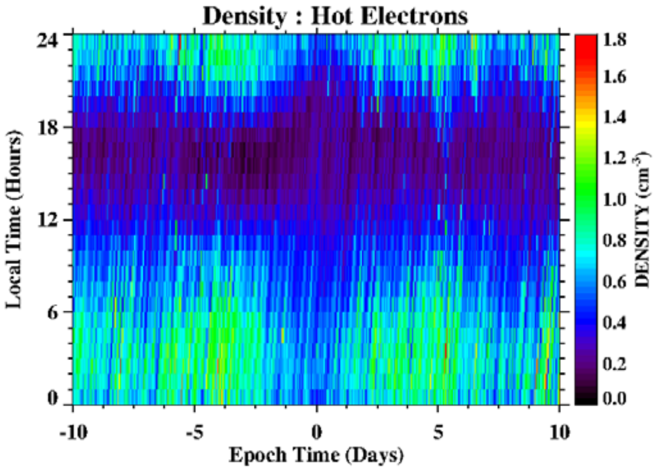
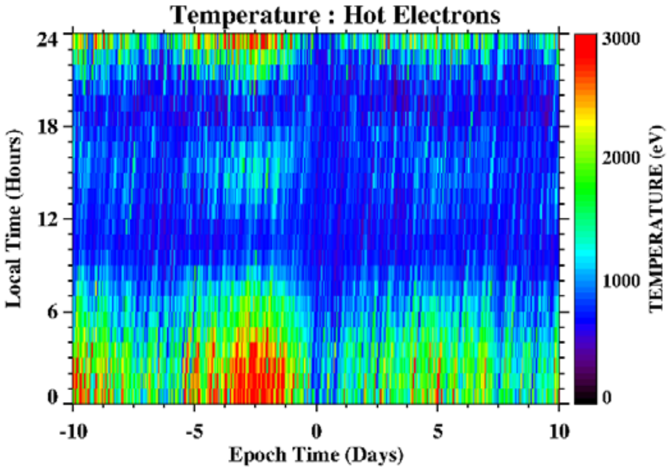


Figure 6. Showing the superposed plasma sheet ion density and temperature (left column), and the superposed plasmasphere density and flow speed (right column), calculated from LANL/MPA observations during 43 trailing edges of HSSs .


Density : Hot Electrons
Local Time (Hours)
24
18
12
6
0
-10
-5
0
5
10
Epoch Time (Days)
DENSITY (cm^{-3})
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0


Temperature : Hot Electrons
Local Time (Hours)
24
18
12
6
0
-10
-5
0
5
10
Epoch Time (Days)
TEMPERATURE (eV)
3000
2000
1000
0

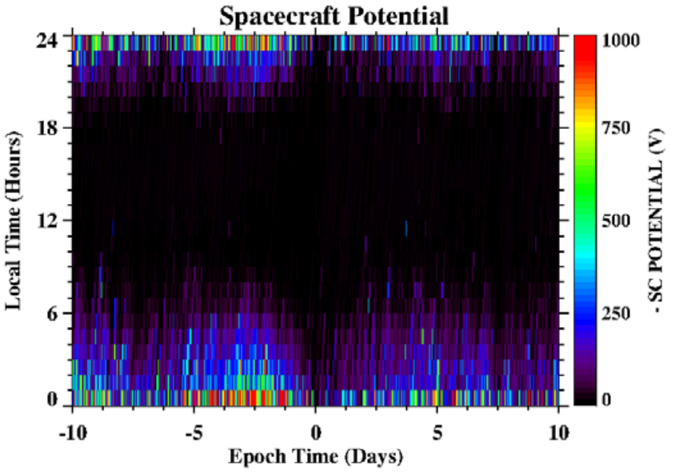
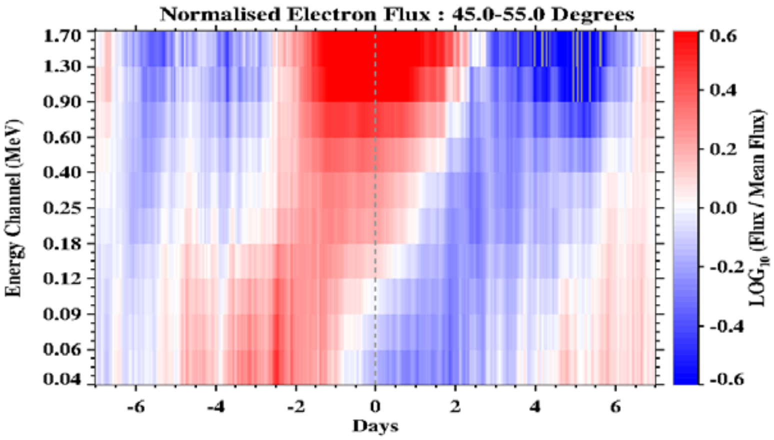
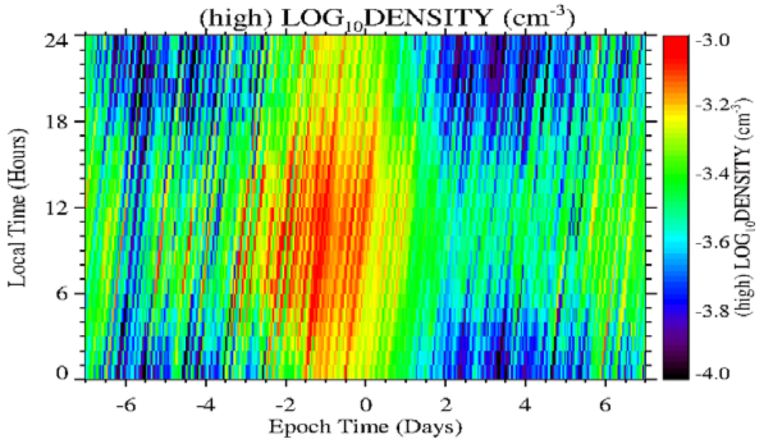

Spacecraft Potential
Local Time (Hours)
24
18
12
6
0
-10
-5
0
5
10
Epoch Time (Days)
- SC POTENTIAL (V)
1000
750
500
250
0

Figure 7. Showing the superposed plasma sheet electron density (top panel), temperature (middle panel), and negative spacecraft surface potential, calculated from LANL/MPA observations during 43 trailing edges of HSSs .


Normalised Electron Flux : 45.0-55.0 Degrees
Energy Channel (MeV)
1.70
1.30
0.90
0.60
0.40
0.25
0.18
0.12
0.09
0.06
0.04
-6
-4
-2
0
2
4
6
Days
LOG_{10} (Flux / Mean Flux)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6


(high) LOG_{10}DENSITY (cm^{-3})
Local Time (Hours)
24
18
12
6
0
-6
-4
-2
0
2
4
6
Epoch Time (Days)
(high) LOG_{10}DENSITY (cm^{-3})
-3.0
-3.2
-3.4
-3.6
-3.8
-4.0

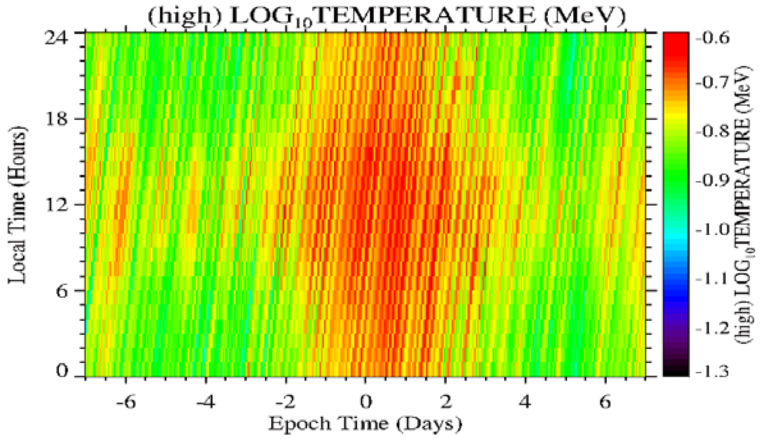

(high) LOG_{10}TEMPERATURE (MeV)
Local Time (Hours)
24
18
12
6
0
-6
-4
-2
0
2
4
6
Epoch Time (Days)
(high) LOG_{10}TEMPERATURE (MeV)
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3

Figure 8. Showing superpositions of the normalized superposed electron flux from the SOPA instrument (top panel), the electron density (middle panel), and the electron temperature (bottom panel), also from SOPA. The electron MeV flux peaks during the passage of the trailing edge whilst the density peaks prior to the arrival of the trailing edge. The temperature (hardness) of the electron spectrum remains elevatetd for ~2 days after the passage of the trailing edge.

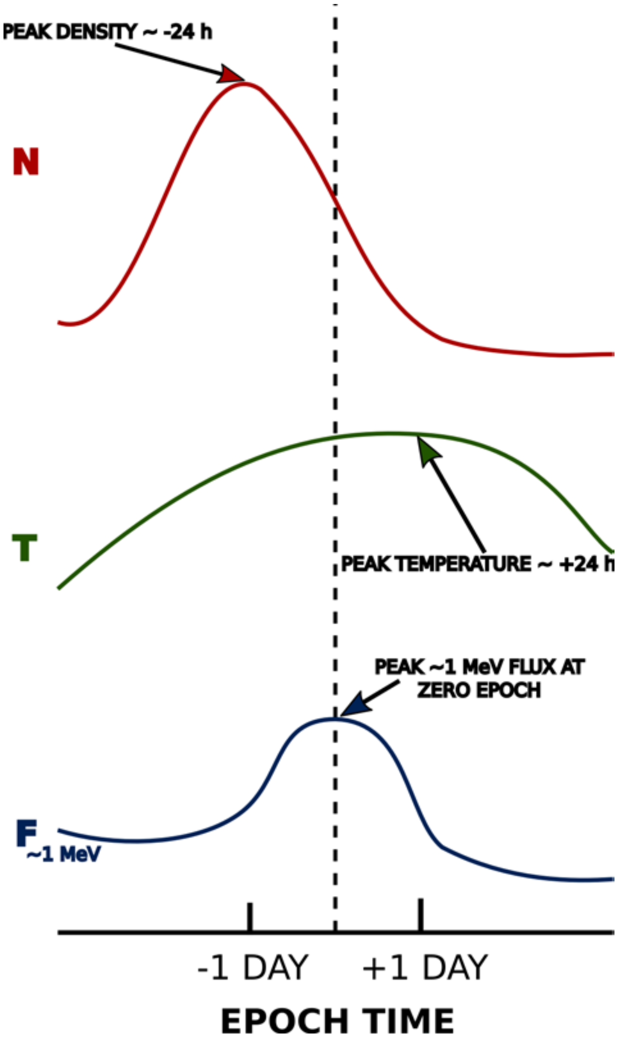


Figure 9. Schematic showing the behavior of the density N, temperature T, and flux F, during the passage of a leading edge stream interface and a trailing edge stream interface.

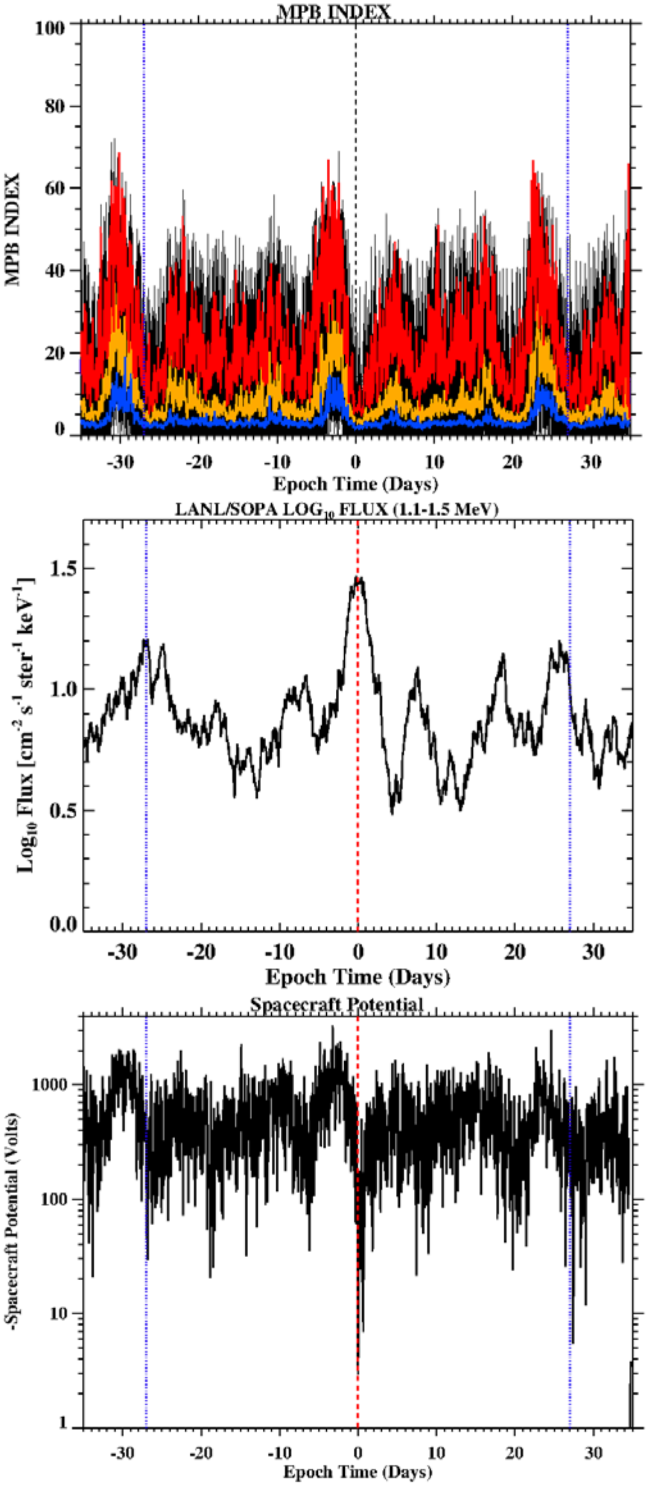
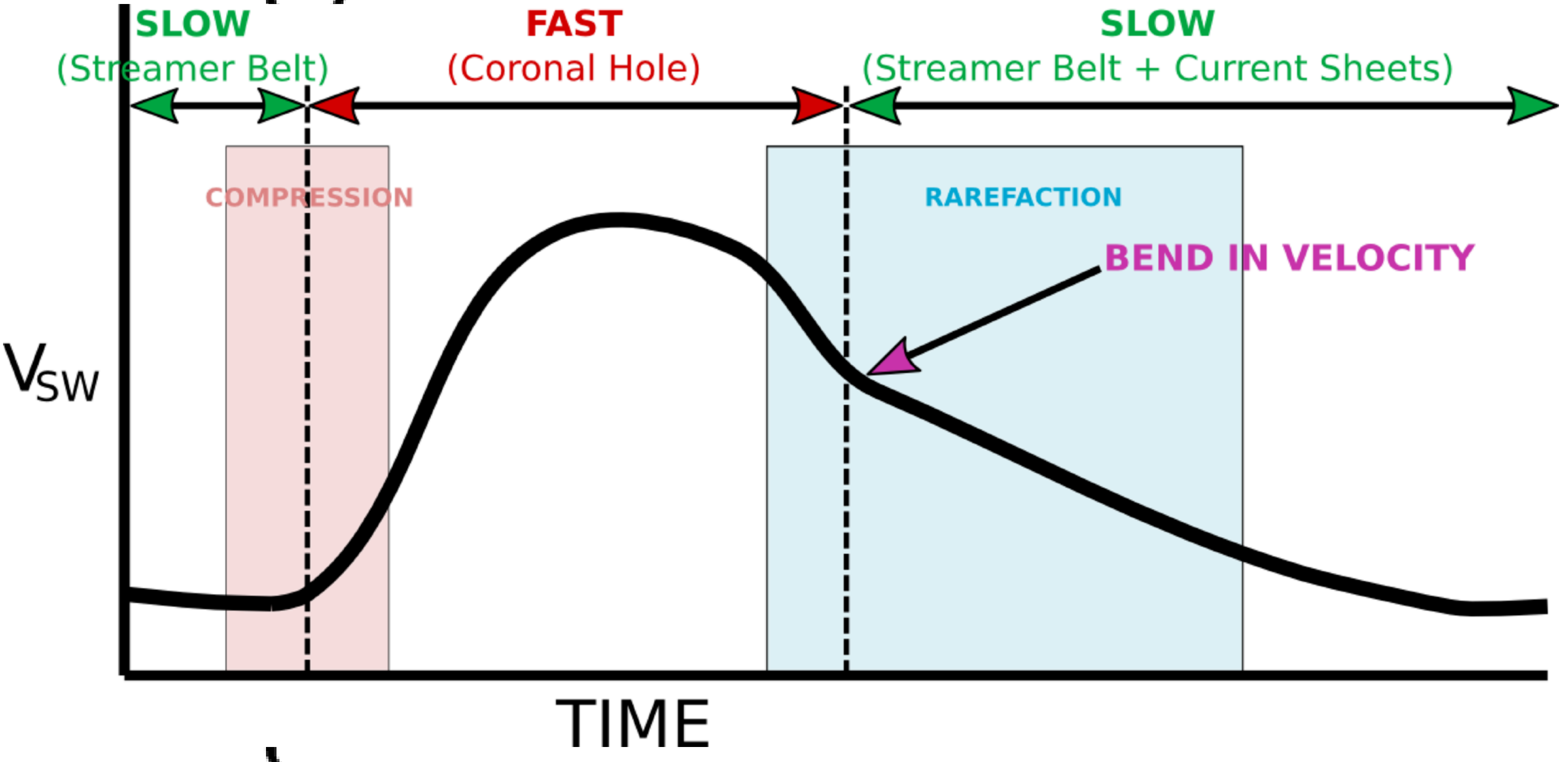
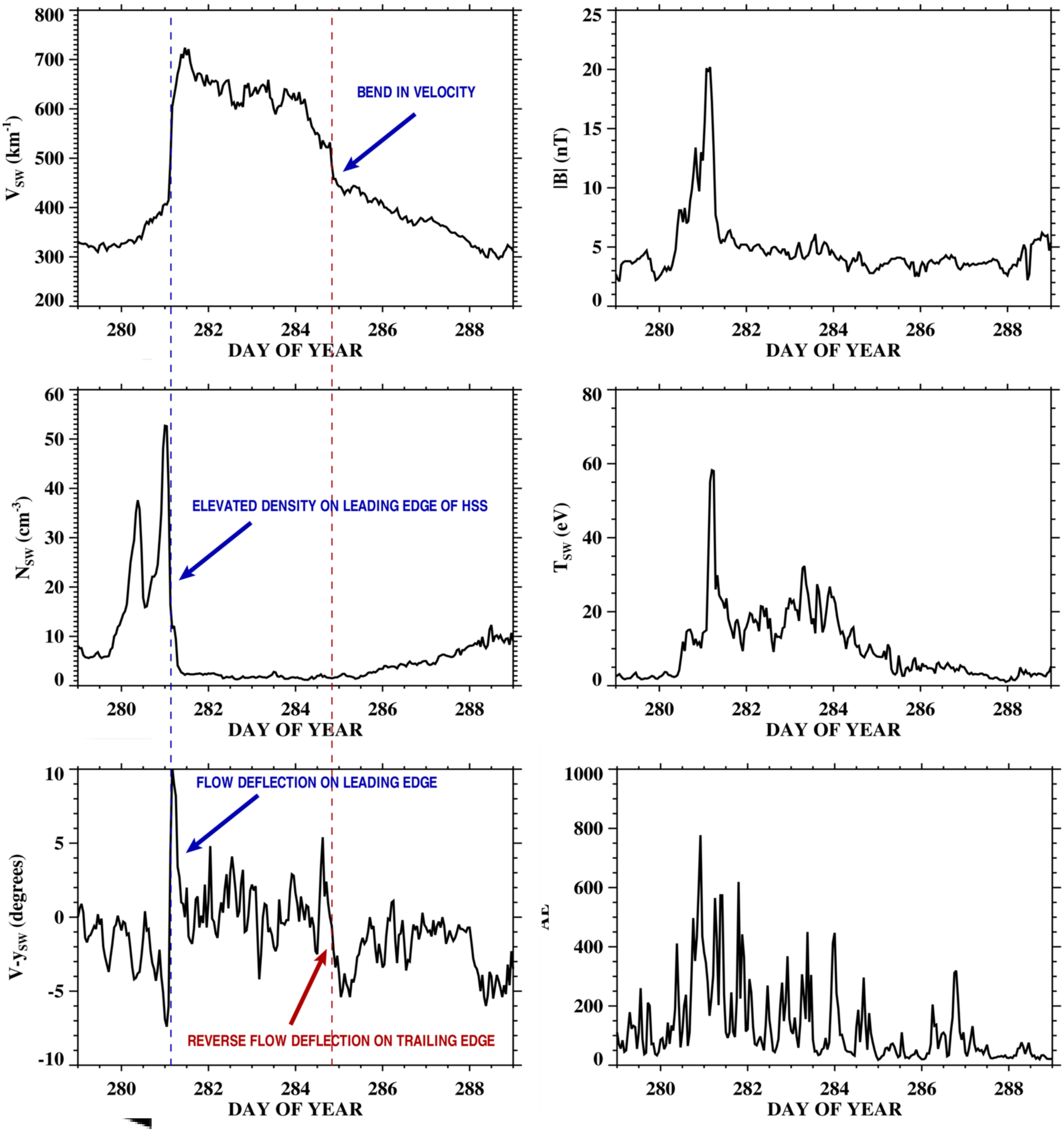

MPB INDEX
MPB INDEX
0
20
40
60
80
100
-30
-20
-10
0
10
20
30
Epoch Time (Days)
LANL/SOPA LOG10 FLUX (1.1-1.5 MeV)
Log10 Flux [cm-2 s-1 ster-1 keV-1]
0.0
0.5
1.0
1.5
-30
-20
-10
0
10
20
30
Epoch Time (Days)
Spacecraft Potential
-Spacecraft Potential (Volts)
1
10
100
1000
-30
-20
-10
0
10
20
30
Epoch Time (Days)

Figure 10. Superpositions of the MPB index (top panel), the SOPA electron flux at 1.1-1.5 MeV (middle panel), and the measured MPA surface potentia (bottom panel). All parameters display a 27 day periodicity. The relativistic electron radiation belt flux is maximized at the time of the trailing edge, the spacecraft surface potential, and the MPB index are minimized during the passage of the trailing edge.



2016ja023592-f01-z-.eps



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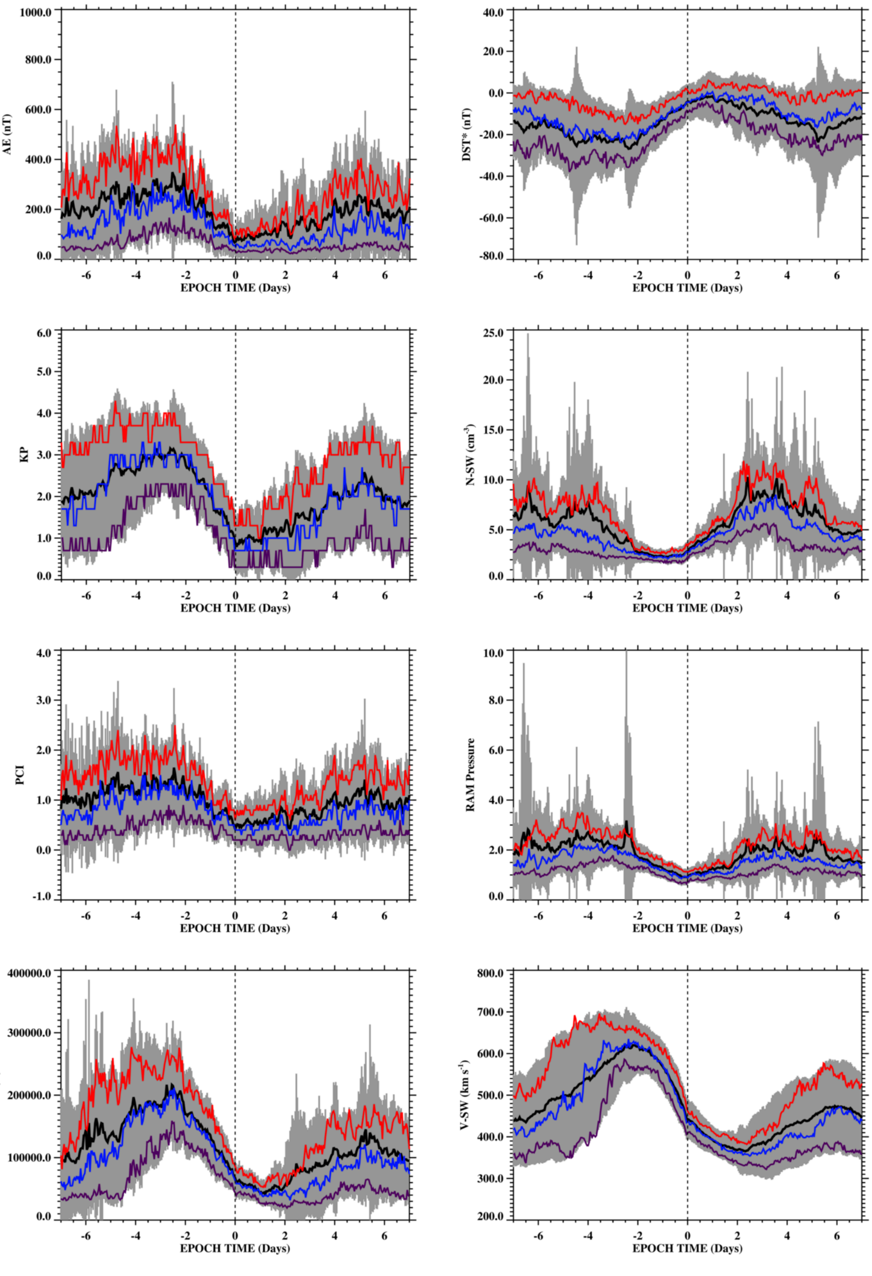

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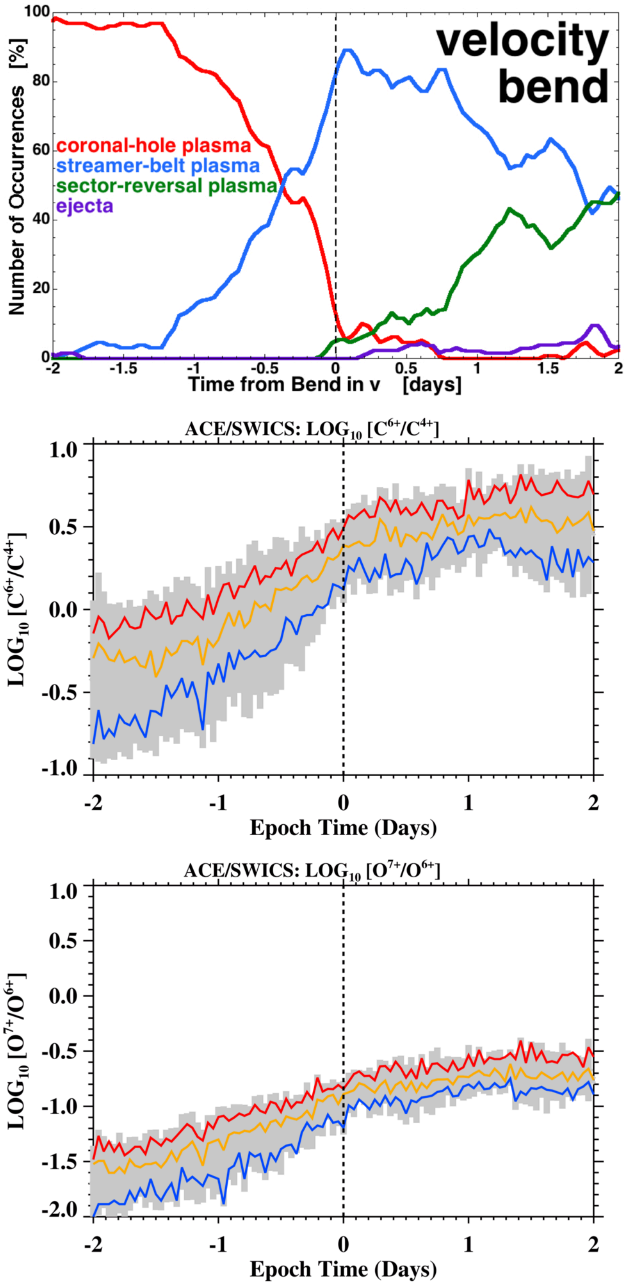

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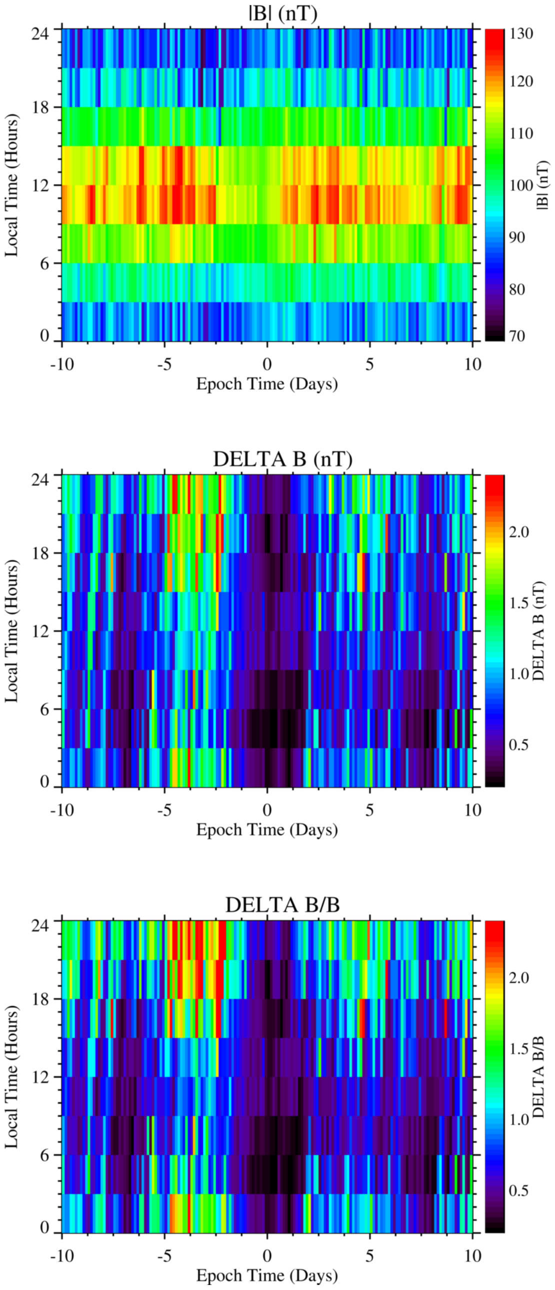

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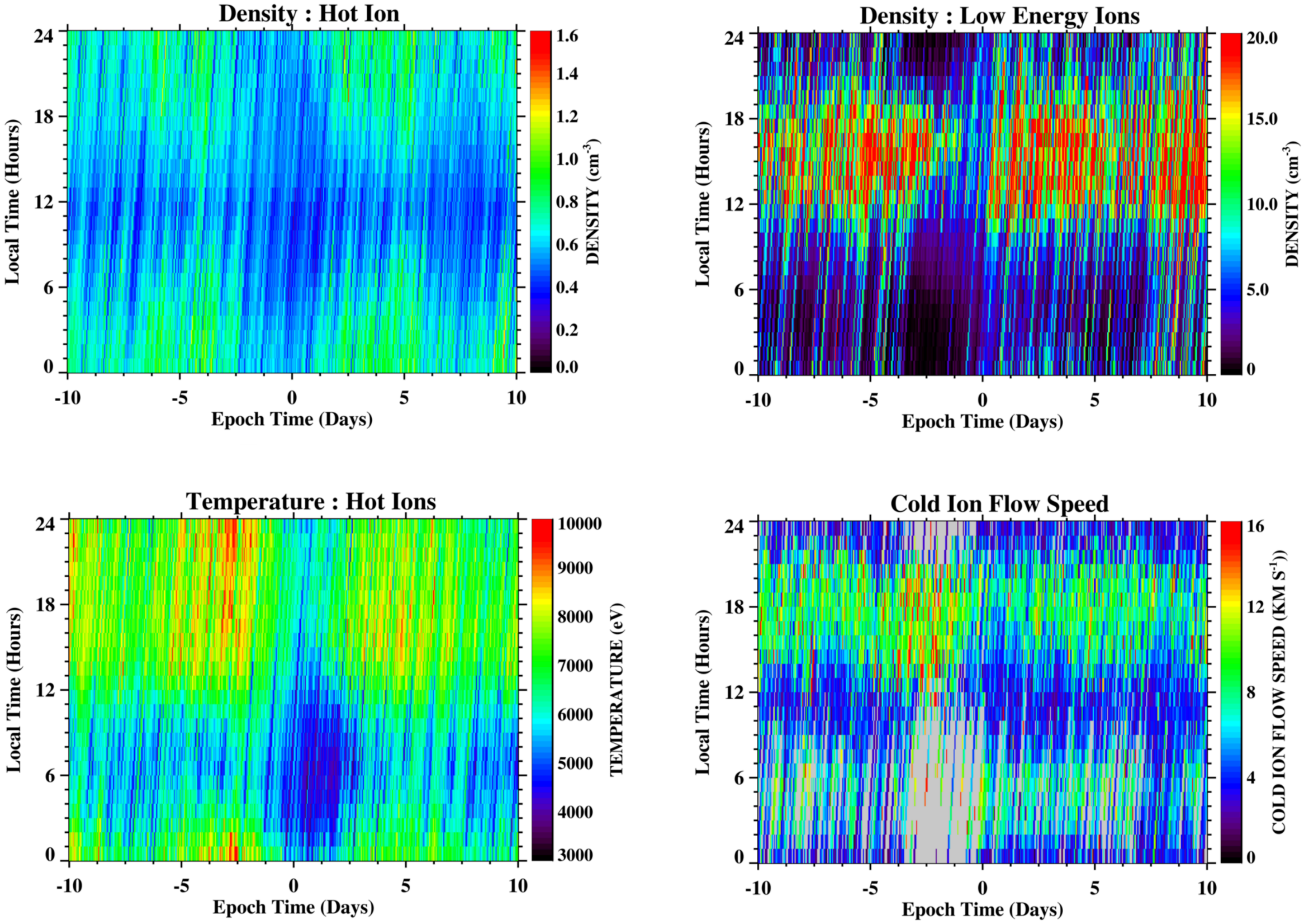

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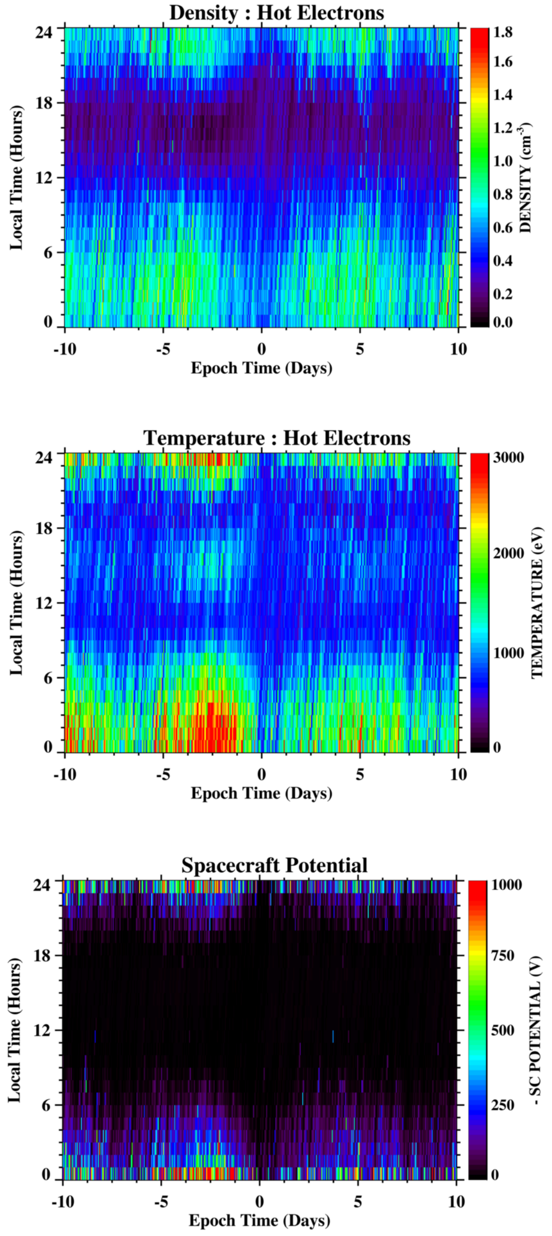

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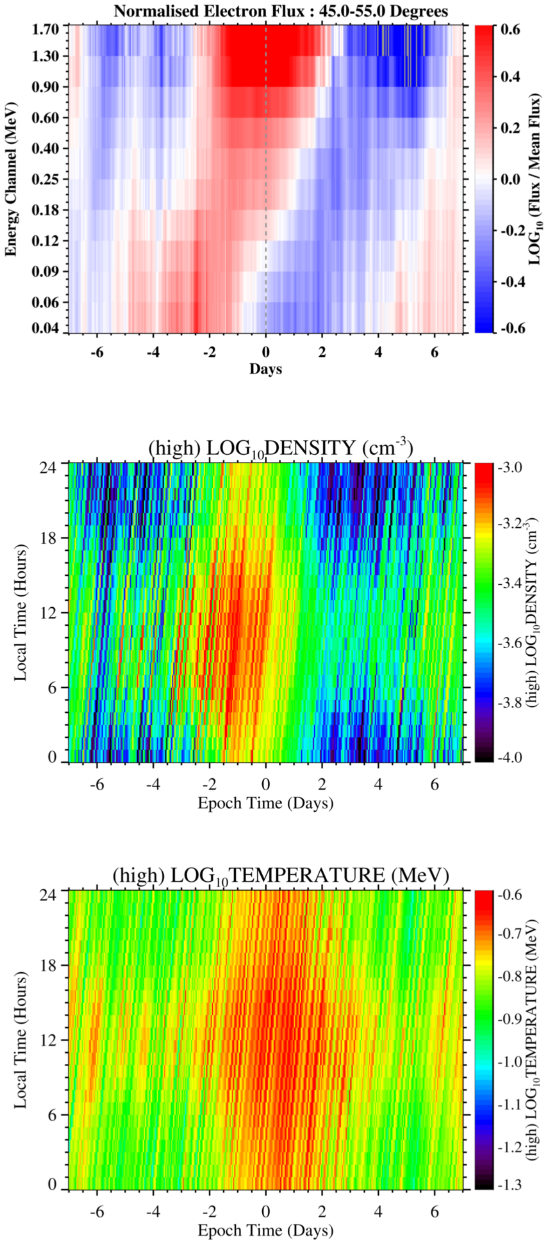

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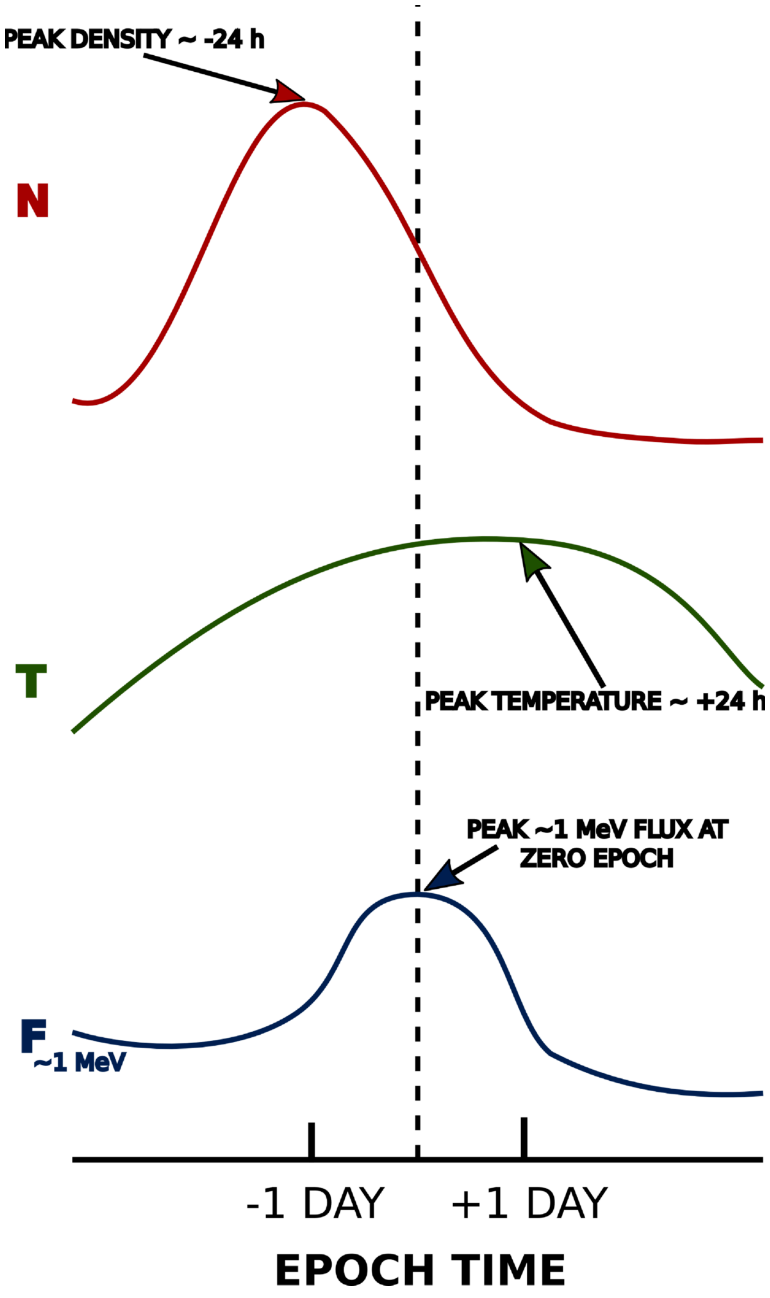

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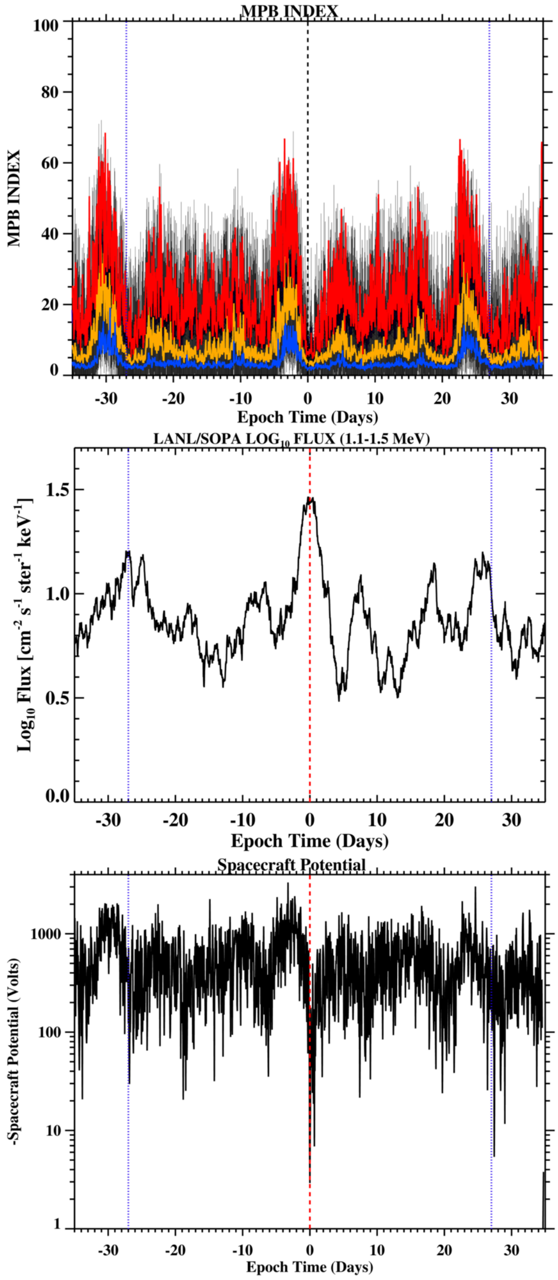

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