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Relationship between Interplanetary Conditions and Changes in the Geomagnetic Field to Understand the Causes of Geomagnetically Induced Currents

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Abstract

Geomagnetically Induced Currents (GICs) are electrical currents induced in ground-level conductive networks, like power lines and pipelines, which can cause costly damage to infrastructure. GICs are induced in response to fast changes in the geomagnetic field (GMF) according to Faraday’s Law of Electromagnetic Induction. The purpose of this study was to identify the parameters of the solar wind and interplanetary shocks which are most strongly correlated with large, fast changes in the magnitude of the GMF. GMF data is 1-min averaged time series of mid- and high-latitude magnetometer measurements in the Sym/H and AL indices, respectively. For solar wind data, I used an existing database of fast-forward interplanetary shocks compiled from measurements made by the WIND spacecraft. I performed t-tests, and created linear fits to determine which parameter(s) are likely responsible for large 1-min changes in the Sym/H and AL indices. Large changes in Sym/H are most strongly correlated with speed jump at the shock and the change in the square root of dynamic pressure and large changes in AL with speed jump at the shock. To determine the causes of events with larger 1-min changes than the fit, I created a subset of shocks which follow the trend with the same distribution as the outliers to find causes for the outliers. This revealed that faster shock and stronger upstream magnetic field are associated with stronger GMF changes.

1. Introduction

Geomagnetically Induced Currents (GICs) pose one of the largest risks to modern day infrastructure and, by extension, economies. One event worthy of mention is the geomagnetic storm of March, 1989, which caused the collapse of the Hydro-Quebec Power Grid in Canada. GICs induced in the ground over-taxed the power transmission system causing a twelve hour blackout across the network, closing schools, businesses, and public transportation systems. The event was caused by a coronal mass ejection (CME), a billion ton cloud of solar particles ejected from the sun, traveling at about a million mph toward Earth. The storm was so strong that the northern lights, typically visible only in the far north, were visible as far south as Texas and Cuba [Odenwald, 2009]. It is estimated that events of this magnitude cause on the order of $2-$3 trillion in damages to electrical power systems, globally. Costs from events of this scale to US GDP are estimated to be on the order of $100-$600 billion [Eastwood et al., 2017]. Clearly, it is important to learn how to predict the occurrence of GICs to potentially mitigate the damage done to the infrastructure and the economy.

GICs are electrical currents that can manifest in ground-level conductive networks like electrical power lines. These currents can damage the hardware and lead to large-scale power outages. GICs are caused, in short, by a rapidly changing geomagnetic field (GMF) according to Faraday’s Law of Electromagnetic Induction, which states that a temporally changing magnetic field will
create an electric field. Specifically, GICs are induced primarily because of sudden impulses (SIs) [Carter et al., 2015] or storm sudden commencements (SSCs) [Araki and Shinbori, 2016]. Both SIs and SSCs are compressions of the GMF due to increased dynamic pressure in the solar wind; they differ in that SIs tend to be associated with the passage of tangential discontinuities and SSCs tend to be associated with shocks and are associated with the occurrence of geomagnetic storms; but both ultimately have very similar structure and properties [Joselyn and Tsurutani, 1990]. The important feature to look at here is that the compression of the GMF leads to an enhanced geoelectric field which can drive electrical currents in the ground and in ground-level conductors.

GICs can be induced anywhere in the world in response to a compressed, i.e. temporally changing, GMF [Carter et al., 2015; Ngwira et al., 2013; Ngwira and Oliveira, 2017; Pulkkinen et al., 2012]. It is generally the case that these currents are more of a risk in auroral regions, where the auroral electrojet enhances the geoelectric field; however Carter et al. (2015) showed that a similar phenomenon occurs in which the equatorial electrojet enhances the geoelectric field in equatorial regions. Enhanced geoelectric field leads to increased risk of GIC, as the geoelectric field is the driver for the currents. Moreover, events on the scale of the March 1989 geomagnetic storm had effects in the central United States, indicating that GICs, though potentially more common in certain regions, could manifest in most parts of the world in response to large compressions of the GMF.

I used the assumption that GICs could potentially manifest anywhere globally in response to fast GMF compressions to motivate a study into the likely causes of the compressions. Specifically, I examined parameters of fast forward (FF) IP shocks and the resulting temporal change of the GMF. I show that speed jump and dynamic pressure are the best predictor variables for fast changes in the GMF, and that upstream magnetic field conditions and shock speed are associated with increased time rates of change of the GMF.

2. Data

To learn the causes of GMF compressions, I performed statistical analysis to learn the relationship between various parameters of IP shocks and the resulting effects on the amplitude of the GMF. I used 1-min averaged magnetic field data in the AL and Sym/H indices from December, 1994 through May, 2017.

The AL index contains meridional magnetic field measurements averaged between about twelve northern magnetometer stations [Lyatskaya et al., 2009]. The auroral magnetic field fluctuates greatly, and the auroral electrojet enhances the geoelectric field in the region, increasing the risk of high amplitude GICs [Carter et al., 2015; Pulkkinen et al., 2012].

The Sym/H index is an average of mid-latitude magnetometer stations weighted by the cosine of their latitude. The data in this index is designed to be uninfluenced by enhancements from the auroral and equatorial electrojets, and thus provides a good measure of perturbations caused by the solar wind on the global GMF [Carter et al., 2015]. The Sym/H index provides good insight into the GMF changes which could increase the risk of GICs outside of the auroral and equatorial zones.

Both AL and Sym/H indices offer the highest resolution GMF data available. The Dst index, which used to be a common indicator for SIs and SSCs, is virtually identical to Sym/H in data collection range, but it is only available in 1-hour resolution. This causes the data to be smoothed, resulting in less accurate peak GMF amplitude when averaged over an hour. Ngwira and Oliveira
show that during the March 1989 storm there were several large jumps (~100 nT) in Sym/H amplitude during the 24 hours of peak storm intensity, the largest of which was a change of about -400 nT in roughly 30 min; this jump was preceded by a jump of about +225 nT in roughly 30 min. One hour resolution is insufficient to capture these features, but 1-min resolution is sufficient to capture the rapid fluctuations of one of the largest geomagnetic storms in the modern age.

Shock data was obtained from the IPSHocks database [ipshocks.fi/database]. Most shocks are FF shocks at 1 AU [Oliveira and Raeder., 2015] – meaning the shock front moves faster than the solar wind medium – so I used FF shock data measured with the WIND instrument located at the L1 Lagrange point. Data is available from December, 1994 to May, 2017, for a total of 471 FF shocks. Each shock entry contains data on each shock’s date and time, magnetic field magnitude and vector, shock and solar wind velocity, proton temperature, proton density, sound speed, Alfvén and magnetosonic Mach numbers and velocities, plasma beta, and shock normal. I examine many of these parameters to find any association they may have with large 1-min changes in the AL and Sym/H indices.

In addition, I referenced a database compiled by Ian Richardson and Hilary Cane containing the dates and times of CMEs from 1996 to 2017. I used this to compare the passage of CMEs to the times of the largest 1-min changes in both magnetic indices and to the times of shocks. Lugaz et al. [2015], reported that about 20% of geomagnetic storms during solar cycle 23 were caused by shocks propagating in CMEs, and that about 9% of all CMEs have shocks propagating in them. For this reason, the times of CMEs, in addition to IP shocks, should be compared to times of large 1-min changes in the GMF to consider all the potential causes.

3. Methods

This study focused on the relationship between various parameters of interplanetary shocks and the time rate of change of the GMF in response to the shocks. The time rate of change of both the AL and Sym/H indices in response to a shock was determined by finding the largest 1-min change in each index which was recorded within 90 minutes of the shock, which is sufficient to capture the peak GMF response to the shock [Oliveira et al., 2015]. More specifically, it is the largest 1-min change magnitude in each index that is of importance, operating, again, on the assumption that large 1-min changes in the GMF magnitude will increase the risk of GICs. There were primarily two stages to this study, and one minor follow-up evaluation.

3.1 Finding a Pattern

I looked for linear correlations using least squares regression between parameters of IP shocks and the largest resulting 1-min in the AL and Sym/H indices. Specifically I looked into linear relationships with the upstream magnetic field magnitude of the solar wind ($B_{up}$), upstream north-south magnetic field magnitude of the solar wind ($B_{z,up}$), the difference between up- and downstream solar wind speed at the shock ($\Delta V$), shock speed ($V_{sh}$), plasma beta ($\beta$), and magnetosonic Mach number ($M_{ms}$). Plasma beta is the ratio of the hydrodynamic pressure and magnetic pressure, and indicates whether the solar wind plasma is magnetically dominated or not. The magnetosonic Mach number is the speed of the shock given as a fraction of the solar wind sound speed, which itself is a function of the temperature and density of the medium.

Furthermore, based on the work of Oliveira and Raeder (2015), I looked into the correlation between the impact angle ($\theta_x$) – the angle between the shock normal and the Sun-Earth line – and the time rate of change of the AL and Sym/H indices. They
examined the relationship between impact angle and the largest total change in GMF magnitude following a shock using the SML geomagnetic index. They report an increasing correlation for increasing shock speed. Similarly, I also examined the relationship with the angle between the upstream magnetic field and the shock normal ($\theta_{Bn}$).

Lastly, I looked at the linear relationship between the dynamic pressure of the solar wind and the time rate of change of the GMF. Siscoe et al. (1968) report a linear relationship between SSC amplitude and the square root of dynamic pressure ($P_{dyn}^{0.5}$). Specifically, they report that the change in the GMF amplitude is proportional to the change in the square root of dynamic pressure ($\Delta P_{dyn}^{0.5}$) at the shock. To clarify, this means that the change in GMF amplitude is proportional to the difference between square roots of the up- and downstream dynamic pressure at the shock, and not the square root of the difference. Dynamic pressure refers to the amount of kinetic energy per unit volume of a fluid. Dynamic pressure is cited as the main cause of compressions of the GMF [Araki and Shinbori, 2016; Lugaz et al., 2015; Ngwira et al., 2013; Siscoe et al., 1968], so I looked into its effects on the time rate of change of the GMF.

Linear models were created using a robust fit model, which reduces the weight of outliers from the model to find a stronger fit unaffected by outliers. The purpose of section one of the study was to find a pattern between parameters of IP shocks and the time rate of change of the GMF to identify potential predictor variables for fast changes in GMF magnitude. The second part of the study used the most strongly correlated parameter as a trend for predicting the time rate of change of the GMF.

### 3.2 Deviations from the Pattern

After finding the parameter of IP shocks with the strongest correlation with the time rate of change of the GMF, I looked at the potential causes of events which strayed from the linear trend. Events which had time rates of change greater than two times the linear fit line were marked as outliers. Two times the fit line was selected as an arbitrary cut-off to differentiate extreme events for which the time rate of change of the GMF was much larger than events which fit the line. To do this, I selected a subset of events under this cut-off – I will refer to these as inliers – that had a similar distribution to the outliers. The goal of this was to have the subset of inliers match the outliers so that a two-variable t-test reports no significant difference between the samples with 95% confidence. This essentially controls the most correlated variable, allowing me to examine which parameters are significantly different between inliers and outliers.

In this section, I performed two-variable t-tests between the outliers and inliers of the most correlated parameters for time rates of change in AL and Sym/H from section one to find statistically significant differences between the two sets of parameters. For the inliers and outliers, I examined linear fits between the GMF time rate of change and the parameters for which there was a significant difference between inliers and outliers. I also compared the medians – as a measure of average – of the two sets. The goal of this section was to identify the parameters that could cause the extreme time rates of change and the extent to which they affect it.

### 3.3 Evaluation of Study

The third section of the study was an evaluation of the relevance of the study in terms of the data used. Essentially, was the use of IP shock data justified, or should I have considered alternative catalysts for GMF
compressions? I identified the fifty largest time rates of change in AL and Sym/H, individually, then compared the times of these events to the times of FF IP shocks and CMEs. So, whereas in sections one and two I focused on the largest 1-min change in AL and Sym/H immediately following a shock, in this section I identified the absolute maximum 1-min changes in all the available AL and Sym/H data. I do this to check if this study captured the majority of the largest events, or if there were many more large events not caused by FF IP shocks.

4. Results and Analysis
4.1.1 Finding a Pattern: AL

In the first section I compared parameters of IP shocks to GMF time rates of change as indicated in AL and Sym/H. Figure 1 shows scatter plots relating the largest 1-min change in AL to (a) upstream magnetic field magnitude, (b) magnetosonic Mach number, (c) change in the square root of dynamic pressure, and (d) shock speed, in order of increasing correlation strength. From this set, the time rate of change of AL is most strongly correlated with shock speed, suggesting that fluctuations in the auroral magnetic field are associated with the strength of the shock. Also worth noting is the association between $\Delta P_{\text{dyn}}^{0.5}$ and the time rate of change of AL. This suggests that, like total change in GMF amplitude [Siscoe et al., 1968], the time rate of change of the GMF is linearly associated with the change in the square root of dynamic pressure.

The relationship between impact angle and time rate of change of AL (Figure 2.a) is very weak. Shock impact angle is a measure of the angle between the shock normal and the Sun-Earth line; 180° indicates zero inclination, i.e. parallel shock, when approaching Earth, and 90° indicates a perpendicular shock. Oliveira and Raeder (2015) report a clear linear relationship between impact angle and the total change in auroral magnetic field amplitude, but my results suggest that there is no such relationship for the time rate of change of the auroral magnetic field, as the strength of the fit is weak: $R^2 = 0.29$. Furthermore, Figure 2.b suggests, similarly, that the time rate of change of the auroral magnetic field is independent of $\theta_{\text{Bn}}$. There is apparently no linear relationship between the time rate of change of the auroral magnetic field and $\theta_{\text{Bn}}$, suggested by the weak correlation: $R^2 = 0.28$.

![Figure 1: Linear correlations between the time rate of change of AL and (a) $B_{\text{up}}$ in nT, (b) $M_{\text{ms}}$, (c) $\Delta P_{\text{dyn}}^{0.5}$ in nPa$^{0.5}$, and (d) $V_{\text{sh}}$ in km/s. The vertical axis is the largest 1-min change in AL following a shock. Each point represents one FF IP shock.](image)
The strongest correlation with the time rate of change of AL is the speed jump at the shock, i.e. the difference in solar wind speed between the up- and downstream solar wind. Shown in Figure 3, the correlation coefficient is $R^2 = 0.56$, making this parameter the best predictor variable for determining the temporally changing auroral magnetic field in response to an IP shock for use in section two. Time rates of change exceeding two times the fit line – marked by the dashed line – are marked as outliers, signifying that they are extreme events that differ from the fit due to some other factor(s); of the 471 events, 101 (~21%) are marked as outliers. In addition, I performed a two-variable t-test between the outliers and the full set of inliers to confirm a statistically significant difference between the two sets. The full set of inliers has an average $\Delta V$ of 64.15 km/s and standard deviation of 47.81 km/s. The set of outliers has an average $\Delta V$ of 78.54 km/s and standard deviation of 69.72 km/s. The p-value is 0.016, indicating a statistically significant difference with 95% confidence.

4.1.2 Finding a Pattern: Sym/H

Figure 4 shows the linear correlations between time rates of change of Sym/H and (a) upstream magnetic field, (b) shock speed, and (c) magnetosonic Mach number, again in order of increasing correlation strength. Interestingly, the shock speed is very weakly correlated with the time rate of change of Sym/H, compared to AL. As Sym/H is representative of global GMF perturbations unaffected by the auroral and equatorial electrojet enhancements, this suggests that the auroral magnetic field is more sensitive to stronger shocks, i.e. faster shocks, perhaps related to the enhancements to the geoelectric field caused by the auroral electrojet.

Similarly to AL, Figure 5.a indicates little to no correlation ($R^2 = 0.24$) between impact angle and the time rate of change of Sym/H, suggesting that the GMF perturbations caused by the solar wind are independent of impact angle. Likewise, there is very little correlation between $\theta_{Bn}$ and the time rate of change of Sym/H. The research done by Oliveira and Raeder (2015) showed that impact angle was linearly correlated with the total change in the auroral magnetic field.
This suggests that perhaps the auroral magnetic field is more sensitive to varying impact angle, similar to shock speed. Furthermore, the effects of varying impact angle are likely more gradual, perturbing the GMF greatly over longer periods of time.

The most correlated parameter with time rate of change of Sym/H, shown in Figure 6.a, is the speed jump at the shock. The correlation coefficient for this fit is $R^2 = 0.73$. Speed jump is also the most correlated parameter for the time rate of change of AL, suggesting that perturbations in GMF due to shocks are highly affected by stronger shocks, characterized by larger speed jumps. This also suggests that speed jump at the shock is a strong predictor variable for fast changes in GMF amplitude.

Importantly, the second strongest correlation for the time rate of change of Sym/H, shown in Figure 6.b with $R^2 = 0.67$, is $\Delta P_{\text{dyn}}^{0.5}$. Dynamic pressure is largely associated with SIs and SSCs and is considered in many works [Araki and Shinbori, 2016; Lugaz et al., 2015; Ngwira et al., 2013; Siscoe et al., 1968] to be the primary driving force for compressions of the GMF. Here I show that it is strongly associated with the time rate of change of the GMF, in addition to the total change. This supports the linear relationship presented in Siscoe et al. (1968) between the total change in GMF amplitude and $\Delta P_{\text{dyn}}^{0.5}$, and supports the use this parameter as a predictor variable for geomagnetic storms.

The distribution of outliers of the linear fit for the time rate of change of Sym/H and $\Delta P_{\text{dyn}}^{0.5}$ is statistically different from the full set of inliers. The average $\Delta P_{\text{dyn}}^{0.5}$ for the outliers is 1.19 nPa$^{0.5}$, and the standard

**Figure 4:** Linear correlations between the time rate of change of Sym/H and (a) $B_{up}$ in nT, (b) $V_{sh}$ in km/s, and (c) $M_{ms}$. Vertical axis is the largest 1-min change in Sym/H. Each point represents a FF IP shock.

**Figure 5:** Correlation between the largest 1-min change in Sym/H, in nT/min, and (a) $\theta_x$ in degrees, and (b) $\theta_{Bn}$ in degrees, based on Oliveira and Raeder (2015). Horizontal axis in (a) represents angle between shock normal and Sun-Earth line; 180° is along this line, directed toward Earth. Horizontal axis in (b) is the angle between $B_{up}$ and the shock normal.
deviation is 0.79 nPa\(^{0.5}\). For inliers, the average \(\Delta P\)\(^{0.5}\) is 0.87 nPa\(^{0.5}\) and standard deviation is 0.55 nPa\(^{0.5}\). The p-value from a two-variable t-test is 0.0003. I used the relationship between \(\Delta P\)\(^{0.5}\) and the time rate of change of Sym/H in section two because it is more interesting to explore the causes of these outliers. There is no significant difference between the inliers and outliers of the speed jump relationship, and this parameter was explored using its relationship with the time rate of change of AL. While speed jump is a strong predictor variable, it is more interesting to explore deviations from the dynamic pressure relationship.

4.2.1 Deviations from the Pattern: AL

A subset of 101 (~21%) inliers from Figure 3 was chosen to produce a set of shocks with the same number and distribution as the outliers regarding the speed jump parameter. The outliers of this fit have a median speed jump of 49.49 km/s and standard deviation of 69.72 km/s, and the inlier subset has a median speed jump of 49.49 km/s and standard deviation of 48.41 km/s. I used a two-variable t-test to confirm that there is not a statistically significant difference between these sets. I use the median as a measure of average because there is a sufficient number of data points that it is an acceptable representation of the middle of the set, and it is not skewed greatly by outlying values like the mean.

The process of obtaining a subset of inliers with no statistically significant difference from the outliers essentially controls the speed jump parameter, which enables identification of the parameter(s) associated with the extreme values from the fit. I performed two-variable t-tests on the parameters examined in section one of this study between the inlier subset and outliers. Figure 7 shows least-squares regression fits for the parameters for which there is a statistically significant difference between the inliers and outliers. I performed linear correlations on the two sets independently to compare events which follow the trend in Figure 3 to events which do not. Interestingly, while there is virtually no linear correlation with the upstream magnetic conditions (Figure 7.a and 7.b), there is a linear correlation with shock speed, albeit somewhat weak, for both inliers and outliers (\(R^2_{in} = 0.40\) and \(R^2_{out} = 0.38\)); the outliers have a steeper relationship with shock speed, suggesting that there is likely another factor which caused the outliers to be affected more by faster shocks. Furthermore, comparing the distributions of the inliers and outliers for each parameter reveals that, on average, greater upstream magnetic field and shock speed, and negative upstream north-south magnetic field component are associated with

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*Figure 6*: The two strongest correlations for 1-min changes in Sym/H; (a) \(\Delta V\), in km/s, is the difference in solar wind speed between the up- and downstream conditions of a shock and (b) \(\Delta P_{dyn}^{0.5}\), in nPa\(^{0.5}\), is the difference in the square root of dynamic pressure between the up- and downstream conditions of the solar wind. The vertical axis is the largest 1-min change in Sym/H, in nT/min, following a shock. Each point represent a FF IP shock. Outlier are shocks with 1-min change in Sym/H values greater than two times the fit, represented by the dashed line.
larger 1-min changes in AL; the t-test results and distributions are summarized in Table 1.

This is consistent with a study by Liou et al. (2003) on the external triggers for auroral substorms, brief enhancements in the auroral magnetic field caused by injection of high energy particles from the solar wind, usually due to reconnection in the magnetotail. They reported an average positive $B_{z,up}$ for inactive shocks (AL > -100 nT) and an average negative $B_{z,up}$ for active shocks (AL < -100 nT). While they reported that the majority of negative up- and downstream $B_z$ were not associated with the occurrence of substorms, they do show that larger changes in AL tend to be associated with negative $B_{z,up}$. Based on this, my results (Figure 7.b) suggest that a preexisting southward upstream magnetic field primes the GMF for an auroral substorm, resulting in a large 1-min change in the auroral GMF even for weak shocks with small speed jumps. Further investigation may reveal that the steeper $V_{sh}$ relationship for outliers (Figure 7.c) could be related to negative $B_{z,up}$, but this is speculative.

4.2.2 Deviations from the Pattern: Sym/H

For this section, I used the relationship between the 1-min change in Sym/H and the change in the square root of dynamic pressure. A subset of 50 inliers from Figure 6.b was chosen to produce a distribution similar to that of the 50 (~11%) outliers. The outliers have a median $\Delta P_{dyn}^{0.5}$ of 1.0584 nPa$^{0.5}$ and standard deviation of 0.7903 nPa$^{0.5}$. The subset of inliers has a median $\Delta P_{dyn}^{0.5}$ of 1.0718 nPa$^{0.5}$ and standard

<table>
<thead>
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<th>Parameter</th>
<th>Inliers</th>
<th>Outliers</th>
<th>$p$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{up}$</td>
<td>Median: 5.2750 nT, SD: 3.0853 nT</td>
<td>Median: 6.8100 nT, SD: 3.4670 nT</td>
<td>0.0008</td>
</tr>
<tr>
<td>$B_{z,up}$</td>
<td>Median: 1.1000 nT, SD: 3.9098 nT</td>
<td>Median: -1.8200 nT, SD: 3.4807 nT</td>
<td>0.0002</td>
</tr>
<tr>
<td>$V_{sh}$</td>
<td>Median: 446.7750 km/s, SD: 139.4308 km/s</td>
<td>Median: 498.1100 km/s, SD: 176.3549 km/s</td>
<td>0.0058</td>
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Table 1: Table containing the median and standard deviation for the sets of data in Figure 7. The $p$-value shows that the inliers and outliers have a statistically significant difference on a 95% confidence interval.
deviation of 0.6767 nPa$^{0.5}$. Once again, I confirmed that there is not a statistically significant difference between the inliers and outliers using a two-variable t-test with 95% confidence so I can control the predictor variable ($\Delta P_{\text{dyn}}^{0.5}$) and find which parameter(s) contributed to the extreme values in Figure 6.b.

Figure 8 shows linear correlations and distributions for the parameters of IP shock for which there was a statistically significant difference between inliers and outliers. Important to note is that larger 1-min changes in Sym/H are associated with, on average, greater (a) upstream magnetic field, (b) difference in up- and downstream magnetic field, (c) shock speed, and (d) speed jump. Larger magnitudes of these parameters of IP shock appear to be associated with larger 1-min changes in the GMF. Distribution data is summarized in Table 2.

As expected, speed jump is associated with larger 1-min changes in Sym/H. Similarly to Figure 6.a, which shows that 1-min changes in Sym/H are very strongly correlated with speed jump, the outliers have a slight linear correlation with speed jump, indicating that, intuitively, stronger shocks (larger speed jump) cause greater perturbations in the GMF. Furthermore, larger 1-min changes in Sym/H are associated with stronger upstream magnetic field conditions. Compressions of the GMF like SI's and SSCs are primarily caused by increases in the solar wind dynamic pressure, which itself is related with a pressure balance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inliers Median</th>
<th>Inliers Standard Deviation</th>
<th>Outliers Median</th>
<th>Outliers Standard Deviation</th>
<th>P-Value</th>
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<td>$B_{\text{up}}$</td>
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<tr>
<td>$\Delta B$</td>
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<td>3.7675 nT</td>
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<td>5.7211 nT</td>
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<tr>
<td>$V_{\text{sh}}$</td>
<td>445.2200 km/s</td>
<td>141.7419 km/s</td>
<td>633.4200 km/s</td>
<td>247.7048 km/s</td>
<td>3.95x10$^{-6}$</td>
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<tr>
<td>$\Delta V$</td>
<td>59.5250 km/s</td>
<td>55.6501 km/s</td>
<td>109.7750 km/s</td>
<td>84.2456 km/s</td>
<td>0.0006</td>
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</table>

Table 2: Table containing the median and standard deviation for the sets of data in Figure 8. The p-value shows that the inliers and outliers have a statistically significant difference on a 95% confidence interval.
at the magnetopause \cite{Siscoe et al., 1968}. The results presented in this sections suggest that increased upstream magnetic field may affect the pressure balance at the magnetopause, especially when compressed by a strong, fast shock.

4.3 Evaluation of Study

In this section, I compared the times of the 50 largest 1-min changes in all of AL and Sym/H to times of FF IP shocks from IPShocks, and to times of CMEs in Cane and Richardson’s CME list to evaluate the accuracy of this study’s approach. Of the 50 largest 1-min changes in AL, 15 occur during the passage of an IP shock sheath or a CME sheath, 23 occur during the passage of a CME ejecta, 6 are likely internal processes, like spontaneous substorms with no external cause, and 6 are likely data gaps or errors, evident by inexplicable spikes in the data. As for the 50 largest 1-min changes in Sym/H, 25 occur during the passage of an IP shock or CME sheath, 18 occur during the passage of a CME ejecta, and 7 are likely data errors, evident again by inexplicable spikes lasting only a minute. This is important because this study focused solely on the effects of IP shocks on rapid changes of the GMF. Of the 50 largest 1-min changes in Sym/H from the past twenty years, 25 (50%) were likely caused by the passage of a shock, meaning this study accounted for those events. Furthermore, with AL, 15 (30%) were likely caused by a shock. However, while this study did account for those events, 23 (46%) of the largest AL 1-min changes were likely caused by the passage of a CME sheath, meaning they were not captured by the scope of this study. Likewise, the 18 (36%) largest 1-min changes in Sym/H were likely caused by the passage of a CME ejecta. Based on this evaluation, although I did not capture 60% (combined) of the largest 1-min changes, I did account for 40% of the 50 largest events of the past twenty years, which is validation for this study.

5. Conclusion

This was a study of the potential causes and predictors for fast changes in GMF amplitude which lead to enhanced geoelectric fields and an increased risk for GICs. Using IP shocks data from WIND I show that speed jump at the shock is the strongest predictor for fast time rates of change for the GMF, as indicated in AL and Sym/H. Furthermore, I support the use of the dynamic pressure as a predictor for SIs and SSCs, indicated by its strong correlation with 1-min changes in Sym/H. In section two of this study, I show that fast changes in AL are associated with increased upstream magnetic field conditions and shock speed, and that auroral substorms can be preconditioned by a southward (negative) upstream magnetic field component, causing increased GMF amplitudes even in response to weak shocks. Furthermore, I show that increased time rates of change in Sym/H are possibly associated with upstream magnetic field conditions which modify the pressure balance between the dynamic pressure of the solar wind and magnetic pressure of the magnetosphere, and fast, strong shocks which compress the GMF. Finally, I show that this study captures 40% of the largest 50 events of the past twenty years, validating the use of IP shock data.

As 60% of the largest events of the past twenty years were outside the scope of this study, a similar study using CME data could be conducted to spread a wider net over the causes of large fluctuations of the GMF. Ground magnetometer stations, as of recent years, are becoming more capable of measuring GMF data with 1-s resolution, but no global indices have been compiled yet. Once this data is available a similar study could look at GMF response to specific, strong events to further understand how the GMF is perturbed by the solar wind.
Furthermore, a continuation of this study which tracks the impact of IP shocks to the induction of GICs would help to identify which factors other than interplanetary conditions affect the induction of these potentially harmful currents.

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References


