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The influence of the interplanetary shock front inclination angle on the sudden commencement amplitude asymmetry

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Interplanetary shocks which are observed in the solar wind can cause sudden changes of magnetic field observed at ground-based stations. The observed sudden changes, called sudden commencements, differ for different stations at different magnetic latitudes and local times. The main objective of this work is to identify the relationship between the impact angles of the interplanetary shocks on the resulting sudden commencement amplitudes, measured by ground-based magnetometers. For this purpose, an open database of interplanetary shocks (Oliveira, 2023) with shock front normal directions defined for each case and magnetic indices from the SuperMAG database (Newell, Gjerloev, 2012) is used, which, unlike the traditionally considered SYM-H and Dst indices, allow one to consider geomagnetic field variations for different local times. We have found out that in most of the cases considered, the SC amplitude in the dusk sector exceeded the SC amplitude in the dawn sector, despite the approximately uniform distribution of the interplanetary shock impact angles. This effect can be described by the influence of ionospheric currents. However, it has been shown that for very large angles of shock impact arriving from dawn side, the SC amplitude in the dawn sector may exceed the SC amplitude in the dusk sector, which can be described by the effect of currents on compressed magnetopause.

Keywords: Interplanetary shock, magnetosphere, sudden commencement

1 Introduction

When solar wind charged particles encounter the obstacle – Earth's intrinsic magnetic field, positive and negative particles are deflected in opposite directions. As a result of this charged particles motion the current sheet is formed, which is called

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the magnetopause current sheet. The magnetic field of these currents (called the Chapman–Ferraro currents) decreases Earth's field outside the magnetopause and increases it inside. The magnetopause position and shape is determined by the pressure balance between the magnetic field and plasma pressures on both sides. The external pressure is dominated by the dynamic pressure of the solar wind with a small contribution of magnetic field pressure. The situation is the opposite inside the magnetopause – here the Earth's magnetic field pressure dominates with a small contribution from the magnetospheric plasma pressure.

To describe the geomagnetic disturbance fields in mid-latitudes with high-time (i.e. 1 minute) resolution, a longitudinally asymmetric (ASY) and a symmetric (SYM) disturbance index were introduced and derived for both H and D components, that is, for the components in the horizontal (dipole pole) direction H (SYM-H, ASY-H) and in the orthogonal (East–West) direction D (SYM-D, ASY-D) (Iyemori, 1990).

Interplanetary shocks and discontinuities, which are observed in the solar wind, can be the cause of sudden changes in solar wind parameters such as speed, pressure, and magnetic field. A sharp increase in the solar wind dynamic pressure at an interplanetary shock or discontinuity leads to a change in the balance of forces at the daytime magnetopause (Araki, 1977, 1994). The compression of the magnetosphere leads to an increase in the Chapman-Ferraro currents at the daytime magnetopause. The increase in these currents leads to an ambient magnetic field growth in the magnetosphere, and information about the magnetic field growth propagates to the Earth in the form of a fast hydromagnetic wave (Tamao, 1964; Araki, 1994). As a result, the geomagnetic field component parallel to Earth's dipole (H-component) observed by ground-based magnetometers suddenly changes. This rapid change of magnetic field is called a sudden impulse (SI) (Matsushita, 1962). If an interplanetary coronal mass ejection (ICME) driving the shock and/or the shock sheath contains a southward pointing magnetic field, the resulting SI is followed by a magnetic storm and thus called the sudden storm commencement (SSC). The physical mechanisms of SSC and SI are the same. These phenomena, both SSC and SI, are commonly referred to as SC (Curto et al., 2007). The field growth begins suddenly with a duration of around 4 minutes (Takeuchi et al., 2002a).

Global SI can be either positive (the observed magnetic field increases) or negative (the observed magnetic field decreases). A positive sudden impulse (SI+) or SC indicates a sudden compression of the magnetosphere, while a negative sudden impulse (SI-) indicates a sudden expansion of the magnetosphere (Nishida, Jacobs, 1962). The main causes of SC (SI+) are fast interplanetary shocks, while SI– are caused mainly by tangential discontinuities (Takeuchi et al., 2002b). In this paper, we will study SI+, or SC.

The SC waveform observed by ground-based magnetometers is quite complex and strongly dependent on latitude and local time (Araki, 1994). It mainly has a form of a two-pulse structure at high latitudes and at the daytime magnetic equator, consisting of a preliminary pulse (PI) lasting about 1 min, followed by a main pulse (MI) lasting several minutes. Araki (1977, 1994) proposed a model to explain how a simple stepwise increase in solar wind dynamic pressure can lead to a complex global distribution of the SC waveform. According to this model, there are three different physical processes, which occur during SC. During sudden magnetospheric compression, a hydromagnetic compression wave propagates across the geomagnetic field up to the low- and mid-

latitude ionosphere and causes a sudden increase in the H geomagnetic component, the amplitude of which is maximum at the equator and decreases with increasing latitude. This field is called DL, which stands for low-latitude dominant disturbance. At the same time, the dusk-dawn electric field along the front of the hydromagnetic compression wave is transmitted to the polar ionosphere (Tamao, 1964). This electric field induces an ionospheric current system of two vortices, which creates a sharp impulse called preliminary impulse (PI) with a typical duration of 1–2 min. This field is called $DPpi$ (DP means a field of polar origin disturbances). PI manifests itself as a clear negative impulse of the H component at the auroral latitudes at the dusk sector and as a positive impulse at the dawn sector. When the compression wave passes to the magnetotail, magnetospheric convection will be enhanced if increased dynamic pressure is constantly supported by the interplanetary shock. As a result, the dawn-dusk convection electric field will be enhanced, which will be also transmitted along the geomagnetic field lines via field-aligned currents to the polar ionosphere, creating an ionospheric current system of two vortices, directed opposite to the $DPpi$ field. This current system creates the main impulse (MI) of polar origin with a typical duration of 5–10 min, called the $DPmi$ field. This current system produces negative and positive magnetic field variations in the dawn and dusk sectors near subauroral latitudes, respectively (Russell, Ginskey, 1995). Thus, the disturbance field of SC can be decomposed into three components: $Dsc = DL + DPpi + DPmi$, where pi, mi denote preliminary impulse and main impulse, respectively.

Interplanetary shocks are known to arise in association with corotating interaction regions (CIRs) and ICMEs. Although in many cases CIRs are not fully developed at 1 AU, some interplanetary shocks formed by the interaction of slow and recurrent fast moving stream emanating from a coronal hole have indeed been observed (Berdichevsky et al., 2000). Typically, interplanetary shocks caused by ICMEs have their shock normals with a small deviation from the Sun–Earth line, while shocks caused by CIRs have their shock normals with a large deviation from the Sun–Earth line (Oliveira, Samsonov, 2018). In this work we focus on search of dawn-dusk SC asymmetry arising due to the different interplanetary shock impact angles.

A large review on geoeffectiveness of interplanetary shocks controlled by impact angles is given at Oliveira, Samsonov (2018). For example, shock orientation can play an important role in determining the SC rise time as a highly oblique shock requires more time to compress the forward part of magnetosphere (Takeuchi et al., 2002; Wang et al., 2006). Generally speaking, a highly oblique shock causes asymmetric compression of the magnetosphere with respect to the noon-midnight meridian, takes more time to sweep by magnetosphere, and thus results in a longer rise time of the SC. Wang et al. (2006) analyzed the relationship between interplanetary shock speeds and orientations and the rise time and amplitude of the SC's for 225 events. Their results show that for shocks with similar speeds, the bigger the angle between the shock normal and the Sun–Earth line, the shorter the SC rise time.

Several studies have been devoted to the local time asymmetry of SC's. Francia et al. (2001) statistically examined 34 SCs at one low-latitude station during northward IMF conditions, that is, when no substorm/storm activity is present. They found that the amplitude of the geomagnetic response is characterized by a strongly depressed response in the dawn with respect to dusk. Shinbori et al.(2009) performed the statistical analysis of SC amplitude observed from middle latitude (MLAT = 45.5 degrees)

to the magnetic equator, using geomagnetic field data with high time resolution of 1 s for the 10-year period. Later, Shinbori et al. (2012) investigated the magnetic local time and latitude dependence of amplitude of the SC's main impulse using high time resolution (1–3 sec) geomagnetic data in the latitudinal range 27–70 degrees for the period 1996–2010. Shinbori et al. (2009, 2012) showed that at mid latitudes, SC amplitude variations in the daytime sector exhibit a strong dawn-dusk asymmetry, with minimum and maximum values occurring at 08:00–09:00 MLT and 15:00–17:00 MLT, respectively. This dependence of SC amplitude on MLT in the daytime sector is similar to that at subauroral latitudes (L = 3) (Russell, Ginskey, 1995). Shinbori et al. (2009) attributed this dawn-dusk asymmetry to DP currents, which influence the ground measurements magnetic field values up to low latitudes.

Interplanetary shock orientation may affect SC amplitudes at different ground-based magnetometers. Samsonov et al. (2015), using magnetohydrodynamic modeling showed that the impact of an inclined shock leads to an asymmetric response of the magnetosphere. If the interplanetary shock or discontinuity is inclined toward the dawn or dusk sector of the magnetosphere, the compression (expansion) of the magnetosphere will begin at a point distant from the subsolar point. Thus, the compression (expansion) wave front propagates in the magnetosphere asymmetrically relative to the day-night meridian, which can lead to different SC at different ground-based stations.

Therefore, knowledge of the orientation of the interplanetary shock front is important for space weather forecasting and the response of ground-based magnetometers. The main aim of the current paper is the identification of the relationship between the inclination angles of the interplanetary shock and the resulting SC amplitudes, which are measured by ground-based magnetometers. We consider many events, not limiting ourselves to the consideration of one or several cases. The novelty of the proposed research in this paper is that we consider for the first time the difference in the observed SC amplitudes in dawn and dusk sectors depending on the interplanetary shock impact angle.

The paper has the following structure: in section 2 we describe the experimental data – the database of interplanetary shocks and geomagnetic measurements, in section 3 we describe the research methodology, in section 4 we discuss the obtained results and in section 5 we present the conclusions.

2 Experimental data

2.1 Oliveira interplanetary shock catalog

In this paper we use the interplanetary shocks database, compiled in Oliveira (2023). This catalog is available via https://zenodo.org/records/15121223. The parameters and front normal orientations of the interplanetary shocks in this database were calculated using solar wind plasma and interplanetary magnetic field (IMF) data collected by Wind and ACE spacecraft at the L1 Lagrange point. Shock fronts are assumed to be flat structures larger than the Earth's magnetosphere. All data used for calculations in this database is presented in geocentric solar-ecliptic (GSE) coordinates. The temporal coverage of this list of 650 interplanetary shocks registered from January

1995 to December 2024. Having the normal vector to the front, we can calculate the impact angle of the interplanetary shock.

2.2 SuperMAG geomagnetic indices

To determine the exact impact of interplanetary shocks on the Earth's magnetosphere, we use SMR indices from the SuperMAG database (Gjerloev, 2012; Newell, Gjerloev, 2012). In this database, magnetic field magnitudes from 98 stations located below 50° magnetic latitude are presented with a resolution of 1 minute. The SMR index is similar to SYM-H index, but the data is collected from 98 stations instead of 6 stations for SYM-H (or 4 in the case of Dst index). This amount of stations made it possible to calculate indices, depended on magnetic local time – for midnight (SMR00, 21:00 – 03:00 LT), dawn (SMR06, 03:00 – 09:00 LT), noon (SMR12, 09:00 – 15:00 LT) and dusk (SMR18, 15:00 - 21:00 LT). Each of indices is the average N component measured in the magnetic local time quadrant center, N is the northward component of the SuperMAG NEZ coordinate system, and it can be considered as the disturbance part of the conventional H component (Gjerloev, 2012). SMR is the average of these four sub-indices. In the current paper we use SMR06 and SMR18 indices to determine the dawn–dusk asymmetry of the resulting disturbances.

Shinbori et al. (2009) concluded that the SC amplitude in the SYM-H index is entirely or mainly due to the Chapman–Ferraro currents, or DL field. Piersanti, Villante (2016) made a comparison between SC observations and Tsyganenko and Sitnov (2005) magnetosphere model and showed that the DL field may be well represented by the magnetopause current field alone, even in the nightside. SMR index ground magnetometer stations are located at low and middle geomagnetic latitudes, where DL field prevails. Thus, comparing SC amplitude by SMR06 and SMR18 indices, we can try to extract data on DL field change asymmetry, which can be caused by the inclination of the interplanetary shock.

Ohtani (2021) showed that there is local time asymmetry in magnetic field observed during the main and recovery phases of magnetic storm. They discovered that the dawn–dusk asymmetry of ground magnetic depression during the main phase of geomagnetic storms is strongly connected with the enhancement of the dawnside westward auroral electrojet, which may arise due to the dawnside wedge current system (Ohtani et al., 2018). Thus, we won't consider disturbed conditions in our analysis to exclude the ring current and auroral electrojet influences. To exclude the influence of the currents in auroral ionosphere, such as auroral electrojets, we impose a condition on SuperMAG auroral index SME (Newell, Gjerloev, 2011). It is calculated from SMU and SML SuperMAG indices, which are upper and lower envelopes of N observed at stations from +40 to +80° of magnetic latitudes, as SME = SMU - SML. SMU and SML indices are the measures of the eastward and westward auroral electrojets, respectively; they represent the maximum intensities of the corresponding equivalent currents.

3 Research methodology

3.1 Determination of interplanetary shock inclination angles

The Oliveira (2023) catalog contains information on the components of the interplanetary shock normal vectors (n_x, n_y, n_z) in the GSE coordinate system (X towards the Sun and Z perpendicular to the plane of the Earth's orbit, positive North). Figure 1 shows the schematic representations of shock normal vector in the X-Y plane. For the current study, it is necessary to know the angle corresponding to the local time of impact, i.e., in the equatorial plane. This angle θ is defined as $\arctan(n_y/n_x)$ and takes the values $[-90°; 90°]$, and the local time of impact is defined as $LT = -\theta/30° + 12$. In the case of negative n_y (i.e., the shock propagation is directed to the dawn side and first affects the dusk side), and the values $[-90°; 0°]$ the local time of impact $LT > 12$; in case of positive n_y (i.e. the shock propagation is directed to the dusk side and first affects the dawn side) the local time of impact $LT < 12$. LT here denotes the local time of shock impact.

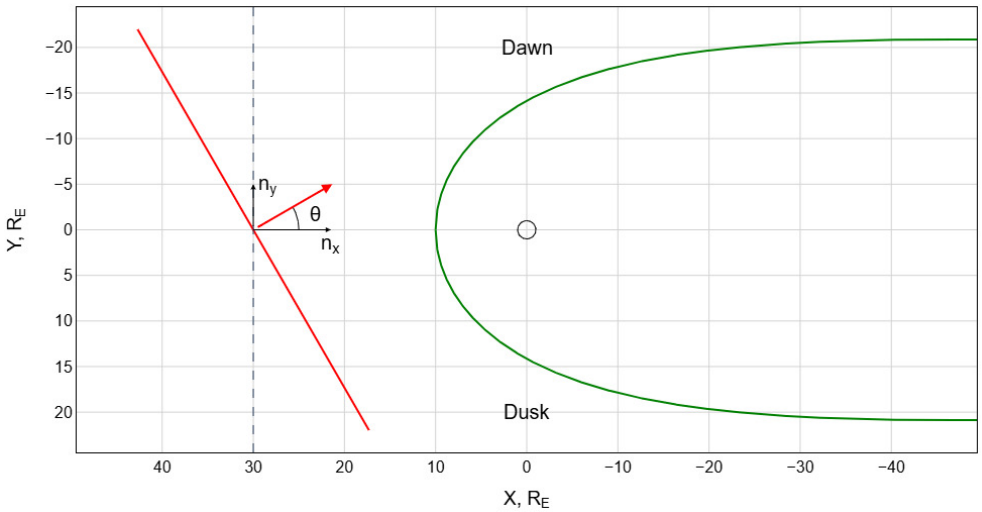


Figure 1 Schematic representation of the considered angle of inclination of the interplanetary shock in X-Y plane of GSE coordinate system. Shock surface and normal are shown in red. Earth's magnetopause surface is shown in green.

3.2 Determination of SC amplitude

To define a SC event Shinbori et al. (2003) proposed the following quantitative estimate: a rapid growth of SYM-H value with more than 5 nT within 10 min. Curto et al. (2007) proposed to use an abrupt change (with a minimum tilt of about 10 nT over 3 min) in the SYM-H. The Oliveira (2023) catalog includes the SC start time corresponding to each interplanetary shock determined by SMR index. To determine the magnetic impulse amplitude in our work we took the SC start time (1) and the

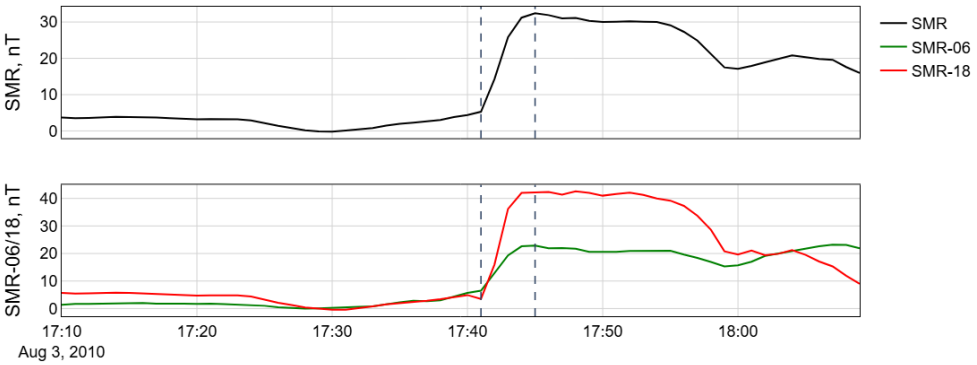


Figure 2 An example of a SC event based on the SuperMAG database. The top panel shows the global SMR index (black line), and the bottom panel shows the local indices SMR06 (green line) and SMR18 (red line). Vertical black dashed lines show the beginning and the end of SC jump determined by global SMR index.

moment when the changes in the magnetic field become less than +1 nT/min (2) from the global SMR index. Having the already determined SC start time, we thus improve the accuracy of determining the maximum of SMR index during SC. After that, for these two moments in time, the values of the SMR06 and SMR18 indices were determined and the amplitudes of the magnetic field jumps in the dawn sector (ΔSMR06 = SMR06(2) - SMR06(1)) and in the dusk sector (ΔSMR18 = SMR18(2) - SMR18(1)) were determined. Figure 2 shows the SC example according to the SuperMAG SMR indices data for event on 3 August 2010. As one can see the impulse at the dusk sector ($\sim$ 35 nT, red line) was much larger than the impulse at the dawn sector ($\sim$ 15 nT, green line).

From the data presented in Figure 2, we are interested in the difference between the changes of local dusk and dawn SMR indices (*Delta* = ΔSMR18 $-$ ΔSMR06). We expect that the impact direction from dusk would lead to the larger impulse in the dusk than in the dawn, and the *Delta* will be positive. And vice versa, with the impact direction from dawn would lead to the larger impulse in the dawn than in the dusk and the *Delta* will be negative. This expectation is due to the fact that the compression of the magnetopause should be greater from the side exposed to the interplanetary shock impact.

To avoid the influences from asymmetries in storm-time magnetosphere, we impose a restriction on the SMR index value at the beginning of SC: SMR should be larger than –10 nT (Ohtani, 2021). To avoid the influences from auroral current systems, we impose a restriction on the SME index value at the beginning of SC: SME should not be larger than 100 nT. A typical threshold value for the substorm intensity in automated identification is 100 nT (Tanskanen et al., 2005), or –50 nT for AL index (Partamies et al., 2013), which is analogous to SML index. Thus, from 650 events, initially presented in Oliveira (2023) catalog, we obtain 163 events, which satisfy the imposed conditions.

Ozturk et al. (2017) have shown that the ground magnetic perturbations during solar wind dynamic pressure increase depend on the IMF B_y component. Thus we

also have to take into account the B_y influence on differences between ΔSMR18 and ΔSMR06. To obtain IMF B_y values at the moment of SC start time we use online OMNIWeb dataset (https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/modified/) provided by the Goddard Space Flight Center. In the 163 selected cases, the distribution of IMF B_y is almost uniform as shown in Figure 3. The final distribution by local times of interplanetary shocks arrival is close to uniform, but has slightly more events on the dawn side, as shown in Figure 3.

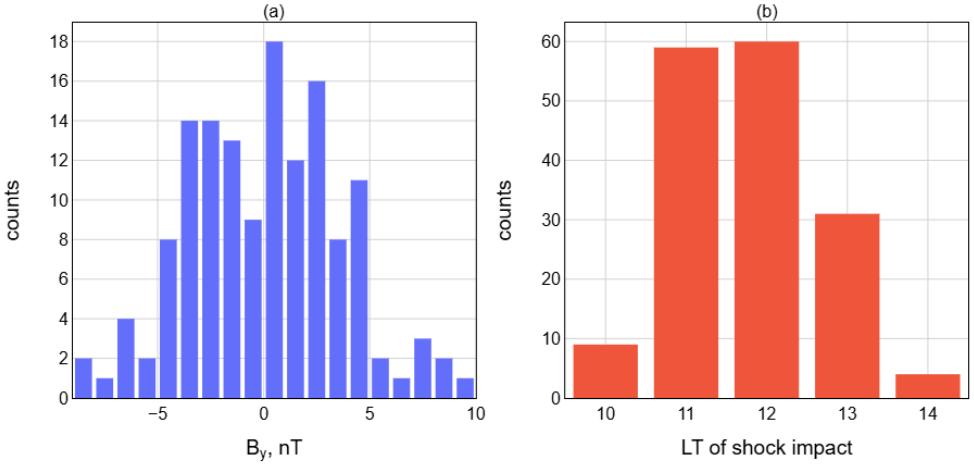


Figure 3 Distribution of 163 cases under analysis by (a) IMF B_y component at the SC start time, (b) local time of interplanetary shock impact.

3.3 Dependency analysis

Firstly we have calculated *Delta* for all 163 cases and plotted it depending on the local time of the interplanetary shock impact for different IMF B_y cases: $B_y > 0$ (Figure 4) and $B_y < 0$ (Figure 5). That was done to find out the possible influence of B_y on differences between ΔSMR18 and ΔSMR06. Selected events were then fitted with linear dependence using the *scipy* library for Python programming language.

As one can see from Figures 4 and 5, the slope k of the fitting line changes significantly from $k = 1.63$ for $B_y > 0$ to $k = 3.53$ for $B_y < 0$. From this we can conclude that for events with $B_y < 0$ *Delta* is larger and B_y influences the *Delta* value and thus leads to additional dawn–dusk asymmetry. To identify the influence of the direction of the interplanetary shock impact we have to exclude the B_y influence. OMNIWeb data, which we use in our analysis, uses ACE and Wind spacecraft data to obtain the IMF value. In the range ±10 nT the difference between an observed value from one of spacecraft and value computed for both is less than 0.2 nT (https://omniweb.gsfc.nasa.gov/html/ow_data.html). There are only 6 events in the limit of 0.2 nT so we impose a limit on the $|B_y|$ value to be less than 0.3 nT to account for the discrepancy in OMNIWeb data, thus analysing 9 events, which are shown in Figure 6.

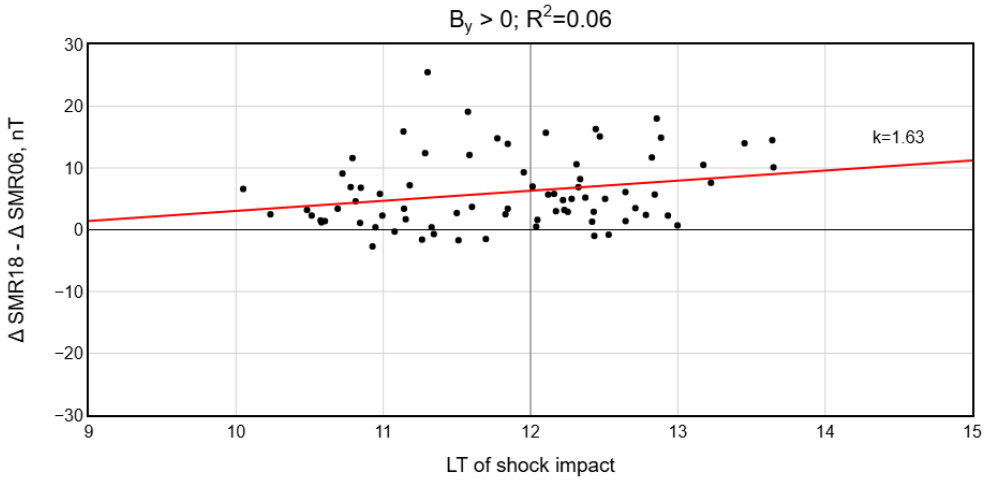


Figure 4 The difference between the dusk ΔSMR18 index jump and the dawn ΔSMR06 index jump depending on the local time of arrival of the interplanetary shock for IMF $B_y > 0$. Red line shows the linear fit with coefficient of determination R^2 shown above the plot.

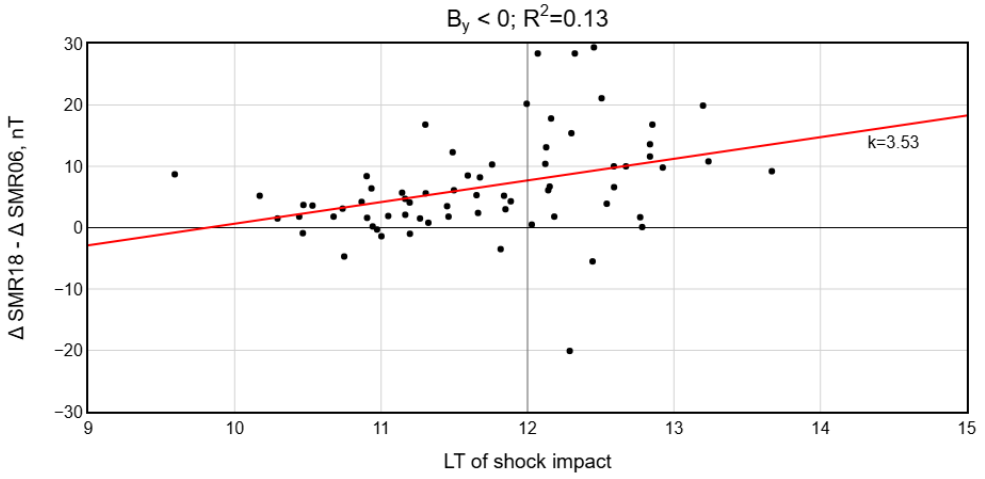


Figure 5 The difference between the dusk ΔSMR18 index jump and the dawn ΔSMR06 index jump depending on the local time of arrival of the interplanetary shock for IMF $B_y < 0$. Red line shows the linear fit with coefficient of determination R^2 shown above the plot.

As one can see from Figure 6, the most *Delta* = ΔSMR18 – ΔSMR06 values are greater than zero for the entire range of local times. This means that the SC amplitude on the dusk is almost always larger than the SC amplitude on the dawn. However, the expected trend of growing *Delta* with increasing local time of shock impact, remains. From Figures 4, 5 and 6 we can conclude that for the local times of shock impact less than around 10 the ΔSMR06 amplitude tends to be larger than or equal to ΔSMR18.

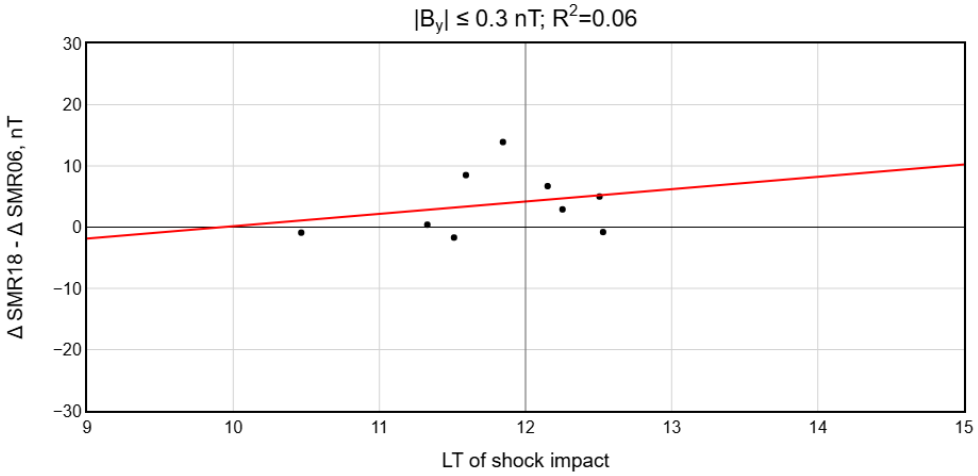


Figure 6 The difference between the dusk ΔSMR18 index jump and the dawn ΔSMR06 index jump depending on the local time of arrival of the interplanetary shock for IMF $B_y \leq 0.3$ nT. Red line shows the linear fit with coefficient of determination R^2 shown above the plot.

4 Discussion

In this paper we used local dawn and dusk SMR indices to find the influence of interplanetary shock impact direction on the SC amplitudes at dawn and dusk. After excluding factors which can influence the dawn–dusk asymmetry, such as storm-time conditions, strong auroral disturbances, IMF B_y value, we still obtained that SC magnetic field amplitude in the dusk (SMR18) is larger or approximately equal to SC magnetic field amplitude in the dawn (SMR06). The considered number of events is not large (9 cases) due to imposed restrictions, especially limit on B_y. But, increasing the threshold value, either choosing the $B_y > 0/ < 0$ cases does not change the result, as can be seen from Figures 4 and 5. Of these 9 events, 5 interplanetary shock impact directions were from the dawn sector and 4 from the dusk sector.

The solar wind flow is almost always directed along the Sun–Earth line within several degrees (Zastenker et al., 2015). Thus, the solar wind pressure on the magnetopause is greatest in the noon sector and symmetrically decreases as we move toward the flanks of the magnetopause and thus cannot create dawn–dusk asymmetry. However, there are disturbances in the heliosphere, which move differently from the solar wind. For example, it is well known that the large scale, corotating pressure waves can greatly affect the SIR/CIR dynamics (Burlaga, 1983). Even without corotating pressure waves and even in the case of strictly radial propagation of the solar wind, irregularities in it will have the visible corotation with the source on the Sun and have the shape of spirals (Kislov, Kuznetsov, 2022). Thus, the solar wind pressure on the magnetopause can be greater in the dawn sector due to the peculiarities of the propagation of spiral structures.

Nevertheless, we attribute the fact that ΔSMR18 is larger than ΔSMR06 in most cases to the DP field, described in the introduction. Shinbori et al. (2009) showed that for magnetic latitudes larger than 35°, the dawn–dusk asymmetry during SC's can become large due to the influence of ionospheric Hall currents, which are generated by the enhanced dawn–dusk electric field arising from magnetospheric compression (Araki, 1994). Shinbori et al. (2009) showed that during the main impulse phase in SC in the dawn sector, the field-aligned currents and Hall currents weaken the Earth's magnetic field, while the Pedersen currents strengthen it. At the same time, in the dusk sector, the Hall and Pedersen currents strengthen the ground magnetic field, while the field-aligned currents weaken it. Thus, the SC dawn–dusk asymmetry occurs. Shinbori et al. (2009) mentioned that it is mainly observed for stations located at middle and high latitudes, where the contribution of DP currents prevails, but the effect of DP currents can be observed at low latitudes up to 16.54°. We used SMR index which includes stations up to mid-latitudes to find the possible influence of interplanetary shock impact direction, but found out that the contributuion of DP currents is still large. Nevertheless, with decreasing local time of interplanetary shock impact the difference between dusk and dawn SC amplitudes becomes smaller. From this we conclude that there is a certain influence of interplanetary shock direction on SC amplitude.

It is worth noting that there is an ionospheric current system in a limited-in-latitude region of increased conductivity on the dayside magnetic equator, called the "equatorial electrojet" (Forbes, 1981). Although the equatorial electrojet is weaker than the auroral electrojets, its influence on the local magnetic field is quite significant (Yizengaw et al., 2014). Studies have shown that the equatorial electrojet affects SC (Russell et al., 1994). Therefore, at stations located near the equator, a slight asymmetry may be observed due to local time variations of the equatorial electrojet, which is mainly located in this region (Shinbori et al., 2009).

Conclusions

We have considered the relationship between the impact angles of the interplanetary shocks on the resulting sudden commencement amplitudes, measured by ground-based magnetometers. To do this, we examined statistically 650 SC's connected with interplanetary shocks with known parameters from Oliveira (2023) catalog using the SuperMAG geomagnetic indices over the period 1995–2024. We have found out that in most of the cases considered, the SC amplitude in the dusk sector exceeded the SC amplitude in the dawn sector, despite the approximately uniform distribution of the interplanetary shock impact angles, which we associate with the influence of ionospheric currents. However, it has been shown that for very large angles of shock impact from dawn side, the SC amplitude in the dawn SMR06 index may exceed the SC amplitude in the dusk SMR18 index, i.e., the contribution to the observed magnetic field from magnetopause currents (increased by the shock impact) will exceed the contribution from polar ionospheric currents. This result might be important for predicting geomagnetic disturbances at different local times on Earth.

Although there are some uncertainties in determining the shock parameters, we do not believe such uncertainties will change our statistical results significantly. Also,

we assumed that the propagation through the bow shock and magnetosheath does not lead to a significant change in the orientation of the front plane which could be incorrect. We suggest several ways to check and refine the obtained results:

1. Use another database, for example Harvard CfA Interplanetary Shock Database (https://lweb.cfa.harvard.edu/shocks/).
2. Conduct a case-study research with several cases, analysing solar origins and shock normal using several spacecraft data.
3. Use data from low latitude INTERMAGNET ground magnetometers with 1-sec time resolution (e.g. Shinbori et al., 2012) for precise local times instead of 1-min SMR index resolution only for large dawn/dusk local times interval.
4. Check the magnetic field data from several spacecraft located in the dawn and dusk sectors at the moment of interplanetary shock arrival.

Conflict of interest

The authors declare no conflict of interest.

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The OMNI data were obtained from the GSFC/SPDF OMNIWeb interface at https://omniweb.gsfc.nasa.gov.

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