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Physical processes underlying the geomagnetic effects of solar wind dynamic pressure (Pd) variations

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Abstract. A concise review of recent studies of the ground-level geomagnetic storm sudden commencements (ssc's)/positive sudden impulses (si's) observed in the dip equatorial region and at low latitudes is presented highlighting the incremental additions to our empirical knowledge of the characteristics of ssc's/si's and understanding of the physical processes responsible for them.

Keywords : interplanetary (IP) shocks – geomagnetic storm sudden commencement (ssc)/sudden impulse (si) – ground-level effects at equatorial and low latitudes – polar ionosphere – low latitude ionosphere electrical coupling

1. Introduction

The solar wind dynamic pressure (Pd) at the Earth's orbit (1AU) exhibits considerable temporal variability and induces corresponding variability in the magnetospheric configuration and the various current systems of the magnetsophere-ionosphere domains. Of particular relevance here is the step-like increase in Pd due to fast forward interplanetary (IP) shocks, whose impact on the sub-solar magnetopause causes a sudden magnetospheric compression leading to the so-called geomagnetic storm sudden commencements (ssc)/positive sudden impulses (si^+) at ground level. The impact of tangential discontinuities in solar wind, on the other hand, causes sudden magnetospheric expansion and geomagnetic negative sudden impulse (si^-). The global characteristics of ground-level ssc's have been extensively investigated since the first International Polar Year (IPY1), and it is well established that the ssc waveform exhibits a complex dependence on latitude and local time, clearly indicating a significant contribution of not only the distant magnetopause currents but also of near- Earth ionospheric currents. Araki (1977,1994) developed a phenomenological model of ssc based on a synthesis of the extensive observational results and theoretical ideas of Tamao (1964). According to this model, the ssc disturbance consists of two basic components, DL and DP. The disturbance field, DL represents the fundamental effect of enhanced Chapman-Ferraro currents due to the sudden magnetospheric compression induced by the IP shock and results in a step- like increase of northward H-component everywhere but predominantly at low latitudes, away from the influence of both the auroral and equatorial electrojets. DP represents the disturbance field due to ionospheric currents of polar origin and accounts for the preliminary impulse (pi) that precedes the main impulse (mi) of the ssc and also contributes to enhancement of mi amplitude at the dayside dip equator. In other words, at the dayside magnetic equator, the pi is exclusively due to currents and electric fields of polar origin (DP_{pi}), while the mi is due to the combined effects of magnetospheric compression and electric fields/currents of polar origin, DL+ DP_{mi}. The model is supported by substantial experimental work (see, Sastri et al. 1993; Araki 1994 and references therein). There is, nevertheless, some disagreement between observations and the model regarding the preliminary impulse (pi), (see for example, Yamada et al. 1997; Yumoto et al. 1997; Engebretson et al. 1999) indicating that our understanding of the ssc in general, and of its preliminary impulse (pi) in particular, is far from being complete. In contrast to ssc, there continues a glaring dearth of studies of negative sudden impulses (si^-). The isolated efforts of Araki & Nagnao (1988) and Sastri et al. (1995), however, indicated that si^- can as well be explained by the physical model of ssc, but with a reversal in the polarity of the current systems responsible for the ground-level geomagnetic field variations.

In the following, I shall endeavor to profile the recent noteworthy studies of ground level ssc's in the dip equatorial region and at low latitudes and their implications to the understanding of ssc.

2. Recent results

2.1 Dayside dip equator

At the dayside magnetic equator, ssc manifests in two basic configurations with more or less equal frequency at it's diurnal maximum around local noon, namely, (1) the conventional sc characterized by a monotonic increase of H-field, i.e., the main impulse (mi) and (2) sc* wherein the mi is preceded by a short-lived (1-2 min duration) but distinct negative pulse, referred to as the preliminary reverse impulse, pri (Rastogi & Sastri, 1974; Araki et al. 1985). This two-pulse structure is rarely seen at low latitudes but reappears again at high latitudes in the afternoon sector, simultaneously with that at the dip equator (see, Araki, 1977 and references therein). As already mentioned, this global pattern of sc* occurrence has been explained in terms of the superposition of the magnetic effects of twin-vortex DP2 type ionospheric current system of polar origin that penetrates instantaneously to the dip equator (Kikuchi et al. 1978; Kikuchi & Araki 1979), on that due to the basic magnetospheric compression, i.e., DL field (Araki 1977, 1994). Recent MHD simulations of the magnetospheric response to a solar wind impulse lend substantial support to the physical model of Araki as regards the establishment in quick succession of short-lived field-aligned currents (FACs) that carry the large-scale magnetospheric electric field to the polar ionosphere where it excites the twin-vortex DP2 current system (Slinker et al. 1999; Fujita et al. 2002 a, b).

Though the prevalence of ssc/ssc* is known since a long time, the absence of simultaneous observations at different longitudes along the dip equator hampered evaluation of the longitudinal (local time) dependence, if any, of their characteristics. It is only in recent times this limitation could be overcome due to the establishment of several equatorial magnetometers with high time resolution and sensitivity by Prof K. Yumoto, Kyushu University, Japan as part of the Circum-pan Pacific Magnetometer Network (CPMN). This network, which is currently operated as the MAGDAS project of the International Heliophysical Year (IHY) program, has the potential to enrich our knowledge of equatorial ssc*, besides other geophysical phenomena. The comprehensive study of the preliminary impulse (pi) of the ssc of November 18, 1993 by Sastri et al. (2001) is a case in point. Using the data of several magnetometer networks including CPMN, IMAGE as well as GOES satellite observations they had shown that, in deviation to the conventional wisdom based on earlier statistical studies of single station observations and available models, the pri of the ssc* under study, didn't appear at the noon magnetic equator, while it is distinctly seen in the pre-noon sector simultaneous with that at high latitudes on the afternoon side. From theoretical calculations, it is suggested that the global current system driven by a pair of FACs at 80 deg. latitude and with a morning side rotation (current centres at 1300LT and 0300 LT) could, in general, account for the observed behaviour of the pri, except at the dusk magnetic equator.

The mechanism of propagation of the pri of ssc* from the polar region to the magnetic equator has become a topic of some debate and controversy at the beginning of the current decade. The polar origin of equatorial pri is widely accepted and never disputed. The equatorial pri is conventionally understood in terms of the instantaneous propagation all the way to the equator of the large-scale electric filed imposed on the polar ionosphere through the Earth-ionosphere wave guide as a zeroth-order transverse magnetic (TM) mode at the speed of light, where it generates measurable currents because of enhanced Cowling conductivity there. This interpretation which is an important element of the model of Araki (1977, 1994) is well supported by HF Doppler observations of ionospheric vertical plasma motions (Kikuchi et al. 1985; Kikuchi 1986; Sastri et al. 1993) and theoretical calculations (Kikuchi et al. 1978; Kikuchi & Araki 1979). Some doubts about the efficacy of the wave guide explanation of equatorial pri were cast earlier from the view point of ground vertical electric field associated with the pri signal (Yumoto et al. 1997), but it is only in recent years this view point gained some further support.

In a study of the ssc event of September 24, 1998, using magnetometer data from 35 stations on the American continent and West Pacific region of the globe, Chi et al. (2001) found small but measurable time differences in the 'arrival time' of the preliminary impulse (pi) at high latitudes and preliminary reverse impulse (pri) at lower latitudes, as may be seen from Fig. 1. They have explained the observed 'zigzag' latitudinal profile of the ‘arrival time’ in terms of the propagation of compressional waves in the magnetosphere from the location of the first compression to the ground, by doing the relevant calculations. Kikuchi & Araki (2002) commented on the work of Chi et al. (2001) by pointing out that the definition of ‘arrival time’ of pri adopted by Chi et al. (2001), namely, the time of maximum amplitude of pri, is quite different from the time of first inflection or onset used by Araki (1977), and of the uncertainties in timing the pi at high latitudes due to localized disturbancesetc, that have implications to the interpretation of the origin of equatorial pri signal. They defended the Earth-Ionosphere wave guide propagation model of equatorial pri by highlighting, among other things, the inadequacy of the MHD propagation model of Chi et al. (2001) in explaining the occurrence of vertical ionospheric plasma motions on the night side simultaneous with that of pi at high latitudes (Kikuchi, 1986). This was replied to by Chi et al. (2002) who asserted that MHD waves provide the dominant scheme for pri signal to propagate to low latitudes, though the MHD theory of pri needs refinement in several respects. They accomplished this task quite recently by performing an MHD numerical simulation of the propagation of sudden impulses (si’s) in the three-dimensional magnetosphere (Chi et al. 2006). It is shown that the ‘travel time’ of si is strongly influenced by the inhomogeneous Alfven velocity profile so much so that the si ‘travel time’ varies with invariant latitude in a ‘zigzag’ manner as observed by them in the ssc event of September 24, 1998. In contrast, the si ‘onset time’ varies little with invariant latitude as established by past observations, but without the need to invoke the Earth-ionosphere wave guide model.

To sum up, it is fair to say that the mechanism of propagation of pri from high latitudes to the magnetic equator remains an open question at the moment, and merits further concerted studies using high time resolution magnetometer data with GPS synchronization for timing accuracy, which is essential to settle the question. This effort must be done for a large number of ssc events corresponding to different IMF Bz conditions to gain better insight into the mechanisms at work in individual events and attempt an assessment of the relative adequacy of the two competing mechanisms advanced thus far.

This leads us to the more fundamental question regarding equatorial ssc* that has not received due attention so far, namely, why it does not always manifest at the day side dip equator. At any given equatorial location, ssc* is seen only for about 50 per cent of the time even at the time of its diurnal maximum around local noon (Rastogi & Sastri 1974; Araki et al. 1985). The root cause of this behaviour seems to lie in the way the coupled magnetosphere-ionosphere domains respond to the impact of the IP shock, depending perhaps on its characteristics and the ambient orientation of IMF Bz. This is because the two-pulse structure as seen in ground level ssc* is not seen in IP space and the ssc waveform at the dayside dip equator (ssc* or conventional ssc) is always the same as that seen at high latitudes (Araki 1977). As an exploratory step in identifying the controlling factors, Sastri et al. (2006) conducted a statistical study of the characteristics of daytime ssc’s recorded simultaneously at Kodaikanal (10.25°N, 77.5°E, dipole lat.0.6°N) and Alibag (18.6°N, 72.9°E, dipole lat. 9.5°N) from 1957 through 2002. They found that at Kodaikanal, the amplitude of the mi of ssc* is, on the average, higher

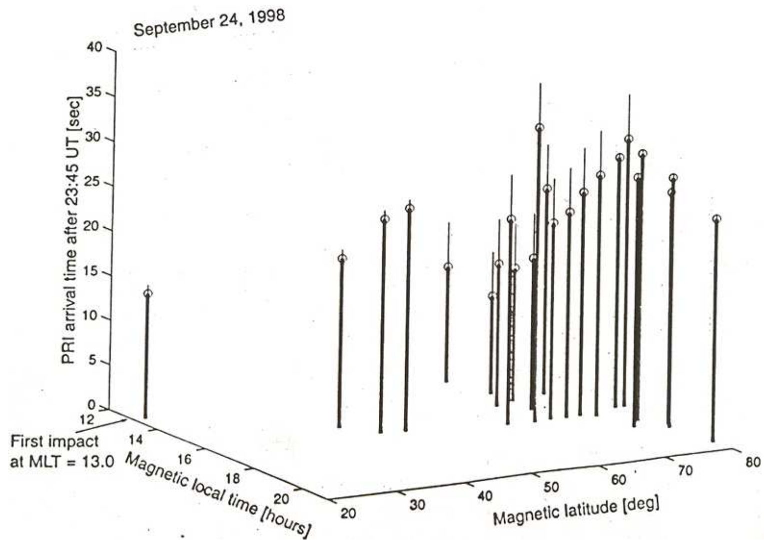

Figure 1. Latitudinal variation of the arrival times of preliminary reverse impulse, pri of the sudden commencement on September 24, 1998, as observed at 23 stations of the magnetometer networks: MACCS, CANOPUS, IGPP-LAN and CPMN. The data are displayed with reference to the locations of the stations in magnetic local time and magnetic latitude. The thin line segments above the circles represent the uncertainty in determining the arrival time due to the time resolution of the data. Note the 'zigzag' pattern of the PRI arrival time - PRI arrives earlier at mid-latitude stations outside the plasmapause latitude and at low-latitude stations (source: Chi et al. 2001).

than that of conventional ssc(+) and such a feature is not apparent at Alibag away from the influence of the equatorial electrojet. This behaviour can clearly be seen from the statistical data in Fig. 2 (left panel). Moreover, the study brought to light the existence of a linear positive relationship between the event-to-event variability of the amplitude of pri and mi of ssc* at Kodaikanal, as may be seen from the mass plot presented in Fig. 2 (right panel). These statistical results imply that ionospheric currents of polar origin play a significant role when ssc* is excited at the dayside magnetic equator, and the orientation of IMF Bz may be one of the factors (if not the only one) that determines the nature of response of equatorial H-field to the impact of fast forward IP shocks. Evidence in support of this inference was also found by Sastri et al. (2006) from CPMN data, though limited to a few but well identified ssc events. It is demonstrated that the impact of an impulse in the solar wind dynamic pressure under southward IMF (northward IMF) is associated with ssc* (ssc) in the dip equatorial region of the sunlit hemisphere (see Figures 4 and 5 of Sastri, et al. 2006). The study was, however, not conclusive because the earlier case study of Kikuchi et al. (2001) showed that the dynamic pressure impulse that occurred under northward IMF conditions can also be associated with ssc* at the dayside dip equator, contrary to the behaviour noticed in the event sample analyzed by

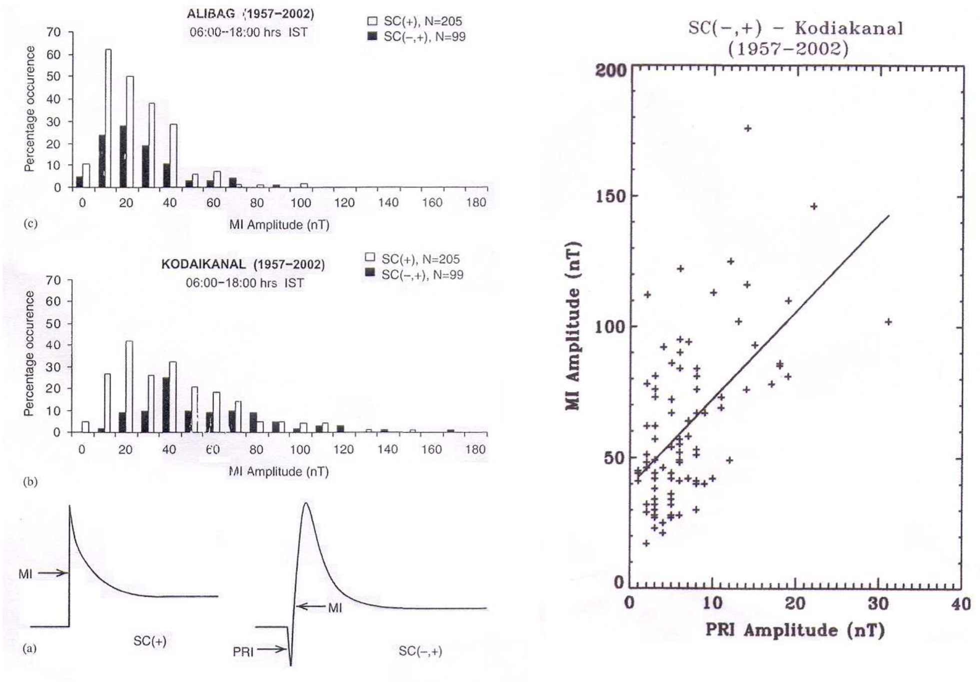

Figure 2. (left) Schematic of the two types of ssc that are seen in H-field at the day side dip equator (bottom panel), distribution of the amplitude of the main impulse, MI of the two types of ssc at the dip equatorial station, Kodaikanal (middle panel) and at the low latitude station, Alibag (top panel); (right) Mass plot of the amplitudes of the preliminary reverse impulse, PRI and main impulse, MI of ssc* events at Kodaikanal over the period 1957-2002 (source: Sastri et al. 2006).

Sastri et al. (2006). It follows, therefore, that factors other than IMF Bz may play a crucial role at times and the search to identify these external/internal factors and the ambient solar wind-magnetosphere-ionosphere conditions they represent must continue to comprehend the origin of the bi-modal response of equatorial H-field (conventional ssc and ssc*) to sudden magnetospheric compressions.

2.2 Low latitudes

The cleanest ground level geomagnetic effects of sudden magnetospheric compressions by fast forward solar wind shocks are generally seen at low latitudes and this has facilitated evaluation of the quantitative relationship of the ground level H-field response to the causative change in the solar wind dynamic pressure (Russell et al. 1992; Araki et al. 1993). Even here, the H-field response to dynamic pressure changes depends on local time with higher sensitivity at noon than at midnight, and also depends on the direction of the north-south component of interplanetary magnetic field, IMF. The dayside H-field response is smaller when IMF Bz is southward than when northward possibly because of the effect of Region 1 current system associated with reconnection induced by southward Bz, and an opposite situation prevails at night (Russell et al. 1994a,b). The recent years have witnessed some refreshingly new results concerning the characteristics of ground level ssc at low latitudes indicating that ssc in this region of the globe is not as benign as is commonly believed.

The rise time of the main impulse of ssc varies over the range 2 min to 10 min with a preference for about 4 min. Many explanations are offered for the rise time and its variability but without any consensus. Nishida (1966), in particular, suggested that the ssc rise time is determined by the time required by the IP shock to sweep by the magnetosphere, thereby hinting at the relevance of shock orientation to ssc rise time. This explanation just now gained support. Taekuchi et al. (2001) evaluated the spatial structure of the IP shock that led to the ssc of December 15, 1995 and attributed the abnormally large rise time of about 30 min at low latitudes to the high inclination of the shock and the gradual magetospheric compression it entails. They introduced the concept of 'geoeffective magnetopause' to replace the 'magnetic cavity' of Nishida and argued that the rise time of the ssc is primarily determined by the time the IP shock takes to sweep by the 'geoeffective magnetopause', and hence the orientation of the causative shock. The most recent statistical analysis of Wang et al. (2006) confirmed the dependence of ssc rise time on the orientation of the IP shock and revealed a dependence on the shock strength as well. From a study of 225 fast forward shocks and the resultant ssc's as seen in SYM-H index, they had shown the rise time to exhibit a negative correlation with the shock speed and the angle between the shock normal and the Sun-Earth line. This means that for a given range of orientation, shocks with higher speeds take lesser time to sweep by the geoeffective magnetopause and hence shorter rise time. And for shocks within a given range of speeds, the larger the angle between the shock normal and the Sun-Earth line, the shorter would be the ssc rise time. The latter feature is illustrated in Fig. 3 for shock speeds in the range 550–650 km s^{-1}.

A new dimension to the quantitative relationship of low latitude ssc's to the causative enhancements in solar wind dynamic pressure has been added by the very recent statistical study of Huang & Yumoto (2006). They have used data of low latitude stations of the 210 Magnetic meridian chain of magnetometers which are at the same magnetic latitude but in different hemispheres and solar wind data information was sourced from the databases of Wind and ACE satellites. They found a striking hemisphere asymmetry in the response of low latitude H-field to sudden dynamic pressure enhancements. During the June solstice, the amplitude of the geomagnetic disturbance is larger in the Northern hemisphere compared to the southern hemisphere and the reverse is the pattern during the December solstice. Moreover, this hemisphere asymmetry practically disappears during the both the equinoxes and is more prominently seen during Pd enhancements when Bz was southward than northward. This behaviour is illustrated in Fig. 4 for southward Bz

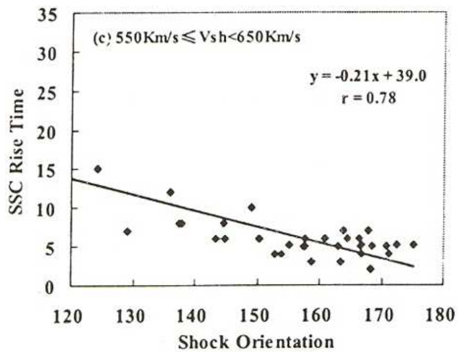

Figure 3. SSC rise time as function of shock orientation for shocks in the speed range 550 km s^{-1} - 650 km s^{-1} (source: Wang et al. 2006).

conditions. The hemispheric difference of geomagnetic disturbances, which is suggested to be due to tilt of the Earth's magnetic axis, can vary by a factor 2. It thus has important implications to the categorization of magnetic storms using the Dst index derived from low latitude magnetic data of three Northern hemisphere stations and just one station in the southern hemisphere. In addition, quantification of the response of low latitude H-field to solar wind dynamic (Pd) pressure enhancements with a large database by Huang & Yumoto (2006) showed that the correction factor usually adopted for Dst index to remove the effect of magnetopause current related to Pd (e.g. Burton et al. 1975) is grossly underestimated.

Enhancements of solar wind dynamic pressure can influence auroral electrojet activity (e.g., Shue & Kamide 2001) as well as auroral oval characteristics (Boudouridis et al. 2003). The most recent studies brought to light the fact that the asymmetry of the magnetospheric ring current can also be affected by solar wind dynamic pressure (Pd) enhancements. Shi et al. (2005) found that Pd enhancements that occurred during storm main phase under strong and steady southward IMF Bz further increase significantly the already asymmetric ring current, represented by the ASY(H/D) index. Pd increases that occurred during early recovery phase of the storm when Bz was turning northward while still being southward lead to only a moderate increase of the already slightly asymmetric ring current. In contrast, Pd increases that occurred during late stage of storm recovery under strongly northward Bz didn't affect the symmetry pattern of the ring current at the time. These event-based results show that the ambient state of the ring current asymmetry, which is dependent on Bz conditions, pre-determines the effect of dynamic pressure increase. In a follow up statistical study using 186 dynamic pressure enhancements that occurred over the period June 2003 through September 2004, and corresponding to both storm time and non-storm time conditions, Shi et al. (2006) confirmed the results of their case studies and also showed that the response of ring current asymmetry also depends on the strength of the pressure increase: for the same Bz conditions, the larger the Pd enhancement, the stronger is the intensification of the ring current asymmetry. The study

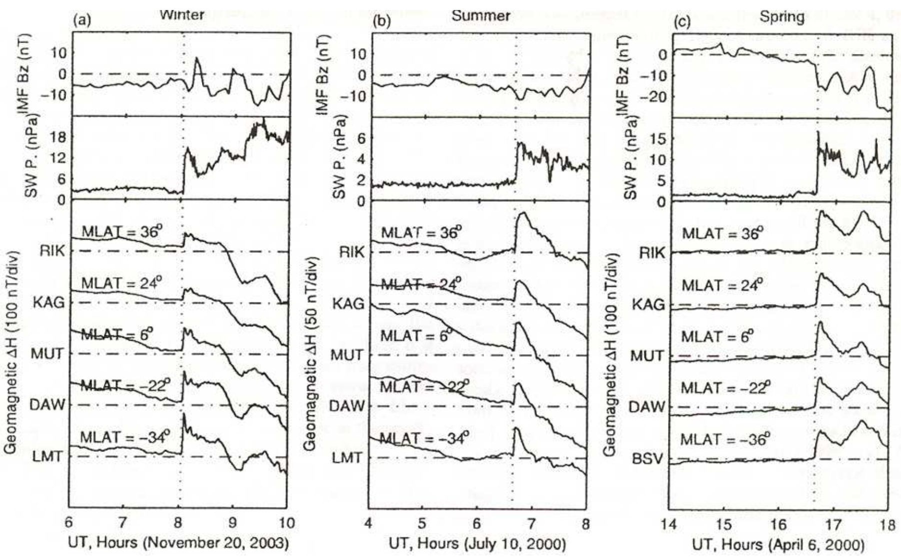

Figure 4. Illustration of the sudden increase of H-field at low latitude stations caused by sudden enhancement in solar wind dynamic pressure for events representing the December and June solstices and March equinox that occurred during southward Bz conditions. Note the remarkable difference in ssc amplitude between stations at the same magnetic latitude (MLAT) but located in the Northern and Southern hemispheres and the presence of this behaviour only in the solstices and not in March equinox (source: Huang & Yumoto 2006).

points to a significant contribution of the effects of field-aligned currents (FACs), the substorm current wedge and ionospheric currents of polar origin (region 1) to low latitude H-field disturbances around local noon and midnight (day-night polarity and amplitude asymmetry) as well as the ASY-H index. It is worthwhile to recollect in this context that at low latitudes, FACs, ionospheric (Hall and Pedersen) currents and the magnetopause currents (DL field), all contribute to the amplitude of ground level ssc. While the effect of FACs depends on latitude and local time, that of ionospheric currents depends on latitude, local time and season. So much so, the amplitude of ssc in individual events depends on the net magnetic effect of the various current systems.

The very recent statistical and case studies of the diurnal variation of ssc amplitudes at low latitudes conducted by Araki et al. (2006) also support the above line of understanding of the current systems involved in the low latitude response to Pd enhancements. They found that at Kakioka (Geomag. Lat. 27.4 deg), ssc's with an H-field amplitude >40 nT occurred more frequently during night, while those with amplitudes <30nT occurred more frequently during daytime. Case studies further indicated that this behaviour depends on the ambient orientaion of Bz-the night-to-day difference in ssc amplitude is larger when Bz was southward than when it was northward. It is imperative that further innovative studies are required to assess the relative contribution of the different current systems to H-field disturbances caused at low latitudes by enhancements in the solar wind dynamic pressure.

3. Concluding remarks and unsettled issues

Studies of the ground level geomagnetic ssc and positive si have a rich heritage beginning with the Ist International Polar Year (IPY1) when they provided the first awareness of the simultaneous appearance of ssc on a large spatial scale (Adams 1892; Ellis 1892), to the present times of the International Heliophysical Year (IHY) when we have a reasonably good understanding of the transient current systems that develop in the magnetosphere-ionosphere system to the impact of IP shocks, and their role in the global manifestation of ssc/si$^+$. This long journey was rendered rewarding by the contributions of many gifted individuals, both theoreticians and experimentalists, advances in magnetometer instrumentation and the dawn of space age that provided the all important information on IP shocks and discontinuities responsible for ssc/si$^+$.

We have to continue to surge forward building on this foundation to achieve comprehensive understanding of ssc/si$^+$. It is pertinent to recollect here that a majority of the studies thus far focused on the terrestrial side of ssc/si$^+$ and not much attention is paid to the causative IP shock/discontinuities. Further studies may now gainfully be conducted by examining the geomagnetic effects of well identified and accurately characterized IP shocks (as regards for example, magnitude, ΔP and relative strength of pressure enhancement, $\Delta P/P_0$; ambient IMF conditions, and orientation of the shock) to address the unresolved questions and derive new information concerning the characteristics of ssc in the dip equatorial and low latitude regions, keeping the global perspective in tact. The unsettled issues and the new advances that need to be made include the following:

1. The controversy (Earth-ionosphere wave guide versus MHD waves) regarding the mechanism of propagation of the pri signal from the polar region to the dip equator must be resolved through careful analysis of data of the various magnetometer networks (210MM/CPMN, IMAGE, CANOPUS, SAMBA, Greenland West and East coast chains and other national networks such as in India) for a large number of IP shocks of varying strengths and different ambient IMF conditions. Such an effort is required to assess whether the mechanism remains invariant of shock characteristics and the background IMF conditions or different mechanisms operate for different situations.

2. Continued efforts have to be made to address the more basic physics question as to the origin of the bi-modal response of the equatorial H-field (ssc or ssc*) in the sunlit hemisphere.

3. The amplitude of the main impulse (mi) of either ssc or ssc* undergoes enhancement at the dayside dip equator due to the contribution of DPmi, the disturbance field of

polar origin. Quantification of DPmi and identification of the factors that determine its event-event variability, if any, needs to be achieved. This is warranted because it is not known whether the mi amplitude in the dayside dip equatorial region depends entirely on the large-scale electric field imposed on the polar ionosphere and the twin-vortex current system excited there by it OR whether local equatorial electrojet (EEJ) conditions also play a role. The conspicuous absence of dip equator enhancement in the latitudinal profile of ssc amplitude in the event at 112 UT on July 13, 1961 observed in the Indian sector by Sastri (1975) points to an influence of ambient EEJ conditions on ssc behaviour, and hence the necessity to study this aspect further for a better understanding. Since the DPmi disturbance manifests as a negative impulse superposed on the main impulse at mid-latitudes in the forenoon sector (Tsunomura 1999), it would be interesting indeed to ascertain whether the nature of variability of DPmi field as seen both in the equatorial and mid-latitude data remains the same on individual occasions.

4. Precious little is known of the longitudinal (local time) dependence of the characteristics of both ssc and ssc* (amplitudes of mi and pri and their ratio) from simultaneous observations along the magnetic equator at different meridians. The MAGDAS project of IHY may be expected to fill this glaring gap in our empirical knowledge of equatorial ssc, which may then be compared with theoretical model calculations (Osada 1992; see also Figure 15 of Araki 1994) to assess their efficacy.

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