A Study of Intense Magnetic Storms Development (Using Dst Signature) and Its Association With Magnetic Clouds

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This paper attempts to study the development of intense magnetic storms using storm time Dst index and its association with magnetic clouds. For the purpose of this work, we have selected eight rather strong geomagnetic storms occurred in different seasons in 1976-2002. The Dst index is used in relation to other interplanetary and geomagnetic parameters because changes in the large-scale electric fields in the solar wind during intense geomagnetic storms can be reproduced from the variation in Dst value. It was observed that over 70% of the storm events under investigation are generated from magnetic clouds which are characterized by low beta plasma, high Interplanetary Magnetic Field (IMF) magnitude and large scale coherent field rotations often including large and steady north-south components. It was also shown that the storm events having peak Dst < -250nT are more prone to having magnetic clouds as their main source of generation than others. However, this class of storms takes a longer time to recover after its main phase than those between the range -250nT ≤ peak Dst < -100nT with respect to their Dst plots.

1. Introduction

Major geomagnetic storms represent a significant dissipation of energy by the magnetosphere. The energy is derived from the solar wind flow and the subsequent powerful conversion of that energy takes different forms. Amongst these are the ring current injection and decay, ionospheric Joule heating, and a host of other physical processes being exhibited clearly in large storm events. The dominant interplanetary phenomenon causing intense magnetic storms are the interplanetary manifestation of fast coronal mass ejections (CMEs) ([1] and the reference therein). Two interplanetary structures are important for the development of such class of storms: the sheath region just behind the forward shock and the CME itself. According to [2], these structures frequently lead to the development of intense storms with two-step growth in their main phase. These structures also lead sometimes to the development of very intense storms, especially when an additional interplanetary shock is found in the sheath plasma of the primary structure accompanying another stream [2, 3]. Of importance is also the solar wind ram pressure in the ring current energization. The transfer mechanism solar wind energy is magnetic reconnection between the IMF and the earth's magnetic field. The energy transfer efficiency is of the order of 10% during intense magnetic storms. However, viscous interaction, the other prime energy transfer mechanism proposed, has been shown by [4] to be only <1% efficient during intense northward directed IMFs.

The dominant solar/coronal events which occur near the maximum sunspot phase of the solar cycle are impulsive ejecta, often referred to as coronal mass ejections (CMEs). These events have different speeds, but the ones that are most effective in creating magnetic storms are the fast events with speeds exceeding the ambient wind speed by the magnetosonic wave speed, thus forming a fast forward shock. As the fast plasma and field structure propagates from the sun through the interplanetary space, it sweeps up and compresses the slower plasma and field ahead thus creating a 'sheath' between the shock and the interplanetary manifestation of the ejecta. It was, however, observed that roughly five out of six fast ejecta do not cause Dst < 100n T storms. This is because they lack large southward field components persisting for three hours or longer. It is also important to note that on several occasions more than one complex interplanetary structure can be associated with the origin of intense storms. These complex structures have been studied by many researchers (e.g., [2, 5, 6]). Also, most of these reported complex structures involve a fast forward shock followed by a magnetic cloud and usually another high speed stream is found in the magnetic cloud [7]. This paper thus attempts to study the development of intense magnetic storms and its association with magnetic clouds using storm time Dst index.

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2. Data

The interplanetary and geomagnetic parameters data used in this study consists of hourly values of embedded interplanetary magnetic field (IMF) Bz (in GSM coordinates), the Dst, flow speed, proton density, plasma beta, electric field and the corresponding plasma temperature. These hourly observations are from the NSSDC's OMNI database (http://nssdc.gsfc.nasa.gov/omniweb) for the eight rather strong geomagnetic storms which occurred in different seasons during 1976-2002. This paper is aimed at studying the development of intense magnetic storms using storm time Dst index, and its association with magnetic clouds. The Dst index is used in relation to other interplanetary and geomagnetic parameters, it is because changes in large-scale electric fields in the solar wind during intense geomagnetic storms can be reproduced from the variation in Dst value.

3. Storm's responses

The evidence is overwhelming that solar wind dawn-to-dusk electric fields directly drive magnetospheric convection (e.g., [8, 9]). However, there are four major mechanisms responsible for this drive: the interplanetary coronal mass ejections (ICMEs); the corotating interaction region effect (CIRs), which is the interaction of fast stream with slow stream ahead creating plasma and field compression; Russel-McPherron effect; and the Alfvenic IMF fluctuations. According to [10], of these four, only ICMEs and CIRs can be considered the primary events driving the storms, while the other two are modifiers which generally do not produce storms without an ICME or CIR. Note that these four mechanisms can interact differently from one event to the other. Meanwhile, in the interplanetary region following CIRs, the southward field components caused by these waves can cause magnetic reconnection, small injections of plasma into the magnetosphere, and prolonged recovery phases of the storms. These events are regarded as "high intensity, long duration, continuous AE activity" (HILDCAA) events. The southward IMF (in GSM) field is probably more important because of its far greater variability [4]. Similarly, a very important signature of a magnetic storm is a depression in the H component of the magnetic field lasting over some tens of hours. This depression however is caused by the ring current encircling the earth in the westward direction and can be studied using the Dst index. However, it is now a general phenomenon that the magnitude of magnetic storms can be explained using the minimum Dst values.

October 22, 1999 Storm

Fig. 1 shows the plot of interplanetary and geomagnetic observations for October 21-23. It was observed that there is an increase in both plasma density and flow speed between 04:00UT and 07:00UT on October 22, 1999 (which is the storm day). This is coincident with a sharp turning of Bz to a minimum peak value of -29nT within the same time interval on October 22. These are all indicative of arrival of a shock in the planetary medium. However, there is rarely a forward shock of geomagnetic storms associated with co-rotating interaction region (CIR) – like plasma signatures that rarely have minimum Dst < -100n T. Therefore, the compression is gradual with no "sudden impulse" or SSC. We note that in most cases [11], the very high plasma densities associated with the heliospheric plasma sheet can overcome the associated low wind speeds, creating a ram pressure increase and a storm 'initial phase' which actually precedes the CIR [10].

The Dst plot shows a rather quiet observation until around 00:00UT on October 22, when it falls sharply reaching a peak value of -230nT at 06:00UT on the same day. This sharp decrease is coincident with a southward turning of Bz to a peak value of -29nT before it and thereafter turns northward and recovers throughout October 23, 1999. However, enhancement of the plasma beta and proton temperature at the same point confirms that the shock produced was followed by ejecta which were not a magnetic cloud type [12]. A magnetic cloud is a region of slowly varying and strong magnetic fields (10-25nT or higher) with exceptionally low proton temperature and plasma beta typically ~0.1 ([13] and references therein). Following this ejecta, one can observe a high speed stream overtaking it. According to [12], the interaction of the high stream and ejecta results in an increase in speed, density and temperature. This can also be seen from our plots. Meanwhile, a general relationship between the intensity of the Bz field and its duration, ΔT, as a function of storm intensity, Dst, has not been found to-date [8]. However, [14] referring to intense storms with peak Dst $\leq$ -100nT, have suggested threshold values of Bz $\geq$ 10nT and $\Delta T \geq 3$ hours. Also, preliminary studies of moderate storms with -100nT < peak Dst $\leq$ -50nT confirm earlier suggestions made by [15] for associated threshold values of Bz $\geq$ 5nT and $\Delta T \geq 2$ hours.

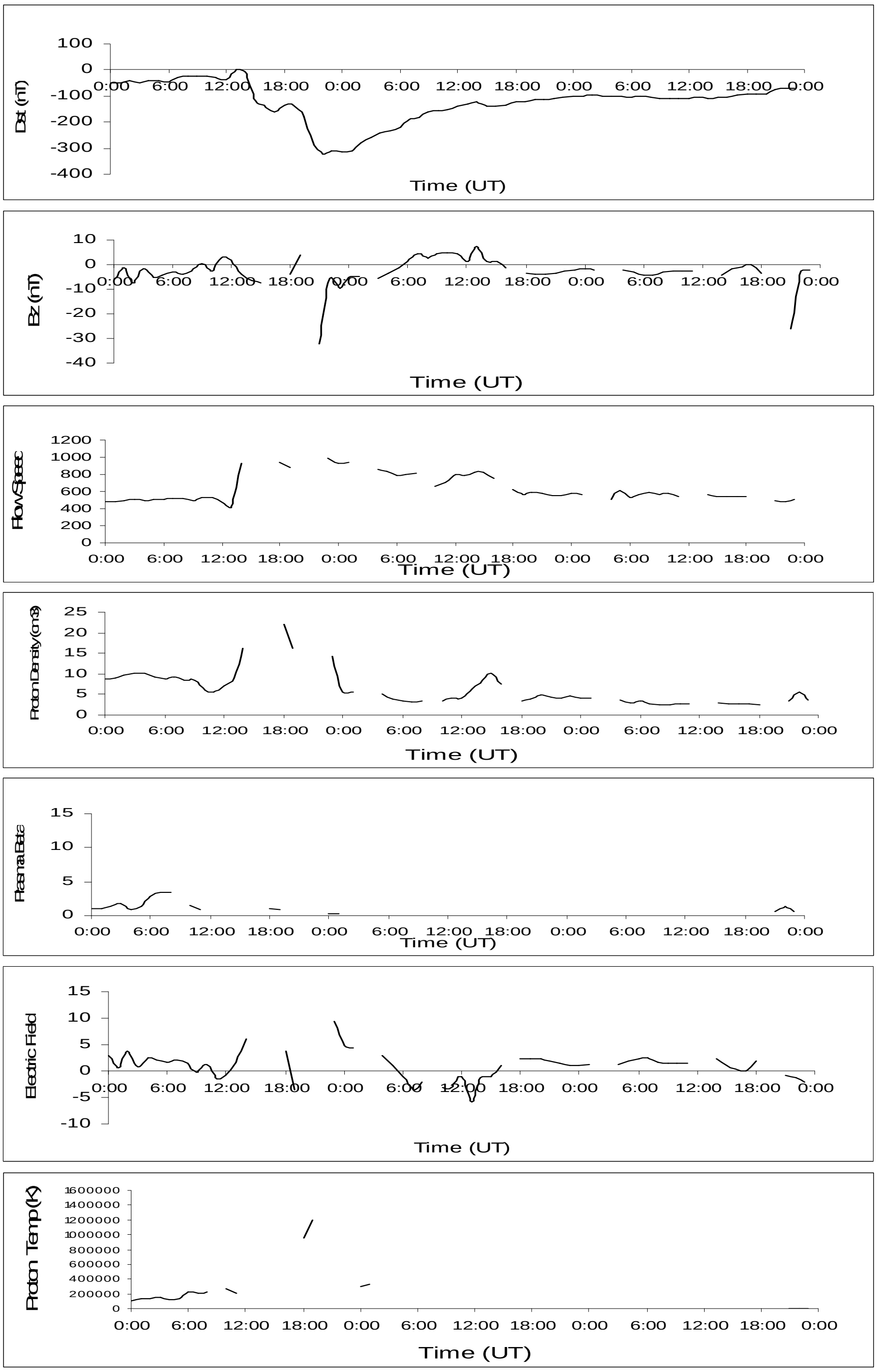

Fig. 1: Interplanetary and Geomagnetic response for July 13-15, 1982.

September 22, 1999 Storm

The plot for this storm day is shown in Fig. 2 spanning the period September 21-23, 1999. The Dst plot indicates that from 00:00UT of September 21 to the pre-noon hours of September 22, 1999, the Dst values have been between -2nT and -48nT. However, beginning from 18.00UT on the same day, Dst was depressed sharply to a minimum peak value of 185nT at 19:00UT on September 22. Thereafter, Dst recovers rather gradually throughout September 23, 1999. The Dst plot is indicative of a double step storm in which Dst reached its lowest value in the second step. The Bz plot shows that there was a southward turning of Bz between 00:00UT on September 21 and 02:00UT on September 22 to a first minimum value of -7.5nT indicating that the IMF has experienced over 20 hours of southward component. It thereafter experiences northward turning up till around 17:00UT on September 22. It should be noted that the sharp southward turning of Bz at 18:00UT of the same day to a minimum peak value of -15nT must have triggered the depression of Dst beginning from 18:00 UT of the same day. At 20:00UT Bz had rotated northward attaining a value of -4nT, fall shortly, and continues in the northward direction again throughout September 23. According to [16], the duration for which Bz is negative is important factor in the relationship of solar and interplanetary plasma parameters with geomagnetic storms.

The flow speed plot shows a moderate speed stream from 0000UT on September 21 to 12:00UT on September 22. The stream got to a peak value of 450 km/s at 13:00UT on September 22. Thereafter, it maintains a steady values and then increases again to its second peak value of 590km/s at 20:00UT on September 22. It should be noted that throughout September 21 till 18:00UT on September 22, the solar wind never attained the 500 km/s, in which case it could never meet the criterion of the fast solar wind. However, we want to point out that, still, geomagnetic storm should occur at the solar wind speed shown in the plot. According to [17] and the reference therein, moderate or strong storms occurred only when solar wind speed was above 350 km/s. Above this limit, any value of Dst in a wide range of a factor of ~2, or any value Dst could be associated with any value of solar wind speed in a wide range of a factor of ~2 [16].

The proton number density plot shows the proton number density not really having much effect until around 18:00UT on September 21 to a value of ~15.0/cm^3. This increase, according to [18], signifies the arrival of a shock in the interplanetary medium. However, beginning from around 11:00UT on September 22, there was a rapid increase in the proton number density reaching to a peak value of 46.3/cm^3 at 13:00UT. This appears to indicate the presence of CME ejecta containing a magnetic cloud. The plasma beta plot shows that the plasma beta has relatively high values throughout September 21 with sharp increases to the values of 2.80 and 3.85 at 06:00UT, respectively. Thereafter, the plasma value became very low and reaching reference level as we move up towards September 23, 1999. The dusk-ward electric field plot shows that starting from 00:00UT on September 21 to 15:00UT on September 22, electric fields were less than 5.00mV/m. But, as from 19:00UT on September 22, it began a gradual increase reaching a value of 10.00m V/m two hours later. Hence, these electric field conditions, which gave Bz > 10nT, are indicative of an intense storm. The plasma temperature plot shows a relatively low temperature. However, with effect from 07:00UT on September 22, there came along an abrupt rise in temperature to a peak value of 275000K, drops for a while and then rises again to its second consecutive peak value of 325000K at 19:00UT on September 22. This indicates the arrival of a shock in the interplanetary medium. Thereafter, the plasma temperature decreased gradually to a value less than 50000K and during September 23, 1999 including. It is however suggestive at first approximation that between 00:00UT and pre-noon hours of September 22, a magnetic cloud existed. This is due to low plasma beta values which are coincident with low proton temperature.

October 20, 1999 Storm

This is shown in Fig. 3 spanning the period between October 19 and 21. The Dst index reached its first minimum value of -82nT at 07:00UT on October 19. It could therefore be argued that the solar wind became geoeffective even before the storm day [17]. According to [19] and [10], if a new major particle injection occurs, it leads to a further development of the ring current with Dst index decreasing. It should also be noted that the increase in both plasma density and flow speed are indicative of the arrival of a shock in the interplanetary medium. It was also observed that the solar wind speed increased approaching the storm day and far above the value of 350km/s. Kane [16] had proposed earlier that moderate or strong storms occurred only when solar wind speed was above ~350km/s. The plot thereafter shows the arrival of another shock in the interplanetary medium at ~10:00UT on October 20. According to [14], a major storm occurred when the IMF experienced more than 10n T southward component for more than three hours. This is further indicated by the first decrease in Dst at ~10:00UT. Therefore, apart from October 19 moderate storm, the Dst plot presents a three step main phase event taking over 24 hours to develop.

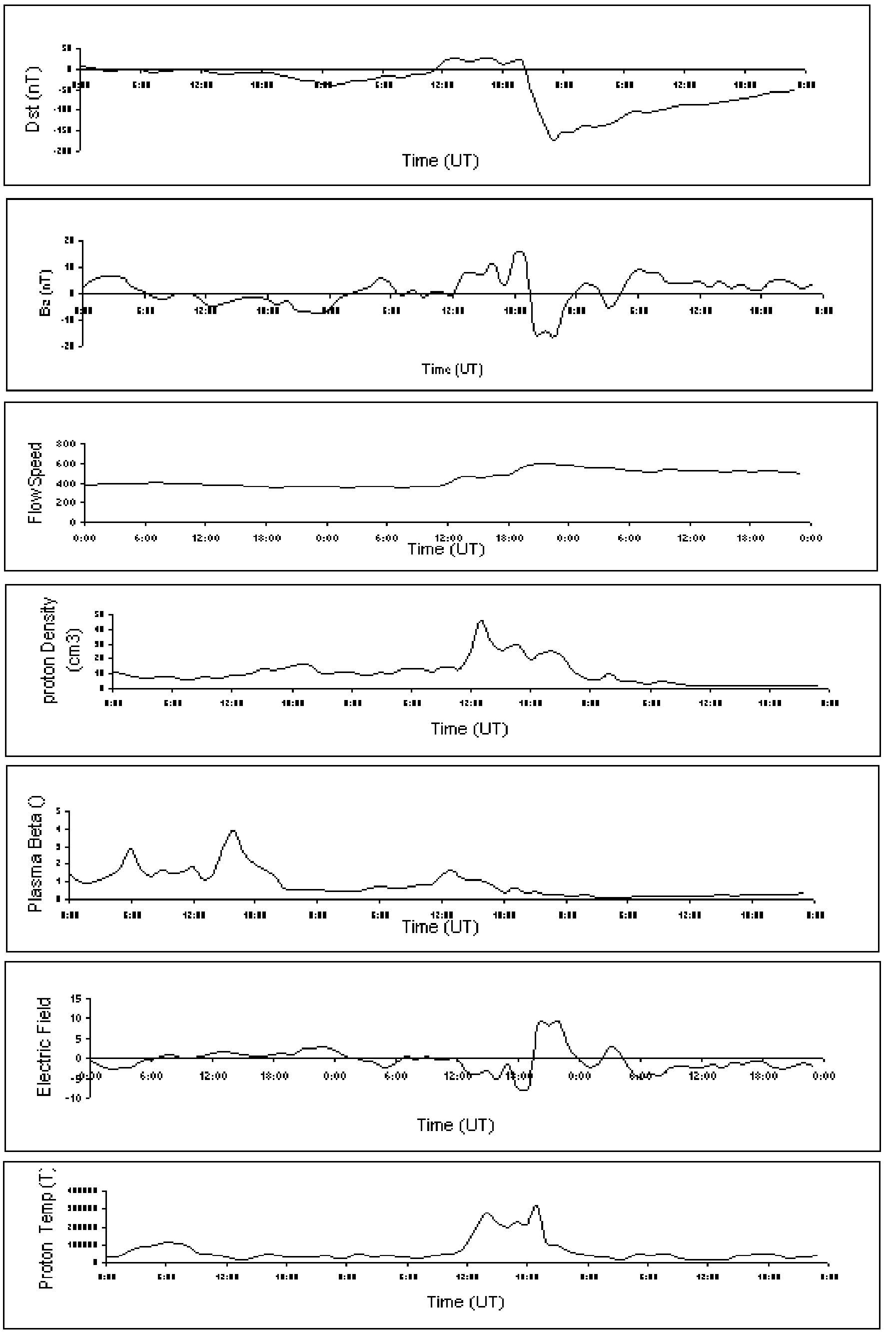

Fig. 2: Interplanetary and Geomagnetic response for September 21-23, 1999.

The first step of the main phase with Dst ~ -202nT started at 16:00UT on October 20. Also, the second step is associated with the sharp southward turning of Bz at 16:00UT. Thereafter, Dst and Bz reached peak values of -186nT and -10.4nT, respectively, at around 17:00UT on October 20. Also, after Bz has reached the peak value, it sharply rotated to northward, whereas this decrease in the intensity of the southward component of the IMF was followed by a recovery in Dst. Paucity of data would not allow determination of components of Bz and solar wind plasma between 02:00UT and 14:00UT on October 21. The third step of the main phase began with the rapid decrease in Dst value at 08:00UT on October 21. Hence the third phase confirmed the October 20 storm as a very intense geomagnetic storm resulting from the enhancement of the second phase.

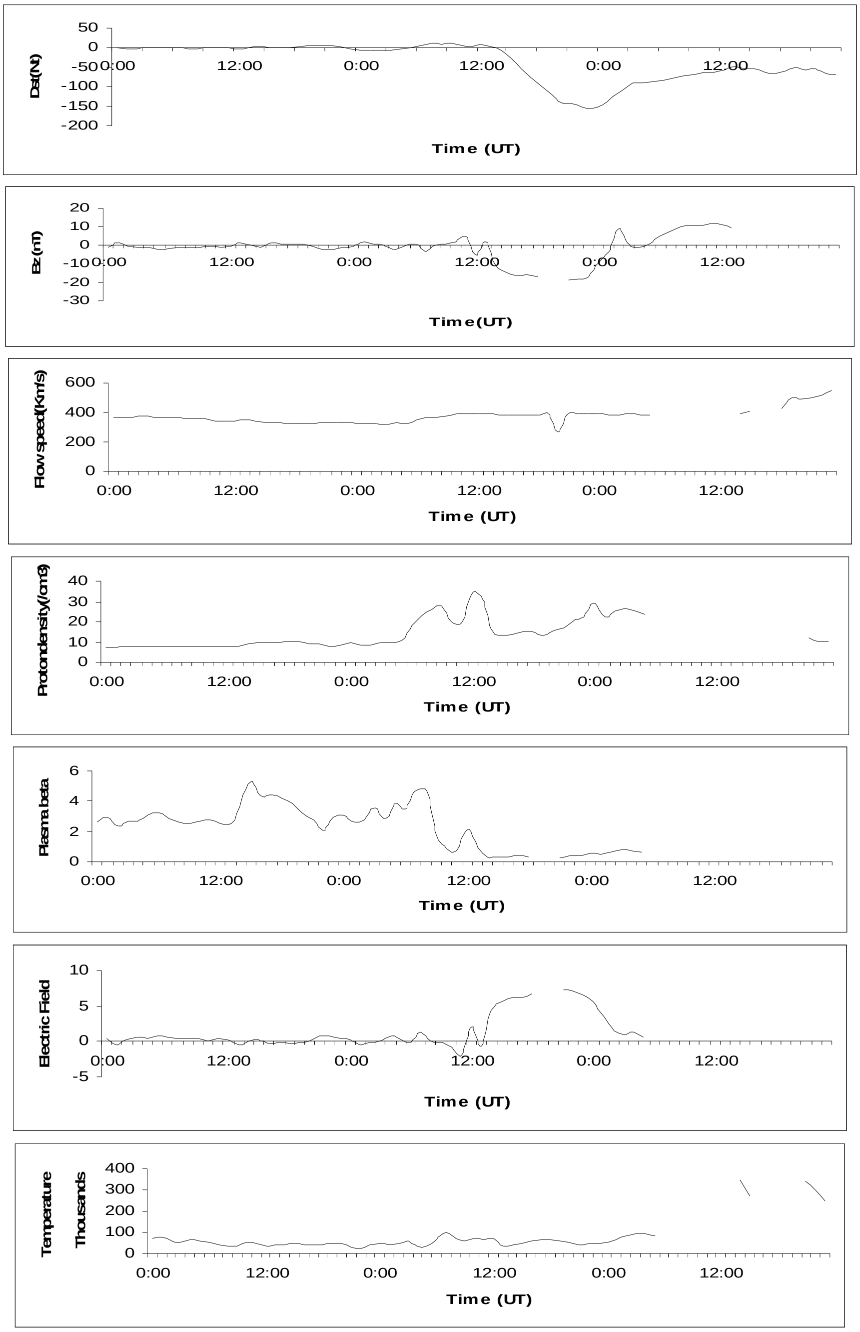

Fig. 3: Interplanetary and Geomagnetic response for January 9-11, 1976.

Moreover, the structure of the geomagnetic storm of October 20, 1989 is illustrated further by the flow speed, the plasma density, the electric field and the plasma temperature. It was observed that there is a high value of plasma beta and plasma temperature on October 20. Hence, it can be inferred from this that the shock was followed by ejecta, which was not a magnetic cloud type [12].

April 11, 2001 Storm

Fig. 4 shows that interplanetary and geomagnetic plot for this storm event spanning April 10-12, 2001. From the Dst plot, the variations appear to reveal a slow 36-hour build up that began with gradual commencement at around 15:00UT on April 11. From this point onward, Dst decreased sharply to -100nT at 18:00UT, remained that way for the next two hours and then continued decreasing to its minimum peak value of -270 nT at 23:00UT on April 11. This decrease in Dst amplitude is an indicative of the arrival of a shock leading to the commencement of a very intense storm. This point is further buttressed with the southward orientation of Bz to a value of -20nT at this same time on April 11. The orientation of Bz is irregular between 00:00UT of April 10 and 18:00UT on April 11. However, starting from this point, a southward turning was experienced which lasted for more than 3 hours between 20:00UT on April 11 and 08:00UT on April 12 signifying an intense storm. However, between 13:00UT and 16:00UT on April 11, the storm day, a change in Bz of $\delta Bz = 12.5nT$ was observed. This appears to coincide with an increase in proton density and flow speed. Also, associated with this change in Bz is the first decrease in Dst at around 17:00UT. It could therefore be argued that the solar wind became geoeffective between 13.00 and 16:00UT on April 11. According to [19] and [10], if a new major particle injection occurs, it leads to a further development of the ring current with Dst index decreasing. However, the aforementioned change in Bz could be the reason why ionospheric responses are observed at some stations hours after it occurred. This is because Chukwuma [17] and reference therein) have shown that a southward turnings with a change in Bz of $\delta Bz > 11.5nT$ often results in foF2 showing a marked decrease in amplitude, reaching a minimum value about 20 hours after the southward turning. Hence, the Dst plot presents a very intense, double step storm event.

The solar wind flow speed shows a low stream within the period of 00:00UT on April 10 and 17:00UT on April 11. It thereafter began its rise to a peak value ~710km/s around 18:00UT on April 11. Note that this rise corresponds to an increase in plasma temperature to a peak value of 900000 degree/K as well as an enhancement in the plasma beta value (1.5). It transpires from this high plasma beta and temperature values that the shock was followed by ejecta, which may not be a magnetic cloud type. Moreover, the electric field plot given by –V x Bz shows that no activity was observed until 13:00UT on April 11 when it began its activity reaching its first peak value of 8.00mV/m. It thereafter reduces shortly to a value less than 2.00mV/m, before it starts to rise again to its highest value of 14.00m V/m; and then recovers again through April 12, 2001. However, the unnoticeable activity between 00:00UT on April 10 and 13:00UT on April 11 of a value less than 2.00m V/m confirms that Bz < 10n T. Also, the peak value of 14.00m V/m condition that gave Bz > 10n T is indicative of a major storm.

January 10, 1976 Storm

Fig. 5 shows composition of interplanetary and geomagnetic parameters of solar wind plasma for the period of January 9-11, 1976, but the plot covers a day before and a day after the storm event. The storm is summarized using the low latitude magnetic index Dst [2] and is interpreted using available interplanetary data. However, storms are classified as weak (when Dst > -50nT), moderate (when Dst is in-between -50nT and -100nT) and intense (when Dst < -100nT). From the plot, beginning from 14:00UT on January 10, Dst decreased sharply reaching a peak value of -160nT at 23:00UT, thus indicating the commencement of an intense storm. Thereafter, it begins to recover through January 12. The Bz plot shows that at around 12:00UT on January 10, there was a sharp southward turning of Bz. At 23:00UT of the same day, Bz reaches a -20nT peak value indicating that the IMF has experienced about seven hours of southward component. At around 20:00UT of the same day, Bz rotates sharply northward reaching a value of 12.5nT. The IMF structures leading to intense magnetic storms have intense (>10nT) and long duration (>3hr) southward component([1] and references therein).

The solar wind speed plot shows the existence of a slow stream in the period 00:00UT, January 9 with V_{SW} < 400km till 03:00UT on January 10. It thereafter begins to rise until around 06:00UT, when it drops sharply to a value of V_{SW} = 280km/s and then rises again through January 12. According

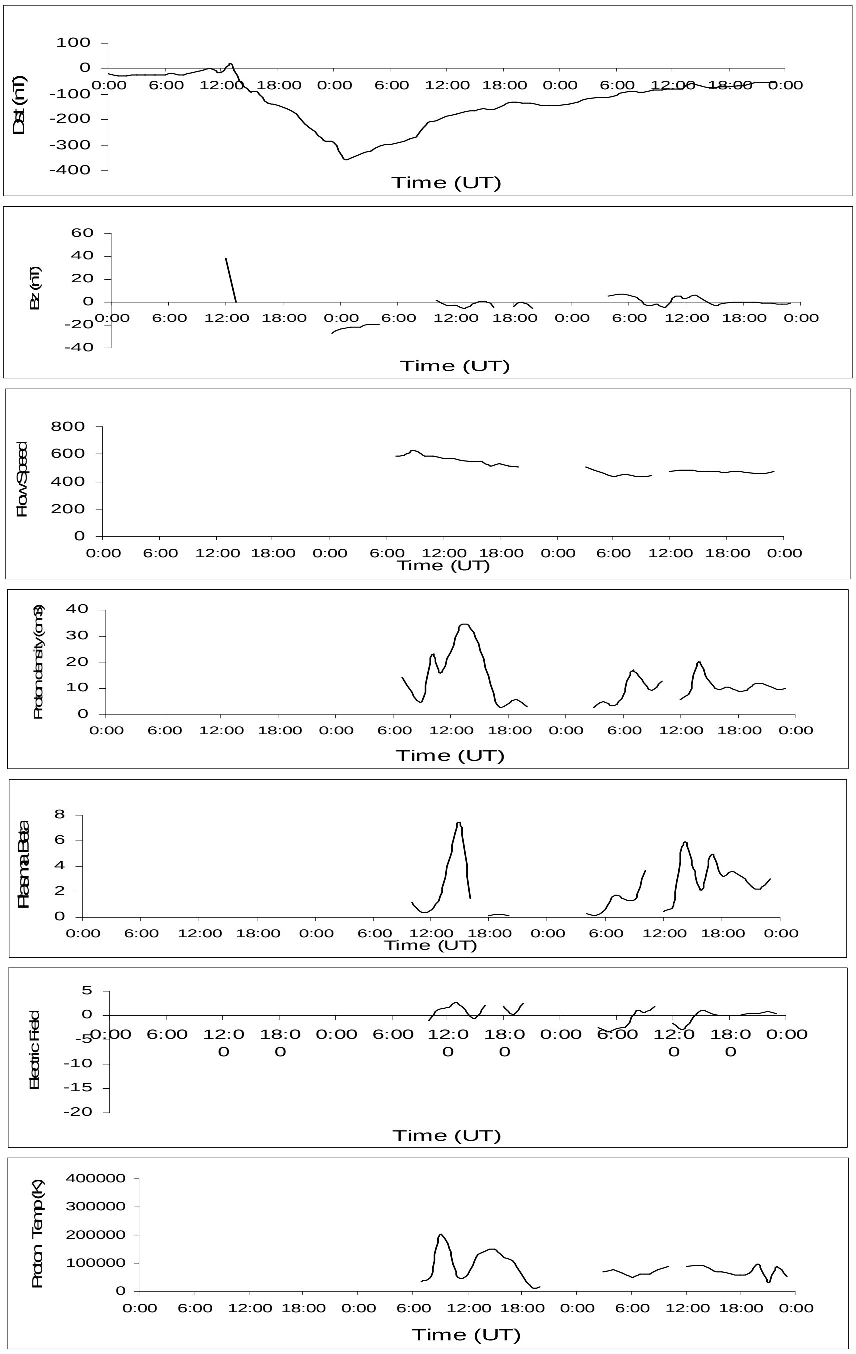

Fig. 4: Interplanetary and Geomagnetic response for November 7-9, 1991.

to [2, 13], intense magnetic storms (Dst < 100nT) occur when the solar wind speed is substantially higher than the average speed of V_{SW} = 400km/s. Note that the coincident increases in V_{SW} and proton density Np indicate the arrival of shocks. The rapid increase in the proton density between January 9 and mid January 10 appears to indicate the presence of a magnetic cloud. Also, the plasma beta value reduces sharply around 06:00UT of January 10 and further diminishes to reference level. Given this low values, which is coincides with the low proton temperature, the profile of the plasma beta appears to present a criterion for magnetic clouds. As regards the interplanetary electric field, given by –VxBz, Fig. 5 shows that throughout January 9 and until pre-noon hours of

January 10, the electric field values were less than 2.00mV/m, confirming that Bz < 10nT. At ~02:00UT on January 10, the electric field began to rise getting to a peak value of 7.30mV/m at 23:00UT before decreasing to 0.70mV/m at 06:00UT on January 11. Hence, this electric field condition, which gave Bz > 10nT, is an indication of a major storm.

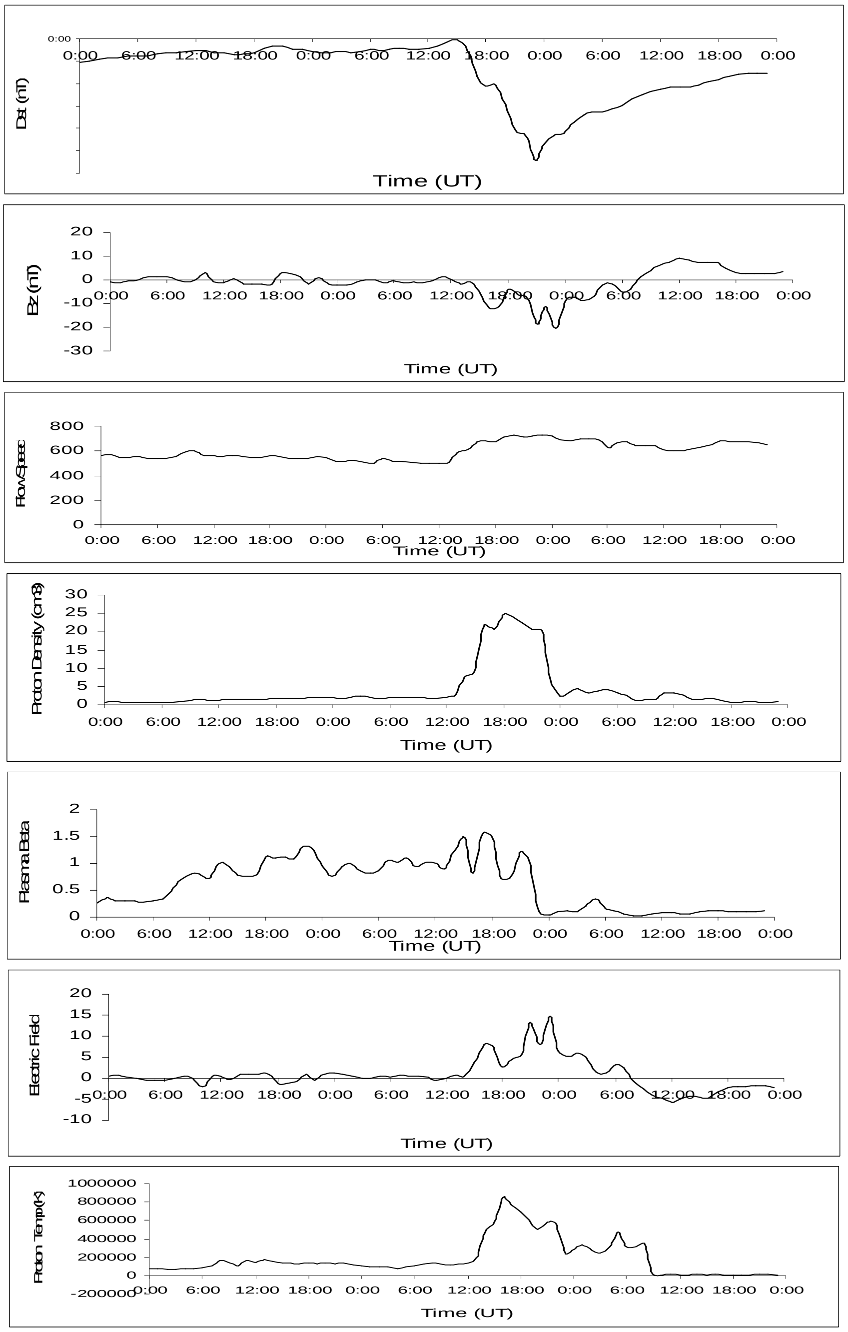

Fig. 5: Interplanetary and Geomagnetic response for April 10-12, 2001.

The plasma temperature plot shows a peak value of 350000^0K on January 12. The paucity in plots is for days when no data was available. However, according to [20] magnetic clouds that are geoeffective have a southward and then northward (or vice versa) magnetic field directional variation. When the magnetic cloud has a very high velocity, it compresses the plasma ahead of it and forms a "collision-less" shock [17]. Behind this shock is a sheath, which contains heated plasma and compressed magnetic fields. These intense sheath magnetic fields, in its turn, can also cause magnetic storms.

November 8, 1991 Storm

Fig. 6 illustrates the response of November 8, 1991 storm between November 7 and 9, 1991. It was observed that except for the Dst plot, there is no data available for November 7, a day before the storm event, for all other interplanetary and geomagnetic parameters. Note the scanty plots observed on the Bz plot for this same period. The unavailability of data is even more extended to pre-noon hours of November 8 except for the Dst plot. It may not be surprising to note that the reason for this 'no record' of data could have been due to the very intense nature of the storm (Dst = -360nT) in which case the recording satellite may have been impaired during this period, just like the case of March 13-14, 1989 storm, which was a period of some extraordinary activity and the greatest storm event ever recorded (Dst = -583nT). The Dst plot shows that the Dst began its activity around 13:00UT on November 7, as it experiences a sharp decrease to a minimum peak value of -360nT spreading to 02:00UT on November 8. It thereafter begins to recover through November 9. This shows that the storm is a single step, very intense storm. However, this depression in the value of Dst coincides with the southward orientation experienced on the Bz plot at this same period signifying a shock before the storm sudden commencement. Thereafter, Bz maintains a northward turning and then stabilizes towards the later hours of November 9.

The plasma beta plot shows a peak value of 7.70 for November 8 at 14:00UT, which is coincident with low proton temperature, the profile of the plasma beta appears to present a criterion for magnetic clouds. The available data for the plot of electric field shows that throughout the storm period, the electric field was less than 2.00mV/m, confirming that Bz < 10nT during this period. Moreover, the increase in the plasma density corresponds to a rise in plasma temperature just immediately after noon on November 8. This was the same case for 14:00UT on November 9, when the proton density shows an increase in value. This shows the arrival of a shock in the interplanetary medium as indicated. However, this argument was further enhanced with the confirmation in the decrease of solar speed around this same period. It is worthy of mention here that of recent, both linear and nonlinear autoregressive and moving average filters for predicting Dst, were reviewed and evaluated by [21]. It was however shown by [22] that by using measurements made during the main phase, Dst development following the maximum depression could be modeled by assuming a lognormal distribution. However, using the solar wind and Dst data, one can predict both the main phase onset as well as its time development. Meanwhile, the development of geomagnetic storm models has been complicated by evidence that substorms were essential to Dst evolution [23, 24, 25].

September 8, 2002 Storm

The plot of the response of September 8, 2002 is shown in Fig. 7. The plot spans a period from September 7 to 9, 2002. From the figure, Dst reached its first minimum value of -142nT around 18:00UT on September 7, it rotates northward shortly, and then southward again reaching a minimum peak value of -180nT at 00.00UT on September 8. It thereafter begins to recover until around 21:00UT when an abrupt decrease was noticed again to a value of -78nT, and then continued recovering. The three minimum peak values observed is an indicative of a magnetic shock in the interplanetary medium. This is so because these three points coincides with a significant southward turning of Bz at this exact three periods. However, the occurrence of a new major particle injection leads to a further development of the ring current with Dst index increasing for the second time. We may thus assumed that the presence of both sheath field and the magnetic cloud field, and argue that both the sheath field and the cloud field have the proper orientation, and there is magnetic reconnection from both phenomenon resulting in a 'triple storm'. This is so, as it is most likely that the first step of the storm was caused by the sheath Bz, while the second and the third was from the second magnetic cloud field. Thus, in the interplanetary region following CIR, the southward field components caused by these waves can cause magnetic reconnection, small injections of plasma into the magnetosphere and prolonged recovery phases of the storms. Events of this type are known as 'high intensity long duration, continuous AE activity' or (HILDCAA) events. It is of great interest to note that at around 17:00UT on September 7, 2002, when Bz had its minimum peak value of -22nT, the plasma temperature, proton density, plasma flow

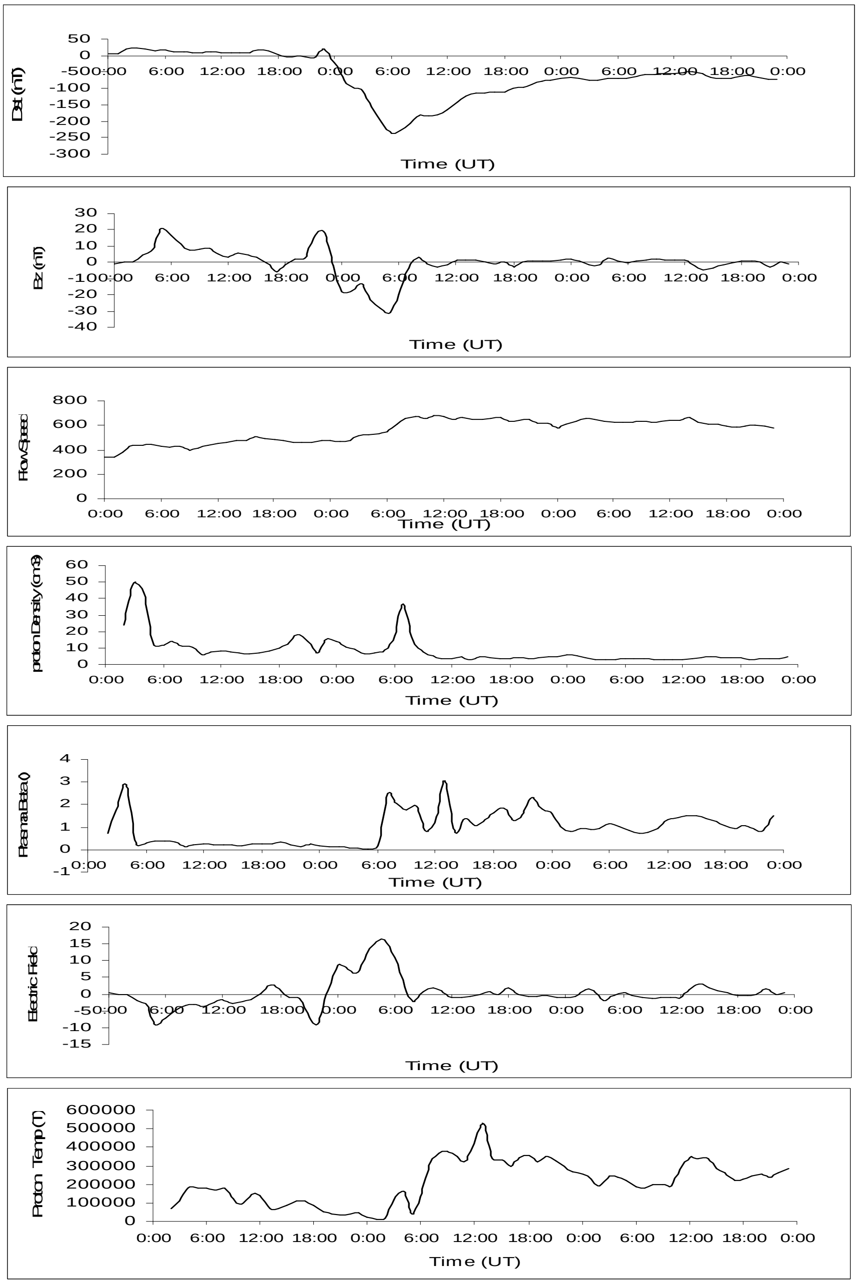

Fig. 6: Interplanetary and Geomagnetic response for October 21-23, 1999.

speed, and plasma beta recorded their first enhancement values, indicating a shock before the storm sudden commencement SSC. Moreover, the abrupt northward rotation of Bz at 22:00UT on September 8 is a reflective of the recovery state of the storm through September 9. This is also evident with the sharp fall in plasma temperature through this period. As regard the electric field plot, up till 16:00UT on September 7, it was observed that the electric field value is not up to 5.00mV/m, confirming that Bz < 10nT. But, with effect from this hour, the electric field began to rise reaching to a peak value of 18.00m V/m at 17:00UT, decreased for a while and then begins to rise again reaching to its second peak value of 8.00m V/m on September 7, before it begins to decline again about the reference level through September 9. The point of the first peak value of the plot of electric field coincides with a rise in plasma flow speed to a value of 580km/s, indicating a major storm.

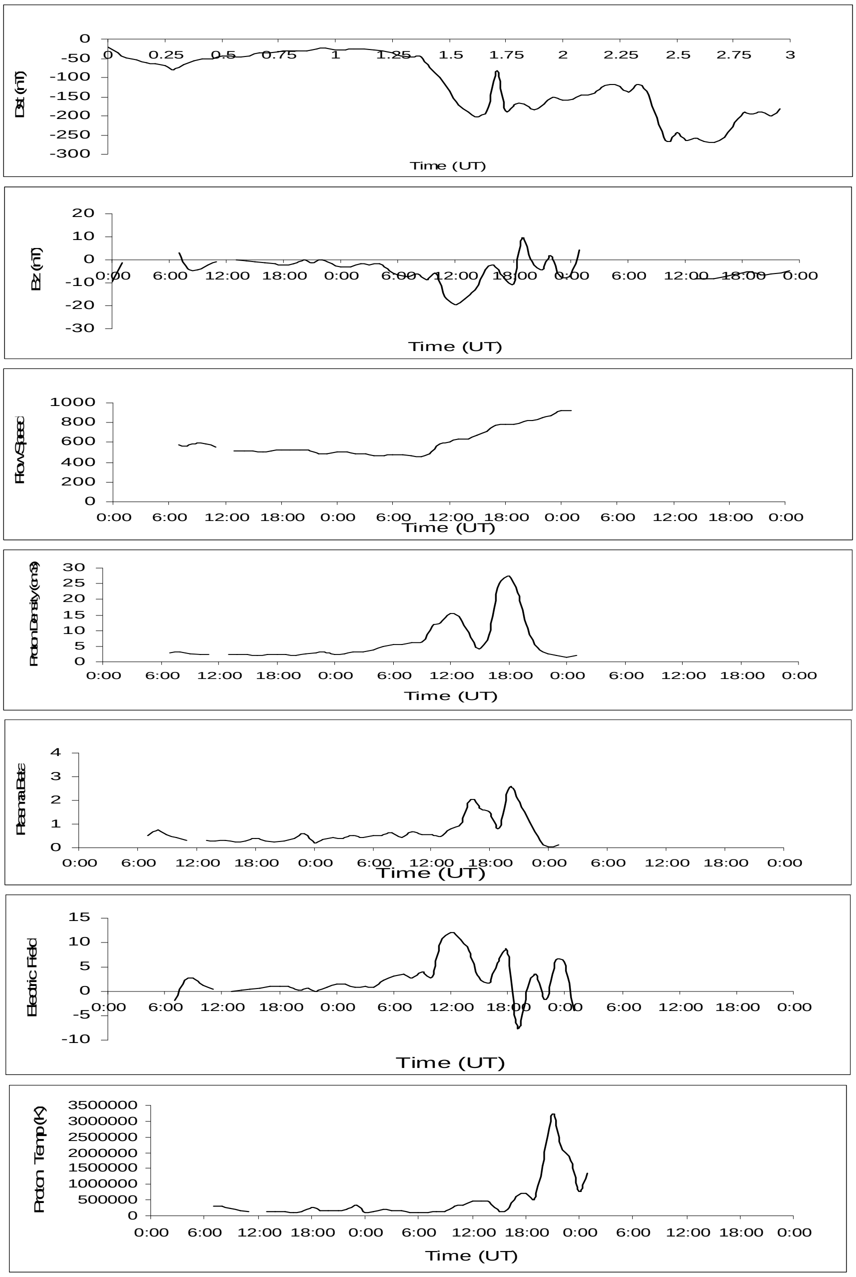

Fig. 7: Interplanetary and Geomagnetic response for October 19-21, 1989.

July 14, 1982 Storm

The composition of interplanetary and geomagnetic observations for July 13-15 is shown in figure 8. The areas, where there is paucity on the plot, indicate that no data was available for such periods. The Dst variations appear to reveal a slow 12-hour build up that began with gradual commencement at ~14:00UT on July 13. Storms can be classified as

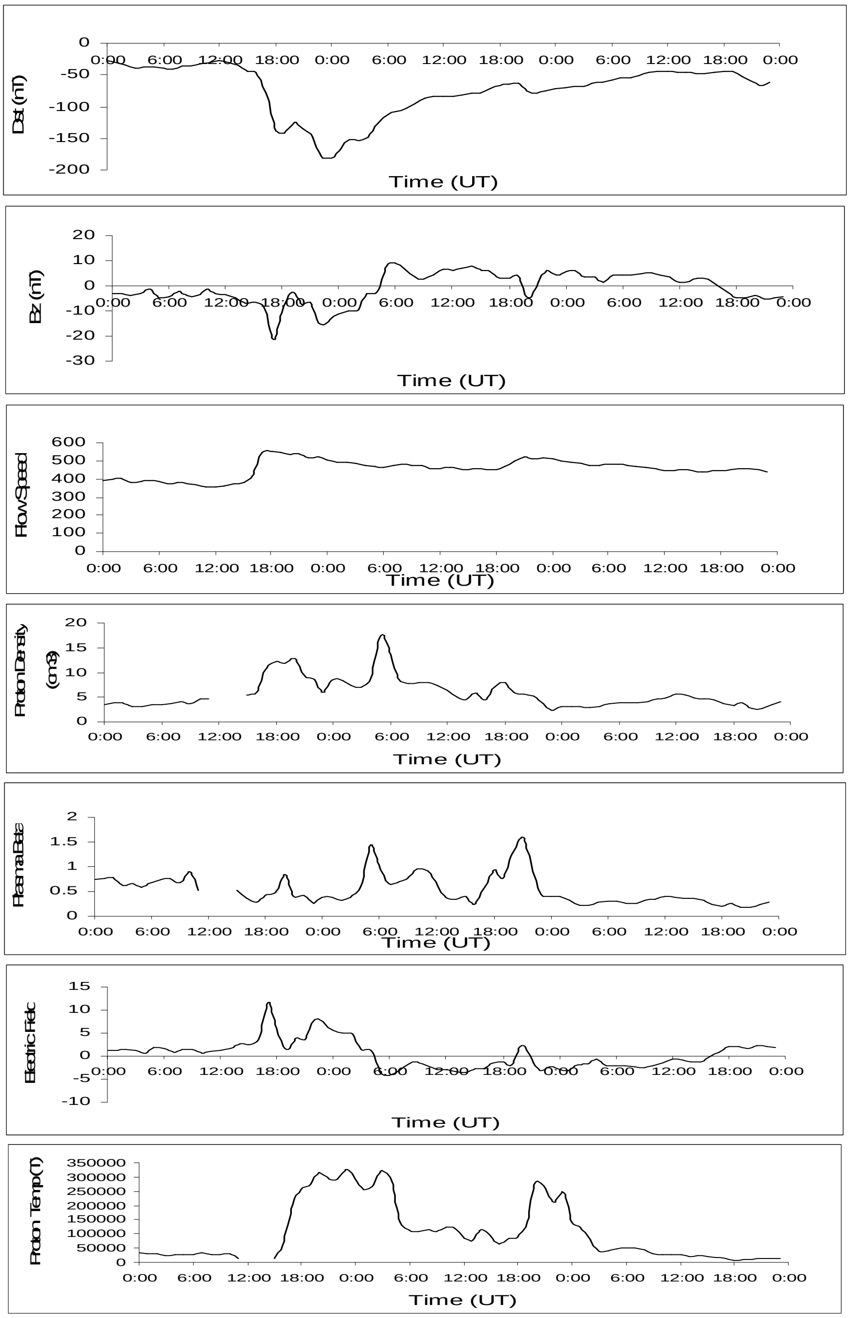

Fig. 8: Interplanetary and Geomagnetic response for September 7-9, 2002.

follows: weak (Dst > -50nT), moderate (-50nT < Dst < -100nT) and intense (Dst < -100nT) [26]. According to this classification, the Dst plot indicates that at 17:00UT on July the Dst had decreased to a value of -160nT indicating the commencement of an intense storm. However, Dst recovers rather gradually to -130nT at 19:00UT and thereafter decreased to -325nT at 23:00UT signifying a very intense storm. The Dst recovered again at 02:00UT on July 14 to a value of -120nT and continued with the recovery process through July 15. However, the recovery of Dst beginning at 19:00UT on July 13 and 02:00UT on July 14 are indicative of northward turning Bz, as can be seen from the Bz plot. Geomagnetic activity is known to decrease precipitously whenever IMF is directed northward [27]. The southward orientation of Bz to a value of -33nT at ~22:00UT on July 13 is an indication that there is going to be a dramatic enhancement in geomagnetic activity. According to [27], such a configuration tends to increase the coupling between the solar wind and magnetosphere with the result that relatively more solar wind energy can then enter the magnetosphere.

Also, the plasma flow speed shows an increase during the period. Hence, when the magnetic cloud has a very high velocity, that is, if the speed differential between the CME and the slow, upstream solar wind is greater than the magnetosonic wave speed (50-70 km/s), it compresses the plasma ahead of it and forms a collision-less shock. Meanwhile, if both the sheath field and the cloud field have the proper orientation, there will be magnetic reconnection from both the phenomena and a 'double storm' will result [10]. In complex cases, where there is a multiple solar flaring, there will also be multiple solar ejecta, multiple shocks and thus multiple plasma and field compressions. Triple storms etc. will result [20]. The proton density plot shows proton density increasing steadily from 5.0cm^{-3} at 11:00UT to 16.5cm^{-3} at 14.00UT on July 13. No data was available between 15:00UT and 17:00UT of the same day. Thereafter, it reaches its maximum value of 23.5cm^{-3} before it starts to fall again. The large increase in the proton number density at 17:00UT on July 13 and July 14 signals the arrival of a shock in the interplanetary medium at these times. As a result, the enhanced solar wind flow draw the plasma sheet density leading to the injection of the ring current and this caused the sharp depression in Dst in-between this interval on the Dst plot. This assertion derives from the fact that plasma sheet density is found to correlate well with high solar wind density drives plasma sheet density, with the source of the ring current particles being the plasma sheet. There is not enough data available for the interpretation of plasma beta and plasma temperature. However, the observed peak value of 125000K on the plot of the plasma temperature at 19:00UT on July 13 coincides with the sharp southward rotation of Bz and an enhancement observed on the plasma flow speed plot, all suggesting a shock.

4. Discussion

The intense interplanetary magnetic fields can be thought of as being associated with essentially two parts of a high-speed stream, the sheath fields and the driver gas fields. Within the driver gas, there are sometimes strong N-S magnetic field components. This occurs primarily in the low beta plasma region [28, 29], where the magnetic fields are relatively free of discontinuities and the wave change occur slowly. These regions of large N-S field variations are called magnetic clouds. However, according to [8] and references therein, a more recent field configuration of magnetic clouds has been proposed. This states that the field configuration is a giant flux rope, with the force-free field generated by currents flowing along the magnetic axis. Meanwhile, there is a variety of causes of southward IMFs in the high speed stream sheath region and are divided as: (a) Sheath fields comprising of shocked southward fields [29], turbulence waves, shocked heliospheric current sheets [30], and draped magnetic fields [31]; and (b) Driver gas fields comprising magnetic cloud, flux rope [32] and magnetic tongue [33].

The magnetopause connection proceeds as a series of discrete and limited but frequent 'flux transfer events'. Connections in the tail go in less frequent but cataclysmic events, which is the basis of substorms. Three phases of storms are therefore identified: the growth phase, the expansion phase and the recovery phase. In Fig. 1, it was discovered that the direction of the north-south component of the interplanetary magnetic field Bz regulated the growth of the ring current. The southward turning of Bz at 16:00UT on October 20 is associated with a depression in the Dst value. Thereafter, Bz and Dst reach peak values of -10.4nT and -186nT, respectively, around 17:00UT on October 20. Daglis [19] had proposed that if a new major particle injection occurs, it leads to a further development of the ring current with Dst index decreasing a second time. It was also observed that the northward orientation of Bz results in a recovery stage of the storm event of April 11, 2001, which could be seen from the Bz and Dst plots in Fig.1. Moreover, an over 24-hour slow plasma build up before the storm events of April 11, 2001 (Fig. 4), October 10, 1999 (Fig. 1) and January 10, 1976 (Fig. 5) is a result of the north orientation of the Bz component. It was observed from the Bz and Dst plots of these three storm events that immediately after the Bz turns southwardly, there was a sharp depression in the value of Dst as well as an immediate enhancement in the plasma flow speed. Hence the initial phase of the storm could be regarded as a period of time after the onset of the SSC during which the IMF was oriented primarily northward. In other words, this implies that little energy was entering the magnetosphere irrespective of the speed and particle number densities in the plasma flow. Majorly, the most essential feature of a storm is the significant development of a ring current and its subsequent decay.

Also, Gosling [34] and Taylor [35] have shown that there are a variety of ejecta speeds, but it has been statistically shown that the ones that are most effective in creating magnetic storms are events that are fast, with speeds exceeding the ambient wind speed by the magnetosonic wave speed, thereby causing a fast forward shock (as explained in Fig. 1 and Fig. 7 of October 22, 1999 and September 8, 2002 storm events, respectively). It should be noted here that both the remnant ejecta fields and plasma, and those of the sheath can be geoeffective depending on the field orientation. Hence, most geoeffective ICMEs are magnetic clouds. It was observed that over 70% of the eight rather strong storm events under investigation are generated as a result of magnetic clouds which are characterized by low beta plasma, high IMF magnitude and large scale coherent field rotations, often including large and steady north-south components.

5. Conclusion

There is a variety of causes of southward IMFs in the high speed stream sheath region. Firstly, if there is a pre-existing southward component upstream of the shock, the shock compression will intensify this component. As these fields flow towards the driver gas region, the draping effect will intensify the fields further for the earth's magneto-sheath fields. According to [36], another type of field draping created northward and southward is near the solar magnetospheric plane. Turbulent waves and discontinuities can also be associated with strong northward and southward IMFs. It is thus evident from the aforementioned that the interplanetary magnetic field Bz plays a prominent role alongside Dst in the generation of intense magnetic storms. Moreover, the interplanetary electric field E also plays a major role because it is given by –V x Bz, consisting of solar wind velocity V and the southward IMF Bs. It has been empirically shown that intense storms with peak Dst $\leq$ -100nT are primarily caused by large Bs $\geq$ 10nT fields with duration greater than 3 hours, and are often associated with high speed streams.

Over 70 % of the storm events studied (which spans between 1976 and 2002) are generated as a result of magnetic clouds, which are characterized by low beta plasma, high IMF magnitude and large scale coherent field rotations and often including large and steady north-south component. Moreover, the September 22, 1999 event could have been a result of high densities of the heliospheric plasma sheet wind that creates an increased compression of the magnetosphere. It was also shown that the storm events having peak Dst < -250nT are more prone to having magnetic clouds as their main source of generation than others. However, this class of storms takes a longer time to recover after its main phase than those between the range -250nT $\leq$ peak Dst < -100nT, with respect to their Dst plots.

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