J. Astrophys. Astr. (2006) **27,** 227–235

Geo-effectiveness of Solar Wind Extremes

Hari Om Vats
Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India.
e-mail: vats@prl.ernet.in

Abstract. Examples of extreme events of solar wind and their effect on geomagnetic conditions are discussed here. It is found that there are two regimes of high speed solar wind streams with a threshold of $\sim$ 850 km s^{-1}. Geomagnetic activity enhancement rate (GAER) is defined as an average increase in Ap value per unit average increase in the peak solar wind velocity (Vp) during the stream. GAER was found to be different in the two regimes of high speed streams with +ve and −ve IMF. GAER is 0.73 and 0.53 for solar wind streams with +ve and −ve IMF respectively for the extremely high speed streams ($<$ 850 km s^{-1}). This indicates that streams above the threshold speed with +ve IMF are 1.4 times more effective in enhancing geomagnetic activity than those with −ve IMF. However, the high speed streams below the threshold with −ve IMF are 1.1 times more effective in enhancing geomagnetic activity than those with +ve IMF. The violent solar activity period (October–November 2003) of cycle 23 presents a very special case during which many severe and strong effects were seen in the environment of the Earth and other planets; however, the z-component of IMF (Bz) is mostly positive during this period. The most severe geomagnetic storm of this cycle occurred when Bz was positive.

Key words. Geomagnetic storms—geomagnetic activity—solar wind streams—interplanetary magnetic field—space weather.

1. Introduction

Solar wind is a continuous flow of hot plasma from the solar corona. This flow is supersonic and is caused due to very high coronal temperature which helps plasma overcome the gravitational attraction of the Sun. The flow is largely radial in nature and fills the entire heliosphere around the Sun. The density and speed of this flow is highly variable both in time and space. This results into the common occurrence of the plasma irregularities in the medium around planets. These irregularities give rise to a very interesting phenomenon of radio astronomy called as interplanetary scintillation. By observing the scintillation of a number of compact radio sources it is possible to estimate the solar wind speed and the spectra of plasma density in the regions of interplanetary medium (which is largely inaccessible by satellites) around the Sun. Thus the technique of interplanetary scintillation provides very valuable information about solar wind. The solar wind speed and density is also regularly monitored by satellites. The flow of solar plasma is controlled by the energetic events, e.g., solar flares, filament eruptions, coronal mass ejections, coronal holes, etc. The volumes of data that have been collected over the last several decades have provided evidence of many extremes (both high and low type) in solar wind density and speed. Many low density and low speed events are found to correlate with the co-rotating coronal streams. The geo-environment is affected by both high and low extremes of the solar wind in a variety of ways.

Geomagnetic activity is caused by the transfer of momentum and energy from the solar wind to the magnetosphere. Rastogi (2001 and references therein) gives a historical background of the geomagnetic activity phenomena and its interesting features. Now it is an established fact that the major mechanism of energy transfer from the solar wind to the Earth's magnetosphere is magnetic reconnection (Dungey 1961). If the interplanetary magnetic field is directed opposite to the Earth's magnetic field, there is magnetic erosion on the dayside magnetosphere (by magnetic connection) and magnetic field accumulation on the nightside magneto tail region. Subsequent reconnection on the nightside leads to plasma injection at these local times. As the magneto tail plasma get injected into the nightside magnetosphere, the energetic protons drift to the west and electrons to the east, forming a current around the Earth. This current, is termed as the 'ring current', which causes a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial magnetic stations. Carovillano & Siscoe (1973) have shown that the decrease in the equatorial magnetic field strength is directly related to the total energy of the ring current particles and thus it is a good measure of the energetics of the magnetic storm.

In general, the energy and momentum transfer occurs in response to the reversal of IMF or when Bz turns southward and remains so. When IMF possesses a southward component, reconnection between oppositely directed IMF and the magnetospheric fields occurs on the dayside magnetopause (Aubry & McPherron 1971). Snyder *et al.* (1963) showed a possible link between interplanetary solar wind speed V and geomagnetic index Kp, such a relationship has been examined by many workers and found to be rather loose.

Geomagnetic storms can occur due to several interplanetary features, including magnetic clouds, but it is only when the magnetic field of the interplanetary feature engulfing the Earth has a strong southward component (Wang *et al.* 2003). The interplanetary causes of geomagnetic storms have been extensively studied (Tsurutani *et al.* (1992) and references therein). The Earth-directed solar wind speed and southward component of interplanetary magnetic fields are of atmost importance in enhancing geomagnetic disturbances. In this article two distinct cases of solar wind extremes are reported for their geo-effectiveness in the following sections;

- high speed streams which were found to be associated with solar flares and coronal holes are discussed for their geo-effectiveness, and
- interesting period of most violent solar activity during October–November 2003.

The period October–November 2003 was very important for space weather investigations and to understand various geophysical phenomena. A special issue of *Geophysical Research Letters* 32(3), 2005, published a series of research papers covering various aspects of solar terrestrial relationship during this period.

2. High speed streams

A high speed stream is identified by a large increase ($\geq 100\,\mathrm{km\ s^{-1}}$) in solar wind in a day and lasting for several days. Using these criteria Lindblad & Lunstedt 1981, 1983 and Lindblad *et al.* 1989 made catalogues of high speed solar wind streams from the observations made by near Earth probes and spacecraft for the period 1964 to 1982. These streams were associated with coronal holes and solar flares. There were 637 high speed streams from which 117 were associated or generated by solar flares. Vats (1992a) found that the total duration of high speed streams and its product with mean enhancement in speed correlates very well with solar activity. Mavromichalaki *et al.* (1988) prepared a catalogue of 423 well-defined high speed streams from the solar wind observations during 1972–1984. Vats (1992b) used this catalogue and found that

- flare associated streams created more severe storm (~ 2.7 times more Ap enhancement) than coronal hole associated streams and
- coronal hole associated streams caused a geomagnetic storm of longer duration than flare associated streams.

The temporal plots of Ap (continuous curve) and Dst (dotted curve) are shown in Figs. 1 and 2 for July 1975 and July 1980 respectively. There are straight lines marked on them as CS +, CS −, FGS + and FGS −. CS and FGS stand for coronal hole associated streams and flare associated or generated streams respectively. The signs + and − indicate the polarity of Interplanetary Magnetic Field (IMF). In these examples, it is interesting to note that both CS and FGS with +ve and −ve IMF produce enhancement in geomagnetic activity.

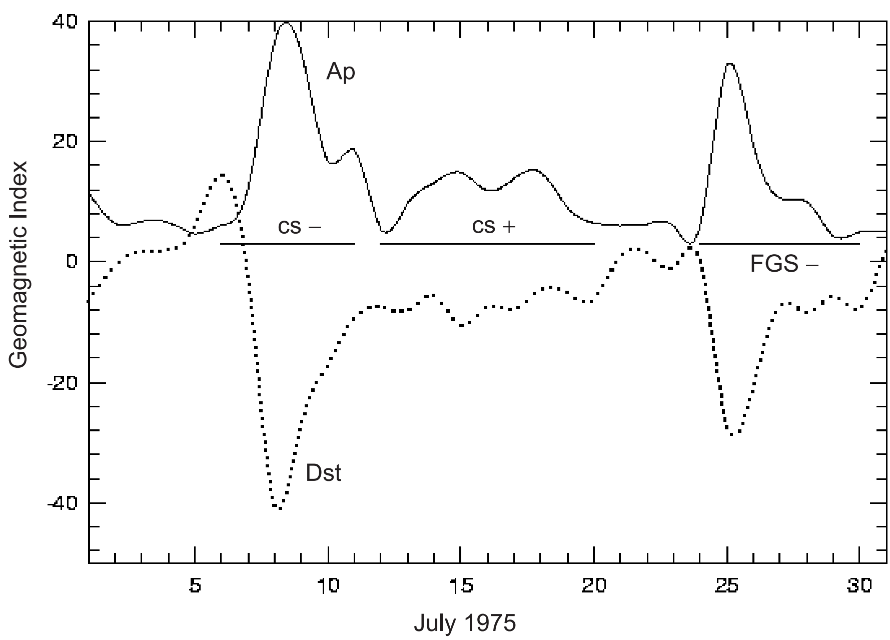

Figure 1. Temporal variation of geomagnetic indices Ap and Dst during July 1975, the straight lines marked with CS−, CS+ and FGS− show the duration of high speed streams.

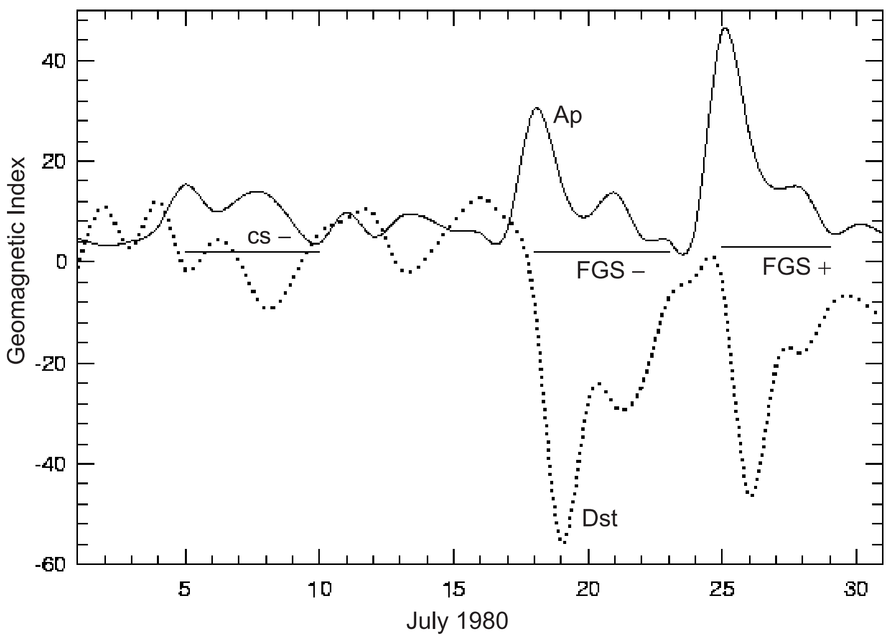

Figure 2. Same as Fig. 1 for July 1980, the straight lines marked with CS−, FGS− and FGS+ show the duration of high speed streams.

All the 423 high speed streams were grouped in two sets with +ve and −ve polarity from Mavromichalaki *et al.* (1988) catalogue. These sets were further divided in subgroups with speed increments of $100\,\mathrm{km\,s^{-1}}$. For each of these subgroups average enhancement in Ap values were calculated. To examine the effect of increase of peak velocity Vp of the streams on the enhancement of Ap, average Vp was calculated for the subgroups. The average Ap enhancement for each subgroup was plotted with average peak velocities Vp of the same subgroup. These curves for streams with −ve IMF (dotted curve) and for streams with +ve IMF (continuous curve) are shown in Fig. 3. From this (Fig. 3), it is clear that the streams with +ve and −ve IMF are both effective for the enhancement of magnetic activity. These curves for +ve and −ve IMF have two slopes, one for $\mathrm{Vp} < 850\,\mathrm{km\,s^{-1}}$ and other one for $\mathrm{Vp} > 850\,\mathrm{km\,s^{-1}}$. Thus, the high speed streams with velocity $< 850\,\mathrm{km\,s^{-1}}$ can be termed as extremely high speed streams. It is possible to define 'Geomagnetic activity enhancement rate' (GAER) as below:

$$\mathrm{GAER} = \frac{\text{Increase of average Ap value}}{\text{Increase of average Vp}}.$$

GAER for streams with +ve IMF are 0.08 and 0.73 for $\mathrm{Vp} < 850\,\mathrm{km\,s^{-1}}$ and $\mathrm{Vp} > 850\,\mathrm{km\,s^{-1}}$ respectively. Similarly GAER for streams with −IMF are 0.09 and 0.53 in the two regimes of Vp. This indicates that the extremely high speed streams ($< 850\,\mathrm{km\,s^{-1}}$.) with IMF +ve and −ve are more effective in enhancing geomagnetic activity than the high speed streams with lower Vp. The ratio of GAER for the extremely high speed streams with +ve and −ve IMF is 1.4 which indicates that streams with +ve IMF in this regime ($\mathrm{Vp} < 850\,\mathrm{km\,s^{-1}}$) are relatively more effective

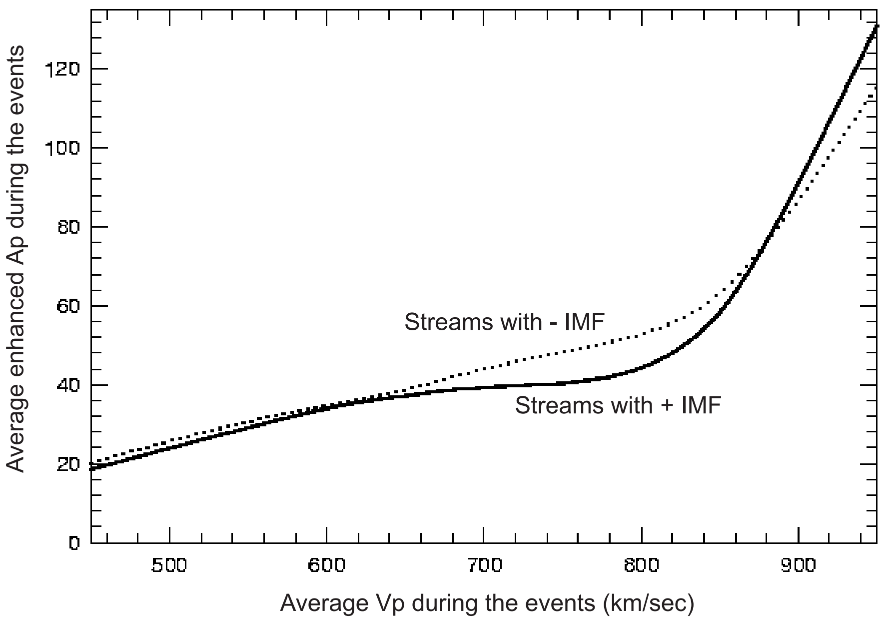

Figure 3. Ap enhancement as a function of Vp for the streams with + and −IMF.

to enhance geomagnetic activity than those with −ve IMF. However, for high speed streams Vp $< 850\,\mathrm{km\,s^{-1}}$ the value of GAER 0.08 and 0.09 for streams with +ve and −ve IMF respectively. This indicates that the streams with − IMF are slightly (~ 1.1 times) more effective in enhancing the geomagnetic activity.

3. Violent solar period

During October–November 2003, three solar active regions produced a series of eruptions. These eruptions were extreme in terms of their origin and terrestrial consequence (Gopalswamy *et al.* 2005). Kane (2005) remarked that the largest Dst value was −589 nT on 13 March 1989 with velocity (V) only $\sim$ 550–800 km s^{-1}. The next largest Dst values were near −400 nT, but their V values were vastly different (Halloween events, 29 October 2003, Dst −401 nT, V $\sim$ 2000 km s^{-1} and 20 November 2003, Dst −472 nT, V $\sim$ 700 km s^{-1}). Figure 4 shows the solar X-ray observations of GOES satellite during the period of October–November 2003. This period had a large number of solar flares, three flares on October 28, 29 and November 4 were of class X17.2, X10 and X28 respectively. The X28 was the largest solar X-ray flare observed and recorded so far. All the three of these flares are one among the 14 most powerful flares observed in the last three decades. Thus the Sun was most active and violent during October–November 2003. Bhardwaj *et al.* (2005), reported that during November 26–29, 2003 XMM-Newton observed soft (0.2–2 keV) X-ray emission from Jupiter for 69 hours. The simultaneous light curves of Jovian and solar X-rays show similar day-to-day variability. A large solar X-ray flare occurring on the Jupiter-facing side of the Sun was found to have a corresponding feature in the Jovian X-rays. Thus X-ray emission from Jovian low-latitudes appears to be solar X-rays scattered

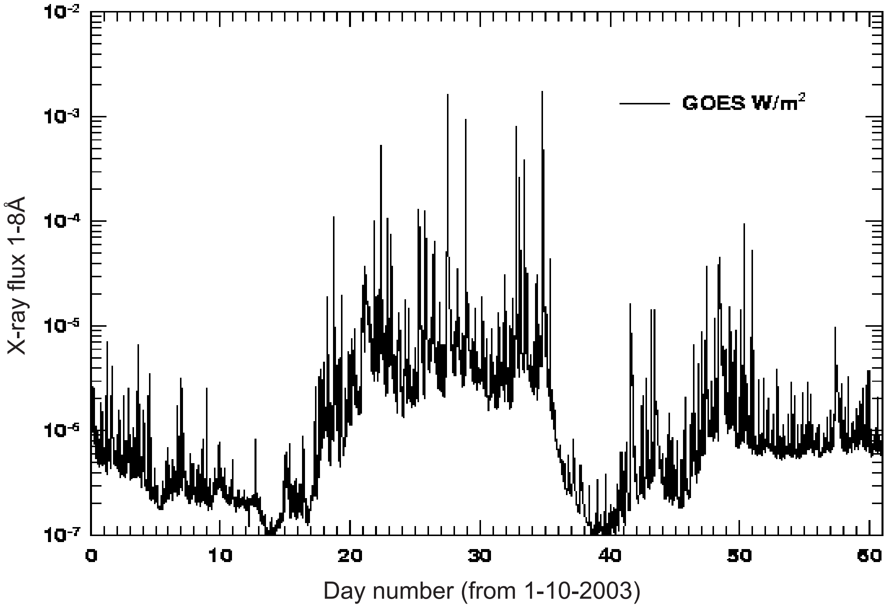

Figure 4. Temporal variation of solar X-ray flux during October–November 2003.

from the planet's upper atmosphere. Here we report only the geomagnetic effects due to violent solar activity period by way of investigating the temporal variation of Ap and Dst and the associated IMF conditions.

The temporal variation of Ap and Dst is shown in Fig. 5. The Dst values in Fig. 5 are negative during the entire period, indicating that this period was geo-magnetically disturbed. The enhancements in Ap and the depletions in Dst were simultaneous and at the same time very large too. Almost everyday there was at least one geomagnetic storm; ranging from weak to very strong one. October 28–31 and November 20, 2003 were the most violent in terms of geomagnetic activity. Gopalswamy *et al.* (2005) reported that the largest geomagnetic storm of the solar cycle 23 occurred on November 20, 2003 with a Dst index of -472 nT, due to a coronal mass ejection (CME) from active region 0501. The CME near the Sun had a sky-plane speed of $\sim$ 1660 km s^{-1}, but the associated magnetic cloud (MC) arrived with a speed of only 730 km s^{-1}.

The temporal variation of north–south component of IMF (Bz) during October–November 2003 is shown in Fig. 6. This figure shows that Bz during October–November 2003 has more $+$ve excursions than $-$ve. The period during which Bz was $+$ve is larger than that for $-$ve. The magnitude of all the negative values of Bz during this period were less than 10 whereas positive values of Bz went up to as high as $<$ 50 nT. Comparing the temporal variations shown in Figs. 5 and 6, it is clear that:

- whenever there is a severe geomagnetic activity indicated either by the enhancement in Ap value or by a corresponding decrease in Dst value, the Bz is positive, and
- on November 20, 2003, Ap and Bz are most positive and the Dst is most negative.

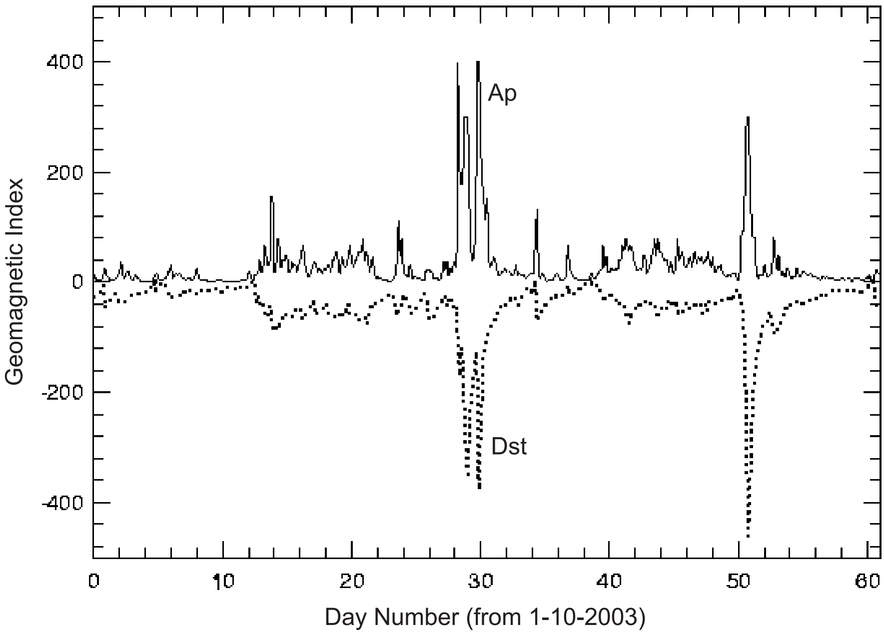

Figure 5. Temporal variation of Ap and Dst during October–November 2003.

Thus, the most violent geomagnetic storm took place when Bz is highly +ve. This is contrary to the common belief that the geomagnetic activity is always associated with negative Bz. Another associated space weather complexity was observed in the form of first day time auroral records during this violent solar period (Pallamraju and Chakrabarti 2005). They reported high spectral resolution measurements of OI 6300 Å emissions during daytime on 30 October 2003 from Boston. These observations revealed prolonged auroral activity from 1415–1900 h LT. Intense enhancement in brightness of 38 K Rayleighs was observed at 1509 h LT, which was six times larger than the normal daytime emission rates for that day. During this event the solar zenith angle was 74 Å and the solar background continuum was 4×10^6 Rayleighs $Å^{-1}$. During this period of auroral observations Bz was relatively high and +ve.

4. Conclusion and discussion

The examples of high speed streams associated with solar flares (FGS) and coronal holes (CS) with +ve and −ve IMF and the corresponding Ap and Dst variation indicate clearly that the high speed streams FGS and CS both are effective in enhancing geomagnetic activity. There were geomagnetic storms with both +ve and −ve IMF. The geomagnetic activity enhancement rate (GAER) is different in the two regimes of high speed streams. From the investigations of coupling between interplanetary parameters and geomagnetic activity, Ballatore (2002) found that the correlation coefficients obtained for data points corresponding to solar wind slower than 550 km s^{-1} are equal or slightly higher than the global correlations. The observations showed that generally lower correlation coefficients for faster solar wind speeds < 550 km s^{-1}.

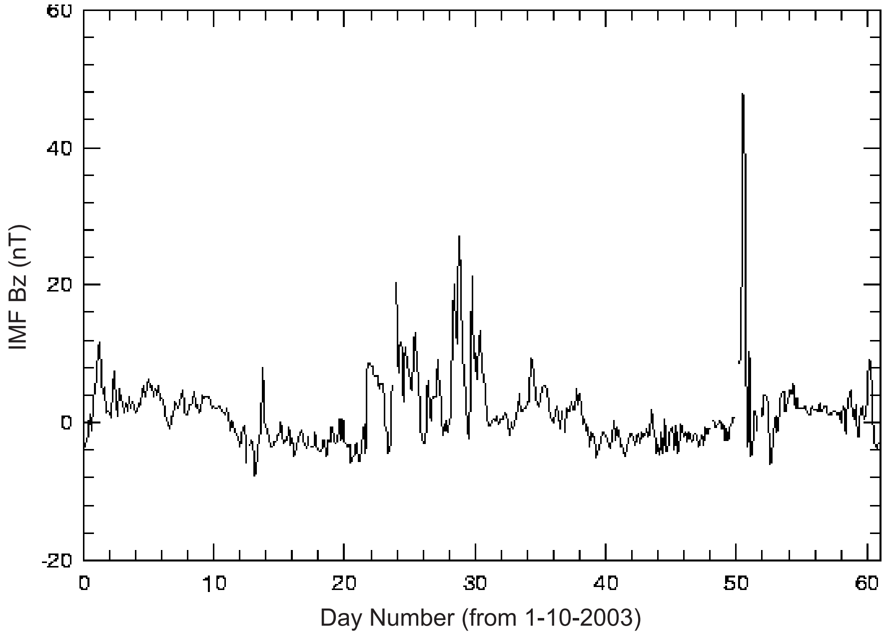

Figure 6. Temporal variation of Bz during October–November 2003.

These results are quite in contrast with the present studies. However, the one similarity between these two studies is that the relationship between the interplanetary medium and the geomagnetic activity are found to be different during periods of solar wind faster or slower than a threshold speed. The threshold speed in the present analysis was found to be 850 km s^{-1} whereas; in Ballatore (2002), it was considerably less (550 km s^{-1}). The processes responsible for the coupling between the interplanetary medium and the magnetosphere could certainly be different during different regimes of solar wind speed. Fenrich & Luhmann (1998) studied 29 magnetic cloud events and found that 40–45% of magnetic clouds, independent of polarity, are followed by fast streams which compress the tail end of the cloud. The compression results in an increase in the solar wind density and in 64% of the cases an increase in magnetic field strength also. Such tail end compression may have a significant effect upon geomagnetic activity if the magnetic cloud is of N–S polarity. The observations of violent solar period are unique in that major geomagnetic disturbances and daytime auroral emissions are associated with +ve Bz. In the literature Bz −ve is usually termed as a necessary condition for the creation of severe geomagnetic disturbance and intense aurora. The examples presented here are not in agreement with this belief. Thus more careful analysis is needed to ascertain the role of polarity of Bz in transfering the solar wind energy to magnetosphere and beyond.

Acknowledgements

The author wishes to acknowledge the data used here for the period October–November 2003, this was downloaded from the website of NOAA, namely, http://spidr.ngdc.noaa.gov/spidr/. The research at Physical Research Laboratory is supported by Department of Space, Government of India.

References

Aubry, M. P., McPherron, R. L. 1971, *J. Geophys. Res.*, **75**, 7018.
Ballatore, P. 2002, *J. Geophys. Res.*, **107(A9)**, 1227.
Bhardwaj, A., Branduardi-Raymont, G., Elsner R. F., Gladstone, G. R., Ramsay, G., Rodriguez, P., Soria, R., Waite, J. H., Jr., Cravens, T. E. 2005, *Geophys. Res. Lett.*, **32**, L03S08.
Carovillano, R. L., Siscoe, G. L. 1973, *Rev. Geophys.*, **11**, 289.
Dungey, J. W. 1961, *Phys. Res. Lett.*, **6**, 47.
Fenrich, F. R., Luhmann, J. G. 1998, *Geophys. Res. Lett.*, **25**, 2999.
Gopalswamy, N. L., Barbieri, G. Lu, Plunkett, S. P., Skoug, R. M. 2005, *Geophys. Res. Lett.*, **32**, L03S01.
Kane, R. P. 2005, *J. Geophys. Res.*, **110**, A02213.
Lindblad, B. A., Lundstedt, H. 1981, *Solar Phys.*, **74**, 197.
Lindblad, B. A., Lundstedt, H. 1983, *Solar Phys.*, **88**, 377.
Lindblad, B. A., Lundstedt, H., Larson B. 1989, *Solar Phys.*, **88**, 377.
Movromichalaki, H., Vassilaki, A., Marmatsouri, E. 1988, *Solar Phys.*, **115**, 345.
Pallamraju, D., Chakrabarti S. 2005, *Geophys. Res. Lett.*, **32**, L03S10.
Rastogi, R. G. 2001, *Curr. Sci.*, **81**, 1462.
Snyder, C. W., Neugebauer M., Rao, U. R. 1963, *J. Geophys. Res.*, **68**, 6361.
Tsurutani, B. T., Gonzalez, W. D., Tang, F., Lee, Y. T. 1992, *Geophys. Res. Lett.*, **19**, 73.
Vats, H. O. 1992a, *Solar Phys.*, **138**, 379.
Vats, H. O. 1992b, *Geol. Soc. India Memoir.*, **24**, 365.
Wang, Y. C., Shen, C. L., Wang, S., Ye, P. Z. 2003, *Geophys. Res. Lett.*, **30(20)**, 2039.