Low latitude geomagnetic signatures following two major solar energetic particle events at different phases of solar cycle-23

R. Rawat, S. Alex and G. S. Lakhina

Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai 410206, India

Abstract. Occurrence of transient astrophysical phenomena is well known to enhance greatly during the solar maximum period. Acceleration of energetic particles takes place in abundance at heliosphere by different transient processes, giving rise to solar energetic particle (SEP) events. Solar cycle 23 witnessed many powerful solar flares and coronal mass ejections producing intense solar energetic particle events, out of which two intense SEP events will be dealt with in the present work. One of the events occurred at solar maximum period and the other during the descending phase. The present work discusses role of interplanetary and solar wind conditions in generation and subsequent development of geomagnetic storms for the events under study. The SEPs are found to exhibit varying intensities, counts and ionic charges in different elements. A comparison of elemental and isotopic abundance variation, the subsequent formulation, development and decay of storm main phase is discussed in current work.

Index Terms. Coronal mass ejections, geomagnetic storms, solar energetic particle events.

1. Introduction

Instabilities in solar magnetic field due to twisting and shearing of field lines give rise to various explosive processes. Solar maximum is characterized by increase of transient energetic eruptions like solar flares and coronal mass ejections (CME) while solar minimum is featured by other processes like coronal holes and fast wind streams. A tremendous amount of energy of the order of ~ 10^{27} ergs and ~ 10^{32} ergs is released through solar flares and CMEs respectively. The heliosphere is enriched with a large variety of charged particles ranging from Z=1 to Z>26. The high energy released through solar flares and CMEs energizes and accelerates the existing heliospheric population sufficiently, leading to expulsion from the solar surface. Such outbursts of energetic particles are called as solar energetic particles (SEP) events. First evidence of SEP was observed by Forbush (1946) during the large solar events of February and March 1942, marked by an abrupt enhancement in the intensity in ground level ion chambers. Later on different properties exhibited by SEP events revealed distinct types and hence broad classification brought two categories, gradual and impulsive. Various properties observed for categorization include association with solar flares and coronal mass ejections (Cliver et al., 1983; Kahler, 1986, 1992), difference in ratio of proton to electron populations (Cane et al., 1986), different elemental, isotopic abundance and charge state variation during the events (Reames, 1999). SEP events are distinguished by abrupt enhancement in the proton flux at all energy levels.

The current study deals with two large solar energetic particle events occurring in different phases of solar cycle-23. One event is the largest SEP event of November 4, 2001 that occurred in solar maximum period and was associated with solar flare followed by coronal mass ejection. Other SEP event of January 20, 2005 occurred in descending phase of solar cycle and was preceded by a series of multiple flares and SEP events between the duration of January 15-20, 2005. This event is identified as the fastest rising SEP event of current solar cycle. Present work investigates the differing behaviours in the two solar particle events and subsequent storm formulation in response to the varying IMF conditions. An attempt has been carried out to distinguish the two events on the basis of elemental and isotopic abundance variation.

2. Data set and methodology

In order to study the several characteristics exhibited by the two events, the data has been obtained from following sources. X-ray flare information is acquired from GOES solar X-ray imager onboard geosynchronous satellite GOES-10 (long. 135° W) that provides X-ray flux at two wavelengths of 0.5-4 Å and 1.0-8.0 Å. Proton flux variation data is taken from Electron, Proton and Alpha Monitor (EPAM), and Solar Isotope Spectrometer (SIS) instruments onboard ACE satellite. Interplanetary magnetic field and solar wind parameters used in current study are obtained from ACE satellite with 5-minute resolution. The November 4, 2001 was a remarkably strong SEP event, during which huge proton showers saturated the spacecraft and continuous recording of solar wind data could not be taken, therefore to observe the solar wind characteristics, 1 hourly data is taken from SOHO satellite. For determining ground magnetic variation during the studied events, low latitude observatory data is acquired from Alibag (geographic lat. 18.62° N, long. 72.87° E; geomagnetic lat. 10.17°N, long. 146.15°) and Pondicherry (geographic lat. 11.92° N, long. 79.92° E;

geomagnetic lat. 2.85˚N, long. 152.33˚). In order to remove the daytime effects in the horizontal component; quiet time variations have been subtracted from the storm days considered in current study. Storm time disturbance (Dst) index data is taken from World Data Center, Kyoto website. In order to examine the elemental variation, 1 hourly $^3He/^4He$ and Fe/O data in 0.32-0.64 MeV/nuc energy range is taken from ULEIS instrument onboard ACE satellite.

Interplanetary conditions play a crucial role in generation and development of geomagnetic storms, specifically interplanetary meriodonal component *Bz* (Tsurutani et al., 1997, Wang et al., 2003). An observational and comparative study is made to bring out the role of these parameters in the events studied here.

3. Case Studies

3.1 Case 1: November 4, 2001

3.1.1 Proton Flux characteristics

This event occurred at solar maximum and is observed as most intense solar energetic particle event of solar cycle-23 as reported by CELIAS/MTOF instrument onboard SOHO satellite.

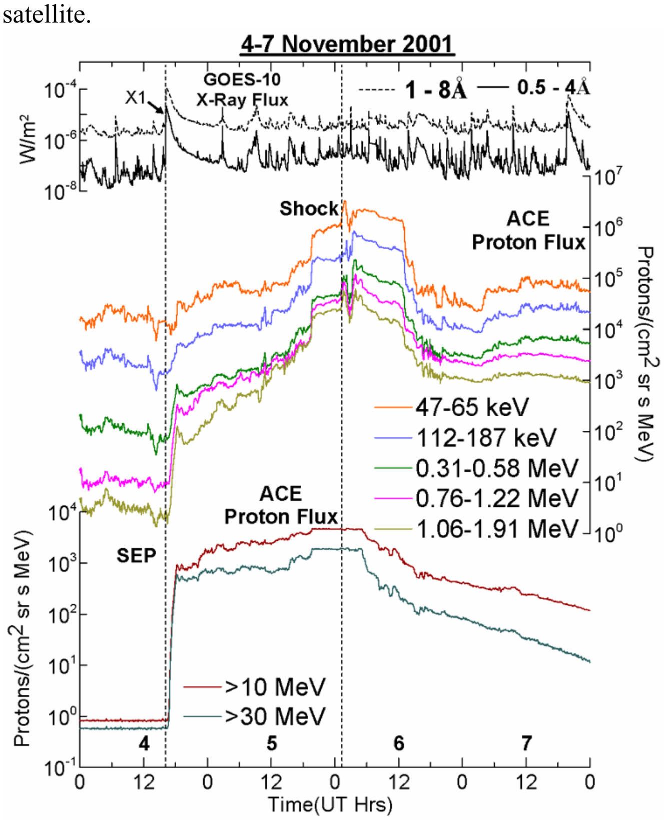

Fig. 1. X-ray and proton flux profiles for November 4-7, 2001. Flare magnitude is shown by an arrow. Vertical dashed lines mark the SEP onset and shock passage time respectively.

A strong X1.0 flare erupted at 1603 UT on November 4, 2001 and maximized shortly at 1620 UT. Around 45 minutes after flare maximum, a major proton event occurred at 1705 UT on November 4, 2001. A sudden enhancement in proton flux (first vertical dashed line) at all energy ranges is distinctly seen in Fig. 1. This enhancement is followed by a steady and gradual increase that continued till another hike is confronted at the shock passage time, 0120 UT on November 6, 2001. Magnitude of proton event can be clearly assessed from the order of increase in proton flux for >10 and >30 MeV energy levels at the SEP onset time. A salient feature observed in this case is the persistence of proton flux large magnitude for about 6 hrs in all energy ranges after the shock. SEP event decay started after this duration.

3.1.2 Interplanetary conditions and geomagnetic response

The solar flare maximum was followed by a full halo coronal mass ejection at 1635 UT on November 4, as observed by LASCO/SOHO, 2001 with a speed of ~ 1810 km/s.

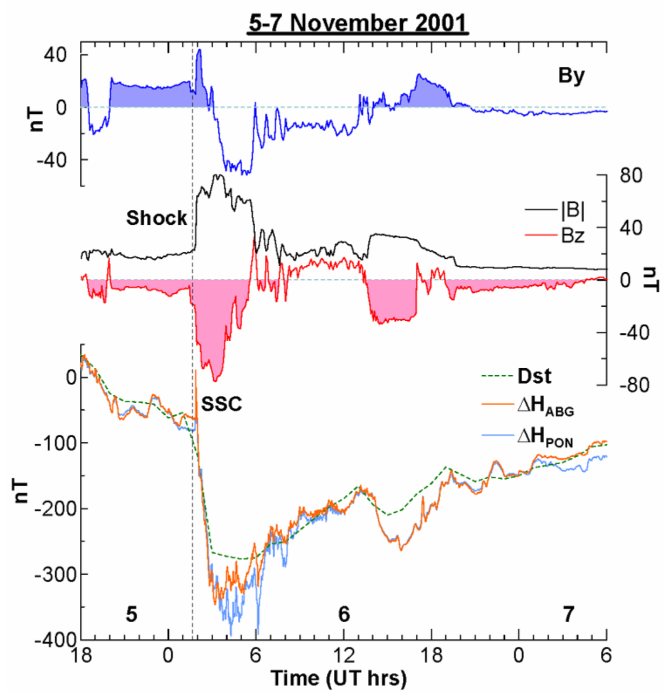

Fig. 2. Illustrated here from top to bottom are IMF *By*, |*B*|, *Bz*, Dst and Δ*H* at Alibag and Pondicherry for November 5-7, 2001. Shock passage time is marked by vertical dashed line. SSC time shown here is time shifted to interplanetary shock time. SSC amplitudes recorded for Alibag and Pondicherry are ~ 70 nT and ~ 90 nT respectively.

Fast CME on November 4, drove a strong interplanetary (IP) shock after about 33 hrs at 0120 UT on November 6, 2001, characterized by abrupt increase in solar wind speed (*Vsw*), proton density (*Np*), nearly by 220 km/s, 35 cm^{-3} respectively as recorded by PM/SOHO (not shown here) and total interplanetary magnetic field (|*B*|) increased by ~ 37 nT, as recorded by MAG/ACE (Fig. 2.). The abrupt increase in solar wind pressure to a value of ~ 16 nPa pushed the magnetopause up to ~ 5.3 R_E (not shown here). Fig. 2 depicts the interplanetary magnetic field state prior to the onset and during the storm. A special feature to be observed in this case is ~ 6 hrs southward *Bz* prior to shock with magnitude ~ 10 nT. During this period IMF *By* was continuously dusk ward with magnitude ~ 20 nT. At the shock passage time, IMF *Bz* traversed southward steadily reaching a significantly large peak value ~ - 80 nT. Southward orientation continued for ~ 4 hrs followed by northward traversal. The impingement of

CME on magnetosphere lead to a magnetopause compression featured as a storm sudden commencement (SSC) as recorded at Alibag and Pondicherry observatories, with amplitudes of ~70 nT and ~90 nT respectively at 0152 UT on November 6, 2001 after about 32 minutes of interplanetary shock. Strong and prolonged southward *Bz* aided development of intense geomagnetic storm (bottom panel of Fig. 2). Both the ground stations clearly show the prominent correspondence with modulations in the interplanetary magnetic field components. Minimum values in the geomagnetic field as recorded at Alibag and Pondicherry are ~ -346 nT and ~ -394 nT respectively which correspond to the Dst minimum value -292 nT.

3.2 Case 2: January 20, 2005

3.2.1 Proton Flux characteristics

Associated with series of solar flares, coronal mass ejections and few coronal holes, this event was identified as the fastest rising SEP event during the descending phase of solar cycle-23, since October 1989 (as reported by CELIAS/MTOF/PM onboard SOHO satellite). Series of flares started from January 15, 2005, with magnitudes above M8 until an intense solar flare of magnitude X7.1 occurred at 0636 UT on January 20, 2005 and maximized at 0701 UT.

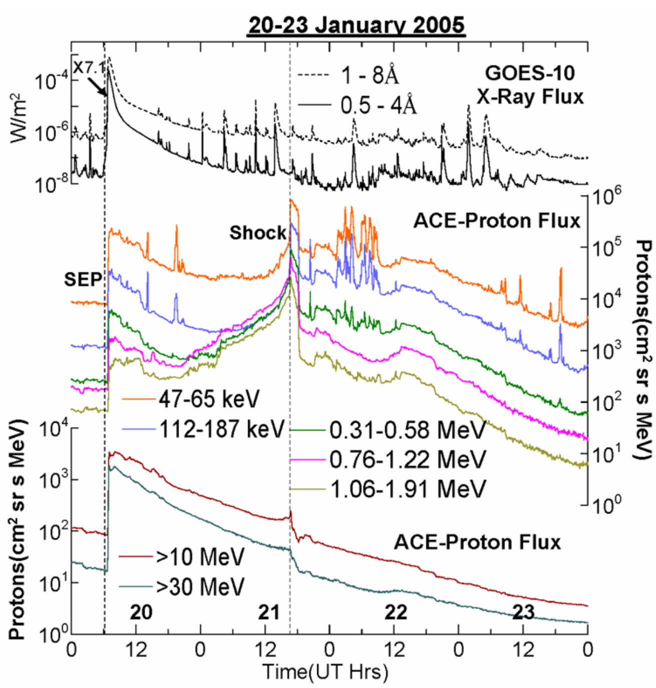

Fig. 3. Depicted here are X-ray and proton flux profiles for January 20-23, 2005. Flare magnitude is shown with an arrow. Vertical dashed lines mark the SEP onset and shock passage time respectively.

Prompt enhancement in proton flux at all energy levels is observed shortly after the flare onset at 0650 UT on January 20, 2005 marking the beginning of an intense proton event (second and third panels in Fig. 3). Soon after attaining a peak at 0805 UT on same day, the >10 MeV proton flux dropped sharply while lower energies 47 keV to 1.91 MeV underwent a gradual decay for ~ 18 hrs, with a further rise to produce a spurt in the proton flux at shock passage on November 21, 2005 at 1640 UT.

3.2.2 Interplanetary conditions and geomagnetic response

A halo CME with speed ~ 882 km/s associated with the X7.1 solar flare was ejected at 0654 UT on January 20, about 7 minutes prior to the flare maximum.

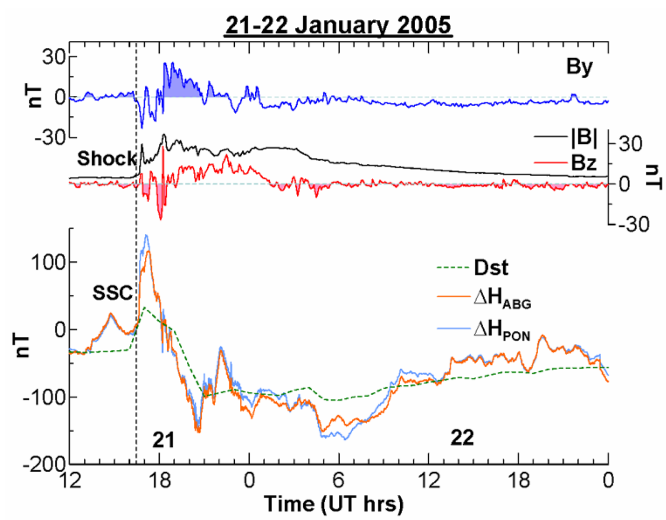

Fig. 4. Illustrated here from top to bottom are IMF *By*, |*B*|, *Bz*, Dst and ΔH at Alibag and Pondicherry for January 21-22, 2005. Shock passage time is marked by vertical dashed line. SSC time shown here is time shifted to interplanetary shock time. SSC amplitudes recorded for Alibag and Pondicherry are ~ 100 nT and ~ 120 nT respectively.

The halo CME drove an IP shock at 1640 UT on January 21, 2005 identified by sudden increase in *Vsw*, *Np* and |*B*| by values ~ 120 km/s and ~ 5 cm^{-3} and ~ 10 nT respectively as recorded at ACE satellite. Sharp increase in solar wind pressure to value ~ 28 nPa compressed the magnetopause to ~ 4.7 R_E. Solar wind pressure confronted another kink up to ~ 80 nPa further (not shown here). Solar wind speed was at higher levels ~ 550 km/s, prior to shock and further increased upto a value of ~970 km/s after shock (not shown here), thus giving an idea that it was a fast stream during the descending phase of solar cycle. IMF *By*, *Bz* components were fluctuating prior to shock with low values ranging between -4 to + 4 nT. Oscillations in IMF continued after the shock passage for ~ 3 hrs ranging from - 20 to + 20 nT, followed by northward traversal of *Bz*. Impact of interplanetary shock wave generated on January 21 on the magnetopause was detected as a strong storm sudden commencement (SSC) after about 32 minutes of shock, with amplitude of ~ 100 nT and ~ 120 nT at Alibag and Pondicherry respectively (bottom panel of Fig. 4). The intensity of magnetopause compression and the related enhancement in the sudden commencement amplitude at the local night conditions explain the extreme background state. Despite strong solar wind conditions prior to the shock, the oscillating *Bz* could be ascertained as a strong cause to hinder the development of storm, as evident from ground magnetic data from both low latitude stations. The minimum values recorded for ΔH_{ABG} and ΔH_{PON} during main phase are ~ -153 nT and ~ -163 nT with lower Dst minimum value (-105 nT).

4. Results and Discussion

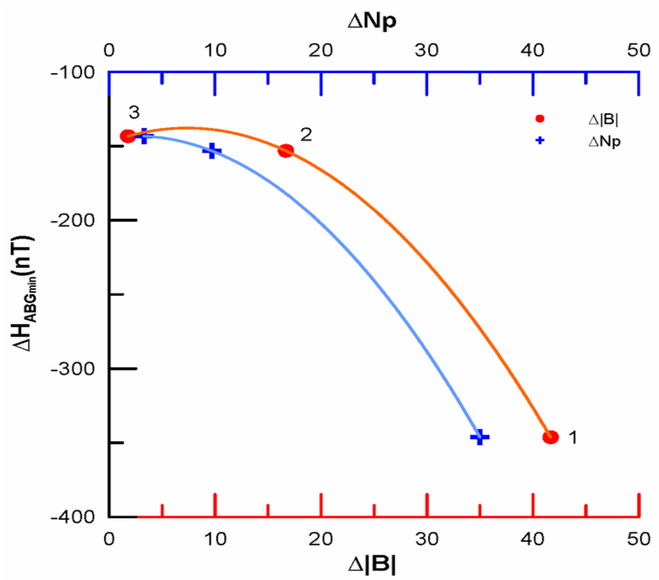

Fig. 5. Variation of minimum value attained by ground magnetic field at Alibag during main phase for three events, with change in solar wind density (*Np*) and interplanetary total magnetic |*B*| during shock passage time. Polynomial fits are shown for *Np* and |*B*| with blue and orange curves respectively. Numerals 1, 2, 3 respectively represent three events of November 6, 2001, January 21, 2005 and January 17, 2005.

Present study summarizes the results from three SEP events to ascertain the precursory conditions of interplanetary and solar wind parameters for formulation and development of storms, originated following solar radiation storms. Third event considered for this purpose is January 17, 2005 (not shown here). This event is associated with X2.6 solar flare at 2302 UT on January 16. Subsequently, a small storm developed with SSC at 0748 UT on January 17. IMF *By* and *Bz* for this event were of less magnitudes and highly fluctuating for the whole duration of storm and hence, impeding the development of intense main phase.

1) Fig. 5, illustrates the one to one correspondence obtained between the abrupt increase in the intensity of the proton density (*Np*) and total interplanetary magnetic field (|*B*|) during the interplanetary shock as observed at ACE (240 R_E) and the degree of minimum Δ*H* during the main phase of storm as recorded at Alibag. From both the fitted curves it is evident that increasing proton density and stronger |*B*| support the growth of intense main phase.

The vital role of interplanetary conditions guiding the formulation and development of geomagnetic storms has been a well established fact (Gonzalez and Tsurutani, 1987; Tsurutani et al., 1997; Feldstein et al., 2003). Sharp and steady southward orientation of *Bz* aids the magnetic reconnection (Dungey, 1961) and hence large energy transfer from the ejecta into the magnetosphere takes place. Steady dusk ward *By* guides towards the magnetic reconnection site. Significant reinforcement in the ring current population and energy leads to intense main phase development. The intense storm of November 6, 2001 (Fig. 2) distinctly reflects the results stated in earlier studies.

Therefore, considering the contribution of all solar wind and interplanetary parameters towards storm manifestation, it can be suggested that larger increase in proton density, *Np* and total interplanetary magnetic field, |*B*| at the shock passage time in presence of a dominating southward *Bz* and dusk directed *By* may help in tremendous amount of energy transfer, subsequently leading to geomagnetic storm with rapid and intense main phase.

2) Study of relative elemental and isotopic abundances in SEP events provides rich information about their origin and history of the populations of energetic ions (Reames, 1999 and Tylka, 2001). Isotopic and elemental abundance ratios for the intense proton events under examination are shown in Fig. 6, where SEP onsets for the two events are marked (dotted lines for November 2001 event and dashed lines for January 2005 event).

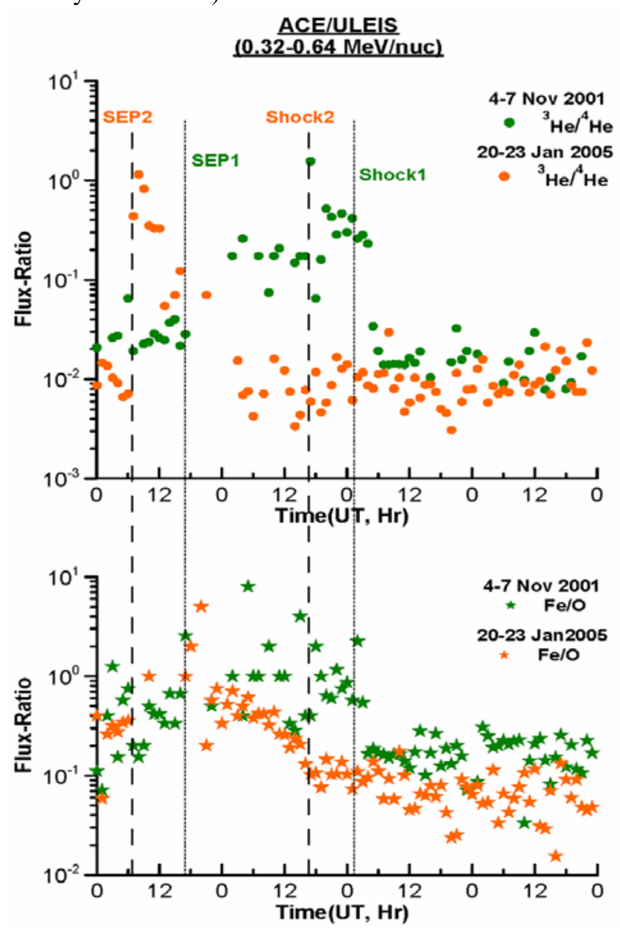

Fig. 6. Isotopic ratio ^{3}He/^{4}He for January 20-23, 2005 and November 4-7, 2001. Vertical lines (dashed line for January 2005, dotted line for November 2001) represent SEP onset and shock passage times in the order. Bold coloured titles SEP1, Shock1 refer to November 2001 and SEP2, Shock2 refer to January 2005 events respectively. Bottom panel depicts Fe/O ratios for January 20-23, 2005 and November 4-7, 2001.

Fig. 6 (upper panel) exhibits a prompt enhancement in the isotopic ratios ^{3}He/^{4}He at SEP onset time at 0650 UT on January 20, 2005 (SEP2) from values of 7×10^{-3} to 4×10^{-1}

particles/cm^2 sr s MeV further a rapid decay for January 20, 2005 event is seen. Despite intense interplanetary and solar wind conditions for November 4, 2001 event, enhancement in $^3He/^4He$ ratio is relatively gradual and weaker from values of 3×10^{-2} to 2×10^{-1} particles/cm^2 sr s MeV. However, an abrupt increase to a value of 2 particles/cm^2 sr s MeV is observed for November 2001 event before the IP shock time (Shock1). Increase of two orders of magnitude in $^3He/^4He$ ratio at SEP onset time for January 2005 (SEP2) case can be attributed to remnant flare suprathermals in the source material (Mason et al., 1999), as this SEP event was preceded by multiple intense flare activity ranging from magnitude orders of ~ M8 to ~ X4.

November 2001 event witnessed a growth in Fe/O ratio from 5×10^{-1} to 2 particles/cm^2 sr s MeV at the shock passage time (SEP1, Shock 1) whereas in January 2005 event decay of Fe/O ratio started shortly after attainment of maximum value of 5 particles/cm^2 sr s MeV (SEP2) (Fig. 6, bottom panel).

3) A striking feature noticed in November 4, 2001 event (SEP1) is significant growth in $^3He/^4He$ and Fe/O ratios prior to shock passage time. This observation can be attributed to the steadily increasing proton flux at all energy ranges that is relatively higher in MeV energy levels during the same period (Fig. 1). This observation is in good agreement with the work of Ng et al. (1999) wherein the temporal changes in elemental abundance ratios are explained on the basis of effect of proton generated Alfvén waves on the scattering of SEP ions during the propagation from the acceleration region to the observer. Further, ground magnetic field records show sharp and intense main phase development for November 2001 event. Hence, it may be proposed that large values of isotopic and elemental ratios in the pre-storm periods could contribute towards the intensity of geomagnetic storms. Present study reveals that even events fulfilling the criteria of one particular category amongst gradual or impulsive can also exhibit differing elemental abundances depending on pre-event solar conditions. In order to quantify the attempts made in this work; study is on dealing with more number of events.

Acknowledgements. We thank the ACE Magnetic Field instrument team, ACE SWEPAM instrument team and ACE Science Center for providing the ACE data. The authors thank the CELIAS/PM experiment on the Solar Helisopheric Observatory (SOHO) spacecraft. SOHO is a joint ESA and NASA mission. We are also thankful to WDC-C2, Kyoto, for supplying Dst index.

References

H. V. Cane, R. E., McGuire and T. T. von Rosenvinge, "Two classes of solar energetic particle events associated with impulsive and long duration soft x-ray flares", *Astrophys. J.*, vol. 301, pp. 448-459, 1986.

E. W. Cliver, S. W. Kahler and P. S. McIntosh, "Solar proton flares with weak impulsive phases", *Astrophys. J.*, vol. 264, pp. 699-707, 1983.

J. W. Dungey, "Interplanetary magnetic field and the auroral zones", *Phys. Rev. Lett.,* vol. 6, pp. 47-48, 1961.

Y. I. Feldstein, I. A. Dremukhina, A. E. Levitin, U. Mall, I. I. Alexeev and V. V. Kalegaev, "Energetics of magnetosphere during the magnetic storm", *J. Atmos. Sol. Terr. Phys*., vol. 65, pp. 429-446, 2003.

S. E. Forbush, "Three unusual cosmic ray increases possibly due to charged particles from the Sun", *Phys. Rev*., vol. 70, pp. 771-772, 1946.

W. D. Gonzalez and B. T. Tsurutani, "Criteria of interplanetary parameters causing intense magnetic storms (Dst < -100nT)", *Planet. Space Sci.*, vol. 35, pp. 1101-1109, 1987.

S. W. Kahler, "Solar flares and coronal mass ejections", *Ann. Rev. Astron. Astrophys*., vol. 30, pp. 113-141, 1992.

S. W. Kahler, E. W. Cliver, H. V. Cane, R. E. McGuire, R. G. Stone and N. R. Sheely, "Solar filament eruptions and energetic particle events", *Astrophys. J*., vol. 302, pp. 504-510, 1986.

G. M. Mason, J. E. Mazur and J. R. Dwyer, "^{3}He enhancements in large solar energetic particle events", *Astrophys. J.,* vol. 525, pp. L133-L136, 1999.

C. K. Ng, D. Reames and A. J. Tylka, "Effect of proton amplified waves on the evolution of solar energetic particle composition in gradual events", *Geophys. Res. Letts*., vol. 26, pp. 2145-2148, 1999.

D. V. Reames, "Particle acceleration at the Sun and in the Heliosphere", *Space Sci. Rev*., vol. 90, pp. 413-491, 1999.

B. T. Tsurutani and W. D. Gonzalez, "The interplanetary causes of magnetic storms: A review", in *Magnetic Storms*, *Geophys. Monogr. Ser*., vol. 98, B. T. Tsurutani et al., Eds. AGU, Washington, D. C., 1997, pp. 77-89.

A. J. Tylka, "New insights on solar energetic particles from WIND and ACE", *J. Geophys. Res*., vol. 106, pp. 25,333-25,352, 2001.

C. L. Wang, C. L. Shen, S. Wang and P. Z. Ye, "An empirical formula relating the geomagnetic storm's intensity to the interplanetary parameters: *-VBz* and Δt", *Geophys. Res. Letts*., vol. 30, pp. 2039-2042, 2003.