Unique observations of a geomagnetic $SI^+ - SI^-$ pair: Solar sources and associated solar wind fluctuations

R. G. Rastogi,[1] P. Janardhan,[1] K. Ahmed,[2] A. C. Das,[1] and Susanta K. Bisoi[1]

Received 21 May 2010; revised 30 August 2010; accepted 20 September 2010; published 21 December 2010.

[1] This paper describes the occurrence of a pair of oppositely directed sudden impulses (SI) in the geomagnetic field (ΔX) at ground stations, called $SI^+ - SI^-$ pairs, that occurred between 1835 UT and 2300 UT on 23 April 1998. The $SI^+ - SI^-$ pair was closely correlated with corresponding variations in the solar wind density, while solar wind velocity and the southward component of the interplanetary magnetic field (*Bz*) did not show any correspondence. Further, this event had no source on the visible solar disk. However, a rear-side partial halo coronal mass ejection (CME) and an M1.4 class solar flare behind the west limb took place on 20 April 1998, the date corresponding to the traceback location of the solar wind flows. This event presents empirical evidence, which to our knowledge is the most convincing evidence for the association of specific solar events to the observations of an $SI^+ - SI^-$ pair. In addition, it shows that it is possible for a rear-side solar flare to propagate a shock toward the Earth.

Citation: Rastogi, R. G., P. Janardhan, K. Ahmed, A. C. Das, and S. K. Bisoi (2010), Unique observations of a geomagnetic $SI^+ - SI^-$ pair: Solar sources and associated solar wind fluctuations, *J. Geophys. Res.*, *115*, A12110, doi:10.1029/2010JA015708.

1. Introduction

[2] It is well known that space weather events observed at 1 AU are all linked to the dynamic evolution of the solar photospheric magnetic field. This evolution, in conjunction with solar rotation, drives space weather through the continuously changing conditions of the solar wind and the interplanetary magnetic field (IMF) within it. In spite of the fact that there have been substantial observations and discussions on the close correspondence between solar wind parameters at 1 AU and ground-based geomagnetic field variations [*Dungey*, 1961; *Heppner and Maynard*, 1987; *Goodrich et al.*, 1998; *Lu et al.*, 1998], it is not straightforward under this broad framework to pinpoint either the solar origins of specific space weather events or to find specific correlations between solar wind parameters at 1 AU and ground-based magnetic observations. This is because such signatures are generally weak and are usually washed out or masked by the large variety of interactions that can take place both in the interplanetary medium and within the Earth's magnetosphere. Space weather events are, however, often preceded by the arrival at 1 AU of strong interplanetary (IP) shocks. Since such storms can have adverse effects on human technologies, the study of IP shocks can yield important inputs for numerical models that simulate the propagation of solar-initiated IP disturbances out to 1 AU and beyond.

[3] On the other hand, solar sources of space weather events can range from coronal mass ejections (CME), very energetic solar flares, filament eruptions, and corotating interaction regions (CIR). Though a vast majority of such events are caused by explosive and energetic solar events such as CMEs and flares, some recent studies have unambiguously associated large space weather events at 1 AU, such as "solar wind disappearance events," to small transient midlatitude corona holes butting up against large active regions at central meridian [*Janardhan et al.*, 2005, 2008a, 2008b]. These studies have provided the first observational link between the Sun and space weather effects at 1 AU, arising entirely from nonexplosive solar events.

[4] Though the very first observations, by the Mariner 2 spacecraft in 1962, of interplanetary shock waves showed the possibility of the existence of double-shock ensembles in the interplanetary medium [*Sonett et al.*, 1964], the existence of such shock pairs was firmly established only some years later, by the careful analysis of plasma and magnetic field measurements associated with shocks [*Burlaga*, 1970; *Lazarus et al.*, 1970]. However, the very unusual plasma and field variations associated with these structures prompted *Sonett and Colburn* [1965] to suggest that the first or forward shock would give rise to a positive *H*-component at ground-based observatories while the second or reverse shock would cause an oppositely directed or negative change in the *H*-component of the Earth's horizontal field, as measured along the local geomagnetic meridian (H). These impulses, referred to in the rest of the paper as sudden impulse or $SI^+ - SI^-$ pairs, were typically separated by a few hours in time and were hypothesized, as already stated, to be caused by the arrival at 1 AU of the forward and reverse shock pair convected toward the Earth by the solar wind. *Razdan et al.* [1965] described

[1] Physical Research Laboratory, Astronomy & Astrophysics Division, Ahmedabad, India.
[2] Indian Institute of Geomagnetism, Navi Mumbai, India.

0148-0227/10/2010JA015708

worldwide occurrences of such $SI^+ - SI^-$ pairs and suggested that they were associated with solar disturbances driving interplanetary shocks at highly oblique angles to the solar wind streaming direction. They did not, however, find any solar activity or associated occurrences of solar radio emission during the period of $SI^+ - SI^-$ pairs. In a more recent study of a number of $SI^+ - SI^-$ pairs, covering the period 1995–1999, *Takeuchi et al.* [2002] concluded that the observed SI^- (or negative impulses) in their sample were not associated with reverse shocks and showed no preferential association to any particular kind of solar wind structure, such as high- and low-speed stream interface discontinuities or front boundaries of interplanetary magnetic clouds.

[5] Early theoretical support came from *Dryer* [1970, 1972], who introduced the physics of finite electrical conductivity within the forward and reverse shock pairs, to derive reasonable first-order predictions for the observed distribution of solar wind speed, density, and temperature, and this was followed up by several other early papers [*Eviatar and Dryer*, 1970; *Shen and Dryer*, 1972; *Dryer et al.*, 1975] along similar lines. In more recent times, there have been a number of theoretical models that have used inputs from solar data to predict the arrival of IP shocks and IP CMEs at Earth [*Odstrcil*, 2003; *Vandegriff et al.*, 2005; *Tóth et al.*, 2005; *Detman et al.*, 2006], including the well-known Hakamada-Akasofu-Fry model (HAFV2) [*Fry et al.*, 2003], which is the only model to date to have been substantially validated in an operational forecasting environment [*Smith et al.*, 2009a, 2009b] during solar cycle 23.

2. The $SI^+ - SI^-$ Pair of 23 April 1998

[6] An $SI^+ - SI^-$ pair was identified at three Indian geomagnetic observatories on 23–24 April 1998. Figure 1 (bottom) shows the tracings of H magnetograms (projected onto the X or geographic north direction and marked ΔX in Figure 1) on 23–24 April 1998 at the three Indian stations Gulmarg, Alibag, and Trivandrum, respectively. A sudden positive impulse in H was recorded at all three Indian observatories at 1835 UT (23 April 2335 LT), followed by a sudden negative impulse at 2300 UT (24 April 0430 LT). During the time interval between the SI^+ impulse and the SI^- impulse, the amplitude of H first decreased and then attained a peak of 44 nT at Trivandrum that progressively increased to 54 nT at Alibag and 76 nT at Gulmarg. Between 2100 and 2300 UT, large fluctuations were recorded at all stations. The fluctuations in H at all stations were remarkably similar with the amplitude increasing from Trivandrum to Gulmarg. Also shown in Figure 1 (starting from the top and going down) are the corresponding variations of the solar wind velocity, the IMF-*Bz*, the interplanetary electric field, the solar wind flow pressure, the solar wind density, and the symmetrical H Field, respectively. The curve for the solar wind density, as observed by the Advanced Composition Explorer (ACE; *Stone et al.* [1998]) has been shaded in Figure 1 in the region between the $SI^+ - SI^-$ pair. The vertically oriented dashed parallel lines in all parts of Figure 1 demarcates the time interval between the SI^+ impulse and the SI^- impulse. It is to be noted that the symmetric H field (SYM/H), characterizing the mean variation of H at all middle latitude stations around the world, too had remarkably similar variations as the H at Indian stations. This therefore implies that the $SI^+ - SI^-$ pair was a global event.

[7] *Rastogi and Patel* [1975] showed that solar plasma moving toward the Earth's magnetosphere with the velocity, V, and having a frozen-in magnetic field normal to the ecliptic (IMF-*Bz*) is equivalent to an electric field, $E_{sw} = (-V \times Bz)$, which is transmitted without any time delay to the polar region and then to the low-latitude ionosphere. This belongs to a process known as overshielding electric field in the magnetosphere, which has been extensively studied [*Nishida*, 1968; *Vasyliunas*, 1970; *Spiro et al.*, 1988; *Wolf et al.*, 2001; *Goldstein et al.*, 2002]. Prompt penetration occurs owing to the slow response of the shielding electric field at the inner edge of the ring current that opposes the time varying convection field in the presence of an IMF-*Bz*. The time scale of this process is generally of the order of an hour but can sometimes be longer [*Vasyliunas*, 1970; *Senior and Blanc*, 1984]. During a period of sudden northward turning of the IMF, from a steady southward configuration, the convective electric field shrinks while the shielding electric field takes a longer time to decay and produce a residual electric field, known as the overshielding electric field. The direction of this field is opposite to the normal direction of the ionospheric electric field. The E_{sw} has a direction of dusk-to-dawn for positive IMF-*Bz* and dawn-to-dusk for negative IMF-*Bz*.

[8] It can be seen from Figure 1 that ΔX at Indian stations just after the SI^+ at 1835 UT (around local midnight) had gradually decreased until 2000 UT. This effect is due to the prompt penetration of the electric field when the IMF-*Bz* is negative during the period. At around 2000 UT, ΔX again increased suddenly to values much above the first impulse level. Correspondingly, it can be seen that IMF-*Bz* turned from southward to northward at this instant, implying that it is due to the overshielding condition described above. After this, the level of ΔX went down, with some oscillations, and finally came down to normal level at 2300 UT. It is interesting to note that the fluctuations in ΔX between 2130 and 2200 UT were very well correlated with the solar wind density rather than with the IMF-*Bz* or the solar wind speed. The SI^+ at 1835 UT was associated with a sudden increase of both the solar wind density and speed causing a sudden pressure on the magnetosphere (as first suggested by *Gold* [1959]). The SI^- at 2300 UT was associated with the sudden decrease of solar wind density.

2.1. Global Geomagnetic Fields

[9] Figure 2 shows the variation of ΔX from 11 low-latitude stations around the world on 23–24 April 1998. The stations, starting from Alibag (ABG − Lat. 18.64; Long. 72.87) (uppermost curve), and arranged in increasing order of geographic longitude are, respectively, Gnangara (GNA − Lat. −31.78; Long. 115.95), Esashi (ESA − Lat. 39.24; Long. 141.35), Honululu (HON − Lat. 21.32; Long. 202.00), Fresno (FRN − 37.10; Long. 240.30), Del Rio (DLR − Lat. 29.49; Long. 259.08), Kourou (KOU − Lat. 2.21; Long. 307.27), Ascension Island (ASC − Lat. −7.95; Long. 345.62), Hermanus (HER − Lat. −34.42; Long. 19.23), Addis Ababa (AAE − Lat. 9.02; 38.77), and Tananarive (TAN − Lat. −18.92; Long. 47.55). The geographic longitude of the ground stations is indicated at the left of each curve in

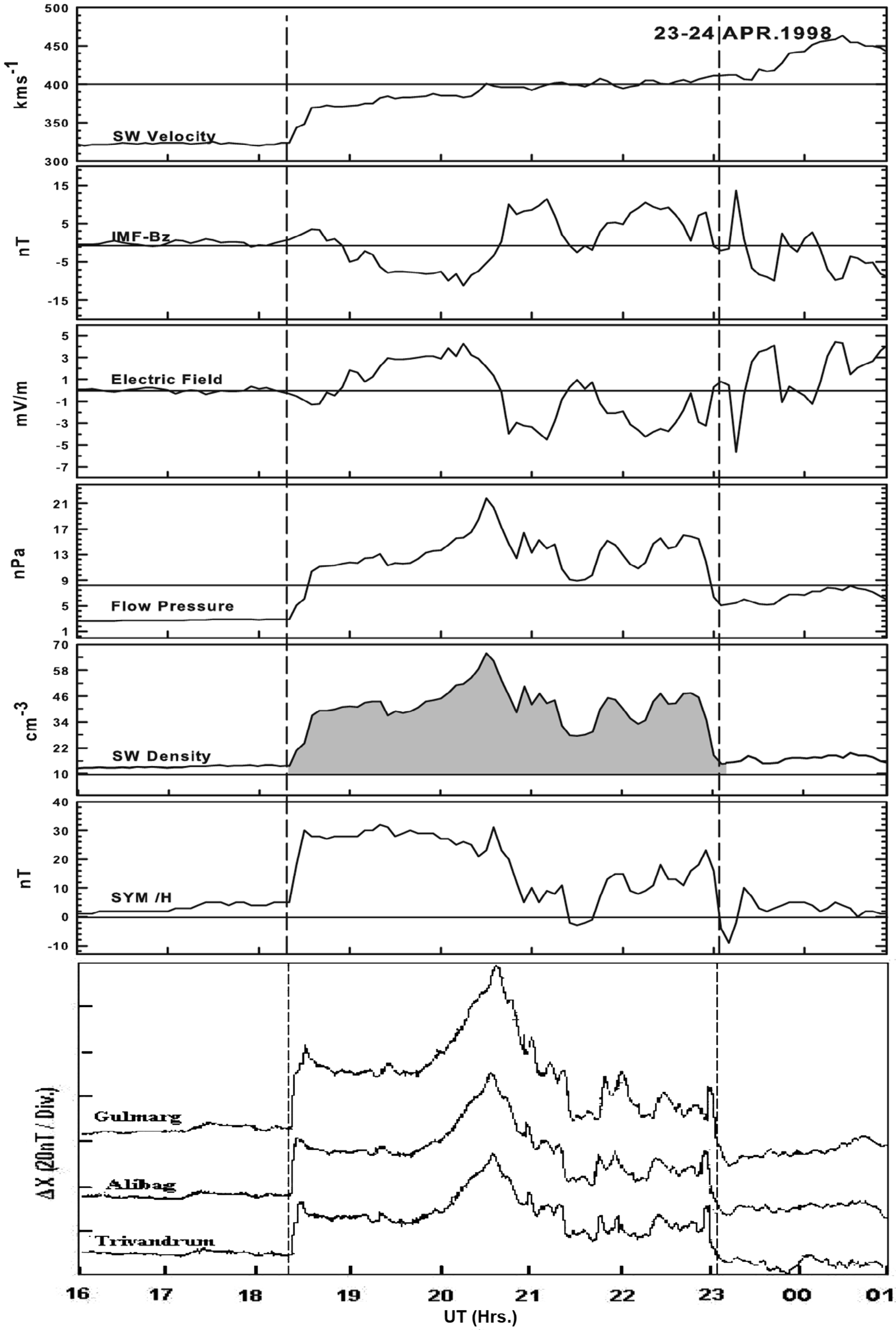

Figure 1. The first six parts starting from the top show the variations as a function of time in UT on 23–24 April 1998 of the solar wind velocity, *Bz*, the electric field, the solar wind flow pressure, the solar wind density (shaded), and the the symmetrical H field, respectively. Observations of the H field at Indian geomagnetic stations Gulmarg, Alibag, and Trivandrum are shown at the bottom. The pair of dashed vertically oriented parallel lines in all parts demarcate the times 1835 UT and 2300 UT. These times correspond, respectively, to the times of the SI^+ impulse and the SI^- impulse in the H field that were observed at Indian stations.

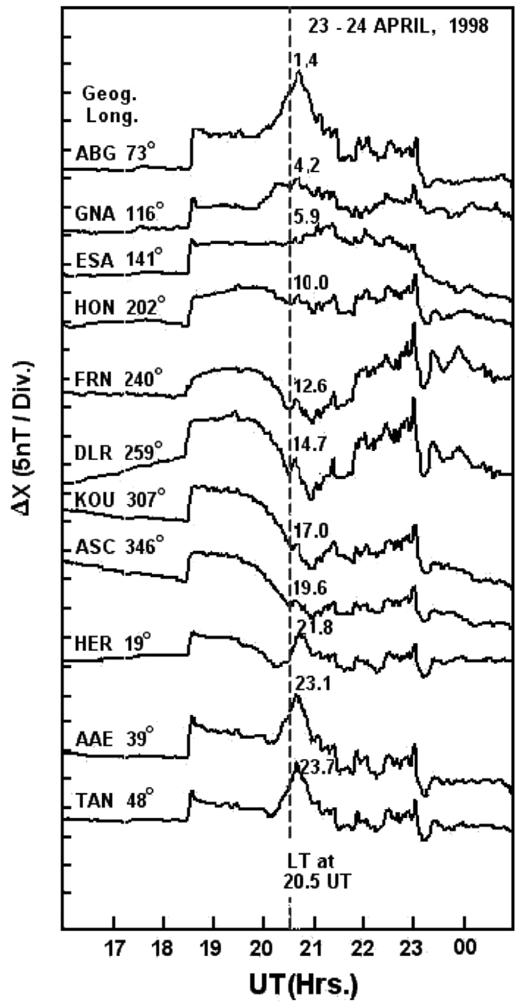

Figure 2. Variation of the horizontal component of the geomagnetic field projected onto the x-direction at 11 low-latitude stations around the world on 23–24 April 1998. The vertical dashed line is marked at 20.5 UT, and shown alongside it, for each curve, is the corresponding local time at each station. Also indicated on the left of each curve is the geographic longitude of the station.

Figure 2. Also indicated to the right of the vertical dashed line (marked at 20.5 hours UT in Figure 2) for each curve is the local time at 20.5 hours UT. The stations chosen range from geographic longitudes of 19° to 346° corresponding to local times of ~22 hours through the midnight, dawn, noon to dusk (20 hours).

[10] The negative IMF-*Bz* between 1835 and 2000 UT caused a decrease of ΔX at stations in the night sectors (HER, AAE, and TAN) and an increase at stations in the midday sector (FRN, DLR, KOU, and ASC). Around 20.50 UT, ΔX showed strong positive peaks at AAE, TAN, and ABG, no change at ESA and HON, and negative peaks at FRN, DLR, and KOU. These data conform very well with the process of prompt penetration and overshielding electric field [*Nishida*, 1968; *Vasyliunas*, 1970; *Rastogi and Patel*, 1975; *Spiro et al.*, 1988] wherein a southward IMF-*Bz* (between 1835 and 2000 UT) would cause a decrease of ΔX at nightside stations and an increase of ΔX at dayside stations of the Earth while a northward turning of IMF-*Bz* would produce a strong positive ΔX at stations in the night sector and negative ΔX at stations in the dayside sector owing to the imposition of either a dusk-to-dawn or dawn-to-dusk electric field. The fluctuations in ΔX between 2130 and 2300 UT are synchronous at all stations in the day as well as in night sectors, suggesting that the effect is due to solar wind flow pressure and not to the IMF-*Bz*. It is important to note here that the solar wind density fluctuations virtually mirror those seen in ΔX at ground stations, thereby implying that the solar wind density was the main key or driver for this event. Qualitatively, the fluctuations seem to be independent of the latitude. The dominant parameter is the solar wind pressure that makes the magnetosphere shrink and expand self-similarly, with some scaling factor depending on the pressure. This is reflected in the magnetic field data at all latitudes and longitudes in a configuration where the IMF appears to have no role to play. Thus, this was a unique space weather event in which one could unambiguously associate solar wind density variations with variations in ΔX at ground stations while no such changes were seen in the solar wind speed or magnetic field.

3. Solar Source Locations

[11] It is well known that owing to the rotation of the Sun ($\Omega = 1.642 \times 10^{-4}$ deg s^{-1}), a radially directed outflow of solar wind from the sun will trace out an Archimedean spiral through the interplanetary medium. For a steady state solar wind with a velocity of 430 km s^{-1}, the tangent to this spiral, at 1 AU, will make an angle of 45° with the radial vector from the Sun [*Schwenn*, 1990]. As a consequence, the longitudinal offset (ϕ_R) of a solar wind stream with a velocity v, when traced backward from a distance R_1 (say, 1 AU) to a distance R_2, will be $\phi_R = \Omega(R_1 - R_2)/v$. We can thus project the observed solar wind velocities back to the Sun to determine the sources of the solar wind flows at the Sun. The earliest instance of using such a technique to trace solar wind outflows back to the sun was by *Rickett* [1975]. For the present event, we have back-projected the observed ACE velocities along Archimedean spirals to the source surface at 2.5 $R_\odot$ to determine its solar source location. Though this method is generally applicable to a steady-state flow of the solar wind, it has also been applied in cases when the solar wind outflows were not steady state and highly nonradial. For example, during the well-known disappearance event of 11 May 1999, the work by *Janardhan et al.* [2005] and *Janardhan* [2006] has shown that solar source locations determined by the traceback technique, using constant velocities along Archimedean spirals, do not have significant errors, even though the solar wind flows were known to be highly nonradial during that period. In the case under discussion, the solar wind flows would have been highly kinked and nonradial due to the propagating forward and reverse shocks arising from the optically occulted flare and the rear side CME. Therefore, if the $SI^+ - SI^-$ pair had a source on the solar disk, the ambiguity about the location of the source region would be within reasonable errors as shown by *Janardhan et al.* [2005] and *Janardhan* [2006]. Figure 3 shows a map of the solar photosphere indicating the locations of the active regions. The back-projected region of the solar wind

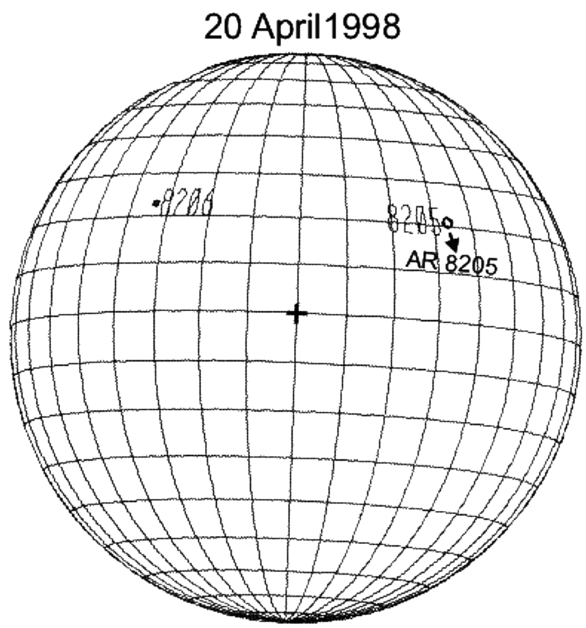

Figure 3. Map of the solar photosphere on 20 April 1998 corresponding to the back-projected region of the solar wind flows observed at 1 AU. The map shows the locations of the large active regions with active region AR8205 indicated by an arrow for convenience.

flows go back to the vicinity of the large active region AR8205 located at N21W25, to the west of central meridian on 20 April 1998 and indicated by a solid arrow in Figure 3. Typically, the solar disk shows a large number of active regions during the rising phase of the solar cycle. A detailed theoretical study by *Schrijver and DeRosa* [2003], has shown that solar wind outflows from active regions comprise ≤10% during solar minimum and up to 30–50% during solar maximum. However, the visible solar disk on 20 April 1998 showed no activity in terms of flares or CMEs and had only two active regions AR8206 and AR8205 as shown in Figure 3. The active region AR8206 was smaller than AR8205, being around 245 millionths of the solar disk in size as compared to 312 millionths of the solar disk for AR8205. Also, AR8205 was less than 30° west of the central meridian as compared to over 40° east of the central meridian for AR8206. It may be noted that a central meridian location would imply that any activity like a large CME or flare would be Earth-directed. However, there was no flare or CME on the entire visible solar disk on 20 April. Images from the Extreme-ultraviolet Imaging Telescope (EIT; *Delaboudinière et al.* [1995]) and the Michelson Doppler Imager (MDI; *Scherrer et al.* [1995]) onboard the Solar and Heliospheric Observatory (SoHO; *Domingo et al.* [1995]) were also examined carefully to confirm that there were no other possible source regions on the solar disk on 20 April 1998.

3.1. The Rear Side CME and Optically Occulted Flare of 20 April 1998

[12] On 20 April 1998, a rear side, fast (~1850 km s^{-1}) partial halo CME occurred in association with an optically occulted GOES M1.4 class flare which took place just behind the limb at S43W90. It must be pointed out here that most forecasters of space weather events generally ignore the possibility that a limb or backside solar explosive event could propagate a disturbance toward the Earth. However, there have been some instances where such cases have been studied and reported in recent times [*McKenna-Lawlor et al.*, 2006; *Smith et al.*, 2009a, 2009b].

[13] The GOES M1.4 flare at S43W90 was first detected in 1–8 Å band at 0915 UT on 20 April 1998 and reached its maximum at 1021 UT. The rear side partial halo CME was first seen in the LASCO coronograph C2, at 1004:51 UT on 20 April 1998, as a bright, sharply defined loop structure spanning ~80° in latitude and extending to ~3.1 $R_\odot$. The same was first observed by C3 at 1045:22 UT. Both the CME and the flare have been extensively studied and reported [*Bastian et al.*, 2001; *Simnett*, 2000, 2002], and it has been shown that the CME, which was radio loud [*Gopalswamy*, 2000], actually pushed aside preexisting streamers while moving beyond the LASCO C3 field of view. Since this was a rear side CME, the shock front that it drove would have been in a direction away from the Earth. In a study of the arrival time of flare-driven shocks at 1 AU and beyond [*Smart and Shea*, 1985; *Janardhan et al.*, 1996], it was assumed that the trailing edges of flare-driven shock waves travel at roughly half the velocity of the shock in the flare radial direction. It is therefore not unreasonable to assume that the trailing edges of the CME-driven reverse shock would be much slower and could be convected outward toward the Earth by the solar wind. The flare and the rear side CME would thus provide the forward and reverse shocks to cause the SI^+ and SI^- pair. Figure 4 shows hourly averaged value of the absolute magnitude of the magnetic field, as observed by the ACE spacecraft, as a function of time in UT. It is expected that the strength of the magnetic field would increase at the forward shock or SI^+ impulse and decrease at the reverse shock or SI^- impulse. It can be easily seen in Figure 4 that there is a sharp increase in the magnetic field at around 1835 UT, corresponding to the

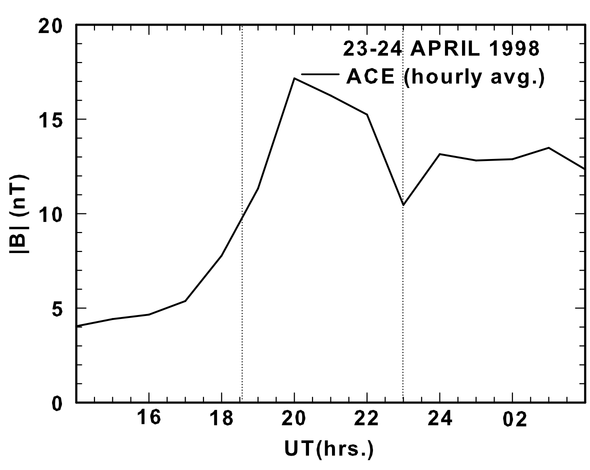

Figure 4. Hourly averaged total magnetic field as a function of time in UT as observed by the ACE spacecraft located at the L1 Lagrangian point at 1 AU. The vertically oriented dashed parallel lines at 1835 UT and 2300 UT correspond to the time of the SI^+ and SI^- impulse, respectively.

arrival of the forward shock associated with the SI^+ impulse, and a decrease in the magnetic field at 2300 UT, corresponding to the arrival of the reverse shock associated with the SI^- impulse. The vertically oriented dashed parallel lines in Figure 4 are marked at 1835 UT and 2300 UT, the time corresponding to the SI^+ and SI^- impulse, respectively.

4. Discussion and Conclusions

[14] From an observational point of view, the present work has been able to link interplanetary structure during this particular event with worldwide magnetospheric response, using the Indian magnetic observatories to provide the first clue. In particular, this event has been unique in that the solar wind density variations have played a key role, as seen through the close correspondence between the fluctuations in the solar wind densities and the ΔX at ground stations while no such changes were seen in the solar wind speed or magnetic field. Though there has been a large body of work over the past four decades that has addressed the issues concerned with forward/reverse shock pairs, their manifestation at 1 AU, and their relation to specific solar events, we believe that this paper presents empirical evidence, which to our knowledge is the most convincing evidence for the association of specific solar events to the observations of an $SI^+ - SI^-$ pair. In addition, it shows that it is possible for a rear side solar event to propagate a shock toward the Earth.

[15] We have seen that the SI^+ impulse 1835 UT was associated with a sudden increase of both the solar wind density and speed causing a sudden pressure on the magnetosphere while the SI^- at 2300 UT was associated with the sudden decrease of solar wind density. The southward IMF-*Bz* between 1835 and 2000 UT caused a decrease of ΔX at nightside stations and a increase of ΔX at dayside stations of the Earth owing to the imposition of a sudden electric field caused by the prompt penetration of electric field to low latitudes. As stated earlier, a northward turning of IMF-*Bz* produces a strong positive ΔX at stations in a night sector and negative ΔX at stations in the day side sector due to the effect of overshield electric field which is in a direction opposite to the normal electric field in the ionosphere. Between 2015 and 2300 UT, the fluctuations in ΔX were similar at all stations in the day or night sectors and were well correlated with the fluctuations in solar wind flow pressure, reflecting the shrinking and expansion of the magnetopause as a result of strong solar wind pressure variation.

[16] The solar event lasting only for some 4–5 hours showed signatures of all mechanisms involving solar-magnetosphere-ionosphere relationships. The arrival at 1 AU of the forward and reverse shock pair associated with the SI^+ and SI^-, respectively, is clearly seen in the behavior of the hourly averaged values of the total magnetic field, which shows a sharp increase at ~1835 UT and a decrease at ~2300 UT. The effect of sudden changes in the solar flow pressure due to a change of only the solar wind density has been clearly identified. The effect of the slowly varying IMF-*Bz* has been shown to impose dusk-to-dawn or dawn-to-dusk electric field globally, depending on the southward or northward turning of the IMF-*Bz*. Though theoretical first-order predictions for the observed distribution of solar wind speed, density, and temperature (as in Figure 1) during the propagation of forward and reverse shock pairs were derived four decades ago [*Dryer*, 1970, 1972], the analysis of the event has been rewarding owing to the relatively quiet solar conditions prevailing as it allowed us to identify specific solar sources as the possible drivers of the SI^+ and SI^- pair. The only activity on the Sun was the rear side CME and the associated solar flare. This is thus a very unique observation wherein a pair of SI events have been shown to be associated with corresponding changes in the solar wind density while no such changes are seen in the solar wind speed or magnetic field. Many more such events need to be observed, retrieved, and studied, both from archival records and future observations, before a clearer understanding of the exact nature and physics behind such events is obtained. High resolution, high dynamic range radio imaging techniques [*Mercier et al.*, 2006] can also provide useful information in this regard.

[17] **Acknowledgments.** The authors thank the two referees for their very constructive suggestions that have gone a long way in improving this paper. One of the authors (JP) thanks Murray Dryer for specific and focused comments. The authors thank J. H. King and N. Papatashvilli, of Adnet Systems, NASA, GSFC, the CDAWeb team, the ACE SWEPAM instrument team, the ACE Science Center, and the EIT and MDI consortia for making data available in the public domain via the World Wide Web. SoHO is a project of international collaboration between ESA and NASA.

[18] Philippa Browning thanks Murray Dryer and another reviewer for their assistance in evaluating this paper.

References

Bastian, T. S., M. Pick, A. Kerdraon, D. Maia, and A. Vourlidas (2001), The coronal mass ejection of 1998 April 20: Direct imaging at radio wavelengths, *Astrophys. J.*, *558*, L65–L69.

Burlaga, L. F. (1970), A reverse hydromagnetic shock in the solar wind, *Cosmic Electrodyn.*, *1*, 233–238.

Delaboudinière, J.-P., et al. (1995), EIT: Extreme-Ultraviolet Imaging Telescope for the SOHO Mission, *Sol. Phys.*, *162*, 291–312.

Detman, T., Z. Smith, M. Dryer, C. D. Fry, C. N. Arge, and V. Pizzo (2006), A hybrid heliospheric modeling system: Background solar wind, *J. Geophys. Res.*, *111*, A07102, doi:10.1029/2005JA011430.

Domingo, V., B. Fleck, and A. I. Poland (1995), The SOHO Mission: An overview, *Sol. Phys.*, *162*, 1–2.

Dryer, M. (1970), Some effects of finite electrical conductivity on solar flare-induced interplanetary shock waves., *Cosmic Electrodyn.*, *1*, 348–370.

Dryer, M. (1972), Interplanetary double-shock ensembles with anomalous electrical conductivity, *Solar Wind 2*, *NASA SP-308* (C. P. Sonett, P. J. Coleman Jr., and J. M. Wilcox, Eds.), *2*, 453.

Dryer, M., Z. K. Smith, T. Unti, J. D. Mihalov, B. F. Smith, J. H. Wolfe, D. S. Colburn, and C. P. Sonett (1975), Pioneer 9 and OGO 5 observations of an interplanetary multiple shock ensemble on February 2, 1969, *J. Geophys. Res.*, *80*, 3225–3234.

Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47–48.

Eviatar, A., and M. Dryer (1970), Finite conductivity and interplanetary piston-driven shock waves, *Cosmic Electrodyn.*, *1*, 371–379.

Fry, C. D., M. Dryer, Z. Smith, W. Sun, C. S. Deehr, and S. Akasofu (2003), Forecasting solar wind structures and shock arrival times using an ensemble of models, *J. Geophys. Res.*, *108*(A2), 1070, doi:10.1029/2002JA009474.

Gold, T. (1959), Motions in the magnetosphere of the Earth, *J. Geophys. Res.*, *64*, 1219–1224, doi:10.1029/JZ064i009p01219.

Goldstein, J., R. W. Spiro, P. H. Reiff, R. A. Wolf, B. R. Sandel, J. W. Freeman, and R. L. Lambour (2002), IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000, *Geophys. Res. Lett.*, *29*(16), 1819, doi:10.1029/2001GL014534.

Goodrich, C. C., J. G. Lyon, M. Wiltberger, R. E. Lopez, and K. Papadopoulos (1998), An overview of the impact of the January 10–11, 1997 magnetic cloud on the magnetosphere via global MHD simulation, *Geophys. Res. Lett.*, *25*, 2537–2540, doi:10.1029/98GL01159.

Gopalswamy, N. (2000), Type II solar radio bursts, in *Radio Astronomy at Long Wavelengths*, edited by R. G. Stone, K. W. Weiler, M. L. Goldstein, & J.-L. Bougeret, p. 123.

Heppner, J. P., and N. C. Maynard (1987), Empirical high-latitude electric field models, *J. Geophys. Res.*, *92*, 4467–4489, doi:10.1029/JA092iA05p04467.

Janardhan, P. (2006), Enigmatic solar wind disappearance events: Do we understand them?, *J. Astrophys. Astron.*, *27*, 193.

Janardhan, P., V. Balasubramanian, S. Ananthakrishnan, M. Dryer, A. Bhatnagar, and P. S. McIntosh (1996), Travelling interplanetary disturbances detected using interplanetary scintillation at 327 MHz, *Sol. Phys.*, *116*, 379–401.

Janardhan, P., K. Fujiki, M. Kojima, M. Tokumaru, and K. Hakamada (2005), Resolving the enigmatic solar wind disappearance event of 11 May 1999, *J. Geophys. Res.*, *110*, A08101, doi:10.1029/2004JA010535.

Janardhan, P., K. Fujiki, H. S. Sawant, M. Kojima, K. Hakamada, and R. Krishnan (2008a), Source regions of solar wind disappearance events, *J. Geophys. Res.*, *113*, A03102, doi:10.1029/2007JA012608.

Janardhan, P., D. Tripathi, and H. E. Mason (2008b), The solar wind disappearance event of 11 May 1999: Source region evolution, *Astron. Astrophys. Lett.*, *448*, L1–L4.

Lazarus, A. J., K. W. Ogilvie, and L. F. Burlaga (1970), Interplanetary shock observations by Mariner 5 and Explorer 34, *Sol. Phys.*, *13*, 232–239.

Lu, G., et al. (1998), Global energy deposition during the January 1997 magnetic cloud event, *J. Geophys. Res.*, *103*, 11,685–11,694, doi:10.1029/98JA00897.

McKenna-Lawlor, S. M. P., M. Dryer, M. D. Kartalev, Z. Smith, C. D. Fry, W. Sun, C. S. Deehr, K. Kecskemety, and K. Kudela (2006), Near real-time predictions of the arrival at Earth of flare-related shocks during Solar Cycle 23, *J. Geophys. Res.*, *111*, A11103, doi:10.1029/2005JA011162.

Mercier, C., P. Subramanian, A. Kerdraon, M. Pick, S. Ananthakrishnan, and P. Janardhan (2006), Combining visibilities from the giant meter-wave radio telescope and the Nancay radio heliograph: High dynamic range snapshot images of the solar corona at 327 MHz, *Astron. Astrophys.*, *447*, 1189–1201.

Nishida, A. (1968), Coherence of geomagnetic DP 2 fluctuations with interplanetary magnetic variations, *J. Geophys. Res.*, *73*, 5549–5559, doi:10.1029/JA073i017p05549.

Odstrcil, D. (2003), Modeling 3-D solar wind structure, *Adv. Space Res.*, *32*, 497–506.

Rastogi, R. G., and V. L. Patel (1975), Effect of the interplanetary magnetic field on the ionosphere over the magnetic equator., *Proceedings of the Indian National Science Academy Part A*, *82*, 121–141.

Razdan, H., D. S. Colburn, and C. P. Sonett (1965), Recurrent $SI^+ - SI^-$ impulse pairs and shock structure in M-region beams, *Planet. Space Sci.*, *13*, 1111.

Rickett, B. J. (1975), Disturbances in the solar wind from IPS measurements in August 1972, *Sol. Phys.*, *43*, 237–247.

Scherrer, P. H., et al. (1995), The solar oscillations investigation: Michelson Doppler Imager, *Sol. Phys.*, *162*, 129–188.

Schrijver, C. J., and M. L. DeRosa (2003), Photospheric and heliospheric magnetic fields, *Sol. Phys.*, *212*, 165–200.

Schwenn, R. (1990), Large-scale structure of the interplanetary medium, in R. Schwenn and E. Marsch, *Physics of the Inner Physics of the Inner Heliosphere 1*(9), pp. 99–181, Springer-Verlag, Berlin.

Senior, C., and M. Blanc (1984), On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities, *J. Geophys. Res.*, *89*, 261–284, doi:10.1029/JA089iA01p00261.

Shen, W. W., and M. Dryer (1972), Magnetohydrodynamic theory for the interaction of an interplanetary double-shock ensemble with the Earth's bow shock, *J. Geophys. Res.*, *77*, 4627–4644, doi:10.1029/JA077i025p04627.

Simnett, G. M. (2000), The relationship between CMEs and prominence eruptions, *JASTP*, *62*, 1479–1487.

Simnett, G. M. (2002), The acceleration and release of solar energetic particles in events from April 20–May 9, 1998, *Adv. Space Res.*, *29*, 1493–1500.

Smart, D. F., and M. A. Shea (1985), A simplified model for timing the arrival of solar flare-initiated shocks, *J. Geophys. Res.*, *90*, 183–190, doi:10.1029/JA090iA01p00183.

Smith, Z. K., M. Dryer, S. M. P. McKenna-Lawlor, C. D. Fry, C. S. Deehr, and W. Sun (2009a), Operational validation of HAFv2's predictions of interplanetary shock arrivals at Earth: Declining phase of Solar Cycle 23, *J. Geophys. Res.*, *114*, A05106, doi:10.1029/2008JA013836.

Smith, Z. K., R. Steenburgh, C. D. Fry, and M. Dryer (2009b), Predictions of interplanetary shock arrivals at Earth: Dependence of forecast outcome on the input parameters, *Space Weather*, *7*, S12005, doi:10.1029/2009SW000500.

Sonett, C. P., and D. S. Colburn (1965), The $SI^+ - SI^-$ pair and interplanetary forward-reverse shock ensembles, *Planet. Space Sci.*, *13*, 675.

Sonett, C. P., D. S. Colburn, L. Davis, E. J. Smith, and P. J. Coleman (1964), Evidence for a collision-free magnetohydrodynamic shock in interplanetary space, *Phys. Rev. Lett.*, *13*, 153–156.

Spiro, R. W., R. A. Wolf, and B. G. Fejer (1988), Penetrating of high-latitude-electric-field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, *6*, 39–49.

Stone, E. C., A. M. Frandsen, R. A. Mewaldt, E. R. Christian, D. Margolies, J. F. Ormes, and F. Snow (1998), The advanced composition explorer, *Space Sci. Rev.*, *86*, 1–22.

Takeuchi, T., T. Araki, A. Viljanen, and J. Watermann (2002), Geomagnetic negative sudden impulses: Interplanetary causes and polarization distribution, *J. Geophys. Res.*, *107*(A7), 1096, doi:10.1029/2001JA900152.

Tóth, G., et al. (2005), Space weather modeling framework: A new tool for the space science community, *J. Geophys. Res.*, *110*, A12226, doi:10.1029/2005JA011126.

Vandegriff, J., K. Wagstaff, G. Ho, and J. Plauger (2005), Forecasting space weather: Predicting interplanetary shocks using neural networks, *Adv. Space Res.*, *36*, 2323–2327.

Vasyliunas, V. M. (1970), Mathematical models of magnetospheric convection and its coupling to the ionosphere, in *Particles and Field in the Magnetosphere*, vol. 17 of *Astrophysics and Space Science Library*, p. 60.

Wolf, R. A., T. W. Garner, J. Goldstein, S. Sazykin, and R. W. Spiro (2001), Storm-time magnetospheric effects on electric fields in the subauroral ionosphere, *AGU Fall Meeting Abstracts*, p. A12.

K. Ahmed, Indian Institute of Geomagnetism, Navi Mumbai, 410218, India.

A. C. Das, S. K. Bisoi, P. Janardhan, and R. G. Rastogi, Physical Research Laboratory, Astronomy & Astrophysics Division, Ahmedabad 380 009, India. (jerry@prl.res.in)