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The cause of an extended recovery of ICME induced extreme geomagnetic storm: a case study

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ABSTRACT

Geomagnetic storms are very crucial phenomena during the severe space weather conditions, which directly or indirectly affect communication, navigation, transportation, power grid, and satellite electronic systems. They are usually caused by coronal mass ejections (CMEs) and/or corotating interaction regions (CIRs) of interplanetary space. The Earth's magnetic shield weakened during the geomagnetic storm which allows interplanetary plasma to penetrate inside the magnetosphere which further affects ionosphere as well as upper atmosphere. Mostly, CMEs generated severe/extreme magnetic storms recovers within one or two days. But, here, we demonstrate a case study of a particular extreme geomagnetic storm caused by CME which depicts a longer recovery phase than usual. The $SYM-H$ index lower down to min ~ -305 nT and recovered to ~ -165 nT within ~ 2.5 hrs. However, further recovery of the storm suddenly slowed down i.e. ($\sim 0.79\ nT/hr$) and eventually took ~ 4.5 days. This typical feature of recovery is not expected with CME induced storms and further threatened us by various hazardous effects. The present study suggests that the possible causing agent for such extended recovery of the storm is Alfvén wave. The study implies that the Alfvén waves are not only extending the recovery time of weak or moderate storms but also contribute to slow down the recovery of severe/extreme storms.

Key words: Coronal mass ejection (CME) – Magnetohydrodynamics (MHD) – Alfvén wave – Geomagnetic storm

1 INTRODUCTION

Geomagnetic storms, which have paramount importance in space weather studies are an extraordinary disturbances in the magnetosphere which is usually defined as variations in ground-based low latitude geomagnetic horizontal field component (Chapman & Bartels 1940; Rostoker & Fälthammar 1967; Tsurutani & Gonzalez 1987; Gonzalez et al. 1994, 1999; Echer & Gonzalez 2004; Echer et al. 2005a,b, 2008; Tsurutani et al. 2006a). During storm time, energetic particles injected in magnetosphere from solar wind have direct access to the Earth's ionosphere and upper atmosphere which can disrupt electronics of the satellites (Laštovička 1996; Shelley et al. 1972; Förster & Jakowski 2000), navigation and telecommunication systems, and high potential power grids that could black out entire city (Rao et al. 2009; Thomson et al. 2005; Foster & Tetenbaum 1991), in fact, their direct and indirect effects can engender threat to the global economy (Oughton et al. 2017).

The southward interplanetary magnetic field (IMF) B_z component in the solar wind is the primary cause of geomagnetic storm (Rostoker & Fälthammar 1967; Gonzalez & Tsurutani 1987; Gonzalez et al. 1994; Tsurutani et al. 1988). The magnetic re-connection between southward directed IMF and northward pointed Earth's magnetic field allows the energy and plasma transfer between solar wind and Earth's magnetosphere (Dungey 1961; Gonzalez & Mozer 1974; Akasofu 1981). In general, on the basis of D_{st} and/or Sym_H index value, geomagnetic storms are divided into three different sets *i.e.* weak ($> -50\ nT$), moderate ($-50\ to\ -100\ nT$), strong/intense ($-100\ to\ -200\ nT$) and severe/extreme ($< -200\ nT$) (Gonzalez et al. 1994, 1999; Gonzalez & Tsurutani 1987; Echer et al. 2008; Tsurutani et al. 1995a; Zhang et al. 2007).

The study of geomagnetic storms dependence on solar cycle is used for clear and better understanding of various sources of geomagnetic storms. During the solar maximum phase, the Sun's activity is highly dominant by erupting coronal mass ejections (CMEs) (Gonzalez et al. 1999; Tsurutani et al. 2006a). The most of the intense and extreme/ severe storms were observed during a solar maximum phase, which were often associated with the interplanetary CMEs (ICMEs) (Gonzalez et al. 1999; Tsurutani et al. 1992, 1988; Zhang et al. 2007; Echer et al. 2008). The ICMEs have two distinct sub-structure i.e. magnetic clouds and sheath region which also

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modulates cosmic rays intensity. (Gonzalez et al. 1999; Pulkkinen et al. 2007; Huttunen et al. 2006; Raghav et al. 2014, 2017; Shaikh et al. 2017, 2018). Out of these, magnetic clouds have slowly varying magnetic field, low plasma temperature, plasma beta, and dynamic pressure whereas ICME sheath often have highly fluctuating fields and high plasma temperature, plasma beta, and dynamic pressure (Gonzalez et al. 1999; Tsurutani & Gonzalez 1995; Farrugia et al. 1993; Choe et al. 1992; Pulkkinen et al. 2007). In contrary *i.e.* during the solar minimum, polar coronal holes are dominant and play major role in the interplanetary space (Gonzalez et al. 1999; Tsurutani et al. 2006a). Coronal holes generates regions of high speed streams (HSSs) (Phillips et al. 1995; Gonzalez et al. 1999; Burlaga & Lepping 1977; Sheeley et al. 1976; Tsurutani et al. 2006a). Their interaction with slow solar wind streams induces co-rotating interaction regions (CIRs) whose further interaction with magnetosphere cause weaker and moderate recurrent geomagnetic storms (Burlaga & Lepping 1977; Gonzalez et al. 1999; Sharp et al. 1976; Tsurutani et al. 1995b; Echer et al. 2008; De Lucas et al. 2007; Yermolaev et al. 2018). In summary, literature suggest that the CIRs and ICME substructures (i.e., magnetic cloud and shock-sheath) are the major drivers of geomagnetic storm, see few papers, for instance, by Tsurutani & Gonzalez (1997); Gonzalez et al. (1999); Zhang et al. (2007); Yermolaev et al. (2010a); Tsurutani & Gonzalez (1997); Gonzalez et al. (1999); Yermolaev & Yermolaev (2006); Zhang et al. (2007); Turner et al. (2009); Yermolaev et al. (2012b, 2010b, 2011); Nikolaeva et al. (2011); Gonzalez et al. (2011); Guo et al. (2011) and references therein.

The geomagnetic storm profile are separated into three different phases. The storm usually starts with a sudden increase in the Earth's magnetic field considered as sudden shock commencement or initial phase. The interval of a large decrease in the $Dst/SYM-H$ index represents the main phase *i.e.* period following the initial phase which is usually of few hours to one day (Dessler & Parker 1959; Gonzalez et al. 1994). The main phase is followed by a recovery phase in which the Earth's magnetic field return to normal condition. It is relief of main phase stress through the transfer of energy of trapped protons to the neutral atmospheric hydrogen atoms i.e. ion-atom charge exchange process (Dessler & Parker 1959). However, it is important to note that the storm recovery is highly complex mechanism in which one side ring current losing its particles via charge exchange process, wave-particle interaction, coulomb collisions etc. whereas on the other hand, the continuous particle/energy pumping into the ring current which extends the recovery phase of the storm (Gonzalez et al. 1994; Fok et al. 1995; Jordanova et al. 1997; Søraas et al. 2004; Tsurutani et al. 2006a; Miyoshi et al. 2003; Kasahara et al. 2009).

The prediction of time corresponding to the minimum value that the Dst index will reach is the main goal of the geomagnetic storm forecasting research. However, many technological applications rely on the expected time of the disturbed magnetosphere returning to quiet time conditions. These predictions are even more important for extreme/severe geomagnetic storms (Cid et al. 2014). In literature, a linear proportional relation is expected between the decay rate of ring current and Dst index through the Dessler-Parker-Sckopke relationship (Olbert et al. 1968; Greenspan & Hamilton 2000). Therefore, exponential function was accepted to fit the recovery phase Dst index data to find the decay time of the storm, *e.g.*, (Burton et al. 1975; Hamilton et al. 1988; Ebihara & Ejiri 1998; O'Brien & McPherron 2000; Dasso et al. 2002; Kozyra et al. 2002; Wang et al. 2003; Weygand & McPherron 2006; Monreal MacMahon & Llop-Romero 2008). In few cases, the decay time was expected to be a constant value (Burton et al. 1975). Moreover, in some cases, this was dependent on the convective electric field E_y (O'Brien & McPherron 2000), or also dependent on the dynamic pressure (Wang et al. 2003). However, the intense and/or extreme storms shows two-phase recovery profile, *i.e.*, early fast recovery phase followed by slow recovery. Therefore, it was difficult to model the observational data assuming a unique exponential function (Akasofu et al. 1963; Hamilton et al. 1988; Gonzalez et al. 1989; Prigancová & Feldstein 1992; Liemohn et al. 1999; Monreal MacMahon & Llop-Romero 2008). This issue was resolved by assuming hyperbolic decay function (Aguado et al. 2010; Cid et al. 2014). In this model the entire recovery phase dependent on two parameters, i.e., minimum Dst value (D_{st0}, the intensity of the storm or the value of D_{st} index when the recovery phase starts) and the recovery time (τ_h, the time to get the value of $D_{st0}/2$). A superposed epoch analysis of recovery phases of intense storms from 1963 to 2003 suggest that the hyperbolic decay function reproduces experimental data better than what the exponential function does for any types of storms, which indicates a nonlinear coupling between decay rate of D_{st} and D_{st} (Aguado et al. 2010; Cid et al. 2014).

Generally, recovery phase takes one to two days or sometimes more than two days which depends on the source of magnetic storm (Dessler & Parker 1959; Gonzalez et al. 1994; Tsurutani et al. 2006a; Kozyra et al. 1997). ICMEs generate extreme storms with an exponential / hyperbolic profile of recovery phase of one or two days whereas the CIR and high-speed stream (HSS) driven magnetic storms can last from a few days up to a few weeks (Tsurutani et al. 2006a; Aguado et al. 2010). Most probably, the Alfvénic fluctuations embedded within CIRs as well as the HSSs that trail the CIR triggered the magnetic re-connection between the Alfvén waves embedded magnetic field and the magnetospheric fields which slowly inject solar wind energy and plasma into the magnetosphere, which slow down the recovery rate and causes the extended recoveries of the storms (Tsurutani et al. 2006a, 1995a). The extended recovery phase during ICME induced geomagnetic storms are highly intriguing. Recently, Raghav et al. (2018) observed Alfvén wave in a magnetic cloud of ICME and suggest that they significantly control the dynamics of the moderate magnetic storm ($\sim -30\ nT$) and responsible for the extended recovery. However, the physical mechanism involves in the extended recovery of severe /extreme magnetic storms are ambiguous to date. In light of the aforementioned discussion, we search the signature of Alfvén wave in a magnetic cloud of ICME which causes extreme geomagnetic storm event and has extended recovery phase. For the selected case study, we also investigate the effect of Alfvén wave embedded magnetic cloud and trailing solar wind on the exponential or hyperbolic recovery profile of the extreme storm.

EVENT DETAILS

The studied event is a severe /extreme geomagnetic storm ($SYM-H = -305$ nT) occurred on 15^{th} May 2005 which was induced by CME erupted on May 13, 2005 (Yurchyshyn et al. 2006). The geomagnetic pulsations are studied during the initial phase of the storm (Kozyreva & Kleimenova 2007). The ionospheric response during the storm is investigated in detail for the Brazilian sector, South African sector and Indian regional sector (De Abreu et al. 2011; Ngwira et al. 2012; Sastri et al. 2002). The large enhancements in total electron content (TEC) is observed during the storm which is a cause of concern for satellite-based navigation and ground positioning. Further, the modulations in TEC confirms the presence of traveling atmospheric disturbance over a wide range of longitudes

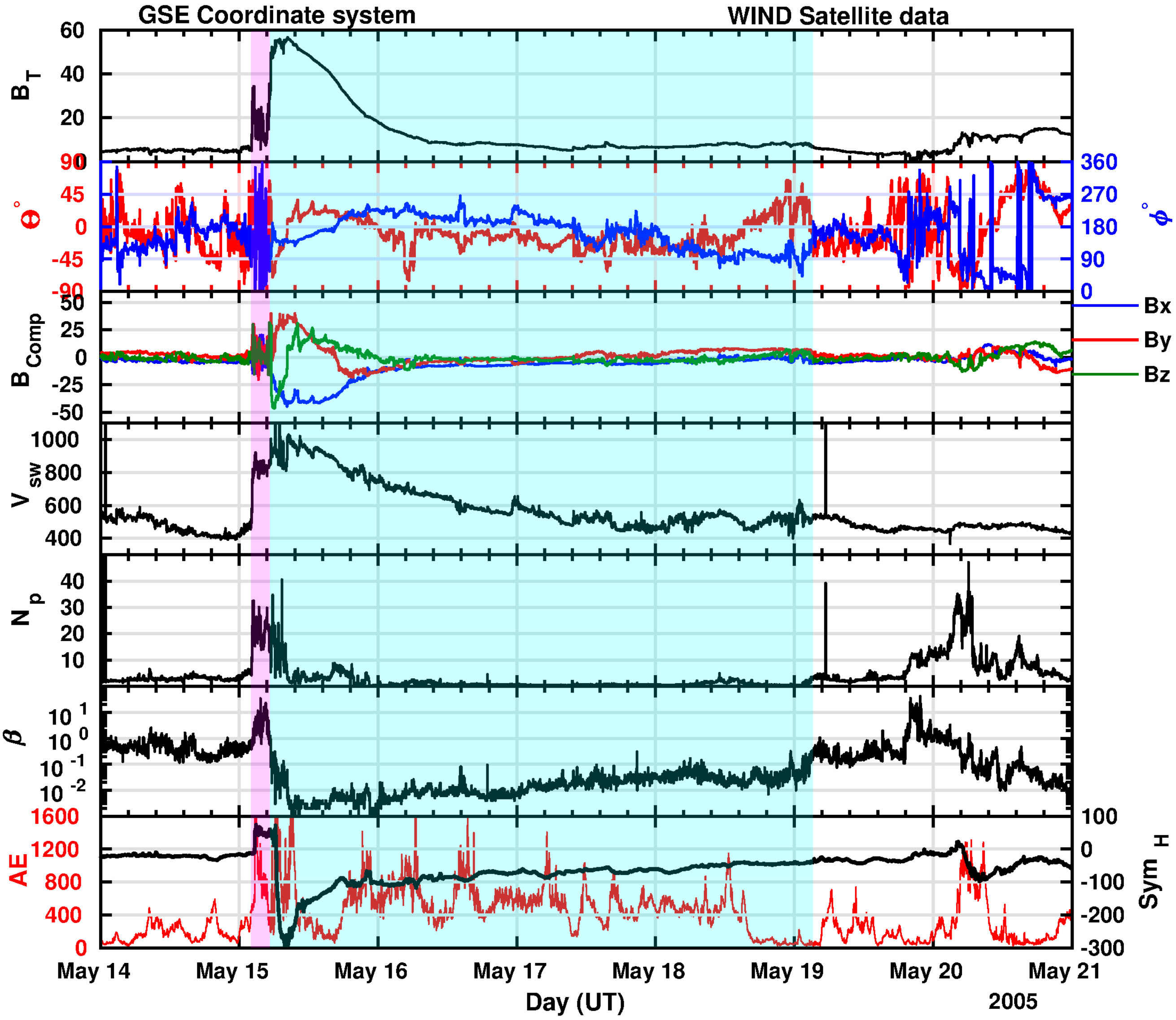

Figure 1. *From top to the bottom, the first panel shows the magnetic field strength ($|B|$), the second panel shows angle θ and ϕ. The third, fourth, and fifth panel show the vector components of the magnetic field, solar wind speed, proton density in GSE coordinate system respectively. The sixth panel shows the plasma beta profile(data taken from Wind satellite with time cadence of 92 sec). The bottom panel shows $SYM-H$ and AE index(data taken from Omni database with 60 sec time resolution). The pink shaded region represents ICME sheath and the cyan shaded region is the magnetic cloud of ICME.*

(Sharma et al. 2011). In fact, the dynamics of energetic electrons and protons of the outer radiation belt during the storm is analyzed (Tverskaya et al. 2007).

The Figure 1 demonstrate the temporal evolution of the interplanetary magnetic field (IMF) and plasma parameters measured by Wind spacecraft. The total IMF B_T, solar wind speed V_{sw}, proton density N_p show a sharp enhancement on 15^{th} May suggesting the arrival of shock front at spacecraft. In general, the presence of the shock should be confirmed with Rankine-Hugoniot relation. The CfA Interplanetary Shock Database available at `https://www.cfa.harvard.edu/shocks/wi_data/00398/wi_00398.html` validates the observations. In this database, various methods are utilized to estimate the shock characteristics. The average shock normal angle (θ_{Bn}) is about 82.1 degree. High fluctuations are observed in IMF components, IMF orientation, plasma density and plasma β which interpreted as ICME sheath region(see, pink shaded region). The excess speed of magnetic cloud of ICME generates the shock front whereas the sheath region developed due to the high compression of plasma between shock-front and magnetic cloud. The slow and gradual decrease in total IMF and its components, slow rotation of IMF orientation, gradual and steady decrease in solar wind speed, and proton density and low plasma β are the characteristics of a magnetic cloud of the ICME which are clearly seen in Figure 1 (see cyan shaded region). The sharp enhancement is also observed in $SYM-H$ index with an approximately half hour of delay with shock front which is explained on the basis of the distance of spacecraft from bow-shock of the Earth which further interpreted as a sudden commencement of shock. The sharp and step decrease to −305 nT is observed in the $SYM-H$ index associated with the onset of a magnetic cloud. This indicates the main phase of the extreme geomagnetic storm. The main phase is followed by a fast recovery up to −165 nT within ∼ 2.5 hrs. However, the recovery rate suddenly slowed down to ∼ 0.76 nT/hr (the rate is estimated for 16 to 20 May 2005 $SYM-H$ data) such that the complete recovery lasted for ∼ 4.5 days which leads to the long duration strong, moderate and weak storm like conditions.

IDENTIFICATION OF ALFVÉN WAVE

Non-compressible Magnetohydrodynamic fluctuations *i.e.* Alfvén wave are primal fluctuations in magnetize plasma. In this, the magnetic field and particle fluctuations are perpendicular to the background field direction and their motion is along the magnetic field tension force. The recent work associated with Alfvén wave in solar wind employed Walén relation to identifying them which is described as (Walén 1944; Hudson 1971)

$$V_A = \pm A \frac{B}{\sqrt{\mu_0 \rho}} \tag{1}$$

where A is the anisotropy parameter, B is magnetic field vector and ρ is proton mass density. In the solar wind, the negligible thermal anisotropy leads to $A = \pm 1$ (Yang et al. 2016; Raghav et al. 2018; Raghav & Kule 2018a,b).

In Walén test, proper estimation of background magnetic field is important. But, it is not an observable quantity and therefore the average value of de Hoffmann-Teller (HT) frame or the mean value of the magnetic field is utilized (Raghav & Kule 2018a; Raghav et al. 2018; Raghav & Kule 2018b; Yang & Chao 2013; Gosling et al. 2010). However, HT frame can change in high-speed solar wind streams and the solar wind fluctuations are pertinent to a slow varying base value of magnetic field (Gosling et al. 2009; Li et al. 2016). Therefore, to minimize the uncertainties in Alfvén wave identification, we apply the bandpass-filters to the plasma velocity and magnetic field observations. The evenly divided 10 logarithmic frequency bands are selected. The possible filters are 10s-15s, 15s-25s, 25s-40s, 40s-60s, 60s-100s, 100s-160s, 160s-250s, 250s-400s, 400s-630s, and 630s-1000s. The Walén relation for each band-passed signal is diagnosed as follows:

$$V_i = \pm V_{Ai} \tag{2}$$

Here V_i and V_{Ai} are the band-passed V and V_A components with the i^{th} filter. The significant value of correlation coefficient of respective components of V_i and V_{Ai} confirms the existence of Alfvén wave or Alfénic fluctuations in the region of examination. The + or − signs, express the propagation parallel and anti-parallel to the background magnetic field respectively. The similar approach is utilized by Li et al. (2016). The complete region under study is divided in the sub-regions (each with 30 minute of time window). The Figure 2 show the contour plot of frequency-time distribution with bin size of 30 min. Here, the absulute value of correlation coefficient of each sub-region are displayed as color map on the contour plot. The correlation coefficient > 0.65 are included in the map whereas the lower values are explicitly discarded. Therefore, the color-strips in the contour-map of Figure 2 represents existence of dominant Alfvénic flow along the x-, y-, and z-components.

RESULT

Here, we studied the extreme geomagnetic storm ($SYM-H(min) = -305\ nT$) induced by ICME. Generally, ICMEs generated geomagnetic storms recovery phases are of few hours to maximum one day or rarely two days (Tsurutani et al. 2006a), but we observed extended recovery phase of extreme storm *i.e.* ∼ 4.5 days. Interestingly, we noticed the correlated variations in magnetic and solar wind velocity components (not shown here). The detail investigation employing filters to velocity and magnetic field observations indicate presence of Alfvén waves in the magnetic cloud corresponding to the extended recovery phase. Alfvénic fluctuations are identified in solar wind *i.e.* well before the onset of shock. It is important to note that the Alfvénic fluctuations are weak or absent in ICME-sheath region (on 15 May 2004, 2:40 to 06:18 UT) and in the front edge of magnetic cloud region (on 15 May 2004, 06:18 to 10:00 UT). As the magnetic cloud crosses the spacecraft, the Alfvénic nature in lower frequency domain significantly appeared. The strong Alfvénic behavior clearly observed from 17 May 2004 to 20 May 2004. However, for small time interval the Alfvénic nature reduces. Certainly, it appears that the Alfvénic nature is dominant in the trailing solar wind as well. The $Sym-H$ index variations show gradual recovery corresponding to the interplanetary region in which the Alfvénic fluctuations are present either weak and/or strong. Here we opine that in current analysis, the frequency domain between 10^{-1} Hz to 10^{-3} Hz is considered. However, lower frequency domain i.e. high wavelength Alfvén waves are not considered. Figure 2 also indicate that the region which display weak Alfvén fluctuation, the Alfvénicity is increase from higher frequency to lower frequency domain. It also possible that the lower frequency Alfvén wave may have existence through out the magnetic cloud.

MODEL FIT

The studied storm event demonstrates two phase recovery profile i.e. fast and slow. To study the features of extended recovery profile, exponential decay, hyperbolic decay, and linear (constant decay rate) equation were fitted to the recovery phase of the storm as suggested in literature (see top panel of Figure 3). The fast recovery phase of the storm clearly replicate by exponential as well as hyperbolic decay function, however both the functions significantly deviated from the actual data during slow recovery phase (see bottom panel of Figure 3). The value of τ for exponential decay is 11.11 hr where as for hyperbolic decay it is 9.09 hr. The τ value for exponential decay represent time requires to reduce the initial value of the Dst index (minimum value) to its $1/e$ value. Moreover the τ value for hyperbolic decay represent time requires to reduce the initial value of the Dst index to its $1/2$ value. It implies that the derived value of τ using both the functions are consistent with each other during fast recovery phase. The maximum deviation for exponential decay is ∼ 100% where as for hyperbolic decay is more than ∼ 50% during slow recovery phase. The constant recovery rate i.e. 0.79 nT/hr (linear fit) is clearly observed during slow recovery phase with minimum deviation as compare to other two decay functions. The significant deviation of any of the decay function in slow recovery phase imply that there would be either a constant plasma energy/particle injection to the magnetosphere or there may be a physical mechanism which slow down the decay rate of the ring current. We believe that the identification of Alfvén wave corresponding to the slow recovery phase could be the possible source. The more detailed study is needed in this direction.

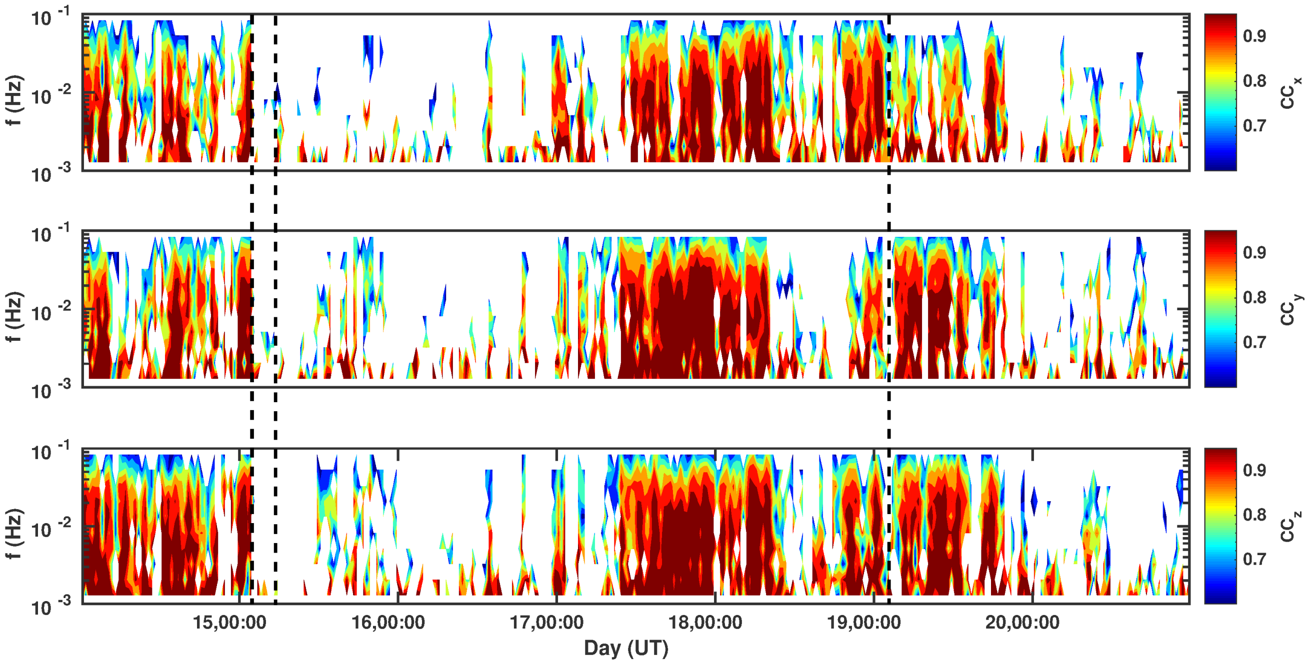

Figure 2. *Time-frequency distribution of correlation coefficient between V_{Ai} and V_i for complete event. The vertical dash line indicate the ICME sheath and magnetic cloud boundaries. Wind satellite* 3*s observations are utilized for the analysis.*

Moreover, we have also found similar extended recovery during the extreme storm occurred on 17 March 2015 and 26 June 2014 (not shown here).

DISCUSSION AND CONCLUSION

In the geomagnetic storm, ring current formation and decay is the key element (Daglis et al. 1999; Keika et al. 2006). The solar wind and terrestrial ionosphere are the ultimate main sources of ring current particles Stern (2005). Prominently, ring current decay occurs due to charge exchange with exospheric neutrals, wave- particle interaction and Coulomb collisions with thermal plasma (Daglis et al. 1996; Yermolaev et al. 2012a; Keika et al. 2006). Since neutralized ring current particles can escape the inner magnetosphere trapping region, charge exchange acts as a major loss mechanism for ring current and it must consider carefully in any ring current decay model Daglis et al. (1999); Keika et al. (2006). Intense plasma waves provide a mechanism for energy transfer between various components of plasma. Moreover, thermal heavy ions plasma and Alfvén waves are particularly important for heating mechanism (Gendrin & Roux 1980; Horne & Thorne 1997; Mauk 1982; Anderson & Fuselier 1994). In fact, polar observations by W1 provide evidence that Alfvénic Poynting flux is responsible for transferring the power needed for acceleration of all the energized auroral partical populations accelerated into the ionosphere and also streaming out into the magnetosphere (Wygant et al. 2002; Volokitin & Dubinin 1989). Besides this, high-speed stream/CIR induced magnetic storms show long recovery phase, in which it is suggested that the sporadic electron injections sustain the ring current is driven by Alfvén waves (Kasahara et al. 2009; Tsurutani et al. 2006a). Moreover, Raghav et al., 2018 suggest that Alfvén waves embedded in ICME magnetic cloud are also responsible for the extended recovery of the moderate geomagnetic storm. In light of the aforementioned result and discussion, the present study clearly demonstrates that the presence of Alfvénic fluctuations can also slow down the recovery of an extreme/severe storm (considering the analogy with past reported studies) which drastically leads to increase the geomagnetic storm threat in all perspective.

The storms with long recovery phases could be accounted in another special category *i.e.* High Intensity Long Duration Continuous AE Activity (HILDCAA) events (Tsurutani & Gonzalez 1987; Tsurutani et al. 2006a; Guarnieri et al. 2006). There are conditions for the identification of HILDCAA events *i.e.* AE index must reach at least 1000 nT, it should not fall below 200 nT for more than 2 hours and the condition must persist for at least two days (should not consider the main phase of magnetic storms). The HILDCAA events associated with generation of magnetospheric relativistic electron acceleration (Paulikas & Blake 1979; Baker et al. 1986; Meredith et al. 2003; Tsurutani et al. 2006a,b; Hajra et al. 2013, 2014a,b). The most of these events occur in recovery phase of CIR generated storms and comparatively very few events occur in the ICMEs induced events (Guarnieri et al. 2006; Hajra et al. 2014b). Our study also indicate that the present ICME event is also the possible candidate for HILDCAA event (see *AE* index in figure 1).

IMPORTANCE AND IMPLICATION

The investigation of extended recovery phase of the storm is important and have strong implications. During the magnetically disturbed period, the flux of relativistic electron's (energy range MeV) shows dynamic variations (Daglis et al. 1999). There are arguments that particles are not produced by the main phase but produced by extended recovery phase (Miyoshi et al. 2003; Daglis et al. 1999). In fact, atmospheric losses of relativistic electrons are more intense

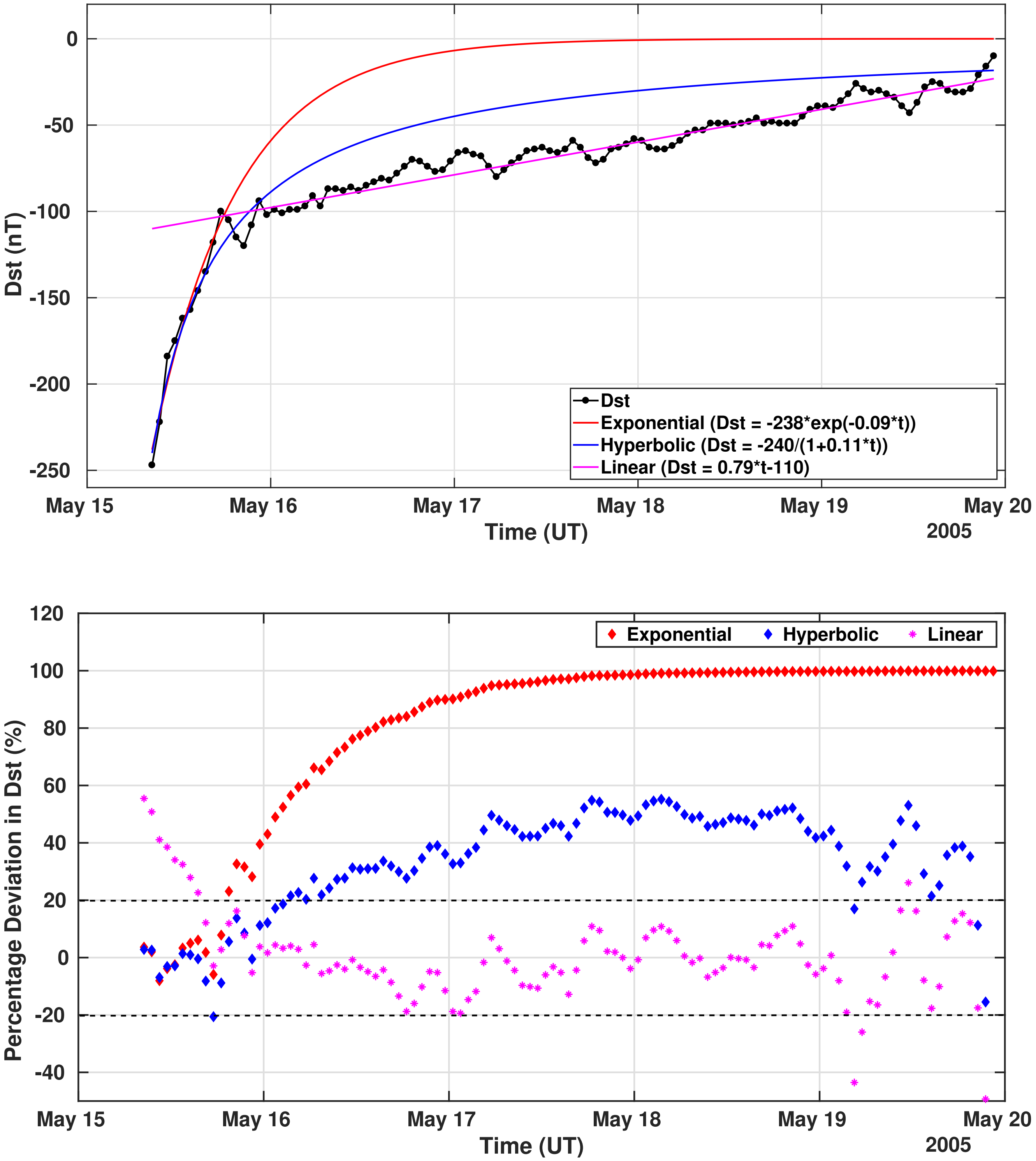

Figure 3. *Top panel shows temporal variation of D_{st} index with exponential, hyperbolic, and linear fitting of recovery phase of the studied storm. Bottom panel demonstrates deviation of each model fit values with observational Dst index.*

during the long recovery phases than the fast recovery phases (Wang et al. 2016; Sandanger et al. 2009). Besides this, high-m poloidal waves are observed during the recovery phase of 22^{nd} June 2015 magnetic storm (Le et al. 2017). These waves can exchange energy with energetic particles and therefore it is important to the dynamics of inner magnetosphere (Zong et al. 2009; Le et al. 2017).

The Electromagnetic Ion Cyclotron (EMIC) waves occur during the main phase as well as in the recovery phase of the storms (Cornwall et al. 1970; Denton et al. 2014; Fraser & Nguyen 2001; Kawamura et al. 1982; Wang et al. 2016). The geomagnetic pulsations PC1 and PC2 are rarely observed on ground during main and early recovery phase but as the recovery phase progresses, these waves increasingly observed (Engebretson et al. 2008; Wang et al. 2016).

We opine that the magnetosphere investigation during similar interplanetary condition may unfold the mystery of how Alfvénic fluctuations affect the ring current acceleration and decay processes. We will definitely pursue the zeal of this investigation in the future. In Alfvén waves, plasma particles move along the field lines, therefore, we opine that interplanetary field re-connection with Earth's magnetic field provides direct access to plasma particles with minimum resistance (which possibly advance the particle diffusion in a magnetic field) even-though B_z fluctuating near zero. In summary, we suggest that the extreme/severe storms create hazardous scenarios in many ways and their extended recovery phase adds burning fuel to it. There are various physical phenomena materialize during the recovery phase of the magnetic storm which establishes the importance of the present study.

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