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Determination of Magnetic Reconnections in a Low and a High Activity Year

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Authors' contributions

This work was carried out in collaboration between both authors. Author GIO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author IAA managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

When there is a temporary disturbance of earth's magnetosphere, then a geomagnetic storm (or solar storm) has occurred. It is caused by a solar wind shock wave and/or cloud of a magnetic field that interacts with the Earth's magnetic fields. The interaction of Interplanetary Magnetic Fields (IMF) of the sun [1] with the earth's magnetic fields in opposite directions is known as magnetic reconnection. Magnetic reconnection (often referred as "reconnection") is the breaking and reconnecting of oppositely directed magnetic field lines in plasma at a neutral point which leads to converting the magnetic field energy into plasma kinetic and thermal energy. It occurs either in the day-time (day reconnection) where the sunward convection near the polar cusps allows energised particles to be transmitted earthward or night-time (tail reconnection) where particles are injected into the magnetosphere, thus releasing stored energy in the form of auroral substorms. A geostorm can be determined by changes in the Disturbance-storm time (Dst) Sokolov [2]. However not all geomagnetic storms have an initial phase and not all sudden increases in Dst

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or SYM-H are followed by a geomagnetic storm. This paper attempts to determine when the magnetic reconnection occurs in the solar cycle 24 considering a low activity year 2009 and a high activity year 2012. We analysed 39 and 202 geomagnetic storms in 2009 and 2012 respectively considering the Dst indices and IMF Bz values of each month obtained from the OMNIWeb database. Our results showed that storms were frequent and intense at high levels of solar activity due to the frequent occurrence of CMEs and ICMEs in the year 2012 than in the year 2009 which occurred in 10% and 45% of days in the year 2009 and 2012 respectively. This study also revealed that negative Bz occurrences were 47.54% and 52.18% of Bz occurrences in 2009 and 2012 respectively. Thus, the more intense the geostorms, the more Bz would go south and the more magnetic reconnection and subsequently auroral substorms which can increase radiation doses for occupants of transpolar flights, disruption of shortwave radio communications, distortion of compass readings in polar regions, failure of electrical transmission lines, increased corrosion in long pipelines, anomalies in the operations of communications satellites, and potentially lethal doses of radiation for astronauts in interplanetary spacecraft.

Keywords: Interplanetary magnetic fields; solar cycle 24; disrupt radio communications; magnetic reconnection; plasmoid.

1. INTRODUCTION

The disruption of electric power distribution grids, satellite operations, communication, navigation and a variety of socio-eco-technological losses are caused by adverse space conditions [3-9]. These conditions are results of magnetospheric reconnections both at the bow shock and magnetotail when the Bz component in the geocentric solar measurement (GSM) coordinate system of the interplanetary magnetic field (IMF) turns south. The near-earth magnetic cloud (plasmoid) formed after the magnetospheric reconnection, carries the amount of solar wind energy to be transferred to the earth's magnetosphere. Gonzalez et al*.,* (1994), Sugiura et al*.,* (1991) and Sokolov [2] established that changes in the Disturbance-Storm Time (Dst) index can be used to define a geomagnetic storm. The Dst index evaluates the globally averaged change of the horizontal component (one-minute SYM-H component) of the magnetic field of the earth at the magnetic equator based on measurements from a few magnetometer ground stations. The Dst index is calculated once per hour and conveyed in near-real-time. The values of Dst during quiet times range from +20 to −20 nano-Tesla (nT). Gonzalez et al*.,* (1994) further stated that there are three phases in a geomagnetic storm which are initial, main and recovery phases. The initial phase often referred to as storm sudden commencement (SSC) is trademarked by Dst with values from -20 to -50 nT occurring in tens of minutes. Conversely, not all geomagnetic storms have an initial phase and not all sudden increases in Dst or SYM-H are followed by a geomagnetic storm. The Dst values in the main phase of a geomagnetic storm begin from −50 nT with a duration of 2 – 8 hours. Anyway, the selection of −50 nT to define a storm is rather arbitrary. The minimum value of Dst during a storm is between −50 and approximately −600 nT. During the recovery phase, the values of Dst changes from its minimum value to its quiet time value which does last from 8 hours to 7 days. Cander et al*.,* (1998) stipulated that during the main phase, the size of a geomagnetic storm is classified as moderate (−50 nT > minimum of Dst > −100 nT), intense (−100 nT > minimum Dst > −250 nT) or super-storm (minimum of Dst < −250 nT).

The intense southward IMF Bz is associated with two types of origins [10]. The first type has an intrinsic solar origin. The southward IMF Bz events are just a part of the internal magnetic field in the ejected plasmas from the Sun. These ejected plasmas may be identified as one of the solar eruptive phenomena: Coronal Mass Emission (CME), flare ejecta, eruptive filament or prominence, etc., which all may be called "ejecta" [11,12]. The ejecta does not imply a particular shape or magnetic topology nor refer to a solar region. The term "ejecta" applies to any parcel of the solar wind with "unusual" characteristics that result from a transient solar event. The other type of source has an interplanetary origin. Several physical processes in the solar wind have been suggested to generate the southward IMF Bz events. The draped interplanetary magnetic field [13], kinky heliospheric current sheets [14-16] and compressions of plasma and magnetic field fluctuations in the corotating interaction regions [17] are examples of this type. The temporal evolution of Alfven intermittent turbulence in the corotating interaction region may become unstable and generate large IMF Bz [18].

Although the source or the origins of southward IMF Bz still need further investigation, quantitative prediction of southward IMF Bz has been attempted [19-21]. The intense IMF Bz inside a magnetic cloud (or driver gas) are solar source originated and that outside a magnetic cloud is mainly caused by IMF draping and shock compression [22]. This paper attempts to determine the magnetospheric reconnection which precedes the occurrence of geomagnetic storms whether it be SSC, moderate or intense.

Magnetism plays one of the most significant roles in determining the interactions between the solar wind and the earth. In addition to carrying solar particles away from the Sun, the solar wind blows the magnetic field of the Sun out to the rest of the solar system. The Sun's extended magnetic field is called the interplanetary magnetic field (IMF) which interacts with the region of space around the earth's magnetosphere [23]. Typical magnets can attract or repel depending on how they are lined up to one another. Interactions between the IMF carried by the solar wind and earth's magnetosphere are similarly dependent on how the directions of their magnetic field lines line up relative to each other. The IMF is a vector quantity with a three-axis component, two of which (Bx and By) are orientated parallel to the ecliptic which is not important for auroral activity. The third component, the Bz value is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind as shown in Fig. 1 below.

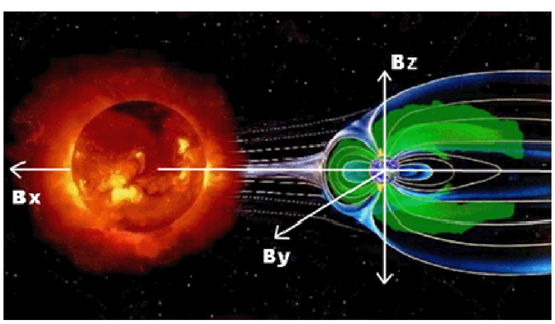

Fig. 1. The connection between the IMF and the earth's magnetosphere
Source: NASA

The magnetic field strength, in general, is denoted as B, and Bz refers to the strength of the magnetic field in the north-south direction. If the Bz of the Coronal Mass Ejection (CME) is northward (recorded as positive values in the ACE data) then the IMF lines are pointing in the same direction as earth's magnetic field lines. As a result, the interaction between the two sets of field lines is minimal and auroral activity is also minimal. If the Bz is southward (recorded as negative values in the ACE data), then the IMF field lines are pointing in the opposite direction as earth's magnetic field lines. When this alignment occurs, it allows for the reconfiguration of earth's magnetic field lines by an energy transfer process called magnetic reconnection. Southward Bz acts in such a way to "peel" the magnetic field lines from the sun-side of earth's magnetosphere and layer them on the night-side, in the magnetosphere's long tail. A larger southward Bz value allows for a more effective energy transfer from the sun's magnetic field lines to the earth's and this creates a more vibrant aurora. The magnetic field of the sun doesn't stay around the sun itself. The solar wind carries it through the solar system until it reaches the heliopause. The heliopause is the place where the solar wind comes to a stop and where it collides with the interstellar medium. Because the Sun turns around her axis (once in about 25 days) the interplanetary magnetic field has a spiral shape which is called the Parker Spiral. This classical Archimedean spiral describes the rotating sun, coupled with its continual radial ejection of plasma as it twists its magnetic field (which is referred to as the interplanetary magnetic field) [24-27] as depicted in Fig. 2 below.

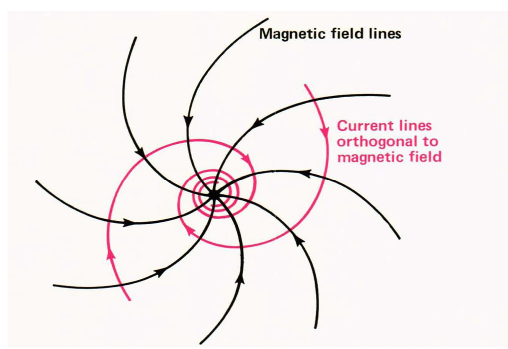

Fig. 2. The Parker Spiral
Source: Potemra, 1983[24]

The years under consideration in this study lie in solar cycle (SC) 24 as depicted in Fig. 3 below where 2009 is at the minima and 2012 is at the first maxima as shown by the black arrows.

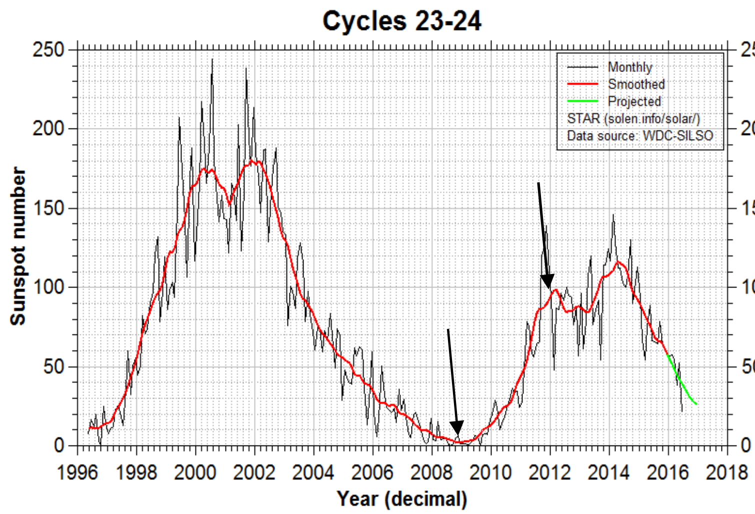

Fig. 3. Solar cycles 23 and 24
Source: www.solen.info

During solar minimum, the sun's magnetic field and the earth's magnetic field are similar. It looks a bit like an ordinary bar magnet with closed lines close to the equator and open field lines near the poles. Scientist call those areas a dipole. The dipole field of the sun is about as strong as a magnet on a refrigerator (around 50 gauss). The magnetic field of the earth is about 100 times weaker.

Around solar maximum, when the sun reaches her maximum activity, many sunspots are visible on the visible solar disk. These sunspots are filled with magnetism and large magnetic field lines which run material along with them. These field lines are often hundreds of times stronger than the surrounding dipole. This causes the magnetic field around the sun to be a very complex magnetic field with many disturbed field lines.

Yihua [28] described how storms occur in phases during solar maximum and minimum as depicted in Fig. 4 below. He reveals that during solar maximums, the initial phases exist in a short time, the main phases exist in a shorter time while the recovery phases stay longer. During solar minimum, the initial and main phases exist longer than the solar maximum. The depths in the main phase are longer in solar maximum than in solar minimum. More energized particles are released during solar maximum than the solar minimum, thus the recovery phase in a solar minimum is faster than in solar maximum.

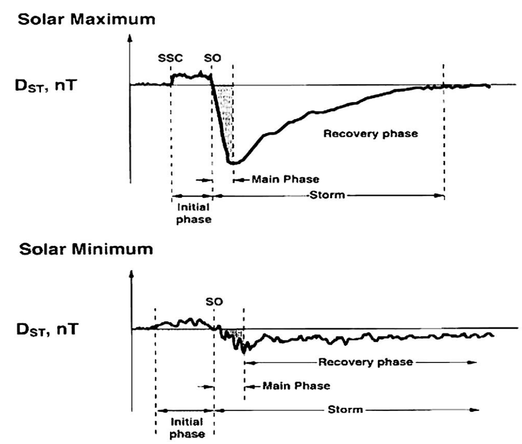

Fig. 4. The behaviour of Dst during solar maximum and minimum
Source: Yihua, 2014 [28]

2. THE MAGNETIC RECONNECTION

The north-south direction of the IMF Bz is the most important ingredient for auroral activity. When it is orientated southward, it will connect with Earth's magnetosphere which points northward. An ordinary bar magnet is known for its two opposite poles to attract each other. With a southward Bz, solar wind particles have a much easier time entering our magnetosphere. Thereafter, they are guided into the atmosphere by earth's magnetic field lines where they collide with the oxygen and nitrogen atoms that make up the atmosphere, which in turn causes them to glow and emit light. When a neutral point develops, magnetic reconnection occurs. During the southward Bz, there are two neutral points, one at the bow shock (dayside) and the other at the magnetotail (nightside) as shown in Fig. 5 below.

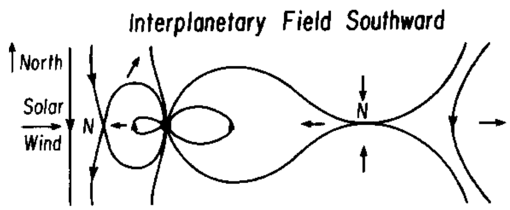

Fig. 5. The neutral points N when IMF Bz is southward
Source: Yihua, 2014 [28]

The dayside neutral point is due to the direct contact of the solar wind with the bow shock while night side neutral point is due to the dissipation of compressed energies stored in the magnetotail about $10R_E$ away. The arrows after the reconnections describe how the dissipated energy travels sunward (dayside) and earthward (night side). Being a cavity mode in the plasmapause, the night side reconnections predicts more of the occurrence of Pi2 pulsations than the dayside phenomena.

When Bz is northward, there are two neutral points as well. They occur at the nightside when the compressed plasma sheet touches the north and south lobes of the magnetotail as described in Fig. 6 below.

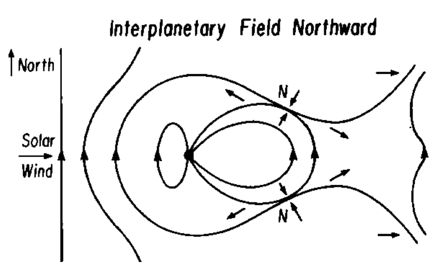

Fig. 6. The neutral points N when IMF Bz is northward
Source: Yihua, 2014 [28]

Magnetospheric reconnection is simply a process whereby magnetic field lines from different magnetic domains meet at a neutral point, then split apart and re-aligned itself changing the overall topology of the magnetic field. There are three stages for a magnetospheric reconnection to occur.

2.1 The Initial Stage

At this stage the two closest magnetic fields from the upper (north field) and lower (south field) lobes of the magnetotail to the outermost dipole field line of the plasma sheet in the plasmapause seem parallel to each other as shown in Fig. 7 below. The red field is the north field while the black field is the south field.

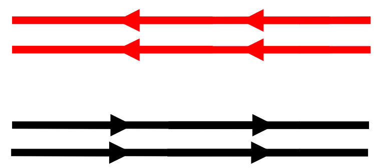

Fig. 7. The direction of magnetic field lines during the initial stage of magnetic reconnection

2.2 The Reconnecting Stage

The two closest magnetic fields from the upper and lower lobes of the magnetotail to the outermost dipole field line of the plasma sheet in the plasmapause seem to touch each other, spliced themselves and reconnect again as shown in Fig. 8 below.

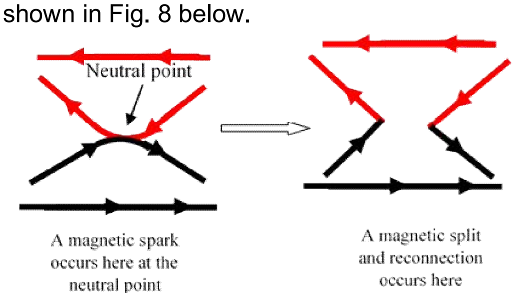

Fig. 8. The direction of magnetic field lines during the reconnecting stage of magnetic reconnection

2.3 The Final Stage

Here the two reconnected magnetic fields change their orientation to a vertical position as shown in Fig. 9 below. At this final stage, the lobe field lines of the magnetopause changes to the dipole field lines of the plasmapause, allowing the formation of plasmoids which diffuse earthwards or into outer space depending on where it is formed.

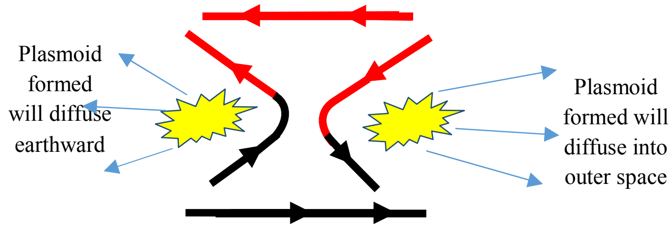

Fig. 9. The direction of magnetic field lines during the final stage of magnetic reconnection

3. DATA USED

The data for this study were obtained from the database in the World Data Center and OMNIWeb. The plots of Bz, Solar Wind plasma speed and Dst index were obtained from https://omniweb.gsfc.nasa.gov/form/dx1.html, the plots of Bz against solar wind speed was obtained from https://omniweb.gsfc.nasa.gov/form/om_scat_min.html and Dst indices for each month in 2009 and 2012 were obtained from http://wdc.kugi.kyoto-u.ac.jp/dst_final/yyyymm/index.html (where yyyymm represent 200901 for example). We considered all the months in 2009 (a low activity year) and all the months in 2012 (a high activity year).

4. RESULTS AND DISCUSSIONS

In this paper, we shall analyse the Bz, Dst indices and solar wind speed of each month in 2009 and 2012 to establish the determinants of the magnetic reconnection.

4.1 The Bz Factor

The H-component of the earth's magnetic field is an important concept because its magnitude is equal to the total field intensity at the point of magnetic reconnection. The True North (X) and True East (Y) fields are revolved by the Magnetic North (H) at a declination angle (D) to X as shown in Figure 10 below. Thus, H is the total horizontal component of X and Y.

The Z-component is the total vertical component of the earth's magnetic field. The F-component is the total intensity of total horizontal intensity (H) and total vertical intensity (Z) at an inclination angle (I) to H.

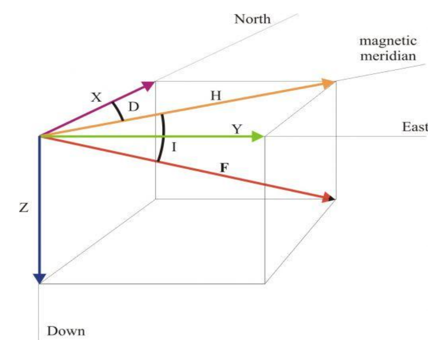

Fig. 10. The elements of earth's magnetic field

Source: http://roma2.rm.ingv.it/en/research_areas/1/earth-s_magnetic_field/8/elements_of_the_geomagnetic_field

Mathematically, $\sin I = \frac{B_Z}{B}$

$$\cos I = \frac{B_H}{B}$$

where B_Z is the vertical magnetic field B and B_H is the horizontal magnetic field B

We know that $\sin^2 I + \cos^2 I = 1$

Thus,

$$\left(\frac{B_Z}{B}\right)^2 + \left(\frac{B_H}{B}\right)^2 = 1$$

$$B_Z^{\ 2} + B_H^{\ 2} = B^2$$

When,

$B_Z = 0$ then $B_H = B$

This shows that an analysis of the H-component of the earth's magnetic field is a robust analysis of the whole magnetic field B at a point. The higher the value of B, the better it is for enhanced geomagnetic conditions. For a moderately strong field, B should exceed 10nT; for a strong field, B should begin at 20nT and for a very strong field, B should exceed 30nT. The Interplanetary Magnetic Field (IMF) B is a vector with a three-axis component, two of which (Bx and By) are orientated parallel to the ecliptic. The Bx and By components are not important for auroral activity but the third component, the Bz value is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind. Dst changes occurred every time the Bz component of IMF B turned negative [29]. Reconnection was first applied to magnetospheric physics by Dungey [30], as a key ingredient of his alternative theory of convection. He proposed that an X-type neutral point (or line) at the front of the magnetosphere enabled terrestrial field lines to link up with interplanetary ones and produce “open” field lines, with one end on earth and the other in distant space.

During southward IMF, storms (invariably substorms) are less frequent in the year 2009 than in the year 2012 as seen in Tables 1 and 2 below. In the year 2012 which is a high activity period, the polar caps with open field lines are fairly large and display a well-defined 2-cell convection pattern and auroral currents are steady and strong. Thus, there is more magnetic reconnection in 2012 than in 2009. The magnetosphere is quieter during the northward IMF as the polar caps shrinks and their electric field weakens. Burton et al*.,* [31] reiterate that when Bz is southward, the increased magnitudes of the solar wind are correlated with the increased activity.

From Table 1 below, Bz went south during 192,707 events which make 47.54% of the total of 405,327 Bz events in the year 2009. It has its highest minima of -17.15 in July and an annual minima average of -11.17 in the year 2009. The magnetic reconnection in 2009 is minima due to low negative Bz events.

As shown in Table 2 below, out of 402,052 Bz events in the year 2012, Bz went south during 209,806 events which make 52.18%. It has its highest minima of -27.36 in January and an annual minima average of -18.12 in the year 2012. The magnetic reconnection in 2012 is maxima due to higher negative Bz events.

4.2 The Dst Index Factor

The classifications of the storms are charted in Table 3 below based on the obtained Dst index data for the year 2009. The plots for the monthly Dst (final) is also shown in Fig. 11(a-l).

We discovered that there were 38 SSC (initial phase) all through the months except December in the year 2009 which occurred in 38 days of the year which is 10% of the 365 days in the year 2009. Being a low activity year, it is expected that there should more quiet times than storm times. There was only one moderate storm recorded in the year 2009 which occurred on the 22 July. There was no intense storm at all.

Table 1. Number of monthly occurrence of Bz in the year 2009

NUMBER OF OCCURRENCE OF Bz IN THE YEAR 2009						
Month	**Bz<0**	**Bz=0**	**Bz>0**	**Total**	**Max**	**Min**
January	17961	65	15819	33845	9.00	- 9.69
February	15535	81	16895	32511	12.06	-15.60
March	14902	88	20385	35375	14.23	-11.49
April	16045	72	16023	32140	10.07	- 7.25
May	19073	70	15444	34587	7.60	- 8.31
June	16625	79	19408	36112	11.41	-16.07
July	17482	81	17229	34792	13.64	-17.15
August	16342	70	17786	34198	12.65	-13.49
September	14402	60	19437	33899	9.13	- 8.65
October	14701	37	16349	31087	10.13	- 8.82
November	14586	87	19166	33839	9.37	- 8.81
December	15053	94	17795	32942	7.39	- 8.65
Total	**192707**	**884**	**211736**	**405327**	**10.56***	**- 11.17***
% Occurrence	**47.54%**	**0.22%**	**52.24%**			

**Average Annual Maxima and Minima of Bz*

Table 2. Number of monthly occurrence of Bz in the year 2012

NUMBER OF OCCURRENCE OF Bz IN THE YEAR 2012						
Month	**Bz<0**	**Bz=0**	**Bz>0**	**Total**	**Max**	**Min**
January	17663	42	18095	35800	30.68	- 27.36
February	15822	31	15725	31578	11.86	- 12.11
March	20243	34	11711	31988	23.78	- 22.46
April	19223	38	12714	31975	14.30	- 15.94
May	17448	37	18011	35496	11.01	- 14.27
June	16265	39	16768	33072	37.92	- 18.35
July	18396	40	18495	36931	21.35	- 20.03
August	16990	56	16659	33705	14.08	- 12.08
September	14674	42	15459	30175	15.22	- 22.90
October	19151	48	14298	33497	13.24	- 21.20
November	18572	59	15702	34333	22.05	- 20.57
December	15359	77	18066	33502	11.12	- 10.11
Total	**209806**	**543**	**191703**	**402052**	**18.88***	**- 18.12***
% Occurrence	**52.18%**	**0.14%**	**47.68%**			

**Average Annual Maxima and Minima of Bz*

Table 3. The classification of magnetic storms in 2009 using the Dst index

Month	**Days of Storms**				**Total Number of days of storm**	**Total Number of days**	**% of storm per month**
	Initial Phase	**Main Phase**					
	Sudden Storm Commencement (from -20nT to -50nT)	**Moderate storm (from -50nT to -100nT)**	**Intense storm (from -100nT to -250nT)**	**Super storm (from -250nT to -600nT)**			
Jan-2009	26	None	None	None	1	31	3%
Feb-2009	4, 5, 6, 14, 15, 16, 17, 23	None	None	None	8	28	29%
Mar-2009	13, 14, 15, 22, 24	None	None	None	5	31	16%
Apr-2009	9, 13, 18	None	None	None	3	30	10%
May-2009	8, 9	None	None	None	2	31	6%
Jun-2009	29	None	None	None	1	30	3%
Jul-2009	14, 22, 23, 24	22	None	None	4	31	13%
Aug-2009	5, 6, 9, 19, 30, 31	None	None	None	6	31	19%
Sep-2009	21	None	None	None	1	30	3%
Oct-2009	22, 23, 24, 25, 30	None	None	None	5	31	16%
Nov-2009	8, 26	None	None	None	2	30	7%
Dec-2009	None	None	None	None	0	31	0%
Total Number of Storms	**38**	**1**	**0**	**0**	**38**	**365**	**10%**

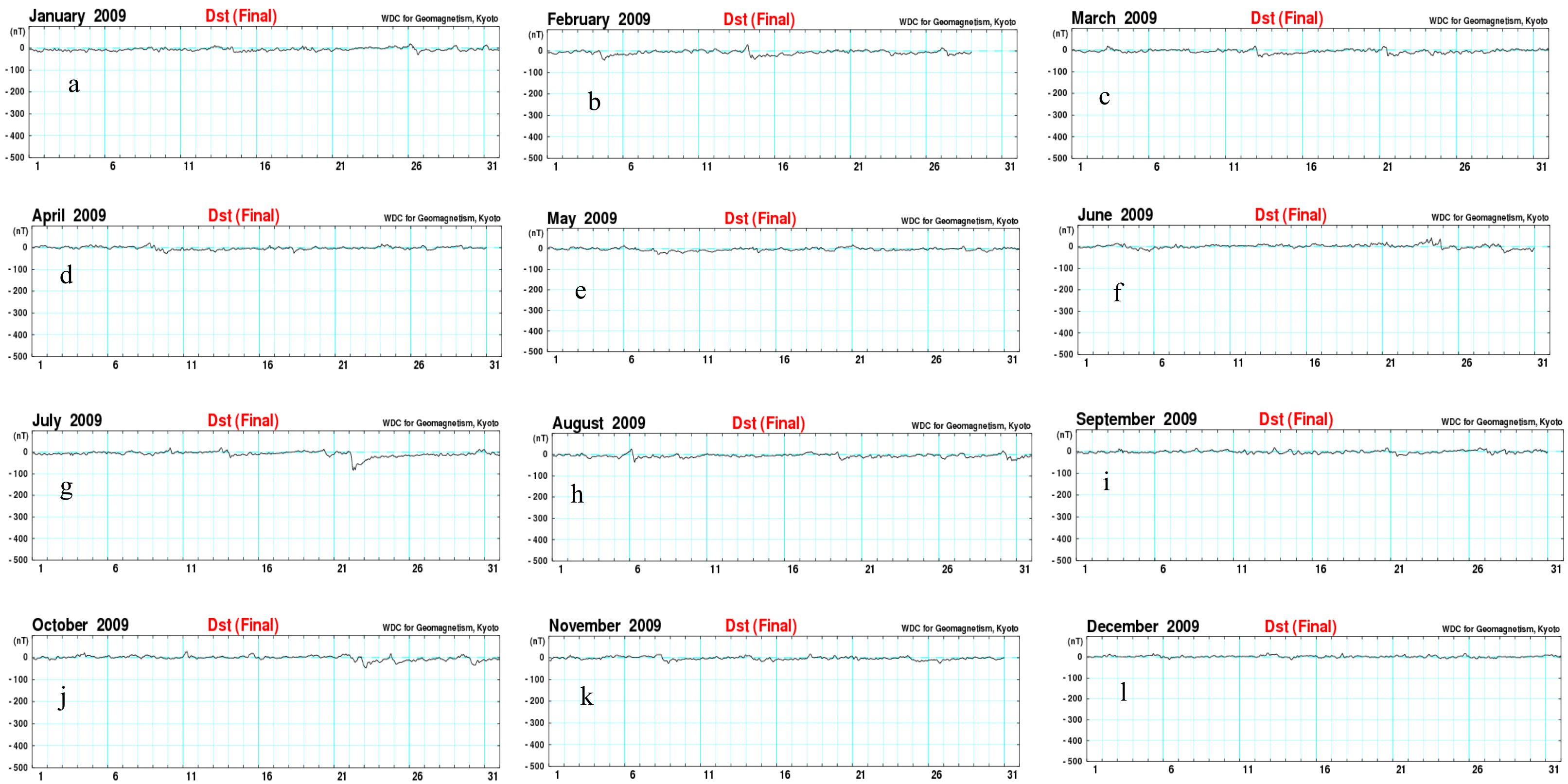

Fig. 11(a – l). Plots of the Dst final for all the months in the year 2009

Source: WDC for Geomagnetism, Kyoto

Table 4. The classification of magnetic storms in 2012 using the Dst index

Month	Days of Storms				Total Number of days of storm	Total Number of days	% of storm per month
	Initial Phase	Main Phase					
	Sudden Storm Commencement (from -20nT to -50nT)	Moderate storm (from -50nT to -100nT)	Intense storm (from -100nT to -250nT)	Super storm (from -250nT to -600nT)			
Jan-2012	3, 23, 24, 26, 27, 29	23	None	None	6	31	19%
Feb-2012	1, 4, 5, 6, 7, 8, 13, 14, 15, 16, 17, 19, 20, 21, 22, 27, 28, 29	15, 19, 27	None	None	18	29	62%
Mar-2012	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 27, 28, 29	2, 7, 9, 10*, 11, 12, 13, 15, 16, 17, 18, 28	9	None	27	31	87%
Apr-2012	1, 2, 3, 4, 5, 7, 12, 13, 14, 17, 18, 20, 22, 23, 25, 26, 27, 28, 29	5, 13, 23, 24*, 25, 26	None	None	20	30	67%
May-2012	3, 9, 10, 11, 12, 13, 14, 16, 17, 18, 22, 23, 24	None	None	None	13	31	42%
Jun-2012	2, 3, 4, 5, 6, 11, 12, 13, 17, 18, 19, 20, 21, 30	12, 17, 18	None	None	14	30	47%
Jul-2012	1, 2, 3, 6, 9, 10, 11, 12, 13, 15, 17, 18, 19, 20, 21, 22, 25, 28, 29, 30, 31	9, 10, 15, 16, 17	None	None	21	31	68%
Aug-2012	2, 3, 6, 8, 9, 16, 17, 19, 20, 23, 25	None	None	None	11	31	35%
Sep-2012	2, 3, 4, 5, 6, 7, 8, 19, 20, 30	3, 5	None	None	10	30	33%
Oct-2012	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	1, 8, 9, 13, 14	None	None	16	31	52%
Nov-2012	1, 2, 13, 14, 15, 16, 20, 21, 24	1, 14	None	None	9	30	30%
Dec-2012	None	None	None	None	0	31	0%
Total Number of Storms	**163**	**39**	**1**	**0**	**165**	**366**	**45%**

*The asterisk sign * indicates a pure storm day where only one phase of the storm occurred without including other phases of storms as stated in this paper. In this case, 10 March 2012 and 24 April 2012 are pure storms days of moderate storms. Unlike 9 March 2012, which is an impure storm day where sudden storm commencement, moderate and intense storms occurred.*

In the year 2012, it was discovered that there were 163 events of SSC (initial phase of geostorm), 39 events of moderate storms and 1 event of an intense storm. Out of the 366 days in the year 2012, magnetic storms were recorded in 165 days which is 45% of the occurrence of storms in the year. It was also observed that December was quiet. However, there were two pure days where only one phase of the storm occurred all through, the days were 10 March and 24 April in which only moderate storms occurred. There were occurrences of both SSCs and moderate storms in all the months in the year 2012 except in May, August and December as shown in Table 4 above and the plots of Dst in Fig 12(a – l).

Generally, there were more storms in the year 2012 than in the year 2009. In comparison with their phases of storm, Tables 5 and 6 have shown that the number of storms in their initial phases was more in the year 2012 than in the year 2009. As shown in Figures 13 and 14, the peaks of storms in their initial phases (<-50nT) and moderate phases (<-100nT) occurred in March, July and October in the year 2012.

Zhang et al*.,* [32] and Gopalswamy et al*.,* [33] reiterated that storms are frequent and intense at high levels of solar activity due to the frequent occurrence of CMEs and ICMEs (interplanetary CMEs). According to Richardson et al., 2001 [34], Tulasiram et al*.,* 2010 [35] and Cramer et al., 2013 [36], during solar minimum, the interaction of co-rotating interaction regions (CIRs) of solar origin with the magnetosphere produces weak recurrent storms as confirmed by this paper. At low activity year, there are low storms and otherwise. The global nature of the storm is indicated by the widespread distribution of the disturbance at all local times according to Moore T. E. et al*.,* 2001 [37]. The disturbance is created by a westward current loop encircling the Earth, the so-called *ring current*. The disturbance enhances the total magnetic moment of the planet, inflating the inner magnetospheric field.

Table 5. Number of SSC in 2009 and 2012

Geomagnetic storms (<-50nT) in 2009 and 2012		
Month	**2009**	**2012**
January	1	6
February	8	18
March	5	26
April	3	19
May	2	13
June	1	14
July	4	21
August	6	11
September	1	10
October	5	16
November	2	9
December	0	0
Total Storms	**38**	**163**

Table 6. Number of Moderate storms in 2009 and 2012

Geomagnetic storms (<-100nT) in 2009 and 2012		
Month	**2009**	**2012**
January	0	1
February	0	3
March	0	12
April	0	6
May	0	0
June	1	3
July	0	5
August	0	0
September	0	2
October	0	5
November	0	2
December	0	0
Total Storms	**1**	**39**

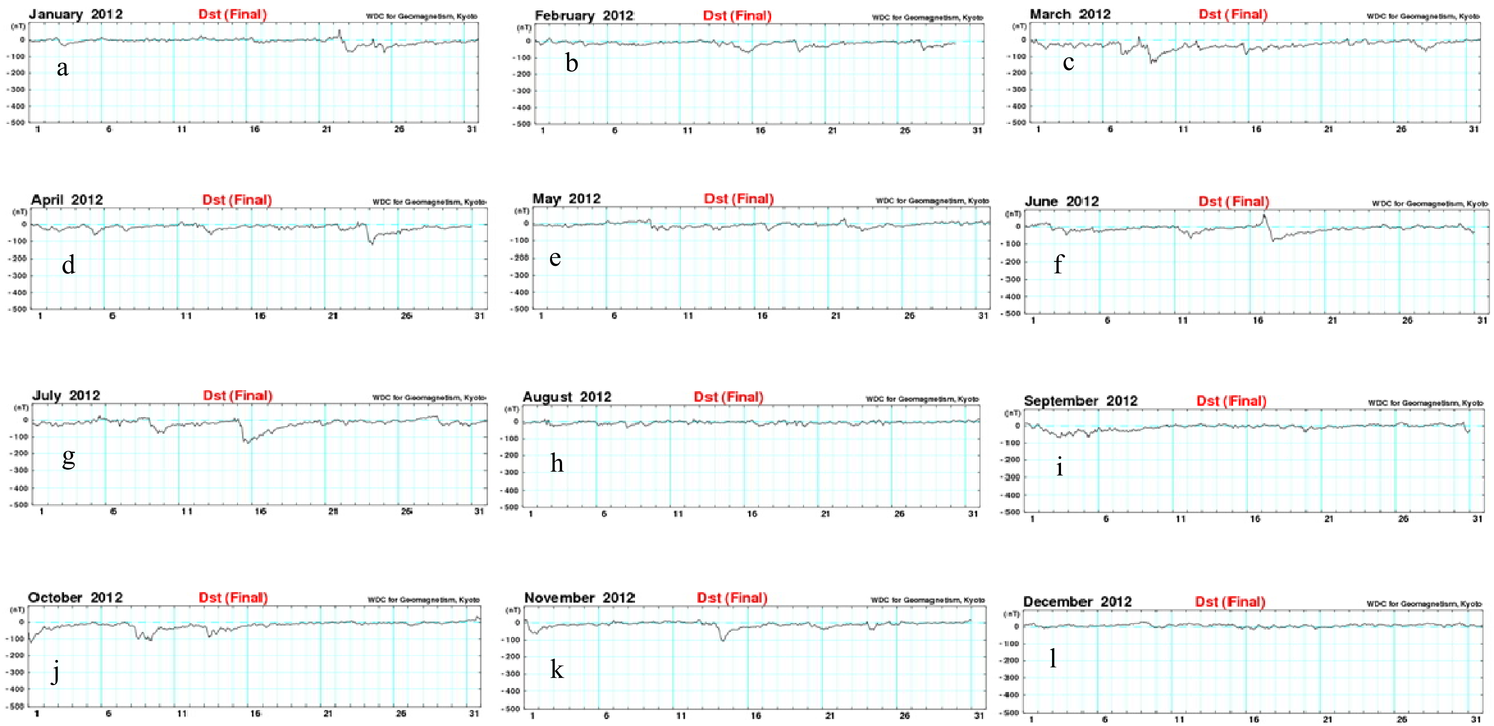

Fig. 12(a – l). Plots of the Dst final for all the months in the year 2012
Source: WDC for Geomagnetism, Kyoto

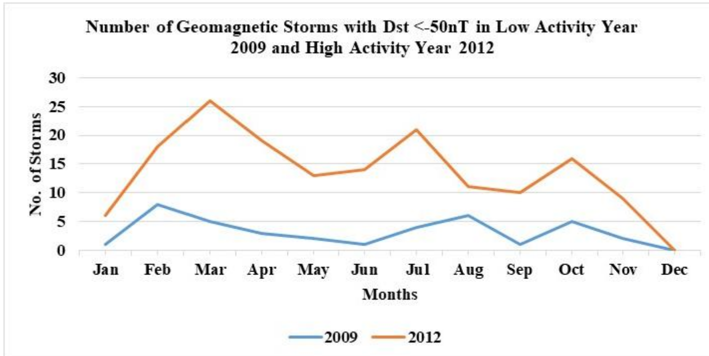

Fig. 13. Plots of SSC in 2009 and 2012 showing the peaks

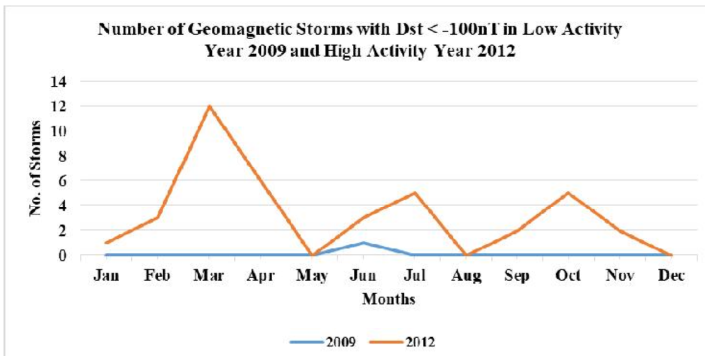

Fig. 14. Plots of moderate storms in 2009 and 2012 showing the peaks

4.3 The Solar Wind Plasma Speed Factor

The solar wind speed can only be a determinant that supports magnetic reconnection if it enhances negative Bz either when it increases or reduces in magnitude. The solar wind has a part to play in the creation of neutral points because it is the main driving force of the convective plasma. Fairfield [38,39] discovered that the level of magnetospheric "storminess" and the energy transferred from the solar wind to the magnetosphere depended on the IMF Bz. The plots of Bz, solar wind plasma speed and Dst index for the year 2009 have shown visually that the solar wind plasma speed is not relevant in the determination of magnetic reconnection because the values of most Bz were positive at higher speeds as shown in Fig. 15(a) below. In a low activity year like 2009, even at a day of an intense storm like 22 July 2009 (Day 203), we found out that solar wind speed supports north Bz as shown in Fig. 15(b) below. To establish this assertion, the 1-minute resolution OMNI data set was used and it was discovered that higher solar wind speed, the more Bz becomes positive which in turns will lead to low magnetic reconnection. The positive correlation coefficient of 0.44 suggests that as speed increases, the Bz is positive as shown in Fig. 15(c).

The plots of Bz, solar winds and Dst index for the year 2012 have shown visually that the solar wind plasma speed is relevant in the determination of magnetic reconnection because the values of most Bz are negative at higher speeds as shown in Fig. 16(a) - (c) above. To establish this assertion, the Bz, SW plasma speed and Dst index of the Days 69 - 70 (9 - 10 March 2012) where an intense storm and a moderate storm occurred respectively were analysed. Slavin et al., [40] iterated that the International Sun – Earth Explorer (ISEE-3) has also shown and Geotail has confirmed, that in the distant tail past about 100 R_E, plasma flowed tail-wards at velocities that tended to increase with distance, up to where they about matched the velocity of the solar wind. This might be due to viscous transfer of plasma and momentum, but could also be the result of reconnection. Using the 1-minute resolution of the OMNI data set of Days 69 - 70, this paper has reaffirmed that one of the determinants for magnetic reconnection to occur in a high activity year is the solar wind plasma speed. We can deduce from

Fig. 16(c) that the negative correlation coefficient of 0.53 affirms that as the solar wind speed increases, the values of Bz were negative which in turn will enhance magnetic reconnections. According to Burton et al., [31], the negative correlation between IMF Bz and speed proves that the more the speed, the more the IMF Bz goes southward especially during high activity year.

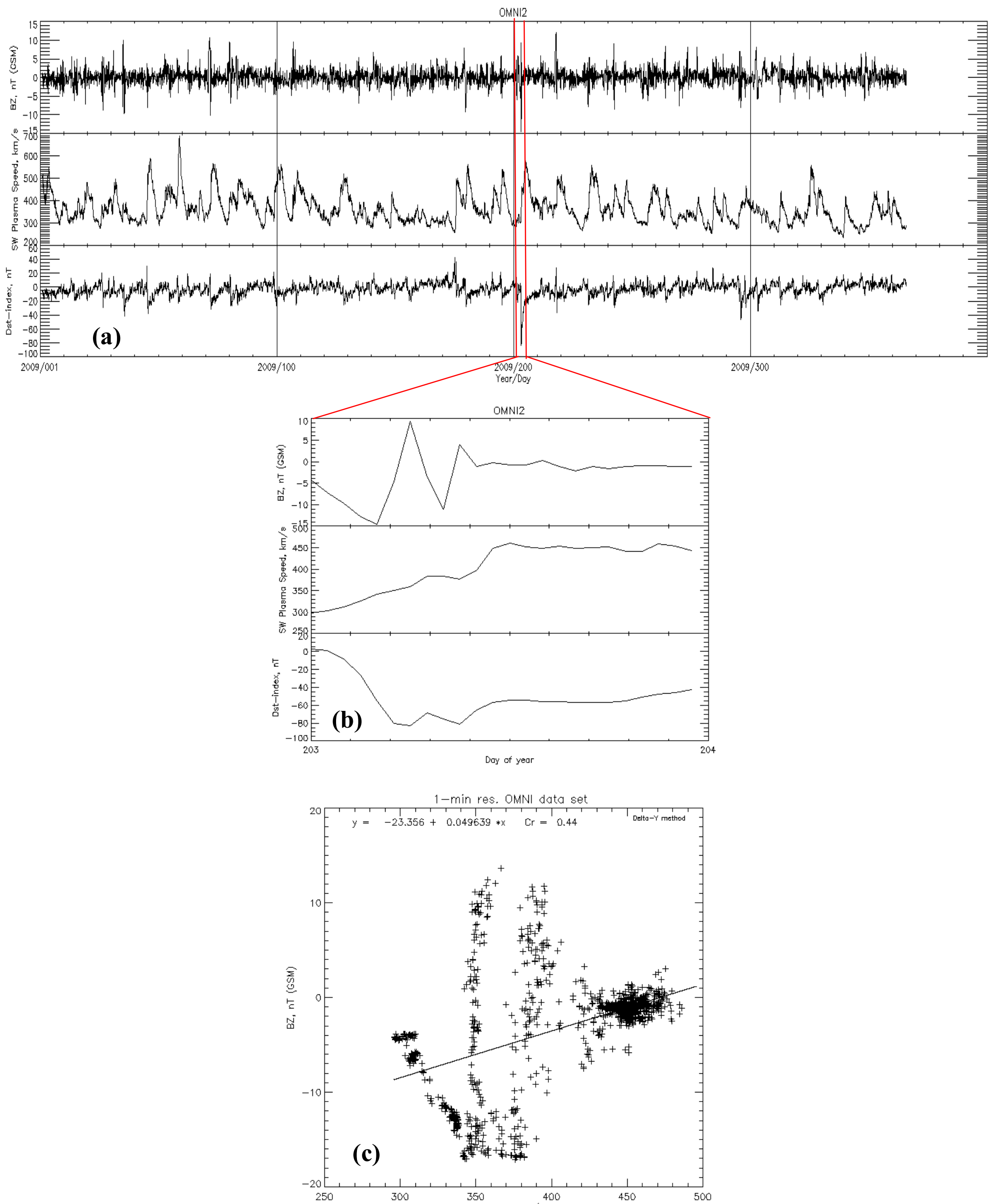

Fig. 15. (a) Plots of Bz, Solar Wind plasma speed and Dst index for the year 2009, (b) plots of Bz, Solar Wind plasma speed and Dst index for the Day 203 (22 July 2009) and (c) plot of Bz against Solar wind plasma speed of the Day 203

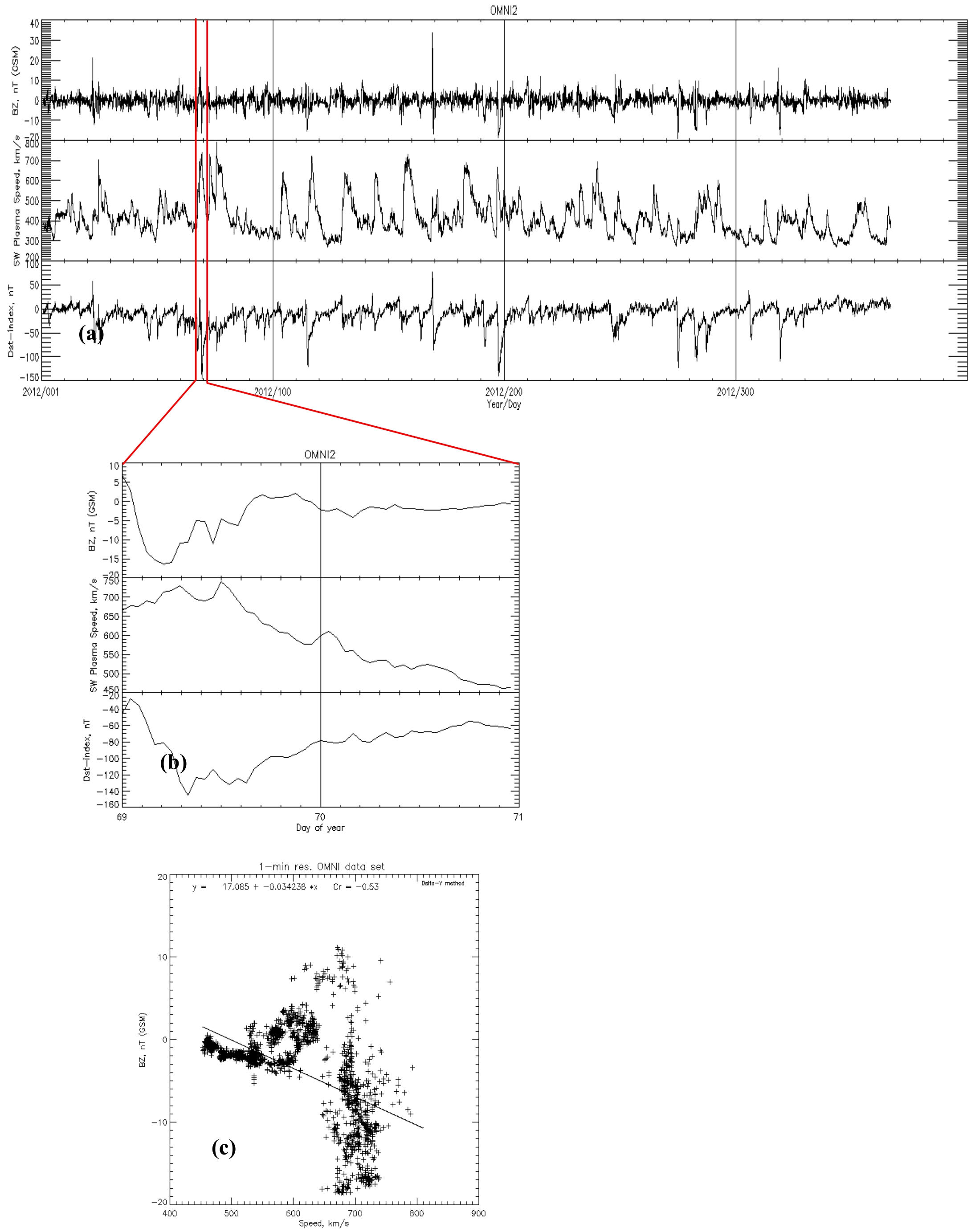

Fig. 16. (a) Plots of Bz, Solar Wind plasma speed and Dst index for the year 2012, (b) plots of Bz, Solar Wind plasma speed and Dst index for the Days 69 and 70 (9 – 10 March 2012) and (c) plot of Bz against Solar wind plasma speed of the Days 69 and 70

5. CONCLUSION

The determinants for magnetic reconnection in a low activity year 2009 and a high activity year 2012 were examined using these geomagnetic parameters: Bz, Dst indices and solar wind plasma speeds. We identified 39/202 storms in the years 2009/2012 which include 38/163 sudden storm commencement (−20 < DstMin ≤ −50 nT), 1/39 moderate storms (−100 < DstMin ≤ −50 nT), 0/1 intense storms (−250 < DstMin ≤ −100 nT). The storms occurred at 10% and 45% of the days in the years 2009 and 2012 respectively. It was observed that there are more magnetic reconnections when Bz is negative in a high activity year than otherwise with the number of negative Bz occurrence as 47.54% and 52.18% of Bz occurrences in 2009 and 2012 respectively. The level of storminess is indicated the value of the Dst index. With more negative Dst index, we found out that there were more magnetic reconnections, especially in the high activity year. In December for both years, it was discovered that there were no storms. This could be attributed to the cold weather during the winter season in December generally. We deduced using a 1-minute resolution that, in a high activity year when solar wind speed is high, the Dst index will reduce and Bz will go south which will result in magnetic reconnection while in low activity year, even in a day of an intense storm, high solar wind speed does not support magnetic reconnection. The frequency of magnetic reconnection is higher during a high activity year than during a low activity year. Thus, negative Bz and Dst indices are major determinants of magnetic reconnection in either a low activity year or a high activity year while the solar wind plasma speed is a major determinant in a high activity year but not in a low activity year.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Yousif ME. The source of the interplanetary magnetic field (IMF) measured by pioneer V. J Astrophys Aerospace Technol. 2014;2:108. DOI:10.4172/2329-6542.1000108 Available:https://www.researchgate.net/publication/265510247_The_Source_of_the_Interplanetary_Magnetic_Field_IMF_Measured_by_Pioneer_V [accessed Dec 28 2020].
2. Sokolov SN. Magnetic storms and their effects in the lower ionosphere: Differences in storms of various types. Geomagn. Aeron. 2011;51:741–752. Available:https://doi.org/10.1134/S0016793211050124
3. Hines P, Apt J, Talukdar S. Trends in the history of large blackouts in the United States. Presented at the Power and Energy Society General Meeting − Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, July 20-24, 2008, Pittsburgh, Pennsylvania. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey; 2008.
4. Kirkham H, Makarov YV, Dagle JE, DeSteese JG, Elizondo MA, Diao R. Geomagnetic storms and long-term impacts on power systems. Pacific Northwest National Laboratory, Richland, Washington, 99352. Prepared for U.S. Department of Energy under Contract DE-AC05-76RL01830 (PNNL-21033) in December 2011; 2011. Available:https://core.ac.uk/download/pdf/204552371.pdf
5. Boteler DH. Space weather effects on power systems, in space weather, Geophys. Monogr. Ser., vol. 25, edited by P. Song, H. J. Singer, and G. L. Siscoe, AGU, Washington, D. C. 2001;347–352.
6. Love JJ, Rigler EJ, Pulkkinen A, Balch CC. Magnetic storms and induction hazards, Eos Trans. AGU. 2014;95(48):445–452.
7. Kappenman JG. Storm sudden commencement events and the associated geomagnetically induced current risks to ground□based systems at low□latitude and midlatitude locations, Space Weather. 2003;1(3):1016. DOI:10.1029/2003SW000009
8. Kappenman J. Geomagnetic storms and their impacts on the U.S. Power Grid. Published by Metatech Corporation 358 S. Fairview Ave., Suite E Goleta, CA 93117 January 2010. Prepared for Oak Ridge National Laboratory; 2010. Available:https://fas.org/irp/eprint/geomag.pdf
9. Ngwira CM, Pulkkinen A, Wilder FD, Crowley G. Extended study of extreme

geoelectric field event scenarios for geomagnetically induced current applications, Space Weather. 2013;11:121–131. DOI:10.1002/swe.20021
10. Gonzalez WD, Tsurutani BT. Criteria of interplanetary parameters causing intense geomagnetic storms (Dst<-100nT). Planet Space Sci. 1987;35:1101-1109.
11. Chao JK. Steepening of nonlinear waves in the solar wind, J. of Geophys. Res. 1973;78:5411-5424.
12. Bravo S. The forecasting of intense geomagnetic storms, GeofisicaInternacional. 1999;36: 127-135.
13. Gosling JT, McComas DJ. Field line draping about fast coronal mass ejecta: A source of strong out-of-the-ecliptic interplanetary magnetic fields, Geophys. Res. Lett. 1987;14:355-358.
14. Akasofu SI. Energy coupling between the solar wind and the magnetosphere, Space Sci. Rev. 1981;28:111.
15. Tsurutani BT, Russell CT, King JH, Zwickl RJ, Lin RP. A Kinky Heliospheric current sheath: Causes of the CDAW6 Substorms, Geophys. Res. Lett. 1984;11:339.
16. Tang F, Akasofu SI, Smith E, Tsurutani B. Magnetic fields on the sun and the north-south component of transient variations of the interplanetary magnetic field at 1 AU, J. Geophys. Res., 1985;90:2703-2712.
17. Tsurutani BT, Ho CM, Arballo JK, Goldstein BE, Balogh A. Large amplitude IMF fluctuations in co-rotating interaction regions: Ulysses at midlatitudes, Geophys. Res.Lett. 1995;22:3397.
18. Chian ACL, Borotto FA, Gonzalez WD. Alfven intermittent turbulence driven by temporal chaos, Ap. J. 1998;505:993-998.
19. Wu Chin-Chun, Dryer M. Predicting the initial IMF Bz polarity's change at 1 AU caused by shocks that precede coronal mass ejections, Geophys. Res. Lett. 1996;23:1709-1712.
20. Wu Chin-Chun, Dryer M. Three-dimensional MHD simulation of interplanetary magnetic field changes at 1AU caused by a simulated solar disturbance and a tilted heliospheric current/plasma sheet, Sol. Phys. 1997;173:391-408.
21. Hoeksema JT, Zhao X. Prediction of magnetic orientation in driver gas associated -Bz events. J. Geophys. Res. 1992;97:3151-3156.
22. Chao JK, Chen HH. Prediction of southward IMF Bz, American Geosphysical Union. 2001;125:183-189.
23. Sean McCloat. What is magnetic field strength and “Bz” have to do with the aurora? Aurorasaurus; 2015. Available:http://blog.aurorasaurus.org/?p=178
24. Potemra TA ed. Magnetospheric currents, American geophysical union, Washington, D.C. Johns Hopkins APL Technical Digest. 1983;4(4).
25. Parker EN. The Solar-Flare Phenomenon and the Theory of Reconnection and Annihiliation of Magnetic Fields. Astrophysical Journal Supplement, vol. 8, p.177 (1963). doi: 10.1086/190087
26. Christoph L, Yasuhito N. Kinematic models of the interplanetary magnetic field. Ann. Geophys., 37, 299–314, 2019 https://doi.org/10.5194/angeo-37-299-2019
27. Ana-Maria Piso (2009). The Interplanetary Magnetic Field (Parker Spiral). http://demonstrations.wolfram.com/TheInterplanetaryMagneticFieldParkerSpiral/ Wolfram Demonstrations Project
28. Yihua Zheng. Space weather in the magnetosphere, SW REDI Engineers. 2014;28 Available:https://ccmc.gsfc.nasa.gov/RoR_WWW/SWREDI/training-for-engineers/Zheng_Mag_2014 Winter.pdf
29. Rajaram PK. Evolution of Dst and auroral indices during some severe geomagnetic storms. Published on Rev. Bras. Geof. São Paulo Apr./June 2009. Revista Brasileira de Geofísica. 2009;27(2). Print version ISSN 0102-261X. Retrieved on 12 January 2021 from Available:https://doi.org/10.1590/S0102-261X2009000200001
30. Dungey James W. Interplanetary magnetic field and the auroral zones, Phys. Rev. Letters. 1961;6:47-48.
31. Burton Rande K, McPherron RL, Russell CT. An empirical relationship between interplanetary conditions and Dst, J. Geophys. Res. 1975;80:4204-4214.
32. Zhang J, Richardson IG, Webb DF, Gopalswamy N, Huttunen E, Kasper JC. Solar and interplanetary sources of major geomagnetic storms (Dst < −100 nT) during 1996–2005. J Geophys Res. 2007;112:A10102. DOI:10.1029/2007JA012321
33. Gopalswamy N, Yashiro S, Michalek G, Xie H, Lepping RP, Howard RA. Solar

source of the largest geomagnetic storm of cycle 23. Geophys Res Lett. 2005;32:L12S09. DOI:10.1029/2004GL021639

34. Richardson IG, Cliver EW, Cane HV. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000. Geophys Res Lett. 2001;28:13. DOI:10.1029/2001GL013052
35. Tulasiram S, Liu CH, Su SY. Periodic solar wind forcing due to recurrent coronal holes during 1996–2009 and its impact on Earth's geomagnetic and ionospheric properties during the extreme solar minimum. J Geophys Res. 2010;115:A12340. DOI:10.1029/2010JA015800
36. Cramer WD, Turner NE, Fok MC, Buzulukova NY. Effects of different geomagnetic storm drivers on the ring current: CRCM results. J Geophys Res; 2013. DOI:10.1002/jgra.50138
37. Moore TE, Collier MR, Burch JL, Chornay DJ, Fuselier SA, Ghielmetti AG, Giles BL, Hamilton DC, Herrero FA, Keller JW, Ogilvie KW, Peko BL, Quinn JM, Stephen TM, Wilson GR, Wurz P. (2001). Low energy neutral atoms in the magnetosphere. Geophysical Research Letters, 28(6), 1143–1146. doi:10.1029/2000gl012500
38. Fairfield Donald H, Lawrence G, Cahill Jr. Transition region magnetic field and polar magnetic disturbances, J. Geophys. Res. 1966;71:155-169.
39. Fairfield Donald H. Polar magnetic disturbances and the interplanetary magnetic field, Space Research VIII. 1967;107-119.
40. Slavin A, James Edward J, Smith David G, Sibeck Daniel N, Baker Ronald D, Zwickl. An ISEE 3 study of the average and substorm conditions in the distant magnetotail, J. Geophys. Res., 1985;90(10):875-10:895.

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