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IMF and substorm associated plasmoids

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Abstract : The association of sunspot numbers to geomagnetic activity during 1979–90 has been carried out in the present study. Also, the substorm energy and the orientation of interplanetary magnetic field (IMF) B_z on plasmoid formation are studied. It is revealed that the sunspot numbers influence mildly on geomagnetic activity during 1979–90. Plasmoid formation is found to be associated with geomagnetic activity and both southward as well as northward IMF. Plasmoid size is found to depend on the energy input into the magnetosphere

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1. Introduction

A magnetosphere extracts energy from the solar wind continuously and dissipates it within the system. The energy released in the solar wind-magnetosphere interaction depends on the solar wind velocity and on the magnitude and direction of IMF. In the near-earth neutral line model, at substorm onset a near-earth neutral line is formed between –10 and –20 R_E causing ring current injection, particle energization and the severance of plasma sheet to form a plasmoid (PMD) [1]. Earlier studies showed the association between the onset of substorms and the occurrence of tailward moving plasmoids [2–5]. Near-earth neutral line suggests that the magnetic reconnection in the near-earth tail forms a plasmoid and finally ejected down the magnetotail. Moldwin and Hughes [6] suggested two different plasmoids due to the different energy states of the magnetosphere during southward and northward interplanetary magnetic field as classic and proto-plasmoids respectively. Mugellesi and Kerridge [7] suggested that there exists a correlation of geomagnetic activity and solar cycle variation since the solar wind speed is the obvious link between the sunspots and geomagnetic activity.

This paper studies the association of sunspot numbers to geomagnetic activity during 1979-90. Also, the substorm energy and the orientation of IMF B_z on plasmoid formation are studied.

2. Data and method

The data used in the present study are : sunspot numbers, K_p and A_p indices during 1979-90 and AE and D_{st} indices during 1979-83. We have selected storms and plasmoid event of 1979 and 1983 since most of the plasmoids were reported during this period. The storms [8] used are occurred in summer, winter and equinotical months of 1979 solar maximum, since the energy input into the magnetosphere is high and hence it is a suitable period to study magnetospheric phennomena like substorms and hence plasmoids. We have selected plasmoid events [9] occurred in January to March 1983.

Statistical correlation method is used to find the association between solar and geomagnetic activity for each month as well as seasons. To study the effect of seasonal variation, the data have been divided into summer [May–August], winter [November–February] and two equinotical periods March–April and September–October. Also, using Student's t distribution we tested the significance of correlation.

To study the effect of IMF B_z and solar wind magnetosphere coupling to plasmoids, we have selected six storms, which occurred in summer [August 29,0500–1000 UT], winter [February 21,0200–2200 UT] and equinotical [March 22 (0100–2400 UT), March 28–29 (0800–2200 UT), April 24–25 (2300–1500 UT) and September 17–18 (2100–1000 UT)] months of 1979 solar maximum.

In order to determine the mechanism by which the energy input has been dissipated in the magnetosphere, energy budget of the magnetosphere during substorm has to be studied. To study the role of IMF B_z on plasmoid formation, we have averaged the AE index, input and output energy corresponding to the averaged negative as well as positive B_z of all selected storms.

3. Magnetospheric energetics

To estimate the substorm energy, we need the following steps : The energy transfer rate between the solar wind and magnetosphere was given by the solar wind magnetosphere coupling function [10] as

$$\varepsilon = V_{sw} B^2 \sin^4(\theta/2)\, l_0^2 . \tag{1}$$

where V_{sw} is the solar wind speed, B is the magnitude of IMF, $\theta (= \tan^{-1} B_y/B_z)$ is the angle between the GSM Z direction and the projection of IMF in the Y–Z plane and l_0 is a constant equal to 7 R_E.

The total energy consumption rate of the magnetosphere [E_{TS}] is the sum of ring current injection rate E_{RC}, auroral particle flux E_A and the Joule heat production rate E_J in the ionosphere :

$$E_{TS} = E_{RC} + E_A + E_J , \tag{2}$$

where $$E_{RC} = -4 \times 10^{20}\left[\partial D_{st}/\partial t + D_{st}/\tau\right], \tag{3}$$

$$E_A = AE \times 10^{15}, \tag{4}$$

$$E_J = 2 \times 10^{15}\, AE, \tag{5}$$

and D_{st} and AE are geomagnetic indices indicating ring current strength and substorm activity respectively.

4. Results and discussion

4.1. Solar and geomagnetic activity :

(i) Monthly variation :

Our study on monthly and seasonal correlation between sunspot numbers and geomagnetic activity [K_p, A_p and AE] indices during 1979-90 showed that sunspot numbers have virtually no effect on geomagnetic activity during this period.

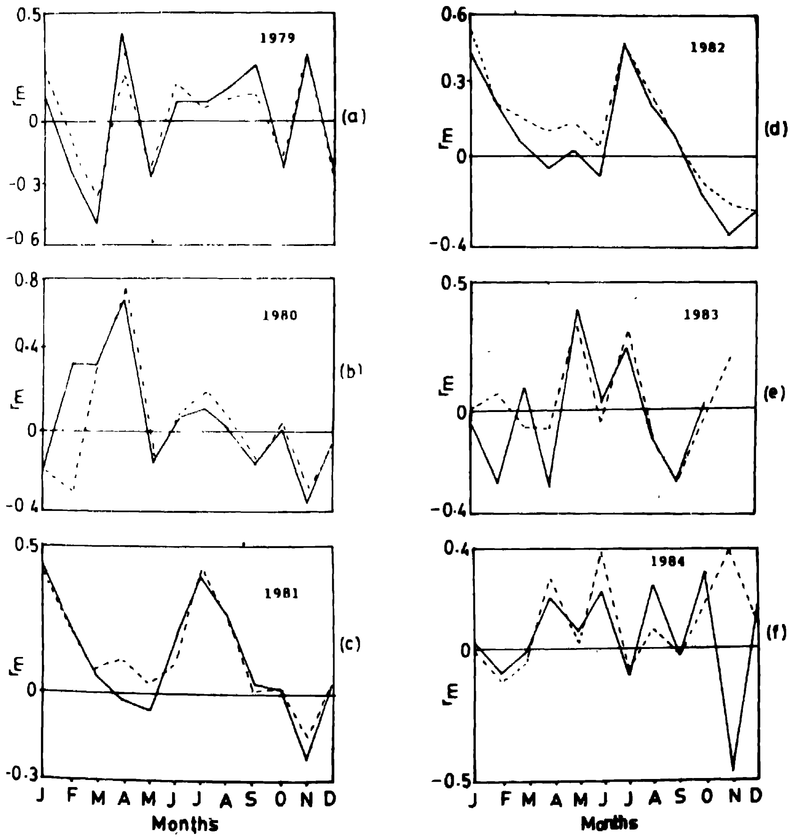

Figure 1(a–f). Monthly correlation coefficient (r_m) of K_p (–) and A_p (---) indices with sunspot numbers during 1979–84.

The computed correlation coefficient between sunspot numbers and geomagnetic indices showed that eventhough there exists a correlation between sunspot numbers and geomagnetic activity, it is not so significant. Figures 1(a) – 1(l) indicate the correlation

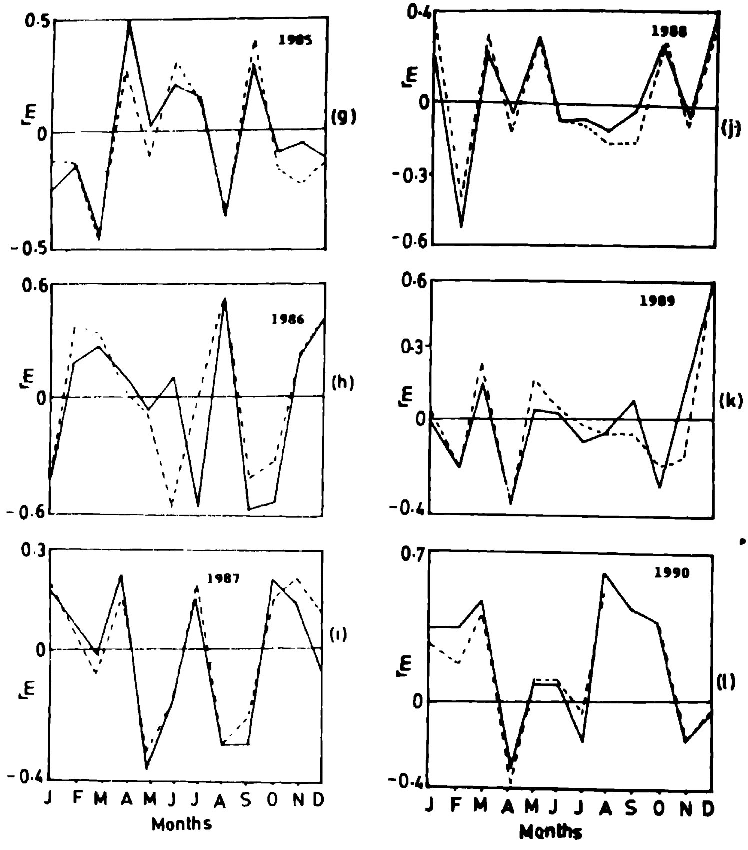

Figure 1(g–l). Monthly correlation coefficient (r_m) of K_p (-) and A_p (---) indices with sunspot numbers during 1985–90

coefficients r_m and r_r between sunspot numbers and K_p (solid line) and A_p indices (dotted line) respectively for each month during 1979-90. It is obvious from figures that there is no periodic variation with geomagnetic activity.

An anticorrelation is observed in K_p and A_p in February 1983 and in November 1984 and large fluctuations in r_m can be observed in 1983 and 1984. Negative correlation is more frequent than positive correlation during 1986 and 1989. Maximum correlation is obtained in April 1980 and August 1990.

Table 1. Significant correlation of geomagnetic index using Student's *t* distribution

79	80	81	82	83	84	85	86	87	88	89	90
		0.4531*	0.4587**				-0.4257*				
		0.4760**	0.5557**				-0.4138*				
							0.3812*		-0.5506**		
0.5005**	0.3684*					0.4674**			-0.4240*		0.4781**
	0.3608*					0.4712**					0.4002*
0.4255*	0.7271**					0.4852**				0.3866*	-0.3947*
	0.7667**										
				0.4057*	0.3884*			0.3748*			
		0.4458*	0.4983**				-0.5792**				
							-0.5948**				
		0.4249*	0.4808**								
						-0.3617*	0.5193**				0.6077**
						-0.3601*	0.5353**				0.5067**
							-0.5855**				0.4417*
											0.3815*
					0.4000*		-0.5398**				0.3800*
			-0.3652*		-0.4805**						
							0.4478*		0.3878*	0.5317**	
							0.4511*			0.5211**	

* Correlation coefficient at 5% significance.
** Correlation coefficient at 1% significance.

Table 1 shows the significant correlation of geomagnetic activity index during 1979–90 using Student's *t* distribution. Here, the degrees of freedom are 26, 27, 28 and 29 and the significant values of these correlation coefficient at 5% (confidence level 95%) and 1% (confidence level 99%) level of significance are respectively 0.374, 0.367, 0.361, 0.355 and 0.478, 0.470, 0.463, 0.456. Any correlation coefficient greater than the respective values are considered to be significant. It is evident from Table 1 that during 1979–90, only two or three months have significant correlation. However, in 1986, six months show significant correlation. The significance test on the monthly correlation revealed that the sunspot numbers did not greatly influence on geomagnetic activity.

(ii) Seasonal variation :

The degree of correlation between sunspot numbers and geomagnetic indices (AE and K_p) in different seasons of the cycle are also found to be not so significant. The equinotical months March–April of 1980 have the maximum correlation coefficients ($AE = 0.5698$ and $K_p = 0.5523$ respectively). The maximum r_s is ~0.3 in winter and +0.32 in summer.

During the declining phase (1979-83), winter and equinotical months March–April show cyclic variations. In the present study, the equinotical months show maximum correlation between sunspot numbers and geomagnetic indices except in 1981, 82 and 86 where the summer months have maximum correlation. This indicates that during 1979–90 the geomagnetic activity having peaks in equinotical months. The results thus obtained are in agreement to Tohru Nosaka's [11] conclusion that geomagnetic activity exhibit a semi-annual variation having peaks in March and September which may or may not be of solar origin. Thus, from the present study limited to twelve years, it is evident that sunspot numbers has only a minor influence on geomagnetic activity.

Since plasmoid (PMD) formation is found to depend on geomagnetic activity [5] we have selected storm events during 1979 solar maximum to study IMF association on PMD formation.

4.2. Solar wind magnetosphere coupling :

This section deals with the input and output energy of selected storms using the hourly values of AE, D_{st}, B_z and solar wind velocity. For a substorm to develop, ε is in between 10^{11}–10^{12} W. The electric field strength E_y is calculated using the solar wind velocity V_{sw} and IMF B_z. We considered here six geomagnetic storms and pointed out the peak values of which occurred in each storm. If a geomagnetic storm is reported during a period and is found to be > 10^{11} W, we can say that a substorm is formed during that period. Figures 2(a)–2(f) show the solar wind parameters, AE, D_{st}, E_y, ε (solid line) and E_{TS} (dashed line) respectively for the selected six storms with universal time. The southward turning of the electric field strength E_y can be used to determine the strength of substorms.

(i) February 21, 1979 (0200–2200 UT) Figure 2(a)] :

A geomagnetic storm was reported on February 21, 1979 at 0200–2200 UT and in association to this two peaks of input power can be seen at 0700 ($\varepsilon = 2.5656 \times 10^{12}$ W) and

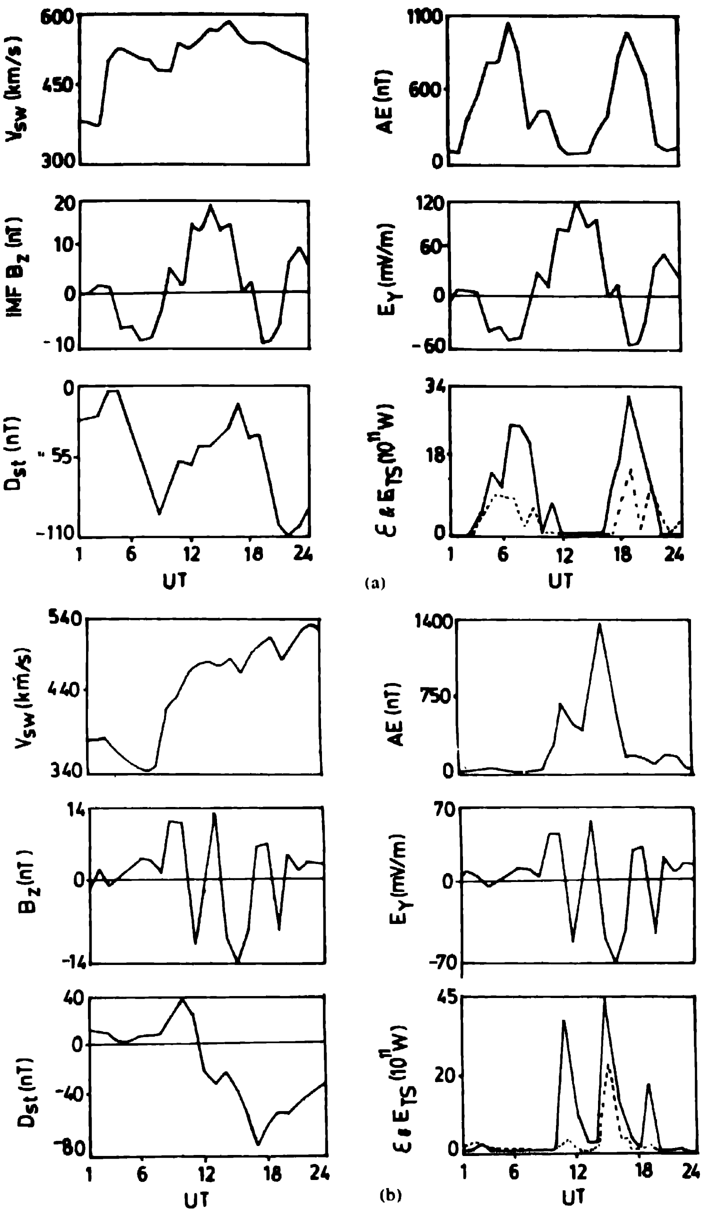

Figure 2(a, b). From the top, solar wind velocity V_{sw}, IMF B_z component, D_{st} index, AE index, the electric field E_y and solar wind magnetosphere coupling ε (solid line) and total energy dissipatron rate E_{TS} for February and March 22, 1979 storm.

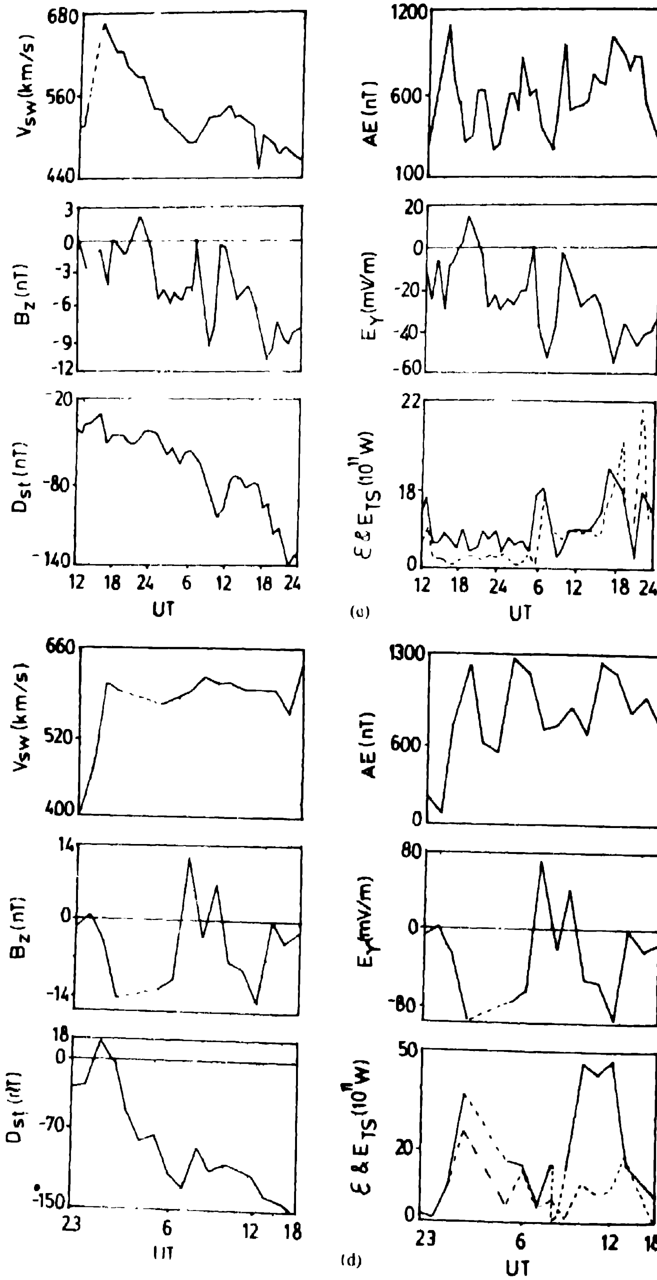

Figure 2(c, d). Same as Figure 2(a, b) for March 28–29 and April 24–25, 1979 storm.

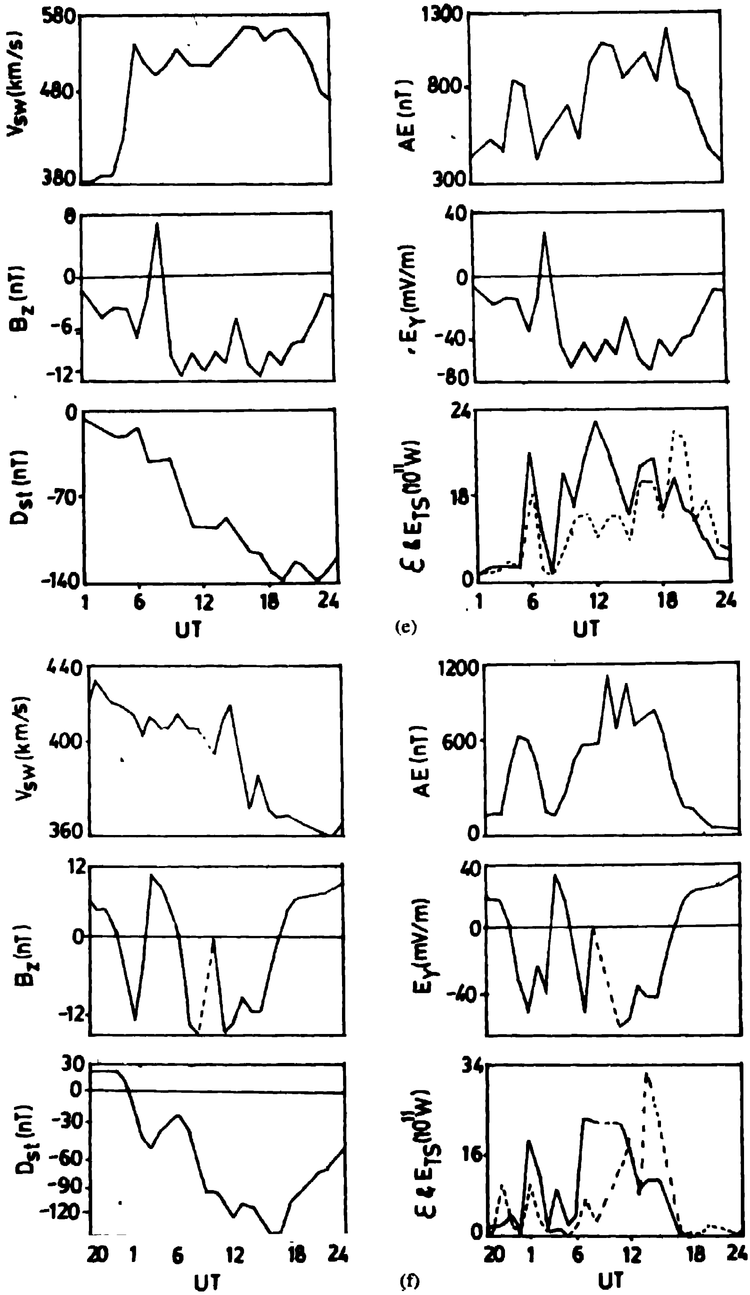

Figure 2(e, f). Same as Figure 2(a, b) for August 29 and September 17–18, 1979 storm.

1900 UT ($\varepsilon = 3.2758 \times 10^{12}$ W). The enhanced ε is due to the substantial southward IMF (−10.3 and −10.2 nT) during this period. During 0500–0900 UT and 1700–2100 UT, when B_z is southward (at 1800 UT B_z is northward), ε is found as $1.1155 \times 10^{12} - 1.5518 \times 10^{12}$ W. Eventhough at 1800 UT, IMF is northward (2.5 nT) ε is 1.7692×10^{12} W. The input power and the total power dissipation E_{TS} show uniform variation during 1200–1600 UT and both are reduced to a minimum value. In this storm eventhough $\varepsilon > 10^{12}$ W, no plasmoid was observed

(ii) March 22, 1979 (0100–2400 UT) [Figure 2(b)] :

The two coupling parameters ε and E_y show large fluctuations between 0800–2000 UT. ε has three peaks at 1100 (3.6478×10^{12} W), 1500 (4.2811×10^{12} W) and 1900 UT (1.8656×10^{12} W) which is very well-correlated with southward IMF (B_z = −12, −16 and −8.8 nT). The sharp enhancement in AE (1390 nT) and B_z (−16 nT) at 1500 UT corresponds to the maximum input power (4.2811×10^{12} W).

Around 1050–1118 UT, a PMD event was reported [12]. At 1000 UT, ε is 10^6 W (dotted line) corresponding to a northward IMF of 10.6 nT. When the PMD is observed (1058 UT) the IMF is in the northward direction (10.6 nT) having an AE index of 273 nT and $\varepsilon = 1 \times 10^6$ W. AT 1100 UT, the IMF changes in the southward direction (12 nT) having an AE index of 656 nT and ε increases to 3.6478×10^{12} W. Eventhough at 1200 UT and 1300 UT are followed by a northward IMF, ε remains in the highest value (10^{12} W and 2.1754×10^{11} W) In this case the PMD formation is associated with northward IMF.

(iii) March 28(0800 UT)–March 29 (2200 UT), 1979 [Figure 2(c)] :

As shown in Figure 2c, the IMF is southward for about nineteen hours resulting a huge amount of input energy. It is obvious from Figure 2c that the storm was highly fluctuating, ε has respectively its maximum at 0700 (1.0997×10^{12} W), 1700 (1.3888×10^{12} W) and 2200 UT (1.0607×10^{12} W) on March 29, 1979. On March 28 during 1800–2000 UT, eventhough the IMF is northward, ε has not reduced much ($2.4887 \times 10^{11} - 1.99473 \times 10^{11}$ W). B_z is southward throughout March 29 except at 0500 UT (B_z = 0.2 nT, $\varepsilon = 1.7695 \times 10^{11}$ W) and is highly reflected in ε and E_y. On an average, the energy input into the magnetosphere is high during this storm of equinotical period.

A PMD was reported [13] on March 29 at 1630–1638 UT. At 1600 UT, B_z is −6.5 nT having an AE index of 669 nT and $\varepsilon = 4.2236 \times 10^{11}$ W which is sufficient for a substorm to develop. This PMD is connected with southward IMF.

(iv) April 24 (2300 UT 30′)–April 25 (1500 UT) 1979 [Figure 2(d)] :

During this storm, the energy input into the magnetosphere is rather high ($> 10^{12}$ W) (April 25) except at 0900 UT where ε is reduced to 1.6491×10^3 W (dotted line). At 0700 and 1300 UT even if IMF is northward (B_z = 12.5 and 0.3 nT), ε is found to be 4.0537×10^{11} W and 1.7935×10^{12} W respectively. During 1000–1200 UT, E_y (> 50 mV/m) as well as ε ($> 4 \times 10^{12}$ W) is rather high as indicated in Figure 2d. On April 25, 1979 between 1000 and 1200 UT, a PMD was reported and during this time ε has its highest range (> 4×10^{12} W).

(v) August 29 (0530–1900 UT) 1979 [Figure 2(e)] :

Throughout the storm, the IMF B_z is southward except at 0800 UT where IMF is northward (6.6 nT) and causes a reduction in input energy from ~10^{12}W to 1.1507×10^{10} W. When ε is between 10^{11}–10^{12} W, the magnetosphere is considered to be in the substorm state. Growth and decay of substorms is controlled primarily by a rise and fall of ε and E_y respectively which in turn depends on the direction of IMF B_z. During this storm no plasmoid was reported.

(vi) September 17 (2100 UT)–September 18 (1600 UT) 1979 [Figure 2(f)] :

On September 17 at 2400 UT, ε decreases to 1.2716×10^{10}W but AE remains in its highest range (639 nT). A large variation can be seen on the coupling parameter and maxima occurs at 0100 ($B_z = -13.6$ nT, $\varepsilon = 1.9235 \times 10^{12}$ W), 0700 ($B_z = -14.1$ nT, $\varepsilon = 2.3552 \times 10^{12}$ W), 0800 ($B_z = -15.5$ nT, $\varepsilon = 2.3103 \times 10^{12}$ W) and at 1400 UT ($B_z = -11.7$ nT, $\varepsilon = 1.1794 \times 10^{12}$ W). During this storm also no plasmoid was observed.

The magnetosphere-solar wind energy coupling is strongly influenced by the orientation of the IMF. When the southward period is abruptly ending, this disturbance itself may act as a trigger. The same situation holds good for August 29 [Figure 2e] and March 28-29 [Figure 2c] storm. Even if IMF turns from southward to northward [*e.g.*, March 28 (1800–2000 UT), March 29 (0500 UT)], ε remains at its highest values (> 10^{11} W) and this energy is sufficient to trigger a substorm. Tsurutani and Gonzalez [14] showed that the typical efficiency of solar wind energy injection into the magnetosphere is 100 to 300 times less efficient than during periods of intense southward IMFs. The results of all the six storms revealed that the solar wind energy input into the magnetosphere is high during southward IMF than northward IMF [*e.g.*, Figures 2(a)–(d)].

In the selected storms, at 1100 UT on March 22, 1600 UT on March 29 and 1000–1200 UT on April 25, 1979 [Figure 2(b)–(d)] we have found enhancements in the crosstail electric field which are associated with the PMD events is in agreement with Slinker *et al* [15]. They reported strong enhancements in crosstail electric field E_y on the PMD passage. Nishida *et al* [16] observed that in geomagnetically active times, E_y is directed from dawn to dusk and in quiet times it is directed from dusk to dawn. All the selected storms in the present work [Figures 2(a)–(f)] indicated that E_y is directed in the southward direction when the energy input into the magnetosphere is high (active times) and is northward directed when ε is low (quiet times).

Our study on selected storm events which occurred in summer, winter and equinotical months of solar maximum shows that the energy input into the magnetosphere is high in summer (*e.g.*, August 29, 1979) and in equinotical (*e.g.*, March 28–29 and April 24–25, 1979) period. Almost in the entire storm period, ε is found to be > 10^{11} W for storms in summer and equinotical period than in winter. This revealed that the coupling should be strong in summer and equinotical months of 1979 solar maximum than in winter.

4.3. Geomagnetic activity dependence of plasmoids :

Table 2 shows the IMF B_z component, AE and K_p indices and the computed values of ε and E_{TS}, of Coordinated Data Analysis Workshop (CDAW 8) PMDS observed in 1983 [January 27 (0251–0255), January 28 (0827–0845, 2214–2227), March 16 (1211–1222), March 17 (0214–0233), March 18 (2228–2240) as well as the PMDS reported on April 25 (1112), March 22 (1058) and March 25 (1630 UT) of solar maximum, of an hour prior to PMD, at the onset of PMD and an hour after PMD observations. The hourly values of solar wind parameters, AE and D_{st} are used in the present study

The energy input into the magnetosphere was higher approximately one hour before the time of PMD observation on January 27, 1983 and April 25, 1979. E_{TS} exceeds at the time of PMD interval on January 27 (ε = 1.7 × 10^{11} W, E_{TS} = 1.9 × 10^{11} W), March 17 (ε = 1.7 × 10^{11} W, E_{TS} = 1.8 × 10^{11} W) and March 18 (ε = 8.7 × 10^{11} W, E_{TS} = 9.2 × 10^{11} W) of 1983. Of the nine cases studied (Table 2) formation of eight plasmoids are associated with southward IMF. On March 22, 1979 a plasmoid is formed at 1058 UT where the IMF (10.6 nT) is in the northward direction. At 1100 UT, IMF turns southward (–12 nT). Here, the plasmoid formed can be classified as a proto-plasmoid since it is formed during northward IMF. Moldwin and Hughes [6] suggested that proto-plasmoids are plasmoids that did not completely form because the reconnection process stopped before all the field lines could reconnect AE index is found to be > 200 nT except on January 27 (AE = 165 nT) and March 16 (68 nT) and the K_p index during the same period is > 3 except on January 28 (K_p = 1) at 0827–0845 UT. The IMF B_z, AE and K_p (> 3) indices values on an hour prior to PMD observation, at the onset of PMD and an hour after PMD observation time shows a geomagnetically active period. Thus from Table 2, it is clear that the PMD observation periods (one hour prior to, at the time of and one hour after PMD observation) are associated with a geomagnetically active period.

Renuka *et al* [17] reported that the total energy content in a plasmoid is ~ 10^{14} J. The rate of energy loss due to PMD ejection was found to be ~10^{11}–10^{12} W. As an example, the energy loss rate E_{pmd} due to PMD ejection in January 28 is estimated as 2.77965 × 10^{11} W. Since its duration is 25 mins (Table 2), the total energy content in the PMD is 4.1695 × 10^{14} J. The total solar wind energy transferred to the magnetosphere over a period of one hour is 9.2 × 10^{14} J and the corresponding E_J, E_A and E_R are 7.5 × 10^{13} J, 1.1 × 10^{13} J and 4.2 × 10^{14} J respectively so that E_{TS} is 5.06 × 10^{14} J. The input energy (9.2 × 10^{14} J) and the dissipated output (5.06 × 10^{14} J) energy differs by 4.14 × 10^{14} J and this difference in energy goes down the solar wind in the form of PMDs. Here. the energy carried away from the magnetosphere by the PMDs is 4.16 × 10^{14} J and the difference in energy is 4.14 × 10^{14} *J* which shows that the PMD energy content is a fraction of the energy available to drive a substorm. The rate of energy loss due to PMD ejection (2.77 × 10^{11} W) is comparable to the energy dissipated in the ionosphere (1.166 × 10^{11} W) through Joule heating. These results

Table 2. B_Z, AE, K_P, ε and E_T of an hour prior to, during and after plasmoid observation period.

Time	One hour prior to plasmoid					At the time of plasmoid					One hour after plasmoid observation				
	B_Z	AE	K_P	ε	E_T	B_Z	AE	K_P	ε	E_T	B_Z	AE	K_P	ε	E_T
UT	nT	nT		10^{11} W	10^{11} W	nT	nT		10^{11} W	10^{11} W	nT	nT		10^{11} W	10^{11} W
Jan. 27, 1983 (0231–0255)	−1.4	97	2^+	2.5	2.5	−1.5	165	3	1.7	1.9	−0.5	187	3	1.4	1.9
Jan. 28, 1983 (0820–0845)	−3.3	118	2^-	-	0.7	−3.1	208	1	2.6	1.4	−1.6	75	2^+	-	-
Jan. 28, 1983 (2214–2227)	−1.8	252	3^-	2.5	11.8	−7.5	541	4	5.61	2.4	−5.3	495	3^-	0.5	4.0
March 16, 1983 (1211–1222)	2.3	175	2^-	-	-	−2.4	68	4	-	-	−3.4	657	1^+	3.6	4.3
March 17, 1983 (0214–0233)	0.8	188	4^-	0.6	0.7	−1.5	394	3^+	1.7	1.8	−0.4	390	2^+	0.9	1.2
March 18, 1983 (2228–2240)	−7.2	276	4	0.4	0.8	−4.5	613	6^-	8.7	9.2	−3.9	533	5^-	9.3	10.4
April 25, 1979 (1112)	−8.3	715	-	48.3	12.2	−9.3	1275	-	44.0	8.5	−17.9	1202	-	49.1	10.8
March 29, 1979 (1630)	−6.2	358	5^-	3.2	0.9	−6.5	669	5^-	4.2	0.9	−8.3	662	5^-	3.2	0.12
March 22, 1979 (1058)	10.6	273	4	0.00001	0.5	−12.0	656	6^-	36.5	32.1	1.3	463	6^-	11.2	0.00

reveal that the energy released in a substorm is roughly equipartitioned between three different deposit regions namely auroral ionosphere, ring current and down tail solar wind.

The energy content in a PMD increases with the longitudinal extent of the PMD [18] which shows that PMD size depends on the intensity of substorms and hence, the energy input into the magnetosphere. Thus, it can be concluded that PMD formation depends on geomagnetic activity.

4.4. IMF and plasmoids :

This section deals with the variation of E_{TS} and AE index with northward as well as southward IMF B_z and hence studies the dependence of IMF B_z orientation to PMD formation.

The present study on the selected storm events showed that the input power ε, rate of power dissipation E_{TS} and AE index increases as B_z is more and southward and decreases when the IMF is northward. However, we have found enhancements in these values even for positive B_z and this is due to the dissipation of energy that has been previously stored in the tail during the southward IMF. As an *e.g.*, for the storm in February 21, 1979 at 1800 UT when IMF B_z is 2.5 nT, ε is found to be 1.762×10^{12} W for an AE index of 794 nT. For the storm on April 25, 1979 at 0700 and 1300 UT even if IMF B_z is northward (12.5 nT and 0.5 nT), ε is 4.05×10^{11} W and 1.79×10^{11} W for AE indices of 952 nT and 897 nT. Raeder *et al* [19] suggested that the tail reconnection is significantly weaker when the IMF is northward than when it is southward. The present work showed that classic PMD formation is associated with southward IMF (section 4.3) which is in agreement with Raeder *et al* [19]. Thus PMD formation is found to depend on the energy input into the magnetosphere and substorms. From our analysis it appears that abrupt transient variation in IMF B_z direction may enhance the rate of energy transfer from solar wind to magnetosphere (ε) which in turn causes the geomagnetic substorms to take place as well as occurrence of plasmoids.

5. Conclusion

The present study reveals that the sunspot numbers did not greatly influence on geomagnetic activity during 1979-90. We found that plasmoid formation is associated with geomagnetic activity as well as southward and northward IMF. Plasmoid size is found to depend on energy input into the magnetosphere.

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