Geomagnetic Storms and Related Solar Phenomena

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地磁気嵐と太陽面の関連現象

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要旨：1977年1月から1978年6月までの1年半の期間に起きた磁気嵐に対して，その原因と考えられる太陽フレアおよびコロナホールの対応づけを行った．判定の基準は，(1) 太陽面現象と地磁気嵐の時間的関係，(2) 太陽風の速度，密度，温度等の変化の特徴，(3) コロナホールの磁場極性と惑星空間の磁場極性の比較，(4) 太陽フレアおよび同時に発生する電波現象の特徴による磁気嵐を起こす確率の評価等である．この結果，上記の1年半に起きた44例の *Dst* が -50γ を越す磁気嵐のうち40例の原因が推定できた．調査の対象とした期間は，一般には地磁気じょう乱の回帰性が低下するといわれる太陽活動の上昇期にあたるが，いくつかのはっきりした回帰性地磁気嵐の系列が認められ，原因となるコロナホールともよく対応している．また，この期間の特徴として，寿命の短いコロナホールが存在し，それらが原因となる地磁気嵐が多数認められた．

Abstract: This is an attempt to identify the causes of geomagnetic storms which occurred during a year and a half from January 1977 to June 1978. The assignment of geomagnetic storm causation to appropriate coronal holes or solar flares has been made by considering (1) their apparent association with storms, (2) characteristic variations in the solar wind velocity, density, and temperature, (3) coincidence between the coronal hole magnetic field polarity and the interplanetary magnetic field polarity, and (4) storm productivity of solar flares judged mainly from associated radio emission. Of the 44 magnetic storms of $Dst \leqq -50\gamma$ in the 1.5 year period investigated in this paper, 40 storms are found to be explicable by either coronal holes or solar flares. The examined 1.5 year period is in the increasing phase of solar activity in which the recurrence tendency of geomagnetic disturbance is expected to be weak. Actually, however, several series of recurrent magnetic storms have been found which are generally well correlated with coronal holes. It is also shown that there are a number of non-recurrent sporadic storms which are associated with short-lived coronal holes in addition to those series of recurrent geomagnetic storms.

1. Introduction

Many attempts have been made to identify the causes of geomagnetic storms

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during the last several decades (see COOK and MCCUE, 1975, and references therein). In the earlier studies, in general, geomagnetic storms were divided into two groups of 27-day recurrent storms and non-recurrent sporadic storms, and much effort was devoted to relating the storms of the latter group to solar flares having occurred during the preceding three or four days. In particular, those studies directed towards the flare-associated radio emission showed that flares with type II and type IV radio bursts cause subsequent magnetic storms with the highest probability (DEFEITER *et al.*, 1960; DODSON and HEDEMAN, 1964), and that radio energy emitted at meter wavelengths is an important factor controlling the occurrence of magnetic storms (SINNO and HAKURA, 1958; NISHIDA, 1965, PINTER, 1972).

Although the foregoing studies thus revealed some of the important characteristics of the solar flares responsible for geomagnetic storms, there is a certain ambiguity in their procedure to divide magnetic storms into the two categories. It is because the classification of recurrent storms is generally defined only by 27-day recurrence patterns.

In recent years there has been great progress in our understanding of the relationship between recurrent magnetic storms and corotating solar wind streams emanating from long-lasting coronal holes (NEUPERT and PIZZO, 1974; BELL and NOCI, 1976, NOLTE *et al.*, 1976; HANSEN *et al.*, 1976; SHEELEY *et al.*, 1976). These studies generally conclude that large, near-equatorial coronal holes are associated with high-speed streams observed near the earth which produce geomagnetic disturbances. In particular, NOLTE *et al* (1976) not only confirmed the apparent association between high-speed streams and coronal holes, but also showed that the interplanetary magnetic field (IMF) polarity in the streams associated with coronal holes is well correlated with the solar magnetic field polarity below the coronal holes. Their results provide the possibility to determine recurrent-type magnetic storms in a more reliable manner than only by 27-day recurrence patterns and to identify the causes of individual recurrent magnetic storms.

The purpose of this paper is to examine how well the causes of individual magnetic storms can be assigned to coronal holes or solar flares with the use of recent data from January 1977 to June 1978. Since this period is in the increasing phase of solar activity in solar cycle 21, it is also intended to see the difference, if any, in the evolutionary changes of coronal holes from those in the declining phase of solar activity to which most foregoing studies were restricted.

2. Data and Procedure

Geomagnetic storms investigated in this study are taken from the lists of principal magnetic storms in Solar Geophysical Data (SGD: published monthly by National Geophysical and Solar-Terrestrial Data Center, Boulder). We have chosen only those major magnetic storms with *Dst* lower than -50γ which were reported by at least five geomagnetic observatories. The coronal hole data are synoptic maps of inferred coronal hole boundaries published in SGD, which have been constructed from the HeI 10830 Å observations by Kitt Peak National Observatory. The Hα synoptic maps from SGD are used to determine the polarity of coronal holes. The solar flare and associated radio emission data are taken from the prompt report through the URSIGRAM network, and also from SGD whenever necessary. Other data used in this study to identify the causes of individual magnetic storms are the solar wind velocity, density and temperature determined from the plasma experiments on IMP's 7 and 8 by MIT (Massachusets Institute of Technology), the IMF polarity inferred from the ground geomagnetic observations, and the mean solar magnetic field (MSMF) from Stanford Solar Observatory; they are all published in SGD.

The causation of magnetic storms is assigned to solar flares, if the storms are preceded within the prior 1 to 3 days by flares that seem to be capable of causing magnetic storms. The following are the factors considered in evaluating the storm-producing capability of solar flares:

(1) Hα importance and duration of the flare and structural complexity of the flare region. The flares of Hα importance$\geqq 2$ from magnetically complex sunspot regions are considered to be possible to cause magnetic storms.

(2) Associated occurrence of type II and type IV radio bursts. Greater importance is attached to type IV bursts, particularly at meter wavelengths. In the case of combined occurrence of type II and type IV bursts, the highest probability of magnetic storms is expected.

(3) Intensity and duration of radio emission at meter wavelengths. If the radio events with peak flux around 200 MHz greater than 500 s.f.u. (10^{-22}W/m^2/Hz) and duration longer than 15 minutes are associated with flares, such flares are considered to be capable of producing storms (SINNO and HAKURA, 1958).

(4) Frequency coverage of the associated radio events. The full frequency coverage from about 100 to 10000 MHz is taken as an important factor to estimate the flare-released energy. In fact, it has been shown that the increase in the flux density with frequency in the centimeter range is an important factor controlling the proton emission from the solar flares (CASTELLI *et al.*, 1967).

(5) Position of flares on the solar disc. Flares in the central region of the disc most probably cause magnetic storms, and flares in the western hemisphere tend to cause magnetic storms with higher probability than those in the eastern hemisphere (SINNO and HAKURA, 1958).

As is evident, none of these factors is conclusive by itself. Therefore, the final assignment of storm-causation to an appropriate flare is made rather subjectively by considering the degree to which the flare satisfies the above factors or criteria. If a solar proton event is associated with the flare under consideration, the storm producing capability is evaluated to be high.

The association between geomagnetic storms and coronal holes is evaluated with the following factors:

(1) Heliographic latitude of coronal holes. To assign the storm causation in the present attempt, only those coronal holes are taken into consideration, of which significant portions lie within ±30° latitude from the sub-earth point on the sun.

(2) Coincidence of the coronal hole longitudes with the estimated source longitude of high-speed streams. When the solar wind data are available, the estimation of the source longitude has been made by assuming a constant-speed radial flow. It has been shown that the source longitude can be determined in this way with an accuracy of about 10° (NOLTE and ROELOF, 1973).

(3) Time delay between the central meridian passage (CMP) of coronal holes and the arrival of corotating streams. The 2-to-4 day delay is assumed from the coronal hole CMP to the storm occurrence when the solar wind data are not available.

(4) Coincidence of the IMF polarity with the coronal hole magnetic field polarity.

In addition to the judgement from the factors listed above, it is sometimes possible to discriminate between the recurrent-type magnetic storms and the flare-associated storms in terms of variations in the solar wind velocity, density and temperature. In some typical cases, the solar wind data exhibit the characteristic stream-interface structures which can be considered to be caused by the stream-stream interaction at the front of corotating fast streams (BURLAGA, 1975).

3. Causation of Magnetic Storms during January 1977–June 1978

Fig. 1 exemplifies a typical recurrent-type magnetic storm which is apparently associated with a coronal hole and not preceded by any energetic solar flare. The left-side diagrams show the variations in the solar wind velocity, density and temperature (proton thermal velocity), the *Dst* and *Kp* indices, and variations of the IMF polarity inferred from the ground geomagnetic observations and of the MSMF polarity. The negative polarity is indicated by shading. The dates for the MSMF polarity are shifted by five days in accordance with the transit time of the slow solar wind from the sun to the earth. The right-side diagram is the synoptic map of coronal hole boundaries. The coronal holes with negative polarity are indicated by shadings.

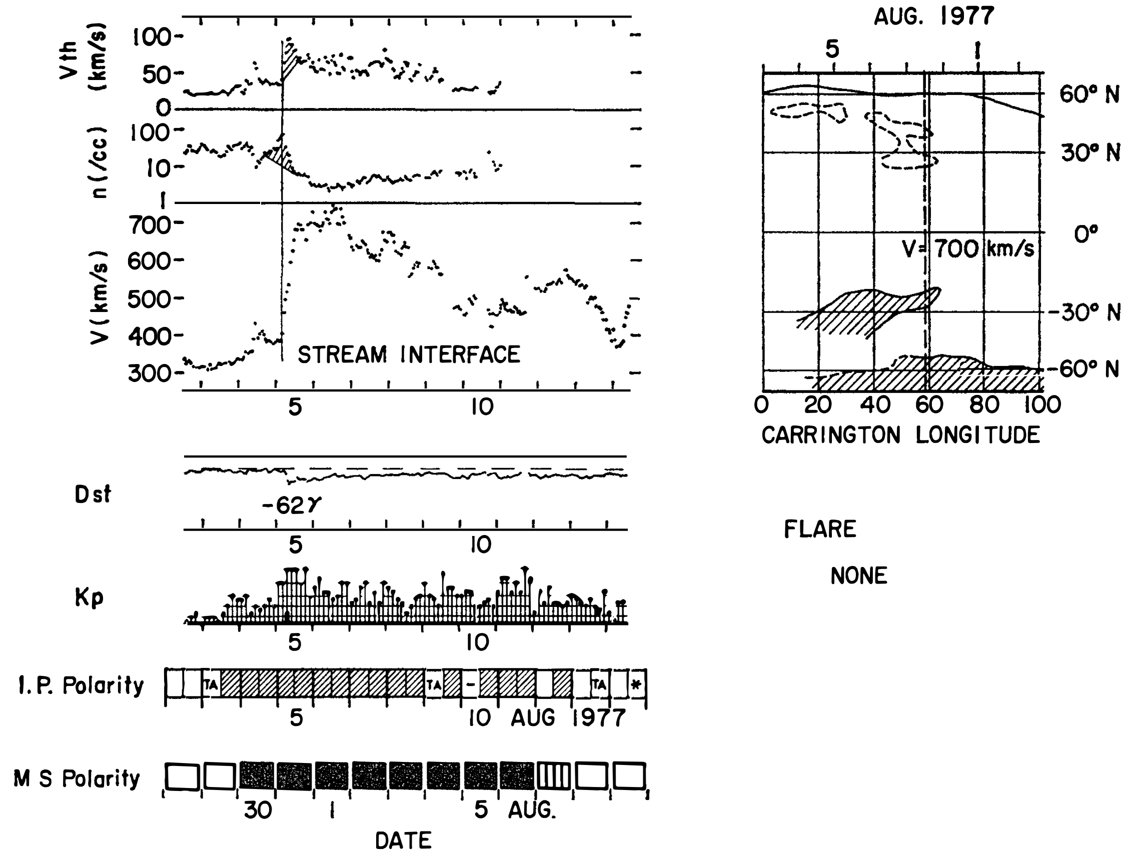

Fig. 1. A typical example of magnetic storm caused by corotating fast stream. On the left are shown variations in solar wind plasma parameters, Dst, Kp, interplanetary magnetic field polarity (dark: negative), and mean solar magnetic field polarity (black: negative). On the right the estimated longitude of stream source is compared with the coronal hole location.

The magnetic storm occurred at about 2300 UT on August 4, 1977 with gradual commencement, and *Dst* reached the minimum value of -62γ at 1100 UT on August 5. The solar wind speed started to increase sharply at about 0300 UT and reached a maximum of 700 km/s around 1400 UT on August 5. A region of high pressure called the interaction region is seen in this rising part of the speed profile extending somewhat ahead of the point where the speed begins to increase. The start time of the storm nearly coincides with the arrival of the interaction region. It is also seen that the region of enhanced density is displaced ahead of the enhanced temperature region as is indicated by shading. According to BURLAGA (1974), these two regions are separated by a thin boundary called the stream interface. In the present case, the stream interface can be seen around 0500 UT as indicated in the figure. The stream interface is considered as the front surface of the corotating fast stream when estimating the location of the stream source.

The heliographic longitude of the stream source can be estimated by assuming that the solar wind velocity was constant and was in the radial direction all the way from the sun to 1 AU Based on the view that the stream had been decelerated from the initial speed near the maximum observed speed of the stream, 700 km/s is taken as the constant speed in estimating the source longitude in this case The estimated source longitude is shown in the figure by a dashed line It can be seen in Fig. 1 that the source location nearly coincides with the location of the near-equatorial coronal hole with negative polarity, in concert with the IMF polarity and the MSMF polarity.

Fig. 2 exemplifies typical flare-associated magnetic storms. There occurred two SC-type magnetic storms successively at 2042 UT on January 3, and at 1628 UT on January 5, 1978 The solar wind data show characteristic shock structures with sudden jumps in velocity, density and temperature at the times of SC's Prior to these magnetic storms, several solar flares took place in the McMath plage regions 15081 and 15083 which existed in the central region of the solar disc Of those solar flares, two flares shown in the figure were associated with intense radio emission with the full frequency coverage of 100–10000 MHz

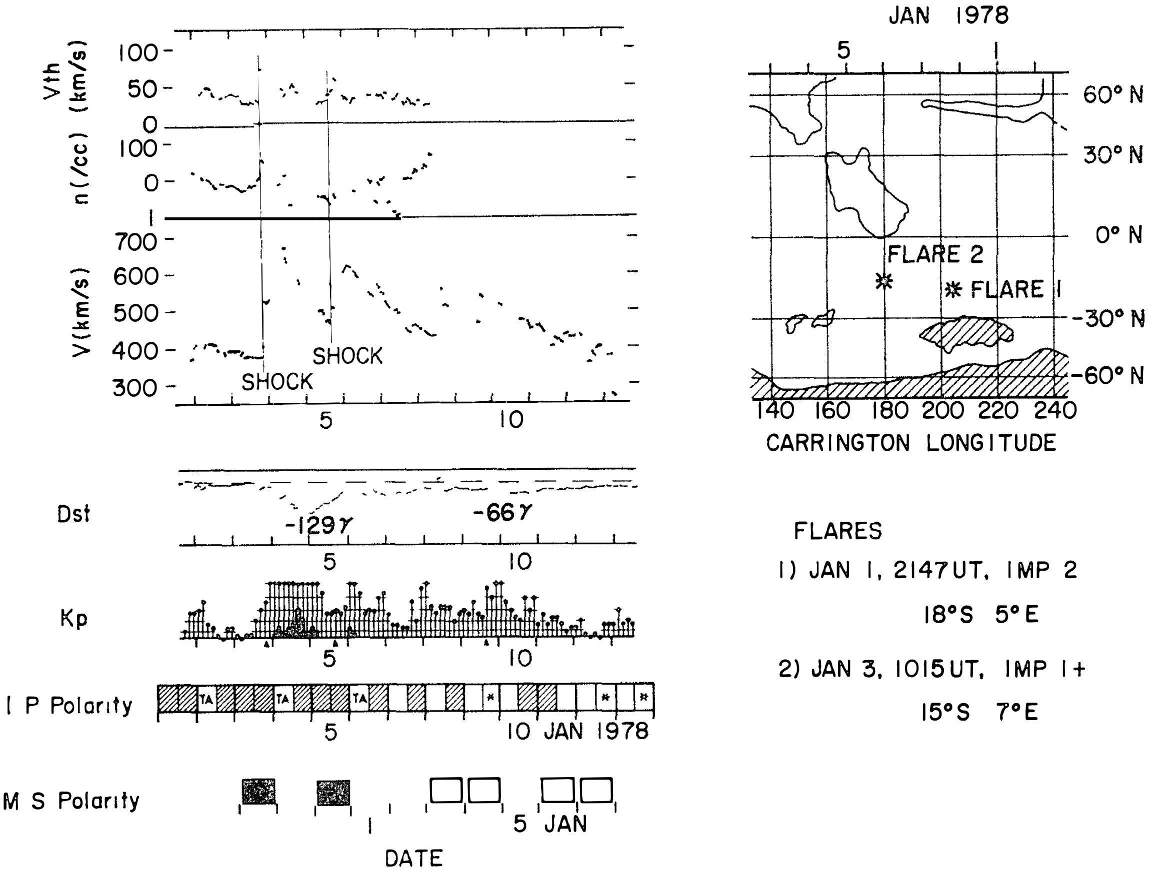

Fig 2 Same as Fig 1 except for typical flare-associated storms.

The first one is the flare of Hα importance=2 having occurred at 2147 UT on January 1 at 18°S 5°E (McMath No. 15081). This flare was associated with type II and type IV radio bursts, and the 200 MHz radio emission continued for more than one hour with the peak flux density greater than 1200 s.f.u. The second flare is the importance 1_+ flare at 1015 UT on January 3 at 15°S 7°E (McMath No. 15083). This flare was also associated with type II and type IV radio bursts and strong, long-lasting meter wave emission (from SGD). Therefore, it is reasonable to assign the causes of the two SC's to these two solar flares. The equatorial coronal hole at the 190°–160° longitude is considered to be responsible for the disturbance on January 8 (see also Fig. 3).

Table 1 summarizes the association between all the major magnetic storms and coronal holes or solar flares during the period from January 1977 to June 1978. In the table, the storm commencements of uncertain type are indicated by brackets. (For storms No. 32 and No. 41, SC's are reported just after the starts of storm intervals; see also Fig. 3.) The magnitude of the storm is represented by the sum of the *Kp* indices for the 24-hour period that gives the maximum value during the storm interval (the notation $\overset{s}{\sum}$ is used in the table to emphasize this), and also by the lowest *Dst* level. The coronal holes listed in the table are those within ±10° longitude from the estimated source location of the solar wind stream and within ±30° latitude from the sub-earth point on the sun. The longitude ranges of coronal holes are defined for the portion within the above-mentioned latitude range. The coronal holes are classified into three types; near-equatorial (E), extended from the northern polar region (PN), and extended from south (PS). Unstable or questionable coronal holes are indicated by attaching U. The coronal hole data taken from the Preliminary Report from ERL/NOAA are bracketed. The polarity of coronal holes has been determined by comparing coronal hole boundaries with Hα synoptic charts. Uncertain polarity is indicated by X. The MSMF polarity is also listed, which is taken from the date when the solar wind started from the source region near the sun. The inferred IMF polarity is shown for three 12-hour intervals beginning with the interval in which each magnetic storm commenced. Naturally, the MSMF polarity is, in general, coincident with the polarity of the coronal hole in the central region of the solar disc. It can also be seen that the coronal hole polarity generally coincides with the IMF polarity particularly in the second interval in case of storms associated with coronal holes.

In the last column of the table, the association between these 44 major magnetic storms and coronal holes and/or solar flares is shown with the degree of confidence in three grades; double circle=excellent, circle=good or fair, and triangle=possible. These grades have been determined subjectively depending on the degree to which criteria for the association mentioned before are satisfied. The question mark attached

Table 1. Association of major magnetic

Storm No.	Commencement			End	Magnitude		Coronal hole			
	Date	Time (UT)	Type	Day hr (UT)	$\sum^{8} Kp$	*Dst*	Type	Long.	Lat	Polarity
	1977									
1	Jan. 28	1839	SC	31 15	34−	−69	EU	42- 29	18N-37N	−
2	Apr. 6	12--		9 22	45	−110	E E	212-200 208-185	2N-12N 22S-42S	X −
3	Apr 19	0106	SC	20 18	40−	−97	E	57- 46	21S-33S	−
4	May 1	15--		3 12	44	−98	PN	281-270	23N-	+
5	May 11	06--		12 14	32	−65	E	164-139	17N-32N	+
6	July 29	0027	SC	30 13	40−	−100	E	182-149	5S-22N	+
7	Aug. 4	23--		8 08	36	−62	E	63- 12	20S-40S	−
8	Aug 17	04--		19 14	32−	−54	PN	(262-225)	30N-	+
9	Aug 25	05--		26 01	31+	−56	E E	179-165 169-153	24S-35S 2N-23N	+ +
10	Sep 12	2113	SC	14 11	33−	−68	PN	254-243	26N-	+
11a	Sep 19	1138	SC	cont			E	184-150	8S-25N	+
11b	Sep. 21	2044	SC	24 04	46−	−103	E	172-162	26S-32S	+
12	Sep 26	0732		27 13	34+	−95	(E	100- 83	31N-40N	−)
13	Oct 11	1300	.	13 16	34−	−81	(E	261-245	27N-45N	+)
14	Oct 14	1151	SC	16 09	28	−62		none		
15	Oct. 18	1000		19 20	35−	−108	E	184-172	3N-13N	+
16	Oct 21	2300		22 23	28+	−79	EU EU E	152-133 140-129 130-120	21S-33S 0N-12N 25N-35N	X − X
17	Oct 26	2330	SC	29 02	47	−172		none		
18	Nov 12	01--		16 15	39+	−76		no data		
19a	Nov 25	1227	SC	cont.						
19b	Nov 26	1704	SC	27 14	29+	−98	PS	15- 0	27S-	−
20	Dec 1	2029	SC	3 20	44	−136		none		
21	Dec 4	1400		5 23	31−	−85	E	280-253	18N-38N	+
22	Dec 10	2000		13 15	37	−125	PN	205-148	3S-	+

storms with coronal holes or solar flares.

Mean solar mag. field	Solar wind		Flare					Radio burst type		Association	
	Polarity	Speed	Date	Time (UT)	Position	Imp.	ΔT (hr)	II	IV	CH	F
−	+−−	470								△	
−	−−+	680								○	
−	−−X	580								◎	
+	CX+	450								△	
+	++X	350								△	
+	+X+	450								◎	
−	−−−	700								◎	
+	+−−	650								△	
+	+++	470								◎	
+	+++	400	Sep. 9	1604	10N 80E	2+	77			△	△
+	X+X	420	Sep. 16	2120	8N 20W	2+	62	yes	yes		◎
+	−X−	>700	Sep. 20	0321	15N 55W	3	41				◎
U	++−	400	Sep. 24	(0554)	unknown		49				△
−	+++	470								◎	
−	X−+	470	Oct. 12	0151	8N 3W	1	58	yes	yes		◎
+	+++	480								◎	
+	+++	450								△	
+	CX−	370									
+	+++	420								?	
+	++−	350	Nov. 22	0930	23N 40W	2	75				○
−	−−C	540								◎	
+	−+−	370									
−	++−	430								○	
+	−+U	500						yes	yes	◎	

Table 1

Storm No	Commencement			End	Magnitude		Coronal hole			
	Date	Time (UT)	Type	Day hr (UT)	$\overset{s}{\sum} Kp$	Dst	Type	Long	Lat	Polarity
	1978									
23a	Jan 3	2042	SC	cont.			E	225–193	29S -46S	—
23b	Jan. 5	1628	SC	7 03	50−	−129				
24	Jan 9	1625	SC	10 22	31	−66	E	189–160	1S -33N	+
25	Jan. 16	0800		17 01	26	−64	E	107– 90	22S -40S	+
26	Jan 28	1853	SC	31 24	35+	−96	(PS	247–230	23S -	—)
27	Feb 14	2147	SC	16 03	35	−118	E	12– 1	10S -23S	—
28	Feb 21	0800		22 23	28−	−73	E	311–297	29S -40S	X
							E	296–277	14N-30N	+
29	Feb 25	1928	SC	3 03	38	−80	PS	220–190	13S -	—
30	Mar 8	1439	SC	10 00	29+	−111		no data		
31	Mar 16	0100		18 00	32	−53	E	11–349	13S -30S	—
32	Mar 25	2200	( )	28 22	45+	−110	PS	215–189	18S -	—
33	Apr 2	2057		6 04	38−	−120	EU	129–116	22S -38S	+
34	Apr 10	1306	SC	12 20	44	−127		none		
35	Apr 13	1100		15 16	42−	−86	E	347–342	10N-19N	—
							E	345–337	20S -28S	—
36	Apr 17	2345	SC	21 02	39+	−71	E	285–261	28S -40S	+
37	Apr 23	1400		25 21	39+	−78		none		
38a	Apr 30	0951	SC	cont			PN	104– 84	11N-	+
38b	May 1	0828	SC	cont.						
38c	May 1	1835	SC	cont						
38d	May 2	2318	SC	4 23	55	−218				
39	May 8	11--		10 03	46+	−191	EU	34– 23	5S - 8N	—
40	May 10	2005	SC	11 22	32+	−110		none		
41	May 20	1600	( )	24 18	35	−115	(E	224–197	22S -41S	—)
42	May 29	1831	SC	31 03	26+	−86		none		
43	June 1	2143	SC	4 04	47+	−61	PN	87– 70	25N-	+
44	June 4	1211	SC	6 02	38	−75		none		

(*continued*).

Mean solar mag. field	Solar wind		Flare					Radio burst type		Association	
	Polarity	Speed	Date	Time (UT)	Position	Imp.	ΔT (hr)	II	IV	CH	F
−	−X−	520	Jan 1	2147	18S 5E	1	47	yes	yes		◎
ND	−X−	650	Jan. 3	1015	15S 7E	1+	54				◎
+	U+−	540	Jan. 7	0123	23S 60W	1	63	yes	yes		◎
+	+−+	330								△	
−	−−−	580								○	
−	+−−	630	Feb 13	0129	15N 15W	2	44	yes	yes		◎
+	−++	470								△	
−	+−C	650								△	
	C+−		Mar 6	(1150)	21N 7W	2	51				○
	−−−									○	
	X−−									○	
	+++									△	
	+X+		Apr. 8	0123	19N 3W	1	60		yes		◎
	−−−		Apr 11	1334	19N 57W	2+	45		yes	△	○
	−++		Apr 15	0637	15N 8W	0	65	yes	yes	○	○
	−−−										
	X−+		Apr. 28	1308	22N 41E	4+	45				◎
	+−−		Apr. 29	1854	22N 19E	3+	37				◎
	−−+		Apr. 30	1439	20N 11E	3+	28				○
	C−+		May 1	1914	22N 10W	3+	28				○
	+C+		{May 6	(2013)	unknown		39	yes	yes		○
			{May 7	0320	22N 64W	2+	32	yes	yes		
	+−−		May 8	1212	22N 76W	2+	56		yes		◎
	+++										
	−−−		May 26	1734	18N 54E	1+	73				△
	−++		May 31	1009	23N 50W	2+	36			○	○
	−−−										

to the storm No. 18 indicates that this storm was probably caused by the corotating stream from the coronal hole although no coronal hole data were available. Blanks in this column indicate that appropriate causation could not be found.

It is noticed that there are a number of SC-type storms caused by streams from coronal holes, and that 40 storms out of 44 major magnetic storms could be explained by coronal holes or solar flares. Further, it can be said that the causes of the unexplained 4 storms may become clearer, if more data particularly of solar flares and solar wind parameters become available. In fact, the storm No. 37, for example, may be explained by the corotating stream as is mentioned in the next section.

Finally, it is interesting to note that the time of the flare occurrence nearly coincides with the time of coronal hole CMP in some cases (storms of Nos. 10, 11, 24, 27, 36, 38, 43). The close examination of these cases suggests that magnetic storms seem more likely to be caused by solar flares when the flare position was just on the west side of the coronal hole. It would be reasonable to suppose from this tendency that the flare-associated shock will arrive at the earth earlier than the corotating stream because the shock will propagate ahead of the stream

4. Summary of Geomagnetic Disturbances during January 1977–June 1978

Geomagnetic activity during January 1977–June 1978 is illustrated in Fig. 3, where $\sum Kp$, $\sum K$ from Kakioka (36°N, 140°E), and the lowest Dst value in every 12-hour interval are plotted in the Bartels' recurrence diagram. The magnetic storm intervals and SC's taken from SGD are also shown by horizontal bars and triangles, respectively. In particular, the storm intervals and SC's reported by at least five observatories are indicated by thick bars and solid triangles. The storm numbers in Table 1 are also attached to the major magnetic storms. As a reference, the magnetic storm predictions through the International Ursigram and World Days Service network are also shown at the bottom of the diagram for each 27-day interval.

For major magnetic storms and some other minor disturbances, their possible association with coronal holes or solar flares is indicated by attaching the letter H or F. The association with the unstable or questionable coronal holes is indicated by Hu. The magnetic polarity of the coronal holes is also shown. The major storms of which apparent causation could not be found are indicated by attaching double question marks.

We can identify three distinctive series of recurrent magnetic storms in this period. The most remarkable series began with the SC-storm having occurred at 0027 UT on July 29, 1977 (rotation 1968, storm No. 6), and lasted to the gradual storm on De-

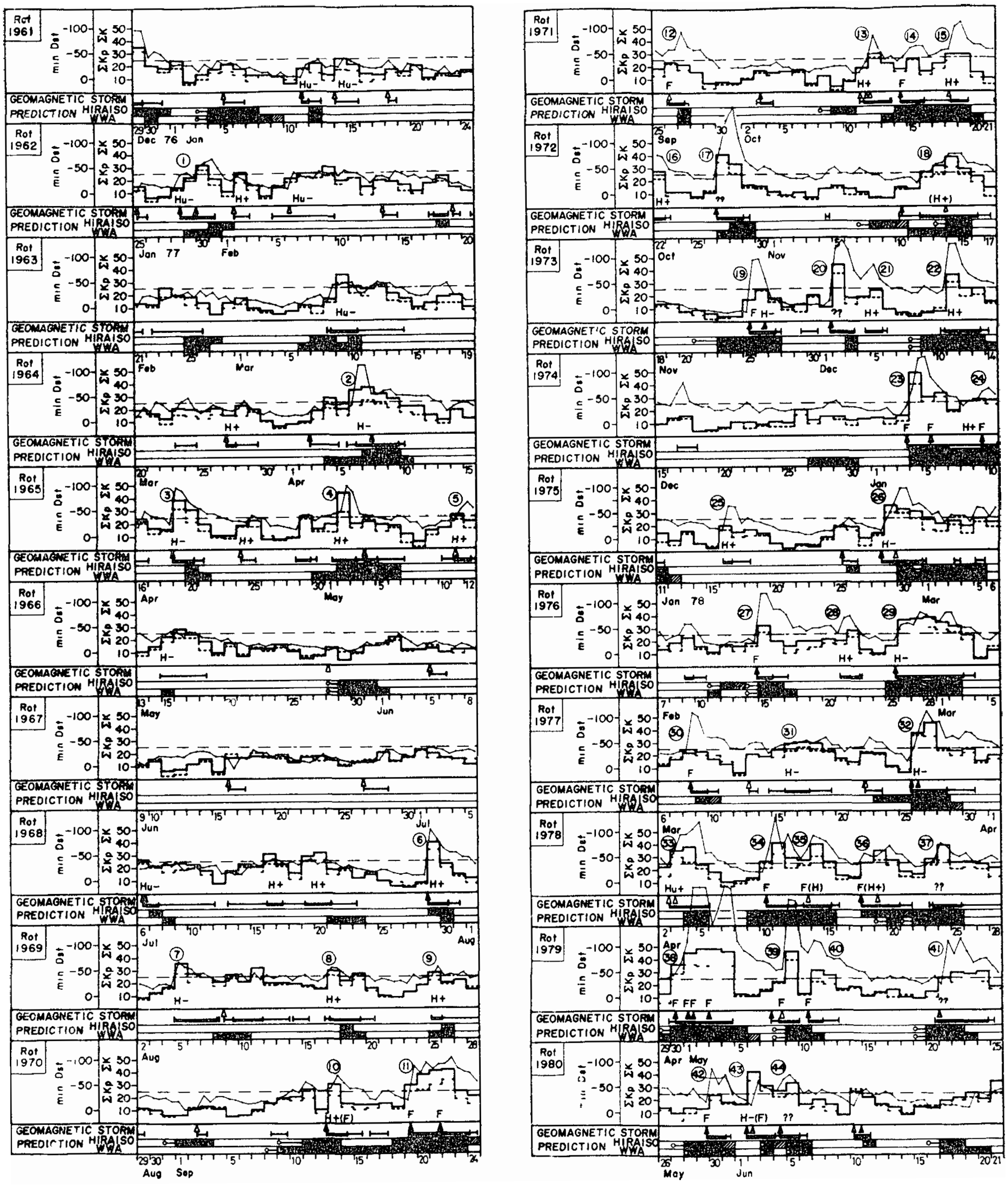

Fig. 3. Geomagnetic activities for Bartels rotations 1961–1980 presented by ΣKp (thick solid line), ΣK from Kakioka (dashed line) and the minimum Dst in every 12-hour interval (dots connected by thin line). Possible association between disturbances and coronal holes (H) or flares (F) is indicated

cember 10 (rotation 1973, storm No. 22), though the SC-storms on September 19 and 21 are to be attributed to the flares in McMath region 14943. The evolution of the near-equatorial coronal hole which is responsible for this series of recurrent storms seems to have been correlated with the development of active centers in its vicinity.

That is, the growth of the coronal hole was seen in September and December in correlation with enhanced flare activity in the surrounding region. The increase in $\sum Kp$ on January 8, 1978 prior to the sudden commencement of the storm No. 24 in rotation 1974 may be regarded as the continuation of this series caused by another return of the same coronal hole.

The second most distinct series began with the SC-storm at 1853 UT on January 28, 1978 (rotation 1975, storm No. 26), and lasted to the storm No. 32 in rotation 1977. These storms are associated with the coronal hole extending from the southern polar region with negative polarity. It can be seen in the figure that the recurrence period of this series is near 28 days. The storm No. 37 in rotation 1978 seems to be regarded as the continuation of this series, though the distinct coronal hole could not be observed in this rotation. Recently BURLAGA *et al.* (1978) showed that the region of open magnetic field lines remains sometimes even after the corresponding coronal hole disappeared and is well correlated with solar wind streams. The above interpretation of the storm No. 37 is consistent with this finding. Although the storm No. 41 in the next rotation appears to be another return of this series, it does not seem true because the IMF polarity was positive during the period of this storm.

It is interesting to note that these two distinctive series of recurrent storms occurred at nearly the same phase in the Bartels' recurrence diagram. This implies that these two series could be easily regarded as a single series of recurrent storms, if the corresponding magnetic field data were not consulted.

Another series of recurrent storms can be seen from a minor magnetic disturbance on July 18, 1977 (rotation 1968) to the storm No. 13 in rotation 1971. These storms are associated with the coronal hole extending from the northern polar region with positive polarity. It is seen that the recurrence period of this series is also near 28 days. Although weak recurrence tendency can be seen from rotation 1962 to 1964, the association between these disturbances and the coronal holes is not so clear as those described above, except for the storm No. 2. It is evident that the storm No. 4 is not a return of this recurrent series but is related to another coronal hole with positive polarity which was seen only in this rotation.

As is evident in the figure and also from the above discussion, there are a number of non-recurrent magnetic storms which are apparently associated with short-lived coronal holes. This result indicates that it could be misleading to divide magnetic storms into recurrent storms and flare-associated storms only from the 27-day recurrence patterns as was done in many classical works (see discussion in DODSON and HEDEMAN, 1964).

Finally, it can be said that most of the coronal holes within ±30° latitude range from the sub-earth point on the sun caused geomagnetic disturbances although the severity of disturbances is different from one case to another. This seems to stem from the fact that the severity of magnetic disturbance is strongly controlled by the product of the southward component of IMF and the solar wind speed (BURTON *et al.*, 1975), whereas coronal holes mainly control the solar wind speed. In fact, several cases were found in which the coronal hole CMP did not cause magnetic disturbances, profiles of the solar wind speed exhibiting the arrival of fast streams.

5. Concluding Remarks

An attempt has been made to assign the causation of individual magnetic storms to appropriate coronal holes or solar flares. This study is based on the view that the corotating streams from coronal holes and the expanding plasma ejected from solar flares are main causes of the solar wind disturbances which produce magnetic storms. The result shows that, of 44 geomagnetic storms with Dst lower than -50γ during the period from January 1977 to June 1978, 40 storms are explicable by either coronal holes or solar flares.

Some of the important facts confirmed or found in the present study are listed below.

(1) Corotating streams can cause SC-type magnetic storms as well as storms with gradual commencement.

(2) In the increasing phase of solar activity there appear many short-lived coronal holes, and corotating streams from such coronal holes produce many non-recurrent sporadic magnetic storms.

(3) When the coronal hole CMP and the energetic flare occur at nearly the same time, the flare effects seem to be more prominently observed than the effects of corotating stream, if the flare site is just on the west side of the coronal hole.

(4) In the increasing phase of solar activity, the rotation period of coronal holes extending from the polar region seems to be near 28 days, whereas near-equatorial coronal holes seem to rotate with a period of 27 days.

(5) In some cases, the evolution of coronal holes are apparently correlated with the development of active centers of the sun in the surrounding region.

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