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POLAR CAP ABSORPTIONS AND ASSOCIATED SOLAR-TERRESTRIAL EVENTS THROUGHOUT THE 19TH SOLAR CYCLE

by Yukio Hakura

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ABSTRACT

Solar cycle variations in the emission of high-energy particles from the sun are examined, by using daily Polar Cap Absorption (PCA) indices, selected solar-terrestrial events, and satellite observations of low-energy solar protons, between 1954 and 1965. A close relationship between PCA's and type IV solar radio outbursts existed throughout the last solar cycle. The solar corpuscular activity showed three peaks in 1957, 1960, and 1963, giving an asymmetric butterfly shape to the latitude-time distribution of type IV sources. The first peak, which coincides with a sole maximum of sunspot numbers, is characterized by a random occurrence of type IV outbursts, PCA's, and geomagnetic SSC's (geomagnetic storms with sudden commencement). Active centers were restricted in two parts of narrow heliographic longitudes during the second, the most prominent peak, giving a slight 27-day recurrence to the corpuscular activity. Finally, a pronounced peak of 27-day recurrence appeared during the third period in spite of a rather decreased corpuscular emissivity. A recurrent series of solar Mev protons lasted 15 solar rotations, while those of geomagnetic Kp index and galactic cosmic ray intensity lasted 25 rotations. The appearance of recurrent Mev protons in the later phase of a solar cycle is controlled not only by the sector structure of the interplanetary space, but also more fundamentally by the energetic proton productivity of the sun.

CONTENTS

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INTRODUCTION

The sun is a known emitter of energetic particles which cause various electromagnetic disturbances in the earth's upper atmosphere. In particular, during an intense solar flare, it emits not only a magnetized plasma cloud which is responsible for geomagnetic and galactic cosmic-ray storms, but also, on occasions, very high-energy particles known as solar cosmic radiations.

Since the first observation of an unusual increase of cosmic rays in 1942 (Forbush, 1946), at least 14 events with proton energy $E_p > 1$ Bev have been observed by ground-based facilities. Subrelativistic energy particles ($E_p = 1 \sim 1000$ Mev) are not detectable at the ground level, but this information is available from various space vehicles or indirectly from ionosphere observations. These particles emitted from a solar flare precipitate in the polar cap ionosphere, thereby producing an enhanced ionization that causes a severe absorption effect on radio waves. Thus the event is called the Polar Cap Absorption, or PCA (Bailey, 1964; Hultqvist, 1963; Obayashi and Hakura, 1960). Subrelativistic events occur rather frequently; almost 200 outstanding events have been detected by various ionosphere observations since 1938 (c.f. Švestka, 1966; Basler and Owren, 1964).

As possible attributes of a cosmic-ray flare, one may count several particular kinds of landscape or time-variation of the flare observed by various techniques, ranging from radio waves to γ-rays (Ellison, 1963; Kiepenheuer, 1964; Křivský, 1965 and 1966). Among them, dynamic spectral features of solar radio outbursts provide the most promising tool for clarifying the nature of the cosmic-ray flare. Statistical examination of solar radio outbursts and subrelativistic solar protons in the last sunspot maximum shows that the emission of such high-energy particles rises in close association with the occurrence of major type IV outbursts (Hakura and Goh, 1959; Thompson and Maxwell, 1960; Kundu and Haddock, 1960). The relationship seems to be quite reasonable because the type IV outburst is caused by a synchrotron radiation due to highly accelerated electrons

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spiralling in the solar magnetic field; at the same time, the generation of high-energy protons in the excited solar atmosphere can be expected (Boischot and Denisse, 1957).

Satellite observations in the later half of the last solar cycle, however, have revealed numerous increases of low-energy solar protons (E_p = 100 kev ~ 10 Mev) that had apparently little correlation with the type IV radio outbursts. Some of these observations have shown that the Mev protons were confined within a region corotating with the sun which modulated the geomagnetic activity and the galactic cosmic-ray intensity on the orbit of the earth with a 27-day period (Bryant *et al.*, 1965; Fan *et al.*, 1965). The appearance of recurrent geomagnetic disturbances has been known as a prominent feature of the earth storms in the decreasing phase of the sunspot activity (Sinno, 1964).

The solar cycle variation in solar particle radiation is surely one of the most interesting subjects in the field of solar-terrestrial relationships. No relativistic solar cosmic rays were observed during the maximum sunspot activity (c.f. Obayashi, 1964); Švestka (1966), tracing PCA events back to 1938, has shown that the subrelativistic particles also tended to avoid the top of sunspot activity during the last three sunspot cycles. Here, a question arises: "Is the sunspot number a unique measure of solar activity?" The importance of this problem has been emphasized by Gnevyshev (1963), who showed the existence of two peaks of a coronal line intensity observed in the course of the last solar activity. The purpose of the present paper is to list the PCA's and associated solar-terrestrial events that occurred during the 19th solar cycle on a basis of reasonably uniform criteria, and reexamine their casual relationship in various phases of solar activity. Three distinguishable peaks of solar corpuscular activity that appeared in 1957, 1960, and 1963 will be discussed.

POLAR CAP ABSORPTIONS AND ASSOCIATED EVENTS IN YEARS 1954-1965

Daily Indices of f_{min} Increase

Various ionosphere observations such as VHF forward scatter transmissions, riometers, vertical absorptions, transpolar-cap VLF transmissions, and the f_{min} of vertical ionosphere sounders (c.f. Sawyer, *et al.*, 1966) are useful PCA detectors. The minimum observable frequency, f_{min} on vertical sounding ionogram, has some advantages in the worldwide coverage of observing stations and the retrospectivity due to its long observational history.

The value of f_{min} increases when an abnormal ionization is produced in the polar cap ionosphere by precipitating solar cosmic radiations. When all ionosphere echos are completely absorbed by an intense ionization, the resulting condition is called the "blackout." As an example, a solar-geophysical event of August 16, 1958 is plotted in Figure 1. On that date an intense flare of importance III+, associated with a major type IV radio outburst, occurred at 04:32 UT. Simultaneously with the onset of the flare, a Sudden Ionosphere Disturbance (SID) was noted in an f_{min} observation at Alert, Canada; this was attributed to an excessive solar X-ray burst emitted from an excited coronal condensation at the time of the flare. A few hours after the SID, f_{min} began to increase again, indicating the onset of a PCA event. Concurrently, an incidence of solar

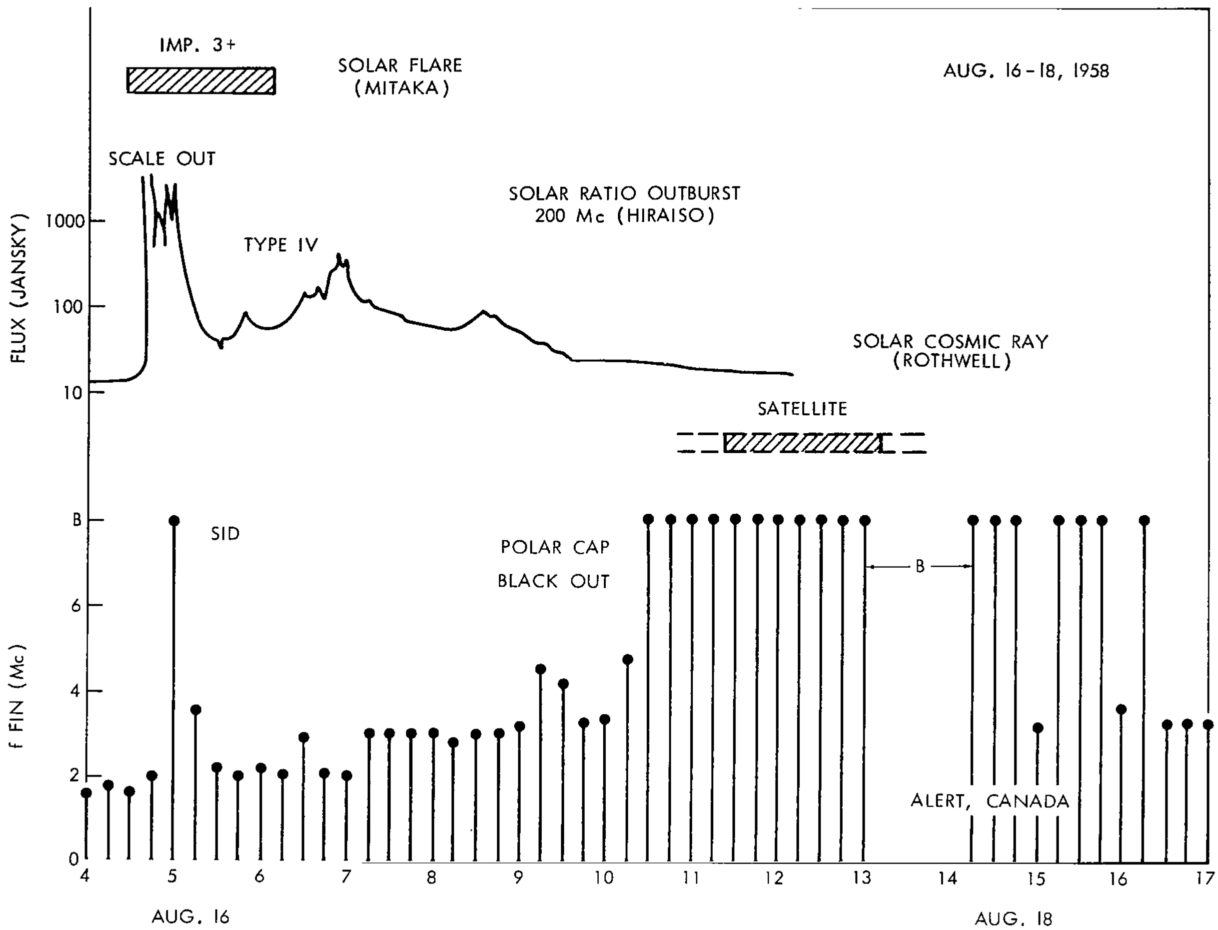

Figure 1—Solar-terrestrial events on August 16-18, 1958.

cosmic-ray protons of energies 10 to 100 Mev was detected by a direct measurement of energetic particles by Explorer 4 in its orbit. The enhancement of f_{min} lasted for about 3 days.

A general morphology of PCA's has been established on a series of synoptic studies of outstanding events observed during the IGY 1957-1958, when an extensive observing network was in operation (Hakura *et al.*, 1958; Obayashi and Hakura, 1960; Hakura and Nagai, 1964; Hakura, 1967). The results have shown that the stations with invariant geomagnetic latitudes greater than 80 degrees are safe from any influence of the auroral-zone absorptions, and thus can be a reliable monitor of PCA events. Canadian data are especially useful because of their long history of observation (since 1949). A number of PCA events have been noted by an examination of f_{min}-time series of Canadian stations (Jelly and Collins, 1962; Jelly, 1963).

In this paper, daily indices of PCA activity were computed for Resolute Bay, Canada (84.3 degrees in corrected geomagnetic latitude, Hakura, 1965), using the following definitions:

N_4 = number of hours per UT day with $f_{min} \geq 4$ Mc/s, and

N_2 = number of hours per UT day with $f_{min} \geq 2$ Mc/s.

The indices thus obtained can be a measure of PCA-producing solar cosmic rays, since they indicate some lower limits of total solar cosmic-ray flux in certain energy ranges, impinging upon the polar cap during a day.

The indices were computed for years 1954 to 1965, and the results are displayed in 27-day recurrence tables in Figure 2, where the indices are coded into five grades shown at the top of each table. When the Resolute Bay data were not available, those from Thule, Greenland were supplemented for the missing date. The tables show a general feature of PCA-activity in the whole solar cycle observed with two grades of sensitivity.

Outstanding PCA Events for Years 1954-1965

Using the f_{min} indices, outstanding PCA events for years 1954-1965 were selected. The middle of Table 1 shows various PCA information such as onset date and time in UT, delay time from an associated flare Δt_a, approximate duration in days, importance, and type.

The importance of a PCA is determined from the f_{min} indices according to Table 2. Examples of PCA's of importance I, II, and III are shown in Figure 3.

The onset time of a PCA is determined by consulting f_{min} records of 15-minute intervals and riometers at several polar cap stations. Sometimes the onset time was quoted from published works such as Hakura and Goh (1959), Obayashi and Hakura (1960), Sinno (1961), Obayashi (1962), Yamamoto and Sakurai (1967), and Obayashi (1967).

PCA's are classified into three types according to their delay times from the associated

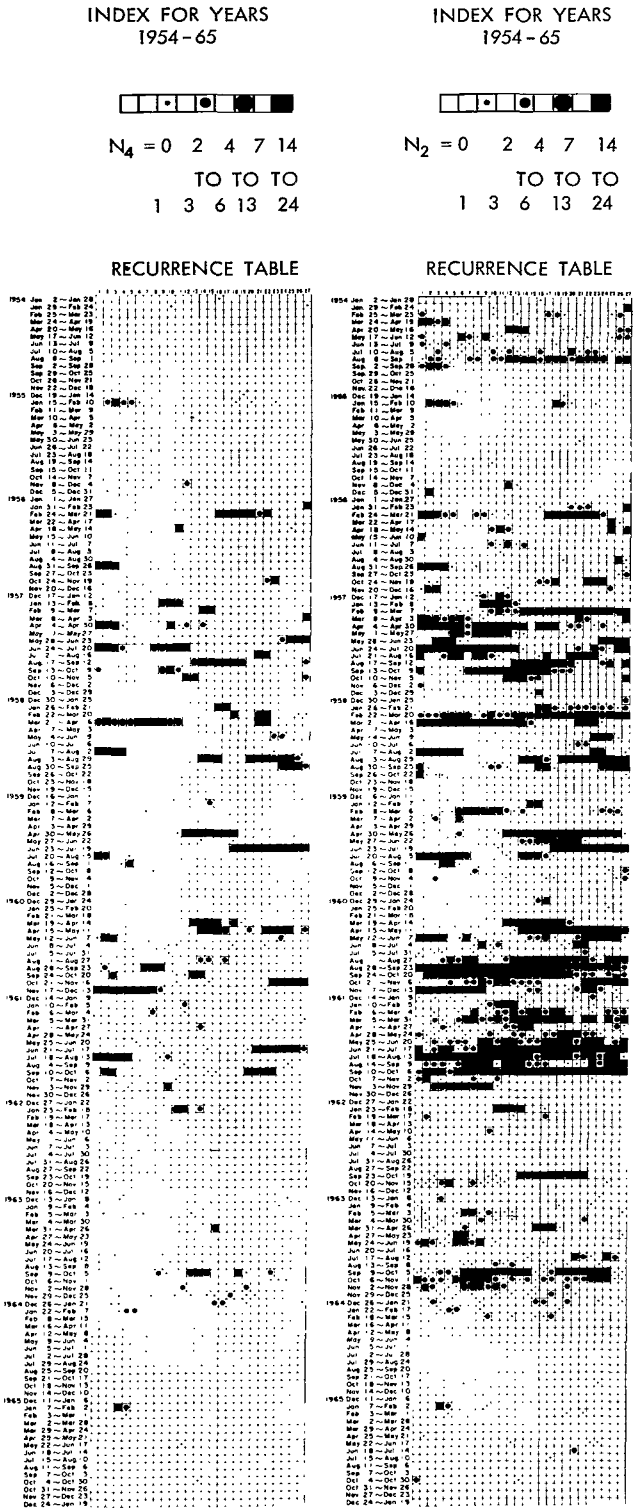

Figure 2—Twenty-seven-day recurrence tables of daily PCA-activity indices, N_4 and N_2.

Table 1

Outstanding Solar-Terrestrial Events in 1954-1965.

Year	Month	Solar flare with type IV outburst					Polar cap absorption						Geomagnetic storm				
		Onset date	Time	Position	Imp.	Imp. of type IV	Onset date	Time	Δt_a (hrs)	Duration (days)	Imp.	Type	Onset date	Time	Δt_m (hrs)	Imp.	Type
1954	V						1	0200		3	I						
	VIII						19			13	I						
1955	I						16			2	II		17	0322		II	SSC
	II						1	0900		1/2	I						
	XI						19	1200		1/2	I		19	1319		II	SSC
	XII						6	0400		1	I		5	2216		I	SSC
1956	II	14	0541			B											
	II	23	0334	N23W74	III+	A	23	0415	0.7	3	III	G, F	25	0307	48	III+	SSC
	III						10	1400		7	II		10	1058		II	SSC
	IV						15	0100		1	I		15	1628		I	SI
	IV	27	2100	N15W34	II	C	27	2200	1	1	II	F	30	0138	53	III	SSC
	V						14	0500		1	I		13	2222		III	SSC
	VIII						28	2300		1	I						
	VIII	31	1228	N18E12	III	A	31	1500	2.5	4	III	F	IX/02	0230	38	III+	SSC
	XI						8			3	I		9	2030		III	SSC
	XI	13	1431	N16W10	II	C	14	[b]0000	9.5	3	II	S	15	0807	42	III	SSC
	XII						25			3	I		25	0754		I	SSC
1957	I	(20	1116	S25W18	III)		20	2215		4	II		21	1255		III	SSC
	II	(21	1605	N13W40	III+)		21	1800		3	II		23	1807		III+	SSC
	III						28	0900		2	I		29	0336		I	SSC
	IV	3	0825	S15W60	III	C	3	1015	2	7	III	F	5	1436	54	II	SI
	IV						11	1300		7	II						
	IV	16	1048	N32E90	II	C							17	2332	37	I	SI
	IV	17	2000	N12E70	III+	C											
	IV						19	0200		3	I		18	1508		III+	SSC
	V						5	0200		2	I						
	V						8	0100		4	I						
	V						30			3	I		30	0822		II	SSC
	VI	19	1608	N20E46	II	C	19	2215	6	6	III	(F)					
	VI	(22	0236	N23E12	II)		22	0500		6	III		24	0340		II	SSC
	VII	3	0712	N14W40	III+	B	3	0930	2	4	III	F	5	0042	42	III	SSC
	VII	16	1740	S33W28	III	C	19			2	I		19	0519	60	I	SSC
	VII	24	1816	S24W22	III	C	24	2015	2	1	I	F	27	1959	74	I	SSC
	VII	(28	1346	S24W75	III)		28	1500		1	I						
	VIII	(9	0690	S09E75	II)		9	1500		3	II		12	1135		III	
	VIII	28	0913	S30E35	III+	C	28	2230	13	3	III	S	29	1920	34	III	SSC
	VIII	31	1257	N20W02	III	C	31	1415	1.5	3	III	F	IX/2	0314	38	III+	SSC
	IX	2	1257	N11W26	I+	B	2	1500	2	3	III	F	4	1300	48	III+	SSC
	IX {	11	0243	N11W03	III	B	12	08	29	2	I	S	13	0046	46	III+	SSC
	IX	12	1520	N10W19	II	C	12	Masked			I						—
	IX	19	0400	N23E01	III	C	19	08	4	2	I	F	21	1005	54	III+	SSC
	IX	21	1340	N10W08	III	C	21			3	II	F	22	1345	24	III	SSC
	IX	26	1907	N26E15	III	C	26	2315	4	2	I	F	29	0016	53	I	SSC
	X	20	1637	S25W45	III+	B	21	05	12	2	II	S	21	2241	30	II	SSC
	XI	(5	0203	N38W63	II)		5	0700		1.5	I		6	1821		III+	SSC
	XI	24	0850	S13E37	III	C							26	0513	44	II	SSC
	XII	13	0215	N22E90		C											
	XII	14	1100	(N17E75)	II)	C											
	XII	17	0734	N22E44	II+	C	17	1200	4.5	1	I	F	19	0937	50	II	SSC
1958	II	9	2108	S13W14	II	A	10	0700	10	2	II	S	11	0125	28	III+	SSC
	III	1	0340			C							3	0931	54	I	SSC
	III	(11	0048		III)		11	0500		2	II		14	1212		I	SSC
	III	14	1508	S23W80	III	C	14	1600	1	2	II	F	17	0750	65	I	SSC
	III						18			16	II		17	0751		I	SSC
	III	23	0950	S14E77	III+	B	25	08	46	8	III	S	25	1540	54	I	SSC
	IV						10	06		3	II		11	2140		I	SI
	VI	4	2140	N15W58	II	C	5	04	6	2	I	F	7	0046	51	III	SSC
	VI	6	0436	N15W77	III	C	6	1345	9	2	I	(S)	8	1728	61	I	SSC
	VI	26	0300	N10E49	II+	B							28	0713	52	I	SSC
	VII	7	0039	N24W09	III+	B	7	[b]0200	1.5	6	III	F	8	0748	31	III+	SSC
	VII	29	0303	S14W43	III	B	29	[b]0415	1	2	I	F	31	1532	60	I	SSC
	VIII	16	0432	S14W53	III+	A	16	[b]0715	2.5	3	III	F	17	0622	26	III	SSC
	VIII	20	0043	N16E23	III	C	21	1445	38	1	II	S	22	0227	50	II	SSC
	VIII	22	1417	N18W09	III	C	22	1530	1	4	III	F	24	0140	35	III	SSC
	VIII	26	0005	N20W54	III	A	26	0215	2	4	III	F	27	0303	27	III	SSC
	IX	14	0830	S10W71	III+	C	14	1045	2	1	I	F	16	0930	49	III	SSC
	IX	(22	1012	N17W65	II-)		22	1430		3	II		25	0408		III+	SSC
	X	21	2330	S02W20	II	B							22	20--	21	III	
	X	24	1440	S04W57	III	C							27	1523	70	III	SSC
	XII	12	1300	S05W07	II	C							13	1148	23	III+	SI
	XII	23	0540	S16E65	III	C							25	2330	66	II	SI

Table 1

Outstanding Solar-Terrestrial Events in 1954-1965 (Continued).

Year	Month	Solar flare with type IV outburst					Polar cap absorption						Geomagnetic storm				
		Onset date	Time	Position	Imp.	Imp. of type IV	Onset date	Time	Δt_a (hrs)	Duration (days)	Imp.	Type	Onset date	Time	Δt_m (hrs)	Imp.	Type
1959	I	7	0245	S12W03	I	C							9	1459	60	III	SSC
	I	(26)	0013	N09W42	II)		26	14		2	I		27	1329	37	I	SSC
	II	9	0200	N13E90	II	C							11	0318	49	II	SSC
	II	12	2300	N12E48	III+	C	13	[b]10	11	4	I	S	14	1142	37	II	SSC
	V	10	2055	N23E47	III+	B	11	0130	4.5	13	III	F	11	2328	27	III	SSC
	V	11	2010	N08E39	II+	C	Masked				III	F	12	1537	20	II	SI
	V	13	0510	N22E26	II	C	Masked				III	F	15	0703	50	II	SSC
	VI	09	1651	S20E00	III+	B	(10	0045	8	1	I	S)	11	0909	40	I	SSC
	VI	(13	1051	N17E27	II)		13	13		4	I						
	VII	9	2030	N18E67	I	B											
	VII	10	0210	N22E70	III+	A	10	0615	4	>4	III	F	11	1625	38	II	SSC
	VII	14	0342	N16E07	III+	A	Masked			>3	III	F	15	0803	28	III+	SSC
	VII	16	2115	N08W26	III+	A	Masked			9	III	F	17	1638	19	III	SSC
	VIII						2			4	I	F					
	VIII	14	0130	N12E28	II+	C							16	0404	50	III+	SSC
	VIII	18	1022	N11W34	III	C	18	13	12.5	2	II	F	20	0412	42	I	SSC
	IX	01	1924	N12E60	II+	C							03	1417	43	I	SSC
	XI	30	0250	N08E16	II	B											
	XII	21	0050	S03W53	I	C	(21	(06)	(5)	1	I-	F)	23	1525	62	II	SSC
1960	I	11	2040	N23E05	III	C	12			2	I		13	1859	46	II	SSC
	I	15	1340	S20W66	II	C							16	2114	31	I	SSC
	III	29	0650	N12E31	III	A	30	[b]1000	27		I	(s)	31	1036	52	III+	SSC
	III	30	1520	N11E15	II+	B	cont. after SID			>2	III	F	31	2142	30	III+	SSC
	IV	1	0845	N13W09	III	C	1	1000	1	>4	III	F	2	2313	39	III	SSC
	IV	5	0215	N12W62	III	A	5	10	8	2	II	S	6	1628	39	I	SI
	IV	28	0130	S05E34	III	C	28	0400	2.5	1	II	F	30	0132	48	II	SSC
	IV	29	0209	N10W22	III	A	29	0600	4	3	III	F	30	1213	32	III+	SSC
	V	4	1015	N12W90	III	B	4	1045	1/2	1	I	G, F	6	1719	55	II	SSC
	V	6	1404	S10E08	III+	C	6	[b]2030	6	3	III	F	8	0421	42	II	SSC
	V	(9	0704	S10E55	III+)		9	11		2	II		11	0435		II	SSC
	V	12	1340	N30W60	I	C	12			1/2	I	F					
	V	13	0522	N30W64	III+	A	13	0845	3	2	II	F	16	1351	80	II	SSC
	V						17	21		1	I						
	V	26	0851	N14W15	II	C	26			3	I		28	2029		I	SI
	VI	1	0830	N28E46	III+	C	1	12	3.5	5	II	F	3	1731	57	II	
	VI	25	1200	N22E05	III	C							27	0145	38	IV	SSC
	VI	25	2040	N18W04	III	C							27	1630	44		
	VI	27	0010	S7E35	III	C											
	VI	27	2140	N17W28	III	C	28			2	I		29	1939	46	III	SSC
	VI	29	0140	N23W56	I	C							30	1720	40	II	SSC
	VIII	11	1920	N22E27	III+	C	13			10	I		14	1510	68	I	SSC
	VIII						26			4	I						
	IX						1			2	I		2	1158		II	SSC
	IX	3	0037	N20E87	III	B	3	08	7	8	III	F	4	1145	37	III	SI
	IX	16	1710	S21E66	I	C											
	IX	26	0530	S19W64	II+	C	26	08	2.5	4	II	F	29	0836	75	II	SSC
	X						4	1600		4	II		6	0237		III+	SSC
	X	11	0520	S18W36	II	C							13	2147	64	I	SI
	X	29	1020	N22E26	III	C	29			3	I						
	XI	10	1010	N29E28	III	B							12	1325	51		
	XI	11	0315	N29E12	II+	A	11	04	1	1/2	I	F	12	1846	40	III+	SSC
	XI	12	1323	N27W01	III+	B	12	1515	2	>3	III	G, F	13	1021	21	III+	SSC
	XI	14	0246	N27W19	II+	A	14	Masked			II	F	15	1304	34	II	SI
	XI	15	0207	N26W32	III+	A	15	03	1	>6	III	G, F	15	2155	20	III	
	XI	20	2017	N25W>90	I	B	20	2300	3	5	III	F	21	2147	26	II	SI
	XII	(5	1825	N27E68	III+)		8			2	I		7	1804	48	II	SSC
1961	II						13			1	I		13	0253		II	SSC
	II						18			4	I		16	0536		II	SSC
	III						17			3	I		Kp	>5			
	IV						14			1	I		13	1450		I	SSC
	VI-VII						VI/4			36	I						
	VII	11	1654	S06E32	III	B	11	2000	3	1	II	F	13	1113	42	III+	SSC
	VII	12	1000	S08E22	III+	B	12	1115	1	6	III	F	13	1113	25		
	VII	15	1520	N15E17	III	C	Masked				III	F	17	1825	51	III	SSC
	VII	18	0921	S06W59	III+	B	18	[b]1000	1	5	III	F	20	0248	41	I	SSC
	VII	20	1600	S05W90	II	B	20	Masked		5	II	F					
	VII	24	0450	N15E18	III+	C	24			7	II	F	26	1950	63	III+	SSC
	VII	28	0230	N10W37	II	C											
	VIII						1			23	I		1	22.8		II	SG
	IX						7			2	I						
	IX	10	1950	N08W80	I	C	10	2315	3.5	2	II	F	13	1554	68	I	SSC
	IX						14			15	I		13	1554		I	SSC

Table 1

Outstanding Solar-Terrestrial Events in 1954-1965 (Continued).

Year	Month	Solar flare with type IV outburst: Onset date	Time	Position	Imp.	Imp. of type IV	Polar cap absorption: Onset date	Time	Δt_a (hrs)	Duration (days)	Imp.	Type	Geomagnetic storm: Onset date	Time	Δt_m (hrs)	Imp.	Type
1961	IX	28	2208	N13E30	III	B	28	2315	1	7	III	F	30	1847	45	III+	SSC
	XI	10	1434	N09W90	I+	C	10	1515	0.7	2	II	F					
1962	II	1	0902	N10W35	II	C	1	2030	11	2	II	S	4	0930	72	II	SI
	II						5			1	II						
	III	1	1640	S14W56	II+	C											
	IX	27	1505	N09W10	I-	C											
	X						6			9	I		7	2026		I	SSC
1963	II						9	1845		8	I		9	2332		III	SSC
	IV	15	1034	S10W07	II	C	15	1215	2	4	II	F	19	0317	89	I	SSC
	V	1	0525	N15E46	II	C	1	1200	7	3	I	(F)	2	2219	41	I	SSC
	V						29			4	I-		27	2028		I	SSC
	VIII	6	0855	N13W11	II	C	6	1115	2	2	I	F					
	VIII	9	2234	N07W80	I	C	9	(2315)	(0.7)	2	I	F					
	IX	15	0015	N15E75	II	A	15	[b]1030	10	>1.5	I	S	16	2229	46		SSC
	IX	16	1430	N12E50	II+	B	16	1600	1.5	>2	I	F	19	0543	63	I	SSC
	IX	18	2230	N12E17	I	B	19	0543	7	2	I	F	21	1413		III+	SSC
	IX	20	2350	N10W09	II+	A	21	0300	3	3	III	F	22	1601	40	III+	SSC
	IX	26	0638	N13W78	III	B	26	1115	4.5	7	II	F	27	1942	37	II	SSC
	X						12			1	I		11	12			SG
	X	28	0230	N11W25	III	B	28	0815	6	2	I	F	29	1359	36	III	SSC
1964	III	16	1553	N06W75	II+	B											
1965	I						10	0900		1	II						
	II	5	1753	N07W25	II	C	(5	1840	1	2	I-	F)	6	1414	20	II	SSC
	X	4	0937	S21W30	II	B	4	1200	2.5	1/2	I-	F	7	0859		I	SSC

Notes: 1. Dates and times are in Universal Time (UT).

2. Durations of PCA's are measured in days.

3. Δt_a and Δt_m in hours stand for the delay-times of a PCA and a geomagnetic storm, measured from the onset of an associated flare.

4. PCA's are classified into three types, i.e. F-type ($\Delta t_a < 8$), S-type ($\Delta t_a \geq 8$), and others (no associated type IV flare). The sign G stands for a ~10 Bev proton event.

5. SSC means a sudden commencement geomagnetic storm, SI a sudden impulse, and SG a gradual geomagnetic storm.

Table 2

Criteria for Determining Importance of a PCA.

Importance	Criterion
III	When $N_4 \geq 10$ for > 3 successive days
II	When $N_4 \geq 10$ for 1 or 2 days
I	When $N_2 \geq 10$ for > 1 day
I–	When under I, but definitely identified as a PCA from other reliable sources

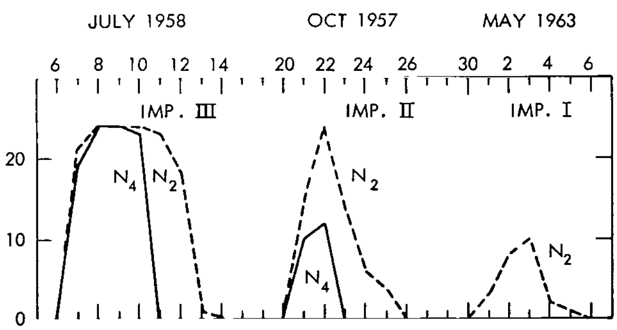

Figure 3—Three PCA events of different magnitudes as expressed by daily PCA-activity indices N_4 and N_2.

type IV-flare: F or fast-onset type ($\Delta t_a < 8h$), S or slow-onset type ($\Delta t_a \geq 8h$), and others (no associated type IV outburst). A sign G represents the ground-level solar cosmic ray event with $E_p \sim 10$ Bev.

Associated Events

Table 1 also includes information concerning solar flares, type IV solar radio outbursts, and geomagnetic storms, which presumably have direct connection with the onset of PCA events.

Solar Radio Outbursts of Type IV and Associated Solar Flares

A typical major outburst consists of microwave impulsive bursts followed by outbursts of types III, II, IVμ, IV_{dm}, and IV_m as shown in Figure 4 (Takakura, 1963; Fokker, 1963). Each type IV outburst is characterized by its continuous spectra with long durations. Thus, in order to obtain a uniform list of type IV outbursts, dynamic spectral observations with a frequency range of 10 to 10^4 Mc/s at at least three stations well distributed longitudinally are needed. However, with some considerations, type IV outbursts can be selected from single-frequency observations with a few key frequencies, such as 200, 500, 3000, and 9000 Mc/s. Actually the selection of type IV outbursts in the present paper was based on the Netherlands stations at Nera, Holandia, and Paramaribo, which are longitudinally well distributed, and on those at Toykawa, Mitaka, Hiraiso, Berlin, Boulder, and Ottawa. The result was adjusted in comparison with "A List of Solar Radio Type IV Bursts in 1957 to 1963" made by Kai (1967). An importance A, B, or C was given to each of the outbursts according to their magnitudes. The outbursts of importance A were fully developed and very intense, while those of importances B and C were of medium and minor scale, respectively.

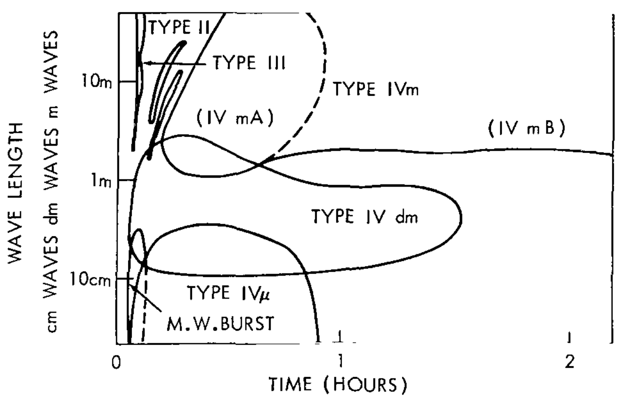

Figure 4—Dynamic spectrum of an intense solar radio outburst.

The onset time, location, and importance of a flare associated with the type IV outburst is shown in Table 1, along with the importance of the type IV outburst. The flare information was mainly obtained from Solar-Geophysical Data (CRPL-FB series) issued by Environmental Data Service of ESSA, Boulder, Colorado.

Geomagnetic Storms

The onset date, time in UT, delay time from the flare, importance, and type of associated geomagnetic storm are given also in Table 1. Most of the data are quoted from the table of solar-terrestrial events made by Hakura and Goh (1959), Obayashi (1962), Yoshida (1965). Reports of the Geomagnetic and Geoelectric Observations, 1954 through 1965, issued by Kakioka Magnetic Observatory, Japan, and lists of geomagnetic storms in the *Journal of Geophysical Research* are also used.

It is almost impossible to compile a complete list of solar-terrestrial events that could convince all researchers. Some minor events selected in Table 1 might be different from those selected by others. However, the events listed in Table 1 can be used safely for statistical analysis of the solar-terrestrial relationship since they have been selected on reasonably uniform bases.

RELATIONSHIP BETWEEN PCA'S AND TYPE IV SOLAR RADIO OUTBURSTS

The following paragraphs provide a statistical examination of the relationship between type IV and PCA events observed in the period 1956-1965, in which observations of both types of events are equally available.

PCA-Producing Probability of Type IV Outbursts

The second and third columns of Table 3 show the number and percentage of type IV outbursts associated with PCA's. Among 116 outbursts, 87 events (75 percent) were followed by PCA's. Moreover, among 29 outbursts without PCA, 22 events (76 percent) were minor events of importance C, and major outbursts of importance A were always followed by PCA's, as shown in Table 4.

Table 3

PCA-Producing Probability of Type IV Outburst for Years 1956-1965.

Condition	No. of type IV outbursts	Percentage
With PCA	87	75
Without PCA	29	25

Table 4

Number of Type IV Outbursts Without PCA.

Magnitude	Number	Percentage
A	0	0
B	7	24
C	22	76

PCA's Associated with Type IV Outbursts

Table 5 shows the number and percentage of PCA's associated with type IV outbursts. Among 131 PCA's, 87 events (66 percent) were related to type IV outburst . Among 44 PCA's that cannot be related to any type IV outburst, 30 events (68 percent) were minor PCA's of importance I (Table 6). As a result, it is evident that a close relationship between type IV outbursts and PCA's, pointed out by Hakura and Goh (1959) using the IGY data, holds especially for events of major importance.

The correlation between both events increases when propagation conditions for PCA-producing particles in the interplanetary space are considered. Actually, our data confirm the east-west longitudinal asymmetry of PCA-producing probability as well as the deficiency of PCA-occurrence in the northern winter months, for which a number of discussions exist (see Obayashi, 1962; Švestková and Švestka, 1966).

Table 5

PCA's Associated With Type IV Outbursts.

Condition	No. of PCA's	Percentage
With type IV	87	66
Without type IV	44	34

Table 6

PCA's Without Type IV Outbursts.

Importance	Number	Percentage
I	30	68
II	13	30
III	1	2

Let us denote for a certain time or space interval:

N(O) = the number of type IV outbursts which did not produce any PCA event, and

N(P) = the number of type IV outbursts which produced PCA events.

Then, the PCA-producing probability P is defined as $P = N(P)/N(P) + N(O)$.

Figure 5 shows PCA-producing probabilities of type IV outbursts in six heliographic longitude intervals. The well-known east-west asymmetry is evident suggesting that the twisted interplanetary magnetic field gives a more favorable propagation condition to the solar cosmic rays originating in the western part of the solar disk than to those in the eastern part. Figure 6

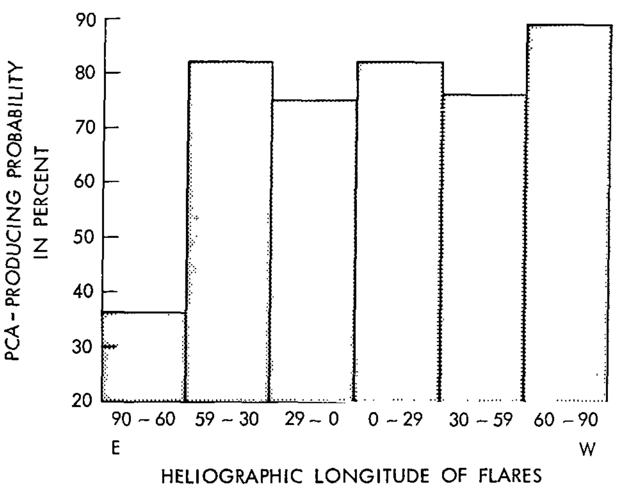

Figure 5—PCA-producing probabilities of type IV sources in six heliographic longitude intervals, inferred from the locations of associated flares.

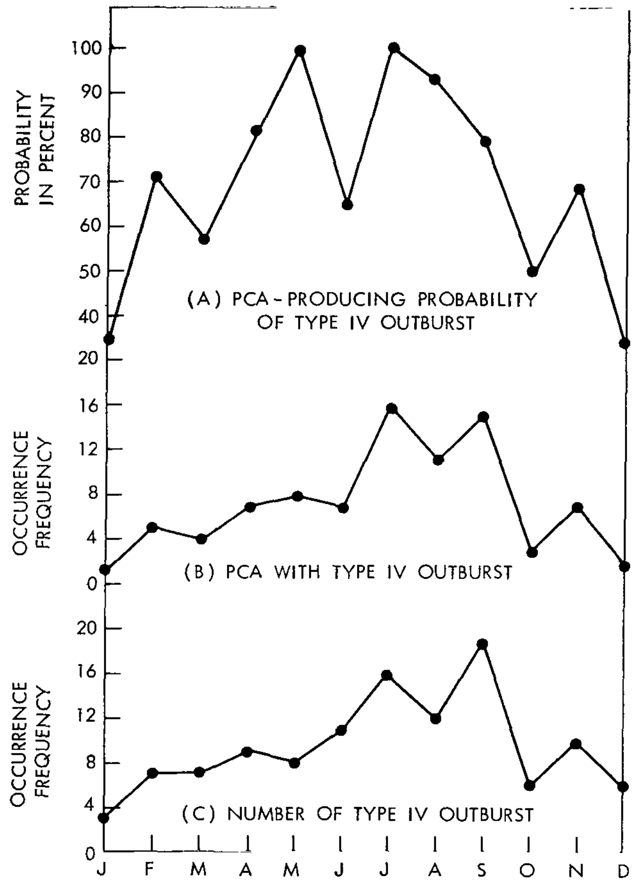

Figure 6—(a) PCA-producing probability of type IV outburst, (b) number of PCA's with type IV and (c) number of type IV outbursts, for each month, January through December.

shows seasonal variations in (a) PCA-producing probability of type IV outbursts P, (b) number of PCA's with type IV outbursts N(P), and (c) number of type IV outbursts N(P) + N(O) for years 1956-1965. The PCA-producing probability shows a deficiency in the northern winter months, though the probability was obtained by excluding a by-chance-seasonal variation of type IV outbursts shown in (c). The deficiency exists even after correcting for a seasonal effect, using data from the southern hemisphere.

SOLAR CYCLE VARIATIONS IN THE CORPUSCLE ACTIVITY OF THE SUN

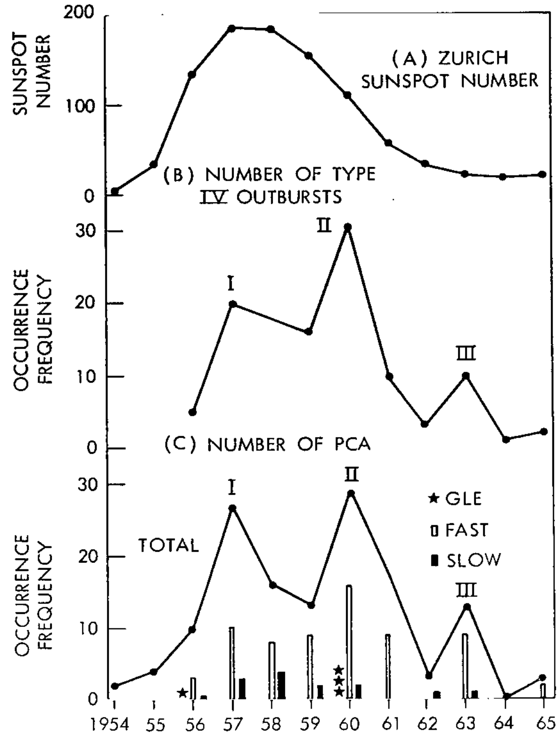

Figure 7—(a) Annual mean of Zürich sunspot numbers, (b) number of type IV outbursts, and (c) number of PCA's (total, identified GLE, fast-, and slow-onset types) for years 1954-1965.

Figure 7 shows variations in (a) annual mean of Zürich sunspot numbers, (b) occurrence frequency of type IV outburst per year, and (c) number of PCA's (total, identified ground-level events of solar cosmic radiations, fast and slow type events) for years 1954-1965. Variations of type IV outbursts and PCA's are roughly parallel throughout the whole solar cycle, showing again that the principal cause of solar cosmic radiations responsible for PCA's is a flare with type IV solar radio outbursts. The affinity is especially close between the occurrence frequencies of type IV outbursts and fast-onset type PCA events, while most well-defined PCA's of the slow-onset type occurred near the maximum of the sunspot number curve.

In Figure 7 three peaks of PCA occurrence frequency occur in 1957, 1960, and 1963, in contrast with the unimaximum curve of Zürich sunspot numbers. The existence of two major peaks in 1957 and 1960 has been known by several investigators including Sawyer *et al.* (1966), Švestka (1966), and Gnevyshev and Křivský (1966). Švestka, retracing PCA events for the last three sunspot cycles, related these two peaks to a general tendency of PCA occurrence frequency peaks to avoid the top of the solar activity curve. The tendency is especially evident for the GLE (ground level events of solar cosmic radiations) as seen in Figure 7. Gnevyshev and Křivský connected the sunspot cycle variations of PCA's with those of coronal intensity by showing that proton flares develop in regions of enhanced coronal brightness, which showed two maxima in 1957 and 1960 (Gnevyshev and Ol', 1966). In this paper, the list of PCA's and related events is based on somewhat uniform criteria throughout the last sunspot cycle. It is worthwhile to make a further detailed study of solar cycle variations.

Figure 8 shows (a) heliographic latitudes of PCA-producing flares and (b) annual occurrence frequencies of northern and southern flares for the years 1954-1965. In his survey of solar

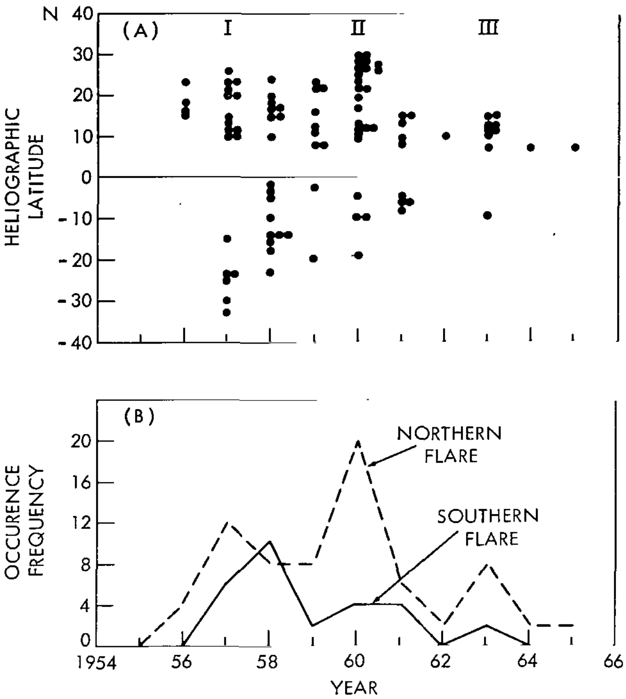

Figure 8—(a) Heliographic latitudes of PCA-producing flares and (b) annual occurrence frequencies of northern and southern flares, 1954-1965.

disturbances associated with PCA events, de Jager (1966) called attention to the north-south asymmetry of flare activity—the occurrence of more PCA sources in the northern solar hemisphere than in the southern hemisphere during the last three cycles. A detailed structure of the north-south asymmetry is seen in Figure 8(b); there are three peaks in the occurrence frequency of PCA-producing flares in the northern hemisphere, and one in the southern hemipshere in 1958.

The distribution of PCA flares in the latitude shown in Figure 8(a) is interesting in comparison with Maunder's butterfly diagram. Examining the latitudinal distribution of sunspots from 1874 to 1913, Maunder (1922) showed that the first spots of a cycle occur at approximately 30°N and 30°S. At sunspot maximum, the zones reach ±15 degrees latitude, and the last spots of a cycle appear at approximately ±8 degrees. The pattern obtained here seems to show details of the Maunder diagram; the northern diagram consists of three (or two) separate parts, and the southern distribution shows a single butterfly pattern. This result, together with the one shown in Figure 8(b) suggests that the last solar cycle consisted of two outstanding peaks of activity and one rather small one, in 1957-1958, 1960, and 1963, respectively.

Localization of PCA-producing centers is often seen on the solar disk. For example, three outstanding PCA events were observed in July 1959, in association with three flares that occurred successively in the same MacMath plage region, on July 10, 14, and 16. It is interesting to examine the absolute longitudinal distribution of PCA sources during the whole course of solar activity.

Let us denote:

d = date of flare observation expressed by (date + hour/24), and

λ = apparent heliographic longitude of the flare.

Then, the data of the CMP (central meridian passage) of the flare are approximately given by

$$d' = d - \frac{27}{360}\lambda$$

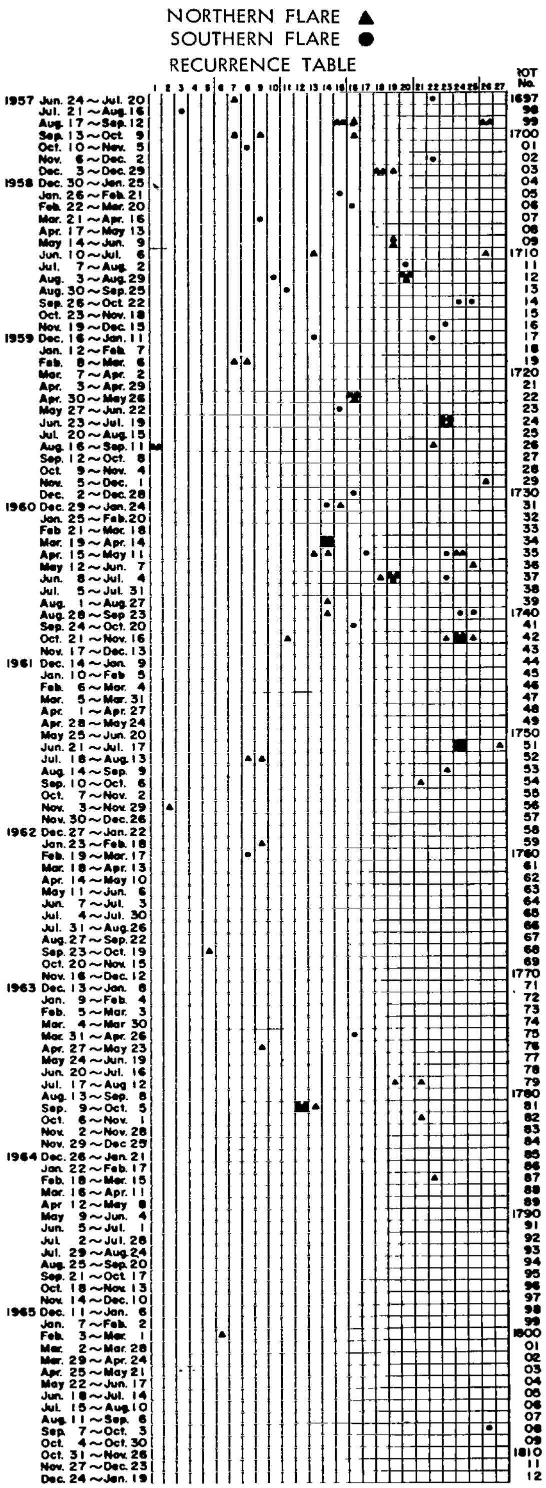

Figure 9—Distribution of CMP dates of PCA-producing flares in the northern and southern hemispheres, on 27-day recurrence chart.

Figure 9 shows the distribution of CMP dates of PCA-producing flares in the northern and southern hemispheres on a 27-day recurrent chart. There is a tendency for the PCA flares to occur in the same active region even for a few solar rotation periods.

Figure 10(d) summarizes the longitudinal distribution of the CMP dates for solar rotation numbers 1697—1795, i.e. July 24, 1957 through October 17, 1964. There are two inactive regions on days 2-6 and 17 and four active regions on days 8-9, 12-17, 19-20, and 23-24, during the whole period of the last solar activity. Figure 10(a) through 10(c) gives the distributions in three different phases of solar activity: (a) solar

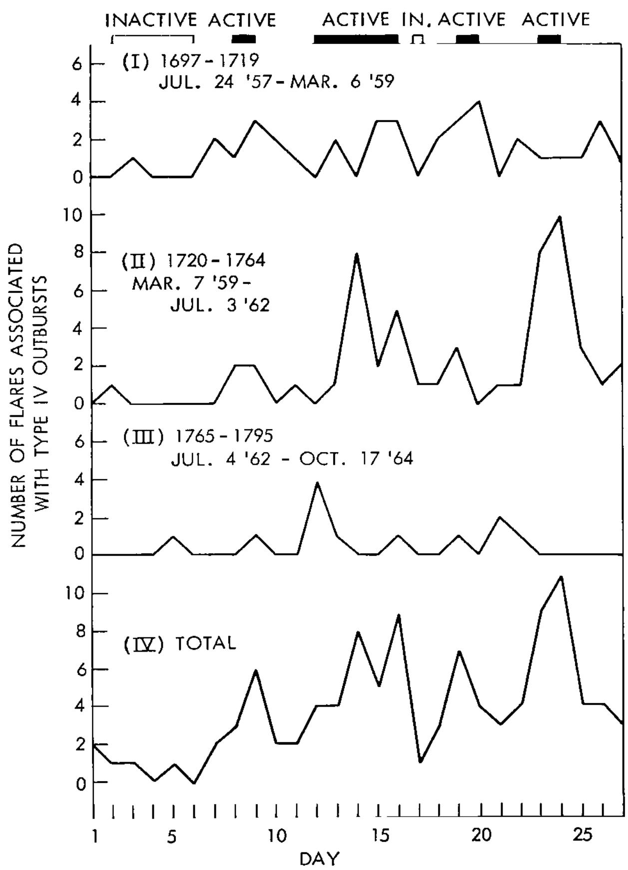

Figure 10—Longitudinal distributions of the CMP dates of type IV sources, for solar rotation numbers (a) 1697–1719, (b) 1720-1764, (c) 1765-1795, and (d) total.

rotation numbers 1697-1719, July 24, 1957 through March 6, 1959; (b) solar rotation numbers 1720-1764, March 7, 1959 through July 3, 1962; and (c) solar rotation numbers 1765-1795, July 4, 1962 through October 17, 1964.

In the period (a) which included the first peak of PCA activity, there were at least four active centers, and their longitudinal distribution looks rather random. On the other hand, the active regions were restricted in two parts of narrow heliographic longitudes in the periods (b) and (c) (c.f. Sakurai, 1966), though the positions of active regions were somewhat different in the two periods. The localization of activity was especially outstanding in period (a) which included the second peak of PCA activity.

It is believed that the interplanetary magnetic field is generated as a result of the transport of the solar magnetic field with the outflowing solar plasma. The localization of solar active centers might mean the simplification of interplanetary field in the declining period of sunspot activity (II) and (III), from the complexity observed in the maximum period (1). Actually, in 1963, the satellite IMP-1 revealed a simple sector pattern of the interplanetary space that lasted for more than several solar rotations (Ness *et al.*, 1964).

RECURRENT GEOMAGNETIC STORMS AND SOLAR COSMIC RADIATION

Figure 11 shows sunspot cycle variations in the annual mean of ΣKp, the 27-day autocorrelation coefficient of ΣKp, and numbers of two different kinds of geomagnetic storm, SC- and G-types, observed at Kakioka, Japan. The SSC's occur rather sporadically and may be connected with the onset of major flares in the central regions of the solar disk. The SG's start gradually, last for a week or more, and sometimes recur with an approximate 27-day period.

In Figure 11 there are two sets of affinity between ΣKp and SSC, and autocorrelation coefficient and SG. It is easily seen that two outstanding peaks of ΣKp in 1957 (I) and 1960 (II) are mainly caused by the occurrence of SSC's. Because of the sporadic nature of the SC storm, the 27-day autocorrelation coefficient of ΣKp showed very low value during the first peak of geomagnetic activity, 1957-1958. A slight enhancement of the coefficient seen in 1960 (II) is due to the locality of flare sources shown in Figure 10. Since the geomagnetic storm-producing probability shows a maximum at the CMP of source flares, the locality

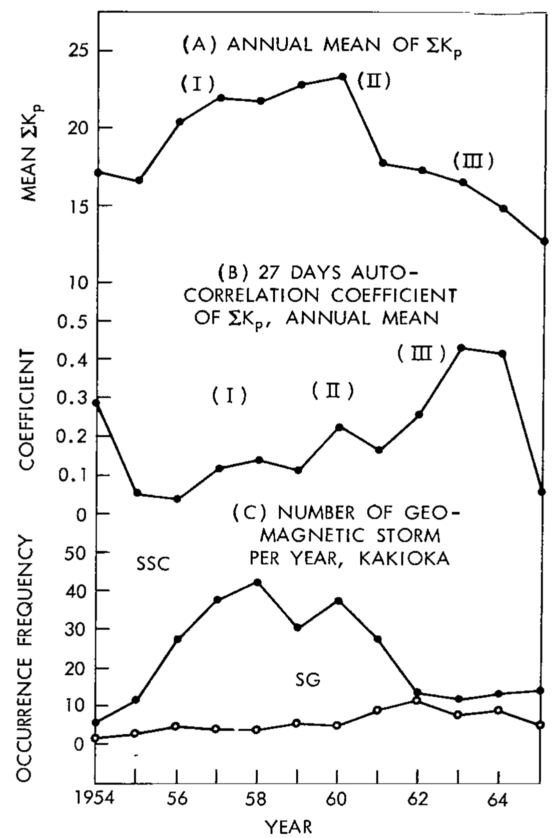

Figure 11—Solar cycle variations in (a) annual mean of ΣKp, (b) 27-day autocorrelation coefficient of ΣKp, and (c) numbers of SC and G-type geomagnetic storms observed at Kakioka, Japan.

of type IV source's causes some recurrency in spite of the sporadic nature of the flare occurrence itself.

Another interesting problem seen in Figure 11 is an inverse relationship of ΣKp value to its recurrency, in 1961-1964. It is known that the ΣKp value is linearly related to a daily average of solar wind velocity (Snyder *et al.*, 1963) and the interplanetary magnetic field magnitude (Wilcox *et al.*, 1967). Thus, the inverse relationship shows that a traffic regulation of 27-day periodicity was established during the end of solar cycle (III) when the solar wind velocity and the interplanetary field became lowered.

Generally speaking, the 27-day autocorrelation coefficient of ΣKp showed a gradual increase toward the sunspot minimum from 1956 to 1964. A similar tendency is seen in the variation of G-type geomagnetic storms. If we assume the occurrence frequency of the SG as representative of the recurrency, we can see a secular variation of the recurrency for four solar cycles from 1924 to 1965 in Figure 12, where occurrence frequencies of SC storms, non-SC storms (SG's), and sunspot numbers are given. The non-SC recurrent storms show a sawtooth distribution with an 11-year period. This, along with a possible periodicity of three solar cycles, might afford a tool for long-term prediction of the recurrence.

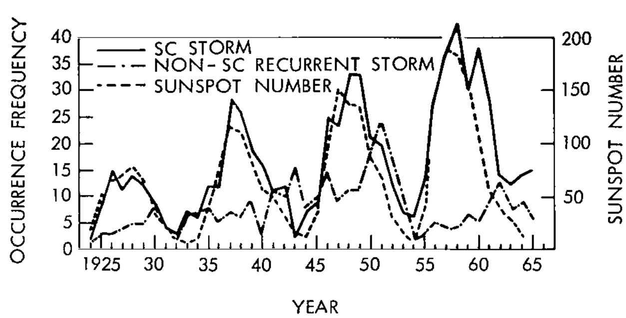

Figure 12—Occurrence frequencies of two kinds of geomagnetic storms per year, observed at Kakioka, and Zürich sunspot numbers for the years 1924-1965.

Evidence for the 27-day recurrent PCA was first shown by Gregory and Newdick (1964) and later criticized by Basler and Owren (1964) using 105 well defined events from Jan. 1957 to Feb. 1962. However, it is obvious from our results that the recurrence of PCA's should be examined for the data obtained during the low solar active period, when the geomagnetic recurrence becomes predominant. Figure 13 shows day-to-day variations in N_2 and N_4 indices for six solar rotations (1773-78). This period is especially interesting since Bryant *et al.* (1965) have presented a clear recurrence of Mev proton events using the Explorer XIV satellite data. Associated phenomena such as solar flares, type IV solar radio outbursts, and geomagnetic storms are indicated by the symbols shown in the top of the figure. Except for a type IV-associated event on April 15, four other detectable PCA events in the present period occurred with approximately 27-day recurrence, starting on days 5-6 in the recurrence table (Figure 2). If we assume these PCA's to be identical with Mev solar proton events, then the recurrent events persisted for the whole period considered here.

Figure 14 shows the relationship between the Mev proton flux given by Bryant *et al.* (1965), and N_2 index of PCA's obtained from Figure 13. Among nine events, eight proton events are well above the threshold value, while only six events can be identified as PCA's (four definite PCA's of Imp. I, a PCA of Imp. I-, and a doubtful PCA of Imp. I--). The result clearly shows the superiority of the satellite data to the ionospheric absorption measurement for the detection of solar Mev proton

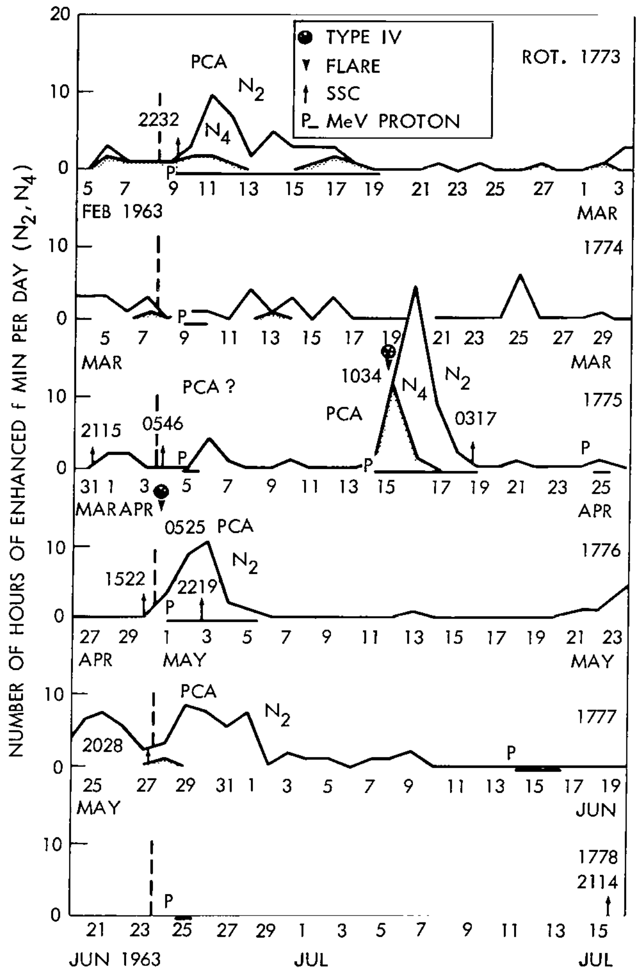

Figure 13—PCA's, Mev proton events, flares, type IV outbursts, and the SSC's observed in solar rotations 1773-78; a recurrent series of PCA's or Mev proton events is indicated by vertical dotted lines.

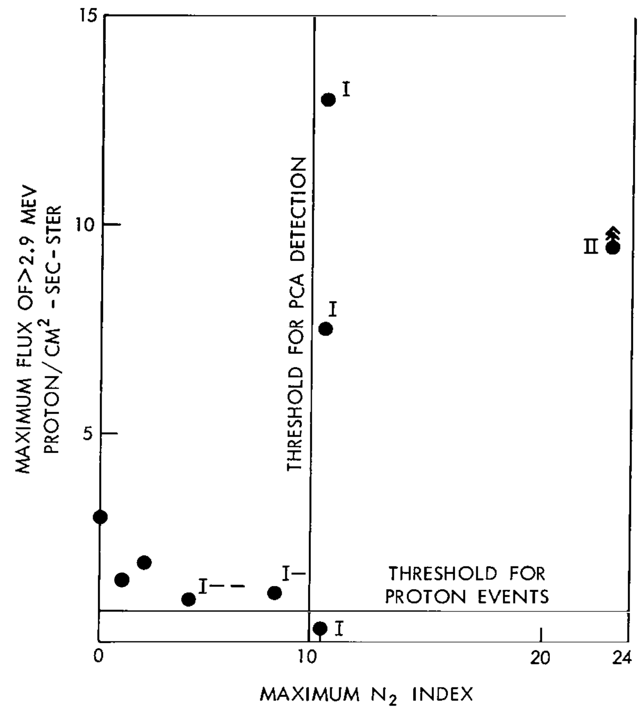

Figure 14—Relationship between maximum flux of Mev proton events and maximum N_2 index of PCA given in Figure 13.

events during the low solar activity period. In recent years, the measurable energy range by space vehicles has continually decreased; numerous increases of solar cosmic-ray intensity have been detected, for example, by the IMP-1 with the 1-Mev proton detector (Fan *et al.*, 1965), and by the Mariner IV with the 0.5-Mev detector (Krimigis and Van Allen, 1966). These data together with f_{min} data (which still have an advantage in retrospectivity or availability for a long time) will afford a tool to examine the recurrence tendency in the low sunspot activity. All low-energy proton observations for solar rotations 1767 through 1811 are shown on the 27-day recurrence table in Figure 15. It is seen that the recurrent series starting from days 5-6 is a really clear one lasting for more than 15 solar rotations in 1963-1964. Figure 15 also shows a 27-day recurrence table for the geomagnetic ΣKp index, digitized in six grades shown at the top of the table. In this case, the recurrence lasted for approximately 25 solar rotations from the end of 1962 to the end of 1964.

An average feature of low-energy proton events during 27-days for solar rotation 1767-84 is shown in Figure 16: (a) the occurrence frequency of Mev proton events, and (b) that of the N_2 index of PCA. In comparison, Figure 16 shows average 27-day variations in (c) geomagnetic ΣKp index and (d) neutron intensity at Deep River, occurrence frequencies of (e) type IV outbursts, and (f)

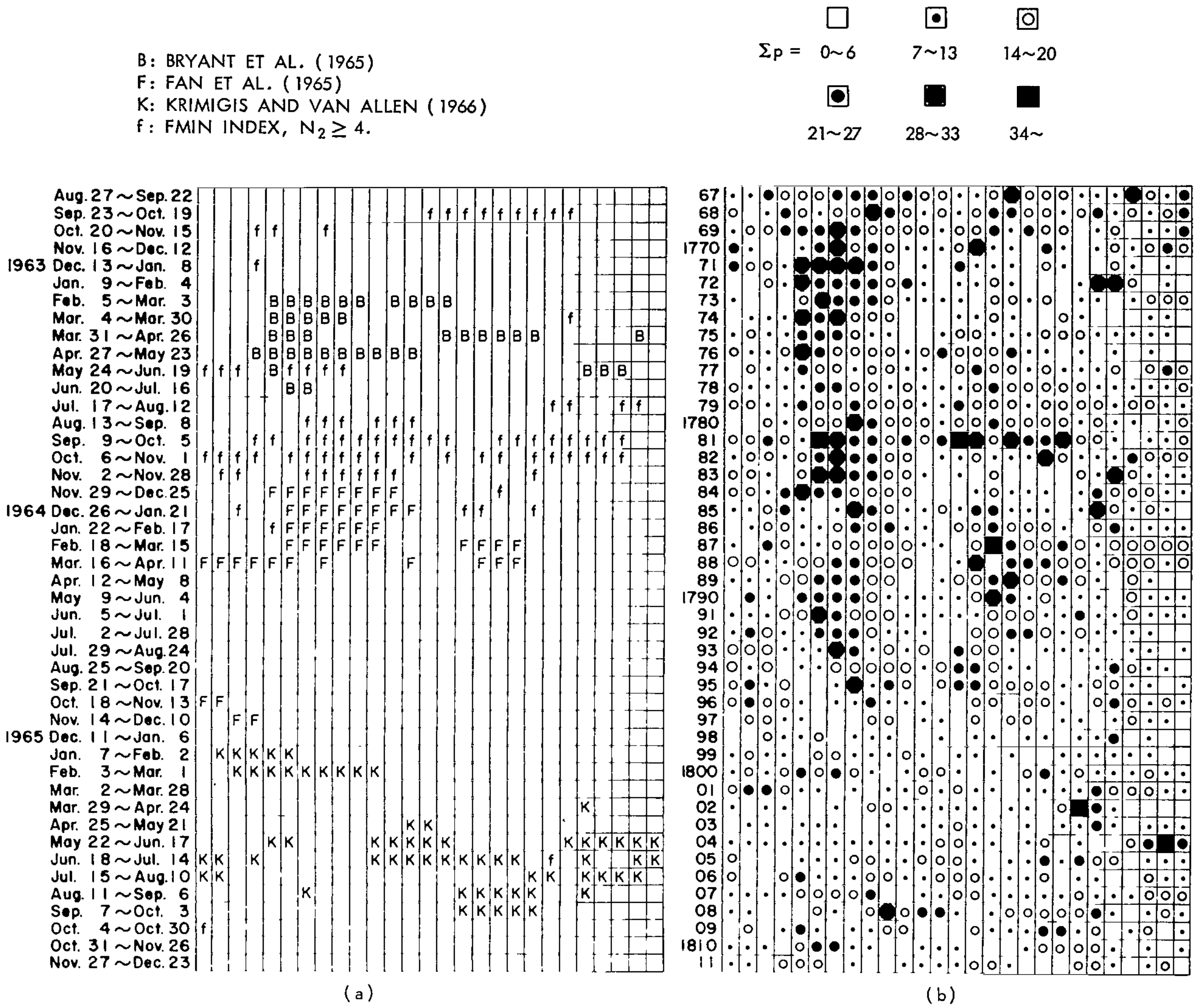

Figure 15—Twenty-seven-day recurrence tables of (a) low-energy solar proton events and (b) geomagnetic ΣKp index, for solar rotations 1767-1811.

CMP dates of the source regions. Predominating peaks observed from the 5th to 12th days in (a) and (b) are caused by the recurrent series of solar Mev proton events. This series coincides with those of (c) geomagnetic ΣKp-index and of (d) neutron intensity variations, which have been reported as traceable for over 20 solar rotations (Mori *et al.*, 1964). Thus, it can be said that the Mev protons were confined within a region corotating with the sun which causes an enhancement of geomagnetic activity and at the same time modulates the galactic cosmic radiations at the orbit of the earth with the 27-day recurrent period.

The distribution of type IV outbursts shown in (e) were almost uniform during the 27 days, showing that these recurrent events have no direct connection with any individual major solar flares. The distribution of CMP dates of type IV sources (f) shows that the recurrent series appeared a few days after the CMP of an inactive region of the 23rd-3rd days, and was entirely out

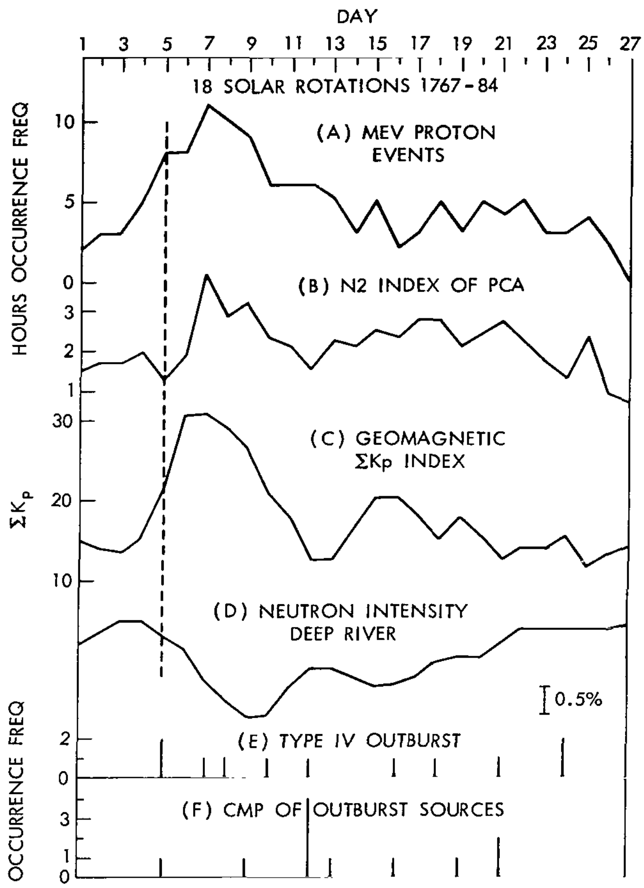

Figure 16—Occurrence frequencies of (a) Mev proton events and (b) N_2 index, average 27-day variations in (c) geomagnetic ΣKp index and (d) neutron intensity at Deep River (Mori *et al.*, 1964), and occurrence frequencies of (e) type IV outbursts and (f) CMP dates of source regions, for 18 solar rotations 1767-84; August 27, 1962 through December 25, 1963.

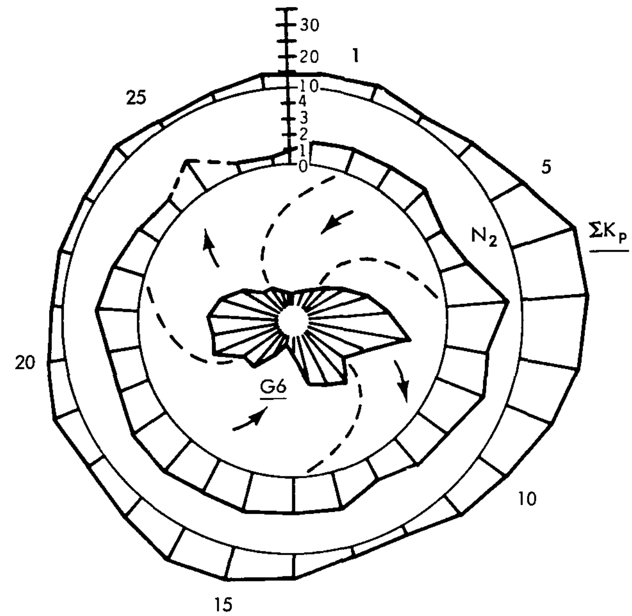

Figure 17—Twenty-seven-day variations in ΣKp, N_2 index and coronal green line G6, and sector structure of the interplanetary space (Ness *et al.*, 1964).

of phase with the most active region of the 12th day. Figure 17 is another expression of 27-day variations in ΣKp, N_2 index, and coronal green line G6 (quoted from Sinno, 1964, and Obayashi, 1964), as well as sector structure of interplanetary magnetic field observed by the satellite IMP-1 in the same period (Ness *et al.*, 1964). The dates 5, 10, 15, 20, and 25 are indicated along the ΣKp variation. The ΣKp and N_2 observed at the orbit of the earth are connected with the solar coronal data observed four days earlier, assuming a solar wind velocity of 500 km/s. It is evident that the maxima of ΣKp and the N_2 index on the 7th day were situated at a sector boundary of the interplanetary magnetic field. This is consistent with a finding by Ness and Wilcox (1965) that the regions of high magnetic field intensity and high solar wind velocity always followed these corotating field reversal regions. As shown elsewhere (Hakura, 1964), the maximum variance of the interplanetary magnetic field observed by Mariner II (Snyder *et al.*, 1963) occurred at the leading part of the velocity enhancement, or at the field reversals.

The turbulence in the interplanetary field may be attributed to Kelvin-Helmholtz instability that developed along the velocity discontinuity (Dessler and Fejer, 1963) and to the sheet pinch instability produced along the field reversal region (Sakurai, 1966). The twisted-fan shaped region of the irregularity corotating with the sun might be the cause of the recurrent cosmic ray modulation shown in Figure 16(d).

The continual presence of Mev proton events, however, needs some particle-acceleration mechanism, and has been explained by the following hypothesis:

(1) The continuous acceleration of Mev protons exists at the bottom of a sector boundary.

(2) The continuous acceleration of Mev protons occurs in an active region of the sun, and energetic particles produced are stored in the interplanetary magnetic field for a few solar rotations.

(3) The continuous acceleration of Mev protons occurs in the interplanetary space in turbulent interface.

The first hypothesis seems to be unreasonable since the Mev protons are connected with an inactive region of the coronal emission as shown in Figure 17. The old active region proposed by Mustel (1961) cannot be the root of the present sector boundary, since days 2-6 remained inactive throughout the last sunspot cycle as shown at the top of Figure 10.

To support the second hypothesis, there was a rather active region that appeared during the third period of PCA activity (III). If this region is connected with the turbulent region with a bottle-shaped interplanetary field, then the solar cosmic rays produced in the active region will propagate along, and be stored in the magnetic bottle, especially in the turbulent magnetic region.

Statistics shown in Figure 18 might support the present hypothesis, where solar cycle variations in $\bar{N}_2$ and $\bar{N}_4$ indices (top), ratio $\bar{N}_2/\bar{N}_4$ (middle), and the 27-day autocorrelation coefficient of ΣKp (bottom) are given. It was noted that variations in $\bar{N}_4$ and $\bar{N}_2$ were almost parallel during the high sunspot number, while the ratio $\bar{N}_2/\bar{N}_4$ became greater in 1961 through 1963. This shows that the Mev proton events represented by enhancement of N_2 index became predominant during the decreasing period of sunspot activity, when the recurrence of geomagnetic activity ΣKp also was enhanced. However, an important point here is the difference between $\bar{N}_2$ and the autocorrelation coefficient in 1964. The PCA-producing Mev proton was absent, $N_2 = 0$, while a still sound sector structure of interplanetary space existed as shown by a high value of the autocorrelation coefficient

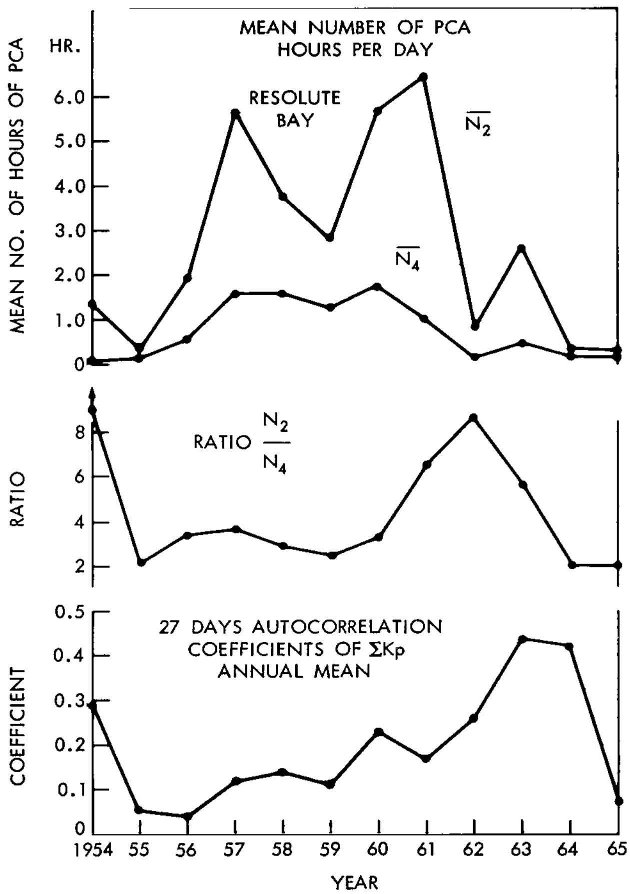

Figure 18—Solar cycle variations in (a) mean N_4 and N_2 indices, (b) ratio N_2/N_4, and (c) 27-day autocorrelation coefficients of ΣKp.

in 1964. The appearance of recurrent PCA's, i.e. Mev proton events, is caused by the formation of a solid sector structure of the interplanetary space. However, it is also controlled strongly by the type IV activity discussed in Figure 7.

As pointed out by Fan *et al.* (1965), the third hypothesis cannot explain all of the field-reversing corotating regions do not contain Mev protons at all times. However, it is interesting to note that the long-lived recurrent storms of galactic cosmic rays were observed only when the same sector boundary swept the earth. Though we do not have any evidence that supports the peculiarity of the present sector boundary, this hypothesis still survives.

CONCLUSION

Daily indices of PCA activity were computed for years 1954-1965, which covers the whole period of the 19th solar cycle. Outstanding PCA events were selected on the basis of the activity indices and correlated with other solar-terrestrial phenomena such as solar flares, type IV radio outbursts, and geomagnetic storms. A study of the solar-terrestrial relationship was made using the daily indices, the table of outstanding events, and satellite observations of low-energy solar protons. Several important results of the solar cycle variation in the corpuscular activity are summarized as follows:

1. A close correlation between PCA's and type IV solar radio outbursts holds throughout the whole solar cycle considered here, especially for events of major importance. The correlation was increased when propagation conditions for PCA-producing particles in interplanetary space were considered. A statistical study showed an east-west asymmetry of a PCA-producing probability of type IV sources and also a deficiency of PCA-occurrence in northern winter months.

2. Solar corpuscular activity inferred from occurrence frequencies of PCA's and type IV outbursts showed three peaks during the last solar cycle—two outstanding peaks in 1957 (I) and 1960 (II) and a small peak in 1963 (III). During the first peak of activity (I), the type IV sources appeared equally in both the northern and southern hemispheres of the sun. However, the active centers existed only in the northern hemisphere during the later phases of solar activity (II) and (III). Consequently, the heliographic-latitude time distribution of type IV sources showed a complicated pattern with three wings in the northern hemisphere, which is different from the Maunder's simple butterfly diagram obtained for sunspot regions.

3. There was a tendency of the PCA flares to occur in the same active regions even for a few solar rotations. A statistic of the longitudinal distribution of CMP dates of the active centers showed that there were at least four active regions in the period (I), while the active regions were restricted in two parts of narrow heliographic longitudes in the periods (II) and (III). Throughout the whole solar cycle there were two definitely inactive longitude regions on the second through the sixth days and the 17th day of solar rotation. The localization of active centers in the later phase of solar activity might be connected with a simple sector pattern of interplanetary magnetic field revealed by the satellite IMP-1.

4. The solar cycle variations in both the annual mean of geomagnetic ΣKp index and occurrence frequency of the SSC (geomagnetic storms with sudden commencement) showed two peaks in periods (I) and (II). Because of the sporadic nature of the SSC occurrence, the 27-day autocorrelation coefficient of ΣKp was very low for the first period (I). On the other hand, the locality of flare sources enhanced the coefficient in the period (II). The solar cycle variation in the SG occurrence (SG represents a gradual geomagnetic storm) was similar to that in 27-day coefficients; both of them increased toward the end of the solar cycle and had a prominent peak in period (III). The sawtooth distribution of the non-SC recurrent storm occurred with 11- (and possibly 33-) year periodicity in the years 1924 through 1965.

5. During the later phases of solar corpuscular activity (II) and (III), various space vehicles detected a number of solar Mev protons which sometimes caused a slight PCA event detectable by the daily PCA index of higher sensitivity (N_2). A recurrent series of the Mev protons starting from the fifth through the sixth days lasted for approximately 15 solar rotations in 1963-1964. This series coincided with a part of recurrent series of geomagnetic ΣKp index and galactic cosmic-ray variations, which were traceable for approximately 25 solar rotations, ranging from the end of 1962 to the end of 1964. The result means that the Mev protons were confined within a region corotating with the sun; this region caused an enhancement of geomagnetic activity and at the same time modulated the galactic cosmic-ray intensity at the orbit of the earth with a 27-day recurrent period. The maxima of ΣKp and Mev proton activity on the seventh day were situated at a field reversal region of the interplanetary magnetic field observed by IMP-1. The root of the field reversal region was identified with the persistently inactive region of PCA productivity and coronal green line G6 intensity.

6. The appearance of recurrent PCA's or Mev protons is no doubt correlated with the formation of a solid sector structure of the interplanetary magnetic field. However, it is also strongly controlled by the productivity of low-energy solar protons. Our available materials seem to support a hypothesis that the continuous acceleration existed in an active region of the sun, and energetic particles produced were stored in the interplanetary magnetic field for a few solar rotations.

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