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Type IV Solar Radio Bursts, Geomagnetic Storms, and Polar Cap Absorption (PCA) Events

Barbara Bell [1]

This paper compares solar radio bursts of type IV identified by means of spectrum observations in the meter bands with those identified from discrete frequency observations particularly in the centimeter bands. The comparison considers certain associated active-sun phenomena and properties of the bursts themselves as well as geomagnetic storm and solar proton (PCA) effects. Solar activity preceding geomagnetic storms is discussed, with sporadic and recurrent storms treated separately. In the final section the disk position of the source is studied as a function of storm intensity.

It has been well established that type IV bursts have a high probability of being followed by geomagnetic disturbance and by ionospheric absorption over the polar cap (PCA). Among the various studies, those by McLean (1959), Thompson and Maxwell (1960a, 1960b), and Bell (1963, hereafter called Paper I) are based exclusively on radio spectrum observations. The others (see Paper I for additional references) have been based wholly or in part upon observations at discrete frequencies.

Paper I contains a detailed examination of the relationship of solar radio bursts of spectral type IV (and also type II) with flares, the Mount Wilson magnetic class of the associated sunspot, the north-south asymmetry, geomagnetic storms, and PCA effects. The study included a total of 96 type IV (and 197 type II) bursts observed in the four years 1957 through 1960 with the dynamic spectrum analyzers at the Harvard Radio Astronomy Station, Fort Davis, Texas, and at the Radiophysics Laboratory of the Commonwealth Scientific and Industrial Research Organization, Sydney, Australia. These instruments record over the frequency range 580 to 25, and 240 to 40 Mc/s, respectively. These same spectral data are used in the present study.

The only published comprehensive list of type IV bursts derived from discrete frequency observations has been compiled by Pick-Gutmann (1961). These bursts are identified primarily by unusually intense ($\geq 10^{-20}$ $W/m^2/Hz$) and long-lived ($\geq$10 minutes) radiation in the centimeter region of the solar spectrum (2800 and 9400 Mc/s). The requirement of intense centimeter radiation makes Pick-Gutmann's bursts of especial interest for comparison with the spectrum bursts recorded at longer wavelengths.

Pick-Gutmann lists 145 type IV bursts in the interval from January 1957 through March 1960. Over the same interval 70 type IV events were recorded at Fort Davis and/or Sydney. (Maxwell, Thompson, and Garmire (1959) estimate that the Harvard and Sydney stations together cover an average of 14 hours per day.) Comparing the two lists we obtain four categories of bursts:

- H/S,P: observed by Harvard or Sydney, and listed by Pick-Gutmann;
- H/S,-P: observed by Harvard or Sydney, but not listed by Pick-Gutmann;
- P,-H/S: listed by Pick-Gutmann, but not by Harvard or Sydney;
- P,n.o.: listed by Pick-Gutmann, no observations by Harvard or Sydney.

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TABLE 1.—*Properties of type IV bursts recorded by spectrum analyzer*

Burst category	Number	Percent with duration				Percent with max. freq.		
		$\leq 15^m$	16–59^m	1^h–3^h59^m	$\geq 4^h$	≥ 580	<580	Unknown
H/S,P	46	9	22	41	28	67	13	20
H/S,-P	24	38	42	12	8	37	42	21
All H/S	70	19	29	31	21	57	23	20

The (H/S,P) bursts radiate strongly on both centimeter and meter wavelengths; the (H/S,-P) bursts are strong in meter bands but fall below Pick-Gutmann's limits in the centimeter region; and the (P,-H/S) are strong in the centimeter bands but weak or absent, or not of spectral type IV, on meter wavelengths. About one-third of the (P,-H/S) bursts have an associated type II burst, and about two-fifths have short-lived ($<5^m$) continuum emission.

Table 1 compares the first two categories of bursts with respect to duration and maximum observed spectral frequency. The latter quantity was available to me only for Harvard observations; the "unknown" are from Sydney. On the left, table 1 shows that the (H/S,P) bursts are of substantially longer duration on the average than the (H/S,-P) bursts. Only 20 percent of the latter, but 69 percent of the former lasted more than one hour. From the values in table 1 it can be found that only 16 percent of the spectral bursts lasting more than an hour lacked type IV centimeter radiation. On the other hand, about 70 percent of the spectral bursts lasting no more than 15 minutes, which in Paper I were shown to be significantly less geoactive than longer lasting bursts, lack type IV centimeter radiation. A check of the radio data in the *IAU Quarterly Bulletin of Solar Activity* revealed that about 57 percent of all (H/S,-P) bursts were too weak at around 10 cm for inclusion in Pick-Gutmann's list; 39 percent had no recorded centimeter radiation; and 17 percent were of too short duration. Among the (H/S,-P) bursts of spectrum duration $\leq 15^m$, 30 percent were apparently (-P) because of insufficient duration but only 10 percent for this reason alone.

On the right, table 1 shows that many more of the (H/S,P) than of the (H/S,-P) bursts are observed at the maximum frequency recorded by the Harvard spectrum analyzer. A substantial percentage of the bursts without sufficient type IV centimeter radiation for inclusion in Pick-Gutmann's list had their maximum observed spectral frequency well below 580 Mc/s.

Table 2 compares the various categories of type IV bursts with respect to association with a major flare (rated importance 3 or 3^+ by at least one observatory, or 2^+ by at least two observatories), association with a sunspot of complex magnetic class, location in the northern solar hemisphere, and distance from the solar central meridian (CM). Paper I gives comparative data for other active-sun phenomena such as flares, sunspots, and type II bursts, as well as a subdivision of the spectral type IV bursts by duration. Bursts observed over the full frequency-range (H/S,P) show the strongest preference for sunspots of the complex classes, and also the highest percentage of association with a major flare. The lowest association with major flares as well as with complex sunspot groups occurs for the bursts that are observed on meter but not on centimeter wavelengths (H/S,-P).

Evidence was presented in Paper I that in recent cycles the concentration to the northern hemisphere tends to increase with the increasing intensity in several manifestations of solar activity. The percentages in the fourth column of table 2 are in accord with this tendency, although taken alone the differences between the various categories are of limited significance.

The last three columns of table 2 show that the spectral (H/S) type IV bursts are more

TABLE 2.—*Association of type IV bursts with major flares, complex ($\beta\gamma$ or γ) sunspots, and position on the solar disk*

Burst category	Percent of bursts associated with					
	Major flare	Complex sunspot	Northern hemisphere	Meridian distance		
				<30°	30°–59°	≥60°
H/S,P	68	64	71	50	36	14
H/S,-P	21	42	60	58	42	0
All H/S	51	57	67	52	38	10
P,n.o.	61	56	67	33	35	32
P,-H/S	38	50	58	34	33	32
All P	55	57	67	39	35	26

concentrated toward the solar central meridian than are the centimeter (P) bursts. The (P,n.o.) and (P,-H/S) bursts indeed show a quite uniform distribution with meridian distance. Pick-Gutmann (1961) found that bursts with the centimeter and the meter radiation of about equal duration were most numerous from beyond 45° from the CM, while most bursts with conspicuously prolonged meter radiation arose from within 45° of the CM. She presented evidence that the latter bursts have a "second phase" which is confined to meter and dekameter wavelengths and which is more directional than the first phase. Because of this directional effect, similar to that observed for ordinary noise storms, the second phase is not often observed in bursts generated in regions remote from the CM.

A subdivision of the spectrum bursts by duration, in table 3, reveals a systematic increase in concentration to the central regions of the solar disk with increasing duration from 16^m upward. The trend is in the direction to be expected if Pick-Gutmann's concept of a directive second phase is correct. On the other hand, it is known that low-frequency waves are more strongly refracted in the corona than are high-frequency waves, and hence meter waves will have more difficulty in reaching the earth from oblique angles than do centimeter waves. Refraction and the associated phenomena of scattering and absorption may account for most

TABLE 3.—*Relation between duration of spectral type IV bursts and distance from the solar central meridian*

Burst category	Duration	Number	Percent with meridian distance		
			<30°	30°–59°	≥60°
H/S,P	$\leq 15^m$	3	67	33	0
	16–59^m	9	22	56	22
	1^h–3^h59^m	19	47	32	21
	$\geq 4^h$	13	69	31	0
All H/S	$\leq 15^m$	10	70	30	0
	16–59^m	32	25	47	28
	1^h–3^h59^m	31	58	26	16
	$\geq 4^h$	17	71	29	0

or all of the relation between meridian distance and duration of the meter wave bursts. As the disturbance weakens in intensity the meter waves can no longer reach the earth in detectable amounts from highly oblique angles. Only the stronger bursts, during their period of greatest intensity, can be observed from large CM distances at meter wavelengths. The strong concentration to the CM of bursts lasting less than 15^m suggests that these bursts come from rather moderate disturbances. The (H/S,-P) bursts are too few in number to establish any systematic trends with duration, but as table 2 shows, none of them originated more than 60° from the CM. (The lower section of table 3 includes the spectral bursts from the last nine months of 1960 in addition to the interval covered by Pick-Gutmann's list.)

The concentration to the central zone of bursts lasting more than 4^h is no doubt related to their outstanding success in producing great geomagnetic storms, found in Paper I. As Newton (1943) first showed, and Bell (1961) and others have confirmed, most great storms follow flares that occur within 45° of the CM. (See also the concluding section of this paper.)

Geomagnetic and PCA effects

Each burst was classified according to its geomagnetic success as measured by the planetary magnetic indices, *Kp* and *Ap*, that is, according to whether it was followed within the interval of 10 hours to 3 days by no storm, a small ($Ap \geq 25$), moderate ($Ap \geq 50$), or great ($Ap \geq 100$ and/or $Kp \geq 9^-$) storm. Table 4 gives data on the geomagnetic success of each category of type IV burst. The last line of the table shows the level of success to be expected from a random sample of days and was derived from the number of storms of each intensity within the four years 1957 through 1960. To facilitate comparison, table 5 summarizes the geomagnetic success of radio bursts of spectral types IV and II from Paper I.

Table 4 shows that type IV bursts that are strong over the full frequency range (H/S,P) have a high probability of being followed within three days by a great storm. In striking contrast, bursts of type IV that are identified only on centimeter wavelengths (P,-H/S) or only on meter wavelengths (H/S,-P) are followed by a great storm slightly more often than might be expected to occur by chance. Moreover, in most of the cases where such a limited-frequency burst was followed by a great or moderate storm, there was also another burst of full frequency range preceding the same storm. Type IV bursts of limited frequency range have no higher level of geomagnetic success than do type II bursts without type IV (see table 5 and Paper I). At most they are significantly associated with small storms.

In the second section of table 4 the bursts of spectral type IV are divided according to their maximum and their minimum recorded spectral frequency. The frequency range over which the burst was intense enough to be recorded, in the case of the Harvard data, proves to be one of the most useful properties of type IV bursts for forecasting the probability of a great or moderate storm. A type IV burst recorded over the entire range from 580 to 100 Mc/s or below has a high probability of being followed by a great or at least a moderate geomagnetic storm. This probability is not significantly above the random for Harvard bursts observed over less than the complete range of the equipment, whether terminating above 100 Mc/s or starting below 580 Mc/s. The latter bursts do, however, show some association with small storms.

Other attributes found useful in Paper I for forecasting the success of a type IV burst are the duration of the burst, and the importance and the location (north or south of the solar equator) of the associated flare. The third section of table 4 shows that the optical importance of the associated flare remains of value in forecasting even when only full-frequency-range bursts are considered. Only when accompanied by a major flare is even a (H/S,P) burst likely to be followed by a great magnetic storm and/or a PCA event. The full-frequency-range bursts with minor flares show an unusually high probability of being followed by a small storm, which suggests some relation between storm intensity and flare importance.

TABLE 4.—*Percentage of type IV radio bursts followed by a PCA, and by various levels of geomagnetic activity, subdivided by properties of the solar event. Values deviating less than 2σ and more than 4σ from the random sample are designated by parentheses and by bold face type, respectively*

Properties of bursts	Number	Percent followed by			
		Great storm	Moderate storm	Small storm	PCA
H/S,P	46	**33**	(20)	(35)	**30**
H/S,-P	24	(8)	(8)	42	(4)
P,n.o.	54	13	(17)	(33)	13
P,-H/S	45	(9)	(11)	(31)	(7)
All H/S	70	**24**	(16)	37	**23**
All P	145	**18**	(16)	35	**17**
Spectral freq. range					
≥580 to ≤100 Mc/s	37	**32**	27	(24)	**41**
≥580 to >100	19	(11)	(21)	(37)	(11)
<580	20	(10)	(10)	50	(5)
Unknown (S)	20	30	(15)	(30)	**30**
H/S,P bursts					
Flare ≥2+	30	**40**	(20)	(27)	**43**
Flare ≤2	14	(14)	(14)	64	(7)
Flare ≥2+ North	21	**57**	(24)	(19)	**48**
Flare ≥2+ South	9	(0)	(11)	(44)	33
Random sample	1460	5	11	23	3

TABLE 5.—*Percentage of radio bursts of spectral types II and IV followed by a PCA, and by various levels of geomagnetic activity (see table 4)*

Events	Number	Percent followed by			
		Great storm	Moderate storm	Small storm	PCA
Type IV	96	**23**	19	34	**24**
Type II	197	**12**	(11)	33	9
II and IV	51	**24**	(17)	(32)	**26**
II, no IV	146	(8)	(8)	34	(3)
IV, no II	35	14	(20)	40	**20**
Random sample	1460	5	11	23	3

A striking contrast appears in table 4 between northern and southern full-frequency bursts with a major flare. In agreement with the results of Paper I, only a northern burst has a high probability of being followed by a great geomagnetic storm; a southern burst is not likely to be followed by more than a small storm in spite of possessing the other auspicious properties of a major flare and full frequency range. On the other hand, the difference in PCA success between northern and southern bursts is less and not statistically significant with the present sample size.

Bursts from complex ($\beta\gamma$ and γ) spot groups have a somewhat greater probability of success than do bursts from β and α groups, but the difference is not statistically significant. Present results confirm the conclusion of Paper I that the magnetic class of the sunspot has its greatest value in longer-range forecasting, in advance of the solar flare and radio burst.

The last column of table 4 shows that the frequency range covered by a type IV burst is also relevant to the occurrence of PCA events. Only bursts of full frequency range are strongly associated with PCA. This conclusion is in accord with the finding by Warwick and Haurwitz (1962) that most PCA's are preceded by a radio burst of unusual intensity and duration at wavelengths from the decimetric to the dekametric. It would appear that most of the Sydney bursts are strong over a wide band of frequencies since their geomagnetic and PCA success is not greatly inferior to that of the 580 to $\leq$100 Mc/s Harvard bursts. The last column of table 5 shows that PCA events are not significantly associated with type II bursts that lack type IV emission.

The greater success of full-frequency-range bursts can be qualitatively understood under the widely accepted hypothesis that type IV bursts are synchrotron emission from high-energy (relativistic) electrons spiralling in a magnetic field. The electrons radiate over a more or less wide band of frequencies. The maximum frequency is proportional to the strength of the magnetic field and to the square of the energy of the electrons. The minimum freqency required for waves to escape from a given depth in the corona is proportional to the square root of the electron density. Thus weakness of type IV radiation at high frequencies (H/S,-P) implies weakness of the magnetic field and/or relatively moderate electron energies. Weakness at low frequencies (P,-H/S) implies that the disturbance never rose high enough in the corona for the meter waves to escape. If the disturbance cannot reach the outer corona, it would seem to have small chance to reach the vicinity of the earth. Without both highly energetic electrons and a disturbance extending into the outer corona, the probability is small that a major corpuscular cloud was ejected.

The spectral meter burst usually starts a few minutes after the 10-cm burst. In my sample the delay time, H/S minus P, varies from -14^m to $+31^m$, with a mean value of $+8^m$ for the Harvard bursts (580 Mc/s) and $+21^m$ for the Sydney bursts (240 Mc/s). These mean values are compatible with the concept of a source of excitation moving outward at around 1000 km/sec. However, the wide dispersion in delay times argues against any simple interpretation of type IV bursts in terms of an outward moving source of excitation directly associated with the ejection of a cloud of storm corpuscles.

Solar activity preceding geomagnetic storms

In the previous section we considered geomagnetic activity following type IV bursts. Here, as in the concluding section of Paper I, we begin with a list of geomagnetic storms, subdivided by intensity, and determine the percentage preceded by a major flare and by a type IV burst of each category. When studying this inverse problem earlier we found that a more refined classification of storm intensity was useful. The two additional measures introduced in Paper I were the maximum 3-hr Kp attained during the storm, and $\overset{4}{\Sigma} a_p$, the sum of the four largest consecutive 3-hr a_p values. Here we shall use mainly the latter index, and consider only storms with a value of $\overset{4}{\Sigma} a_p \geq 160$. This limit excludes 19 of the weakest "small storms".

In Paper I we also found that nonrecurrent storms showed a much stronger association with major flares and type IV radio bursts than did recurrent storms. This result supported the hypothesis first proposed by Allen (1944) that there are two fundamentally different types of magnetic storms—the sporadic SC type which includes most of the great storms, and the recurrent or M-region type of lesser intensity. Allen found that sporadic storms showed a positive association with the central meridian passage of large spot groups, but recurrent storms showed a negative association or a tendency to avoid large spot groups. A similar result was obtained by Saemundsson (1962) from a study of the relation between plages and geomagnetic storms. Bell and Glazer (1956, 1957) obtained a negative relation between recurrent storms and the intensity of the green (λ5303) emission-line corona. Newton and Milsom (1954) showed that SC (sudden commencement) and non-SC storms are differently related to the sunspot cycle.

From these findings it is clear that any future study of solar activity preceding geomagnetic storms should consider separately the sporadic and the recurrent storms. I therefore subdivided the storms according to whether they were recurrent, as in Paper I, and in addition here according to whether they had an SC. Recurrent, as defined in Paper I, means a member of a sequence with at least three recurrences at an interval of 26 to 28 days. A storm was classified as SC only if the SC was observed by 10 or more stations, according to the list of SC's published quarterly in the *Journal of Geophysical Research.*

This subdivision yielded two "pure" and two "hybrid" categories of storm. The pure categories are, of course, the sporadic SC storms, and the recurrent non-SC storms, and together comprise just over two-thirds of the storms in my sample (January 1957 to December 1960). Table 6 shows the population of each category as a function of storm intensity, and demonstrates that the presence of an SC is strongly related to storm intensity. With very few exceptions storms with maximum $Kp \geq 7°$ and/or $\overset{4}{\Sigma} a_p \geq 400$ have an SC observed at ten or more stations, even when they are members of recurrent sequences. The relation between storm intensity and recurrence is much weaker. Among the very great storms, however, only that of 6 October 1960 is recurrent as here defined. Since it appears to lack any explanation in terms of solar activity, and also lacks a PCA, it is probably a genuine M-region storm in spite of its high intensity.

Table 7 shows the percentage of geomagnetic storms preceded within three days (with a minimum delay time of 10 hours) by a major flare, by a type IV burst, and by a PCA. The data confirm the findings of the previous section that type IV bursts of categories (H/S,–P) and (P,–H/S) are of little geomagnetic significance. Type IV bursts of the full frequency range (H/S,P)—including (P,n.o.), and for April to December 1960 also (H/S,n.o.)—show a very strong association with sporadic SC storms with $\overset{4}{\Sigma} a_p \geq 200$. The association increases with increasing storm intensity to 100 percent for storms with $\overset{4}{\Sigma} a_p \geq 1000$. The percentage preceded by a PCA falls off more rapidly with decreasing storm intensity and is significant only for storms with $\overset{4}{\Sigma} a_p \geq 500$.

The recurrent storms without SC show a strong negative relation with both major flares and with (H/S,P) type IV radio bursts, a relation significantly below the association to be expected to occur by chance in each case. All intensities were combined because there was no significant variation with storm intensity. This next-to-last line in table 7 provides additional evidence that M-region storms avoid active solar centers, and thus supports Allen's hypothesis that sporadic and M-region storms have a different mechanism of origin.

The hybrid categories of geomagnetic storm (sporadic without SC, and recurrent with SC) show only a random association with type IV radio bursts, and a negligible association with PCA. The stronger recurrent SC storms show a statistically significant association with major flares, but not with type IV emission. However, the number of such storms is small. The hybrid categories probably represent a mixture of active-center and M-region storms, which tend to cancel each other out in the statistics.

Table 7 may be compared with tables 11 and 12 of Paper I. In particular, we may recall

Table 6.—*Numbers of sporadic sudden commencement (SC) and recurrent geomagnetic storms, as related to storm intensity*

Storm intensity	Total number	Number of storms				Percent sporadic	Percent SC
		Sporadic		Recurrent			
		SC	Non-SC	SC	Non-SC		
Great	26	20	1	5	0	81	96
Moderate	57	31	4	9	13	61	70
Small	87	28	25	9	25	61	42
Max Kp							
$\geq 9^-$	15	13	1	1	0	93	93
8^+ to 8^-	24	14	0	8	2	58	92
$7^+, 7^\circ$	24	18	2	3	1	83	88
$7^-, 6^+$	36	19	4	5	8	64	67
$6^\circ, 6^-$	54	13	16	5	20	54	33
$5^+, 5^\circ$	17	2	7	1	7	53	18
$\overset{4}{\Sigma}a_p$							
≥ 1000	9	8	0	1	0	89	100
500–999	25	16	1	6	2	68	88
400–499	19	12	1	5	1	68	89
300–399	25	18	3	1	3	84	76
200–299	56	18	10	7	21	50	45
160–199	36	7	15	3	11	61	28
Total	170	79	30	23	38	64	60

that the percentage of storms preceded by a type IV burst dropped abruptly for $\overset{4}{\Sigma}a_p$ below 900. The reality of this drop was uncertain because an unusually high percentage of storms with $\overset{4}{\Sigma}a_p=300$ to 900 were preceded by flares that occurred outside the Harvard and Sydney observing hours. Inclusion of the (P,n.o.) bursts substantially raises the percentage of moderate storms preceded by a type IV burst. However, there remains in the data of table 7 some evidence for an abrupt drop in the percentage of storms preceded by type IV emission at around the $\overset{4}{\Sigma}a_p=1000$ level of intensity. With respect to association with type IV radiation, the intensity range from 999 down to 300, perhaps even to 200, appears quite homogeneous.

Note that in tables 4 and 5 (and tables 5 and 6 of Paper I) the apparent statistical significance of the association between small storms and type IV bursts is weakened by the inclusion of the M-region storms in the determination of the random sample. If we excluded all the recurrent non-SC storms—shown in table 7 to have no connection with major flares or type IV emission—then the probability that any given day will be followed within three days by a moderate storm would drop from 11 to 9 percent, and the probability for a small storm would drop from 23 to 14 percent. The percentage of full-frequency-range bursts (H/S,P) followed by a moderate storm would then exceed the corrected random probability by more than 2σ. The statistical significance of the small-storm percentages in table 4 would be more strikingly increased, leaving only the (≥ 580 to ≤ 100 Mc/s) value below 2σ, and raising several values above 4σ.

TABLE 7.—*Percentage of geomagnetic storms preceded within three days by a major flare, by a type IV radio burst, and by a PCA, with storms subdivided by intensity and type. Values deviating less than 2σ and more than 4σ from the random sample are designated by parentheses and bold face type, respectively*

Storm type and intensity $\left(\Sigma a_p^4\right)$	Number	Percent preceded by				
		Major flare	Type IV burst *	Type IV burst: H/S, P P, n.o. H/S, n.o.	Type IV burst: H/S, -P P, -H/S	PCA
Sporadic, SC						
≥1000	8	100	100	**100**	(25)	**100**
500–999	16	88	75	**69**	(19)	**56**
300–499	30	**80**	**77**	**70**	(13)	(20)
200–299	18	72	72	61	(22)	(6)
160–199	7	(43)	(43)	(43)	(0)	(14)
Sporadic, non-SC						
≥200	15	(53)	(34)	(27)	(27)	(0)
160–199	15	13	(13)	(13)	(0)	(0)
Recurrent, SC						
≥500	7	86	(43)	(29)	(14)	(14)
160–499	16	(38)	(25)	(19)	(6)	(0)
Recurrent, non-SC						
≥160	38	**8**	11	3	(8)	(3)
Random sample	1460	41	32	20	12	9

* The percentages in this column are often less than the sum of those in the next two columns because some storms are preceded by both a full-frequency- and a limited-frequency-range burst. The difference between this column and the next would give the percentage preceded only by a limited-frequency burst.

Disk position of geomagnetic storm sources

Table 8 provides a convenient summary of data on the sunspot magnetic class and the position on the solar disk of the sources of geomagnetic storms, and of PCA and ground-level cosmic-ray (GCR) events. Section (a) contains storms preceded by a flare of any importance (mostly major, a few minor) that was accompanied by any category of type IV emission. Section (b) contains storms preceded by a major flare without listed type IV radio emission. Each storm was assigned a single most probable cause, and a flare with a full-frequency burst always ranked ahead of a flare with a limited-frequency burst, which in turn ranked above a flare without any type IV burst.

Section (c) contains the storms of the first two sections together with all storms preceded by a major flare (Bell 1961) in the years 1937–1956, and 1961. The disk position of each of these storm sources is plotted in figure 1. The linkage between a particular flare and storm can, of course, be accepted with most confidence in section (a).

The PCA events in section (e) are divided into large (L, VL), moderate (M), and small (S, VS). The intensities are from Bailey (1962), and the flare assignments are those of Warwick and Haurwitz (1962).

The magnetic class is of interest because major flares from sunspots with complex ($\beta\gamma$ or γ) magnetic field patterns are much more

TABLE 8.—*Sunspot magnetic class and solar disk position of the sources of geomagnetic storms and of solar proton (PCA) and ground level cosmic ray (GCR) events*

Years	Storm source	Storm intensity	Number	Percent complex	Percent north	Percent with CM distance		
						<30°	30°–59°	≥60°
(a) 1957–60	Flare & type IV	$\sum^{4} a_p \geq 1000$	8	75	88	88	12	0
		500–999	16	62	88	47	31	22
		300–499	24	62	71	42	37	21
		200–299	22	52	55	46	27	27
		160–199	6	67	17	50	50	0
(b) 1957–60	Major flare, no IV	300–999	9	33	67	39	17	44
		160–299	10	30	70	10	50	40
(c) 1937–61	Major flare and/or type IV	$\sum^{4} a_p \geq 1200$	8	75	100	88	12	0
		1000–1199	8	75	88	88	12	0
		700–999	28	59	79	54	32	14
		500–699	31	66	84	52	32	16
		300–499	48	50	69	50	33	17
		200–299	54	43	57	41	31	28
		160–199	30	39	37	40	40	20
(d) 1937–59	All major flares		580	41	62	45	33	22
(e) 1956–60	All PCA flares		43	70	70	45	28	27
	L, VL		9	78	89	33	45	22
	M		12	67	67	67	25	8
	S, VS		22	59	64	41	18	41
(f) 1942–60	GCR flares		12	92	92	33	17	50

likely to be followed within three days by a geomagnetic storm than are major flares from a simple bipolar (β) or unipolar (α) spot group (Bell, 1961). Table 8 shows that the GCR and PCA events and the greatest geomagnetic storms tend particularly to come from complex sunspot groups. It was found in Paper I that the geomagnetic success of a major flare with a spectral type IV burst is independent of the magnetic class of the sunspot. However, a $\beta\gamma$ or γ sunspot is about five times more likely than an α or β group of comparable area to produce a major flare with an associated radio burst of spectral type IV.

Bell (1961) found that a major flare in the northern solar hemisphere had a much higher probability of being followed by a great geomagnetic storm than did a major southern flare. The relation of this north-south asymmetry to storm intensity is shown in greater detail in sections (a) and (c) of table 8, where we can see that the percentage of storms coming from northern flares increases systematically with increasing storm intensity. The PCA events show a similar trend.

We should not however expect that the northern hemisphere will continue indefinitely to produce most of the great geomagnetic storms and cosmic-ray events. There is evidence (Bell, 1962; Bell and Wolbach, 1962) that the northern hemisphere of the sun has been the preferred source of great storms for most of

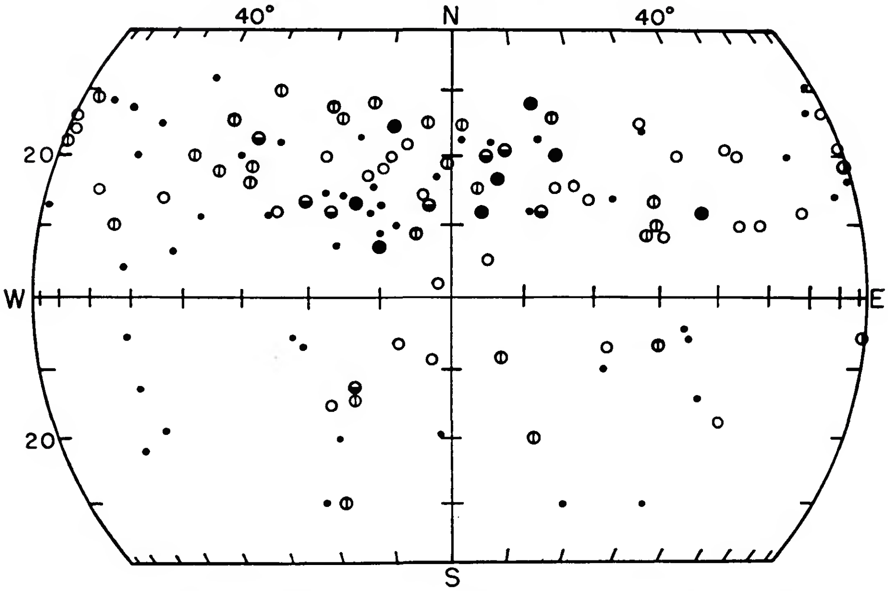

FIGURE 1.—*Plot of the location on the solar disk of probable sources of geomagnetic storms occurring in the years 1937 through 1961. The symbols indicate the intensity of the storm, as measured by the sum of the four largest consecutive values of the a_p index, $\overset{4}{\Sigma} a_p$: ●, ≥ 1200; ⊖, 1000–1199; ⦶, 700–999; ○, 500–699; and •, 300–499.*

this century, while in the latter half of the nineteenth century the southern hemisphere was the more active in production of great storms. It is impossible at present to predict when the southern may again replace the northern as the more geo-active solar hemisphere.

The tendency for the very great ($\overset{4}{\Sigma} a_p \geq 1000$) storms to come from small meridian distances appears clearly in figure 1 and in table 8. All of the very great storms of the present sunspot cycle arose from flares located no more than 30° from the solar CM (one at 30°). Over the past three cycles (section (c) and figure 1) one very great storm came from 37°E. About 80 percent of the very great storms arose from within 20° of the CM and the remainder from the 20–39° zone. All but one arose from the northern hemisphere.

At no intensity level below $\overset{4}{\Sigma} a_p = 1000$ does the distribution of storm sources with CM distance differ significantly from the distribution of major flares (cf. section (d) from Bell, 1961). There is however a tendency for more of the smallest storms to come from the larger CM distances. The distribution of storm sources suggests that the directivity of type IV emission (see table 2) and of low energy corpuscular emission are similar. A parallel can be seen between the sharpening of directivity with increasing duration of the burst (table 3) and with the intensity of the geomagnetic storm.

Among PCA sources there is no clear concentration of the largest events to the CM corresponding to that of very great storms. The distribution of all PCA sources is similar to that of all major flares and all storm sources, except for a slight excess of PCA from meridian distances beyond 60°. The strong concentration of GCR sources beyond 60° (west) has been pointed out by several authors, and is generally attributed to propagation conditions in the interplanetary medium rather than to solar directivity in emission.

The directivity effects in the emission of geomagnetic-storm corpuscles suggest that major corpuscular clouds may have a relatively dense core that is highly directional, with a beam width rarely exceeding 40° in longitude. Such a core is required to produce a very great storm. Surrounding the core, and in lesser clouds existing alone, is a less dense cloud emitted over a wide angle and capable of producing all but the very great geomagnetic storms from any position on the disk. The directivity in emission of high-energy (PCA) protons appears to be low.

Occasionally a great storm, in the range $\overset{4}{\Sigma} a_p$=700 to 1000, arises from a flare near the limb. There is at present no basis for deducing whether such storms arise from intense corpuscular emission over a very broad beam, or from nonradial ejection of a core.

Summary of conclusions

The data presented in this paper suggest that radio bursts commonly classified as type IV are a rather heterogeneous collection of events which, at least for purposes of forecasting geomagnetic and PCA activity, should be subdivided into two categories: those observed over a full range of frequencies from $\geq$2800 Mc/s down to $\leq$100 Mc/s; and those occurring over a limited range of two or three octaves. All of the data presented here support such a separation. The full-frequency-range bursts have a longer duration, and a higher association with major flares and with complex sunspots, and they are strikingly more successful in the production of PCA's and of great geomagnetic storms. Although the two groups may not differ in mode of origin, the frequency range covered is a significant and useful index of the importance of the burst.

The data strongly support Allen's (1944) hypothesis that sporadic and recurrent storms have a different mechanism of origin. Sporadic storms with SC show a strong association with major flares and with type IV radio bursts. Recurrent storms without SC show a statistically significant avoidance of major flares and type IV activity.

The percentage of storms arising from the northern solar hemisphere increases systematically with storm intensity. Very great storms arise from flares within 40°, and usually within 20°, of the solar CM. The distribution of the remaining storms parallels that of major flares.

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References

Allen, C. W.
1944. Relation between magnetic storms and solar activity. Monthly Notices Roy. Astron. Soc., vol. 104, pp. 13-21.

Bailey, D. K.
1962. The detection and study of solar cosmic rays by radio techniques. *In* Proceedings of the International Conference on Cosmic Rays and the Earth Storm, pt. 1, pp. 106-112. Journ. Phys. Soc. Japan, vol. 17, suppl. A-I.

Bell, B.
1961. Major flares and geomagnetic activity. Smithsonian Contr. Astrophys., vol. 5, no. 7, pp. 69-83.
1962. A long-term north-south asymmetry in the location of solar sources of great geomagnetic storms. Smithsonian Contr. Astrophys., vol. 5, no. 12, pp. 187-194.
1963. Solar radio bursts of spectral types II and IV: Their relations to optical phenomena and to geomagnetic activity. Smithsonian Contr. Astrophys., vol. 5, no. 15, pp. 239-257.

Bell B., and Glazer, H.
1956. Geomagnetism and the emission-line corona. Journ. Geophys. Res., vol. 61, pp. 179-182.
1957. Geomagnetism and the emission-line corona, 1950-1953. Smithsonian Contr. Astrophys., vol. 2, no. 5, pp. 51-107.

Bell, B., and Wolbach, J. G.
1962. On short-period relations between north-south asymmetry in spottedness and in great-storm sources. Smithsonian Contr. Astrophys., vol. 5, no. 12, pp. 203-208.

McLean, D. J.
1959. Solar radio emission of spectral type IV and its association with geomagnetic storms. Australian Journ. Phys., vol. 12, pp. 404-417.

Maxwell, A.; Thompson, A. R.; and Garmire, G.
1959. The association of solar radio bursts with auroral streams. Planetary Space Sci., vol. 1, pp. 325-332.

NEWTON, H. W.
1943. Solar flares and magnetic storms. Monthly Notices Roy. Astron. Soc., vol. 103, pp. 244–257.

NEWTON, H. W., AND MILSOM, A. S.
1954. The distribution of great and small geomagnetic storms in the sunspot cycle. Journ. Geophys. Res., vol. 59, pp. 203–214.

PICK-GUTMANN, M.
1961. Evolution des émissions radioélectriques solaires de type IV et leur relation avec d'autres phénomènes solaires et géophysiques. Ann. d'Astrophys., vol. 24, pp. 183–210.

SAEMUNDSSON, TH.
1962. Statistics of geomagnetic storms and solar activity. Monthly Notices Roy. Astron. Soc., vol. 123, pp. 299–316.

THOMPSON, A. R., AND MAXWELL, A.
1960a. Solar radio bursts and low-energy cosmic-rays. Nature, vol. 185, pp. 89–90.
1960b. Solar radio bursts and cosmic rays. Planetary Space Sci., vol. 2, pp. 104–109.

WARWICK, C. S., AND HAURWITZ, M. W.
1962. A study of solar activity associated with polar-cap absorption. Journ. Geophys. Res., vol. 67, pp. 1317–1332.

Abstract

This paper compares solar radio bursts of type IV identified by means of spectrum observations in the meter bands with those identified from discrete frequency observations in the centimeter bands. The comparison discusses associated active-sun phenomena and properties of the bursts themselves as well as geomagnetic storm and polar cap absorption (PCA) effects. Type IV bursts that cover the full frequency range from $\geq$2800 Mc/s down to $\leq$100 Mc/s are found to be strikingly more successful in the production of great geomagnetic storms and PCA events than are type IV bursts limited to two or three octaves of the spectrum.

Evidence is presented that strongly supports the hypothesis that sporadic and recurrent storms come from different types of solar regions. Sporadic SC storms are, in a high percentage of cases, preceded within three days by a major flare and by a type IV radio burst. Recurrent non-SC storms, by contrast, are preceded by major flares and by type IV bursts significantly less often than would be expected by chance.

The disk position of the source is studied as a function of storm intensity. About 80 percent of the very great storms are found to arise from flares located within 20° of the solar central meridian. The distribution of the sources of lesser storms parallels that of major flares and type IV bursts.

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