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SUNSPOTS AND GEOMAGNETISM

by Barbara Bell and Harold Glazer

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Sunspots and Geomagnetism

By Barbara Bell[1] and Harold Glazer[2]

Geomagnetic storms are commonly believed to be of two types: (1) nonrecurrent, great storms, which have a sudden commencement (sc) and follow the general cycle of solar activity in frequency of occurrence; and (2) recurrent or M-region storms, which are of lesser magnitude and more gradual onset and which are most prevalent in the declining phase of the solar cycle. Both types of storm presumably result when electrically neutral streams of ionized particles ejected by the sun reach the earth and disturb its magnetic field, but they appear to differ in the solar source of the corpuscular stream. Disturbances of the first type are often found to be associated with central meridian passage (CMP) of a large sunspot or the occurrence of a major flare (Newton, 1943; Allen, 1944). Recurrent storms, on the other hand, appear to avoid active solar centers. In a recent paper (Bell and Glazer, 1957) we discussed in some detail the recurrent type of storms and their apparent inverse relation to the intensity of the 5303 coronal line. In the present paper we are concerned primarily with the active-center type of storms.

Newton (1949) found, for the period 1914–44, that CMP of large sunspot groups (area ≥ 1500 millionths of the solar disc) tends to be associated with a rise in geomagnetic activity and that this relation diminishes for the group with area 1000–1500 and virtually disappears for spots of area less than 1000 millionths. For the period 1935–44, Newton found also that CMP of spot groups of moderate area that produce a large number of flares tend to be associated with a rise in geomagnetic activity.

Becker (1953) found that CMP of paired sunspots, one north and one south of the solar equator, tends to be followed by relatively quiet geomagnetic conditions. Unpublished results by workers at the Central Radio Propagation Laboratory suggest that CMP of large round stable spots tends to reduce the level of geomagnetic activity. Denisse (1952, 1953) found that 158 mc radio noise provided a useful criterion for separating geomagnetically active and inactive spot groups, that CMP of radio-noisy spots tends to be followed by enhanced geomagnetic activity, and that CMP of radio-quiet spots tends to be followed by decreased geomagnetic activity.

The radio noise results of Denisse (1952, 1953) and of Simon (1956a, 1956b), and other work by Bell and Glazer (1954a, 1954b, 1956, 1957) and Pecker and Roberts (1955) have indicated that active centers on the sun can affect geomagnetism in two contrary ways. An active center may appear to emit solar corpuscles to produce a geomagnetic storm or it may appear to inhibit the emission of solar corpuscles to produce a geomagnetically quiet condition. On the other hand, it may fail to cause any detectable effect; that is, it may seem neither to increase nor inhibit the emission of corpuscles. The essential problem now is how to predict what a given individual active center will do. At present, the best criteria for identifying a storm producer seem to be: radio noise, presence of the 5694 coronal line (Denisse and Simon, 1954; Bell and Glazer, 1957), large area, and numerous flares. Inhibitors of corpuscular emission seem to be characterized by radio quiet, pairing, few flares, and round stable spots of large size.[3]

The distribution of magnetic field in a spot group may be important in determining whether the spot will predominantly eject corpuscles or

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[3] For a more detailed discussion of the literature, see Bell and Glazer (1957).

will inhibit their escape from the sun. In this connection, Nicholson (1940) wrote that "although only about 2 percent of all spot groups are magnetically complex, great magnetic storms are usually associated with groups of that type." The relation between geomagnetic conditions and the magnetic classes of sunspots, however, has not previously been systematically investigated.

Observational data

As a measure of the solar corpuscular radiation reaching the earth,[4] or of the geomagnetic activity, we have used the daily *Kp* index. The *Kp* index of geomagnetic activity is measured for each 3-hour interval, on a scale from 0 (very quiet) to 9 (very disturbed); the daily index is the sum of the 3-hour values, and thus has a theoretical range of 0–72. The largest daily sum so far observed, however, is 62. Our investigation covers the years 1937–53, the major part of two solar cycles. The mean *Kp* for this interval is 19.6, a value derived from all the *Kp*'s in the 17 years, with each yearly mean *Kp* weighted by the annual sunspot number. (The unweighted mean is 19.5.)

For each sunspot group listed by the Mount Wilson Observatory in the Publications of the Astronomical Society of the Pacific, the following quantities were tabulated and punched on IBM cards: Julian date of CMP; latitude of spot group; its magnetic classification; its maximum magnetic field strength, *H*, in units of 100 gauss; a duration factor to indicate whether the spot was in existence at CMP; the number of flares, *F*, observed in the region, as published in the I. A. U. Quarterly Bulletin of Solar Activity; and *Kp*'s from 8 days before to 12 days after the CMP of the spot group. No area data were punched on the cards, but we used the list of spot groups having a mean area equal to or greater than 500 millionths of the solar disc published by the Royal Greenwich Observatory in 1955.

The Mount Wilson classification of sunspots according to their magnetic properties provides the basic data used in our investigation. This system, developed by Hale and Nicholson (1938) from observation of hundreds of spot fields and the distribution of their associated calcium plages, recognizes three basic categories of sunspot groups: unipolar (α), bipolar (β), and complex (γ).

Unipolar (α) groups are single spots or groups of spots having the same magnetic polarity.

Bipolar groups (β) in their simplest form consist of two spots of opposite polarity. Often, however, a bipolar group is a stream of spots, those in the preceding and those in the following parts of the group having opposite polarities.

Complex or multipolar groups (γ) are those having polarities so irregularly distributed that they cannot be classified as bipolar; sharply bounded regions of opposite polarities sometimes exist within the same penumbra.

Intermediate between the complex and the bipolar groups are the semicomplex ($\beta\gamma$) groups in which bipolar characteristics appear but no clearly marked dividing line occurs between the regions of opposite polarities. This category includes groups whose preceding or following members are accompanied by small spots having an opposite polarity.

The results presented here were obtained by the superposed epoch method of analysis (Chree and Stagg, 1927), with zero days defined by the CMP of selected groups of sunspots.

Magnetic class and area of sunspots

Table 1 presents some properties of sunspot groups subdivided according to magnetic class and to area. This table, which includes only long-lived, limb-to-limb sunspots, is based on the Greenwich spot groups with mean areas greater than 500 millionths of the solar disc, and includes also the following smaller spot groups: γ's greater than 300 millionths; $\beta\gamma$'s with $H \geq 1000$ gauss; β's and α's with $H \geq 2000$ gauss. Columns 7, 8, and 9 provide some clues to the relative importance of spot area and of magnetic class. Within each magnetic class, the rows in table 1 are arranged in order of decreasing area. It is immediately apparent that the Kp-conditions in our sample depend more strongly on magnetic class than upon the area of the spot group. We may consider each magnetic class separately and examine within each the area dependence of *Kp* averaged over five days, CMP (0) to (+4), a quantity referred to hereafter as $\overline{Kp}(0, +4)$.

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[4] For a more detailed discussion of the *Kp*-index of planetary magnetic activity, see, for example, Bartels and Veldkamp (1949).

Table 1.—*Geomagnetic conditions associated with CMP of large sunspot groups, 1937–53*

(For explanation of symbols see below)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Magnetic class	Area range	N	$\bar{A}$	$\bar{H}$	$\bar{F}$	$\bar{Kp}(0,+4)$	Kp(max)	$\Delta\bar{Kp}$	$\bar{Kp}\left(\begin{smallmatrix}-3 \text{ to } -1\\ +5, +6\end{smallmatrix}\right)$	$\bar{Kp}\left(\begin{smallmatrix}-6 \text{ to } -4\\ +7, +8\end{smallmatrix}\right)$	N'	$\Delta\bar{Kp}'$	Percent $Kp(0,+4)$		
													≥40	30—39	<10
$l\gamma l$	≥1500	8	2535	3680	36.6	27.0	29.0(0)	+7.4	24.3	25.4	8	+7.4	5.0	37.5	0
	750–1500	6	900	2860	22.8	27.0	29.8(1)	+7.4	25.2	21.4	6	+7.4	13.3	30.0	3.3
	500–750	6	630	2500	19.0	26.0	29.8(2)	+6.4	22.7	20.2	6	+6.4	6.7	25.7	3.3
	300–500	4	445	2050	13.2	26.7	36.8(2)	+7.1	23.6	20.4	4	+7.1	20.0	25.0	10.0
	≥300	24	1300	2910	24.8	26.6	28.3(2)	+7.0	24.0	22.2	24	+7.0	10.0	30.9	3.3
$l\beta\gamma l$	≥1500	9	2610	3560	27.7	24.3	25.6(2)	+4.7	18.7	15.9	9	+4.7	15.6	20.0	11.1
	1000–1500	9	1270	3120	29.7	18.6	19.3(0)	−1.0	17.8	19.3	9	−1.0	9.0	2.1	20.0
	750–1000	12	860	2620	16.0	25.1	27.7(1)	+5.5	18.9	19.2	12	+5.5	10.0	18.4	8.3
	600–750	10	660	2220	10.0	18.0	21.3(2)	−1.6	18.3	19.3	10	−1.6	6.0	8.0	24.0
	500–600	6	545	2800	9.7	23.0	24.5(1)	+3.4	23.6	21.7	6	+3.4	6.7	23.4	13.3
	≥500	46	1200	2840	18.8	21.9	23.2(2)	+2.3	19.1	18.9	46	+2.3	9.6	13.9	15.2
	<500	20		2090	4.1	21.0	23.9(1)	+1.4	18.0	19.4	20	+1.4	2.0	19.0	16.0
$l\beta l$	≥1500	9	2320	3140	25.2	18.8	22.9(2)	−0.8	19.4	18.4	9	−0.8	8.9	4.4	28.9
	1000–1500	15	1210	3280	15.0	19.2	21.3(3)	−0.4	19.7	21.8	15	−0.4	5.3	10.7	13.3
	750–1000	26	850	3260	12.2	19.2	20.5(3)	−0.4	20.2	19.3	25	−1.4	5.6	7.2	14.4
	600–750	36	670	3080	6.9	19.7	21.1(0)	+0.1	19.6	19.2	34	−0.4	2.4	9.4	18.2
	500–600	31	545	3050	4.9	18.9	21.9(0)	−0.7	19.8	19.3	30	−0.8	1.3	10.0	14.0
	≥500	117	870	3140	10.0	19.3	19.8(0)	−0.3	19.8	19.5	113	−0.6	3.7	8.8	16.5
	<500	43		≥3000	5.1	20.6		+1.0			38	−0.6	2.6	9.7	14.2
	<500	130		20–2900	3.6	19.2		−0.4			115	−1.2	2.0	11.1	18.7
	<500	173		≥2000	4.0	19.6		0.0			153	−1.1	2.1	10.9	17.8
$l\alpha l$	≥1000	3	1290	3440	10.3	18.4	27.3(3)	−1.2	19.3	18.5	3	−1.2	6.7	6.6	20.0
	750–1000	3	850	3800	9.0	22.8	27.3(3)	+3.2	22.8	19.1	3	+3.2	0	13.3	0
	600–750	5	685	2780	4.0	24.5	30.0(1)	+4.9	22.1	16.4	4	+3.2	0	25.0	0
	500–600	18	545	3350	4.5	19.4	21.5(3)	−0.2	18.7	18.3	16	−1.9	3.8	3.7	22.5
	≥500	29	675	3310	5.5	20.6	22.1(3)	+1.0	19.8	18.1	26	−0.5	3.1	10.8	16.1
	< 500(α)	50		≥2000	1.1	19.1		−0.5			44	−1.8	0.5	10.4	16.8
	<500(αp)	61		≥3000	1.3	20.9		+1.3			60	+1.1	2.4	19.0	11.3
	<500(αp)	163		20–2900	1.9	20.4		+0.8			146	−0.8	1.0	13.1	17.2
	<500	274		≥2000		20.2		+0.6			250	−0.7	1.2	14.1	15.7
Mean or "expected" values						19.6		0.0	19.6	19.6		0.0	3.7	12.1	15.0

Explanation of symbols used in tables 1–8

$\bar{A}$: Mean area of spot groups.

C: An index of geomagnetic disturbances based on activity scale of 0.0 (very quiet) to 2.0 (very disturbed).

C(max): Highest average value of the C index in the 5-day interval (0, +4), with the day of its occurrence given in parentheses.

$\bar{C}(0, +4)$: C index of geomagnetic activity averaged over the five days (0) through (+4), around central meridian passage of spot groups.

$\bar{C}(-3$ to $-1, +5, +6)$: The average values of the geomagnetic C index for the five days indicated.

$\bar{C}(-6$ to $-4, +7, +8)$: The average values of the geomagnetic C index for the five days indicated.

$\Delta\bar{C}$: The quantity $\bar{C}(0, +4)$ minus the mean, 0.70.

$d_{c,w}$: Spots born around or after central meridian passage of region.

d_e: Spots born on disc east, before central meridian passage of region.

$\bar{F}$: Mean number of observed flares in spot groups.

f: Spots in the favorable solar hemisphere.

f': Spots in favorable solar hemisphere, February–April and August–October.

$\bar{H}$: Mean value of the maximum magnetic field strength of spot groups.

Kp: An index of geomagnetic activity designed to measure the solar corpuscular radiation reaching the earth.

Kp(max): Highest average value of the Kp index in the 5-day interval (0, +4), with the day of its occurrence given in parenthesis.

$\bar{Kp}(0, +4)$: Kp index of geomagnetic activity averaged over the five days (0) through (+4), around central meridian passage of spot groups.

$\bar{Kp}(-3$ to $-1, +5, +6)$: The average values of the geomagnetic Kp index for the five days indicated.

$\bar{Kp}(-6$ to $-4, +7, +8)$: The average values of the geomagnetic Kp index for the five days indicated.

$\Delta\bar{Kp}$: The quantity $\bar{Kp}(0, +4)$ minus the mean, 19.6.

$\Delta\bar{Kp}'$: The $\Delta\bar{Kp}$ based on the number of sunspot groups adjusted as described on page 165.

N: Number of spot groups.

N': Number of sunspot groups adjusted as described on page 165.

Q: Radio-quiet spots.

R: Radio-noisy spots.

s: Spots in the solsticial months, May–July and November–January.

u: Spots in the unfavorable solar hemisphere.

u': Spots in the unfavorable solar hemisphere, February–April and August–October.

+ (in col. 2 of table 4): Excess of flares.

— (in col. 2 of table 4): Dearth of flares.

o (in col. 2 of table 4): Average number of flares.

In each area group of γ spots, $\overline{Kp}(0, +4)$ is conspicuously above average and shows only a minor dependence on spot area, even for spots smaller than 500 millionths. The larger γ spots, however, show an enhanced Kp on a larger number of days, the rise being less concentrated to the days around CMP (see columns 10 and 11), than for the smaller γ spots. With the $\beta\gamma$ spots, $\overline{Kp}(0, +4)$ is also above average, but the rise is smaller and occurs less consistently than for the γ spots. The relation between $\overline{Kp}(0, +4)$ and spot area is not systematic and therefore would appear to be of minor importance. For both the β and α spots, $\overline{Kp}(0, +4)$ appears to be independent of area. For the β's, $\overline{Kp}(0, +4)$ is slightly below average, while for the α's it is slightly above average.

In figure 1 is plotted the average Kp values associated with CMP of large ($A \geq 500$ millionths) spot groups for each of the four magnetic classes of sunspots. Because area appeared to be relatively unimportant in our sample, we combined the various area groups above 500 millionths. To estimate the statistical significance of the results shown, we used the standard error of the mean, $\sigma = 10/\sqrt{N}$, where N is the sample size and 10 is the standard error of a single Kp. In the $\beta\gamma$ curve, only $Kp(+2)$ is more than 2σ above the mean. In the γ curve, 2σ lies at $Kp = 24.1$, so that the Kp on each day (-1 through $+8$, except for $+6$) is more than 2σ above the mean of 19.6; the maximum value, at $Kp(0)$, lies about 3.5σ above the mean. The α and β curves show no statistically significant deviations from the mean.

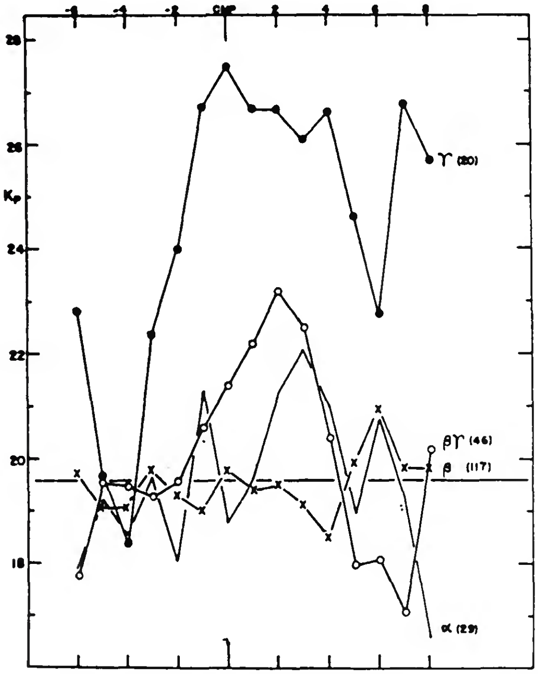

FIGURE 1.—Average geomagnetic conditions (Kp) on days around the central meridian passage (CMP) of large ($A \geq 500$ millionths) sunspots of the four magnetic classes, α, β, $\beta\gamma$, and γ, for the years 1937–1953. The number of spot groups used is given in parentheses.

The standard error for the average of the means of n consecutive days is given by the equation,

$$\sigma_n = \frac{10}{\sqrt{N}} \sqrt{\frac{1}{n}\left[1 + \frac{2(n-1)}{n}\rho_1 + \frac{2(n-2)}{n}\rho_2\right]}, \quad (1)$$

where ρ_1 and ρ_2 are the autocorrelations of the mean Kp's for 1-day lag and for 2-day lag, respectively. From the values of the autocorrelation given by A. H. Shapley (1947), we estimated that $\rho_1 = 0.5$ and $\rho_2 = 0.2$. Substitution of these values in equation (1) gives $\sigma_5 = 6.4/\sqrt{N}$. This standard error may be used to obtain an estimate of the significance of the numbers in columns 7 and 13 of table 1. (Because columns 10 and 11 include nonadjacent days, for them $\sigma_5 = 5.8/\sqrt{N}$.) The statistically significant ($\geq 2\sigma_5$) deviations of $\overline{Kp}(0, +4)$ from the mean of 19.6 are confined to the γ and $\beta\gamma$ spots. For the 46 $\beta\gamma$ spots, the deviation of $\overline{Kp}(0, +4)$ from the mean is about $2\sigma_5$, or barely significant at the 5 percent level. For the individual γ area-groups the deviation from the mean ranges from 2 to $3\sigma_5$; and for the total of 24 spots it is $5\sigma_5$, significant well beyond the 0.1 percent level. There is no evidence for any significant area-dependence of $\overline{Kp}(0, +4)$, in any magnetic class.

The dependence of Kp on sunspot magnetic class may be at least partially reconciled with the apparent area-dependence found by Newton (1949) by considering the frequency of the various magnetic classes in each area grouping. With area greater than 1500 millionths, we have 8γ, $10\beta\gamma$, 9β and 1α; whereas in the area range 500–750 we have 6γ, $21\beta\gamma$, 67β and 23α, that is, a much lower percentage of the geomagnetically more disturbing γ and $\beta\gamma$ spots.

The superior storm-producing efficacy of γ and $\beta\gamma$ spot groups may be further seen by considering the problem conversely. Greenwich (1955, p. 79) lists eight "very great" storms since 1917; four of these appear to be associated with γ spot groups and four with $\beta\gamma$ spot groups. Of 66 Greenwich "great" storms from 1917 to 1953, 18 can be attributed to γ spots, 20 to $\beta\gamma$, 21 to β, and 4 to α; 10 lack any spot of area greater than 200 millionths. Some of these latter are probably not true "great" storms, but rather storms of the recurrent or M-region type. (In assigning the spots, we have taken account of the "notes" and not restricted ourselves to the spots given in the table itself. The total exceeds 66 because a few storms could be assigned equally well to two or more spots.) The geomagnetic index *Ap*, because of its approximately linear scale (*Kp* is a more nearly logarithmic measure of the amplitude of the disturbance), appears especially suited for distinguishing "great" storms. Use of this index yields 33 storms with $Ap \geq 100$ between 1937 and 1953. Of these we can attribute 9 to γ, 11 to $\beta\gamma$, 11 to β, and 1 to α groups, while only one lacks any notable spot group.

Thus we conclude that the great storms appear to be produced in about equal numbers by γ, $\beta\gamma$, and β spot groups. Since $\beta\gamma$, and particularly γ, are relatively uncommon spot types (Hale and Nicholson, 1938; also Bell and Glazer in a forthcoming paper), a given γ or $\beta\gamma$ spot group is more likely to be accompanied by a geomagnetic storm than is a simple bipolar or unipolar group of similar or even much larger area.

Taking this point as established, we next checked the individual cases of large storms (arbitrarily defined as $Kp \geq 40$) occurring near CMP of a large bipolar or unipolar sunspot; we discarded each case where, from geometrical considerations, the storm could belong about equally well to a γ or a $\beta\gamma$ spot, and recomputed the β and α *Kp*-curves. For this recomputation, we also removed the cases of β and α spots whose storms were members of prominent M-sequences; and in the case of spots with area less than 500, we removed spots whose storms could equally well be attributed to a substantially larger β or α spot group. The results make up columns 12 and 13 in table 1, which correspond to the data given in columns 3 and 9 for the complete sample. The net effect is a slight decrease in $\overline{Kp}(0,+4)$ for the β and α groups. These new curves are plotted in figure 2 for spots of area greater than 500 millionths. The γ curve is narrowed by the addition of the four spots in the 400–500 area range; the peak is shifted to $Kp(+2)$, which lies about 4σ above the mean. The $\beta\gamma$ curve is unchanged from that shown in figure 1.

We pointed out earlier that sunspots appear, geomagnetically, to be of three types, which we may call geomagnetically active or "storm producing," "inhibiting," and "inert." (We use these terms for convenience in discussing apparent relations, and do not intend to imply thereby that causal connections have been established between these spots and geomagnetic conditions.) In any superposed epoch

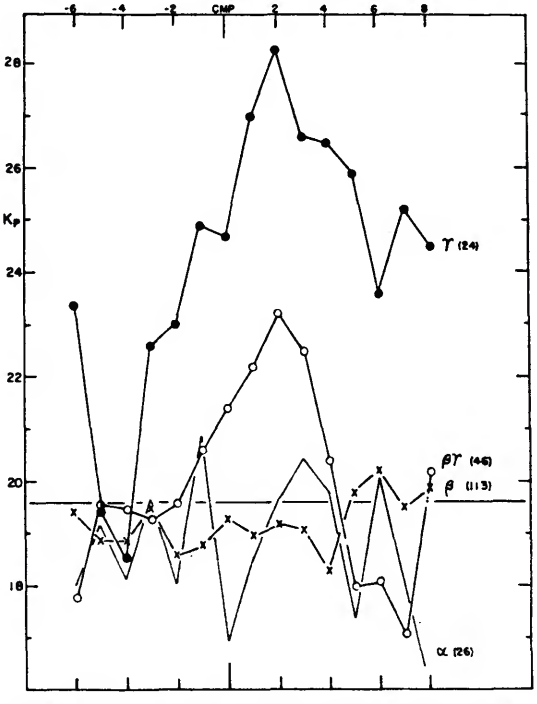

FIGURE 2.—Average geomagnetic conditions (*Kp*) on days around central meridian passage (CMP) of selected large ($A\gamma \geq 400$, others ≥ 500 millionths) sunspots of the four magnetic classes for the years 1937–1953. The number of spot groups used is given in parentheses.

analysis, as Denisse first pointed out, the effects of the storm-producers and those of the inhibitors will tend to neutralize one another, and leave a featureless curve. To explore this situation, for each area group of each magnetic class we have determined the frequency of *Kp* in various intervals for the five days (0, +4), shown in the last three columns of table 1. For all *Kp*'s, 1937–53, the mean percentages are: 3.7 percent $Kp \geq 40$, 12.1 percent 30–39, and 15.0 percent less than 10.

Columns 14, 15, and 16 provide several clues toward understanding the differences in *Kp*-curves associated with the various spot groupings. The γ and $\beta\gamma$ spots appear about equal in percentage of $Kp \geq 40$, containing respectively 2.7 and 2.6 times the average or expected frequency. Although not shown in the table, the γ spots have 3.3 times, and the $\beta\gamma$ spots 5.8 times the expected frequency of $Kp \geq 50$. The frequency of $Kp \geq 40$ shows no relation to spot area for the γ spots, with some suggestion of a relation in the $\beta\gamma$ spots. The difference between the *Kp*-curves associated with CMP of γ spots and those associated with CMP of $\beta\gamma$ spots appears to arise from the large (2.5 times the expected) frequency of *Kp* 30–39, and the very low (0.22 of the expected) frequency of $Kp < 10$ with γ spots, especially the larger ones. For $\beta\gamma$ spots these frequencies are highly variable and show no systematic relation to area, but on the average they are close to the expected values.

In the case of β and α spots, the percentages of $Kp \geq 40$ show some relation to spot area, with the over-all frequencies close to the expected values. The frequency of *Kp* 30–39 is 0.73 of the expected number for β and 0.9 for α spots, and shows no systematic relation to area. The frequency of $Kp < 10$ is 1.1 of the expected value for these spots. For the very large ($A \geq 1500$) β spots, both $Kp \geq 40$ and $Kp < 10$ appear substantially in excess of the expected frequency, and tend to neutralize one another in any superposed epoch analysis.

Having obtained the above results for spots in the period 1937–53, we thought it desirable to test them further, using the Greenwich spots of area equal to or greater than 500 millionths for the years 1917–36. Since the *Kp* index is not available prior to 1937, it is necessary to use the older *C* index of geomagnetic activity. The scale of the *C* index is 0.0 (very quiet) to 2.0 (very disturbed). The results are exhibited in table 2 and figure 3. The mean value of *C* used in the table and the figure, 0.70, was derived as the mean of the 15 points on the β superposed epoch curve; it is therefore less exact than the mean $Kp = 19.6$, which was derived from all the *Kp*'s in the 17 years. The expected frequencies in the various intervals of *C* have not been determined. Twenty-two bipolar spots of variable magnetic class have been omitted from figure 3 and table 2 because of the uncertainty of their classification; they give $\overline{C}$ (0, +4)=0.68.

In general, the results of 1937–53 are supported by those from the earlier period, although the 1917–36 results show somewhat more evidence for an influence of spot area on geomagnetic activity. In terms of geomagnetic consequences, the $\beta\gamma$ spots in the earlier period appear indistinguishable from the β and α spots.

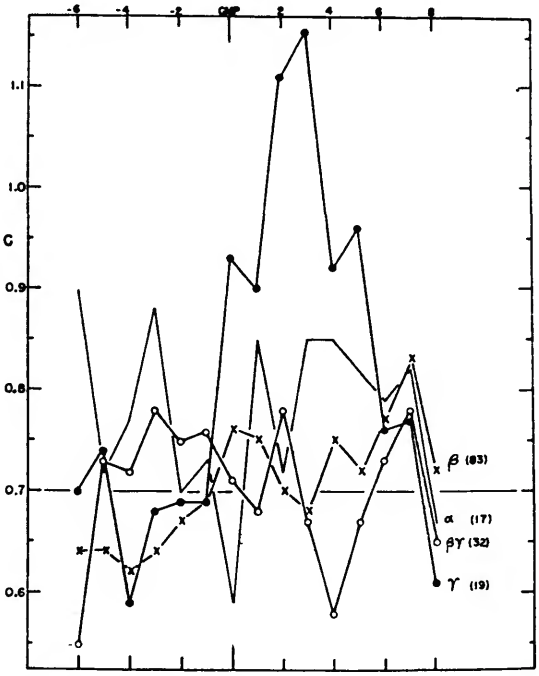

FIGURE 3.—Average geomagnetic conditions (*C*) on days around central meridian passage (CMP) of large ($A\gamma \geq 300$, others ≥ 500 millionths) sunspots of the four magnetic classes, α, β, $\beta\gamma$, and γ, for the years 1917–1936. Number of spot groups used is given in parentheses.

TABLE 2.—*Geomagnetic conditions associated with CMP of large sunspot groups, 1917–36*

(For explanation of symbols see p. 163)

(1) Magnetic class	(2) Area range	(3) N	(4) $\overline{A}$	(5) $\overline{H}$	(6) $\overline{F}$	(7) $\overline{C}(0, +4)$	(8) $C(\max)$	(9) $\Delta\overline{C}$	(10) $\overline{C}\binom{-3 \text{ to } -1}{+5, +6}$	(11) $\overline{C}\binom{-6 \text{ to } -4}{+7, +8}$	(12) Percent $C(0, +4)$ 2.0	(13) ≥1.7	(14) 1.2–1.6	(15) ≤0.2
$l\gamma l$	≥1500	3	1970	3260	----	1.15	1.33(3)	+0.45	0.60	0.50	13.3	40.0	0	6.7
	1000–1500	2	1335	3250	----	1.33	1.75(2)	+0.63	1.22	1.01	30.0	30.0	30.0	0
	750–1000	3	820	3230	----	0.90	1.13(3)	+0.20	0.59	0.66	0	20.0	13.0	20.0
	500– 750	6	595	2700	----	0.67	0.73(2)	−0.03	0.82	0.73	0	10.0	13.3	30.0
	290– 500	5	370	2840	----	1.25	1.48(2)	+0.55	0.69	0.64	12.0	32.0	16.0	0
	≥290	19				1.00	1.16(3)	+0.30	0.76	0.68	8.4	24.2	13.7	13.7
$l\beta\gamma l$	≥1500	4	2350	3420	----	0.94	1.15(2)	+0.24	0.80	0.67	5.0	25.0	5.0	15.0
	1000–1500	8	1240	3140	----	0.68	0.95(2)	−0.02	0.70	0.64	2.5	5.0	17.5	27.5
	750–1000	7	875	2790	----	0.70	0.97(0)	0.00	0.75	0.64	2.9	5.7	14.3	31.4
	500– 750	13	615	2680	----	0.61	0.66(3)	−0.09	0.73	0.75	0.0	1.4	4.3	24.3
	≥500	32				0.68	0.78(2)	−0.02	0.74	0.68	1.9	6.2	10.0	26.2
$l\beta l$	≥1500	3	1840	3060	----	0.55	0.83(1)	−0.15	1.10	0.67	6.7	6.7	6.7	40.0
	1000–1500	12	1130	2840	----	0.66	0.73(1)	−0.04	0.61	0.63	1.7	3.3	15.0	20.0
	750–1000	19	850	3110	----	0.75	0.91(4)	+0.05	0.65	0.61	1.0	4.2	22.1	21.1
	600– 750	21	675	2940	----	0.69	0.71(2)	−0.01	0.67	0.68	0	1.0	16.2	18.1
	500– 600	28	545	2860	----	0.78	0.85(0)	+0.08	0.74	0.78	2.8	5.7	21.4	27.2
	≥500	83				0.73	0.76(0)	+0.03	0.70	0.69	1.7	3.9	18.8	22.9
$l\alpha l$	≥1000	2	1225	2900	----	0.97	1.30(3)	+0.27	0.90	0.74	10.0	10.0	40.0	30.0
	750–1000	4	805	2920	----	0.67	0.80(0)	−0.03	0.71	1.02	0	10.0	10.0	25.0
	500– 600	11	530	3140	----	0.78	0.87(1)	+0.08	0.79	0.77	0	7.3	10.0	11.7
	≥500	17				0.77	0.85	+0.07	0.78	0.78	1.2	8.2	14.1	17.6

The γ spots again appear to be storm producers, and their superiority over the $\beta\gamma$'s is more striking in the earlier period.

In addition to the limb-to-limb or *ll* spots discussed above, a number of young (*dl*) groups are found among the larger spots. In the category with area ≥500 millionths, the *dl* spots are all bipolar, β and $\beta\gamma$; there are no large young γ or α spots. Table 3 gives some results for the larger *dl* spots. $\overline{Kp}(0,+4)$, in column 7, shows no significant ($\geq 2\sigma_5$) deviations from the mean. There is some indication that *dl* spots are more commonly inhibitors than *ll* spots of equal area (cf. column 16), but both the samples and the differences are too small to justify any definite conclusions.

Effect of flare abundance

Newton (1949) found that spots producing large numbers of flares are more likely to produce geomagnetic disturbance than spots having a subaverage number of flares. To investigate this result with our more extensive data, for each magnetic class we plotted area of spot group (column 4) against number of observed flares (column 6 of table 1) and drew a smooth curve through the points. (The relation between flare production, magnetic class, and spot area will be more fully discussed in another paper, in preparation.) We divided the spots of each magnetic type into three groups of approximately equal size: those having an average number of observed flares within about ±5 flares of the curve, those having an excess, and those having a dearth of observed flares, designated by the symbols o, +, and −, respectively.

TABLE 3.—*Geomagnetic conditions associated with CMP of young sunspot groups of large area, 1937–53*

(For explanation of symbols see p. 163)

(1) Magnetic class	(2) Area range	(3) N	(4) $\overline{A}$	(5) $\overline{H}$	(6) $\overline{F}$	(7) $\overline{Kp}(0,+4)$	(8) $Kp(\max)$	(9) $\Delta\overline{Kp}$	(10) $\overline{Kp}\binom{-3 \text{ to } -1}{+5, +6}$	(11) $\overline{Kp}\binom{-6 \text{ to } -4}{+7, +8}$	(12) N'	(13) $\Delta\overline{Kp}'$	(14) Percent Kp ≥40	(15) 30–39	(16) <10
$d\beta\gamma l$	≥1000	2	----	2300	40.5	25.1	38.0(4)	+5.5	20.1	19.2			10.0	40.0	20.0
	500–1000	5	----	2540	15.0	18.3	22.8(2)	−1.3	17.8	23.0			4.0	16.0	28.0
	≥500	7				20.2	24.7(4)	+0.6	18.5	21.9			5.7	22.8	25.7
	<500	18	----	1000		18.0	19.6(4)	−1.6	16.1	17.8					
$d_{o}\beta l$	750–1100	7	----	3020	14.1	18.0	19.8(2)	−1.6	19.9	20.0	6	−3.8	0	3.3	26.6
	600–750	12	----	2850	6.8	17.8	22.2(3)	−1.8	18.3	23.0	11	−3.2	1.8	7.3	25.5
	500–600	12	----	2680	9.1	18.4	20.5(1)	−1.2	19.8	19.5	10	−2.5	0	6.0	12.0
$d_{+,-}\beta l$	500–1000	14	----	2460	5.4	17.7	18.8(4)	−1.9	20.5	20.0			0		
Mean or "expected" values						19.6		0.0	19.6	19.6		0.0	3.7	12.1	15.0

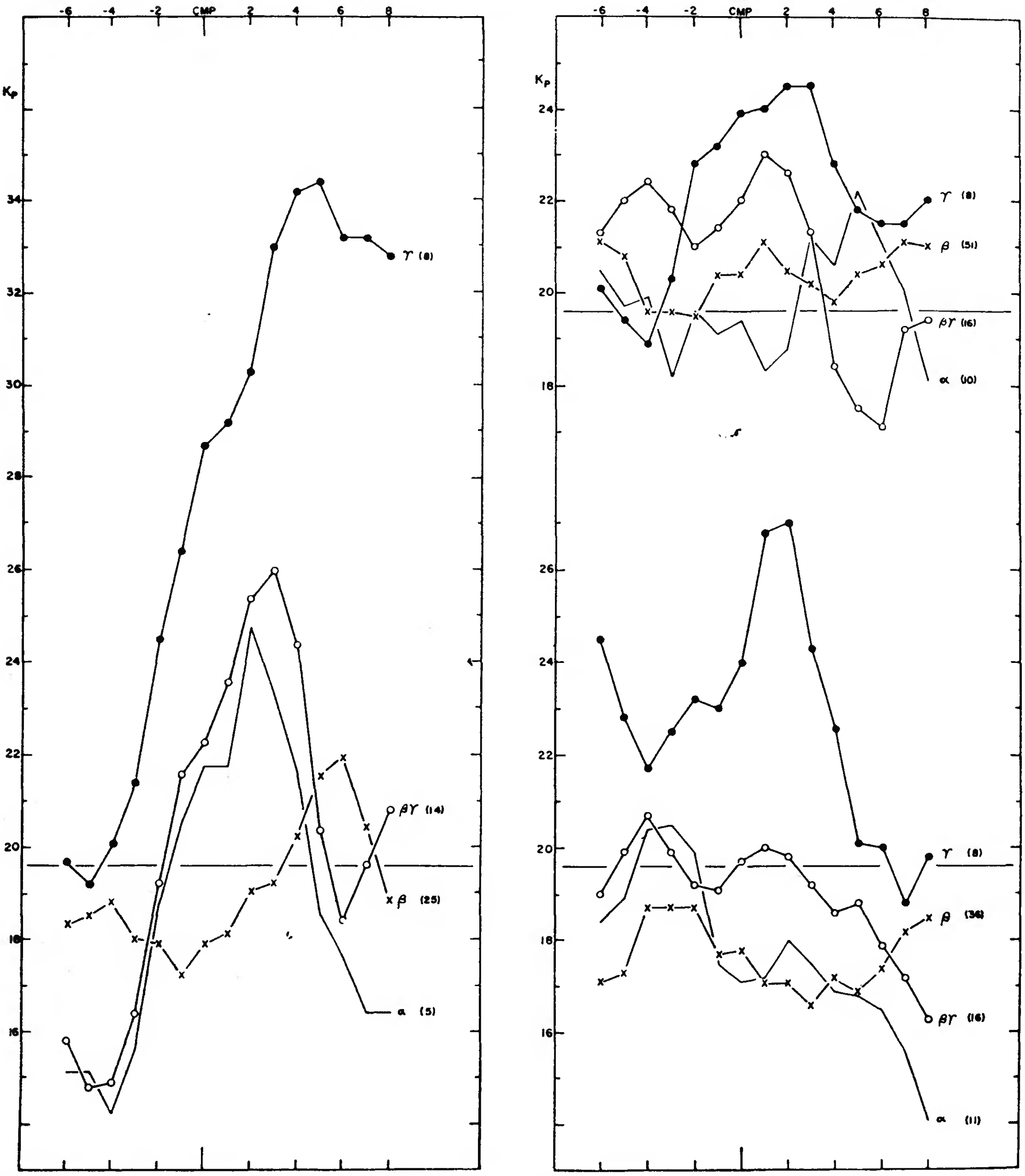

Figure 4.—Average geomagnetic conditions (*Kp*) on days around central meridian passage (CMP) of large sunspots of the magnetic classes α, β, βγ, and γ, having an excess (left), an average number (upper right), and a dearth (lower right) of observed flares. Number of spot groups used is given in parentheses.

TABLE 4.—*Geomagnetic conditions associated with CMP of large sunspots subdivided by magnetic class and by apparent flare productivity*

(For explanation of symbols see p. 163)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Magnetic class	Flares	N	$\overline{A}$	$\overline{F}$	$10\overline{F}/\overline{A}$	$\overline{Kp}(0,+4)$	Kp(max)	Kp(min)	Percent $Kp(0, +4)$ ≥ 40	30–39	<10	≥ 20	At least one $Kp(0, +4)$ ≥ 40	≥ 30
$l\gamma l$	+	8	1210	37.5	.310	31.5	36.8(4)	28.7(0)	20.0	42.5	2.5	82.5	62.5%	100.0%
	0	8	1390	23.8	.172	24.0	25.8(2)	21.9(0)	2.5	25.0	2.5	60.0	12.5	62.5
	−	8	1310	13.2	.101	24.6	30.0(2)	19.5(4)	7.5	25.0	5.0	57.5	37.5	87.5
		24	1300	24.8	.191	26.6			10.0	30.8	3.3	66.7	37.5	83.4
$l\beta\gamma l$	+	14	1270	32.7	.258	24.6	28.2(3)	22.6(0)	12.9	15.7	10.0	62.9	35.7	57.2
	0	16	1200	16.4	.137	21.8	23.9(2)	18.7(4)	11.3	15.0	20.0	48.8	31.2	62.5
	−	16	1130	8.6	.076	19.6	20.4(2)	18.5(4)	5.0	11.3	15.0	41.3	15.0	50.0
		46	1200	18.6	.156	21.9						50.4	30.4	56.5
$l\beta l$	+	25	1010	23.4	.232	18.5	19.7(2)	16.9(0)	4.0	9.6	16.8	43.2	16.0	48.0
	0	51	840	9.1	.109	20.5	21.6(2)	19.7(4)	5.1	7.8	13.0	50.1	17.6	45.2
	−	36	830	3.2	.039	17.2	18.5(3)	15.2(2)	1.7	10.0	21.6	33.3	8.3	50.0
		112	870	10.0	.115	19.3						43.2	14.3	47.4
$l\alpha l$	+	5	620	10.8	.174	22.1	26.2(3)	17.2(0)	0	12.0	0	64.0	0	40.0
	0	10	810	7.7	.095	19.9	25.5(4)	17.6(0)	4.0	14.0	18.0	46.0	20.0	60.0
	−	11	610	1.5	.024	17.1	19.0(3)	15.2(0)	3.6	7.3	21.8	36.3	18.2	36.4
		26	690	5.6	.082	19.1						45.4	15.4	46.2

From superposed epoch analyses we obtained the results plotted in figure 4. Because some of the samples were small, these curves have been plotted as 3-day running means. Further particulars appear in table 4, in the last two columns of which are given the percents of spots associated with at least one daily $Kp \geq 40$, and ≥ 30, in the five-day interval CMP (0 to +4). As a rough estimate of the expected frequencies, we obtain 15 percent for column 14 and 52 percent for column 15. For column 13, the expected value has not been computed; the mean for the 208 spot groups is 47.8 percent $Kp \geq 20$.

In figure 5 we have plotted $\overline{Kp}(0, +4)$ against the ratio $10\overline{F}/\overline{A}$, i. e., the data of column 7 against that of column 6 from table 4. We also plotted $\overline{Kp}(0, +4)$ against area for individual spot groups, with flare frequency distinguished by the three symbols given above. These plots, not included here, show no evidence of a relation between $\overline{Kp}(0, +4)$ and spot area, but do show a moderate tendency for the + symbols to be more frequent among the larger $\overline{Kp}(0, +4)$ values.

The data in table 4 and figures 4 and 5 tend to support Newton's finding that flare-active spot groups are more likely to be geomagnetically disturbing than spots deficient in flares or having only an average number of flares.

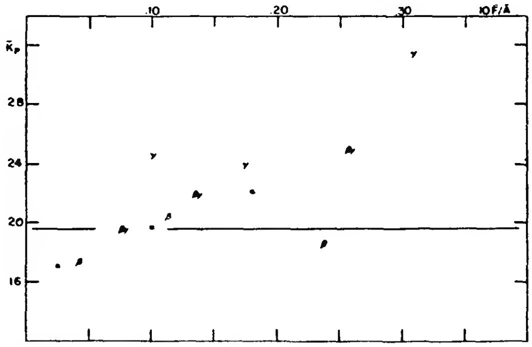

FIGURE 5.—Average geomagnetic conditions (Kp) for days 0 through +4, plotted against flare productivity ($10\overline{F}/\overline{A}$) for spot groups of the magnetic classes α, β, $\beta\gamma$, and γ.

When we consider the separate spot classes, we find that the relation appears fairly clearly for the α, $\beta\gamma$, and γ spots, but seems negligible for the β spots. However, the only statistically significant deviations of $\overline{Kp}(0, +4)$ (column 7) from the mean of 19.6 are $\gamma(+) \simeq 5\sigma_5$, $\beta\gamma(+) \simeq 2.5\sigma_5$ and $\beta(-) \simeq 2\sigma_5$. The γ spot groups tend to be more flare-active than do the other types; but for a given relative flare-activity, $10\overline{F}/\overline{A}$, the γ spots appear to be more disturbing geomagnetically than do the other classes. Therefore it does not appear likely that the greater storm-producing tendency of γ spots arises solely from their tendency to greater flare activity.

TABLE 5.—*Some particulars of flare productivity and area of sunspots associated with various geomagnetic conditions*

(For explanation of symbols see p. 163)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
							Percent spots with		Percent spots in	
Magnetic class	$\overline{Kp}$ range	N	$\overline{Kp}$ (0, +4)	$\overline{F}$	$\overline{A}$	$10\ \overline{F}/\overline{A}$	excess of flares	dearth of flares	favorable hemisphere	equinoctial 6 months
$l\gamma l$	≥30	9	33.7	26.9	1210	.224	56	22	22	78
	25–30	4	27.4	29.5	1200	.246	50	25	50	75
	20–25	6	22.9	27.6	1870	.148	17	50	50	50
	15–20	5	18.0	14.2	870	.164	0	40	0	80
$l\beta\gamma l$	≥30	9	35.6	22.4	1400	.160	44	11	56	78
	25–30	7	27.5	25.2	800	.314	57	0	29	57
	20–25	10	22.0	15.5	1530	.101	20	70	40	40
	15–20	9	17.3	17.1	1170	.146	22	56	50	33
	10–15	5	13.2	13.6	840	.161	20	40	80	80
	<10	6	8.5	17.0	1160	.146	33	17	67	67
$l\beta l$	≥30	6	33.2	17.6	1690	.104	17	0	33	67
	25–30	10	26.9	13.0	790	.165	30	10	50	10
	20–25	32	22.4	6.0	750	.080	12	44	62	53
	15–20	30	17.3	12.7	830	.153	30	20	43	53
	10–15	30	12.8	8.7	830	.105	17	50	60	53
	<10	4	9.0	19.8	1480	.134	50	25	75	25
$l\alpha l$	25–30	6	27.9	5.8	710	.082	16	33	17	50
	20–25	6	22.1	6.3	640	.099	33	33	33	67
	15–20	7	18.1	5.3	620	.085	29	43	43	29
	10–15	3	13.3	10.0	1120	.089	0	33	33	100
	<10	4	7.7	1.8	530	.033	0	75	100	75

We also examined the problem inversely, subdividing each magnetic class of spots according to the value of $\overline{Kp}(0, +4)$ and computing the average values of flares and area, with the results shown in table 5. Columns 8 and 9 give the percent of spots with an excess and with a dearth of flares.

Plotting $\overline{Kp}(0, +4)$ (column 4) against the data in columns 7, 8, and 9 does not reveal any clear relation between flare-activity and the geomagnetic effects of spots. On the other hand, as we have seen, there is a marked inverse relation between geomagnetic storms and the magnetic class of sunspots. Column 6 provides further evidence that no relation exists between spot area and geomagnetic conditions, and agrees with the evidence presented in table 1.

We conclude that, although the data of table 4 and of figures 4 and 5 do indicate some degree of positive relation between flare-activity and geomagnetic conditions, the relation between sunspot magnetic class and geomagnetic conditions is the more pronounced, and probably the more basic. On the other hand, magnetic class alone is not a sufficient basis for accurate prediction, and the use of flare-activity as well as other criteria remains important.

Seasonal effects

The March and September maxima in geomagnetic and auroral activity are well known, but not understood. The semiannual variation in magnetic activity was first demonstrated by Bartels (1932) from the u-figures, and appeared to be present at all phases of the sunspot cycle. We present here some graphs to illustrate the nature of the seasonal variation in the more modern daily Kp-sums.

Figure 6 shows the average monthly value of Kp for three phases of the sunspot cycle: curve (A) covers the periods of high sunspot activity, January 1937 to June 1940 and January 1946 to June 1950; (B) that of declining sunspot activity, June 1940 to June 1944 and June 1950 through December 1953; and (C) that of minimum and early rise in activity, June 1944 through December 1945 and January 1954 through December 1955. Figures 7 and 8 show the average monthly frequencies of $Kp \geq 30$ and $Kp \geq 40$ respectively, with curves (A) and (B) covering the same periods used in figure 6. (For statistics on the seasonal variation in the 3-hour Kp's, see Bartels and Veldkamp, 1951, table 21.)

The exact intervals which represent the different phases of the sunspot cycle are of course

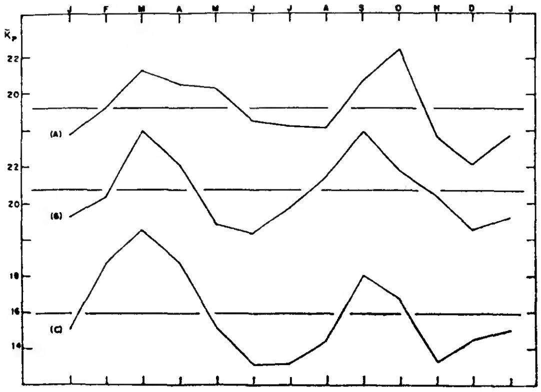

FIGURE 6.—Average monthly values of the geomagnetic index (Kp) for three phases of the sunspot cycle. Curve (A) covers the periods of maximum sunspot activity, curve (B) those of declining activity, and curve (C) those of minimum activity (see p. 170).

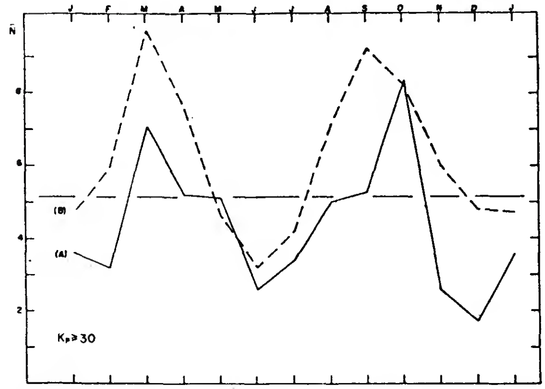

FIGURE 7.—Average monthly frequency ($\bar{N}$) of geomagnetic index $Kp \geq 30$: curve (A), around the maximum; curve (B), in the declining phase of the sunspot cycle.

somewhat arbitrary. In a general way, however, if we follow the ideas of Newton and Milsom (1954), we may consider that curve (A) covers the periods dominated by the nonrecurrent, great storms of sudden commencement (sc); whereas curve (B) covers the periods dominated by the recurrent and moderate-intensity storms. Although it is often difficult to classify an individual storm, it does appear that the corpuscles causing the two types of storms arise from quite different types of solar regions (Bell and Glazer, 1957). The great storms seem to arise from active solar centers, i. e., from large sunspots and/or major flares; whereas the recurrent storms arise from the more obscure M-regions. Because of these different mechanisms of storm-production, one would not necessarily expect that Kp would show a similar seasonal variation at all phases of the solar cycle. Figures 6, 7, and 8, however, each show a clear seasonal variation, and except for a generally lower level of activity around sunspot minimum (figure 6, curve (C)), they show no significant difference with phase of the sunspot cycle, a result in agreement with Bartels' findings from the u-figures.

Figure 9 (top) shows the monthly total numbers of sunspots of area ≥ 500 millionths, 1874–1954, and (bottom), the monthly total numbers of great magnetic storms, 1840–1954 (Greenwich, 1955). The great storms show the same semiannual variation in frequency as did Kp in figures 6, 7, and 8 (8 being the most comparable), whereas no such variation appears in the frequency of sunspots. We included in each

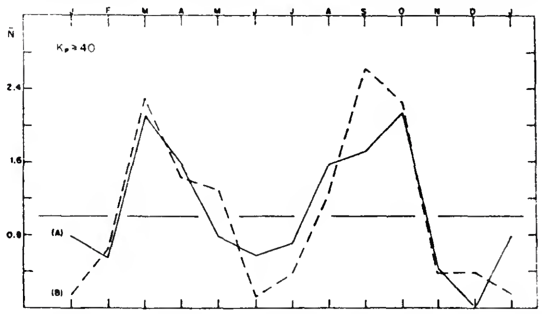

FIGURE 8.—Average monthly frequency ($\bar{N}$) of geomagnetic index $Kp \geq 40$: curve (A), around the maximum, and curve (B), in the declining phase of the sunspot cycle.

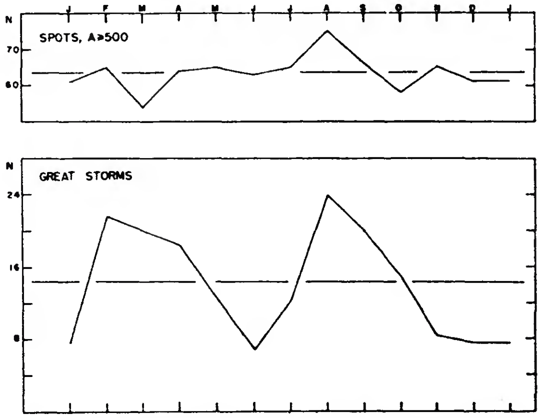

FIGURE 9.—Top: Monthly total number (N) of sunspot groups of area ≥ 500 millionths, for the period 1874–1954. Bottom: Monthly total number of great geomagnetic storms observed at Greenwich, for the years 1840–1954.

curve the longest available series of data, but the shape of the storm-curve would not be significantly altered if we used only the data from 1874 to 1954, corresponding to the available sunspot information. It is apparent that the monthly frequency of large sunspot groups shows no seasonal variation corresponding to that shown by the frequency of great storms. The monthly ratio of storms per spot displays also a clear seasonal variation.

In his original paper Bartels (1932) suggested two possible causes of the seasonal variation in geomagnetic activity, which, following his terminology, we call the equinoctial and the axial explanations. Briefly, the former suggests that the earth is more responsive to disturbances from solar corpuscles around the times of the equinoxes than around the times of the solstices. The axial explanation derives from the fact that the sun's equator is inclined 7.2° to the plane of the ecliptic. The heliographic latitude of the earth varies from 7.2° south around March 5 to 7.2° north around September 7, so that if solar regions are assumed to eject corpuscles in a radial direction, corpuscles from southern solar centers should intercept the earth in greatest numbers in March, and those from northern centers in September.

In the years of predominantly M-region activity, 1950–53, we found evidence (Bell and Glazer, 1956, 1957; Bhargava and Naqvi, 1954) that the tendency to greater storminess around March and September arose primarily from the inclination of the ecliptic to the solar equator, although there was also some indication of a terrestrial component. We denoted solar centers on the same side of the solar equator as the earth as "favorable," and those on the opposite side as "unfavorable." We found that the correlation between geomagnetism and the intensity of the green-line corona was much better for the corona in the favorable than in the unfavorable solar hemisphere. The data for these four years suggested that M-regions were areas of weak 5303 emission (and hence of low density) in the favorable solar hemisphere; and that a reduction in geomagnetic activity tended to follow CMP of bright 5303 regions in the favorable solar hemisphere. This concept of favorable and unfavorable solar hemispheres did not appear to hold for active-center storms associated with regions characterized by yellow (λ5694) coronal-line emission.

Table 6.—*Geomagnetic conditions associated with CMP of sunspots in the favorable or unfavorable solar hemispheres*

(For explanation of symbols, see p. 163)

(1) Magnetic class	(2) Location	(3) N	(4) $\overline{K}p(0,+4)$	(5) Percent Kp ≥ 40	(6) Percent Kp 30-39	(7) Percent Kp 10–29	(8) Percent Kp <10	(9) Percent f/u ≥ 30	(10) Percent f/u <10
$A \geq 500$									
$l\gamma l$	f	7	26.9	8.8	34.2	57.2	0	1.07	0
	u	17	26.5	10.6	29.4	55.3	4.7		
$l\beta\gamma l$	f	24	21.4	11.6	10.0	60.9	17.5	0.91	1.48
	u	22	22.8	7.3	16.4	64.5	11.8		
$l\beta l$	Nf	27	17.6	4.4	7.4	64.5	23.7	0.93	1.33
	Su	27	18.5	3.0	9.6	69.6	17.8		
	Sf	35	18.9	2.3	9.2	74.2	14.3	0.77	1.43
	Nu	24	21.1	5.8	9.2	75.0	10.0		
	f	62	18.4	3.2	8.4	70.0	18.4	0.85	1.30
	u	51	19.8	4.3	9.4	72.2	14.1		
$l\alpha l$	f	11	15.6	1.8	5.5	63.6	29.1	0.39	4.34
	u	15	21.7	4.0	14.7	74.6	6.7		
$d\beta l$	f	14	16.5	1.4	5.7	71.5	21.4	1.97	0.91
	u	11	15.7	0	3.6	72.8	23.6		
$A<500,\ H \geq 2000$									
$l\beta\gamma l$	f	11	21.8	1.8	20.0	67.3	10.9	1.09	0.49
	u	9	20.0	2.2	17.8	57.8	22.2		
$l\beta l$	f	82	....	2.2	11.2	68.1	18.5	1.08	1.09
	u	71	....	2.0	10.4	70.7	16.9		
$l\alpha l$	f	120	....	1.7	13.3	68.0	17.0	0.97	1.16
	u	129	....	0.8	14.7	69.9	14.6		
$l\Sigma(\beta\gamma+\beta+\alpha)l$									
$A \geq 500$	f	97	....	5.1	8.5	67.0	19.4	0.80	1.58
	u	88	....	5.0	12.0	70.7	12.3		
$A<500$	f	213	....	1.9	12.9	67.9	17.3	1.01	1.10
	u	209	....	1.2	13.4	69.7	15.7		
"Expected"			19.6	3.7	12.1	69.2	15.0	....	....

The present sunspot study was undertaken, in part, to explore the possibility of a hemisphere effect in sunspots, either as apparent storm-producers or as inhibitors of corpuscular emission. For this purpose we divided the spots of table 1 into those favorably (f) and those unfavorably (u) located, and carried out superposed epoch analyses. Figure 10 shows the resulting curves for the larger sunspots (area ≥ 500, except γ area ≥ 400) of the different magnetic classes. Figure 11 shows two independent samples, for β spots occurring in spring and in fall half years. Further particulars are set forth in table 6, where the last two columns give the ratio percent favorable to percent unfavorable for $Kp \geq 30$ (from columns 5 plus 6) and $Kp<10$ (from column

8). The columns showing frequencies and ratios are included in an effort to unscramble the effects of storm-producers from those of inhibitors, or at least to allow both to manifest themselves.

We also divided the large spots in each magnetic class into three groups, those occurring in the six solsticial months (*s*), May through July and November through January; and those in the six equinoctial months, subdivided into favorable (*f*′) and unfavorable (*u*′), with the results shown in table 7. The last two columns give percents of spots associated with disturbed (from columns 5 and 9) and with quiet (from columns 6 and 10) geomagnetic conditions. Surprisingly, $\overline{Kp}(0, +4)$ in table 7 shows none of the expected seasonal effect; however, the effect appears clearly in $\overline{C}(0, +4)$ for the earlier period. The reason for this result is unknown.

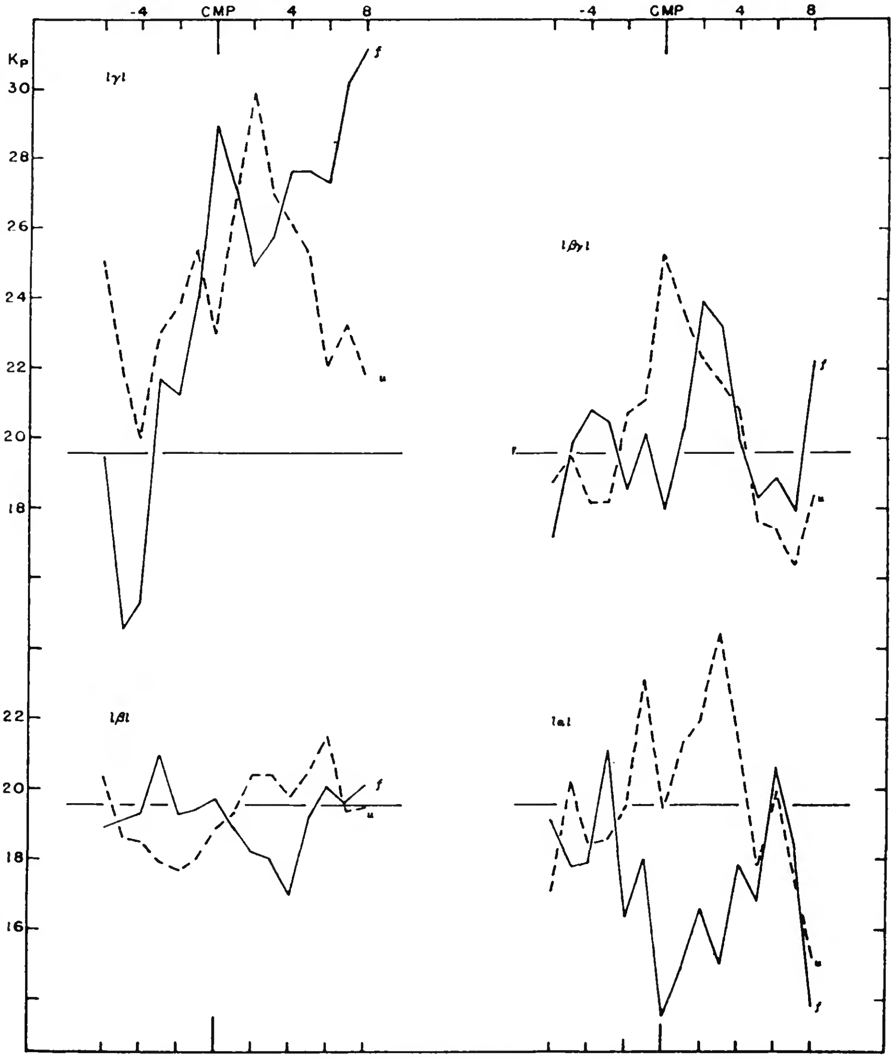

FIGURE 10.—Average geomagnetic conditions (*Kp*) on days around central meridian passage (CMP) of large sunspots of the geomagnetic classes α, β, βγ, and γ; solid line, in the favorable solar hemisphere; broken line, in the unfavorable solar hemisphere.

Table 7.—*Geomagnetic conditions associated with CMP of sunspots subdivided by location and season*
(For explanation of symbols see p. 163)

		1937–1953				1917–1936				1917–1953	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Magnetic class	Location	N	$\overline{Kp}(0, +4)$	Percent $\overline{Kp}(0, +4)$ ≥ 25	Percent $\overline{Kp}(0, +4)$ <15	N	$\overline{C}(0, +4)$	Percent $\overline{C}(0, +4)$ ≥ 1.0	Percent $\overline{C}(0, +4)$ <0.5	Percent geomagnetically disturbed	Percent geomagnetically quiet
$l\gamma l$	f'	4	27.2	75	0	5	1.07	60	0	67	0
	s	7	26.5	43	0	7	0.88	14	0	29	0
	u'	13	26.7	54	0	7	1.08	57	14	55	5
$l\beta\gamma l$	f'	12	21.8	42	50	8	0.84	38	25	40	40
	s	20	20.9	25	15	19	0.65	16	26	20	20
	u'	14	23.2	43	14	6	0.60	0	33	30	20
$l\beta l$	f'	33	18.7	9	30	15	0.85	47	26	21	29
	s	57	19.2	19	30	42	0.66	14	29	17	29
	u'	22	18.6	9	32	26	0.75	19	27	15	29
$l\alpha l$	f'	6	13.9	0	67	3	0.89	33	0	11	44
	s	11	20.1	27	9	11	0.66	18	45	23	27
	u'	9	21.3	33	22	3	1.08	67	0	42	17
$l\Sigma(\beta\gamma+\beta+\alpha)l$											
	f'	51	18.8	16	39	26	0.85	42	23	25	34
	s	88	19.7	22	24	72	0.65	15	31	19	27
	u'	45	20.6	24	24	35	0.75	20	26	22	25

In the previous section we divided the spots according to the value of $\overline{Kp}(0, +4)$, with results given in table 5. Columns 10 and 11 of this table give the percents of favorable spots and of equinoctial spots, respectively, and provide an inverse approach to the problems of hemisphere effects and of seasonal effects.

From an examination of the assorted data in tables 5 to 7 and figures 10 and 11, we conclude that there is no evidence for any hemisphere effect in storm-producing spots. Considering the γ spots, as the most important storm-producers, we find no significant difference between the favorable and the unfavorable spots (figure 10, top left) either in the curves or in the tabulated figures. A similar lack of significant difference appears in the $\beta\gamma$ curves and tabulations. For the β and α spots, table 6, column 9, suggests, if anything, a slight advantage with the unfavorable spots, but this tendency is not confirmed by the data of the earlier period (table 7, right). The absence of any hemisphere effect in sunspots which produce great geomagnetic storms is in accord with earlier results from the yellow coronal line, and does not support any simple axial explanation

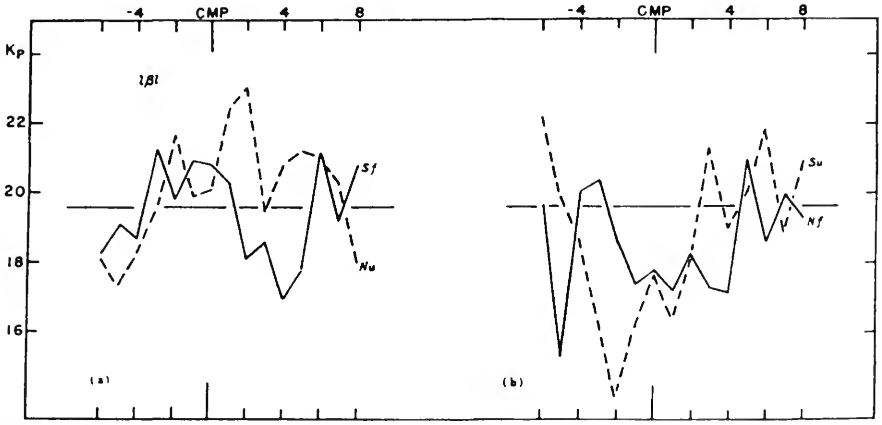

Figure 11.—Average geomagnetic conditions (Kp) on days around central meridian passage (CMP) of large bipolar or β sunspot groups in the favorable (solid line) and in the unfavorable (broken line) solar hemispheres. (*a*), For the spring half-years; (*b*), for the autumn half-years.

for the clustering of great storms toward the equinoctial months. This negative result suggests that Bartels' equinoctial hypothesis continues to merit consideration as at least one of the factors which may contribute to the semiannual periodicity in geomagnetic and auroral activity.

We conclude, secondly, that favorably located spots of area equal to or greater than 500 millionths are more likely to be associated with geomagnetically quiet conditions than are unfavorably located spots. This tendency may be seen in figures 10 (bottom) and 11 for the β and α spots, and in the consistent tendency of the numbers in column 10 of table 6 to be greater than unity for spots of the classes $l\beta\gamma l$, $l\alpha l$, and for the two independent groups of $l\beta l$ spots. None of these curves shows any statistically significant deviations ($\geq 2\sigma$) from the mean. However, the two independent samples of $l\beta l$ spots, from spring and fall, shown in figure 11, agree in having a below average *Kp* in the days following CMP of the favorable spots. Without other evidence for the existence of inhibiting solar regions, such as the radio-noise data (*Q*-spots) and paired spots, and the apparent inhibiting effect of bright regions of the green-line corona in the favorable hemisphere, we should, however, have less confidence than we do in the meaningfulness of these dips in the favorable *Kp* curves for bipolar and unipolar spots of large area.

Radio noise

Simon (1956a, 1956b) has recently extended the work of Denisse on radio noise of meter wavelengths as a criterion for picking out the geomagnetically active sunspots. Simon has investigated also the relation of radio noise to optical properties of sunspots. He finds some tendency for radio-noisy (*R*) spots to be larger, more flare-active, and relatively more common among magnetically complex groups and groups of Zürich type F, than are radio-quiet (*Q*) spots. But these tendencies are not sufficiently striking that *R* and *Q* spots can be distinguished from one another by any of these optical properties of the photospheric levels of the sun. The meter-length radio noise arises from the lower corona and may be considered as a manifestation of spot activity in the higher levels of the solar atmosphere.

Simon's work indicates that geomagnetic activity is more closely linked to the radio-noise properties of sunspots than to any of their optical properties on the photospheric levels. Whichever optical subgrouping of spots he used (area, flare activity, Zürich class, magnetic class, and field strength) Simon found that radio-noise data permitted a marked separation of each subgroup into geomagnetically active and inactive sunspots. His study of geomagnetic effects emphasized area and flare activity and dealt only slightly with magnetic class. For the γ and $\beta\gamma$ classes combined, he found that radio-noise data permitted a separation between geomagnetically active and inactive spot groups. However, he did not investigate the magnetic classes individually.

Since the magnetic class of sunspots is the principal criterion under study in the present paper, we used Simon's (1956a, 1956b) lists of *R* and *Q* spots to investigate whether the amount of geomagnetic activity within the *R* and *Q* categories appears to depend in any degree on the magnetic class of the spot. We obtained the following categories of *R* and *Q* sunspots: area ≥ 500: $l\gamma l$, $l\beta\gamma l$, $l\beta l$, $l\alpha l$, $d_e\beta l$; area <500 and $H \geq 2000$ gauss: $l\beta l$ and $l\alpha l$. For each of these groups we made a superposed epoch analysis. Figure 12 shows the average *Kp* conditions associated with CMP of *R* and *Q* sunspot groups for each of the four magnetic classes. Table 8 gives further particulars. The two area groupings of α and β spots have been combined in the figure, but are listed separately in the table. The γ and $\beta\gamma$ curves are plotted as three-day running means, because of the small size of the samples.

The results given in figure 12 and table 8 are in clear accord with those obtained previously by Denisse and by Simon, in indicating that radio noise on meter wavelengths is an important criterion for separating geomagnetically active and inactive sunspots. The inhibiting effect of Simon's *Q* spots appears less than that of Denisse's *Q* spots. By way of explanation, Simon has pointed out that Denisse's *Q* spots were entirely quiet, whereas he listed as *Q* spots those which failed to attain a certain defined level of noise, and thereby included some slightly noisy spots. Even so, very low values of *Kp* (column 12) on days 0 through +4 are on the average three times as frequent with *Q* spots as with *R* spots. Conversely, values of $Kp \geq 40$ (column 10) are 4.4 times more frequent with *R* than with *Q* spots, being respectively 2.2 and 0.5 times the frequency expected by chance. From column 14, we see that 37 percent of *R* spots are associated with at least one $Kp \geq 40$ during the five days, 0 through +4, whereas only 6.5 percent of *Q* spots are so associated. By chance, one should expect an association of about 17 percent. Similarly for at least one $Kp \geq 30$, the figures are 66 percent and 38 percent for *R* and for *Q* spots, respectively, as compared with a random value of about 53 percent. Moreover, of the 14 great storms listed by Greenwich for 1947–51, the period covered by Simon's radio-noise data, nine can be associated with *R* spots, four with unclassified spots, and one[5] (19 August, 1950) with *Q* spots. It seems clear that very few *Q* spots are associated with storms of large magnitude, but on the other hand, not all *R* spots appear to produce significant disturbance. Almost every major storm can be associated with an *R* spot, but by no means every *R* spot is accompanied by a notable storm.

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[5] According to a private communication from Helen Dodson Prince, this storm was most probably related to a flare with an associated "major early burst" of radio noise, occuring near a *small γ spot*, No. 10444.

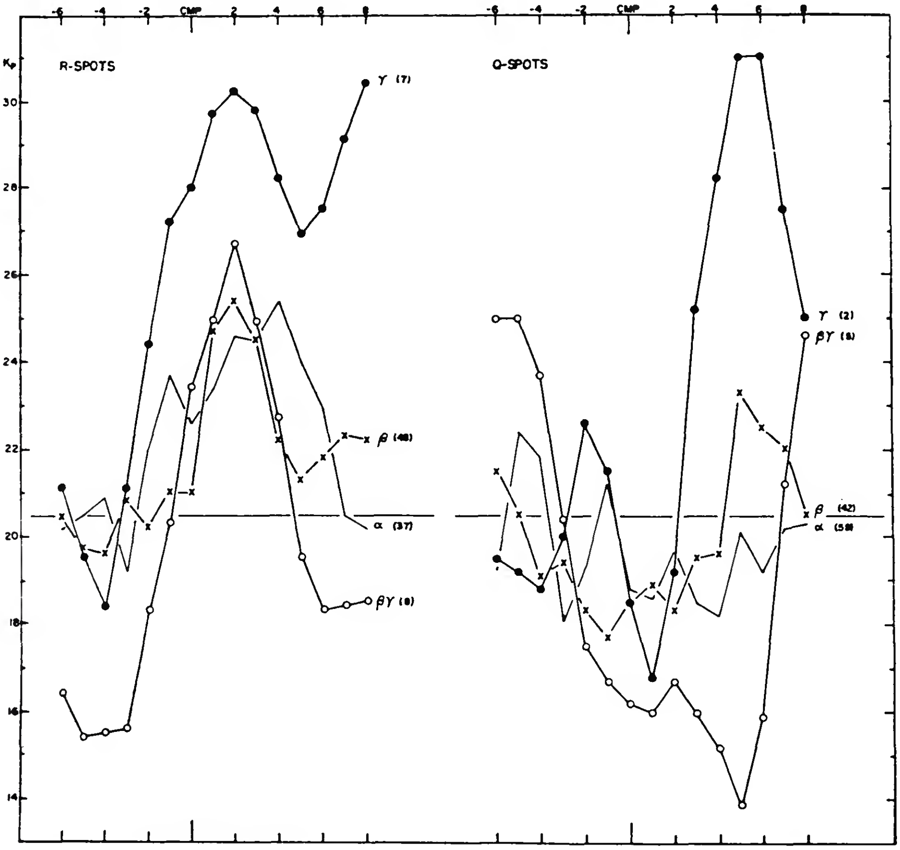

FIGURE 12.—Average geomagnetic conditions (*Kp*) on days around central meridian passage (CMP) of (*R*, left) radio-noisy and (*Q*, right) radio-quiet sunspot groups of magnetic classes α, β, βγ, and γ for the years 1947–1951. Number of spot groups used is given in parentheses.

TABLE 8.—*Geomagnetic conditions associated with CMP of sunspots subdivided according to radio noise properties*

(For explanation of symbols see p. 163)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Magnetic class	Radio noise	N	$\bar{A}$	$\bar{F}$	$10\bar{F}/\bar{A}$	$\bar{Kp}(0, +4)$	Kp(max)	Kp(min)	Percent Kp ≥40	Percent Kp 30–39	Percent Kp <10	Percent Kp ≥20	Percent with at least one Kp ≥40	Percent with at least one Kp ≥30
$l\gamma l$	R	7	1350	31.0	.229	29.4	31.6(2)	27.8(4)	11.4	37.2	0	88.6	57.2	85.7
	Q	2	1150	31.0	.270	20.9	29.5(4)	11.5(1)	0	20.0	0	40.0	0	50.0
$l\beta\gamma l$	R	8	1850	32.2	.174	24.6	27.7(3)	20.5(4)	7.5	30.0	5.0	62.5	37.5	75.0
	Q	5	960	14.4	.150	16.0	18.4(3)	13.8(4)	0	4.0	28.0	36.0	0	20.0
$A \geq 500$														
$l\beta l$	R	28	880	12.7	.145	22.2	23.3(2)	21.2(0)	7.2	10.0	7.2	60.0	25.0	57.1
	Q	16	870	9.3	.107	18.8	21.3(4)	17.2(2)	2.5	10.0	13.8	42.5	6.2	50.0
$l\alpha l$	R	5	740	6.8	.092	26.7	30.2(3)	21.6(4)	8.0	28.0	0	72.0	40.0	100.0
	Q	5	600	6.0	.100	17.4	20.2(0)	13.8(1)	0	4.0	16.0	44.0	0	20.0
$d_e\beta l$	R	5	≥500			19.8	25.0(0)	16.2(1)	4.0	8.0	12.0	44.0	20.0	60.0
	Q	5	≥500			15.6	19.4(4)	12.0(0)	0	8.0	24.0	28.0	0	40.0
$A < 500$														
$l\beta l$	R	20	<500	6.7	>.14	25.5	28.3(2)	17.8(0)	14.0	15.0	2.0	70.0	40.0	65.0
	Q	26	<500	4.4	>.09	19.1	19.6(3)	18.6(4)	2.3	12.3	15.4	39.2	7.7	34.0
$l\alpha l$	R	32	<500	2.2	>.04	23.7	26.0(4)	22.4(0)	10.6	17.5	6.9	57.5	40.6	62.5
	Q	54	<500	2.1	>.04	19.2	20.0(2)	18.5(3)	2.6	12.6	16.3	44.8	7.4	38.9
$l\Sigma Rl$	R	100				24.26			10.0	17.8	5.0	64.0	37.0	66.0
$l\Sigma Ql$	Q	108				18.92			2.2	11.7	15.9	42.6	6.5	38.0
"Expected"						20.4			4.4	12.1	11.0		17	53

Because of the small sample sizes, any further inferences must be only tentative, and the tendencies noted in this paragraph must not be considered as established. In regard to magnetic class, the γ spots retain their appearance of superiority as geomagnetic-storm producers, even the two quiet γ spots showing a degree of geomagnetic activity. Also it should be noted that γ spots contain a higher per cent of R spots than do the other magnetic classes (cf. Simon 1956a, 1956b). The R spots of the other magnetic classes appear about equal in geomagnetic activity, and inferior to the γ spots. Young spots, of the $d_e\beta l$ type, appear less disturbing geomagnetically than do mature, limb-to-limb spots of corresponding radio-noise properties. In regard to area (see table 8), the large α spots appear more effective than the smaller ones, both as storm-producers (R) and as inhibitors (Q); however, the smaller β spots appear to be better storm producers (R) than the larger ones. This supports our earlier finding that area of a sunspot group plays a relatively minor role in its geomagnetic activity.

We find the geomagnetic activity of R spots to be independent of the location of the spot in the favorable or the unfavorable solar hemisphere, in accord with the findings of Simon (1956a) and with our results of the previous section. Nor do we find evidence for any hemisphere effect among the Q spots. The tendency noted in the previous section, for favorably located spots to be more effective inhibitors than unfavorably located spots, is therefore of doubtful significance and requires further exploration as more data become available.

Discussion

The data presented in this paper indicate that no known property of active solar centers is sufficient, in itself, for accurate prediction of geomagnetic activity. They support, however, the conclusion of Denisse and Simon that the level of radio noise on meter wavelengths appears to be the most important single criterion for distinguishing geomagnetically active sunspots. This result appears the more plausible when we consider that the meter radio noise arises in the region of the solar corona, whereas most of the other properties considered arise in lower levels of the solar atmosphere. If a sunspot does not produce a disturbance in the solar corona, there seems little reason to expect it to disturb the vicinity of the earth. For use in forecasting, the radio-noise criterion is imperfect mainly because not all R spots produce storms, rather than because any significant number of storms occur in association with Q spots.

The present paper has investigated primarily the magnetic class of sunspots as a criterion of geomagnetic activity. Among the optical criteria of the photospheric levels, we find the magnetic class of the spot to be the most significant. The CMP of magnetically complex (γ) sunspot groups shows a markedly greater tendency to be associated with a great geomagnetic storm than does the CMP of spot groups with more regular magnetic fields. The very greatest geomagnetic storms, in particular, show a tendency to associate with magnetically complex sunspots. We find also, in confirmation of earlier results by Newton (1949), that flare-active spots tend to be more disturbing geomagnetically than do spots deficient in flares. Sunspot area, however, appears to be less important than previously believed, and to play an insignificant role except for the fact that magnetically complex spots are most common among groups of large area.

Great storms, like recurrent storms, show a marked seasonal periodicity. The evidence, however, appears to be clearly against any hemisphere effect or axial explanation, such as we found earlier for M-regions, in these storms arising from active solar centers. Sunspots in the unfavorable solar hemisphere appear to be as much associated with great geomagnetic storms as do spots in the favorable hemisphere. The cause for the seasonal variation in great storms thus remains obscure, and Bartels' equinoctial hypothesis would appear to continue to merit consideration.

It has for some time seemed probable that the magnetic fields of active solar centers must play a basic role in the ejection and/or inhibition of solar corpuscles, as well as in the direction of the ejected beam. Because of the complexity of the forces arising from the interplay of general and local solar magnetic fields, any one-to-one relation between geomagnetic conditions and an observed solar phenomenon is scarcely to be hoped for. While we may expect additional improvement in the accuracy of geomagnetic forecasting from futher analysis of observational criteria of active centers, it appears doubtful that the most reliable predictions can be made without the aid of a comprehensive theoretical understanding of the behavior of ionized gases in magnetic fields, in conjunction with the various observational criteria. In the meantime, however, the results presented here suggest that increased attention could profitably be given to the patterns of the magnetic fields of sunspot groups.

Acknowledgments

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Abstract

This paper investigates the relation of geomagnetic conditions to the magnetic class, area, flare productivity, radio noise, and location of sunspots. The primary emphasis is on the magnetic class, which is found to be the optical property of sunspots most significant in relation to geomagnetic conditions, although less significant than radio noise. Magnetically complex (γ) sunspots appear to be the most consistently disturbing, geomagnetically, and give a marked rise in the superposed epoch Kp-curve for several days around central meridian passage. Semicomplex ($\beta\gamma$) spot groups give a moderate rise in the geomagnetic index, Kp, while the simple unipolar (α) and bipolar (β) spots give no significant deviation from the mean Kp. Flare productivity appears to be of moderate importance, while sunspot area is relatively unimportant. Earlier results indicating area to be significant can be reconciled with the present findings because the magnetically complex γ-spots are relatively most numerous among spot groups of very large area.

The seasonal variation in geomagnetic activity is also investigated and is shown to occur in the daily Kp-sums at all phases of the sunspot cycle. The axial hypothesis to explain the March and September maxima in great geomagnetic storms is not supported by the evidence. The geomagnetic activity of a sunspot appears to be independent of its location in the favorable or the unfavorable solar hemisphere. The cause of the seasonal variation in great storms remains unknown.

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