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SOLAR LONGITUDE DISTRIBUTIONS OF PROTON FLARES, METER BURSTS, AND SUNSPOTS

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ABSTRACT

The need for an analysis of proton flares over a long time scale is discussed and a sample of inferred proton events, covering a century, is described. The analysis of this sample shows that these high-energy events are distributed non-randomly in solar longitude in a rigidly rotating system with period $27^d.213$, considerably shorter than the Carrington period ($27^d.275$). The distribution of meter bursts associated with the proton flares is also studied in this longitude system and found to be strongly non-random. Two different samples of sunspots, however, studied over as many as eight solar cycles, do not show any significant non-random organization in either the $27^d.213$ or the $27^d.275$ system.

I. INTRODUCTION

The distribution of proton flares in solar longitude appears to be non-random. Different workers, however, have identified different patterns of organization; further, there is lack of agreement as to the statistical significance of the effect.

Several studies show that clustering of proton regions lasts for at least a solar cycle. Such persistence suggests that the underlying sources of the active regions are positioned in a rigidly rotating system. This behavior is clearly distinct from the latitude-dependent rotation rates observed for active centers during their lifetimes.

The apparently non-random clustering of the proton regions, if physically real, is theoretically important in relation to models for solar active-region formation. Practically, the recognition of proton-active longitudes, persisting over a solar cycle or more, would aid in the long-term prediction of the proton events. We hope to give evidence in this study for pattern persistence over a century.

Dodson and Hedeman (1964) studied proton events that occurred between 1952 and 1963. Their basic sample was the list of forty-eight principal events given by Bailey (1964); in a second analysis they used a sample of all the reported cases they could find (sixty-nine events). Dodson and Hedeman positioned the proton flares in a heliographic longitude system based on a $27^d.3$ solar rotation period. This implies, of course, a rigidly rotating system with no latitude dependence. They found a definite clustering of the proton regions in this system.

The analysis by Dodson and Hedeman was followed by the studies of Guss (1964), Warwick (1965), and Wilcox and Schatten (1967). Guss found that the giant event of February 23, 1956, and the outstanding multiple events of July, 1959, November, 1960, and July, 1961, were produced by active regions whose central meridian passage dates were separated from one another by multiples of $27^d.04$; he thus used this period to define his solar longitude system. His total sample contained fifty-six events and covered the period 1955–1962. This sample produced a frequency distribution with a high, narrow peak dominated by the outstanding cases mentioned above. The members of this peak, however, were not all independent, since a majority of them were associated with multiple events from active centers; if an active region is allowed to enter the sample only once, this dominant peak is lost. In any event, Guss concluded that a major fraction of all the very high-energy proton flux encountered at Earth during the last solar cycle was produced by events from a single 10° interval of solar longitude, $L_{27.04\,d}$.

In the studies mentioned so far, no attempts were made to determine the statistical significance of the apparently non-random groupings.

Warwick (1965) studied proton flare regions in a longitude system based on Carrington's rotation period ($27^{d}.275$). Her sample was made up of events which occurred over the solar cycle from 1954 to 1963; the total number of events was seventy-seven, of which forty-five were independent. Warwick found that thirty-three of the forty-five events arose from active regions in one longitudinal hemisphere; the other hemisphere produced only twelve independent events. She concluded that this strong an asymmetry could occur by chance only one time in a thousand. Her computation was based on the a priori selection of a single longitude system, based on a $27^{d}.275$ solar rotation period. Further discussion will be given of the consequences to statistical significance tests if other a priori hypotheses are made.

Since Guss and Warwick had found two different types of proton flare groupings in two different longitude systems, Wilcox and Schatten (1967) questioned the uniqueness of any system, or corresponding rotation period, in organizing the events. They thus allowed the rotation period to be a variable in their analysis. They used the same sample of forty-five independent proton flares that Warwick used. Their "trial" solar rotation periods were varied from 25^{d} to 34^{d} in increments of $0^{d}.01$. For each of these 901 trial periods every possible set of 9 consecutive 20° intervals was scanned to find the hemisphere containing the smallest number of proton regions. This "deficient hemisphere" number was plotted versus the corresponding rotation period; a distinct minimum in this plot would indicate that a unique rotation period (between 25^{d} and 34^{d}) produced the greatest hemisphere asymmetry. Wilcox and Schatten found a dip in the plot at $27^{d}.27$, Warwick's selected period, but also found other minima that were just as striking at several other periods. The authors thus concluded: "It seems doubtful that any physical significance can be attached to the point at 27.2753 days. The present analysis does emphasize the need for caution in analyzing the statistical significance of the apparent clustering tendency."

II. RATIONALE FOR THE PRESENT STUDY: SAMPLE SELECTION

The present study was initiated in the hope that a definitive analysis could be made that would either establish the reality of the clustering tendency or demonstrate its statistical insignificance.

As a first step, it is necessary to expand the sample of proton events, particularly the time scale over which they occurred. To date, the studies have dealt almost exclusively with solar cycle 19. For prediction of events in cycle 20, or in future cycles, we need to determine the degree of pattern stability from cycle to cycle. Also the small samples used have limited the significance of any observed patterns. Unfortunately, riometer and forward-scatter techniques for observing the ionospheric effects of solar protons (the polar cap events or PCE) have been available only since about the beginning of cycle 19. However, from these observations, the characteristics of the solar flares producing the events have been quite well established. First, during the time PCE observations have been available, all of those flares which produced the very high energy particles observed by ground level neutron monitors also produced PCE. We are thus able to add to the sample of PCE the early ground-level events of 1942, 1946, and 1949. Second, flares which are of the highest importance, 3 and 3+, and which have a filamentary appearance (double filaments or Y- or V-shaped configurations) are typically proton producers. In addition, great geomagnetic storms are typically preceded by proton flares. A historical sample of great flares has been described by Hale (1931). The first member of this sample is the famous white-light flare observed by Carrington (1859) and Hodgson (1859). The other flares selected from Hale's sample for inclusion in our study were all photographed; for the most part, they showed filamentary structure; all caused great magnetic storms and were usually associated with remarkable auroral displays. These flares, and early flares described by Newton and Jackson (1951) as class 3+ which produced great magnetic storms, were assumed to have produced major proton events, even though PCE observations were not available. These outstanding events that were added to our sample to provide a much expanded time base are listed in Table 1.

The present sample differs from that used by Warwick and by Wilcox and Schatten not only through the addition of the early events but also because of minor changes in later event selections, plus the addition of the most recent PCE which occurred in 1965 and 1966. The flare of February 21, 1957, has been changed in reported importance from "?" to 3+ on the basis of examination of Sacramento Peak Observatory drawings of the event; its association with an observed PCE is now considered certain, and it has been added to the present sample. Other differences involve minor or questionable events; in no case was any change made with prior knowledge that it would strengthen or weaken the clustering tendency. Non-independent cases have been removed so that a single active center enters the list only once. The resulting sample has sixty cases and covers the period 1859–1966; cycle 19 still dominates the sample, with forty-seven events.

TABLE 1

EARLY GREAT FLARES

1859—September 01 5	Carrington (1859); Hodgson (1859)
1892—July 15 7	Hale (1931)
1908—September 10 2	Hale (1931)
1909—May 12 6	Hale (1931)
1926—January 24 8	Hale (1931)
1938—January 24 1	Newton and Jackson (1951)
1940—March 23 5	Newton and Jackson (1951)
1942—February 28.5	Ground-level event
1946—July 25.7	Ground-level event
1949—November 19 4	Ground-level event
1950—February 17 0	Newton and Jackson (1951)

An important point to make is that these sixty regions are widely distributed in latitude; there are cases very near the equator as well as a number at about 30° north and south. Any differential rotation in latitude affecting these regions would very effectively destroy any longitudinal clustering. Therefore, if this sample exhibits a non-random distribution, it will provide strong evidence that the underlying sources of the regions are positioned in a rigidly rotating system.

III. ANALYSIS: ORGANIZATION PATTERNS FOUND; PROBLEMS IN TESTING FOR SIGNIFICANCE

The approach used here is similar to that of Wilcox and Schatten. There are 3251 trial periods used, from $24^{d}.5$ to $31^{d}.0$, in increments of $0^{d}.002$. If a "true" period exists within the selected range, the most it can differ from one of the trial periods is $0^{d}.001$. The sixty sample events occur over an interval of slightly more than 100 years. Over this time, an error of $0^{d}.001$ in rotation period would cause an error in associated longitude of only about 18° between extreme events.

Histograms of the occurrence frequency of the sixty regions were plotted in 10° intervals of solar longitude; a plot was made for each of the 3251 trial periods (or longitude systems), and all those that passed a certain threshold of strength in clustering pattern were listed. From the appearance of these plots, several different types of patterns were noted. In some systems, a single 30°-wide peak seemed to dominate; in others, two peaks characterized the pattern; in two cases, a 70° interval contained only one event. Over a limited interval of certain adjacent rotation periods, the patterns showed that one longitudinal hemisphere contained many more events than the other. Each of these types of patterns was tested for statistical significance. The general method of testing was the same in each case, so the actual calculations will be given here only for the single type of pattern that was found to have a probability of chance occurrence of less than 0.05.

In all of the tests applied, the problem of estimating the independent sample size entered into all of the tests applied. Part of the problem is concerned with determining the number of independent longitude intervals in a given longitude system. Consider, for example, the case of a single, dominant 30° peak. There are twelve non-overlapping 30° intervals in 360° and thirty-six distinguishable 30° intervals (since histograms are plotted in 10° intervals). As an upper limit, we estimated the number of 30° intervals to be the intermediate value of 20. This will place a conservative *lower* limit on the significance of the peak. This sort of conservative estimation was made for each type of organization pattern. [The strongest 30° peak found (containing sixteen events out of the sixty) turned out to be not significant; $P = 0.27$.]

More difficult and arbitrary is the estimation of the number of independent trial periods. As emphasized earlier, Guss (1964) and Warwick (1965) each used a single "trial" period. Guss's results are not subject to test, since he included in his final sample the cases he had used to define his longitude system, $L_{27\,04\,\mathrm{d}}$. Warwick selected Carrington's period on the basis of previous work by Losh (1938) and Vitinskii (1960), who used samples that were independent of hers; Vitinskii used Carrington's period and Losh used the approximate value 27$^{\mathrm{d}}$3. These authors found longitudinal clustering of sunspots during a number of individual solar cycles. Trotter and Billings (1962) also studied solar active regions in a 27$^{\mathrm{d}}$275 system, but their sample was not independent of Warwick's. Her 10^{-3} probability value was based on the assumption that both the longitude system and the hemisphere boundaries defining the asymmetry were independently predetermined. Because of the work of Losh and Vitinskii, there was a valid basis for her selection of the 27$^{\mathrm{d}}$275 system. The hemisphere boundaries, however, were not based on previous independent results. If the probability figure is recalculated with the boundaries considered as a parameter of the analysis, the significance of Warwick's asymmetry will be lowered by as much as an order of magnitude. Wilcox and Schatten (1967), having found periods other than 27$^{\mathrm{d}}$275 which produced asymmetries just as strong, argued that all the trial longitude systems should be considered. If this were done, neither the asymmetry found by Warwick nor any of those found by Wilcox and Schatten would be significant. Yet, as we just said, Warwick's test, based on a single longitude system, is statistically valid. Also, and this seems the most difficult problem, if longitude system, or solar rotation period, is made a variable of the analysis, the *range* of trial periods then becomes an arbitrary quantity which strongly affects any computed significance levels.

For that part of the study already described, we have varied the trial period in the hope that, with our enlarged sample covering over 100 years, we might be able to distinguish a uniquely effective period within the chosen range (24$^{\mathrm{d}}$5–31$^{\mathrm{d}}$). This range, while arbitrary, is not unreasonable; the latitude-dependent range of rotation periods observed for sunspots during their lifetimes is about 27$^{\mathrm{d}}$0–29$^{\mathrm{d}}$5. None of this, of course, rules out the possibility that some totally unrelated period may define the birth positions of the sunspots.

In our analysis we find that among the various types of clustering patterns observed among all the 3251 trial periods only one is significant with a probability value less than 0.05. The type of clustering is a hemisphere dominance; that is, in one 180° longitude interval many more proton-flare regions occur than in the other. Since the trial periods are very close together (0$^{\mathrm{d}}$002), there is a strong similarity in hemisphere patterns between adjacent periods. In our study, the trial periods 27$^{\mathrm{d}}$211, 27$^{\mathrm{d}}$215, 27$^{\mathrm{d}}$217, and 27$^{\mathrm{d}}$219 all give forty-eight events in one hemisphere and twelve in the other; 27$^{\mathrm{d}}$213 gives the strongest asymmetry with forty-nine and eleven cases. These asymmetries are much stronger than any Wilcox and Schatten found (using Warwick's sample), and they are much stronger than any other hemisphere asymmetries associated with any of our other trial periods. Figure 1 shows two small sections of the total original plot of "deficient" hemisphere count versus trial period. The upper strip includes the group of neighboring periods which gives the greatest asymmetry; the unique point at $27^{\mathrm{d}}.2135$ is indicated. (The trial period increment of $0^{\mathrm{d}}.002$ described earlier has been changed for this plot to $0^{\mathrm{d}}.0025$ to cut down slightly on computer time and record length.) The bottom strip shows the only other periods in the entire record with as few as 16 counts

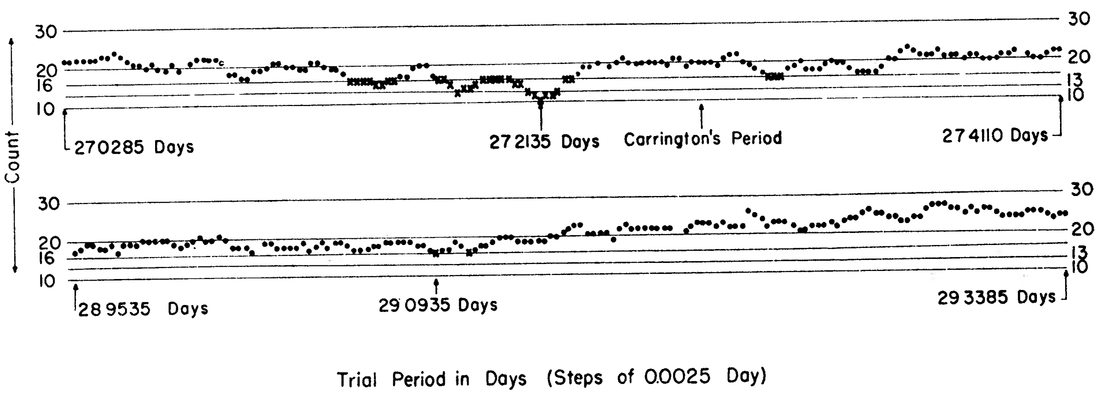

FIG. 1.—Number of proton events in the "deficient" solar hemisphere versus trial rotational period

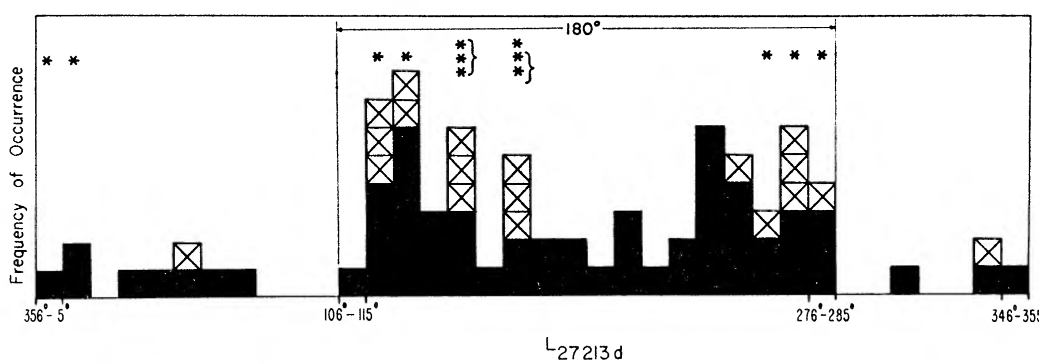

FIG. 2.—Distribution of proton flares in solar longitude, $L_{27\ 213\ \mathrm{d}}$

in the deficient hemisphere. (Points with crosses indicate hemisphere counts of 16 or less.) Figure 2 shows the actual distribution in longitude, $L_{27.213\ \mathrm{d}}$, of the events. The scale has been set arbitrarily with the region which produced the February 23, 1956, event at 0°. The X's represent repeating events from the same region, while the black boxes make up the sample of independent regions. The asterisks above the frequency distribution show positions of the very high energy ground-level events; asterisks in braces are events from the same region. Figures 3 and 4 show the frequency distributions in Carrington's ($L_{27\ 275\ \mathrm{d}}$) and Guss's ($L_{27\ 04\ \mathrm{d}}$) systems. In the former, the strongest hemisphere asymmetry is 39 to 21 events. This is to be compared with the 33 to 12 ratio obtained with Warwick's sample. The loss of asymmetry is due largely to the addition of the eleven early great flare-event regions, of which seven fall in the deficient hemisphere. In the $L_{27\ 213\ \mathrm{d}}$ system only one of the eleven falls in the deficient hemisphere. The X's in the $L_{27\ 04\ \mathrm{d}}$ system show how strongly the peak in Guss's system depends upon repeating events. In this system, the sixty independent regions show no marked clustering tendency.

IV. TEST OF HEMISPHERE DOMINANCE IN THE $L_{27\ 213\ \mathrm{d}}$ SYSTEM

In this section we will test the significance of the hemisphere asymmetry in the $L_{27\ 213\ \mathrm{d}}$ system (49 to 11 events). Although there are 3251 trial periods spaced $0^{\mathrm{d}}.002$ apart, not all of these produce patterns that are independent of one another; hemisphere

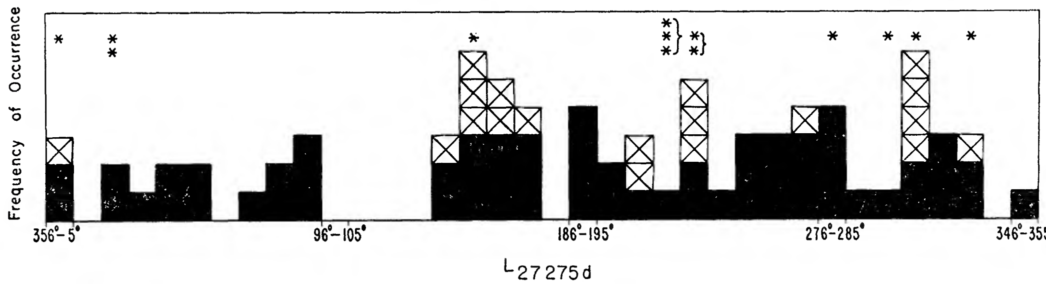

FIG. 3.—Distribution of proton flares in Carrington's solar longitude system, $L_{27\ 275\ \mathrm{d}}$

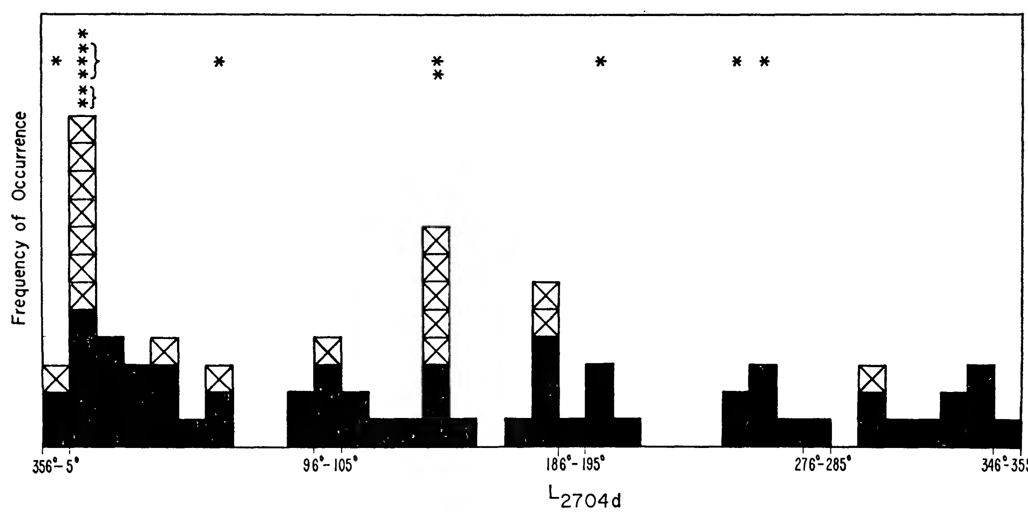

FIG. 4.—Distribution of proton flares in solar longitude, $L_{27\ 04\ \mathrm{d}}$ (Guss 1964)

distributions remain very similar over period differences as large as $0^{\mathrm{d}}.006$. Thus we used $0^{\mathrm{d}}.006$ to define the limiting interval of independence and obtained a sample of $0.002/0.006 \times 3251 = 1084$ independent periods. Although there are only two non-overlapping 180° intervals in 360°, a larger number, of course, partially overlap. We used the value of 5, a high estimate which should lead to a conservative value for asymmetry in any given longitude system. The total independent sample size is then $5 \times 1084 = 5420$.

Let

$p \equiv$ probability of getting an event, in a single try, in the mth 180° interval in the nth period ($m = 1, 2, \ldots, 5$; $n = 1, 2, \ldots, 1084$)

$= \frac{180}{360} = 0.5$;

$q \equiv 1 - p = 0.5$.

Let

$P'(\leq 11) \equiv$ probability of getting ≤ 11 events in the mth 180° interval in the nth period in 60 tries

$$= \sum_{x=0}^{11} \frac{60!}{x!(60-x)!}(0.5)^{60} \sim 3.9 \times 10^{-7}$$

Since either tail of the distribution is possible, we must double this figure, obtaining the probability value 7.8×10^{-7}.

$$Q' = 1 - P'(\leq 11 \text{ or } \geq 49) = 1 - 7.8 \times 10^{-7} .$$

$P(\geq 1) \equiv$ probability that any one, or more, of the 5420 180° intervals will have ≤ 11 or ≥ 49 events

$$= \sum_{y=1}^{5420} \frac{5420!}{y!(5420-y)!}(P')^{y}(Q')^{5420-y}$$

$$\equiv 1 - P(0) = 1 - \frac{5420!}{0!5420!}(P')^{0}(Q')^{5420}$$

$$= 1 - (Q')^{5420} \sim 0.004 .$$

This value indicates that a hemisphere asymmetry of 49 to 11 events, obtained for the trial period $27^{d}_{.}213$, is significant at better than the 1 per cent level. The 48 to 12 ratio obtained for $27^{d}_{.}211$, $27^{d}_{.}215$, $27^{d}_{.}217$, and $27^{d}_{.}219$ periods also is significant at about the 1 per cent level.

V. OTHER CHARACTERISTICS OF PROTON-FLARE EVENT REGIONS IN THE $L_{27\,213\,d}$ SYSTEM

The next natural step is to hunt for properties in addition to hemisphere clustering that characterize the proton flares in the new longitude system.

We find that the strong longitudinal asymmetry is not accompanied by any pattern in latitude.

Also, the regions in the "dominant" and "deficient" hemispheres show no differences in central meridian distance, in geomagnetic storm association, or in phase of the solar cycle.

We did find that events in the dominant hemisphere, in general, have somewhat larger PCE absorption values, although there are two strong exceptions in the deficient hemisphere. Figure 5 illustrates this hemisphere asymmetry in absorption values; we conclude, however, that the effect is not significant. The open boxes are repeating events. The ordinate shows summed absorption values (30 Mc/s riometer absorption or its equivalent). Circles above the histograms show positions of the early flare regions which occurred before absorption observations were available.

The characteristic that most strongly discriminates between proton flares in the dominant hemisphere and those in the deficient hemisphere is the magnitude of the accompanying radio bursts at meter wavelength. The strength of this discrimination is shown in Figure 6. The independent cases (*crosshatched boxes*) can be placed in the following contingency table (Table 2), whose distribution is significant at about the 10^{-3} level. That is, with the 40 to 11 hemisphere asymmetry already fixed and the meter-burst dichotomy level set so as to give almost equal numbers of bursts in the two marginal categories, the probability that the meter bursts could be distributed this strongly by chance is only about one in a thousand. (Only fifty-one independent cases enter this

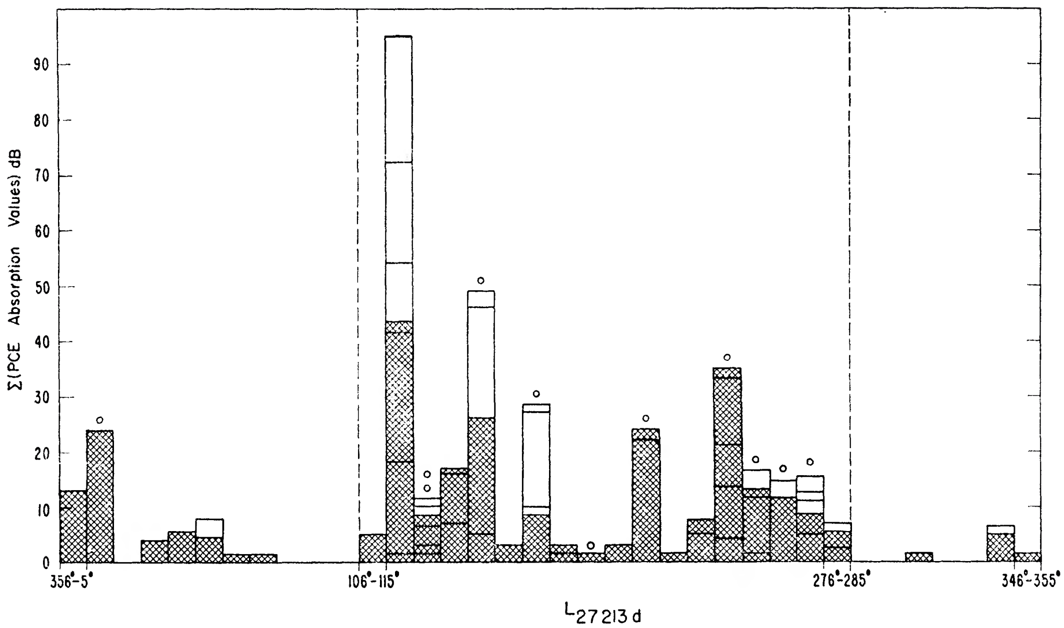

FIG. 5.—Distribution of PCE absorption values in solar longitude, $L_{27\cdot 213}$ d

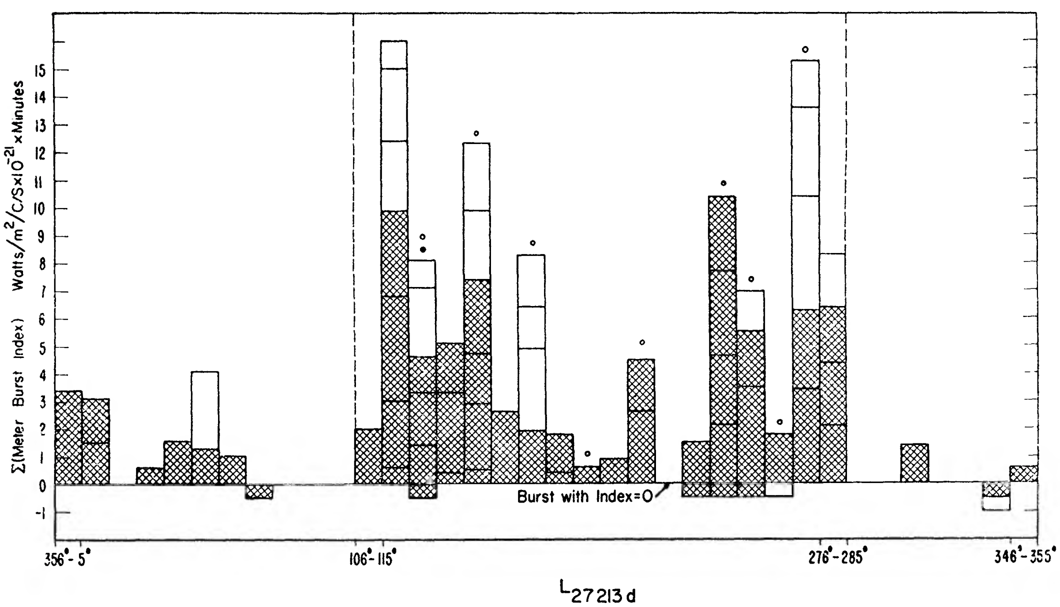

FIG. 6.—Distribution of PCE-associated meter burst indices in solar longitude, $L_{27\;213}$ d

TABLE 2

DISTRIBUTION OF METER BURSTS ASSOCIATED WITH PROTON FLARES

METER BURST INDEX	FLARE REGIONS IN		
	Dominant Hemisphere	Deficient Hemisphere	Total
$\geq +1\;8$	26	1	27
$< +1\;8$	14	10	24
Total ..	40	11	51

sample, since meter burst observations were not yet made at the times of nine of the early proton flares.)

The burst index is defined as

$$\log\,(\text{smoothed flux} \times 10^{-21} \times \text{duration in minutes}) - 3.2\ \text{W m}^{-2}\,(\text{cps})^{-1} \times \text{min.}$$

If no burst occurred for a given PCE, the value is arbitrarily plotted as −0.5 in the histogram of Figure 6.

All the analysis in the preceding sections and that to follow in the last section is concerned with *positions* of solar active regions in different longitude systems. In this section we digress briefly to present results of a search for a periodicity in the times of occurrence of the proton flares themselves. Dodson and Hedeman (1964) found, for their sample, a quite pronounced non-random distribution when times of proton flares were superposed in multiples of the lunar phase period ($29^{d}.53$). For our sample, we find no

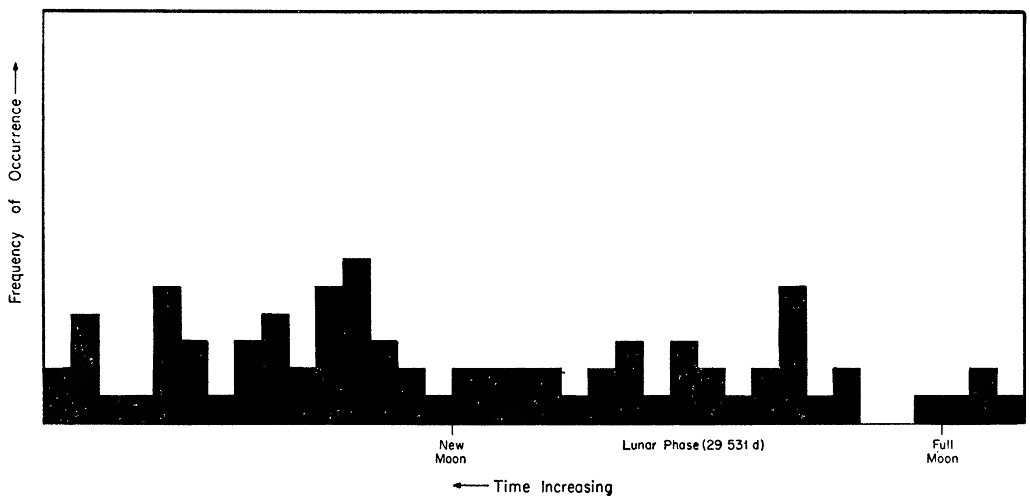

FIG. 7.—PCE flare times, superposed in multiples of lunar phase period, $T = 29.531$ days

significant grouping pattern in lunar phase (see Fig. 7). The slight (but insignificant) clustering which is discernible, however, comes after new moon, in agreement with the results of Dodson and Hedeman. When we make the superposition period a variable ranging from $24^{d}.5$ to $31^{d}.0$, as described previously, we find no period for which times of flare occurrence show any strong non-random grouping.

VI. LONG-TERM CLUSTERING OF SUNSPOTS IN HELIOGRAPHIC LONGITUDE

The strong clustering pattern found for the sixty proton flares suggests that more frequently occurring forms of activity might also be distributed non-randomly in the $L_{27\ 213\ \mathrm{d}}$ system. Earlier studies with sunspot groups, in general, analyzed for long-term patterns in Carrington's system, suggest that a similar analysis in the new system might be fruitful. Even a weak effect could be significant because of the massive sample available.

Losh (1938), Vitinskii (1960), and Ramanathan and Jayanthan (1962) studied sunspot regions over a number of solar cycles, using rotation periods at or near $27^{d}.275$. All found patterns which were apparent during individual solar cycles. Becker (1955) and Tuominen (1962) analyzed the rate of longitude drift of sunspot groups relative to the Carrington system; both found mean rotation rates faster than Carrington's, in agreement with our results with the proton regions. Becker's rate was about 2° to 3° faster, whereas Tuominen's was about 1° faster per rotation. Although these rates were rough estimates, the last value quoted gives a rotation period of about $27^{d}.20$.

The final part of our longitude study, then, is an analysis of sunspot region distributions. First, we consider all regions with area ≥ 250 millionths of the visible hemisphere, averaged over a disk passage; no distinction is made as to type of sunspot configuration, nor is there any adjustment made for longitude drift, due to differential rotation, during any region's lifetime. Solar cycles 12–19 (1880–1963) are used; the resulting sample contains 2369 spot groups. We consider each solar cycle and northern and southern

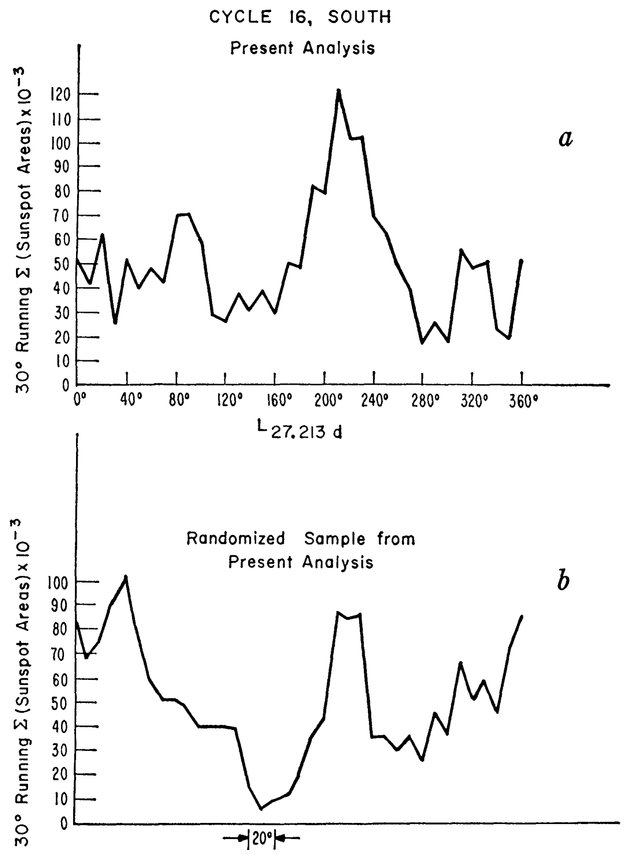

FIG 8 —(*a*) 30° running sums of sunspot areas, solar cycle 16, southern hemisphere, $L_{27\ 213\ d}$; (*b*) 30° running sums formed from randomized sample. The abscissa is determined by the order in which the 10° interval values were randomly drawn.

hemispheres separately, in both the $L_{27.275\ d}$ and the $L_{27\ 213\ d}$ systems. Sums of sunspot areas over each cycle are computed in 10° intervals and plots of 30° running sums are made. The thirty-two curves show patterns of varying strengths, cycle by cycle and north and south, in both longitude systems. In some cases, there are indications of pattern persistence from one cycle to the next, but this is not consistently observed, nor do patterns shift systematically from cycle to cycle. In some cycles there is a striking similarity between north and south; in others there are no similarities or, occasionally, features are in antiphase. Neither longitude system emerges superior to the other in pattern strengths during individual cycles or in persistence, cycle to cycle. To make a rough test of significance, we consider the cycle with the strongest pattern. When the 10° interval values for this case are shuffled to form a random ordering and then 30° running sums made from these, we obtain a pattern with strength comparable to the actual pattern strength. Figure 8, *a*, shows the true 30° running sum pattern for cycle 16, southern hemisphere, in the $L_{27\ 213\ d}$ system. Figure 8, *b*, shows the result with the randomized sample. In addition, when longitudinal hemisphere asymmetries are compared, the random case is very slightly stronger than the actual distribution. We conclude, in this analysis, that individual cycle patterns could quite easily have occurred by chance. We then combine and plot the 30° running sums for all cycles, 12–19. No significant features appear, nor is there any coherence between north and south.

The above negative results lead us to try a different sample of sunspot regions which one may expect to be more flare-active than the previous sample. For this we use those

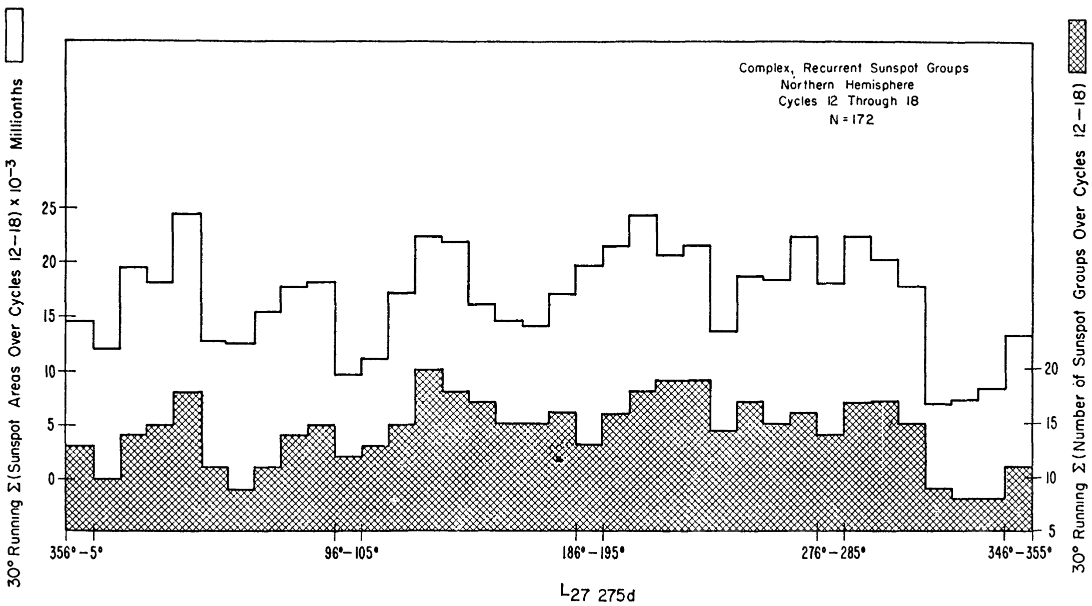

FIG. 9.—30° running sums of sunspot areas and sunspot counts, complex, recurrent groups, cycles 12–18, northern hemisphere, $L_{27\ 275\ d}$.

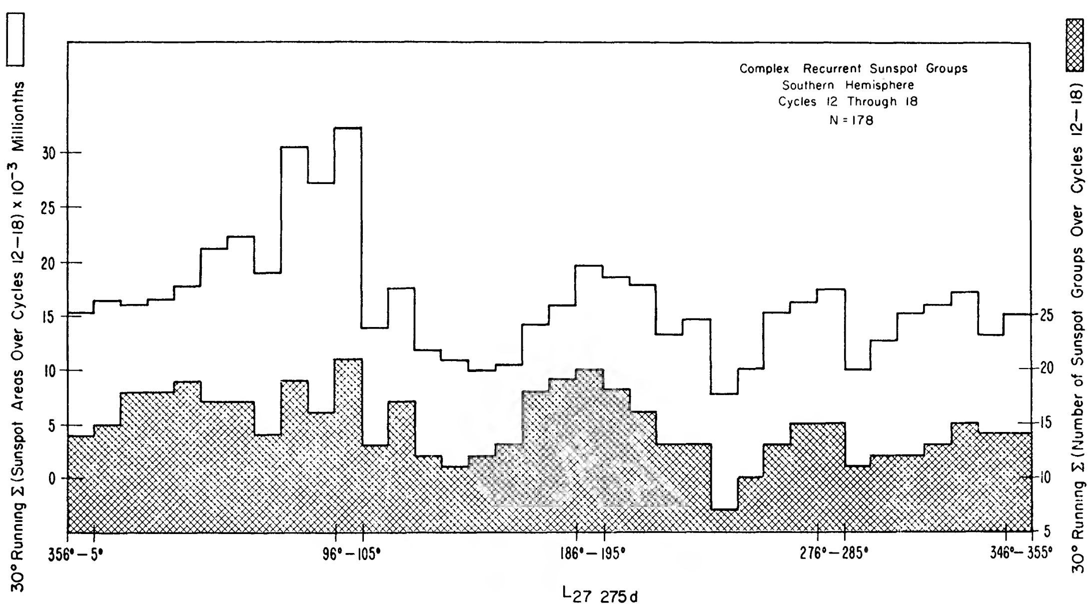

FIG. 10.—Same as Fig. 9 for southern hemisphere

sunspots listed as recurrent (appeared during more than one rotation) in the Greenwich Photoheliographic Results. We further require that they be described as complex (or composite, or streams), since simple configurations, even if large, tend to be deficient in flare activity. The minimum area limit is 500 millionths, but this requirement can be met by an area summed over several rotations, as long as the group remains complex. In order to minimize effects of differential rotation, the position assigned to a region is its mean position during its first rotation. Cycles 12–18 are included. Figures 9–12 show

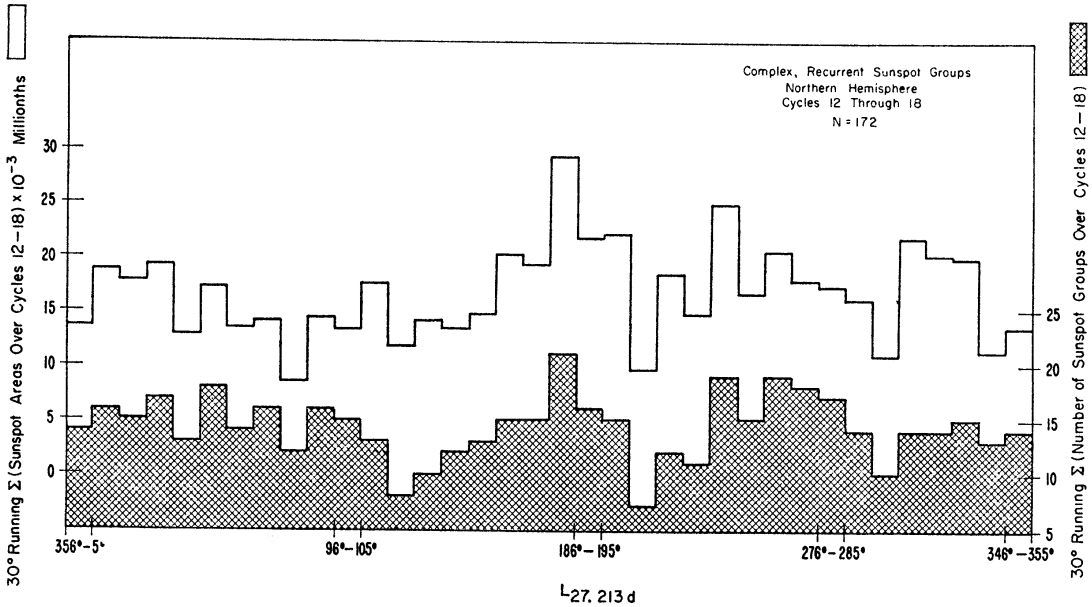

FIG. 11.—30° running sums of sunspot areas and sunspot counts; complex, recurrent groups; cycles 12–18; northern hemisphere, $L_{27.213}$ d.

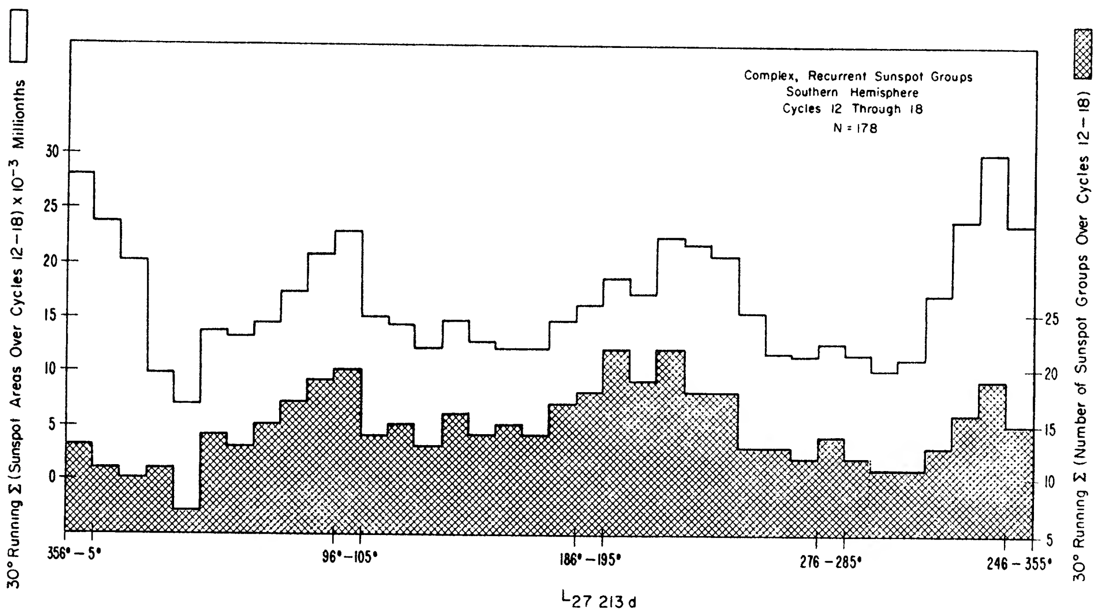

FIG. 12.—Same as Fig. 11 for southern hemisphere

the results of this analysis in which all cycles are combined, with north and south treated separately. There are 350 regions in the sample. Sunspot areas and counts in 30° running sums are shown. Examination of the histograms for both longitude systems forces us to conclude that this smaller sample of important sunspot groups also exhibits no significant long-term organization in heliographic longitude.

Our negative results for the two different sunspot samples and for both individual and combined cycles lead us to question the significance of earlier results with sunspots. The analysis by Vitinskii (1960) is in the best form for comparison with our own. He worked with individual cycles 12–18. Sunspot areas with 40° interval sums were taken as his basic unit, rather than the 10° unit which we used; Warwick (1965) smoothed

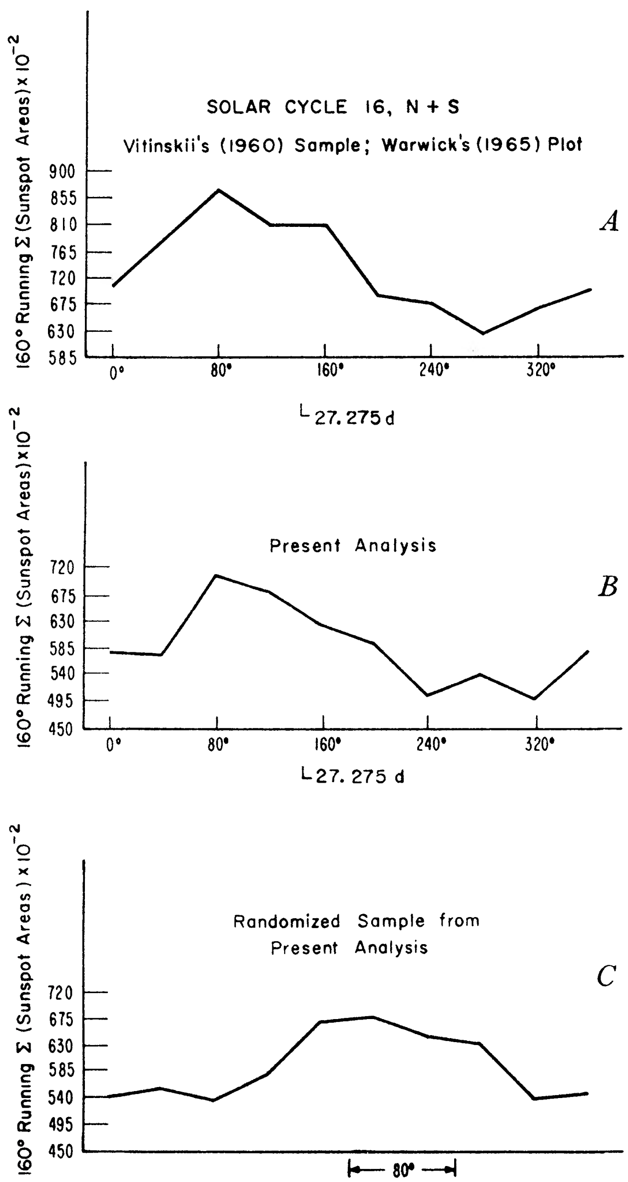

FIG. 13.—(*A*) 160° running sums of sunspot areas, solar cycle 16, northern plus southern hemispheres, $L_{27.275}$ d. (Vitinskii's [1960] analysis, adapted by Warwick [1965].) (*B*) Present analysis. (*C*) 160° running sums formed from randomized sample. The abscissa is determined by the order in which the 10° interval values were randomly drawn and combined in groups of four.

Vitinskii's 40° sums by forming from them 160° running sums. To compare our work with his, then, we combine our 10° intervals into 40° units and form 160° running sums. Cycle 16 is again used, this time the $27^{d}.275$ system, with north and south combined. To obtain a randomized sample for comparison, we again shuffle 10° interval values, randomly combine them into groups of four, and once again form 160° running sums. The results are shown in Figure 13. The top curve is from Warwick's paper, obtained from Vitinskii's analysis; the middle curve is from our analysis; at the bottom is the random curve. Although this last is somewhat weaker than the other two, it is still quite comparable. We conclude that patterns as strong as those in the real sample curves could quite easily occur by chance. We therefore question the reality of the clustering of sunspot regions in solar longitude, both during individual cycles and over several cycles.

VII. CONCLUSIONS

1. A sample of sixty independent proton flares, occurring over a century, are distributed non-randomly in the $L_{27\ 213\ \mathrm{d}}$ solar longitude system. An asymmetry is obtained with forty-nine events in one longitudinal hemisphere to eleven in the other. A lower limit on the significance of the effect yields a probability value of 0.004 for chance occurrence. The proton events show no significant organization of any type in any other (independent) longitude system, including the Carrington system.

2. In the $L_{27\ 213\ \mathrm{d}}$ system, the meter bursts accompanying the proton flares in the "dominant" hemisphere are much stronger than the bursts with proton flares in the "deficient" hemisphere. A 2×2 contingency table analysis shows that this effect is significant with a probability for chance occurrence of only 0.001.

3. Areas of sunspot groups are distributed in both the $L_{27\ 213\ \mathrm{d}}$ and the $L_{27\ 275\ \mathrm{d}}$ systems with pattern strengths which could easily occur by chance. It appears that only when we consider an extreme form of solar activity, the proton flare, do we find any non-random grouping in heliographic longitude. It is interesting to compare this result with Bell's (1962) finding that the north-south asymmetry among those flares which produce geomagnetic storms strengthens very markedly as storm intensity becomes more and more severe.

I wish to thank Constance Sawyer, who made many helpful suggestions throughout this study; her earlier work (Warwick 1965) was largely responsible for initiating this one. Also, I thank Carolyn McLellan who did all of the machine programming required in the analysis. Fred Ward kindly supplied the sunspot data for cycle 19.

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