STATISTICS OF GEOMAGNETIC STORMS AND SOLAR ACTIVITY

by

TH. SAEMUNDSSON

STATISTICS OF GEOMAGNETIC STORMS AND SOLAR ACTIVITY

Th. Saemundsson

(Communicated by the Director, University of London Observatory)

Summary

The geomagnetic effects of Ca-flocculi and large sunspots have been
investigated statistically using the method of superposed epochs. The study
covers the period 1919–1954, and the main results are exhibited in a series
of diagrams. Magnetic storms show a definite relation to the CMP of
active regions, and the correlation is found to persist throughout the solar
cycle without noticeable change of character. This applies to both
recurrent and sporadic storms, but the type of correlation differs markedly
in the two cases. The results lend support to the current hypothesis that
there are two kinds of solar corpuscular emission:
  (i) prolonged emission from M-regions which are largely independent
      of active areas.
  (ii) transient emission from active areas.
In both cases, the emitted particles reach the earth in an average time of
3 days. The hypothesis that the recurrent storms are caused by particle
streams from active areas is shown to be untenable. M-regions tend to
avoid the immediate vicinity of active areas, but are strengthened at a distance
of 30°–90° from the active areas, particularly on the " following " side.
The nature of M-regions is discussed in the light of the statistical evidence.

---

1. *Introduction.*—The 27-day recurrence tendency of magnetic storms was
demonstrated by Maunder (**10**) at the beginning of this century. The recurrent
storms are ascribed to corpuscular streams from unknown regions on the Sun,
and repeated attempts have been made to relate the storm sequences to visible
solar features. But the location of the M-regions (the hypothetical stream sources)
is still a matter of controversy. In this paper we shall consider the possible
connection between M-regions and areas of activity on the Sun. There has been
some divergence of opinion on this subject in recent years. Allen (**1**) came to the
conclusion that M-regions tended to avoid large sunspot groups. Similar views
were subsequently expressed by various authors who studied the distribution of
sunspots, Hα-filaments or coronal emission (Kiepenheuer (**8, 9**), Waldmeier
(**22, 23**), Bell and Glazer (**5**)). The idea that M-regions avoid active solar areas
has been challenged by Mustel and associates (**15**). Their investigation of
calcium flocculi (plages) has led them to conclude, in a series of 20 papers, that
M-regions are identical with active regions on the Sun. According to this hypo-
thesis, the active areas, characterized by Ca-flocculi, bright λ5303 regions and
sunspots, are the sources of approximately radial corpuscular streams. These
views disclose a remarkable lack of agreement.

The prime object of the present analysis was to decide between the conflicting
hypotheses.

2. *Method of analysis.*—At present, the relation between magnetic storms and solar activity can only be elucidated by means of a thorough statistical investigation. Extensive solar and geomagnetic data are required, and these data must be as homogeneous as possible.   Records of coronal emission are rather limited and the following study will therefore be confined to chromospheric and photospheric manifestations of activity.   The Meudon synoptic maps of the Sun (18) provide the necessary records of calcium flocculi.   These maps form a continuous sequence from 1919 onwards.   The present investigation covers the whole period from December 1919 to December 1954.   The method of superposed epochs was used to determine the correlation of magnetic storms with the central meridian passage (CMP) of calcium flocculi.   The brightness of a flocculus is indicated on the Meudon maps.   For the years of declining solar activity the CMP of every flocculus, irrespective of brightness, was taken into account.   To repeat this for the maximum years would not have been practicable owing to the great number of flocculi in those years.   Instead, a separate study was carried out for the brighter flocculi alone and extended over the entire solar cycle.   These flocculi, which will be referred to as "bright" flocculi, constitute approximately one third of the total.
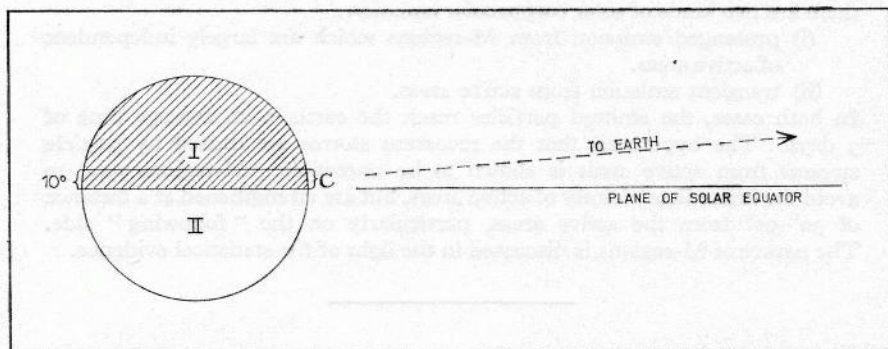

FIG. 1.—*The favourable hemisphere* (I), *unfavourable hemisphere* (II) *and central zone* (C) *of the Sun.*

Ca-flocculi are much more frequent than sunspots and may be regarded as a more general sign of activity.   Sunspots, when they occur, are always accompanied by bright flocculi (the converse is not true).   For comparison, a parallel study was made using large sunspots instead of flocculi.   The dates of CMP of the sunspots were extracted from the Greenwich tables of great sunspots (20).   These include all groups ⩾ 500 units.

It has been suggested (5, 6) that an M-region is much more effective in creating a magnetic disturbance when the Earth is on the same side of the solar equator as the M-region.   With this in mind, the period was divided into 70 half-years determined by the sign of the Earth's heliographic latitude and the correlations were studied for each half-year separately.   A complete distinction was made between flocculi in the "favourable" hemisphere and those in the "unfavourable" hemisphere (see Fig. 1).   On the very rare occasions when a flocculus extended across the Sun's equator it was counted as belonging to one hemisphere only. Particular attention was paid to all flocculi which came within a central zone defined between 0° and 10° heliographic latitude in the favourable hemisphere.

These flocculi were the subject of an independent correlation study.   It should be noted that the centre of the visible solar disk is at all times within the central zone.

In the years 1919–1954, bright flocculi crossed the CM on 2380 days in the favourable hemisphere and on 2382 days in the unfavourable hemisphere.   Central zone transits numbered 946.   Out of a total of 425 large sunspots, 205 appeared in the favourable, and 220 in the unfavourable hemisphere.
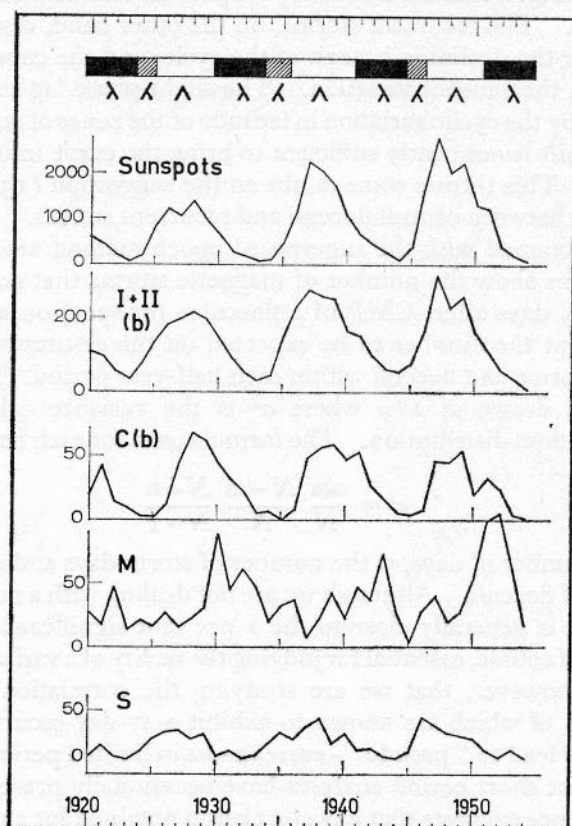

FIG. 2.—*Sunspots, flocculi and magnetic storms in 1919–1954.*
Top curve: mean daily area of sunspots (in millionths of the Sun's hemisphere).
I(b)+II(b):   number of days (per year) of CMP of bright flocculi in both hemispheres.
C(b):   number of days (per year) of CMP of bright flocculi in the central zone.
M: number of days (per year) with recurrent magnetic storms.
S: number of days (per year) with sporadic magnetic storms.
Different shadings define the periods of increasing activity (λ), maximum activity (ʌ) and decreasing activity (λ) referred to in the text.

Magnetic storm data were obtained from Bartel's tables of the daily values of C_p (2, 3).   A list was made of all days for which the C9 index was 6 or higher. These "storm" days were then divided into two classes, M and S.   If a storm day was both preceded and followed by a disturbance of similar intensity (according to a fixed rule) 26, 27 or 28 days away, it was classified as M, the remaining storms forming the group S.   By this method it was hoped to segregate the recurrent storms (M) from the sporadic storms (S).   This is an important precaution, for the two storm types are known to possess very different characteristics.   In addition, the storms included in the Greenwich catalogue of great geomagnetic

storms (**20**) were labelled G and used as the basis of a separate correlation study. The records show 1307 M-storm days, 826 S-storm days and 152 G-storm days during the period of 35 years.

The yearly frequencies of sunspots, flocculi and magnetic storms are shown in Fig. 2. The figure also defines the periods of increasing solar activity (λ), maximum activity ($\wedge$) and declining activity (λ) which will be referred to below. It is evident from Fig. 2 that the frequency of sporadic storms varies in phase with the sunspot cycle. The recurrent storms, on the other hand, display their well-known affinity for the declining branch of the cycle, and the curve is completely out of phase with the sunspot variation. The slight phase lag shown by central flocculi is caused by the cyclic variation in latitude of the zones of activity (Spörer's law). But the shift is not nearly sufficient to bring the curve into phase with the M-storm curve. This throws some doubt on the suggestion (**15**) that there is a close relationship between central flocculi and recurrent storms.

The results obtained with the superposed epoch method are shown in Figs. 3–11. The graphs show the number of magnetic storms that occurred from 15 days before, to 15 days after, CMP of a flocculus (or spot) on a scale in which 100 units represent the number to be expected on the assumption of a random distribution of storms and flocculi within each half-year period. The significance limits have been drawn at $2 \cdot 6\sigma$ where σ^2 is the variance calculated on the assumption of random distribution. The formula used for each half-year period is

$$\sigma^2 = \frac{mn}{N} \frac{N-m}{N} \frac{N-n}{N-1}$$

where N is the number of days, m the number of storm days and n the number of days with CMP of flocculi. Although we are not dealing with a normal frequency distribution, $2 \cdot 6\sigma$ is generally close to the 1 per cent significance level. Significance tests are, of course, essential for judging the reality of a variation. It should be emphasized, however, that we are studying the correlation of two sets of phenomena, both of which are known to exhibit a 27-day recurrence tendency, and this can easily lead to " pseudo "- correlations in limited periods. Hence it is not surprising that short period analyses have occasionally presented conflicting results. Experience suggests that any correlation obtained for a period as a short as a year or two should be treated with scepticism, for the chances are that it will not be repeated in the following years. For similar reasons it would be injudicious to base general conclusions on results drawn from a single solar cycle. The graphs which are shown here relate to 5 years of increasing solar activity, 14 years of maximum activity and 16 years of declining activity. Even larger samples would have been desirable, especially for the early part of the cycle, but the limit is set by the availability of data.

3. *Recurrent storms.*—The M-storms are of major interest here and will be considered first. S- and G-storms will be left for comparison later. Fig. 3 shows the distribution of M-storms relative to the CMP of flocculi in both hemi-spheres taken together. The graphs are drawn for different parts of the solar cycle and also combined to show the correlations over the cycle as a whole. The top curve deserves particular attention because it refers to the descending branch of the sunspot cycle when the M-storms are most numerous. The statistics include the fainter flocculi which are by no means rare ; there were nearly 3 000 days of CMP during the 16 years of declining activity. Examination of the top curve

in Fig. 3 shows that the outstanding feature is a minimum in storm frequency 3 days after CMP. The statistical significance of this feature is $6 \cdot 2\sigma$, corresponding to a chance probability of $1 : 10^9$. The minimum is followed by a maximum reaching $3 \cdot 3\sigma$ on day $+6$ (reckoned from the day of CMP). Both features can be seen in most curves which cover a reasonably long period in any part of the solar cycle. This may be verified by examining the remaining curves in Fig. 3. These curves, which relate to bright flocculi, show similar characteristic features, and there can be no doubt that the same type of correlation persists throughout the
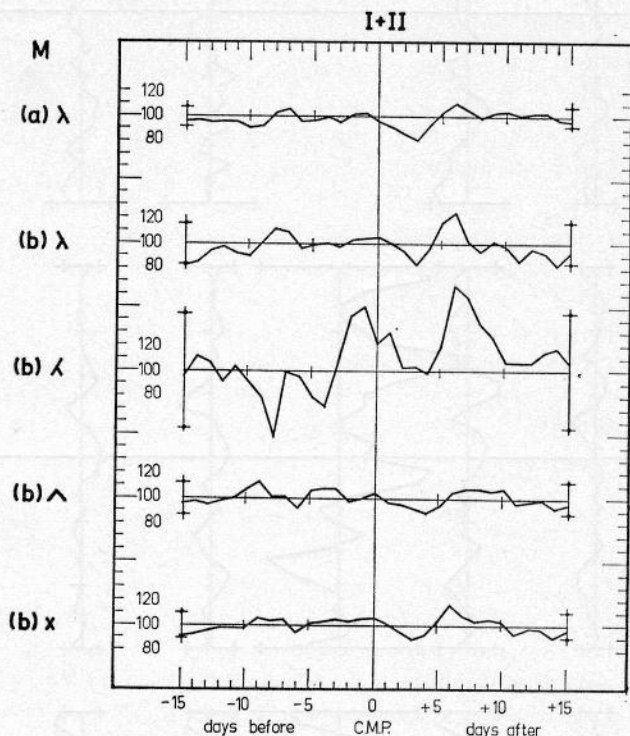

FIG. 3.—*Number of recurrent storms before and after* CMP *of flocculi in both hemispheres in various parts of the sunspot cycle* (λ, $\wedge$, λ) *and over the cycle as a whole* (x). (a)=*all flocculi,* (b)=*bright flocculi. The numbers are normalized so that* 100 *units represent the value expected from random distribution. Significance limits are drawn at* $2 \cdot 6\sigma$.

solar cycle. The final curve (x) shows the mean correlation between bright flocculi and M-storms over the whole period of 35 years. Although the variations are small, the curve as a whole takes the form of a 27-day wave with a maximum near zero day. The amplitude of the wave is only 5 per cent, and it might easily be overlooked in a smaller sample of data. The storm frequency increases slowly up to the day of CMP and then falls to a minimum on day $+3$. The minimum is followed by a maximum on day $+6$, whereupon the storm frequency decreases steadily again.

It is somewhat difficult to decide whether these effects show any dependence on the solar cycle. Examination of all the data available failed to confirm the suggestion (11, 12) that the position of the main maximum drifts to the right in the last stages of the cycle. The features appear with varying strength and are least
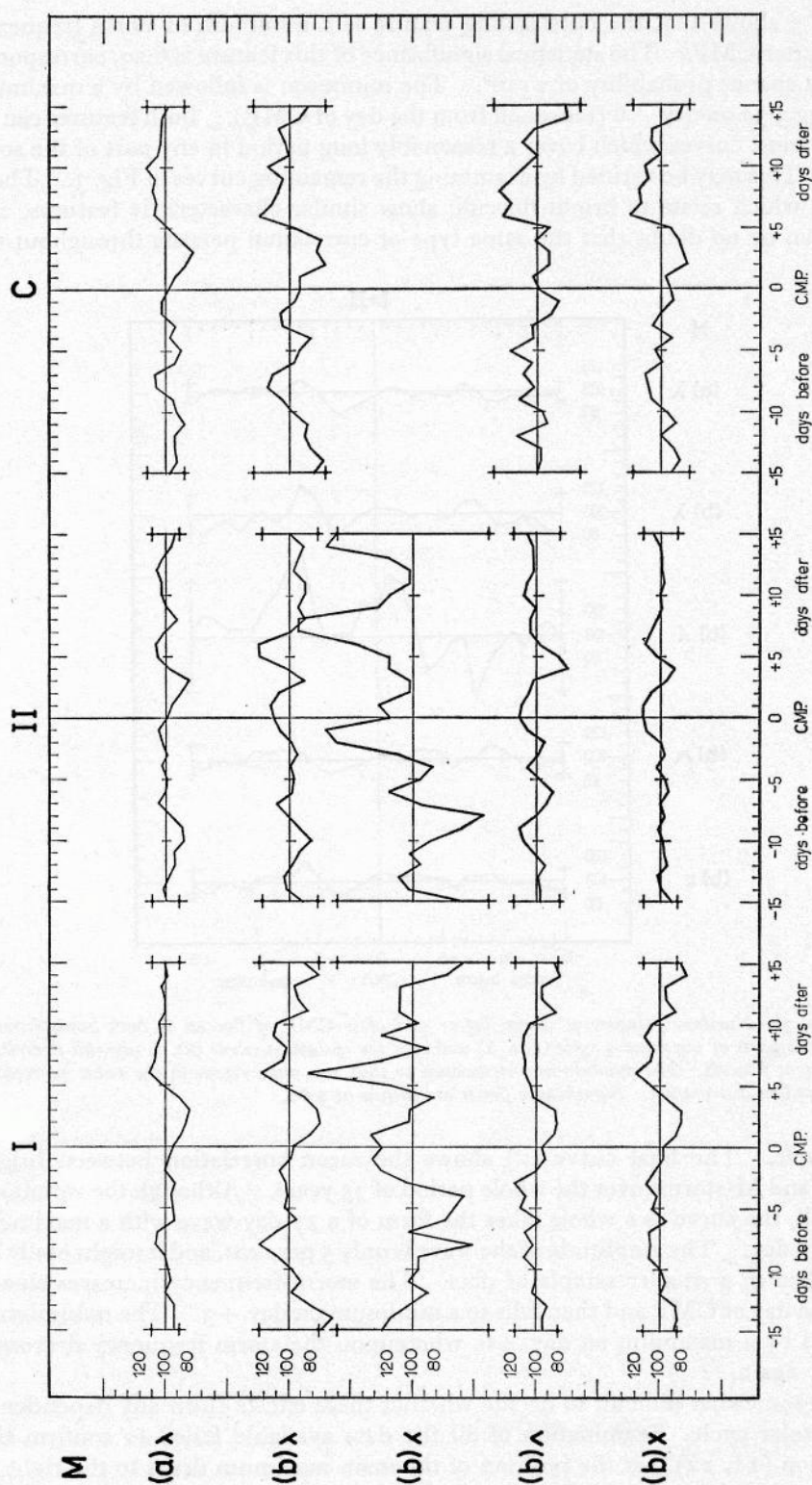
Th. Saemundsson

Fig. 4.—*Number of recurrent storms before and after CMP of flocculi in the favourable hemisphere* (I), *unfavourable hemisphere* (II) *and central zone* (C) *in various parts of the solar cycle (see legend to Figs. 2 and 3).*

pronounced in the periods of maximum activity (∧).   The fluctuations in storm frequency during the years of increasing activity (ϟ) are surprisingly large, but it would be unwise to overestimate the significance of these variations.

The two top curves in Fig. 3 permit a comparison between the effects of all flocculi (*a*) and bright flocculi alone (*b*) in the declining part of the solar cycle. On the whole, one might expect bright flocculi to produce stronger effects than the fainter ones.   If all effects were caused by the bright flocculi, the features of the (*a*)-curve should be enhanced fourfold in the (*b*)-curve.   Inspection shows that the minimum on day +3 which is the main feature of the (*a*)-curve is certainly no deeper in the (*b*)-curve.   On the other hand, the maximum at day +6 is apparently higher.   By itself, this increase is not statistically significant.   But it seems to be a part of a more general effect.   It will be observed that the level of the (*b*)-curve is a little higher than that of the (*a*)-curve for several days on each side of CMP but falls below the (*a*)-level outside this period.   This indicates a slightly greater tendency for M-storms to occur while the bright flocculi are on the earthward side of the Sun.
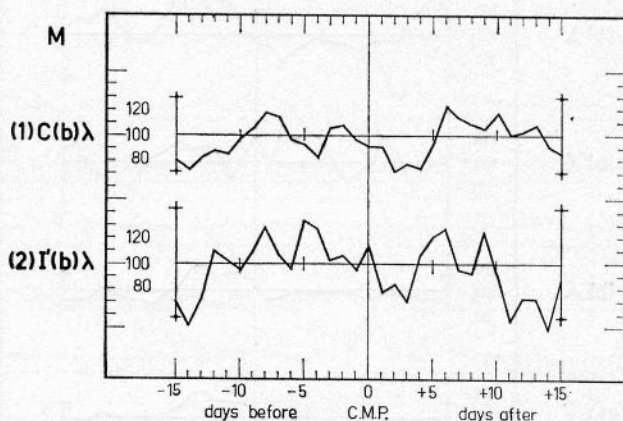

Fig. 5.—*Upper graph: number of recurrent storms before and after CMP of bright flocculi in the central zone.   Lower graph: number of recurrent storms before and after CMP of bright flocculi in the favourable hemisphere but outside the central zone, excluding every flocculus the CMP of which coincides with the CMP of another flocculus in the central zone.   Both curves relate to the declining part of the solar cycle.*

4. *Directional effects and recurrent storms.*—Mention has been made of the hypothesis that recurrent storms are associated with flocculi which happen to pass across the centre of the Sun's disk as seen from the Earth (15).   This possibility will now be considered.   Fig. 4 shows the distribution of M-storms with respect to the CMP of flocculi in the favourable hemisphere (I), the unfavourable hemisphere (II) and the central zone (C).   The C- and I-curves are not independent, of course.   As a rule, the C-flocculi are automatically classified as I-flocculi, and there are numerous occasions when flocculi stretch across the border between the central zone and the rest of the favourable hemisphere.   However, if the central flocculi were of particular importance, the C-curves should differ significantly from the I-curves.   This is not the case.   In the ∧-periods, the maximum from day +6 onwards in the C-curve is a little higher than the corresponding maximum in the I-curve, but statistical tests show that the random probability of such a difference exceeds 30 per cent.   In Fig. 5 the effects of C-flocculi may be compared

with the effects of those I-flocculi which are outside the central zone.   The upper curve is the $C(b)$ λ curve taken from Fig. 4.   The lower curve relates to I-flocculi outside the C-zone in the same periods (the declining part of the solar cycle).   It should be emphasized that these two curves are constructed from non-overlapping data.   Their similarity confirms the results of the statistical tests, and there appears to be no sound basis for the claim that M-storms show a particularly close association with central flocculi.
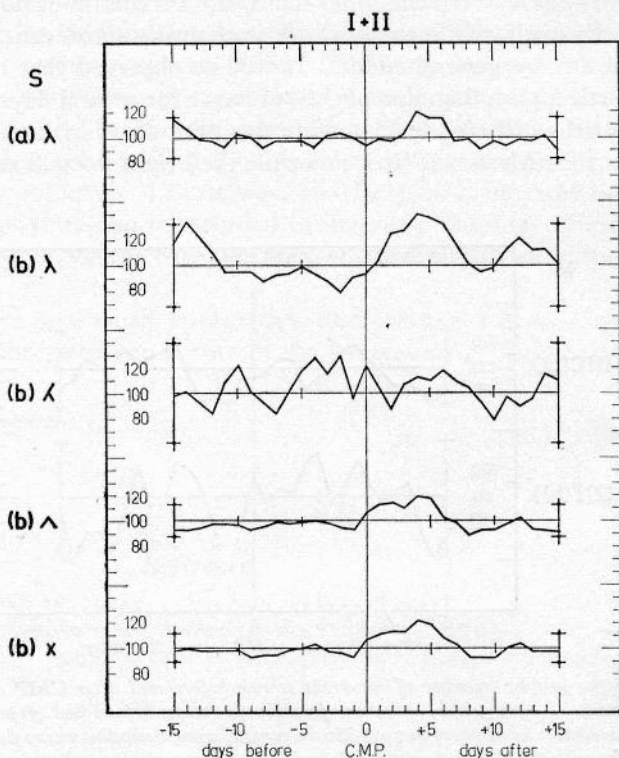

FIG. 6.—*Number of sporadic storms before and after* CMP *of flocculi in both hemispheres* (*see legend to* Fig. 3).

With the aid of Fig. 4, one may also compare curves I and II for the two hemispheres.   According to a statistical analysis, the CMP of flocculi in one hemisphere are not correlated with the CMP of flocculi in the other.   The curves I and II in Fig. 4 may therefore be regarded as completely independent.   Apparent differences are numerous but calculations show that they do not generally attain significant proportions.   The only exception is to be found in the combined results for the whole cycle (**x**), where the maximum near zero day in curve II is completely absent in curve I.   The difference amounts to $2 \cdot 8\sigma$ at day $+1$.   The effect, if real, may be a function of the heliographic distance between the Earth and the flocculus rather than a hemispheric effect.   This is suggested by the fact that the zero day peak appears in curve Iλ.   If the curves are arranged according to the
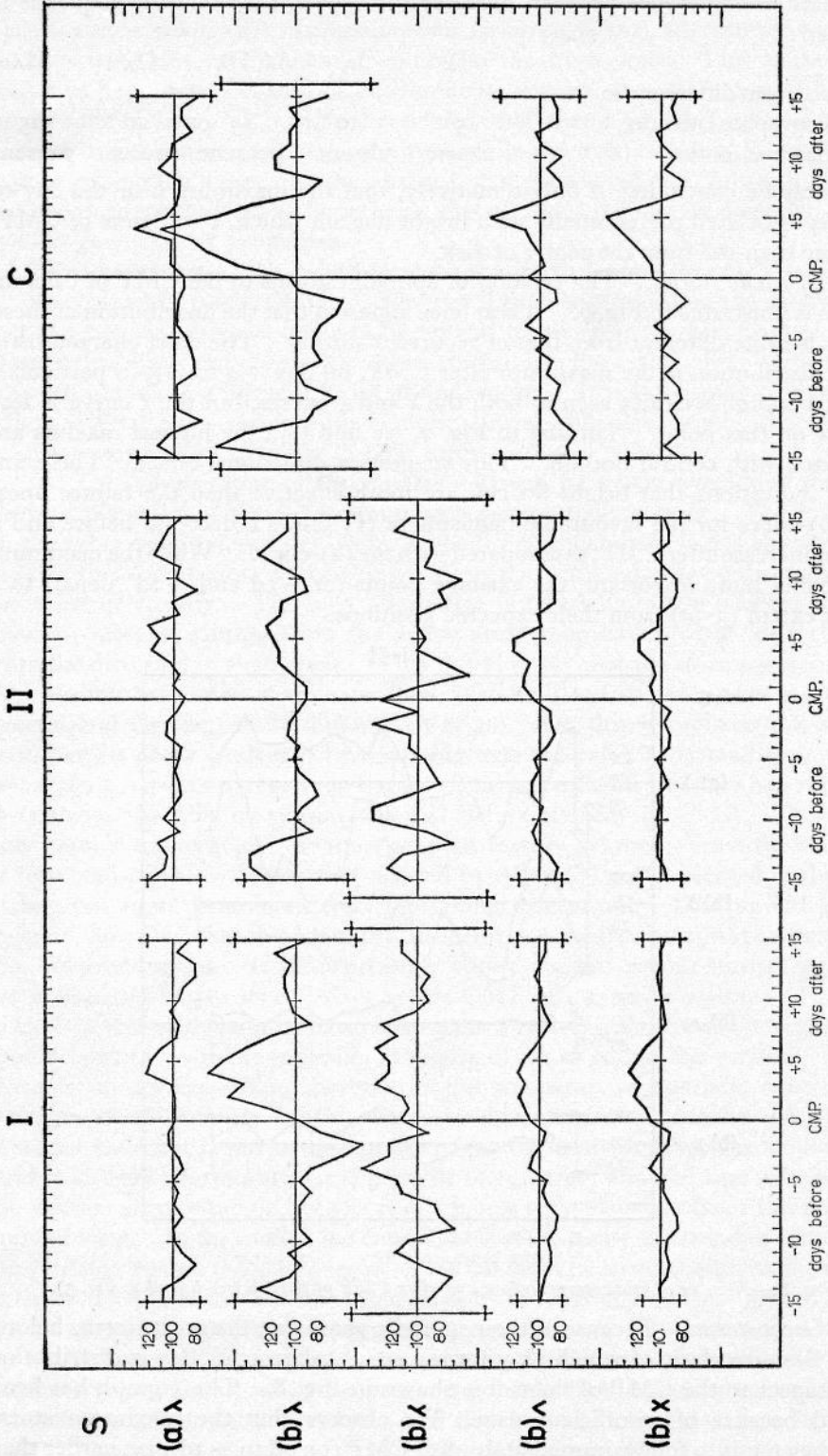
FIG. 7.—*Number of sporadic storms before and after CMP of flocculi (see legend to Fig 4.)*

mean latitude difference between Earth and flocculus, the following sequence is obtained:

Curve	Iλ	Iλ	Iʎ, IIλ	IIλ	IIʎ
Approx. mean difference in heliographic latitude	$5°$	$10°$	$15°$	$20°$	$25°$
Zero-day maximum	absent	absent	present	present	present

It may be concluded, if only tentatively, that the maximum near the day of CMP is associated preferentially with bright flocculi which, at the time of CMP, are more than $10°$ from the centre of disk.

5. *Sporadic storms.*—The relation of sporadic storms to the CMP of calcium flocculi is illustrated in Fig. 6. It is at once apparent that the distribution of these storms is quite different from that of recurrent storms. The chief characteristic of the distribution is the maximum after CMP, on day $+2$ to $+5$ in particular. The maximum is clearly seen in both the λ and ʌ curves, but the ʎ curve is less definite on that point. Turning to Fig. 7, we find that the highest maxima are associated with central flocculi. This suggests a directional effect. There are strong indications that bright flocculi are more effective than the fainter ones. The (b)-curve for the favourable hemisphere (I) shows a decrease before and a quicker increase after CMP, as compared with the (a)-curve. While the maximum is probably more important, the extreme points (at $-2d$ and $+2d$) depart to a similar extent $(3·3\sigma)$ from their expected positions.
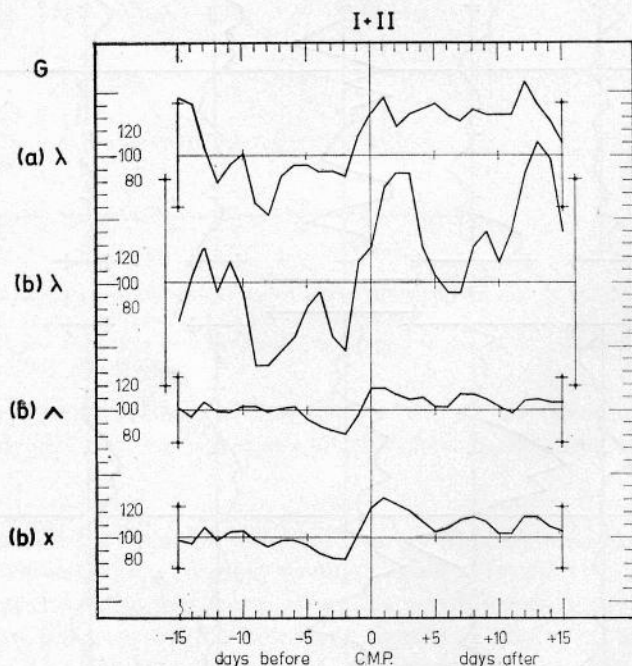

FIG. 8.—*Number of great storms before and after* CMP *of flocculi (see legend to Fig. 3).*

6. *Great storms.*—Because of their sporadic character, the great storms belong to the S-storm class, of which they form a small subgroup. Their distribution with respect to the CMP of flocculi is shown in Fig. 8. The ʎ graph has been omitted because of insufficient data. We observe that the maximum storm frequency tends to follow immediately after CMP (on od to $+3d$), i.e. earlier than the average for S-storms. The increase seems to continue for much longer
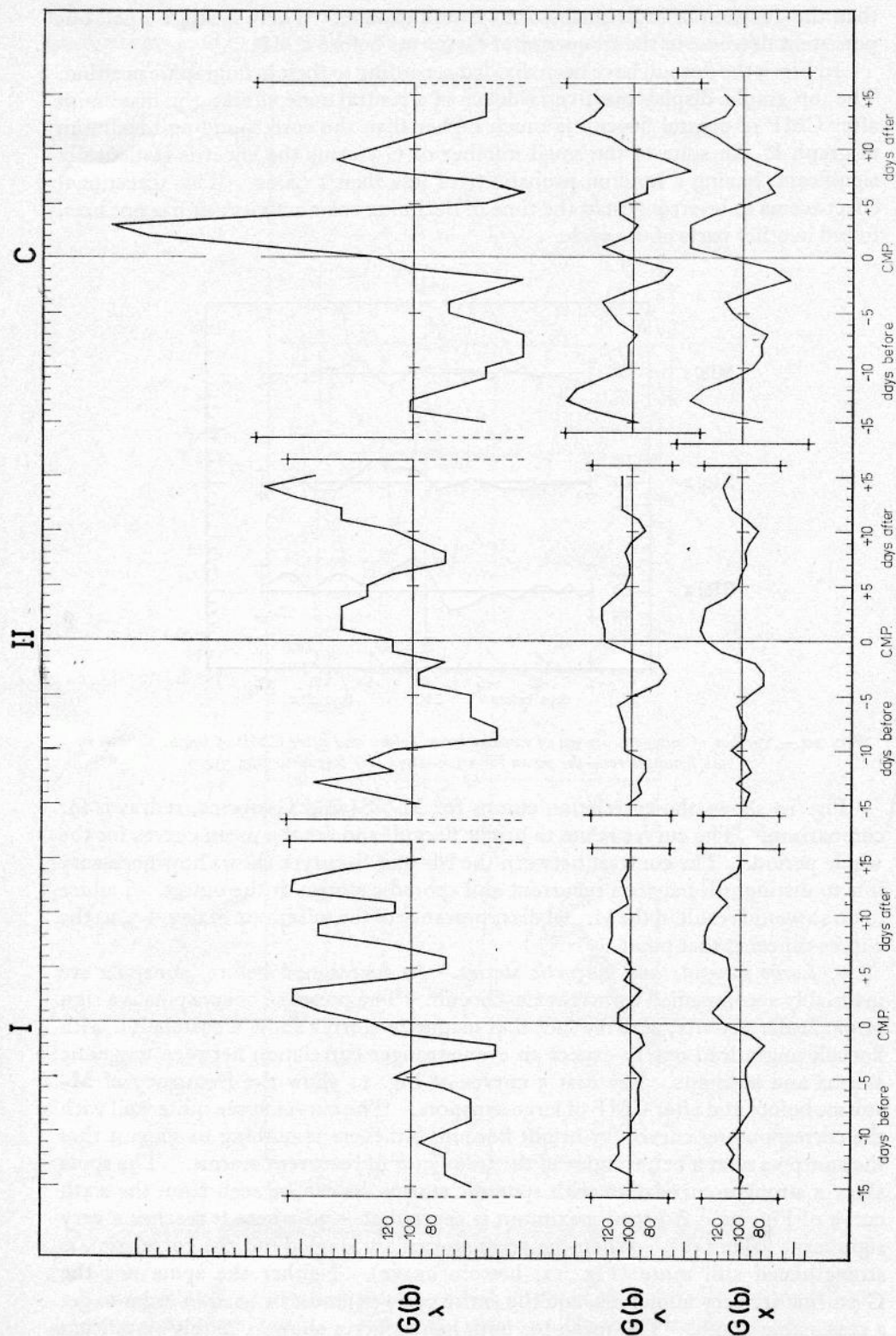
FIG. 9.—*Number of great storms before and after CMP of flocculi (see legend to Fig. 4).*

than the duration of individual storms would explain. There is also a small but persistent decrease in the frequency of G-storms before CMP.

In Fig. 9 the flocculi have been divided according to their heliographic position. The top graphs display positive evidence of a central zone effect: the maximum after CMP of central flocculi is much higher than the corresponding maximum of graph I. In spite of the small number of G-storms the effect is statistically significant, having a random probability of less than 1:2000. This directional effect seems to be strongest at the time of declining solar activity; it has not been found in other parts of the cycle.
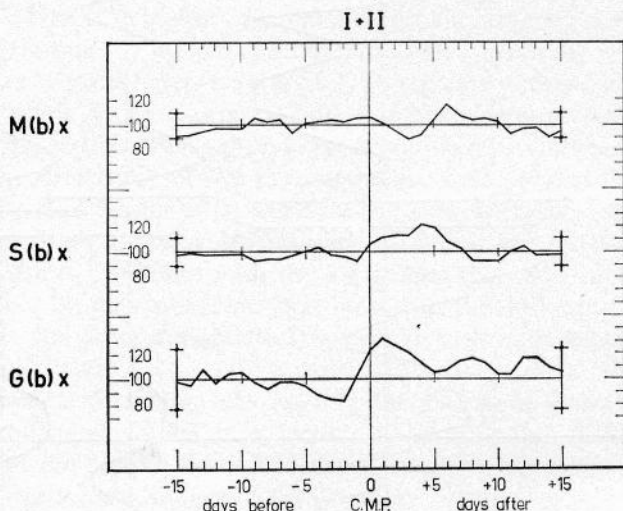

FIG. 10.—*Number of magnetic storms of various types before and after* CMP *of bright flocculi in both hemispheres—the mean for* 1919–1954 *(see legend to Fig.* 3).

Fig. 10 shows the correlation curves for M-, S- and G-storms, redrawn for comparison. The curves relate to bright flocculi and are the mean curves for the whole period. The contrast between the M- and S-curves shows how necessary it is to distinguish between recurrent and sporadic storms at the outset. Failure to do so would result in the virtual disappearance of the minimum at day +3, as the curves cancel at that point.

7. *Large sunspots and magnetic storms.*—As mentioned before, sunspots are invariably accompanied by bright Ca-flocculi. The presence of sunspots is a sign of particular activity, and the fact that magnetic storms show a correlation with flocculi might lead one to expect an even stronger correlation between magnetic storms and sunspots. The first 5 curves of Fig. 11 show the frequency of M-storms before and after CMP of large sunspots. The curves agree quite well with the corresponding curves for bright flocculi, but there is nothing to suggest that the sunspots offer a better index of the frequency of recurrent storms. The spots show a stronger correlation with sporadic storms, as can be seen from the sixth curve of Fig. 11. A broad maximum is centred at +3d where it reaches a very significant value (4σ). When the great storms are singled out the correlation is strengthened still more (Fig. 11, bottom curve). Neither the spots nor the G-storms are very numerous, and the entire cycle (x) must be used in order to get a reasonable graph. The mean for both hemispheres shows a highly significant

maximum with a peak at $+ 1\frac{1}{2}$d and a duration of a few days.   It is evident that the great storms tend to be linked with sunspots rather than with flocculi alone.
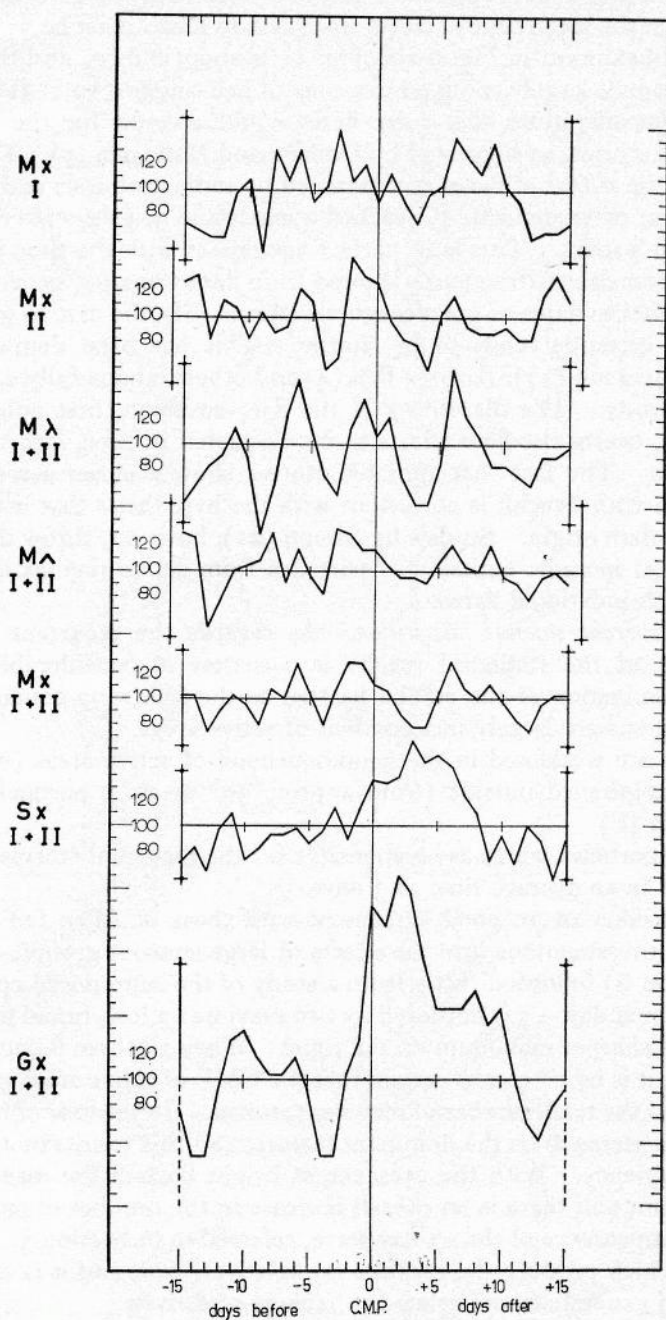

Fig. 11.—*Number of magnetic storms of various types before and after* CMP *of large sunspot groups* (cf. *legends to previous figures*).

8. *The sporadic storms: discussion.*—The origin of the sporadic storms is less controversial and only calls for a brief discussion.   These storms, as we have seen,

are most frequent 1–6 days after the CMP of active regions, and there is no reason to doubt that the storm maximum is caused by particles emitted from the active regions.   Assuming that the emission occurs preferentially in the radial direction, we deduce that the mean time of travel from Sun to Earth must be $3\frac{1}{2}$ days.   The width of the maximum in Fig. 6 and Fig. 11 is about 8 days, and this indicates that the emission is largely confined to a cone of half-angle $\leqslant 50°$.   It would seem from these considerations that solar flares could account for the majority of truly sporadic storms, as suggested by Dodson and Hedeman (**7**).   They studied the geomagnetic effects of flares accompanied by radio outbursts and found that, on the average, magnetic activity reached a maximum 3–4 days after a flare (see Fig. 1 of their paper).   This is in perfect agreement with the time lag deduced above.   Shorter delays, frequently quoted from flare statistics, generally refer to particularly intense flares or great magnetic storms.   In the case of great storms, the time lag certainly tends to be shorter.   This has been demonstrated by Newton and Jackson (**17**), Barbara Bell (**4**) and others, and is fully confirmed by the present study.   The directivity of the flare emission, first pointed out by Newton (**16**), causes the flare effects to be associated in time with the CMP of active regions.   The fact that sporadic storms show a closer association with sunspots than with flocculi is consistent with the hypothesis that many of these storms are of flare origin.   Studies by Simon (**21**), however, throw doubt on the suggestion that sporadic emission of particles from active regions is *necessarily* associated with individual flares.

9. *The recurrent storms: discussion.*—As regards the recurrent storms, the interpretation of the statistical results is a matter of considerable difficulty. A careful examination of the results has led to the following conclusions:

(i) M-regions are largely independent of active areas.

(ii) They are weakened in the neighbourhood of active areas (within about 30°) but strengthened outside (from approx. 30° to 90°), particularly on the following side (E).

(iii) The particles which are responsible for the recurrent storms travel from Sun to Earth in an average time of 3 days.

These conclusions are in good agreement with those of Allen (**1**) which were based on his investigations into the effects of large sunspot groups.

Conclusion (i) follows directly from a study of the superposed epoch graphs. The minimum at day $+3$ is bordered by two maxima: a low, broad maximum on the left and a sharper maximum on the right.   When all three features are taken into account, it is by no means certain that the CMP of active areas results in any net increase in the total number of recurrent storms.   In the case of faint flocculi, the minimum seems to be the dominant feature, and this results in a net *decrease* in storm frequency.   With the presence of bright flocculi the maxima become more important and there is an overall increase in the number of storms.   This leads to the appearance of the 27-day wave, referred to in Section 3.   Even then, the storms which produce the maxima are relatively few, and it is clear that the M-regions in general are not related to regions of activity.

The presence of the highly significant minimum in the superposed epoch graphs is a definite indication that M-regions tend to avoid close proximity to active areas.   This minimum *can only be explained in terms of a region of avoidance*, and it seems highly probable (see below) that this region is centred on the active area.   The maxima on both sides of the minimum suggest a strengthening of

M-regions farther away from the active area. These considerations form the basis for conclusion (ii). An assumption involved is that all recurrent storms are caused by one mechanism, operating in the M-regions. This is the most attractive hypothesis because of its simplicity, but an alternative possibility will be considered later. It cannot be denied that the $+3d$ minimum might be associated with active regions of one type while the maxima could be caused by regions of another type. In the absence of definite evidence, however, it was decided to adopt the simpler hypothesis, that all active regions are essentially alike in their geomagnetic properties.

That the particles take 3 days to reach the Earth (conclusion iii) is indicated by the position of the minimum. The travel time is deduced on the assumption that the particle emission tends to be normal to the solar surface, or at any rate symmetrical with respect to the meridian through the active area. The 3 day lag corresponds to a linear velocity of 600 km/sec. It is interesting to note that although recurrent storms and sporadic storms differ in origin, the particle velocities appear to be similar in both cases.

10. *The interpretation of the maxima.*—It can be firmly concluded that the above explanation of the $+3d$ minimum is substantially correct. The maxima, on the other hand, offer much wider scope for speculation. It has already been implied that the maxima are caused by M-regions situated at some distance from the areas of activity. The only alternative is to attribute the maxima to corpuscular streams issuing from the active areas themselves, or at least coming from the direction of such areas. This would imply that the storms which cause the maxima belong to a separate class, distinct from the recurrent storms in general and fundamentally different in origin. On this hypothesis the second maximum is easily explained by assuming that the particles ejected from active areas take 5–10 days to reach the Earth. The real difficulty arises when we come to consider the first maximum, on and before the day of CMP. This early maximum is undoubtedly the most peculiar feature to emerge from the statistics of recurrent storms. It was first noticed by Allen (1) and it seemed at the time to be even more prominent than the second maximum. The present results indicate, however, that this is not the case, and that the first maximum is generally the less pronounced. It is surprisingly wide; the increase in storm frequency has apparently begun several days before CMP of the active regions. In order to explain this as a result of particle streams directed from the active regions we should have to postulate emission at angles of up to 90° to the vertical. Since there is no corresponding increase in the frequency of sporadic storms, the emission must be fairly continuous for a minimum of 3 months. A general isotropic emission is out of the question, for the individual storms would then tend to last for a fortnight. It is possible to construct a model that will meet all the various requirements, but the result is not very plausible from the physical point of view. In the model, the emission takes the shape of a thin fan containing the vertical through the active area. This fan must be tilted slightly with respect to the parallel of latitude in the same sense as the axis of a sunspot group. The tilt could be dispensed with by proposing a certain velocity distribution within the fan. This model can be used to explain why the first maximum should be particularly prominent when there is a large difference in heliographic latitude between the Earth and the region. It is not intended to suggest, however, that such a fan actually exists, and the idea is only mentioned here for the sake of completeness.

The general conclusion is that the first maximum cannot be satisfactorily explained by postulating streams from active regions. It might be argued that this postulate should be retained for the sole purpose of explaining why the second maximum is stronger than the first. Since the main peak of the second maximum is at +6d when sporadic storms are still frequent, the idea is not unattractive, but the question is not so important because it has no bearing on the problem of recurrent storms in general.

11. *Mustel's hypothesis.*—These conclusions are directly opposed to those reached by Mustel and his associates (15) who maintain that the recurrent storms are produced principally by radial streams of corpuscles from calcium flocculi. In their view (13), the passage of practically every flocculus across the visible centre of the solar disk is accompanied by a geomagnetic disturbance, commencing 5 days after CMP, on the average. This hypothesis is open to criticism on the following grounds:

(i) The importance of central flocculi is overrated.

(ii) The hypothesis fails to account for the majority of recurrent storms.

(iii) It offers no satisfactory explanation of the +3d minimum, nor of the wide maximum which precedes it. This is by far the most serious objection.
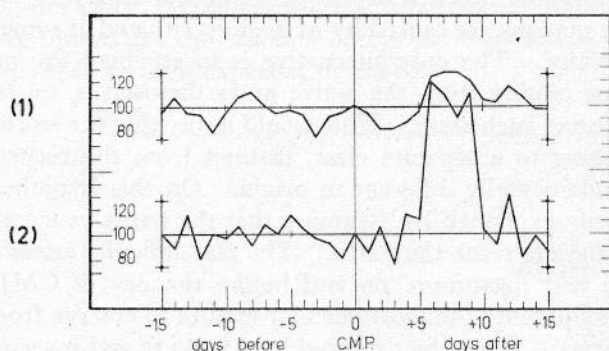

Fig. 12.—*The upper graph (1) gives the number of recurrent storms before and after CMP of central zone flocculi in 1951–1954 (cf. legend to Fig. 3). The lower graph (2) relates to the same number of storms and flocculi, but they have been artificially rearranged so that every storm falls either 6, 7, 8 or 9 days after CMP of a flocculus.*

Let us consider the arguments in turn. It has already been shown (Section 4) that the central flocculi do not have a particularly close association with M-storms.

The second point concerns the actual size of the +6d maximum. If every recurrent storm were caused by a flocculus we should expect the maximum to be very prominent indeed, which is quite contrary to observation. It can be shown by statistical methods that the entire maximum, from day +6 onwards, probably accounts for less than 10 per cent of the recurrent storms in the periods of declining solar activity. Careful estimates give values ranging from 4 per cent to 8 per cent. Fig. 12(1) illustrates the distribution of M-storms relative to CMP of central flocculi 1951–54. This particular period has been chosen because it shows the maximum extremely well. Fig. 12(2) shows an artificial superposed epoch graph, prepared on the assumption that every recurrent storm occurred 6–9 days after CMP of a flocculus. The observed maximum is small by comparison with the "hypothetical" one.

We now come to the third and most important objection. In Mustel's hypothesis the + 3d minimum is dismissed as a statistical curiosity resulting from a tendency of flocculi to appear in certain stable longitudes $\gtrsim 100°$ apart (14). It is implied that the use of the superposed epoch method results in confusing the effect of one flocculus with the effect of another in certain cases. In this way, the maximum on day + 6 could be "reflected" to form another maximum near the day of CMP with a minimum appearing between the two maxima.

The proposed explanation breaks down because the flocculi do not conform to the peculiar distribution required. This is shown by Fig. 13 which gives a measure of the association of flocculi at various times. There is no trace of a maximum between 100° and 180° (8–13 days). In Mustel's results, the sporadic storms were not segregated from the recurrent storms, and this may have been the reason why the significance of the minimum was overlooked.
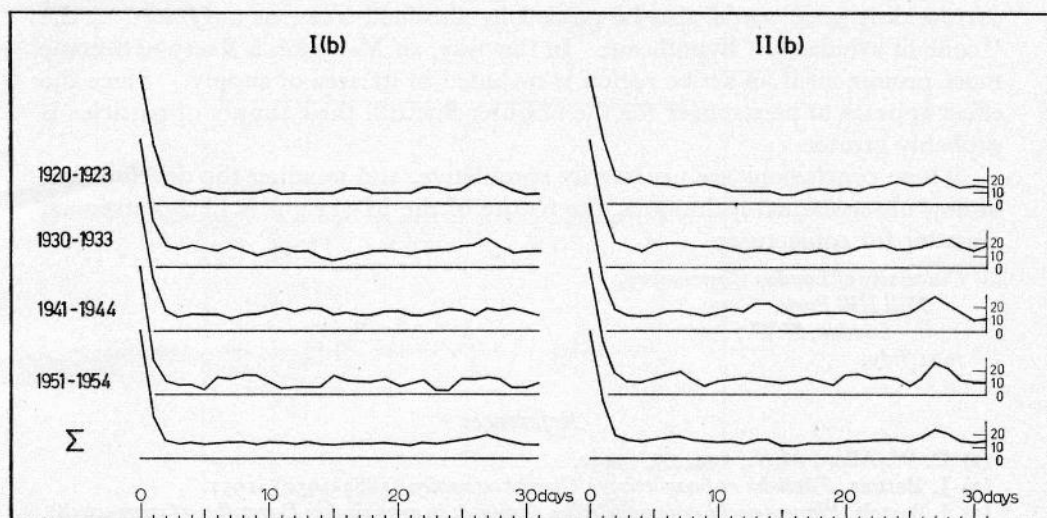

Fig. 13.—*The figure shows the probability that the CMP of a given bright flocculus be followed by the CMP of another bright flocculus up to 31 days later, in different periods of declining solar activity. The secondary peak at 27 days is caused by flocculi which, returning to the meridian after one rotation, are still classified as "bright". (The inclusion of fainter flocculi would have caused a considerable enhancement of the secondary peak, without having any other effects.)*

12. *The "cone of avoidance" hypothesis: concluding remarks.*—A hypothesis relevant to the present study is that of Pecker and Roberts (19). They approached the problem by assuming a *general* corpuscular emission from the Sun, along the lines proposed by Allen (1). They suggested that a "cone of avoidance" is created above an active region, deflecting particle streams from the vertical, thus causing an increase in stream density at the boundary of the cone. An M-region was to be identified with the hard edge of such a cone. This identification implies that recurrent storms in general should be directly associated with active regions—a view which is not supported by the statistical evidence. On the contrary, the M-regions seem to be essentially independent of active regions. The "cone of avoidance" hypothesis may nevertheless be used to elucidate the effects produced by regions of activity.

Most of the observations may be readily understood if the M-regions represent channels of escape for particles coming from wide areas of the solar surface.   The factors determining the location and stability of such channels are at present unknown, but their existence almost certainly requires a coherent radial magnetic field.   This means that the field configuration above an active area would be distinctly unfavourable to the formation of an M-region.   The appearance of new centres of activity might similarly endanger the stability of existing M-regions. It is not surprising, therefore, that M-regions should appear to avoid the immediate vicinity of active areas.   The strengthening of M-regions farther away from these areas can also be explained without difficulty.   Active areas probably provide a generous supply of particles, and the direct outward escape of these particles may well be hindered by the strong magnetic fields.   Diffusing outwards along the diverging field lines, the particles may contribute to the emission in M-regions some distance away.   At the same time, general particle emission from the surrounding area would also be guided by the field lines, as suggested in the "cone of avoidance" hypothesis.   In this way, an M-region is likely to become more prominent if an active region is included in its area of supply.   Since the effect appears to be stronger for the brighter flocculi, their supply of particles is probably greater.

These conclusions are necessarily speculative, and pending the development of new observational techniques, the nature of the M-regions is likely to remain a matter for conjecture.

University of London Observatory,
    Mill Hill Park,
        *London, N.W.*7:
    1961 *July.*

References

(1) C. W. Allen, *M.N.*, **104**, 13, 1944.
(2) J. Bartels, *Tägliche erdmagnetische Charakterzahlen* (1884-1950), 1951.
(3) J. Bartels, *Planetarische erdmagnetische Aktivität in graphischer Darstellung* (1937–1958), 1958.
(4) Barbara Bell, *Smithsonian Contr. Ap.*, Vol. **5**, No. 7, 1961.
(5) B. Bell and H. Glazer, *Smithsonian Contr. Ap.*, Vol. **2**, No. 5, 1957.
(6) B. N. Bhargava and A. N. Naqvi, *Nature*, **173**, 498, 1954.
(7) Helen W. Dodson and E. Ruth Hedeman, *J. Geophys. Res.*, **63**, 77, 1958.
(8) K. O. Kiepenheuer, *Ap. J.*, **105**, 408, 1947.
(9) K. O. Kiepenheuer, *The Sun* (ed. Kuiper), p. 322, 1953.
(10) E. W. Maunder, *M.N.*, **65**, 2, 1904.
(11) O. N. Mitropolskaya, *Astr. Zhurnal*, **36**, 224, 1959.
(12) E. R. Mustel and O. N. Mitropolskaya, *Isv. Crim. Ast. Obs.*, **18**, 162, 1958.
(13) E. R. Mustel and O. N. Mitropolskaya, *The Observatory*, **79**, 15, 1959.
(14) E. R. Mustel, *Astr. Zhurnal*, **36**, 215, 1959.
(15) E. R. Mustel, *Astr. Zhurnal*, **38**, 28, 1961.
(16) H. W. Newton, *M.N.*, **103**, 244, 1943.
(17) H. W. Newton and W. Jackson, *Septième Rapport de la Commission pour l'Étude des Relations entre les Phénomènes Solaires et Terrestres*, 107, 1951.
(18) Obs. de Paris, Meudon, *Cartes Synoptiques de la Chromosphère Solaire*, 1928–1958.
(19) J.-C. Pecker and W. O. Roberts, *J. Geophys. Res.*, **60**, 33, 1955.
(20) Royal Greenwich Obs., *Sunspot and Geomagnetic-storm data* (1874–1954), 1955.
(21) P. Simon, *Ann. Géophys.*, **12**, 167, 1956.
(22) M. Waldmeier, *Z. f. Ap.*, **27**, 42, 1950.
(23) M. Waldmeier, *Vistas in Astronomy*, Vol. **2**, 808, 1956.