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The Relative Positions of Sunspots and Flares

John G. Wolbach[1]

It is well known that solar flares occur near sunspots, usually within the area of the surrounding calcium plage. There is very little detailed information, however, on the relative location of sunspot and flare elements within an active region. This paper presents a study of 11 actively flaring sunspots and the positional relation between flare and spot elements. Nine of the sunspots occurred in 1950, two in 1955.

Current attention to flares associated with polar cap absorption (PCA) and ground-level cosmic-ray events lends particular interest to this question of flare-spot positional relationships. Dodson and Hedeman (1960) noted a conspicuous difference in the location of two importance-3 flares occurring on 16 July 1959, one with and one without intense type-IV radio emission and a PCA. Ellison, McKenna, and Reid (1961) have presented evidence that cosmic-ray flares characteristically cross and obscure one or more spot umbras of high magnetic-field strength, but little information is available about the extent to which non-cosmic-ray flares may also obscure spot umbras. From the present data an estimate is made of the frequency with which a flare may be expected to cover a spot umbra.

Observational data

Daily maps of the solar disc, 40 cm in diameter, from drawings made routinely at the 150-foot tower telescope of the Mount Wilson Observatory, provided the data on sunspots and calcium plages. The flare observations in the form of 35-mm time-lapse photographs of the solar disc in the light of Hα for 1950 came from the High Altitude Observatory and for 1955 from the Sacramento Peak Observatory. I combined the data by projecting the Hα film onto the corresponding Mount Wilson map and drawing the flares on the map. Using additional sunspots and the sun's limb, I was able to superimpose the projected image with sufficient accuracy to show the relative positions of the flares with errors small relative to the dimensions of the sunspots.

The elevation of a flare above the surface of the sun introduces into the determination of its position an error that increases with distance from the center of the solar disc. To investigate this error, working both from maps of some of the spots presented here and from maps of additional spots near the limb, I traced on a single diagram as many spot-flare maps as possible. The flares showed foreshortening, and up to about 75° from the sun's central meridian (CM) there was no obvious concentration of flares on the limbward side of the spots. For spots at 80° from the CM, the flares extended to the limb and beyond and did appear to concentrate on the limbward side of the spot. Foreshortening did not appear to increase beyond 80°, probably because at this distance the apparent areas arise in part from the vertical extent of the flare.

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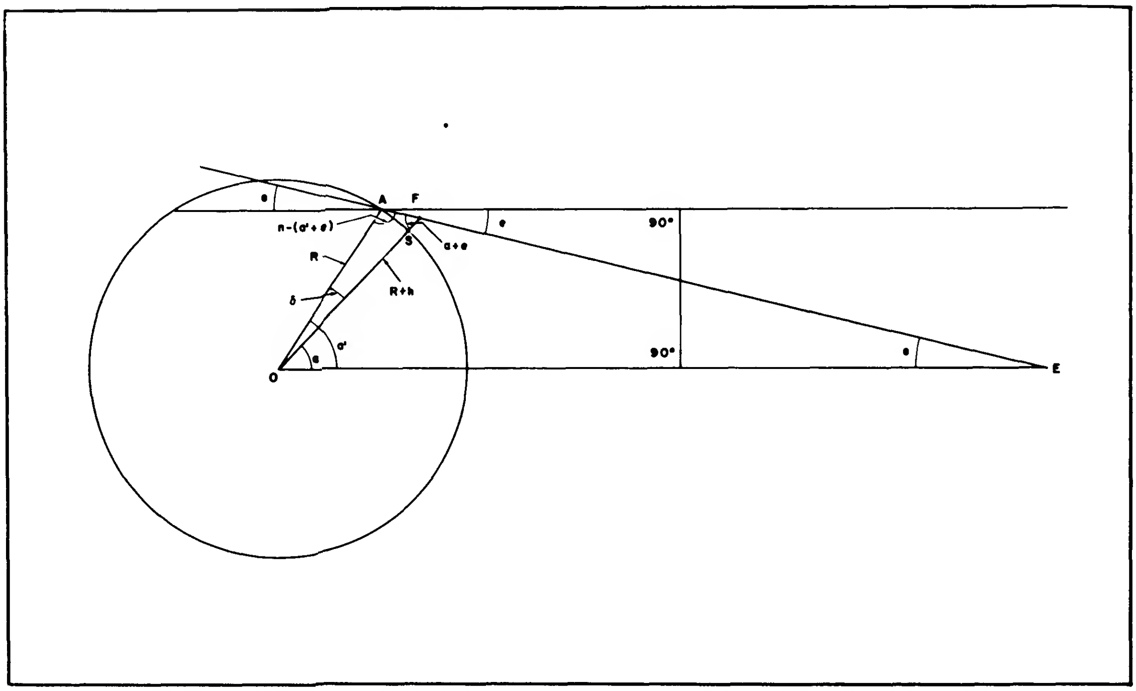

FIGURE 1.—The apparent displacement of a flare owing to its height above the solar surface: a=angular distance of flare F and spot S from center of disc. The sightline EF from the earth cuts disc at A so that the flare appears to be at an angular distance a' from the sun's center. The angle e is formed by the sightlines EF and EO to the center of the sun's disc.

From the quantities diagrammed in figure 1, the height $h=SF$ and apparent displacement $\delta=(a'-a)$ are related by the expression

$$\frac{h}{R}=\frac{\sin (a'-e)-\sin (a+e)}{\sin (a+e)}. \quad (1)$$

For practical purposes the angle e may be neglected; and for small δ, equation (1) may be written as

$$\frac{h}{R}\approx -\frac{\delta^2}{2}+\delta \cot a. \quad (2)$$

We have noted that the displacement of flares toward the limb becomes apparent at about 80°. From this fact, employing $a'=90°$ and $a=80°$, we obtain a flare height of 10,000 km. This procedure, of course, gives only an order of magnitude.

J. W. Warwick (1955) found the most frequent height of flares to be less than 10,000 km and obtained a smooth distribution of flare heights up to 70,000 km. His values were determined statistically from measurements of flare area at different distances from the sun's center. C. S. Warwick (1955) found similar heights from a study of limb flares. J. W. Warwick also determined that the sides of the flare contribute to the area, thus explaining the lack of foreshortening of the flare area very near the limb.

A few flares that had a noticeable appearance of extreme vertical extension were omitted from the analysis. All those discussed here were within 63° of the CM. Statistical results presented below indicate that flaring occurred preferentially in the following component of sunspot groups, whether this component was toward or away from the CM. Since about an equal number of flares occurred east and west of the CM, no systematic errors should be introduced into the statistics by flare heights, although sometimes the height may have caused considerable error.

Figures 2 through 12 show schematically the composite spot-flare and magnetic diagrams for each of 11 spot groups. In each case, all the observed activity of a given spot group has been projected to the center of the disc. I made both sections of the diagrams for a given spot group by superposing each day's observations of the main umbras on the center of the disc. Other features—penumbras, flares, and lesser umbras—for each day were oriented on the composite diagram about the position of the principal umbra. The appropriate Stonyhurst disc was used to estimate the foreshortening and the relative positions of these features at the center of the disc. Any area that was occupied by an umbra on one or more days is shown on the composite map by dense dots. If a region was occupied by penumbra on one day and umbra on another day, it is shown as umbra, but if it was occupied by flaring at any time, the flaring is shown in preference to either umbra or penumbra. The composite map thus aims to provide a general picture of the locations of each type of activity during the disc passage of the spot group.

The upper section of the composite diagram, showing the data on magnetic field strengths and polarities (underlined) was made in the same way, with the lesser elements positioned relative to the superposed main elements. The location of a measured field strength is marked by a small circle. To simplify the diagrams, clusters of small circles were enclosed by a line, with only the average field strength of the elements given. Southern polarities are distinguished by underlining. Figures 2 and 3 do not have adequate magnetic diagrams because of insufficient data.

Table 1 summarizes information on the 11 sunspots.

Discussion of observations

Before figures 2 through 12 are discussed, it would be useful to review the Mount Wilson classification of sunspots according to their magnetic properties (Hale and Nicholson, 1938). This classification recognizes four basic categories of sunspot groups: unipolar (α), bipolar (β), semicomplex ($\beta\gamma$) and complex (γ). Unipolar (α) groups are single spots or clusters of spots having the same magnetic polarity. If the unipolar cluster lies in the preceding or following part of its plage the classification is αp or αf, respectively. (The terms preceding and following are defined with reference to the rotation of the sun, so that the preceding com-

Table 1.—*Summary of data on 11 selected flaring spots*

Figure no.	Mount Wilson no.	CMP date	Latitude	Avg. mag. class	Max. field strength	Avg. area	Max. area	Total flares of importance 1	2	3	Climax and Sacramento Peak flares of importance 1	2	3	Magnetic regions
2	10359	1 June 1950	5 S	$d\beta l$	2000	302	549	21	4	—	4	1	—	$b-b$
3	10324	3 May 1950	14 N	$l\gamma l$	2200	615	1119	14	7	—	5	1	—	$b-c$
4	10434	4 Aug 1950	10 S	$l\beta\gamma l$	3400	770	1126	34	7	—	21	5	—	$b-c$
5	10350	26 May 1950	8 N	$l\beta pl$	3600	924	1115	35	6	—	15	1	—	$c-b$
6	10303	13 April 1950	15 N	$l\gamma l$	4200*	1527	2000	44	8	3	25	2	3	$b-c$
7	10344	22 May 1950	17 S	$l\alpha pd$	3000*	65	116	10	2	—	5	2	—	$b-c$
8	11267	7 July 1955	32 N	$l\beta pl$	2500	193	305	25	1	—	16	—	—	$b-a$
9	11266	5 July 1955	34 S	$l\alpha pl$	2600	222	357	10	1	—	10	—	—	$b-a$
10	10384	25 June 1950	9 N	$d\beta pl$	4200*	373	631	14	2	—	5	2	—	$b-b$
11	10332	12 May 1950	6 N	$l\alpha pl$	3800	511	821	15	7	—	8	3	—	$b-a$
12	10373	15 June 1950	18 S	$l\beta pl$	3600	913	982	16	2	—	7	2	—	$b--a$

*Dr. Seth Nicholson reports that these field strengths are probably too high, perhaps by as much as a factor of 2.

ponent of a spot group is the part first to become visible at the east limb, to cross the CM, etc.) Bipolar groups 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 clusters having opposite polarities. The group is called β if the two clusters are of approximately equal size. If the preceding or following cluster dominates, the classification is βp or βf, respectively. The complex γ groups have polarities so irregularly distributed that they cannot be classed as bipolar; the polarities may be mixed even within a single penumbra. The $\beta\gamma$ groups have bipolar characteristics but lack the β's clearly marked division between regions of opposite polarities; the preceding or following cluster may contain small spots of the "wrong" polarity. The $\beta\gamma$ and γ groups have been shown to produce a disproportionately large percentage of solar flares (Giovanelli, 1939; Bell and Glazer, 1959).

Figures 2 through 6 show the complex sunspots form β to γ, while figures 7 through 12 show those of simpler magnetic configuration. In each case the preceding cluster is projected to the center of the disc. Although αp and some βp groups have only small spots to define the position of the following component during the transit, this region is well defined by flare activity. For β and $\beta\gamma$ groups the following region is well occupied by substantial spots.

When, as in figures 2 and 3, the spotted and flaring regions intermingle, it is because of the drifting of spots within these groups. The spot and flare regions tend to be well separated when there is less activity and drifting of the spots. In the figures both simple and complex groups are presented in order of increasing size to emphasize the more defined separation of the spot and the flare regions as the size of the complex spot groups increases. While this trend is not statistically significant because of the small number of spots, it seems worth noting in view of the spot-flare relationships associated with cosmic-ray flares (discussed in the concluding section).

Examination of figures 2 through 12 shows that nearly all sunspot and flare activity during the transit occurred in an area only one-fourth to one-half as great as the total areas occupied by the calcium plage on one or another day. Occasionally a large flare may extend to the limits of the plage, leaving the flaring region asymmetrical. The composite plage with its peninsular variations is more extended in longitude than in latitude and is roughly symmetrical about an east-west axis that extends through the preceding and following component clusters of the spot group. In a β or γ group the spotted area is similarly extended in longitude.

The flaring area is external to the spots and often appears to curl about them symmetrically. Apparent penetration of the spot clusters by flares can be seen when flaring on one day occupied space in the region that on another day was occupied by sunspots. Less often a flare apparently covered a sunspot.

In αp spot groups the position of the following cluster, often marked by small transient spots of opposite polarity, seems a favored location for flaring. Other flares, appearing as curved filaments, surround the main spot cluster or even partially invade it. In bipolar and complex groups the flares tend to surround the spot clusters.

Magnetic regions

Examination of the composite magnetic diagrams reveals further spot-flare relationships that can be most readily described by a classification of magnetic regions within sunspot groups as follows: *a* regions containing only weak fields, usually of both polarities and including the boundary separating them; *b* regions in which one polarity is represented by strong magnetic fields of a major umbra in either the preceding or the following component, the other polarity being represented at most by weak fields of small transient spots; *c* regions containing strong magnetic fields of both polarities in the same cluster, often within the same penumbra, and usually found only in $\beta\gamma$ and γ spot groups.

A given spot group will contain at least one, and usually two magnetic regions, which can be recognized on the magnetic composite dia-

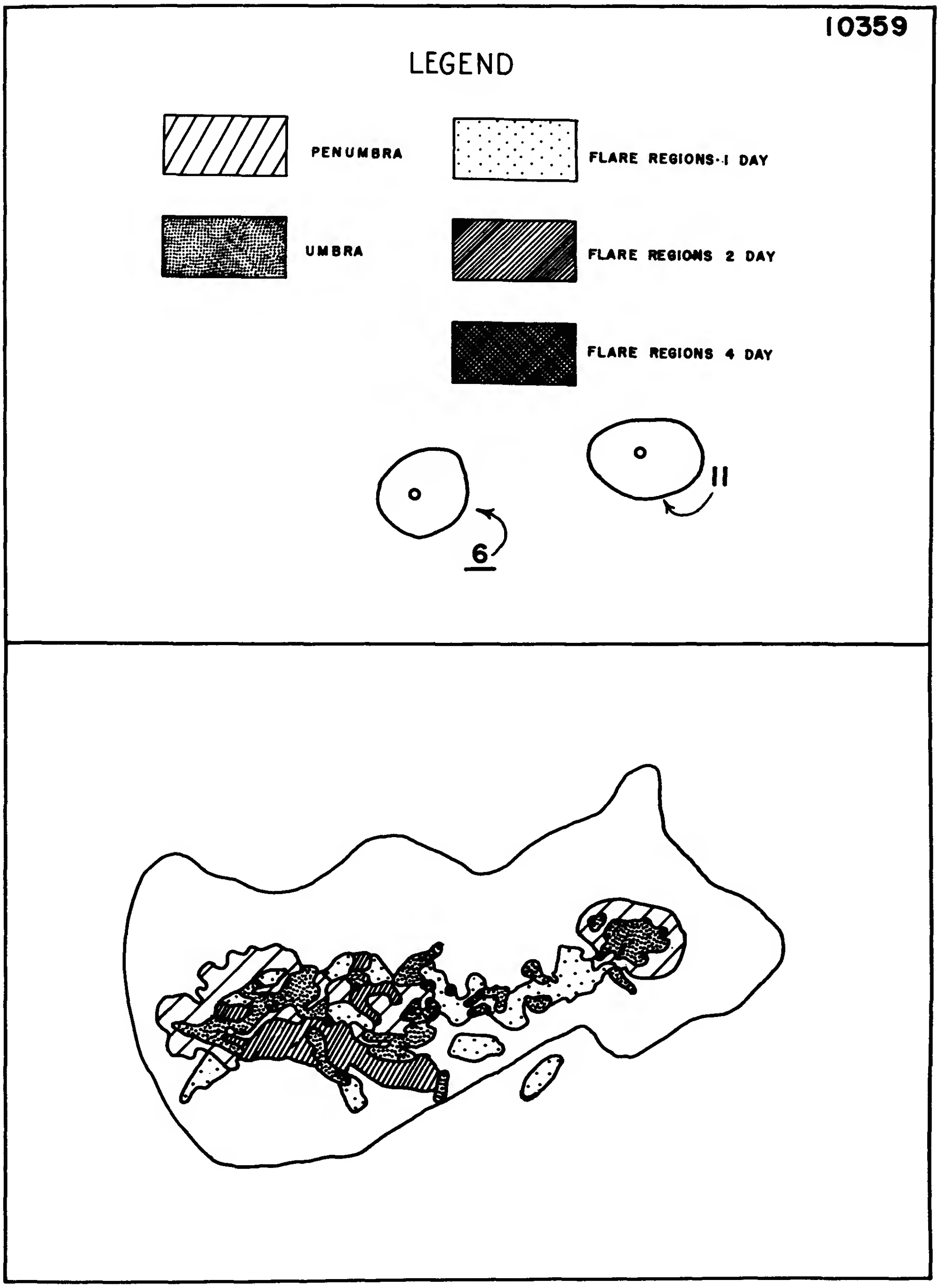

FIGURE 2.—Spot 10359, *dβl*. All flaring originates from *b* regions. Magnetic data are inadequate for analysis. Considerable activity of drifting, merging, and breakup of spot components resulted in intermingling of spot and flare regions, and a scattered appearance of the umbras on this composite diagram. Legend also applies to figures 3–12.

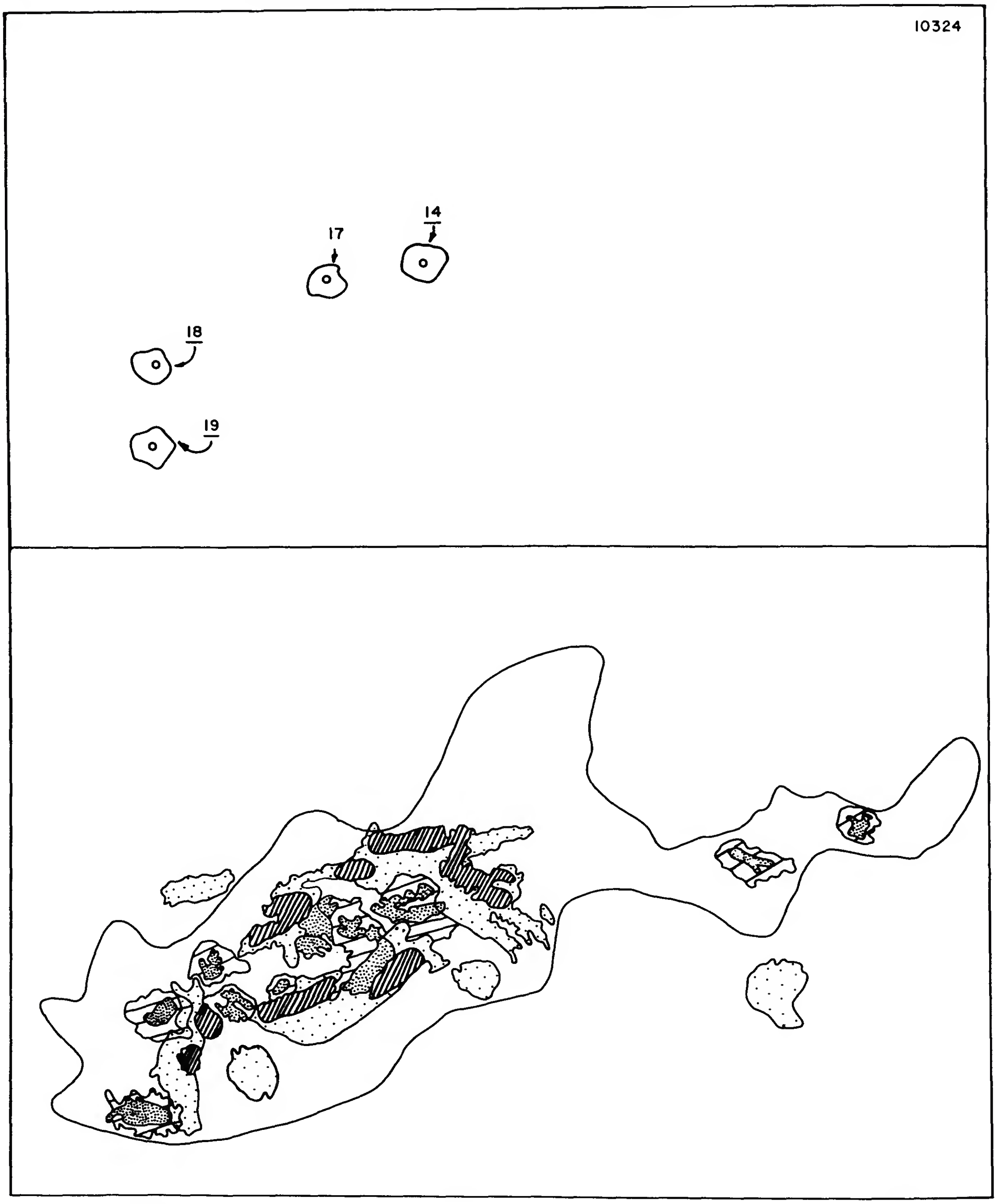

FIGURE 3.—Spot 10324, *l γ l*. Most of the flaring is centered in the *c* region (center of the diagram). The drift, merging, and breakup of spots in this region produces interpenetration of flares as in figure 2. (The small spots to the right are another group.)

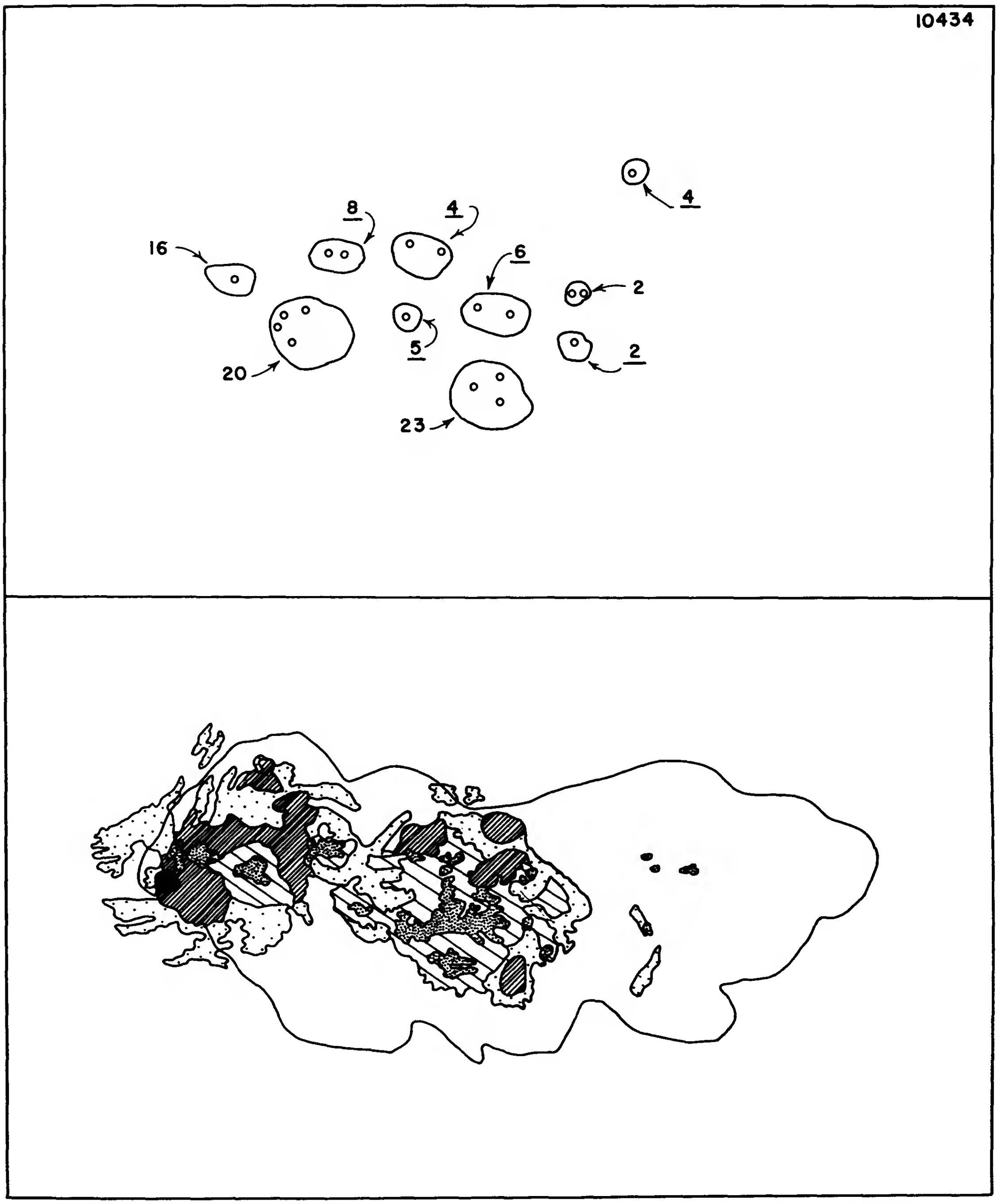

FIGURE 4.—Spot 10434, *l βγ l*. Flaring occurred almost equally in the *b* and *c* regions. The preceding cluster, at first a *b* region, became a *c* region and broke into pieces, separating its northern and southern magnetic polarities. A bridge of sunspots of southern polarity developed from the following to the preceeding cluster, producing an east-west boundary between polarities. Distribution of spots then produced a *b* region, and a *c* region extended from the following component into the northeast of the preceding component.

680448 O—63——2

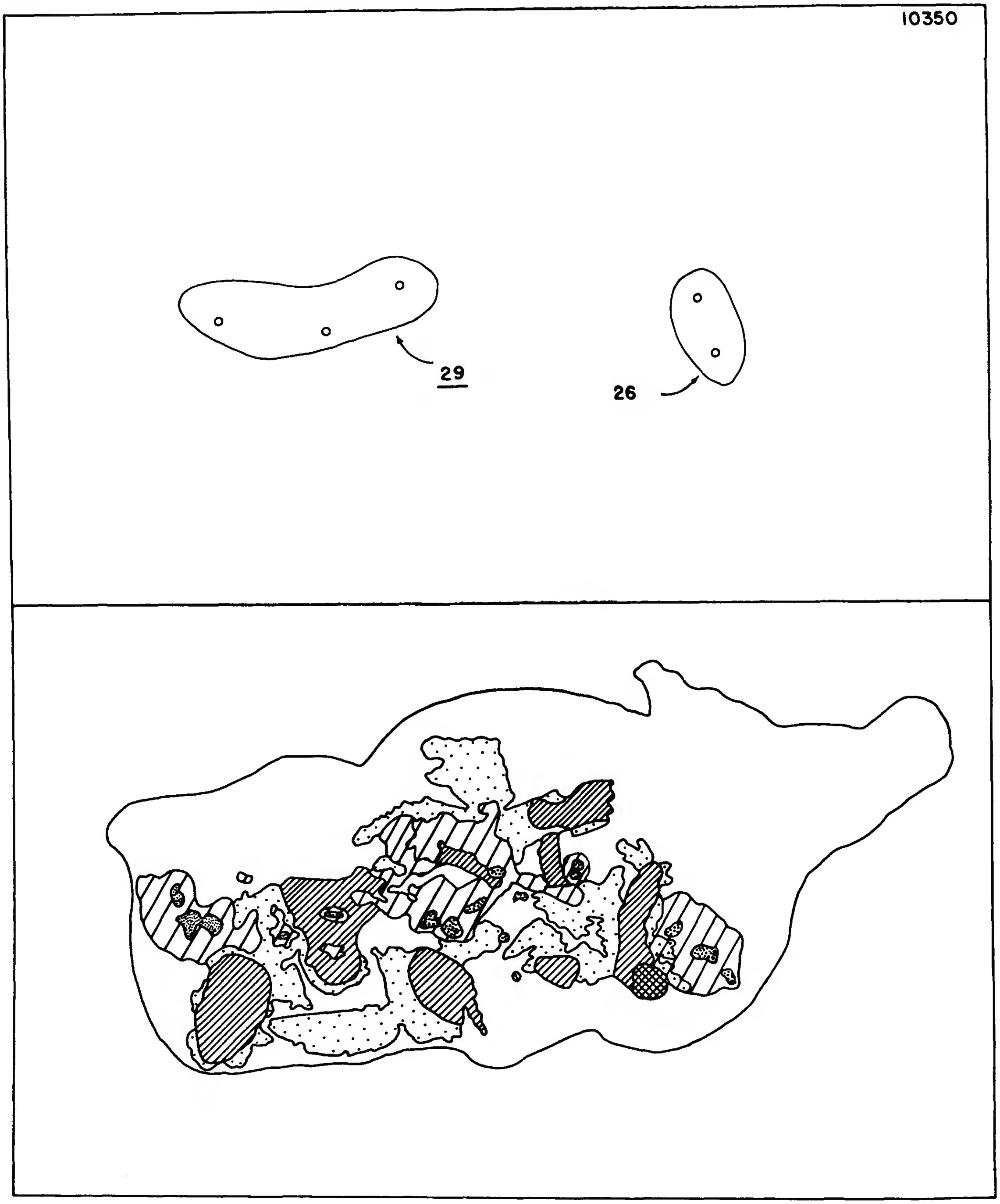

FIGURE 5.—Spot 10350, *lβpl*. For the first three days this spot was $\beta\gamma$, with a *c* and a *b* region, the former responsible for most of the flaring. Spots of northern polarity that extended into the preceding position intermingled with those of southern polarity. Magnetic measures are few. A few spots drifted to the preceding end of the plage as the intruding north polarity died out. The spot then became βp, with the two polarities well separated, and little flaring occurred during the rest of the transit.

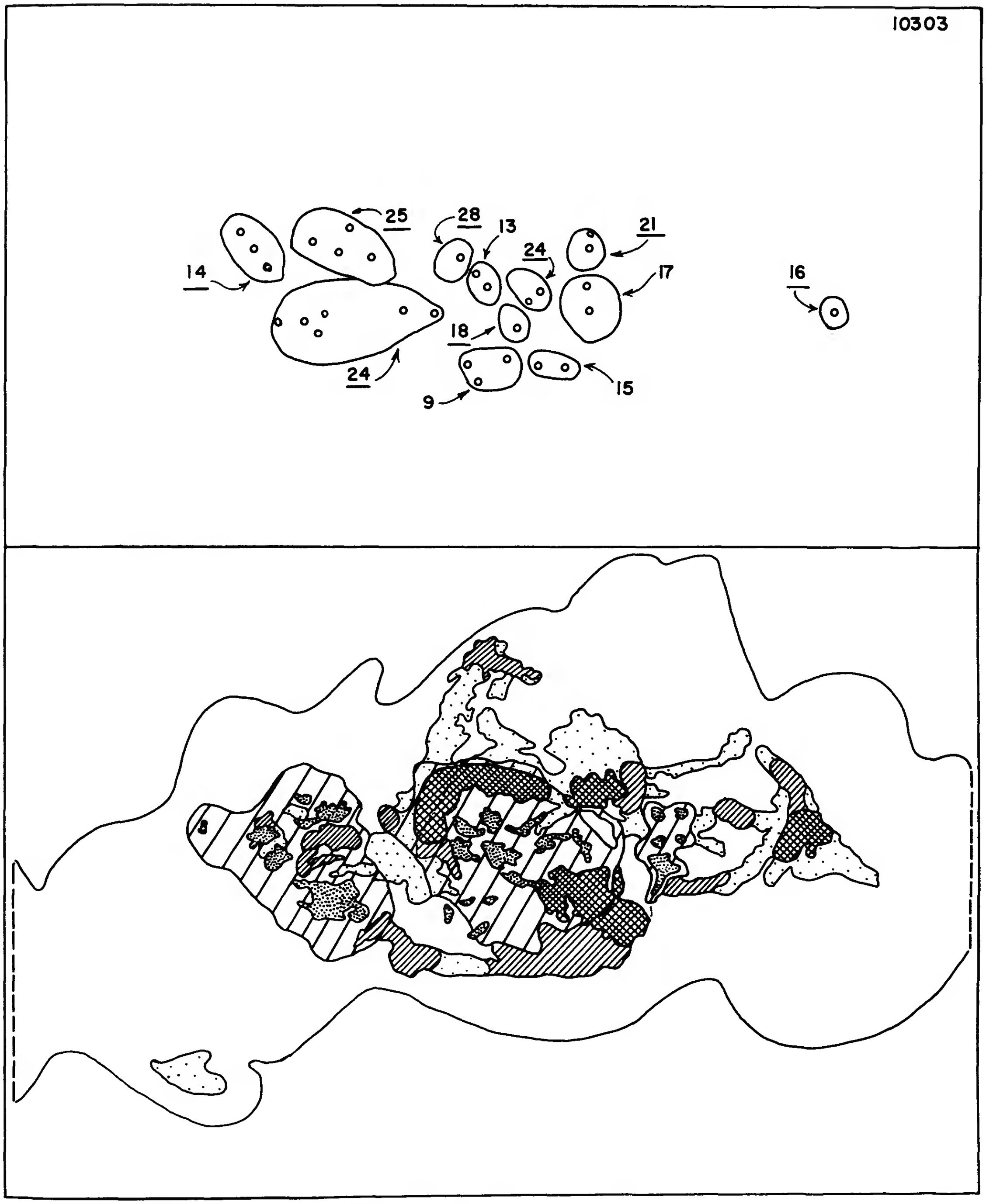

FIGURE 6.—Spot 10303, *lγl*. Most of the flaring surrounds the following component, in the *c* region. The fields of southern polarity were declining in this component toward the end of the transit.

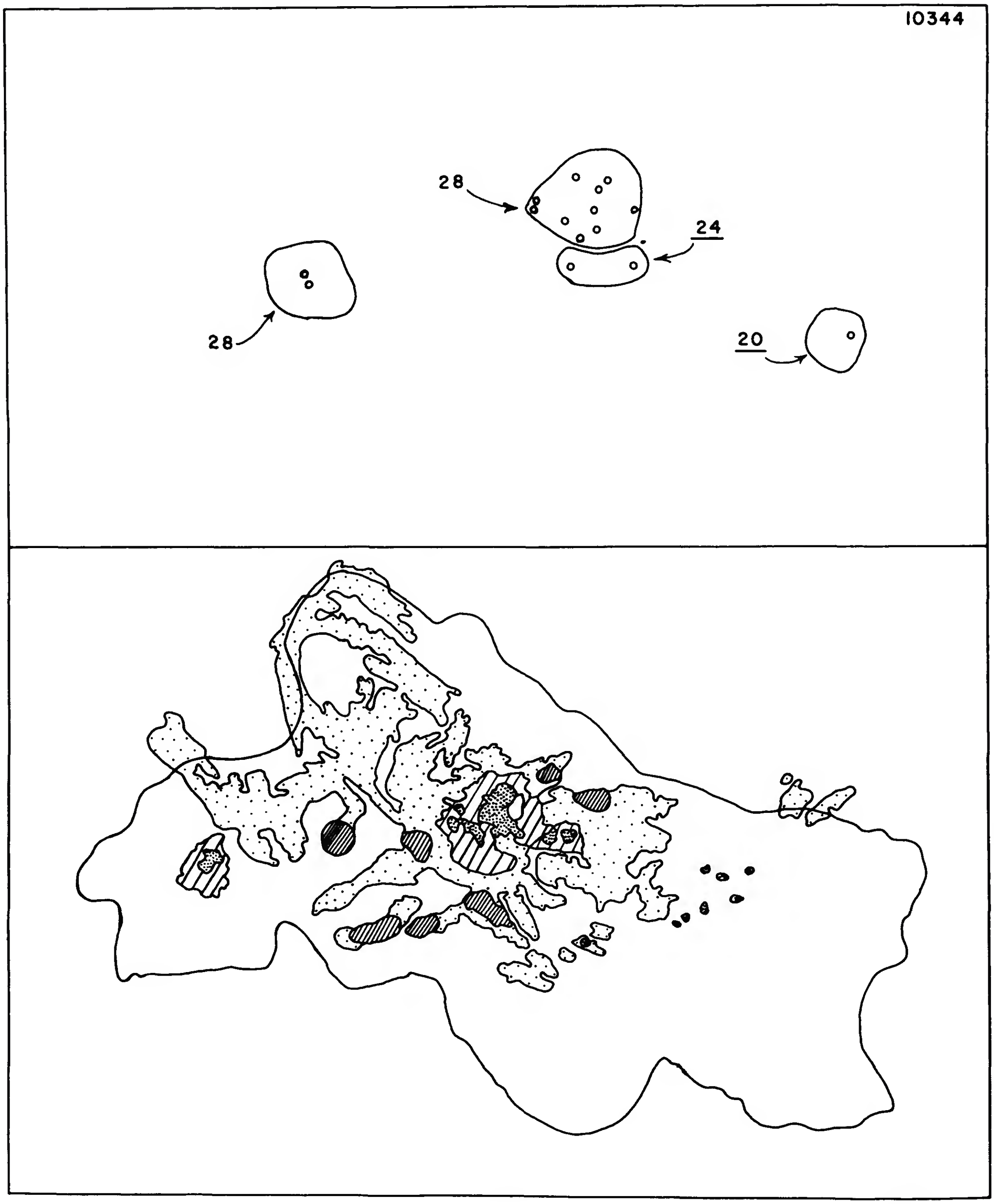

FIGURE 7.—Spot 10344, *l αpd*. For two days the central area is classified as a *c* region because umbras up to 2500 gauss of both polarities existed in the same penumbra (although Mount Wilson called it *βp*). Most of the flaring occurred in the *c* region. The southern polarities disappeared by central meridian passage, and the spot group then became *αp* with a single *b* region and little flaring.

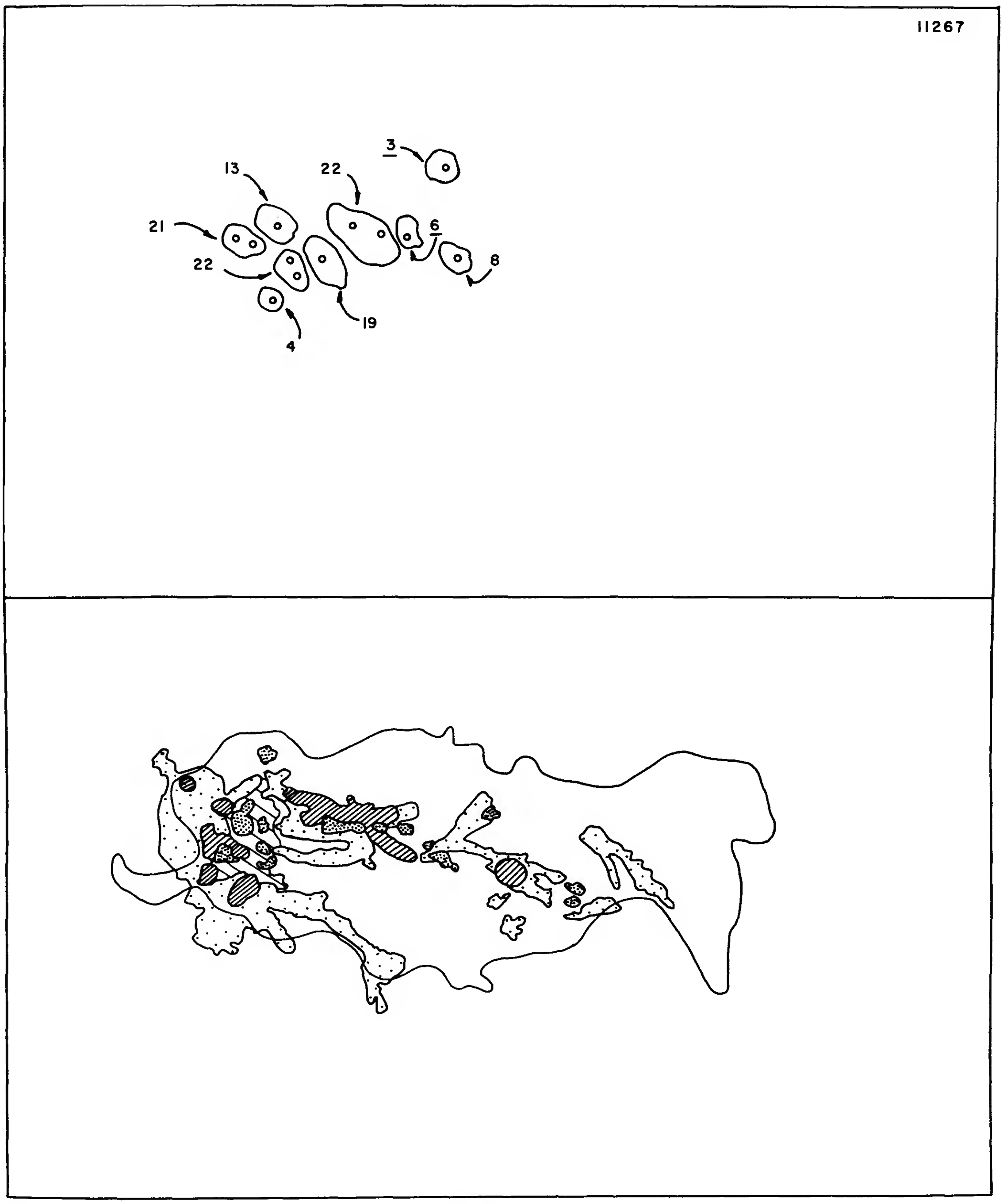

FIGURE 8.—Spot 11267, $l\beta p l$. The larger preceding component grew and spread into a spot stream. The following component, a recurring transient small spot, lay in an *a* region. The majority of the flaring occurred in the *b* region.

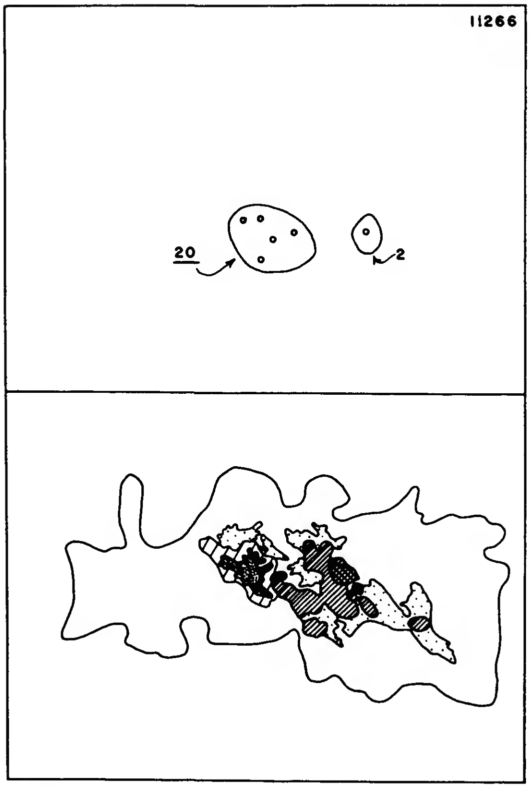

FIGURE 9.—Spot 11266, *l αp l*. The principal flaring occurred in the *a* region. The preceding cluster (*b* region) remained stable during transit. Only small transient spots occurred in the following *a* region.

grams. Table 2 shows the usual relations between these magnetic regions and the Mount Wilson classes of sunspots.

After classifying the magnetic regions by means of the composite diagrams, I re-examined the daily maps and assigned a daily classification to the magnetic regions of each spot group. Some cases had to be omitted because of insufficient magnetic data. In 64 of 70 observing days, my classification was related to the Mount Wilson class as shown in table 2. In the remaining six cases, I assigned a *c* classification to regions in sunspots listed as *βp* by Mount Wilson. According to explanations in the Publications of the Astronomical Society of the Pacific for 1920–1927, when the preceding or following cluster contains a small spot of opposite polarity that plays a transient minor

TABLE 2.—*The usual relation between Mount Wilson sunspot classes and types of magnetic regions in the preceding and following parts of the plage*

Mount Wilson class	Type of magnetic region	
	Preceding	Following
α	*b*	
αp	*b*	*a*
αf	*a*	*b*
βp	*b*	*a*
βp	*b*	*b*
β	*b*	*b*
βf	*b*	*b*
βf	*a*	*b*
βγ, *γ*	*b* or *c**	*b* or *c**

* *βγ* has at least two regions, *γ* at least one region, of which one ore more is a *c*, the other a *b* type region. The position in the plage is not relevant.

part in the cluster the Mount Wilson classification disregards it. However, in the six cases I found a spot of sufficient field strength and closeness to the main umbras such as to demand a *c*-region classification.

For each flare day I determined which magnetic region (of the two in the spot group) had the greater flare area. In most cases the choice was obvious. Table 3 gives the number of

Table 3.—*Number of days on which flaring occurred preferentially in magnetic regions of type* a, b, *and* c; *and the probability* P *that the observed differences are due to chance*

Mount Wilson class	Magnetic regions	No. of days on which flaring favored magnetic regions			*P*
		a	*b*	*c*	
αp	*b–a*	8	1		0. 02
βp	*b–a*	7	4		0. 4
Total	*b–a*	15	5		0. 03
βp	*b–c*		1	3	0. 3
β	*b–c*		1	11	0. 004
	b–c		0	5	0. 024
Total	*b–c*		2	19	0. 0002
All classes			*b*	*a,c*	
			7	34	0. 00003

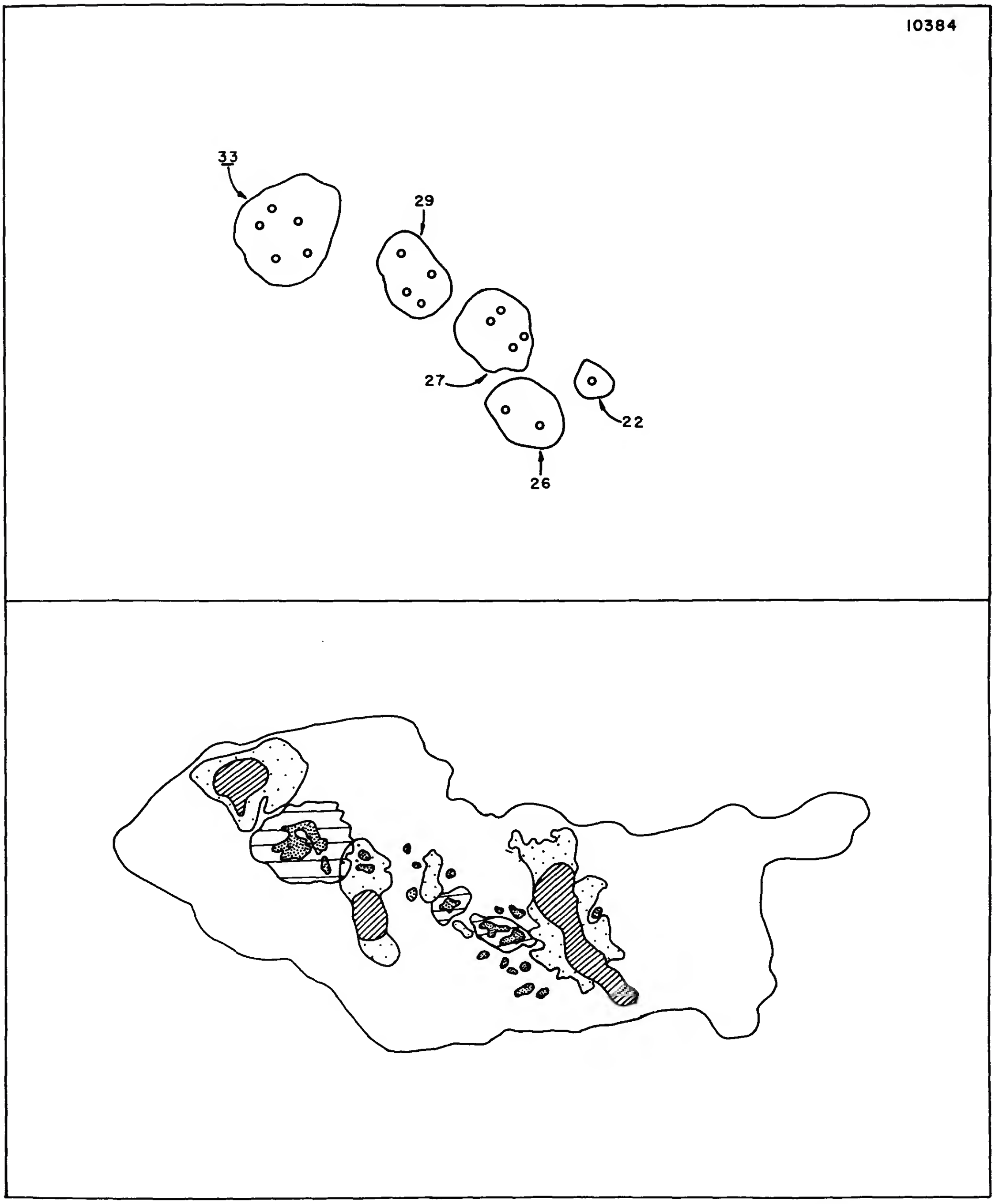

FIGURE 10.—Spot 10384, *dβpl*. Flaring surrounds both spot clusters. The spot grew during transit, and the separation of the components increased.

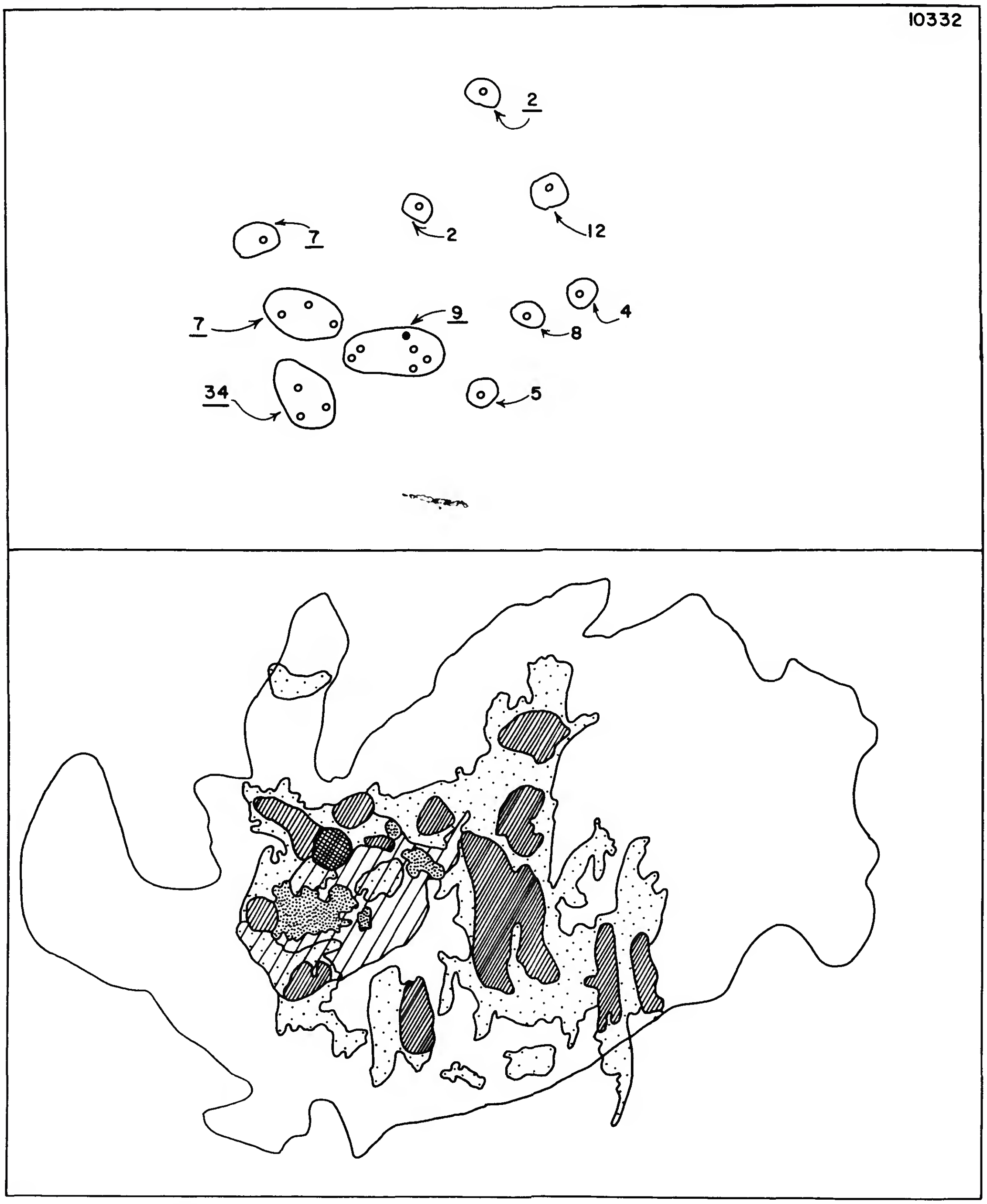

FIGURE 11.—Spot 10332, *l αp l*. The principal flaring occurred in the *a* region, occupied by only transient spots. Some flaring encircles the forward end of the *b* region and covered a small part of the main umbra.

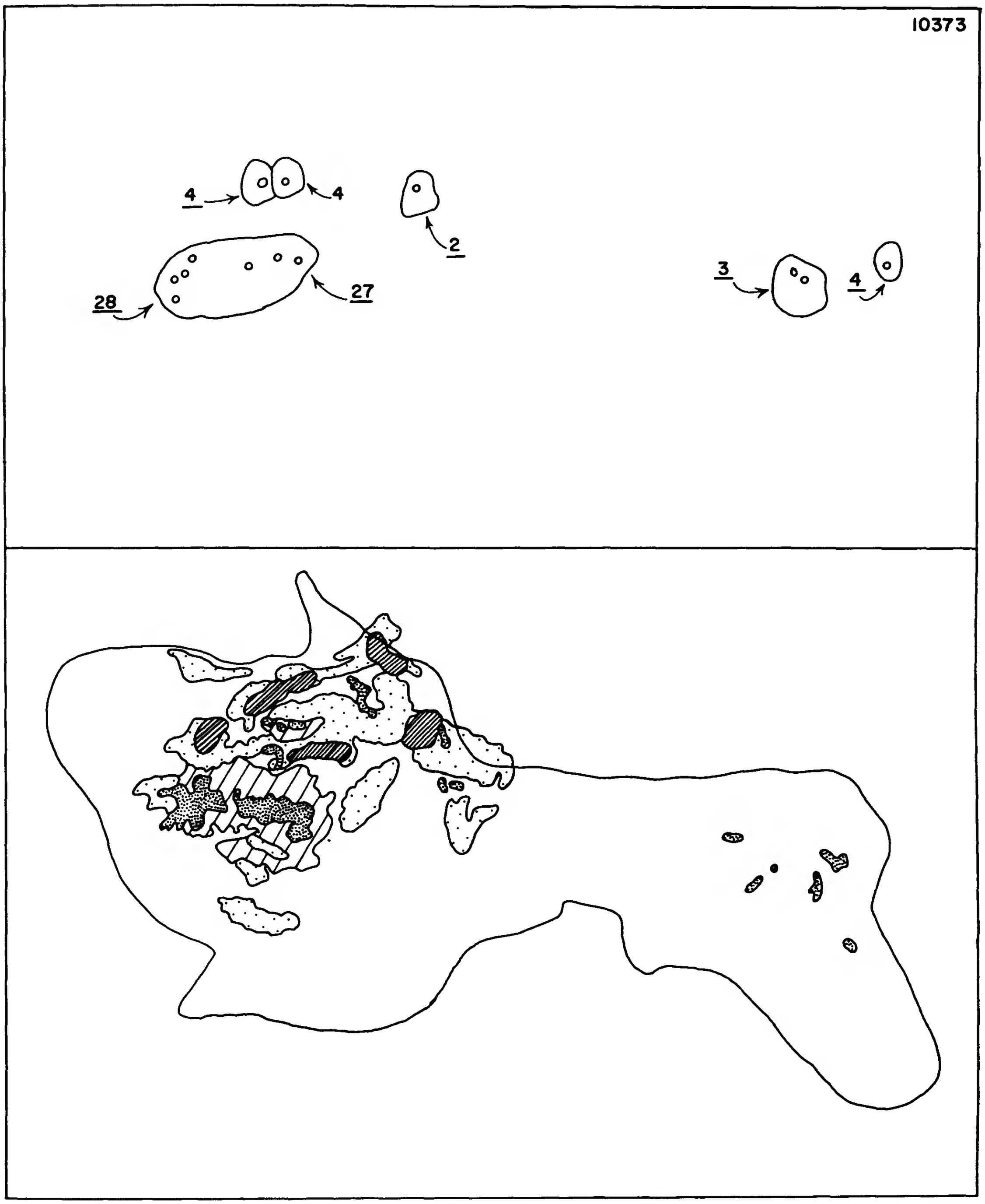

FIGURE 12.—Spot 10373, *l βp l*. Most flaring occurred in the *a* region around the small spots of mixed polarity to the northeast of the major component. The small spots of southern polarity at the following end of the plage have little flaring importance.

days on which each of two types of magnetic region contained a clear preponderance of flare activity. On the assumption that each region had an equal probability of being the more flare-active each day, I computed the probability P that the flare distribution observed between each pair of regions was due to chance. The standard deviation is given by $\sigma=\sqrt{n\,pq}$, where $p=q=0.5$, and n is the total number of flare days; the observed deviation from a uniform distribution is $k-n/2$, where k is the number of days on which the flares favored the more active region. From the ratio of the observed to standard deviation and a table of the normal curve of error I determined the values of P in table 3.

Table 3 shows, even with the small amount of data, that the main area of flaring tends to occur with statistically significant preference in zones of mixed polarities, that is, in *c* and *a* regions. When magnetic regions *b* and *c* were present, the flaring occupied the *c* region with striking preference, tending to surround the spot cluster with the mixed polarities. With the *a* and *b* configuration, when the daily class of the spot group was αp, the flaring tended to prefer the *a* region with borderline significance. With βp spots the difference between *a* and *b* regions is not statistically significant.

Within a *c* or *a* region the boundary separating the polarities of opposite sign appeared a favored location for flaring. However, the boundary between two *b* regions of opposite polarity, as between the components of a β spot group, did not appear to be a favored location for flaring. In β groups the flaring seemed to surround the spot clusters rather than occupy the region between them. Spot components of a single polarity were often surrounded by flares, except when a *c* region was present. In one case (spot no. 10434, fig. 4) when the *b*-type lead cluster was surrounded by bright flares, it became a *c* region on the next day as portions of the disintegrating follower spot drifted into the lead component and became an integral part of it. Probably the preference of flaring for *c* regions is real and may be related to the greater flare productivity of complex spots found by Bell and Glazer (1959).

I attempted to correlate flaring with change or disappearance of magnetic and visual configurations, including the transformation from a *c* to a *b* field. The data were too few for meaningful results.

With additional data I looked for a relation between flare activity and spot activity as manifested by a change in the Mount Wilson magnetic class. From the Greenwich (1954) list of spots with average area greater than 500 millionths of the visible hemisphere, I selected those in the years 1946 through 1957 which, according to the *I.A.U. Quarterly Bulletin of Solar Activity*, produced at least 10 flares. Of these I retained only the 47 that showed one or more major changes in the daily magnetic classification. A major change was one from simple (α or β) to complex ($\beta\gamma$ or γ), or vice versa. I divided the flare days into two main groups: (1) pairs of days between which a change of magnetic class occurred, and (2) the remaining days on which the magnetic classification was steady. I determined the average number of flares per day for α, β, and γ spots when the classification was steady, and the average number of flares per day on the pairs of days bracketing a change from β to γ, and so on. The steady γ classification produced more flares per day than any changing or less complex classification. The greater flare productivity of the γ class was most striking for importance-2 and especially for importance-3 flares. The data provided no evidence that a change in the magnetic class is accompanied by an outburst of flaring.

Frequency of umbra coverage and cosmic-ray flares

Evidence presented by Dodson and Hedeman (1960) and by Ellison, McKenna, and Reid (1961) that cosmic-ray flares may characteristically cover a large spot umbra led me to examine my data in an effort to estimate the frequency of this phenomenon. Is the coverage of a large umbra a rare or a common event?

The cosmic-ray flares discussed by these writers are of importance 3 and 3^+; most of them were followed by a great magnetic storm; and the more recent of them have been found to be associated with a radio noise outburst of exceptional intensity. By contrast, the flares discussed here are mostly of importance 1 and of little or no geomagnetic significance. Only one flare (22 May 1950) was followed within three days by even a small geomagnetic storm.

Table 4 gives data on the frequency with which elements of flares in my sample covered a spot umbra, divided according to the importance of the flare and the area of the umbra.

TABLE 4.—*Number and percentage of flares extending over a sunspot umbra*

Flare importance	No.	No. of flares extending over: Major umbra	Small umbra	Doubtful cases	Percent of flares extending over: Major umbra	Small umbra	Doubtful cases
3	3	1	1	—	33	33	—
2	14	3	1	4	21	7	29
1	120	2	1	4	2	1	3
1, 2, 3	137	6	3	8	4	2	6

Umbras with an area over 20 millionths of a hemisphere were called large; those between 10 and 20 millionths, small. Umbras of less than 10 millionths were ignored. The data indicate that umbra coverage by importance-1 flares is relatively rare, but that it may be fairly common among more important flares. However, flares of importance 2 and 3 are too few to permit definite conclusions.

While umbra coverage by the more important flares may be common, there is a marked difference between the pattern observed in my sample and that described by Ellison *et al.* The cosmic-ray flares appeared as broad, elongated, curved, and sometimes double filaments. In the Ellison paper, tracings of the axes of the flare filaments on Mount Wilson magnetic maps of the sunspots show that the main body of the flares passed directly over one or more major umbras of the spot group. The flare elements were elongated in a direction roughly paralleling the boundary between the north and south polarities.

On the other hand, all the coverings listed in table 4 were accomplished by only a small segment of the flare whose main body lay outside the penumbra of the spot. I found no case in which the main body of the flare lay over a major spot component in the manner of the cosmic-ray flares, an indication that these may be a rather rare configuration.

My observations of spot coverings resembling those described by Ellison *et al.* appeared in the *a* regions, where flares often crossed directly over small (<10 millionths) spots, and lay along the boundaries separating opposite polarities. Larger spot components, whether centers of *b* or *c* regions, were surrounded rather than covered by flares. The flares curved around the spots, occasionally projecting over an umbra. Sometimes an isolated fragment of a flare would lie across a portion of a spot. Since most of the *c* regions were occupied by flares, the associated sunspot of γ or $\beta\gamma$ type was most likely to be thus partially covered. I found five flares that had the form of a double filament, but none passed over the main body of a spot. Only one was followed by as much as a small geomagnetic storm.

Six of the seven cosmic-ray spots had areas similar to those in figures 5 and 6, while the spot of July 1946 had an area in excess of 4000 millionths on the flare day. With the exception of the November 1949 spot, which was βf, all the cosmic-ray spots have been γ or $\beta\gamma$. It is noteworthy that most of the cosmic-ray spots maintained their magnetic type unchanged during their disc passage, in contrast to the variability of the 11 spots studied here. A study of flare positions in steady spots is needed to determine whether such spots are also likely to be encircled rather than invaded by importance-2 and importance-3 flares. Also the cosmic-ray flares were all importance-3^+, in contrast to the lesser importance of those with the glancing coverage here described.

In conclusion, it would appear that the umbra coverage seen in cosmic-ray flares may represent a striking singularity of solar activity. Although chosen for flare activity, the spots investigated here presumably give a more representative picture of spot-flare relationships.

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Abstract

This paper describes a study of 11 flaring sunspots, for which on flare days the relative positions of flares and sunspots have been determined from data provided by the Climax and the Mount Wilson Observatories. For each spot group all data, including the magnetic polarities and field strengths, were projected to the center of the sun's disc and combined.

The maps show that flaring tends to prefer regions containing both polarities rather than unipolar areas within a spot group. The favored zone may be a spot cluster containing both polarities, as within $\beta\gamma$ and γ groups, or a region occupied by transient spots of both polarities, as in the following component of some βp and αp groups. Statistical analysis shows that flares preferred these regions more often than would be expected by chance.

A supplementary investigation including additional sunspots revealed no correlation between frequency of flaring and internal spot activity such as the breakup or merging or small components.

A count of spot umbras covered by flares was made. About 10 percent of the flares show clear or possible coverage of some part of a spot umbra. The flares observed here covered the spots only partially or along the edges, a positional relation markedly different from that found by Ellison *et al.* for cosmic-ray flares where the main body of the flare passed directly over the sunspot.

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