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THE DEPENDENCE OF LARGE FLARE OCCURRENCE ON THE MAGNETIC STRUCTURE OF SUNSPOTS

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ABSTRACT

We have studied 8 yr of active region observations from the United States Air Force/Mount Wilson data set, supplied by the NOAA World Data Center, to confirm the relation between δ spots and large flares. We found that after correcting some errors we were able to describe relationships among active region size, peak flare soft X-ray (SXR) flux (measured by *GOES* 1–8 Å flux), and magnetic classification. We found the Solar Optical Observing Network magnetic classification to be reasonably accurate but its area measures to be inaccurate for many of the regions. This is due partly to transcription errors and partly to wrong correction for limb foreshortening. Errors could, however, be repaired by intercomparison of multiple observations. We confirm Künzel's original idea that regions classified $\beta\gamma\delta$ produce many more large flares than other regions of comparable size. Almost all substantial flares occurred in regions classified $\beta\gamma\delta$ by the Air Force sites. Each region larger than 1000 μh and classified $\beta\gamma\delta$ had nearly 40% probability of producing flares classified X1 or greater. Yet only a half-dozen of those, showing the "island delta" configuration, produced great activity. There is a general trend for large regions to produce large flares, but it is less significant than the dependence on magnetic class.

Subject headings: Sun: activity — Sun: flares — Sun: magnetic fields

1. INTRODUCTION

Künzel (1960) pointed out the first clear connection between flare productivity and magnetic structure. He introduced a new magnetic classification, δ, to supplement Hale's α, β, and γ classes. The δ region included a penumbra enclosing umbrae of both positive and negative polarity. Although Künzel's statistical evidence was weak, time has proven his conclusions correct, and the δ configuration became the critical ingredient to the solar flare problem, widely used by forecasters. Before Künzel's work was widely known, Bell & Glazer (1959) compared flare productivity for different magnetic classes with spot group areas. While there was a good linear correlation for simple spots, they showed that there was a significant intercept above zero for the frequency of flares in complex spots. Mayfield & Lawrence (1985) found good correlation between the total number of flares in 531 regions and the computed magnetic energy. This is comparable to an area versus flare number comparison. More significant for our study, they found the "flare efficiency" for δ spots to be twice as great as for any other class.

Over the years, we have published various discussions of the properties of highly active regions, all of which were δ regions. With the availability of on-line data, we undertook the present study of 8 yr of flare data in which the area and magnetic classification have been compared with the peak X-ray flare from that region. Thanks to on-line digital data, we have 5 times as many regions and can compare the data with *GOES* X-ray fluxes. The availability of the *GOES* data, along with source region identification on-line, made the job much easier. Further, we were able to check the magnetic classifications by direct examination of observational data.

2. DATA SET

We created a database of 104,575 observations of 2789 regions made by the USAF Solar Optical Observing Network (SOON) and the Mount Wilson Observatory in the years 1989–1997. These observations are recorded by the NOAA World Data Center as the USAF/MWL data set and are printed each month in Solar Geophysical Data.[1] The data set lists each flare and the region in which it occurred, if known, along with the magnetic classification, area, and position, as measured at the six SOON sites and some contributing observatories. We ignored the effects of returning spot groups. Highly active regions tend to be short-lived, and the number of returning regions appeared to be few. "Spotless flares," filament eruptions far from active regions (Dodson & Hedeman 1970), are not picked up in these lists because they are not connected to classifiable active regions. Dodson & Hedeman estimate that spotless flares, which are filament eruptions and may be important for coronal mass ejections, comprise 7% of observable flare events.

Three types of error can affect the result: the areas may be inaccurate, the magnetic classifications may be incorrect, and the *GOES* data may be incorrectly transcribed. Area measurements may be affected by observational circumstances, but errors can be eliminated by comparison of results of different stations. Fortunately, each region is on the disk for up to 13 days and is observed by most of the SOON stations, so egregious errors are easily found and discarded. The correction applied for foreshortening at the limb was generally inadequate, as can be seen in Figure 1. Each dark box indicates a measurement from a different SOON site. These data also illustrate the typical scatter in measurements. Foreshortening is eliminated by using the largest spot areas measured near the central meridian passage, where no foreshortening correction was required. While this might not work for regions peaking near the limb, we saw few such regions. If the peak area was more than twice the next listed, it was checked against actual

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[1] Observations are also available from the site ftp://ftp.ngdc.noaa.gov/STP.

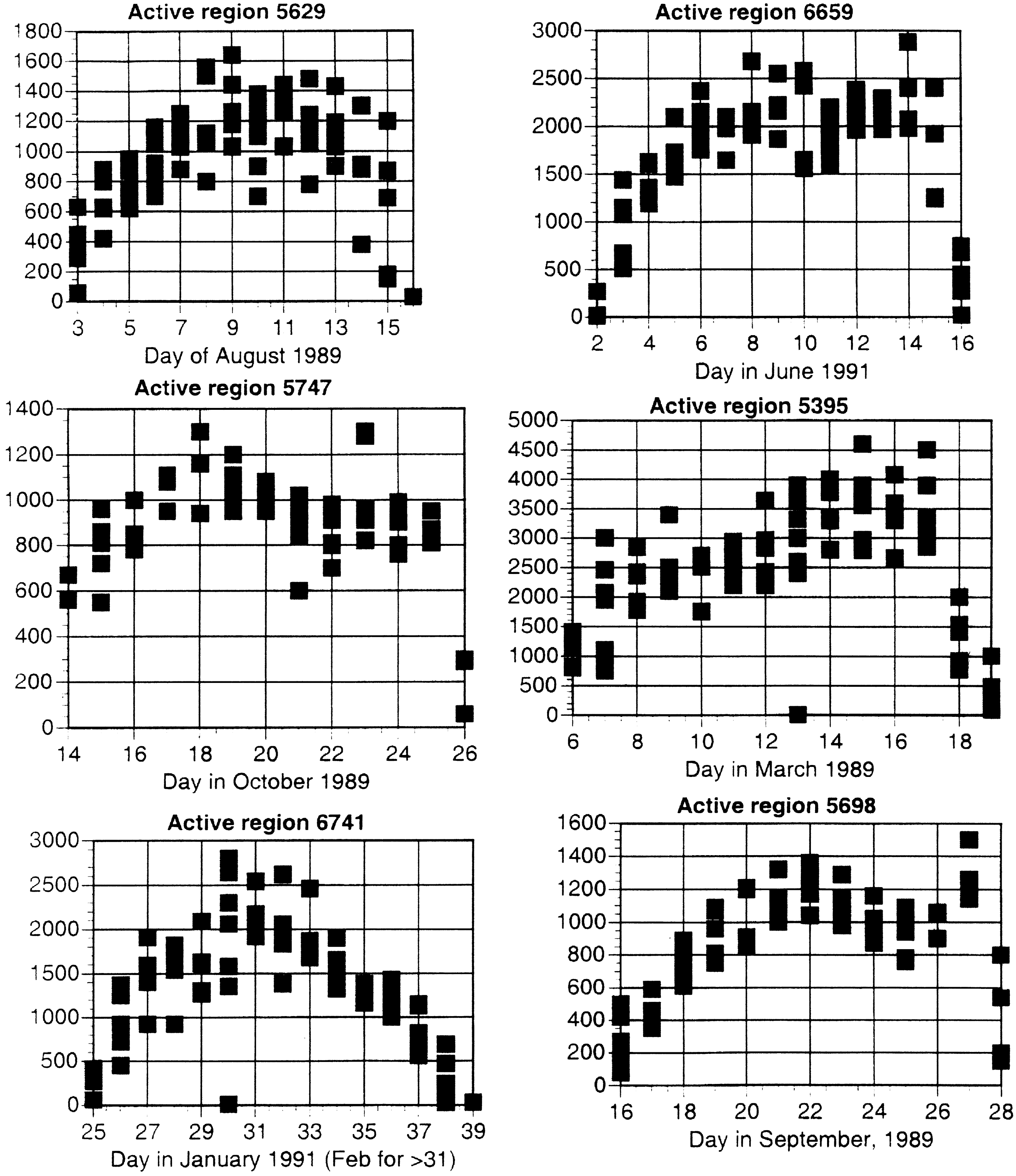
Active region 5629
Active region 6659
Active region 5747
Active region 5395
Active region 6741
Active region 5698

FIG. 1.—Reported spot area as a function of meridian distance. Despite the supposed use of corrections for projection, there is a strong limb foreshortening.

images and discarded, if appropriate. Scatter of 10% is common but unimportant for this survey. The *GOES* data are accurate, but values above 10.0 are incorrectly given an extra zero in the on-line files, so X20 becomes X200. These are readily recognized and corrected, as there are no more than two or three per year and they all end in the extra zero. The mass of data is so great, and our bins so broad, that all these errors tend to average out.

We were concerned by the magnetic classifications, which are difficult. We checked every region producing larger flares (X1 or greater) and classified δ by comparison with Mount Wilson, Big Bear Solar Observatory (BBSO), and KPNO data. These were generally correct. We did not check the classification of α or β regions as they do not produce important flares. Our study was focused on the largest flare in each region, the largest spot area in its

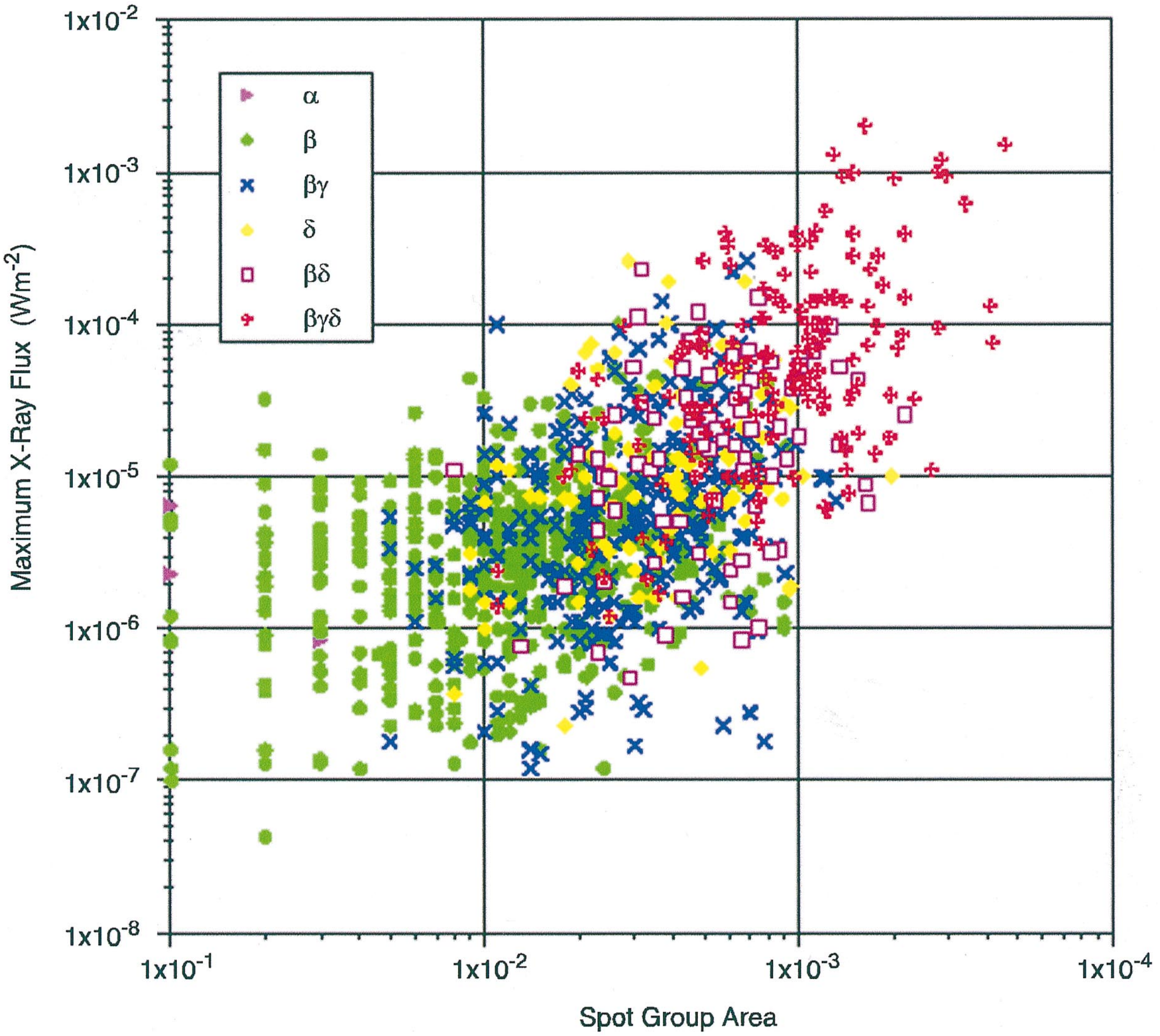

FIG. 2.—Peak flare intensities in W m^{-2} for each spot group as a function of peak area in disk fraction, with each magnetic class plotted separately. Clearly all the big events at upper right occur in δ spots, those classed $\beta\gamma\delta$ by SOON. Regions producing no flares have been omitted.

passage, and the highest (with δ as the highest) magnetic classification. Thus, a region is considered δ if it reached that value once in its disk passage.

Several more minor errors can also cause problems. The SOON sites submit corrections by entering a second report with the same time and date information as the first; on 92 occasions both a corrected and an original report remain in the data set. Variation of area reports on a given day is considerable, but the scatter was similar in both directions. Since we use peak areas, this gives a small upward bias to the areas used. An active effort has been made to match *GOES* flares with optical reports, so most *GOES* bursts, and almost all large ones, are correctly matched with active regions. While we could not do a comprehensive check on the identifications, they generally appear to be correct.

Because the region is observed for several days at several stations, an adequate consensus of its properties is obtained. The X-ray data reported by the *GOES* satellites appear generally reliable, except as noted above. The intercomparison of a large database tends to even out the effects of errors in measurement and philosophy. Since our data show strong effects, they are fully adequate for general flare prediction.

A more important point is that while we perforce use the *GOES* data, there is some question whether or not they represent the true flare "importance." The *GOES* value is a peak value, measuring the time integral of the hard X-ray input, which is probably the primary energy input. But peak values give no weight to extended energy input. This is probably the source of the significant effects attributed to long-duration flares in which the total input is much larger than that implied by the peak value. On the other hand, the *GOES* peak is a reasonable indicator of the integrated hard X-ray input.

3. METHOD AND RESULTS

We compared magnetic classification, spot group area, and the peak soft X-ray (SXR) flux during its disk transit. We assigned to each active region the highest magnetic classification reported during its disk transit, as well as the greatest area reported, and the largest flare. In general, Mount Wilson classified a spot group as δ if any two umbrae of opposite polarity in a group were very close, resulting in many more such regions than the USAF $\beta\gamma\delta$ class, which only recognized regions where the major spots were in a δ configuration. However, all regions classified by SOON are also classified δ by Mount Wilson. Regions classified are all checked directly on BBSO and Mount Wilson data.

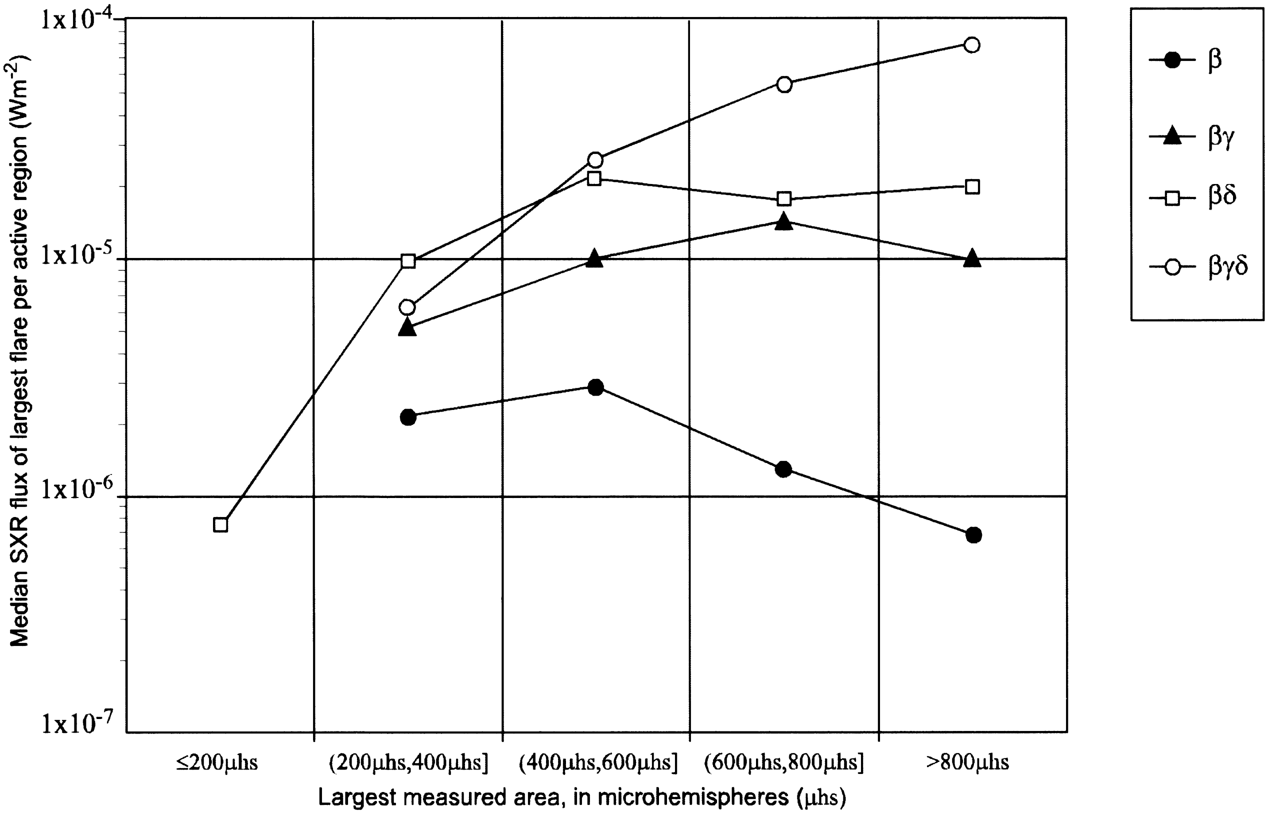

FIG. 3.—Median peak intensity of flares for different magnetic classes as a function of area. Except for small groups, for which δ spots are few, that class produces significantly larger flares.

In Figure 2, we plot the largest flare from each active region against the largest reported area from that region, for each magnetic class. This shows a roughly linear connection between the logs of SXR flux and active region maximum areas. But the dependence on magnetic class is much stronger. All flares above X4 (4×10^{-4} W m^{-2}) come from 11 $\beta\gamma\delta$ regions of area greater than 1000 μh. Thus, these two conditions constitute a necessary, but not sufficient, condition for an X4 flare. Because there are not many $\beta\gamma\delta$ regions, we were able to check all of the regions in the uppermost square for correct classification using Mount Wilson maps and classifications. As the δ classification formally requires both continuum (it is defined in terms of umbrae and penumbrae) and magnetic field images, we also compared nearly contemporaneous images in the Stokes I and Stokes V taken by the BBSO videomagnetogram. A region was classified δ if, and only if, two substantial umbrae of opposite polarity could be found within the same penumbra. Thus, while the mass of smaller regions may include errors, the big ones do not.

We examined the four active regions that produced flares X1 or larger but were not declared δ by any station (NOAA 5800, 6021, 5969, and 6537). Of these, useful data was available only for 5800 and 5969, which clearly had δ spots, albeit unimpressive ones. It should be remembered that, by the old area classification, an X1 (10^{-4} W m^{-2}) event corresponds to what might have been a class one flare. All of the old area classifications are compressed above this level.

The general slope of Figure 2, upward and to the right, confirms the well-known fact that large active regions have more large flares than small ones and also tend to be more complex. To separate these effects, we have binned the active regions by area and by magnetic complexity. Binning should limit the effect of one parameter upon the other. The results are shown in Figure 3. The α class is omitted because it has no flares of significance. While the β and $\beta\gamma$ classes show no particular effect, $\beta\delta$ and $\beta\gamma\delta$ classes have bigger flares for all areas. Thus, there is a real increase of a factor of 2 or 3 in the expected peak flux from a region compared to a simpler magnetic configuration of the same size.

4. SUBSETS OF THE δ CLASSIFICATION

Mount Wilson and the SOON sites treat the δ classification differently. Mount Wilson treats δ as a separate class, counting any region with two opposite polarities in a single penumbra as δ, even if these are not the main spots. The USAF SOON sites treat δ as a modifier upon the β, γ, or $\beta\gamma$ classes (there are no $\alpha\delta$ spots observed) and require the major spots to fulfill the δ condition. We find the $\beta\gamma\delta$ class to be the most active, by far, with the infrequent $\gamma\delta$ a distant second. All of the $\beta\gamma\delta$ regions were classified δ by Mount Wilson, the δ class being more extensive. Since Mount Wilson does not measure areas, δ regions are not plotted separately in Figure 2. Henceforth, we use the term δ to refer to the SOON $\beta\gamma\delta$ class.

The δ classification is not clearly defined. It is not known if the region is more active if the umbrae are equal or unequal, or if only the magnetic gradient is important. Only a few of the configurations found here correspond to great, thoroughly studied regions of the "island delta" variety (Zirin & Liggett 1987). Those regions, with twisted field lines, high field gradients, and considerable spot motions, produce the lion's share of large flares. They are round and compact, compared to the Zürich F class. The fact that the spots classified by Mount Wilson and lesser classes by SOON produce relatively fewer and smaller flares suggests that we should append an area class to the magnetic classification.

5. CONCLUSIONS

The probability of a $\beta\gamma\delta$ spot group larger than 1000 μh producing an X1 or greater event is only 40%, accounting for about 60% of those events. However, 82% of X1 flares and 100% of the more important X4 events occur in δ spots. By comparison, only 24% of all regions greater than 1000 μh produce X1. This is evident from Figure 2. In addition, it should be remembered that in order to complete this work we use only the maximum area and class during any time in the disk transit, and a clearer comparison might be obtained by examining the state of the region just before the flare. These data are counted by region. If we count by flares, the odds are greater: more than half the X flares are produced by five regions greater than 1000 μh. In Figure 2, each region is given the same weight, whether it produced one or more X-class flares. Separate markings for multiflare regions would increase the dominance of the $\beta\gamma\delta$ regions.

That dominance emphasizes the need for theoretical flare studies to focus on the δ configuration. It is likely that the sharp gradient between the δ spots sets up a current sheet where the flares occur, and indeed the first flashes of an impulsive flare occur along the magnetic inversion line separating the polarities (Zirin & Tanaka 1973; Tanaka & Zirin 1985). This has been found by spectroscopic Zeeman measurements (Zirin & Wang 1993) to be a region of strong horizontal fields, as great as the radial sunspot fields. The popular Kopp & Pneuman (1976) scheme, for instance, shows a current sheet forming above a tranquil β (bipolar) group, where, alas, flares do not occur (in fairness, those authors use the model only for loop prominence formation, but others appear to misapply it as a flare mechanism). Fortunately, more realistic versions addressing the strong currents implied by the observed magnetic shear have appeared recently (Antiochos 1998; Antiochos, Devore, & Klimchuk 1999; Melrose 1997). In the δ class the current sheet extends down to the surface and flares.

The increase in flare size with spot size shows that although the sharp gradient and currents of the δ configuration provide the appropriate situation for flare occurrence, the scale offered by a large spot is important in producing great flares.

We remain with a very clear conclusion. All large flares (X4 or higher) occur in spot groups of area greater than 1000 μh classified $\beta\gamma\delta$. Predictions that X1 flares will occur for such a class will enjoy a 41% probability of success with no other considerations. Adding some of the considerations mentioned by Zirin & Liggett (1987) and Zirin & Marquette (1991), particularly Hα brightness and flux emergence, should improve these predictions considerably.

The data collected by SOON, with their faults, could be used for a good prediction program. While higher resolution is useful, the important regions are large enough that their magnetic class can be ascertained.

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