SOLAR CYCLE VARIATION OF MAGNETIC FLUX EMERGENCE

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ABSTRACT

The number of X-ray bright points (XBP) has been measured from solar X-ray images obtained during two rocket flights in 1976. When compared with the data obtained during the Skylab mission (1973), the number is found to be higher by a factor of 2. As the probability of obtaining the result by chance is less than 1 in $5 \times 10^6$, it is concluded that the number of XBP has increased in the 3 year interval. As all other indicators of activity have decreased between 1973 and 1976, the cyclical variation of the short-lifetime end of the magnetic flux emergence spectrum is out of phase with the solar cycle as defined by active regions or sunspots. Since XBP in 1973 contributed more to the emerging magnetic flux than did active regions, the possibility exists that the total amount of emerging magnetic flux may be maximized at sunspot minimum.

Subject headings: Sun: activity — Sun: magnetic fields — Sun: X-rays

I. INTRODUCTION

Soft X-ray images of the solar corona were obtained during rocket flights on 1976 September 16 and November 17. We find that the number of X-ray bright points (XBP) at this time was significantly greater (over a factor of 2) than the average number observed in 1973, suggesting that XBP do not track the usual indices of solar activity, for which 1976 was the year of solar minimum. Between 1973 and 1976 these indices, such as the Zurich relative sunspot index, declined by slightly more than a factor of 3. Using that decline as a base, the number of XBP in 1976 is over 6 times greater than the "predicted" number. This difference is far greater than any variation observed during the Skylab period, and it appears that the solar cycle variation of XBP is out of phase with the standard measures of activity.

X-ray bright points are small, short-lived coronal emission features corresponding to regions of emerging, small-scale, bipolar magnetic flux (cf. Golub et al. 1977 and references therein). Their size and lifetime spectra blend into the "active region" spectra without a sharp transition; and the key physical parameter, in the description of the evolutionary history of individual features, appears to be the total magnetic flux with which the feature emerges. In 1973, during eight solar rotations in the declining phase of the most recent cycle, the data obtained with the S-054 X-ray spectrographic telescope on Skylab (Vaiana et al. 1973) showed that the integral spectrum of emerging magnetic flux was dominated by large numbers of short-lived features. The measured quantity, in that study, was the "full disk number count," i.e., the total number of XBP visible on a given day within ±70° of central meridian passage (CMP) (Golub, Krieger, and Vaiana 1976a). This quantity showed relatively smooth variations from day to day with a maximum difference of a factor of 4 between the lowest and highest readings. Using the mean and dispersion of the 1973 data as a base, both 1976 measurements are at least three standard deviations higher than the 1973 average. Thus we conclude that the average daily bright-point count during 1976 is significantly higher than the 1973 value.

In previous discussions of solar activity, the solar cycle was viewed as an oscillation in the amplitude of the frequency distribution of certain characteristic parameters of active regions—e.g., lifetime, total magnetic flux. It now appears that the activity minimum corresponds to the steepening of a monotonically decreasing flux distribution, which is approximately exponential (Golub, Krieger, and Vaiana 1976b); the steepening reduces the high-flux long-lived tail while increasing the low-flux short-lived component. Thus the total amount of emerging magnetic flux, which depends on the integral under the curve, may or may not minimize at solar minimum.

II. THE OBSERVATIONS

The solar minimum coronal images were obtained during two sounding rocket flights on 1976 September 16 and November 17. Each instrument contained a grazing-incidence mirror with a thermal prefilter and a five-position wheel containing broad-band X-ray filters. The images were recorded on film, and representative exposures through the thinnest filter are shown in Figure 1 (Plate L1).

In order to compare the number of bright points observed on these two occasions with the S-054 data, we have evaluated the relative efficiency of the three detection systems. Since the bright points are cool features, with their emission spectra dominated by lines with wavelengths greater than 20 Å, we have defined a relative efficiency by evaluating the product of the collecting area and the filter transmission at 44 Å. This procedure is adequate since the wavelength dependence of the quantities is similar over the range of wavelengths observed and further enables the product to be evaluat-
Fig. 1.—Broad-band images of the X-ray corona recorded by rocket-borne instruments on 1976 September 16 (1703 UT) and November 17 (1837 UT) 
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ed from experimentally determined quantities. The instruments are compared in Table 1, and the efficiency relative to S-054 for the two rocket instruments is 0.25 and 1.21.

The S-054 daily XBP counts were obtained from 4 s exposures. From the rocket flights we selected 26.2 and 3.7 s exposures, which correspond to 6.5 and 4.5 s exposures when normalized to the collecting efficiency of the S-054 telescope. To compensate for the difference in effective exposure the rocket data have been scaled using the procedure outlined in Golub, Krieger, and Vaiana (1976b). The scaling takes into account the variations in the visibility of bright points as a function of exposure duration and coronal background emission. In the rocket photographs the XBP are observed against a background of diffuse large-scale structures (LSS). At the 4 s exposure level our instruments are less efficient at detecting XBP against this background than, for instance, against coronal holes (CH); and this fact has been taken into consideration in applying the scaling procedure. For the data from September 16, the scaling results in a reduction of the raw number count by a factor of 1.35 while for the November data the correction factor is approximately unity and has been ignored.

If the solar disk were dominated by coronal holes rather than by the large-scale structures, the scaling factor for the September flight would have to be increased to 1.8 as the efficiency for the detection of bright points is increased. This scaling factor has been used to establish a quantity called the absolute minimum bright-point count which provides an absolute lower limit to the number of XBP.

### III. RESULTS

The major results of the investigation are shown in Figure 2 and Table 2, where the relative numbers of XBP in 1973 and 1976 are compared. In Figure 2, the 124 daily averages from 1973 are plotted in the form of a histogram showing the frequency of occurrence of each number count. The histogram approximates to a Gaussian distribution even though there were persistent nonrandom variations during the eight rotations observed (Golub, Krieger, and Vaiana 1976a). We have therefore chosen as a "base" number the mean \( \langle x \rangle = \langle \Sigma x_i \rangle / N \) of the 1973 observations; as a measure of the dispersion we have taken the standard deviation which is defined as the square root of the variance \( \sigma^2 = \frac{1}{N} \sum (x_i - \langle x \rangle)^2 \). The values observed in 1976 are indicated by arrows and lie well outside the range of values recorded in 1973.

The values of \( \langle x \rangle \) and \( \sigma \) for the 1973 data are listed in Table 2. The fact that the dispersion is larger than \( \langle x \rangle^{1/2} \) is indicative of the true variation in XBP emergence patterns, over and above purely statistical fluctuations. We have also included a base number and standard deviation for the distribution obtained from two random observations which can be compared with the mean of the data from the two rocket flights. The latter were separated by 2.3 solar rotations or 124° of solar longitude and thus are independent samples of the 1976 number count; i.e., we have not been deceived by a recurrent feature limited to a small band of longitudes.

![Fig. 2.—Daily X-ray bright point counts. The curve is a Gaussian distribution fitted to the 1973 data. The 1976 observations (hatched) are indicated by arrows.](image-url)
As described in § II, the raw counts for September have been reduced by a scale factor of 1.35 while the November data are unchanged. The two values 90 ± 8 and 75 ± 9 are both consistent with a substantial increase in the number of bright points between 1973 and 1976. In fact, the average of the two 1976 observations, 83, is 110% higher than the combined average, 39, of the 1973 data. Under the assumption that the data from both 1973 and 1976 belongs to the same Gaussian frequency distribution, we have determined the probability that two random observations will result in the 1976 value to be 1 in 5 × 10^4. Even using the lower bounds for the 1976 observations, thus maximizing the probability, the chance of making the observations is still only 1 in 2 × 10^4. We realize that because of deviations from a Gaussian distribution these probabilities are not strictly true; but even so, the inescapable conclusion is that the 1976 data belong to a different frequency distribution with a higher mean value.

The increase in the mean is even more significant if we consider the changes in other indices of solar activity between 1973 and 1976. For instance, the average relative sunspot number \( R \), for the Skylab period 1973 May–November was 35 whereas the (provisional) index for 1976 January–December averaged 13, a decrease by a factor of 3. During the same intervals, the Ottawa 2800 MHz radio flux decreased 20% and the number of reported \( \text{H}_\alpha \) flares dropped by about the same amount as \( R \). Relative to these indices the increase in the number of XBP at latitudes near 30°–40° has dropped by a factor of 3. The combined total of active-region-like XBP should be approximately one-third of its 1973 value, since \( R \) has dropped by a factor of 3. Thus the number density of XBP near the equator would be significantly lower than in 1973, and the overall total number of XBP averaged over all latitudes would be somewhat lower than in 1973.

In Figure 3 we show the latitude distribution of XBP seen on the two 1976 images, compared with the 1973 average. The 1976 data show much larger error bars since only two photographs were available. However, it is clear from the figure that there were more XBP at all latitudes in 1976 than in 1973, with the possible exception of the extreme polar latitudes where the statistical sample is small. Thus it is clear that the emergence of small-scale magnetic flux regions at solar minimum does not follow the pattern set by the larger active regions. Unfortunately, further details of the behavior within restricted latitude intervals cannot be deduced because of the limited statistics of the data sample.

### IV. DISCUSSION AND SUMMARY

We have shown in the preceding sections that the number of XBP on the Sun in 1976 was greater than in 1973, while the level of solar activity in 1976, measured by several indicators, was substantially lower than in 1973. The year 1976 is presently believed to be the year of sunspot minimum, and 1973 was part of the so-called declining phase, corresponding to a gradual reduction in solar activity. Therefore, we conclude that XBP do not vary in phase with the solar cycle, although we are unable to determine the relative phase shift from only two points in the 11 year (or 22 year) cycle.

The latitude distribution of XBP shows a greater number at all solar latitudes in 1976, except possibly for the extreme polar latitudes where the statistical sample is quite small. This increase includes both the

### TABLE 2

<table>
<thead>
<tr>
<th>Observation</th>
<th>Data Set</th>
<th>Full Disk Count ( \pm \sigma )</th>
<th>Excess</th>
<th>Probability of Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973 May–November</td>
<td>Average single observation</td>
<td>39 ± 11</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Average two random observations</td>
<td>39 ± 8</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1976 September 16</td>
<td>Actual count</td>
<td>122</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Best estimate after scaling</td>
<td>90 ± 8</td>
<td>+51 ± 14</td>
<td>&lt;1×10^4</td>
</tr>
<tr>
<td></td>
<td>for LSS</td>
<td>68 ± 6</td>
<td>+29 ± 13</td>
<td>&lt;4×10^3</td>
</tr>
<tr>
<td>1976 November 17</td>
<td>Actual count</td>
<td>75</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Best estimate after scaling</td>
<td>75 ± 9</td>
<td>+36 ± 14</td>
<td>&lt;1×10^4</td>
</tr>
<tr>
<td></td>
<td>for LSS</td>
<td>83 ± 8</td>
<td>+44 ± 11</td>
<td>&lt;7×10^4</td>
</tr>
</tbody>
</table>

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equatorial latitudes in which the last vestiges of old cycle activity are found and the middle latitudes in which new cycle active regions are beginning to emerge.

In Golub, Krieger, and Vaiana (1976a), it was estimated that XBP in 1973 contributed 4 times more magnetic flux to the solar surface than did active regions. Although we do not yet have comparative magnetic field observations from which to deduce the amount of flux contributed by XBP in 1976, it seems safe to assume that the relative contribution of XBP is at least as great as it was in 1973; the number of large regions has decreased, and the XBP in 1976 are more numerous and appear to be similar in size and brightness to those observed in 1973.

If we assume that XBP in 1976 are physically similar to those in 1973, then more magnetic flux is being brought to the surface at solar minimum than during the declining phase. Alternatively it is possible that the distribution of small-scale flux emergence in 1976 has shifted toward more numerous but smaller and shorter-lived regions. The total amount of magnetic flux brought to the solar surface throughout the cycle might then be constant on the average, with the solar cycle representing nothing more than an oscillation in the wave-number distribution of emerging magnetic flux.

In either case, the pattern of magnetic flux emergence has shifted as shown schematically in Figure 4. The long-lived end of the distribution, corresponding to active regions, has decreased substantially, leading to the designation of 1976 as solar minimum. However, the short-lived end (e.g., less than ~2 days) of the distribution has increased. The observation of such a shift toward short-lived regions between 1970 and 1973 was noted by Harvey, Harvey, and Martin (1975), on the basis of calcium plage reports. However, those authors noted the possibility of severe observational bias in the reports and so tended to disregard the observed increase in the number of small plages. Possible biases are far less severe in the X-ray data (unipolar features are not seen), and we believe that the shifts in both the X-ray and calcium data are real.

In order to determine the total amount of magnetic flux emerging over the solar surface it will be necessary to integrate over the entire spectrum of emerging flux. In 1973 the short-lifetime end of the spectrum dominated the integral, and apparently it still does in 1976. Depending upon the shape of the differential distribution, the amount of emerging magnetic flux may in reality be maximized at solar minimum.

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Fig. 3.—The latitude distribution of X-ray bright points in 1973 and 1976.

Fig. 4.—Schematic representation of the cyclical variation in the distribution of emerging magnetic flux.

REFERENCES


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