X-ray Bright Points and the Solar Cycle

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X-ray bright points and the solar cycle

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Soft X-ray filtergrams show the presence on the Sun of large numbers of small, closed regions of coronal emission. These features, called 'X-ray bright points' correspond to small, short-lived regions of emerging magnetic flux. As a function of size or lifetime they form a broad spectrum of activity which is continuous with the active regions. The shape of the Sun's activity spectrum is such that most of all magnetic flux emerging at the surface comes in the form of bright points. From this viewpoint, active regions may be viewed as the long lifetime tail end of the bright point spectrum.

Examination of soft X-ray data obtained from 1970 to 1978 shows that the number of bright points appears to be anticorrelated with traditional activity indices such as sunspot number; the anticorrelation persists after corrections are made for obscuration by active regions. Comparison of X-ray data with KPNO magnetograms shows that to within a factor of 2, the average total amount of magnetic flux emerging over the full Sun is constant through the entire period of observation. The solar cycle therefore appears to be more an oscillation in the wavenumber distribution of emerging flux than of the total quantity of magnetic flux produced.

1. Introduction

High spatial resolution observations of the solar corona in its characteristic radiation, soft X-rays, have proved to be a valuable new tool in the study of solar activity and active regions. For a number of reasons (cf. Vaiana *et al.* 1973), soft X-ray instruments provide extremely high contrast between closed and open magnetic field regions in the solar atmosphere, so that the X-ray emitting plasma observed by imaging instruments belongs primarily to the closed corona. The corona is observed to be highly structured, and recent theoretical work has shown the advantage of considering the corona to be fundamentally inhomogeneous, with loops forming the relatively isolated building blocks (cf. Vaiana & Rosner 1978).

The sharp division in X-ray brightness between open and closed regions is particularly advantageous in studying the small-scale end of the active region distribution, i.e. the X-ray bright points or X.b.p. This name was given to the numerous small regions of bright X-ray emission which were seen on early high-resolution images (Vaiana *et al.* 1970). Now what is significant about these small features is that most of the magnetic flux emerging through the solar photosphere comes up in regions living 2 days or less. Moreover, detailed study reveals major variations in magnetic flux emergence at locations on the Sun for which flux emergence had not previously been considered and with spatial and temporal scales that have not until now been observed. Finally, there is evidence from observations over most of a solar cycle that the total amount of magnetic flux integrated over all emerging scale sizes may vary little, if at all, through the solar cycle. The cycle may represent an oscillation in the wavenumber distribution of emerging fields, rather than in total quantity of magnetic flux.

The distribution of sizes for active regions on the Sun appears to be a continuum and does not peak at any characteristic value. Rather, the differential distribution of number of features emerging per unit time as a function of size or lifetime is a monotonically decreasing function. This means that there is no 'typical' value that can be stated as the size or lifetime of an active region; the distinction between active region and X.b.p. is completely arbitrary, the only constraint being the avoidance of conflict with accepted usage. As a working definition, we have defined an X.b.p. as a closed magnetically bipolar region of soft X-ray emission that is less than 1′ in diameter. This division by size corresponds on a statistical basis to the selection of regions living two days or less; it also corresponds to the lower limit in size or lifetime of regions that are normally classified as 'active regions' by ground-based observers.

Over the past decade we have begun to form a comprehensive picture of the small-scale end of the solar magnetic flux emergence spectrum, with profound implications for solar cycle and dynamo theories. I shall first present the results from Skylab in §2, more recent findings in §3 and discuss the implications and directions for further research in §4.

2. Results from Skylab

Solar bright points had been observed in several rocket flights before the launch of Skylab, and many of their basic properties had been established. Physical parameters such as size, electron temperature and density were known and we were reasonably certain that they represented magnetically bipolar features.

However, the availability of continued observations over many hours and days in the Skylab data provided a new dimension for the analysis. We were able to study the lifetimes and evolution of activity on all time scales and to look for large-scale patterns in emergence on the solar surface. The motivation, of course, was to find out whether X.b.p. represented emerging magnetic flux and if so, how much of it and what new information could be gained about solar magnetic activity from studying these objects.

(a) *The flux spectrum*

It has apparently been recognized for some time that the number of active regions on the Sun increases toward short lifetimes (cf. Harvey *et al.* 1975); i.e. the average number of new active regions living for two months is less than the number living for one month, which is in turn less than the number living for one week, and so on. Using the Skylab data, we have been able to quantify this qualitative statement and to extend the activity spectrum down to lifetimes of only a few hours. The number of regions emerging per unit time continues to rise down to the observational limit of 2 h. Moreover, the rise is so steep that the *integral* spectrum is dominated by the short lifetime portion; this latter deduction involves a statistical connection between lifetime and total magnetic flux for active regions, in addition to knowledge of the lifetime distribution function.

The first step in the series of observations leading to these conclusions is shown in figure 1, the distribution of lifetimes for features present on the disk on 20 August 1973 (Golub *et al.* 1976*a*). The total number of regions present at $t = 0$ was 94. Of these, 12 were found to have a total lifetime greater than 50 h; McMath numbers, indicating the presence of 'active regions', were assigned to six of the twelve.

The solid curve represents an attempt to provide an analytical fit to the observed histogram of lifetimes. We noticed that the distribution of lifetimes (neglecting the smallest bin, which is affected by observing constraints) was approximately exponential. That is, the differential

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number of features living a given length of time was observed to be roughly $n(t) = A \exp(-t/\tau)$. However, the data indicated that a significantly better fit could be obtained by allowing two lifetime parameters. The solid curve in figure 1 is thus of the form $n(t) = A \exp(-t/\tau_1) + B \exp(-t/\tau_2)$. We found $\tau_1 \approx 9$ h and $\tau_2 \approx 1.5$ days with the ratio $A/B \approx 50$.

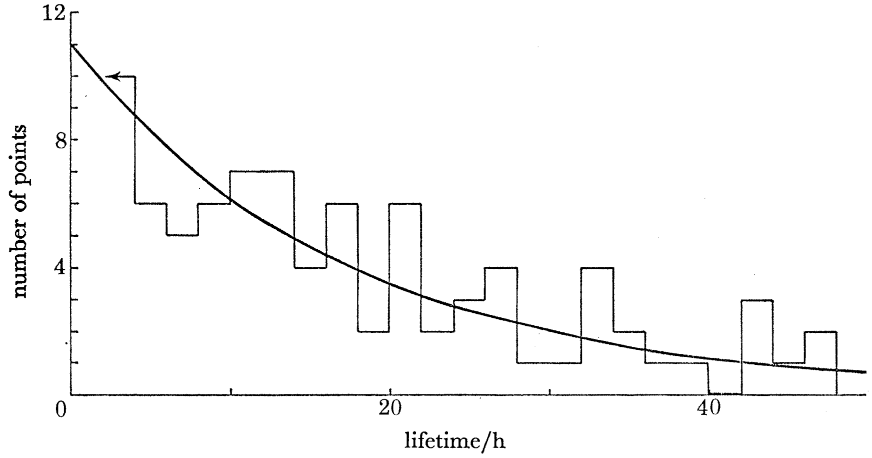

Figure 1. Histogram showing the number of bright points having the lifetimes indicated on the abscissa, 20 August 1973. The solid curve is a predicted fit based on a two-parameter exponential decay model described in the text.

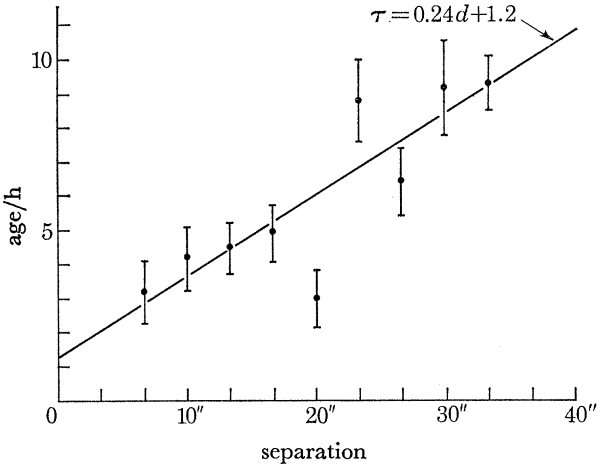

Figure 2. Histogram showing age of X-ray bright points as a function of spacing between magnetic poles in the longitudinal photospheric field.

We note that this fit to the data extrapolates to a finite value at zero lifetime. Since this histogram represents features *present on the disk* at a given time, we observe that the number of features *emerging per unit time* according to the exponential fit becomes infinite, similar to the behaviour of the number of low-energy photons in a Brehmsstrahlung spectrum. This is because the probability of appearing on a random photograph is proportional to lifetime, so that the longer-lived regions are proportionately over-represented in the histogram. More directly relevant is the quantity of magnetic flux emerging per unit time in each interval of lifetime. I shall now show that this total is dominated by the short lifetime features.

By comparing the X-ray data with high-resolution KPNO magnetograms we were able to establish that (Golub *et al.* 1977):

(i) X.b.p. represent emerging magnetic flux and they are bipolar;

(ii) the lifetime in X-rays of X.b.p. is (to first order) linearly correlated with the total magnetic flux in the region;

(iii) the relation between lifetime and Φ_{tot} extends over three orders of magnitude, the proportionality constant being *ca.* 10^{20} *Mx*/day.

This analysis was based on two data sets, each consisting of a KPNO magnetogram embedded in a long sequence of X-ray images having time resolutions of *ca.* 1 h. The X-ray data provided information on the age, size and total lifetime of each feature, while the magnetograms provided bipole spacing, orientation and total longitudinal magnetic flux measurements.

That X.b.p. represent emerging magnetic flux was deduced from the plot shown in figure 2, which compares the age of the X-ray feature with bipole spacing on the magnetograms. This analysis showed that the separation between the poles of the magnetic feature is an increasing function of age, the growth rate being *ca.* 1 km/s. We interpret this as a signature of emerging flux. To an accuracy of ± 1 h the best-fit growth curve extrapolates to zero size at the time of birth, for the sample studied.

Using a similar technique, we found that the lifetimes and total magnetic flux values of X.b.p. are statistically correlated, at the 3σ level for the sample of 40 X.b.p. used. A linear least-squares fit yields $(1.7 \pm 0.6) \times 10^{20}$ *Mx* per day for the relation between flux and lifetime. It is instructive to note that a similar analysis with the use of ground-based methods for large active regions yielded the same flux/lifetime coefficient (Sheeley 1966). This quantity may be interpreted to provide information on the effective diffusion rate of large magnetic flux concentrations over the solar surface.

We may now combine the above flux–lifetime relation with the lifetime curve shown in figure 1 to obtain an analytical expression describing the distribution of magnetic flux values present on the disk. In figure 1 I presented a typical curve for the lifetime distribution and pointed out that the number of features *emerging per unit time* is logarithmically divergent in the limit of zero lifetime. However, if we now substitute total magnetic flux for lifetime and ask how much magnetic flux emerges per unit time in each lifetime interval, the function is again well behaved. It is in fact the same curve as that shown in figure 1 multiplied by the constant of proportionality between lifetime and total magnetic flux.

For the Skylab observing period, the contribution of bright points relative to that of active regions, with the use of two-day lifetime as a demarcation between the two classes, has an average value of 4:1. In other words, features living less than 2 days (but more than 2 h) contributed about 80 % of the total emerging solar magnetic flux.

(*b*) *Patterns of emergence*

Because bright points in a sense represent the 'whole story' of magnetic flux emergence on the Sun, we need to examine the global properties of their emergence. Theoretical models of the solar dynamo and of the cycle could potentially contain enormous systematic errors if the short lifetime end of the activity distribution, which we have shown to contain the vast majority of all magnetic flux, emerged with substantially different properties from those of the large, long-lived active regions. In this regard we have at present only partial answers; these pages may be viewed as a progress report on work that is now being performed.

X-ray bright points have a broader latitude distribution than do longer-lived active regions (Golub *et al.* 1974), which is consistent with magnetograph and CaK observations of ephemeral regions (Harvey & Martin 1973). These results are in turn consistent with the well known observation that pores (small sunspots lacking penumbrae) are more broadly distributed in latitude at a given phase in the cycle than are sunspots (Bray & Loughead 1964). It is apparent that emerging flux regions with pores represent intermediate cases between the shortest-lived bright points and the active regions. Born (1974) has identified such regions as living from 10 to 60 h; shorter-lived regions do not develop pores and longer-lived ones develop penumbral spots. An association between lifetime and total magnetic flux, similar to the one discussed above, was inferred.

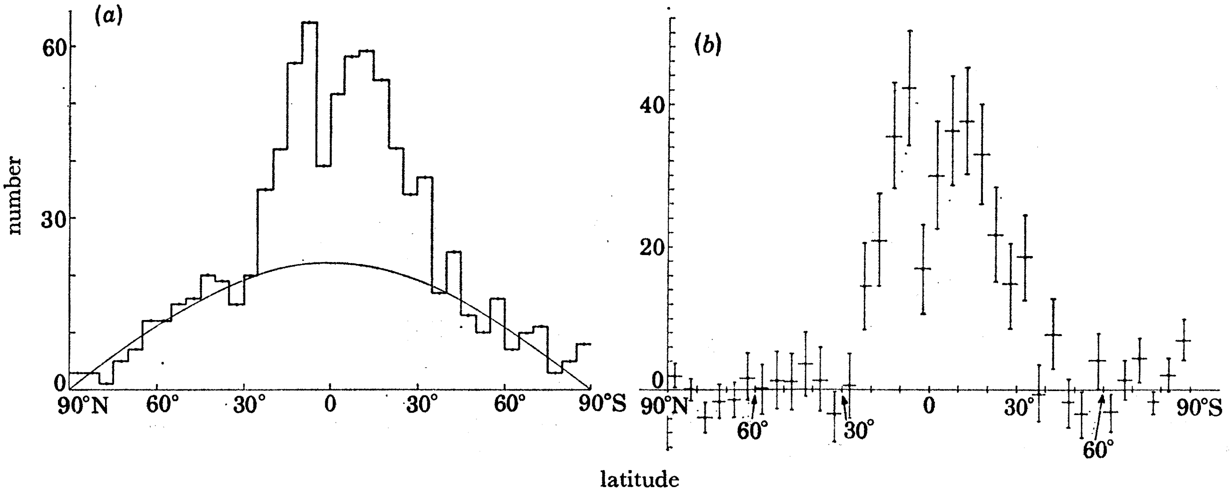

FIGURE 3. (*a*) Latitude distribution of coronal bright points. The solid curve is a cosine representing a uniform latitude distribution. (*b*) Latitude distribution after subtraction of a uniformly distributed component fit to the high latitude data of (*a*).

Although bright points are found at all solar latitudes, their distribution is *not* uniform. A typical latitude distribution is shown in figure 3*a*. This curve represents a uniform component and is normalized to the number of points 30° or more from the equator. In figure 3*b* I show the remainder after subtraction of the 'uniform component'; the result is a distribution that is flat at high latitudes and peaked in the active region belts. The curve resembles the active region distribution even to the extent of showing a dip at the equator.

We have also observed in Golub *et al.* (1975) that the heliocentric longitude distribution of small features was highly non-uniform, with variations up to a factor of 4 observed when the data were divided into 10° Carrington longitude intervals. No obvious association was seen between the non-uniformities and the occurrence of larger active regions. However, we noted that the bright points at high latitudes, i.e. above ± 30°, showed significantly less longitude variation than those found nearer the equator. We concluded that the data were consistent with a dual-natured bright point distribution, half of which were uniformly distributed on the Sun.

We emphasize that the above result is purely a statistical one; we do not know of any other compelling evidence for asserting that there exist two distinct types of bright points. Note also that this two-component fit is not the same as the lifetime curve of figure 1. For the lifetime distribution we found that the short-lived component had an amplitude 50 times greater than the long-lived one. In the present case the two components have approximately equal amplitude.

More recently, we have found that there appear to be large-scale variations in bright point emergence. The total number of points emerging per unit time varies by a factor of 2 over a time scale of 2–3 solar rotations, and there is no obvious correlation with the emergence of large active regions. We are looking into the possibility that the observed variation is connected with a global eruption of X.b.p. over the full Sun.

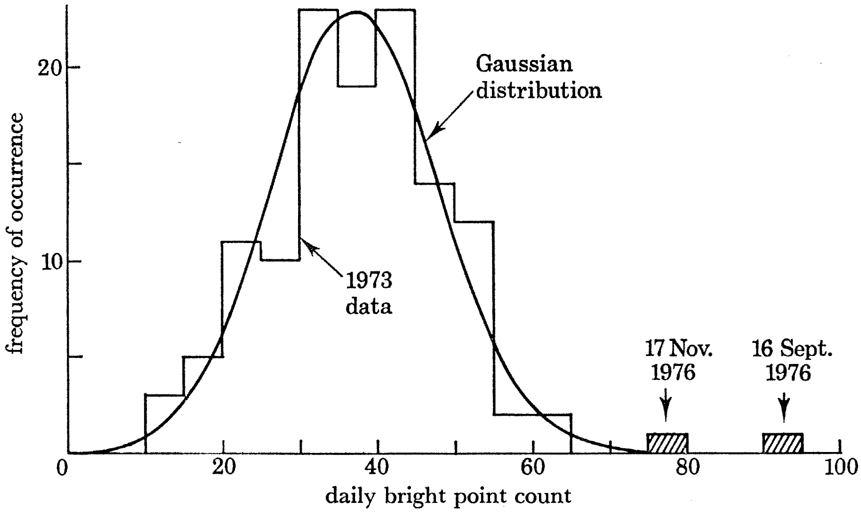

FIGURE 4. Distribution of values of full disk X.b.p. counts during ATM missions. The curve is a normal fit to the 1973 data. The 1976 observations (hatched) are indicated by arrow.

3. SOLAR CYCLE VARIATION

Data obtained from two rocket flights in 1976 revealed a dramatic and unexpected change in the spectrum of solar activity (Davis *et al.* 1977). Whereas the number of large active regions had decreased substantially from 1973 to 1976, the number of bright points observed had *increased* significantly. The extent to which the 1976 observations exceeded those of the ATM period is illustrated in figure 4. I have plotted a histogram showing the frequency distribution of bright point number counts in 1973. The distribution is fitted quite well by a normal curve having a mean of 39 and $\sigma = 11$. The results from the two rocket flights are plotted as small shaded areas; note that each of the two measurements in 1976 yielded a larger number of bright points than did *any* of the 1973 observations.

This anticorrelation between the long and short lifetime end of the activity distribution is not a 'visibility' effect. During the eight months of Skylab observations, the level of activity showed substantial variations; daily values of the sunspot index, R_z, ranged from 0 to over 120. We selected from the ATM data a subset consisting of bright point counts taken during the one-week period in each month that had the lowest average value of R_z. This amounted to examining the hemisphere with lowest activity during each month. For this subset of the data, the average R_z was 6.3 compared with 33.7 for the full data set. However, the average bright point count was 39.4 ± 1.9 compared with an overall average of 38.2 ± 1.0. Clearly, the level of activity is not a significant source of systematic errors in this analysis.

This result prompted a re-examination of other available data from two flights in 1970 and one in 1974; an additional flight in 1978 provided a further data point. Analysis of the six rocket flights plus the ATM data shows a consistent pattern of anticorrelation between the relative number of bright points and the level of activity as measured by the sunspot index. A summary of the measurements is provided in table 1 (Golub *et al.* 1979).

Table 1. Number of bright points compared with Zurich relative sunspot number, 1970–8

date	$N_{\mathrm{X.b.p.}}$	R_z†	R_{pred}
1970 Mar. 7	20 ± 5	111	109
1970 Nov. 24	28 ± 6	83	65
1973 ATM	38 ± 1	34	40
1974 June 27	58 ± 8	21	21
1976 Sept. 16	90 ± 8	13	11
1976 Nov. 17	75 ± 9	11	14
1978 Jan. 31	29 ± 6	49	61

† One-week average around date of flight.

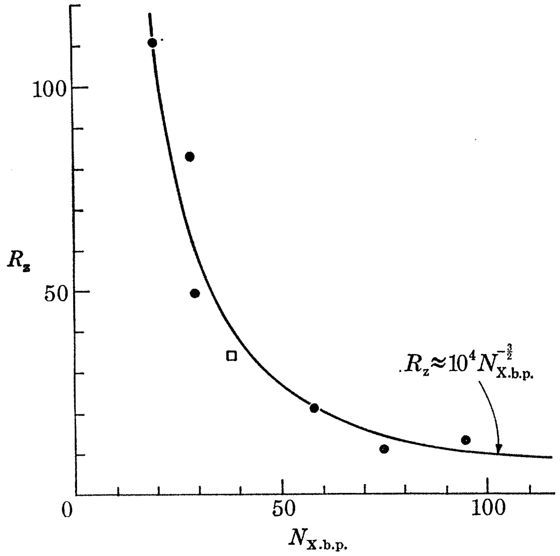

Figure 5. Plot of Zurich relative sunspot number, R_z against X.b.p. number. Six rocket values are shown as filled dots, ATM average as open square. The solid curve is a fit of the form $y = ax^b$.

It is instructive to plot the bright point number against the sunspot index without regard to the time parameter. Figure 5 shows the data plotted in this way; the solid curve is a power-law fit of the form $R_z = aN_x^b$. The deduced values of the parameters are $a = (1.1 \pm 0.4) \times 10^4$ and $b = (-1.54 \pm 0.12)$. The reduced χ^2 for this fit is 1.5 for an acceptable $P(\chi^2)$ of 0.10.

As an exercise, we have used the power law and the observed bright point numbers to calculate 'predicted' values of R_z; these are listed in the last column of table 1. The close agreement between calculated and observed R_z is another indication of how good a fit the power law provides.

Under certain assumptions, the magnetic field measurements discussed in § 2*a* may be used to estimate the relative contributions of X.b.p. and active regions to the total magnetic flux spectrum of the Sun during the period 1970–8. The two necessary assumptions are, first, that the X.b.ps seen in all of the rocket flights are physically the same, and secondly, that the index R_z may be used as a *relative* indicator of the amount of flux emerging in the form of active regions throughout the solar cycle.

With the above considerations, using the relative numbers of X.b.ps and active regions observed from 1970 to 1978 and taking the 1973 fraction of 80 % as a base, we estimate that 40 % of the total magnetic flux in 1970 emerged in the form of X.b.ps, and a peak of *ca.* 95 % in 1976. Early in 1978 the fraction was *ca.* 70 %, much the same as in 1973. We see that X.b.ps represent a substantial contribution to the total emerging flux spectrum throughout the entire solar cycle and are the dominant contributors through the declining, minimum and rising phases.

During the *Skylab* period there were typically 1500 X.b.ps emerging per day,† each with 3×10^{19} *Mx* of flux and active regions added another 20 %. The typical value for magnetic flux emergence on the Sun is therefore more than 5×10^{22} *Mx* per day.

If we assume that the X.b.ps observed in all rocket flights are the same, then the total amount of magnetic flux emerging at solar minimum is twice as great as in 1973; the total in 1970, near maximum, is nearly identical to that in 1973. However, the shift toward smaller regions at minimum could extend down to features as small as X.b.ps, so that the larger number observed does not necessarily imply more total magnetic flux emerging. The possibility of a factor of 2 decrease in the average flux per X.b.p. exists in the 1976 magnetogram data (J. Harvey, private communication) so that within the factor of 2 the average total amount of magnetic flux emerging on the Sun throughout the solar cycle is constant.

4. DISCUSSION

In this paper I have presented the results in decreasing order of certainty. A schematic outline of our knowledge may be portrayed as shown in table 2. It appears that the least certain results are those with the greatest potential significance.

The question of the solar cycle variation is the one that we currently feel to be the most important. Based on the behaviour of the familiar large active regions, one would presumably expect that the short-lived regions and the bright points would have a similar solar cycle variation. That is, the number of regions emerging per unit time or the integrated total quantity of emerging magnetic flux would be expected to vary roughly in phase with other activity indices, such as the sunspot index, R_z. Another possibility which might have been observed would be no average variation in the number of bright points. One could then have argued that these features have no relation to the solar cycle and represent some unrelated surface effect. The observed anticorrelation described in §3 therefore argues not only for a close association between X.b.p. and the solar cycle, but for a possible major revision in solar dynamo calculations.

The issue is at the moment more uncertain because a measurement that could have corrob-

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† The number 1.5×10^3 per day is equivalent to 500 X.b.ps on the full Sun at any one time, or 250 on the visible disk; this number is clearly greater than the average of 38 quoted in the text. The smaller numbers, such as those quoted in table 1, are *relative* counts and are obtained from short exposure images, in order to minimize obscuration and visibility effects from overlying coronal structures. The larger numbers, used for obtaining flux estimates, are based on the scaling of X.b.p. counts in coronal holes on long-exposure images (cf. Golub *et al.* 1974, fig. 7).

orated the X-ray result has instead yielded an apparent conflict. Martin & Harvey (1979) have recently reported measurements of ephemeral active regions identified on Kitt Peak daily full-disk magnetograms from 1970 to 1977. The ephemeral regions are identified by visual inspection and, according to the authors, 'the criteria used for identification were the appearance of two, small, closely spaced, opposite polarity features having approximately the same magnetic flux and occurring in a location where no similar features were observed the previous day'. They also attempted to eliminate mistaken identifications of physically unrelated opposite polarity features 'by excluding small bipolar regions observed in areas where network of both polarities of comparable size and strength was noted on the previous day'.

Table 2. X-ray bright points and solar activity

property	level of certainty	significance
1. Bright points are magnetically bipolar closed regions	certain	They appear to be a little-explored form of solar activity
2. Bright points form the short lifetime end of a continuous distribution of activity	well established	There are no 'characteristic' parameters for active regions on the Sun
3. Bright points represent emerging magnetic flux	Fairly well established	Magnetic flux is produced in a large range of scale sizes in the Sun
4. During the Skylab period most of the magnetic flux on the Sun emerged in the form of bright points	highly probable	The basic method of magnetic flux generation may be small, rather than large, concentrations
5. During most of the past Solar cycle, bright points dominated the emergence of magnetic flux on the Sun	appears likely	Dynamo theories for large active centres may be missing much of the true picture
6. Bright points vary in anticorrelation with long-lived active regions throughout the solar cycle	appears likely	The solar cycle may be an oscillation in wavenumber of flux production rather than in total quantity of magnetic flux emerging
7. The total average rate of magnetic flux emergence on the Sun may not vary with the cycle	suggested by results to date	

The result of this study was the conclusion that the number of ephemeral regions varies nearly in phase with the sunspot cycle. However, the small regions reached a minimum about 1 year before the sunspots did. A straightforward comparison of their results with those presented here shows that the two data sets cannot be reconciled. For example, from early 1976 to late 1977, Martin & Harvey find that the number of ephemeral regions goes up by a factor of 3. The X-ray results, however, show that in the same time period the number of bright points goes down by a factor of 2.

On the other hand, Howard (1976) describes his measurements of total magnetic flux on the Sun. At 12″ resolution he finds that the average difference in total flux between cycle maximum and minimum is less than a factor of 2. Moreover, he finds that 'an interval of low measured total magnetic flux resulted at least in part from an increase in the mixing of magnetic elements of the two polarities on a scale comparable with the aperture size.' This statement may be consistent with the presence of numerous small bipolar features during a period which would otherwise be considered to be one of low activity, as indicated by the X-ray results.

On the other hand, the attempt to find bipoles on magnetograms may to some extent be hampered by contamination of mixed polarity fields from large active regions, yielding apparent bipoles which are not in reality connected. The question should in principle be answerable with existing data.

Although the solar cycle variability is the major unresolved question in bright point research, there are a number of other significant areas still to be explored. For example, there are no simultaneous magnetograph and soft X-ray observations with good time resolution. With such data one could determine unequivocally whether all bright points represent emerging magnetic flux and whether all detectable emerging flux shows up in X-ray emission. Such data could also be of use in answering far broader questions concerning the physical structure of the corona and its relation to the magnetic field.

Other areas of research that have been suggested and which are presently under study include the relation between bright point flares and macrospicules (and spicules), analysis of flare energy storage and release mechanisms by using bright point flare data, and bright points as sources of the solar wind. Clearly, there is a great deal of work yet to be done.

The X-ray data used for most of this work were obtained under the leadership of Dr G. S. Vaiana, who has also guided the analysis of the X-ray data in general and the bright point work in particular. I would like to thank Dr N. O. Weiss for helpful discussions and Dr Vaiana for comments on the manuscripts. Support for this work was provided in part by N.A.S.A. under Contract NAS8-31374 and by the Langley–Abbot Program.

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