MAGNETIC PROPERTIES OF X-RAY BRIGHT POINTS

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Abstract. Using high resolution KPNO magnetograms and sequences of simultaneous S-054 soft X-ray solar images we have compared the properties of X-ray bright points (XBP) and ephemeral active regions (ER). All XBP appear on the magnetograms as bipolar features, except for very newly emerged or old and decayed XBP. We find that the separation of the magnetic bipoles increases with the age of the XBP, with an average emergence growth rate of $2.2 \pm 0.4$ km s$^{-1}$. The total magnetic flux in a typical XBP living about 8 hr is found to be $=2 \times 10^{19}$ Mx. A proportionality is found between XBP lifetime and total magnetic flux, equivalent to $=10^{20}$ Mx per day of lifetime.

1. Introduction

Compact X-ray emitting features (XBP) were first observed in soft X-ray images in 1969 (Vaiana et al., 1970). They typically appear as spots of 20–30 arc sec diameter, often with a 5–10 arc sec bright core. They are associated with bipolar magnetic features (Krieger et al., 1971; Harvey et al., 1975) and are found at all solar latitudes (Golub et al., 1974), although they emerge preferentially in the active region latitudes (Golub et al., 1975). XBP are found to have a wide range of lifetimes, the relative number observed being a decreasing function of lifetime. The characteristic lifetime of XBP is about 9 hr. Approximately $2 \times 10^3$ of these features emerge per day on the Sun in the lifetime range 2–48 hr and the number emerging with shorter lifetime could be much greater (Golub et al., 1976). There is no observed variation of the charactereristic XBP lifetime as a function of solar latitude, except for the presence of a small number of long-lived features (active regions) at low latitudes.

There is a broad spectrum of active region size and lifetime. In the small-scale region of this spectrum the term ephemeral active region (ER) was introduced by Dodson (1953). The properties of ER have been described by Dodson and Hedeman (1967), Harvey and Martin (1973) and Harvey et al. (1975). In brief, ER have lifetimes generally less than 1 day, are recognized on magnetograms as

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small (~20") bipolar regions with total magnetic flux less than about $10^{20}$ Mx and in chromospheric observations as small bright regions. The minimum number of ER present on the Sun in KPNO daily magnetograms is typically several hundred but the number varied in 1970, 1973 and 1975 in parallel with the usual indices of solar activity. The numbers increase rapidly with increased instrumental sensitivity and spatial resolution. There also appear to be significant variations in numbers from month to month. The latitude distribution of ER is very broad and seems to consist of a more or less uniform component plus a component similar to the distribution of larger active regions. There seems to be no preference in the location of ER with respect to the chromospheric network and ER seem to emerge with random orientations.

The work of the above investigators has led to many fundamental questions about the nature of XBP and ER and their role in solar activity. Aside from such qualitative questions as the bipolarity of XBP and details of the magnetic field configuration, there are dynamic and quantitative questions, such as do XBP/ER represent emerging magnetic flux? How much flux do they bring to the solar surface? How does this contribution relate to that of active regions and how does it vary through a solar cycle? What modifications to dynamo theories will be necessary to take into account global flux emergence with a spectrum weighted toward small, short-lived features?

These questions cannot all be answered at the present time. The data available for this study were limited to a short part of a solar cycle (May 1973 to January 1974) and the high resolution magnetograms were at that time limited to one, or at most two per day. We could therefore make static comparisons between XBP and ER to determine bipolarity, magnetic field strength and orientation, quantities of magnetic flux and statistical studies in all of these parameters. The availability of a relatively large number of X-ray photographs allowed some dynamic comparisons by following the evolution of each feature at the coronal level before and after the time of a simultaneous magnetogram measurement. We could therefore compare the quantities measured in the magnetogram with the age, size, lifetime or stage of evolution of the X-ray feature.

The static comparison showed a surprisingly poor correlation between XBP and ER. The overlap is only $\approx 50\%$ if the features are identified independently, without prior comparison of X-ray photos and magnetograms. In all cases, a magnetic bipole at some level of visibility could be found near the location of an XBP. However, some clear bipoles were found which showed no coronal emission at the time of the X-ray photo. The degree of correlation appears to be primarily a function of the evolutionary history of the XBP.

XBP/ER represent emerging bipolar magnetic flux. This has been demonstrated by showing that the spacing between bipoles on the magnetogram is an increasing function of the age of the XBP and by showing a similar relation for the measured total magnetic flux as a function of age. The average lifetime of ER on magnetograms is approximately the same as the X-ray lifetime of XBP, as determined by
the number of features identified on a given photo which can still be identified 24 hr later (≈10%).

The total magnetic flux in an ER is an increasing function of XBP age. We find a linear relation between flux and age, with proportionality constant $1.5 \times 10^{15}$ Mx s$^{-1}$. A characteristic value of total magnetic flux for an XBP is $2-3 \times 10^{19}$ Mx. We also find that, as is the case for active regions, the lifetime of an XBP is proportional to its total magnetic flux, with proportionality constant ≈$10^{20}$ Mx day$^{-1}$.

2. Analysis Procedures

The soft X-ray images used for this study were obtained with the S–054 Spectrographic Telescope flown on the Skylab/ATM mission in 1973 (Vaiana et al., 1973). The images were 64-second exposures taken through a (2–32, 44–54) Å passband filter. The spatial resolution of the telescope is primarily a function of the spectral characteristics of the source and the angle between the source and the optical axis of the telescope (Vaiana et al., 1977). The relatively low temperature of XBP and the fact that only points within ≈ one-half a solar radius from Sun center were used in the comparison, lead us to estimate that the X-ray resolution for XBP is about the same as the magnetogram resolution, i.e., a few arc seconds. Moreover, as indicated by several objective tests described below, the sensitivities of the two instruments for detection of XBP/ER seem about equal.

Line-of-sight component magnetograms employed in our study were obtained with the 40-channel Babcock-type magnetograph (Livingston et al., 1971) and the McMath Solar Telescope on Kitt Peak. In addition to daily full disk observations, we used scans having the same spatial resolution (2.5") but 5 times less noise (∼2 G per resolution element). These observations typically covered an area of 1000" × 1000" centered on the solar disk. A comparison of nearly simultaneous X-ray and magnetic observations is shown in Figure 1.

The magnetic data were prepared for analysis by first converting the tape-recorded digital information into grey-scale pictures of the kind shown in Figure 1. The recorded numbers represent the average line-of-sight field strength within each 2.5" square resolution element and are thus equivalent to magnetic flux measurements at the disk center. No effort has been made to correct observations away from the disk center since we expect our measurements fairly near the disk center not to be greatly different from true flux measurements.

Fluxes were computed by isolating a small region containing a specific magnetic feature and the adding positive, negative and both measurements as separate sums. These sums were computed with a variable lower threshold. The reason for using a threshold is to exclude large areas with weak background flux. Examination of the variation of computed fluxes as a function of threshold frequently showed a change in behavior at values around 20 G per resolution element so this value was selected as the threshold. Though this procedure may discriminate between the physically associated flux in an ER and physically unrelated weak
Fig. 1. Solid circles indicate bipolar magnetic features found to correspond with X-ray bright points, identified separately. Dashed circles indicate some bipole which did not correspond to obvious XBP; most of these are found to be associated with XBP obscured by overlying structures (see text).
background flux, we have been unable to devise a way of discriminating between ER flux and strong unrelated flux that happens to be close to the ER. Such chance associations represent a significant source of noise in our flux measurements.

The basis for the evolutionary comparisons herein reported was a determination of the age of each XBP at the time of the magnetograph scan and a determination of the total X-ray lifetime of each XBP. The time between X-ray exposure sequences was generally one hour in these studies and in each of the two data samples a photo sequence was available midway through the hour which it took to obtain the high resolution magnetogram. The age of a particular XBP was taken to be the time lapse between this latter X-ray photo and the earliest X-ray photo on which the feature could be seen. The total lifetime of each point was determined by taking the length of time for which it could be seen and adding an amount which took into account the time resolution. For example, a point which was first seen on a photo at 0600 and last seen at 1500 lived at least nine hours. If the next photo after 1500 was taken at 1600 and the next earlier photo before 0600 was taken at 0500 and the XBP was not visible on either of these, then its lifetime was less than eleven hours. The lifetime assigned in this case would have been $10 \pm 1$ hr.

### 3. Relation between XBP and ER

#### 3.1. Static Comparison

The most basic level of comparison between XBP and ER is investigation of the amount of overlap between the two types of feature. The expectation was that XBP would be bipolar and that bipoles would appear as X-ray features. While these rules are found to hold in general, there are more exceptions than anticipated.

The comparison was made by identifying the XBP and ER separately before making a comparison. ER were identified on magnetograms by looking for closely spaced regions of opposite ('black and white') polarity having similar size and strength and separated from other magnetic elements by at least a few resolution elements. XBP were located by the method described in Golub et al. (1974), basically by looking for closed compact emission features of size less than $\approx 30$ arc sec. On two high resolution magnetograms a total of 79 ER were located. On the two appropriate X-ray photos 73 XBP were located. However, the direct overlap between the two classes was only 36 features. In almost all cases ($\approx 95\%$) a magnetograph feature interpretable as a bipoles could be found at the location of an XBP if one looked carefully enough. However, there were many clear bipoles on the magnetogram for which no clearly identifiable XBP was seen.

The direct overlap of 36 features out of a possible 73 is substantially more than would be expected if the circles in the two parts of Figure 1 were placed at random. The ER on the magnetogram occupy $\approx 3\%$ of the available total area, as do the XBP on the X-ray photo. The criterion we used for determining correspondence was that the center of the XBP circle should lie within the boundary of
the ER circle. The random overlap (ignoring very small second order effects)
would be just 3%; instead, the overlap is $36 \mid 73 = 49\%$. The probability that this
overlap is a random fluctuation is $P \left( 36 \mid 73, 0.03 \right)$ which is a vanishingly small
number.

Those cases for which a clear bipole was not discernible on the magnetogram
tended to fall into two classes, very young and very old XBP's. That is, the
absence of a clear bipole was associated either with a very newly emerged X-ray
feature or one which was near the end of its lifetime and so presumably was
associated with weak and diffused magnetic fields.

The above considerations are quantified in Table I, which shows the fraction of
XBP not associated with clear bipoles as a function of stage of evolution. The
selection of points was a subjective one. We examined the appearance of the
magnetic field, using the X-ray photos only to determine the location of the
magnetic feature. A point was judged not correlated if the field structure was so weak
or confused that the orientation of the bipole could not be determined. This
sample therefore, includes features which were not detected as bipoles using only
a magnetogram, but which were identified once an X-ray feature was seen.

<table>
<thead>
<tr>
<th>XBP ↔ ER</th>
<th>Young $(t&lt;\frac{1}{4}T)$</th>
<th>Middle $(\frac{1}{4}T &lt; t &lt; \frac{3}{4}T)$</th>
<th>Old $(t &gt; \frac{3}{4}T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>8</td>
<td>39</td>
<td>4</td>
</tr>
<tr>
<td>No</td>
<td>9</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

Degree of correlation between XBP and ER as a function of the
stage of evolution of the XBP. Evolution is defined by the ratio of
XBP age at the time of the comparison to eventual total lifetime
determined from a series of X-ray images. Young, emerging ER
and old, decayed ER are not well correlated with XBP; middle-
aged ER show good correlation with XBP.

The table shows that XBP in the first or last quarter of their lives have roughly
an even chance of correlation with a good bipole on a magnetogram. However,
XBP in the middle half of their evolution are associated with clear bipoles in more
than 5 out of 6 cases. A likely explanation for the poor association of very young
or very old XBP seems to be the existence of closely spaced, unresolved bipoles in
the case of young points (see below) and diffused weak fields for older points.
Moreover, of the 7 features in mid-evolution which could not be identified with
clearly oriented bipoles, 2 were located at the intersection of adjacent magneto-
gram scans lines, 2 others were part of a complex cluster of very closely spaced
XBP and 1 was a very small short-lived XBP. Therefore, 44 of the 46 ‘middle-
aged’ XBP were either associated with clear bipoles or good reasons could be
found for a lack of association.

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The cases in which an ER was identified but an XBP was not observed seem to fall into two categories. In Figure 1, four of these more obvious ER are indicated by dashed circles and the corresponding areas are circled on the X-ray photo. The majority of such cases correspond to areas in which there is overlying X-ray structure which obscures the identification of XBP (see Golub et al., 1974). As shown in Figure 1, the X-ray image generally shows a diffuse brightening under a larger structure, probably indicating an obscured XBP. There still remain approximately 20% of all ER for which no X-ray emission is observed. The likely explanations for these cases are: (1) since the magnetograph scan took an hour, the XBP may have flared or decayed during that time, and (2) the ER was misidentified due to chance association of opposite polarity magnetic flux without a physical connection.

3.2. Dynamic Comparisons
From the total of 73 XBP available in the August 21 and January 23 comparisons, we selected the features for which the magnetogram showed a clear bipole and the X-ray coverage was such that the age could be determined to within 3 hr or better. The resulting subset consisted of 55 points. These were grouped according to the separation of the bipoles, using bin widths of 3.3 arc sec starting at a minimum measurable width of 6.7 arc sec. The measured ages of the XBP in each of these bins were then averaged to produce a set of values $S_n, A_i$ of separation and age, shown in Figure 2.

![Image](https://example.com/image.png)

**Fig. 2.** Linear regression of XBP age on separation between the two polarities in the corresponding bipolar magnetic features. Straight line indicates the best fit, found by the least-squares method, giving an approximate correlation between XBP age and magnetic bipole separation, XBP are found to correspond to emerging magnetic flux.
In order to obtain an order-of-magnitude estimate of correlation between these two quantities we performed a linear least-squares analysis (Bevington, p. 107) to fit the observed ages to the separation bins of the form

$$A_i = aS_i + b.$$ 

Although the true relationship between the parameters may not be a linear one, this fit may be viewed as the lowest order in a polynomial expansion. The limited data sample available does not justify use of a higher order fit.

The resulting values of the parameters $a$ and $b$ for the data shown in Figure 2 are

$$a = 0.24 \pm 0.06 \text{ hr arc sec}^{-1},$$

$$b = 1.2 \pm 1.2 \text{ hr}.$$ 

The value of $b$ indicates that the birth of an XBP is simultaneous with that of an ER to within the accuracy of our measurements. The value of $a$ can be interpreted as an average growth rate for ER, equivalent to $0.8 \pm 0.2 \text{ km s}^{-1}$.

A growth parameter which may be more meaningful can be obtained by restricting the data sample even further. We attempted to find an average rate of increase during the initial growth phase by selecting only those XBP which had lived half or less of their total lifetimes at the time of the magnetogram, e.g., a point whose total X-ray lifetime was 14 hr, was accepted if its age was less than 7 hr at the time of the magnetograph scan. This procedure reduced the data sample to 39 points and yielded an average growth rate of $2.2 \pm 0.4 \text{ km s}^{-1}$. We note that the initial emergence rate of XBP is substantially greater than the overall average rate. This characteristic is qualitatively and quantitatively the same as for active regions (Bumba and Howard, 1965).

As described above, chance occurrence of strong background flux near an ER represented a major source of noise in these measurements. We have, however, been able to ascertain a proportionality between the total flux in an ER and the age of the corresponding XBP. At the same time, assuming that the ER and XBP are born roughly simultaneously (see above) we obtain an estimate of the contamination by background flux.

Using the same sample of developing XBP described above, we have separated the features into two-hour lifetime bins. The measured values of magnetic flux are shown in Table II, where the error bars ($\sigma_\mu$) are obtained from the formulae

$$\sigma_\mu^2 = \sigma^2 / N, \quad \sigma^2 = \sum (X_i - \bar{X})^2 / (N - 1).$$

Again using a least squares fit we obtain a linear relation between XBP age and ER total flux

$$\Phi(Mx) = a + b\tau \text{ (hr)}$$

with

$$a = 500 \pm 130 \text{ f.u.}$$

$$b = 75 \pm 25 \text{ f.u.} \quad (1 \text{ f.u.} = 3.3 \times 10^{16} \text{ Mx}).$$

The parameter $b$ we interpret as a flux emergence rate for XBP/ER and corresponds to $\approx 10^{15} \text{ Mx s}^{-1}$. The parameter $a$ appears to be a measure of the
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TABLE II

Total magnetic flux vs XBP age

<table>
<thead>
<tr>
<th>Age (hours)</th>
<th>$\Phi_{\text{Tot}}$</th>
<th>Number of points</th>
<th>Average total lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–2</td>
<td>550±120</td>
<td>12</td>
<td>5±2</td>
</tr>
<tr>
<td>2–4</td>
<td>750±370</td>
<td>5</td>
<td>11±3</td>
</tr>
<tr>
<td>4–6</td>
<td>1120±300</td>
<td>7</td>
<td>16±1</td>
</tr>
<tr>
<td>6–8</td>
<td>980±240</td>
<td>11</td>
<td>18±1</td>
</tr>
<tr>
<td>8–10</td>
<td>insufficient data</td>
<td></td>
<td>≈21</td>
</tr>
<tr>
<td>&gt;10</td>
<td>1280±250</td>
<td>3</td>
<td>&gt;26</td>
</tr>
</tbody>
</table>

* One flux unit ≈3.3×10$^{16}$ Mx.

Statistical comparison of measured total magnetic flux $|\Phi_+| + |\Phi_-|$ (20 G lower cutoff) with XBP age. Also shown is the number of XBP in each data bin and the average total lifetimes of the points in each bin. Total flux increases with XBP age and lifetime, although the background flux and dispersion in the data are both large.

average contamination by background flux, amounting to ≈2×10$^{19}$ Mx, which is consistent with fluxes measured at random locations in the quiet network. A typical XBP, which has a growth phase lasting ≈1.5×10$^{4}$ s will thus contain ≈1.5×10$^{19}$ Mx of total magnetic flux, with the 20 G background cutoff used here. Lowering the cutoff level to 10 G increases the emergence rate to 1.5×10$^{15}$ Mx s$^{-1}$ and the typical XBP flux to ≈2×10$^{19}$ Mx.

This emergence rate is lower than that usually quoted for active regions, by a factor of 3–5. However, the overall behavior is again similar to that of the larger and longer-lived active region, i.e., initial rapid emergence followed by a more gradual dispersal of the magnetic fields.

4. Summary

High resolution KPNO magnetograms and sets of simultaneous S-054 soft X-ray solar images have been used to compare properties of X-ray bright points and ephemeral active regions. Two sets of observations were used; in both cases an X-ray image was available simultaneous with the magnetograph scan and X-ray images allowing 1–2 hr time resolution for 12 hr before and after the magnetogram were available. These were used to obtain information about the age, lifetime and evolutionary history of each XBP at the time of the comparison.

We find that essentially all (44 of 46) XBP are seen as bipolar magnetic features during the middle stages of their evolution. Very young and very old XBP are frequently not seen on the magnetograms used in this study, probably because the bipoles are closely spaced and therefore unresolved in young XBP and because the magnetic field is dispersed and weak in old XBP.
Approximately half of the ER identified on magnetograms do not coincide with obvious XBP. Closer inspection of the X-ray photos shows that most of these ER coincide with diffuse X-ray brightenings under large scale coronal structures. We interpret these as XBP which are obscured by the overlying structures. The remaining ER ($\approx$20\%) have no associated X-ray emission and represent either chance association of opposite polarity fields or XBP which have flared or decayed during the one hour time interval needed to complete the magnetograph scan.

We find that XBP represent emerging magnetic flux. This has been shown in two ways, both representing indirect statistical methods since time sequences of data were available for the X-ray observations but not for the magnetograms. The XBP were divided into bins on the basis of age and the average values of bipole separation and total magnetic flux were determined for the points in each age bin. Both quantities were found to be increasing functions of XBP age, implying that XBP correspond to magnetic flux which emerges through the photosphere into the corona and diffuses across the solar surface, as do the larger and more easily observed active regions.

In Table II we compared XBP age with the measured total magnetic flux. We expect that on the average the ages of the XBP at the time of the magnetograph scan will be proportional to their total lifetimes. (The proportionality would be a factor of two, except that we specifically chose a sample of developing XBP; in fact the average ages are nearer to a third of the total lifetimes.) We have listed the average total lifetimes of the XBP in each age group and find that the average lifetime of XBP increases with the total magnetic flux.

We noted in Golub et al. (1976b) that there exists a proportionality constant of about $10^{20}$ Mx day$^{-1}$ between total magnetic flux and lifetime for active regions, and suggested that the proportionality may extend to XBP. If we use the flux emergence rate found in Section 3.2 and assume that the flux history of an average XBP is such that flux emerges for about half of its total lifetime, we find a proportionality constant $\approx 5 \times 10^{14}$ Mx s$^{-1}$ between lifetime and flux, or $\approx 0.4 \times 10^{20}$ Mx day$^{-1}$. We note that the value of this 'constant' depends somewhat on the observational method used to determine lifetime. A factor of two difference between reported chromospheric and X-ray lifetimes for small active regions is often encountered (S. Little, private communication); the X-ray lifetime is typically the longer one. The linear relationship between flux and lifetime thus appears to be preserved over the entire spectrum of emerging flux, from large active regions down to the smallest observable features.

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References


