EVIDENCE FOR GLOBALLY COHERENT VARIABILITY IN SOLAR MAGNETIC FLUX EMERGENCE

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ABSTRACT

We examine the large-scale spatial and temporal variations in the emergence of X-ray bright points on the Sun, in order to study the global properties of magnetic flux emergence. Major variations in the rate of flux emergence are observed at all solar latitudes, on a time scale of 3–5 months. The most economical explanation of the observations is that the full Sun participated in a single large eruptive event during the available 8 month observing period from Skylab in 1973. The peak of this global event corresponds in time to the eruption of a major complex of activity. Moreover, it appears that the only portion of the solar surface which deviates from the above pattern of behavior is the low latitude region in the vicinity of the AR complex; this area shows a temporary depletion immediately following the AR outburst. The high-latitude regions in both hemispheres show the same variation and appear to lead the low-latitude emergence by approximately 1 month.

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

I. INTRODUCTION

In this Letter we present in detail one aspect of solar magnetic flux emergence—the presence of global coherence in the emergence process. We have found major variations in the rate of magnetic flux emergence at all solar latitudes and with time scales of 3–5 months. A cross-correlation analysis shows that the variations are temporally correlated at all latitudes and longitudes during the eight solar rotations observed. Only a single region of the solar surface, extending between ±30° and ±30° in latitude and between 150° and 330° in (Carrington) longitude exhibits a temporary deviation from the global pattern of behavior. At this location, there erupted on the Sun a major complex of activity whose appearance coincided in time with the peak of the hypothesized global event. Moreover, the bright point emergence in this region of the solar surface appears to follow the full Sun behavior except for a temporary two-month depletion immediately following the eruption of the activity complex. Finally there is a small but statistically significant phase lag between the high- and low-latitude flux eruption peaks; the northern and southern polar regions both peak simultaneously and about 1 month before the low-latitude peak.

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, Krieger, and Timothy 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. Newly emerging magnetic flux is particularly bright in X-ray emission; we may therefore “tag” the closed regions easily as a basis for studies of magnetic flux emergence.

The sharp division in X-ray brightness between open and closed regions is particularly advantageous in studying the small-scale end of the solar activity distribution, i.e., the X-ray bright points (XBP). 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 two days or less (Golub et al. 1977), except possibly at solar maximum. Moreover, we have shown that simply counting the number of bright points present at any one time in a given area can be translated directly into an estimate of the magnetic flux emergence rate in that area. The number counts presented in this Letter therefore provide direct information about changes in solar magnetic flux emergence during the available 6 months of observation.

II. THE OBSERVATIONS

The X-ray observations and data reduction techniques used in this analysis have been described in detail in previous publications (cf. Vaiana et al. 1977; Golub, Krieger, and Vaiana 1976). For the purposes of the present Letter, the relevant fact is that our previous work has shown that bright points (in 1973) represent the vast majority of emerging magnetic flux on the Sun. Observations of the changes in the relative numbers of these features as a function of time and of location on the solar surface therefore lead directly to conclusions about the nature of magnetic flux emergence, independent of the behavior of the larger active regions. Moreover, the large number of bright

1 Also at Osservatorio Astronomico di Palermo, Italy.
points observed allows us to draw conclusions at a level of statistical significance which is often not possible in active region studies. This advantage is particularly evident for studies involving variability on short time scales or in restricted portions of the solar surface.

In Golub, Krieger, and Vaiana (1976) we reported the existence of major variations in magnetic flux emergence on the Sun over time scales of 3–4 solar rotations. We found that the behavior of high-latitude regions was smooth, with an increase by a factor of 2 during three rotations followed by a return to the starting level in another three rotations. The low-latitude behavior was more complex and could not easily be categorized, except for an approximate agreement with the pattern at high latitudes.

We have now examined the data in more detail and find that the variations can be presented in a simple manner. When the low-latitude data are separated into six longitude intervals, a sharp break divides the behavior of these intervals into two longitude groupings. The four intervals from 120° to 360° all show one characteristic pattern as a function of time, and the two intervals from 0° to 120° both show an entirely different pattern. Within these two groupings the individual 60° intervals show nearly identical behavior, and we have averaged them together in order to increase the statistical significance of the observed variations.

An overall view of the variability is shown in Figure 1. The two upper curves represent the behavior of the low latitudes as described above; the lower curve shows the behavior at high latitudes, with solar north and south added together and no longitude division.

The figure shows the apparent complex variability noted earlier, particularly at low latitudes. The breakup into hemispheres does represent a simplification and we will argue in § III that a simple and coherent interpretation of these variations is possible within the context of a single global event and its aftereffects.

The northern and southern high-latitude data both exhibit the smooth variation shown in Figure 1 for the combined data set. The relative number densities as a function of time for north and south separately are shown in Figure 2. We see that both curves peak during rotations 1604 and 1605 after a rise during three solar rotations. The peak is followed by a 3 month decline that continues to the end of our observing period. The northern-hemisphere data are generally somewhat higher than those in the south.

III. INTERPRETATION

We believe that the apparent complexity of the data shown in Figures 1 and 2 can be interpreted in a simple manner. The elements of the picture are the following: 1. There is a global emergence of X-ray bright points over the full Sun, with rise and fall times of roughly three solar rotations.

2. Coincident in time with the peak of the global emergence, there erupted a "complex of activity" at low latitudes on one solar hemisphere.

3. The active-region eruption was followed by a temporary depletion of bright points in that hemisphere.

4. Following the active-region emergence there was a temporary and well-localized depletion in the emergence rate of small regions and a gradual diminution in the full Sun number of small regions emerging.

5. The increase in bright-point emergence begins first at high latitudes. The low-latitude variation has the same time profile, but with a phase delay of about 3 weeks.

There are several independent consistency checks.
which can be performed to help determine the plausibility of the global event hypothesis. Two fundamental tests are the following: First, perform a cross-correlation analysis to determine whether the coherences in variability between various areas on the Sun are statistically significant. Second, determine whether the "depletion" really is such, by examining the variations in latitude distribution on that hemisphere relative to the rest of the Sun and to other times in the observing period. If, as we will show, these tests are positive, then a global emergence becomes significantly more probable than a chance coincidence of separate events.

A calculation of cross-correlation coefficients for the variation in flux emergence over various portions of the solar surface confirms in a quantitative manner the qualitative description provided above. We have divided the surface into six portions: 30°–90° N, 30° N–30° S, and 30°–90° S, each divided into 0°–120° and 120°–360° longitude bins. We find that a statistically significant temporal correlation exists between every pair chosen from the six areas, except for the portion (30° N–30° S, 120°–360°). Even in this latter case, for which we have argued that a temporary depletion occurred, there is a positive temporal correlation with the remaining areas for all times outside of the depletion.

A list of calculated correlations is provided in Table 1; note that they are all positive and greater than ±0.60. The most significant of these correlations shows the following: the temporal variations in the north and south high-latitude regions are strongly correlated; excluding the area of temporary local depletion during rotations 1605 and 1606, the full Sun high-latitude versus low-latitude data show significant temporal correlation; and finally, introducing a 1 month phase lag between the high- and low-latitude data produces a dramatic increase in the cross-correlation coefficients for high versus low latitudes over the full Sun and over only the inactive hemisphere. The probability that the variations in four separate areas (north, south, active, and inactive regions) show the observed correlation by chance is only 5.3 × 10⁻⁴. If we include the 1 month phase lag as an assumed part of the event, then the probability of random occurrence is smaller than 10⁻⁴.

The dramatic increases in correlation when the low-latitude data sets are advanced by one rotation are statistically significant as shown by the small standard errors. The implication is that the high latitudes, both north and south, exhibit the same temporal variation throughout the course of this event as do the low latitudes, but about 1 month earlier. The only exception is the low-latitude behavior on the active hemisphere during two of the eight rotations.

We can test whether the decrease in bright-point emergence rate during rotations 1605 and 1606 is in fact a depletion. To do this, we examine the latitude distributions of bright points on the two hemispheres in question, and we compare these latitude distributions to the overall average ATM distribution. The comparison is shown in Figure 3, and it is clear that there is a local depletion at equatorial latitudes in the longitude bin 120°–360°, whereas the other hemisphere shows no depletion.

![Figure 3](image-url)  
**Fig. 3.**—Comparison of latitude distributions for X-ray bright points. Solid histogram shows ATM average, circles show latitude distribution of points in the longitude bin 0°–120° during Carrington rotation 1606, and crosses show distribution for points in the 120°–360° longitude bin. There is a relative depletion in the emergence of bright points in the active-region latitudes in the 120°–360° bin.

<table>
<thead>
<tr>
<th>Set A</th>
<th>Set B</th>
<th>r</th>
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</thead>
<tbody>
<tr>
<td>lat &gt;30°, long = 0°–120°</td>
<td>lat &lt;30°, long = 0°–120°</td>
<td>+0.66 (+0.20, -0.38)</td>
</tr>
<tr>
<td>lat &gt;30°, long = 0°–360°</td>
<td>lat &lt;30°, long = 0°–360°</td>
<td>+0.67 (+0.14, -0.22)</td>
</tr>
<tr>
<td>lat &gt;30°, long = 0°–120°</td>
<td>lat &gt;30°, long = 120°–360°</td>
<td>+0.60 (+0.10, -0.50)</td>
</tr>
<tr>
<td>lat 30°–90° N, long = 0°–360°</td>
<td>lat 30°–90° S, long = 0°–360°</td>
<td>+0.82 (+0.10, -0.20)</td>
</tr>
<tr>
<td>lat &gt;30°, long = 0°–120°</td>
<td>lat &lt;30°, long = 0°–120°</td>
<td>+0.98 (+0.01, -0.04)</td>
</tr>
<tr>
<td>(Set A one rotation earlier)</td>
<td>(Set A one rotation earlier)</td>
<td>+0.93 (+0.04, -0.07)</td>
</tr>
</tbody>
</table>

* The two data points in rotations 1605 and 1606, latitude <30°, are excluded from the calculations since these are interpreted as a temporary local depletion (see text).
Several further points should be made here. First, this relative depletion of one hemisphere is not an excess on the other hemisphere, as shown by comparison with the ATM average ratio of low- to high-latitude bright point number. The overall average is 0.75; i.e., about three-fourths of all bright points are found at latitudes <30°. For the longitude bin 0°–120° on rotation 1606, we find the ratio to be 0.77 ± 0.01. The corresponding ratio for the 120°–360° bin is 0.59 ± 0.01, so that the presence of a depletion does seem to be the most likely explanation.

The depletion is not attributable to a visibility effect, such as obscuration by the newly emerged active regions. We have described in detail in Golub, Davis, and Krieger (1979) how corrections for active region presence are made and how we estimate the magnitude of any possible systematic errors. The result of such an analysis for the present case is that, at the peak of the eruption, the active regions could be responsible for an error of no more than 15% in the number of bright points observed. However, the observed number would have to be increased by a factor of ~120% in order for the depletion to be merely a systematic error; we do not consider this to be a likely possibility.

Finally, the two low-latitude curves shown in Figure 1 start at different levels in rotations 1601 and 1602, with the 0°–120° region being substantially lower. This would seem to argue against the global interpretation that we propose. However, it should be recalled that during the preceding rotations 1598–1600 there emerged on the Sun another large complex of activity in the 0°–180° hemisphere. It is thus entirely consistent with our interpretation to say that the low-latitude 0°–120° curve in rotation 1601 is lower because it is recovering from a depletion caused by the earlier active-region emergence.

In summary, we have performed a detailed examination of the global emergence properties of small-scale magnetic flux emergence on the Sun during a 6 month period in 1973. We find that there is a nearly simultaneous coherent increase, by about a factor of 2, in the rate of magnetic flux emergence over the full Sun. Simultaneous with the peak of this global event, there is an eruption of a major complex of active regions at low latitudes on one solar hemisphere. The eruption is accompanied by a local temporary depletion in the emergence of small-scale magnetic flux. Subsequently, the global level of flux emergence gradually decreases over a period of roughly three rotations.

Because of the limited coverage in the Skylab data, it is still possible that the observed variation is not representative of small-scale magnetic flux emergence on the Sun. This possibility can be tested only by examining more extensive data over a longer time period. However, to the best of our knowledge there does not appear to be an unambiguous way of using existing data—such as magnetograms or Hα and Ca K spectroheliograms—to extend our studies, and there are no other suitable X-ray data available. Therefore, while the present result—that the entire 6 months of data encompassed a single global event—has been demonstrated, we regard the further implication that the coherence has a physical basis in the Sun as being a reasonable working hypothesis.

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REFERENCES


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