XUV OBSERVATIONS OF
CORONAL MAGNETIC FIELDS

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Abstract. Spectroheliograms obtained with the Naval Research Laboratory's Extreme Ultraviolet Spectrograph (S082A) on Skylab are compared with Kitt Peak National Observatory magnetograms. A principal result is the characteristic reconnection of flux from an emerging bipolar magnetic region to previously existing flux in its vicinity. Examples of the disappearance of magnetic flux from the solar atmosphere are also shown. The results of a particularly simple, potential field calculation are shown for comparison with the Skylab observations.

1. Introduction

This paper presents essentially two results from the Skylab observations. The principal one is that magnetic flux from emerging bipolar magnetic regions (BMRs) reconnects to previously existing flux in neighboring areas. This reconnection results in a characteristic pattern of emission from new active regions in the corona. This paper is primarily devoted to illustrating these flux connections with several different examples. A second result is the observation of the disappearance of magnetic flux from the solar atmosphere. We devote a few figures to the illustration of this process. For a description of the instrument, the data format, the observational techniques, and other details, we refer the reader to a previous paper (Tousey et al., 1973).

To familiarize the reader with the way in which XUV spectroheliograms seem to map the extension of photospheric magnetic fields into the corona, we begin with a comparison of three spectroheliograms and a magnetogram. These are shown in Figure 1. We have selected spectroheliograms in the lines of Fe xv 285 Å, Mg ix 368 Å, and Ne vii 465 Å. The appearance of the Sun varies considerably between these three lines, presumably corresponding to the widely different temperatures at which they are formed. According to the astrophysical literature (for example, see Jordan, 1969), Fe xv is formed in the relatively hot corona at a temperature in excess of $2 \times 10^6$ K. Mg ix is formed in the relatively cool corona at roughly $1 \times 10^6$ K. Ne vii is formed in the 'corona-chromosphere transition region' at roughly $0.5 \times 10^6$ K.

Thus, we can infer from Figure 1 that the hot corona consists almost entirely of closed loops of emission connecting regions of opposite photospheric polarity. The cool corona shows fewer closed loops than the hot corona, but more emission at the ends of these loops and in open fields that extend a considerable distance from the

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Fig. 1. Comparison between XUV spectroheliograms (negative prints) and a photospheric magnetogram illustrating the apparent connection of photospheric magnetic fields through the corona. The convention used in all photographs of this article is that solar north is upward and east to the left. Also, in the magnetograms positive line-of-sight polarity (directed outward from the Sun) is white and negative is black.
solar surface. In general, the transition region consists of emission from the chromospheric network, from a few loops in active regions, and from spikes of emission at the end points of loops where the emission from the hot corona is relatively weak.

The enhanced Ne vii emission over the large sunspot in Figure 1 is a special case of this effect, as Brueckner and Bartoe (1974) and Foukal et al. (1974) have also observed. In fact, the Ne vii emission is often so intense over sunspots that one can locate sunspots by looking for the brightest features on Ne vii spectroheliograms. Applying this principle to the Ne vii spectroheliogram in Figure 1, it appears that there is a sunspot in the northern hemisphere directly across the equator from the large sunspot in the southern hemisphere. Reference to the magnetogram appears to confirm this suspicion. Although this example appears conclusive, we have found cases where Ne vii is not locally bright over a sunspot. The reason for this difference is not yet clear. One possibility might lie in the fact that the Ne vii intensity frequently varies with time quite rapidly, with major changes occurring in less than thirty minutes.

2. The Observations

In the next several figures, we illustrate the way in which magnetic flux is connected through the corona from one region of the photosphere to another by comparison of Fe xiv coronal spectroheliograms with photospheric magnetograms. Figure 2 shows the emergence of a relatively small bipolar magnetic region (BMR) over a period of three days in September 1973. A relatively large portion of the field of view in the August 31 magnetogram is covered by predominantly positive (white) magnetic flux. This same region is relatively free of emission in the Fe xiv spectroheliogram taken at 01:02 GMT on September 1. (All times quoted in this article are expressed in Greenwich Mean Time).

By 12:09 on September 1 a small emission region has appeared near the center of the field of view. The September 1 magnetogram was obtained at 14:48, and shows a small BMR at this position. We see that the emission region increases in size and perhaps intensity overnight. By the afternoon of September 2, the Fe xiv spectroheliogram shows considerable emission stretching from the negative (black) pole of the BMR to fragments of the positive flux that was present on August 31, prior to the emergence of the BMR as well as more intense emission stretching between the poles of the BMR. This emission apparently indicates lines of force from the negative pole of the BMR that have become disconnected from the positive pole of the BMR and have been reconnected to the positive flux of the previously existing ‘background field’. If this is correct, then some of the flux from the positive pole of the BMR presumably opened perhaps connecting to more distant regions. In the subsequent magnetogram on September 3, the BMR seems already to be in a stage of decay. Also, the lines of reconnection appear more resolved and perhaps having more curvature than they did at 15:54 on September 2, as if they too were relaxing into a decay phase.

Before continuing with additional illustrations, we shall attempt to clarify our interpretation of this apparent reconnection process. Use of the word ‘reconnect’ implies
Fig. 2. A time-lapse sequence of Fe xv 285 Å coronal spectroheliograms and photospheric magnetograms illustrating the apparent reconnection of emerging bipolar flux to its previously existing surroundings.
Fig. 3. A time-lapse sequence of Fe XV coronal spectroheliograms and photospheric magnetograms illustrating both the reconnection of emerging bipolar flux and the disappearance of other bipolar flux.
that previously existing connections somehow disconnect and rejoin in a different configuration. We suppose that this process occurs in the corona. Another possibility is that newly emerging flux connects directly to the 'background field'. There seem to be essentially two ways in which this might happen. In one, the new flux emerges in the form of small, isolated unipolar regions. In the other, segments of the lines of force from the previously existing background field somehow submerge to produce the new BMR in the photosphere. Although this latter way is possible topologically, it is inconsistent with our long-held view based on physical grounds that flux erupts from below the photosphere. Finally, we point out that the new flux connections could not have been present below the photosphere prior to eruption because the background field was already above the photosphere before the BMR emerged.

Figure 3 shows another example of reconnection during the emergence of bipolar flux for the period of December 20–24, 1973. In this case, a pair of new BMRs first appears on December 22 in a region of predominantly positive (white) flux separating a large sunspot from two previously existing BMRs. Reconnections to the positive background flux begin on December 22, and are progressively more pronounced during December 23. Interestingly enough, the northernmost of the two previously existing BMRs decays and is nearly gone by 13:17 on December 23. We shall return to this example of flux disappearance later in this paper. Meanwhile we should point out that the pronounced flux connections visible at 13:17 on December 23 are occurring at the same time that considerable magnetic flux is erupting onto the surface. By 18:08 on December 24 this has become a major BMR. We shall see in Figure 8 that these connections grow into relatively large-scale interconnections between two major active regions 27 days later.

Figure 4 illustrates this now-classic behavior of small BMRs during six days of January 1974. On January 11 there are two BMRs in a background of predominantly positive (white) magnetic flux. The emission structure in the Fe xv spectroheliogram suggests lines of force connecting the negative (black) poles of each BMR to positive flux in its respective environment. Although the easternmost (left) of the two regions decays slowly during this six-day period, it is still visible on January 16. In the Fe xv spectroheliograms, the westernmost (right) of these two regions has faded considerably by 00:10 on January 13, and has disappeared entirely by 13:25 on January 14. However, on January 14 a new region appears at a location nearly midway between the two old regions. (Changes between the apparent position of these regions are associated with perspective due to solar rotation.) The photospheric magnetic flux from the westernmost (right) of the two BMRs visible on January 11 progressively disappears from the magnetograms until at 15:32 on January 13 it has nearly vanished. We think that this disappearance is a real effect indicating the loss of flux from the solar atmosphere. However, an instrumental reason can not be ruled out such as the fragmentation of flux into progressively smaller and smaller pieces that eventually disappear below the detection threshold.

The Fe xv structure of the BMR that first appeared on January 14 is another classic example of the pattern of reconnected flux. In the photograph marked 13:25 January
Fig. 4. A time-lapse sequence of Fe xv coronal spectroheliograms and photospheric magnetograms illustrating both the emergence and disappearance of bipolar flux.
Fig. 5. A time-lapse sequence of Fe xv coronal spectroheliograms and photospheric magnetograms illustrating the coronal magnetic field configuration. (An Fe xv 285 Å spectroheliogram was unavailable for June 16, so we show an Fe xvi 335 Å coronal spectroheliogram for that day.) The east limb can be seen in the June 17 image, but is out of the field on June 18 and 19. On June 14–16 it is obscured by the great amount of emission extending above the limb from the large BMR. Different exposure conditions occur in the various images so that intensity comparison is difficult.
Fig. 6. Comparison of an Fe xv 285 Å coronal spectroheliogram (01:51 September 5, 1973) with a photospheric magnetogram (15:19 September 4, 1973) illustrating the large-scale coronal field connections between major active regions.
14, it appears like a ‘fountain’ with loops emerging in all directions from the center. Reference to the January 14 magnetogram shows that the center corresponds to negative (black) magnetic flux and the loops extend in all directions to positive flux. The intensity of emission is greater in the loops internal to the BMR than in the loops connecting the negative pole to old positive flux external to the BMR. We find this to be generally true for all such regions. Examination of the January 15 and 16 magnetograms suggests that by this time the BMR has begun to diffuse or fragment with the photospheric flux points spreading out on the solar surface. During this same period, the Fe xv spectroheliograms show a progressive expansion of the coronal loops evidenced by the increase in size of the ‘fountain’.

Figure 5 shows another such ‘fountain’ pattern during the six-day period June 14–19, 1973. In this case the main loops of the BMR extend from the negative (black) flux in the center to the positive flux to the west (right). The fainter reconnecting loops extend to the east (left). These reconnecting loops join the negative flux of the BMR to positive flux in the westernmost part of an old, relatively large BMR. In the Fe xv spectroheliogram, one can also see a large region of emission crossing the ‘magnetic neutral line’ between the positive and negative poles of that large BMR. It seems logical that if the western edge of the positive (white) flux of the large BMR connects to the small BMR and if the eastern edge connects to the negative pole of the large BMR, then the flux in the center of this positive region should extend outward a considerable distance from the surface. The observed presence of a coronal hole in this channel is consistent with the hypothesis that coronal holes occur where the magnetic field is open (Altschuler et al., 1972; Krieger et al., 1973).

In the next few figures, we illustrate major flux connections between relatively large and distant photospheric magnetic regions. Figure 6 compares an Fe xv spectroheliogram with a photospheric magnetogram during a particularly active period in September 1973. One can see apparent connections stretching several hundred thousand kilometers through the corona joining large BMRs in the southern hemisphere. The active region in the northeast quadrant is also interesting. A large sunspot with negative (black) magnetic polarity constitutes the leading portion of this BMR. The positive flux trailing behind this sunspot seems to be the center of an enormous Fe xv ‘fountain’ similar to the ‘fountains’ we have already described, but on a much larger scale. This positive flux does indeed appear to be surrounded by a large area of negative background flux.

Figure 7 also illustrates large-scale flux connections. This particular case was chosen partly because it shows connections across the equator which runs left to right slightly above the middle of the figure. It is an enlarged version of the December 22, 1973 Sun that we encountered in Figures 1 and 3. Major, bright connections are present between BMRs in the southern hemisphere. In addition, one can see fainter connections to relatively distant magnetic regions across the equator. In particular, careful scrutiny reveals an apparent giant X-type neutral point near the solar equator just left of center of the figure.

Figure 8 compares the December 22, 1973 Sun with its appearance 27 days later on
Fig. 7. Comparison of an Fe XV 285 Å coronal spectroheliogram with a photospheric magnetogram illustrating the large-scale coronal field connections between distant centers of photospheric magnetic flux. Connections are even visible across the solar equator which runs left to right slightly above the middle of the figure.
Fig. 8. Comparison between Fe xv-magnetogram pairs taken 27 days apart illustrating magnetic field changes taking place on this time scale.
January 18, 1974. The large sunspot visible in the December 22 magnetogram has reduced in size considerably by January 18. (The magnetic polarity of this sunspot is positive (white), the contrasty black center being an indication of magnetograph saturation in the excessively strong magnetic field of the umbra. In fact, the characteristic appearance of this saturation provides the means by which one can recognize sunspots easily on magnetograms.)

Of particular interest is the development of the BMR directly to the west of the large sunspot. We have already shown the early stage in the development of this BMR in Figure 3. This region apparently reached its stage of maximum development near or after its disappearance at the west limb of the Sun late in December 1973. By January 18, the magnetic flux has spread over a much larger area of the photosphere than it covered in December. Of special interest is the fact that the reconnections which we observed on December 23 in Figure 3 (and which are just beginning to form on December 22 in Figure 8) now constitute a major connection between the negative (black) flux of this BMR and the area of positive flux in which the sunspot is located. Figures 3 and 8 apparently document the way in which large-scale coronal flux connections develop.

In both Figure 3 and Figure 4 we noticed examples in which flux seemed to disappear from the solar atmosphere. Next, we shall show another example of flux disappearance. A difference between the previous examples and the one to follow is that whereas the previous cases show flux disappearance in relatively simple magnetic surroundings, the example in Figure 9 shows flux disappearance in a relatively complex magnetic environment.

Figure 9 compares a sequence of Fe xiv spectroheliograms and photospheric magnetograms during the period June 13–19, 1973. (No magnetogram was available on June 13 due to clouds at Kitt Peak.) In the Fe xiv spectroheliogram on June 13 (at the top of the figure) a single bright kernel of emission is visible together with some fainter loop structure in its vicinity. By June 14 (just below the June 13 picture) a second kernel of emission has appeared. Although it is difficult to identify unambiguously the negative (black) flux associated with this second region of bright emission, the positive flux is clearly visible.

It is easy to trace the history of the coronal emission of this second kernel through the remaining days of this period. The emission grows to a maximum by June 15 or 16 and progressively disappears from June 17 to 19. The magnetograms show that the positive flux associated with the second kernel has the same behavior, reaching an apparent maximum on June 15, and having only a few small remnants on June 18. It has vanished entirely by June 19. The fainter connections in the northeast (upper left) part of the active region complex remain much the same as they were prior to the birth of the small region on June 14. However, the large-scale coronal emission on the west side of this complex underwent a significant change on June 16, apparently in association with the major flare that occurred at approximately 14:00 GMT on that day.

We summarize our observations with the statement that coronal magnetic flux
Fig. 9. A time-lapse sequence of Fe xv spectroheliograms and magnetograms illustrating the emergence, growth, and disappearance of a magnetic flux region. The sequence starts with an Fe xv spectroheliogram on June 13, 1973 at the top of the figure. Daily Fe xv-magnetogram pairs run left to right across each row. No magnetogram was available on June 13 due to clouds.
reconnections are apparent in our Skylab data and seem to occur just as soon as new flux appears on the solar surface.

3. Discussion

Work is now in progress to examine these observations in more detail, and in particular, to see what role, if any, electric currents may play in the lower corona. Meanwhile, we present a simple example of how flux connections behave according to potential theory.

In this example we suppose that a small BMR emerges in the vicinity of some previously existing magnetic flux and calculate the amount of flux connecting the BMR to its surroundings as a function of the 'strength' of the BMR. We imagine that this strength increases with time as the hypothetical BMR emerges. To simplify the problem, we adopt the geometry shown in Figure 10 in which magnetic surface fluxes have been replaced by 'point charges' and the magnetic fields themselves are replaced by electric fields. Since this is a potential field problem we can convert from one to the other by interchanging the mks quantities \(q/4\pi e_0\) and \(\phi/2\pi\), where \(q\) is the electric charge corresponding to the source magnetic flux \(\phi\).

Figure 10 shows some field lines for the cylindrically symmetric geometry involving a doublet of 'charge' \(\pm q_1\) in line with a singlet or monopole of 'charge' \(q_0\). In this figure we have taken \(q_1 = 2\), \(q_0 = 1\), and \(a/b = 1/2\). The value of \(\phi\) associated with each field line refers to the amount of flux between that field line and the axis of symmetry. In this example, 56% of the monopole flux, \(q_0\), is connected to \(-q_1\), and an equal

![Diagram](image-url)  

Fig. 10. Field geometry for a simple, cylindrically symmetric distribution of 'charge'. In this case, \(q_1/q_0 = 2\) and \(a/b = 1/2\). The values of \(\phi\) refer to the amount of flux between that field line and the axis of symmetry.
Fig. 11. The fraction, $f$, of the flux $q_0$ that is connected to $-q_1$. $f$ is plotted versus the ratio $q_1/q_0$ which we call $a$. $a'$ refers to the ratio $a/b$.

Fig. 12. An enlargement of Figure 11 in the region of small $a$. 
amount of positive flux from \( +q_1 \) opens to infinity. Next, we consider what happens more generally as a function of \( \alpha = q_1/q_0 \) and \( a' = a/b \).

Figure 11 shows how much flux is connected between the BMR and the monopole \( q_0 \) as a function of \( \alpha \) for various separations of the sources. Specifically, the fraction, \( f \), of \( q_0 \) that is connected to \( -q_1 \) is plotted versus \( \alpha \) for various values of the parameter \( a' \). It is clear from Figure 11 that as the doublet becomes progressively stronger, more and more of the monopole flux becomes connected to \( -q_1 \) until a point is reached where all the monopole flux is connected. In this case the connection between this monopole and the doublet is saturated, and no more flux is available from this monopole no matter how much stronger the doublet becomes. (In the more realistic solar problem, connections would be made to additional monopoles if they should be present.) For small \( a' \), this point is reached when \( \alpha a' = (1.5)^3 = 3.375 \). Since

\[
\alpha a' = \left( \frac{q_1}{q_0} \right) \left( \frac{a}{b} \right) = \frac{q_1 a}{q_0 b},
\]

\( \alpha a' \) is the ratio of two ‘dipole moments’. This means that all of the monopole flux becomes connected to the dipole when the dipole moment \( q_1 a \) becomes roughly three times the dipole moment \( q_0 b \). Similarly, we found that when these dipole moments are equal, approximately 64% of the flux \( q_0 \) is connected to \( -q_1 \). Since one can determine dipole moments relatively easily from magnetograms, one might hope to use these relations to estimate the flux linkage between neighboring magnetic regions.

We may interpret this problem in a different way for small \( \alpha \). In this case, we regard \( q_0 \) as a region of relatively great flux such as a large sunspot, and the doublet as a small BMR nearby. Figure 12 is an enlargement of Figure 11 in the region where \( \alpha \) is small. Figure 12 shows that all of the flux \( -q_1 \) is connected to \( +q_0 \) when \( \alpha \) becomes sufficiently small. (This suggests that the \( -q_1 \) part of the BMR starts out belonging to \( +q_0 \) rather than \( +q_1 \). We can avoid this conclusion by supposing that the poles of a doublet emerge arbitrarily close to each other so that \( a' \) is small and we do not begin on the curve \( f = \alpha \).) At this point all of the positive flux, \( q_1 \), from the doublet opens to infinity. For smaller values of \( \alpha \) of course no more negative flux is available from the doublet, and the large monopole must ‘look for other doublets’. This suggests that if a small BMR emerges near a large sunspot it will completely open up as soon as the photospheric footpoints of the BMR begin to separate.

Although we highly oversimplified this problem, we felt that it was worth solving if only to gain an elementary understanding of the basic characteristics of field line connections according to potential theory. The detailed results of this calculation are shown in the Appendix. It is interesting that this is a slightly generalized version of a problem given in Jeans’ book on electricity and magnetism (1908) 66 years ago.

Appendix

THE MAGNETIC FLUX CALCULATION

Let \( f \) be the fraction of the flux, \( q_0 \), that connects to \( -q_1 \). It can be obtained by eva-
luating the flux integral

\[ q_0 f = \int_0^{r_0} \varepsilon_0 E_z \cdot 2\pi r \, dr, \]

where \( E_z \) is the axial component of the electric field from the three point charges \( q_0, q_1, \) and \(-q_1\) with the geometry shown in Figure 10, and \( r_0 \) is the radial distance of the 'neutral point' (a line in three dimensions) of the electric field.

It is interesting to see how this neutral point moves in the \((r, z)\) plane as the charge ratio \( \alpha = q_1/q_0 \) increases from 0 to \( \infty \). This point starts out arbitrarily close to \( +q_1 \) and moves along the \( z \)-axis toward \(-q_1\) as \( \alpha \) increases. When \( \alpha \) reaches a critical value, \( \alpha_{\text{min}} \), the neutral point separates into two points which leave the \( z \)-axis and move in a circle of radius \( R \) whose center is located on the \( z \)-axis a distance \( z_0 \) beyond \( q_0 \). These two points coalesce to one point again when \( \alpha \) reaches a larger critical value, \( \alpha_{\text{max}} \). For still larger values of \( \alpha \) the point moves progressively farther down the \( z \)-axis. Our calculations show that with \( a' = a/b \)

\[ \alpha_{\text{min}} = \frac{(a')^2}{[(1 + a')^{2/3} + 1]^3}, \quad \alpha_{\text{max}} = \frac{(a')^2}{[(1 + a')^{2/3} - 1]^3}, \]

\[ R/b = \frac{a'(1 + a')^{1/3}}{(1 + a')^{2/3} - 1}, \]

and

\[ Z_0/b = -\frac{(1 + a')^{2/3}}{1 + (1 + a')^{1/3}}. \]

(The minus sign is used because \( +q_0 \) was located at the origin of the coordinates with \( +z \) increasing toward \(-q_1\).)

Finally, the value of the flux integral yielded:

\[ f = \frac{1}{2} \left[ 1 - \left\{ \left( a' \right)^2 + 2a' - \alpha^{2/3} \left( a' \right)^{2/3} \left[ 1 + 2a' - (1 + a') (1 + a')^{1/3} \right] \right\} \times \right. \]

\[ \left. \sqrt{\frac{1 - a'^{2/3} \left( (1 + a')^{1/3} - 1 \right)}{1 + a'}} \right] \]

which reduces to the solution given by Jeans (1908) when we put \( a' = 1 \).

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References