MODELING THE 1994 APRIL 14 POLAR CROWN SXR ARCADE USING THREE-DIMENSIONAL MAGNETOHYDROSTATIC EQUILIBRIUM SOLUTIONS

X. P. ZHAO, J. T. HOEKSEMA, AND P. H. SCHERRER

W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305

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ABSTRACT

The coronal magnetic field in the polar crown soft X-ray (SXR) arcade of 1994 April 14 has been computed using the global photospheric magnetic field distribution constructed for the time of interest and the three-dimensional magnetohydrostatic equilibrium solutions. In the solutions there are two free parameters, α and a , respectively, characterizing the effect of the field-aligned and horizontal electric currents. Magnetic field configurations have been determined for various combinations of α and a . The magnetic arcade computed with $\alpha \rightarrow 0$ and $a = 0.9$ agrees best in shape and size with the well-developed polar crown SXR arcade. This suggests that the well-developed SXR arcade has a potential-like magnetic configuration with non-field-aligned currents. The computed loci of the apexes of lines of force that close above $1.3 R_{\odot}$ match the shape of the bright axial features superposed on the well-developed SXR arcade. This suggests that newly opened lines of force may have reconnected only above $1.3 R_{\odot}$, and consequently the pre-eruption closed lines of force may not be completely opened up during the eruption phase. The SXT images before the formation of the SXR loop show the occurrence of dimmings, supporting the inference of partially “transient” coronal opening.

Subject headings: Sun: corona — Sun: magnetic fields — Sun: X-rays, gamma rays

1. INTRODUCTION

The soft X-ray (SXR) loop arcade of 1994 April 14 occurred over a filament channel with few visible filament segments. The filament channel extended parallel to the southern polar polarity inversion line. The SXR arcade affected an area of $\sim 150^\circ$ in longitude and 30° – 40° in latitude. It is one of largest SXR arcades observed by *Yohkoh*/SXT. Because of its association with an interplanetary disturbance observed by *Ulysses* near 60° S latitude (Gosling 1994) and a geomagnetic storm at Earth (McAllister et al. 1994), this event has been considered to be a good sample for coronal mass ejections (CMEs) on the solar disk (Webb et al. 1997).

The April 14 event was observed almost exclusively by *Yohkoh*/SXT. There was no $H\alpha$ flare, no significant X-ray flare, and no significant $H\alpha$ filament disappearance associated with the event (McAllister et al. 1996). The Mauna Loa Mark III image at ~ 2019 UT on April 13, about 5 hours before the SXR arcade began to form, showed a wide region of nearly radial structure over the SE limb, positioned over the latitudinal center of the subsequent SXR arcade. Based on this image and other images observed on April 9, 14, and 21, McAllister et al. (1996) suggested that a CME occurred between ~ 2019 UT on April 13 and ~ 0126 UT on April 14, and that the SXR arcade formation was the aftermath of the CME (Hiei et al. 1993). He 10,830 images showed the formation of large “ribbons” along the footpoints of the coronal arcade and gave confirmation that a large-scale CME had probably occurred (Alexander et al. 1994).

Studying of the magnetic field configuration over the arcade area is necessary to understand the cause of the event. SXR loops are usually regarded as tracers of large-scale magnetic lines of force. However, it is not easy to determine whether the magnetic field in SXR arcades is potential or nonpotential using SXT images alone, especially if the magnetic field is not far from potential. It is even more difficult to know the magnetic field configuration in the region before the formation of the SXR arcade, espe-

cially whether the lines of force are fully or partially opened up, since no loops were detectable prior to the event.

We previously modeled the magnetic arcade using a monthly synoptic chart of the photospheric magnetic field and the potential-field source-surface model (Alexander et al. 1996). The goal of this effort is to obtain the magnetic field configuration in the region of the well-developed SXR arcade by extrapolating the “instantaneous” global photospheric magnetic field distribution into the corona.

Models commonly used in global extrapolations are potential-like magnetic field models (Zhao & Hoeksema 1995 and the reference therein). Low (1991) found a general class of three-dimensional magnetohydrostatic equilibria solutions that includes the effect of two electric current systems, one following the magnetic field and the other perpendicular to the gravity field. All these solutions admit an arbitrary prescription of the magnetic field at the inner boundary of the domain of interest. Based on this formulation Neukirch (1995) has derived a set of spatial solutions for the case of a plasma around a spherical self-gravitating body. We use this solution to extrapolate the observed photospheric magnetic field into the corona. To distinguish this magnetic field solution from the sheared magnetic configuration produced by force-free magnetic field models, we call it the non-force-free sheared magnetic field model.

Section 2 presents the non-force-free sheared field model and describes its boundary condition. In § 3 we show observations of the SXR formation and the photospheric magnetic field and computations of the coronal magnetic field in the SXR arcade. We conclude with discussion of the results in the last section.

2. THE LARGE-SCALE NON-FORCE-FREE SHEARED MAGNETIC FIELD MODEL

Well-developed large-scale SXR arcades typically change their size with a characteristic velocity of a few kilometers per second. Both the expansion velocity in open regions below the height of cusp points and the characteristic veloc-

ity of evolving large-scale structures are much less than the local Alfvén velocity. Thus the evolution of these coronal structures can be approximately treated as a quasi-static process. The magnetic field in the set of spatial solutions derived by Neukirch (1995) in the spherical polar coordinate system (r, θ, ϕ) satisfies the following equations:

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} + \left[\frac{1}{r^2} - \frac{1}{(r+a)^2} \right] \nabla(r \cdot \mathbf{B}) \times \mathbf{e}_r, \quad (1)$$

where the free parameters α and a are constants that characterize field-aligned and horizontal electric current systems, respectively (Low 1991). The two current systems are separately conserved (Low 1993). Equation (1) is reduced to the current-free magnetic field when both $\alpha = 0$ and $a = 0$; it describes a purely horizontal-current magnetic field when only $\alpha = 0$ (Bogdan & Low 1986; Zhao & Hoeksema 1994), and a constant α force-free magnetic field when $a = 0$ (e.g., Nakagawa 1973).

The non-force-free sheared magnetic field can be expressed as (Neukirch 1995)

$$\begin{aligned} \mathbf{B} = & \sum_{n=1}^N \sum_{m=0}^n \sum_{k=1}^2 \left\{ n(n+1) \frac{g_n^{(k)}(r)}{r^2} P_n^m(\theta) G_{nm}^{(k)}(\phi) \mathbf{e}_r \right. \\ & + \left[\alpha \frac{g_n^{(k)}(r)}{r^2} \frac{P_n^m(\theta)}{\sin \theta} \frac{dG_{nm}^{(k)}(\phi)}{d\phi} + \frac{1}{r} \frac{dg_n^{(k)}(r)}{dr} \frac{dP_n^m(\theta)}{d\theta} G_{nm}^{(k)}(\phi) \right] \mathbf{e}_\theta \\ & \left. + \left[\frac{1}{r} \frac{dg_n^{(k)}(r)}{dr} \frac{P_n^m(\theta)}{\sin \theta} \frac{dG_{nm}^{(k)}(\phi)}{d\phi} - \alpha \frac{g_n^{(k)}(r)}{r^2} \frac{dP_n^m(\theta)}{d\theta} G_{nm}^{(k)}(\phi) \right] \mathbf{e}_\phi \right\}, \end{aligned} \quad (2)$$

where N denotes the principal degree, $g_n^{(k)}(r)$ relates to the spherical Bessel function of the first kind as follows

$$g_n^{(k)}(r) = \begin{cases} \sqrt{r+a} N_{n+(1/2)}[\alpha(r+a)], & k=1, \\ \sqrt{r+a} J_{n+(1/2)}[\alpha(r+a)], & k=2. \end{cases} \quad (3)$$

$P_n^m(\theta)$ is the associated Legendre function with Schmidt normalization, and

$$G_{nm}^{(k)}(\phi) = g_{nm}^{(k)} \cos m\phi + h_{nm}^{(k)} \sin m\phi. \quad (4)$$

There are two sets of unknown expansion coefficients $(g_{nm}^{(1)}, h_{nm}^{(1)})$ and $(g_{nm}^{(2)}, h_{nm}^{(2)})$ to be determined by inner and outer boundary conditions for the non-force-free sheared field solution. As in many solar applications, the normal magnetic flux distribution on the solar surface is given and the magnetic field is taken to vanish at infinity high above the solar surface (e.g., Bogdan & Low 1986; Low 1991; Neukirch 1995). Because the two independent spherical Bessel functions vanish at infinity, each of them is also admissible for the system. For the pure horizontal-current magnetic field model, the boundary condition at infinity requires omitting one set of expansion coefficients (Bogdan & Low 1986). The solution here should have the appropriate asymptotic behavior in the radial coordinates in the limit $\alpha \rightarrow 0$. We thus set $g_{nm}^{(2)} = 0$ and $h_{nm}^{(2)} = 0$. The boundary values of B_r on the solar surface translate into the inner boundary condition

$$\begin{bmatrix} g_{nm}^{(1)} \\ h_{nm}^{(1)} \end{bmatrix} = \frac{2n+1}{IJ} \sum_{i=1}^I \sum_{j=1}^J C_n B_r^{ij} P_n^m(\theta) \begin{pmatrix} \cos m\phi_j \\ \sin m\phi_j \end{pmatrix}, \quad (5)$$

where

$$C_n = \frac{r_o^2}{n(n+1)\sqrt{r_o+a} N_{n+(1/2)}[\alpha(r_o+a)]}. \quad (6)$$

Here B_r^{ij} in (5) denotes the global distribution of the radial component of the photospheric magnetic field, and I and J are the number of grid points in latitude and longitude. Corresponding to the spatial resolution of the magnetogram at the Wilcox Solar Observatory, $I = 30$ and $J = 72$. The symbol r_o in equation (6) denotes the heliocentric distance of the solar surface.

It should be noted that the solutions of equation (2) have a unbounded energy, even though the non-force-free sheared magnetic fields can be made to vanish at infinity. This basic problematic property is caused by the slow rate with which the spherical Bessel functions go to zero at infinity. As pointed out above, the large-scale coronal magnetic field in the well-developed SXR arcade can be treated as a quasi-static field actually only in the domain below the height of cusp points of helmet streamers. In other words, the solution may be representative of the solar magnetic field only in the near region below the height of cusp points. The difficulty is thus alleviated.

The radial component of the magnetic field over the entire solar surface is usually derived from a “monthly” synoptic chart (Wang & Sheeley 1992; Zhao & Hoeksema 1993). The synoptic chart combines central meridian data from a series of magnetograms observed during a whole solar rotation. This approach implicitly assumes that the surface magnetic field does not vary appreciably in time. Such maps cease to be useful on the timescale of such evolving large-scale structures as the well-developed SXR arcade, though they have been successfully used in modeling stable global-scale structures such as the coronal streamer belt (Hoeksema 1991) and polar coronal holes (Wang & Sheeley 1992). Numerical experiments (Zhao et al. 1999) show that a newly emerging bipolar magnetic region near the disk center in the unseen hemisphere has a negligible effect on the coronal magnetic field in the visible hemisphere, to first order. This suggests that we can use more timely data from the visible disk to construct a more timely global photospheric magnetic field distribution called synoptic frame. We begin with standard synoptic data including 360° of longitude range centered at the time when the coronal structure of interest is observed. Then we replace the composite synoptic chart values in the region of interest with data from a single full-disk magnetogram. The synoptic frame is corrected to make the net magnetic flux over entire solar surface zero (see Zhao et al. 1999 for details). This provides our best estimate of the global solar magnetic field at the time of the event.

Figure 1 shows how the computed magnetic field configuration changes as the horizontal and field-aligned current systems change. The top-middle panel shows a purely dipole magnetic field with no currents. The left column displays the effects of changing the horizontal current parameter, a . By decreasing a from 0 to -0.4 (top left panel) the magnetic lines of force contract with respect to the dipole field; as a increases from -0.4 to 4.0 the magnetic lines of force monotonically expand. The middle column shows how the magnetic field deviates from the dipole magnetic field because of the change of field-aligned currents. When α increases the magnetic lines of force become more and more

FIG. 1.—The effect of a horizontal current system and a field-aligned current system on a dipole field. The free parameters a and α characterize the two current system, respectively. The closed magnetic lines of force expand (*left panels*) when the horizontal current parameter a is changed. The shear increases (*middle panels*) as the field aligned current parameter, α , increases. The field expands and becomes twisted (*right panels*) when the two current systems act together.

sheared as well as expanding slightly. When both a and α increase, the magnetic lines of force are expanded and twisted simultaneously (*right column*).

3. OBSERVATION AND COMPUTATION

Figure 2 displays eight SXT images observed between 1711 UT on April 12 and 1815 UT on April 15. The observation time is shown at the top of each image. The April 14 SXR loop arcade first appeared between 0125 UT and 0246

UT on April 14. The SXT image at 0246 UT showed a single, sharply cusped loop at $\sim$ E45S45. Over the next 8–10 hours bright arcade loops appeared to the west and to the east, until the visible structure reached its full extent. The 1426 UT image shows the well-developed SXR arcade. After that the clearly defined arcade started to fade and the loop arcade became a faint structure with diffuse component. The 0415.1815 UT image shows the faded well-developed SXR arcade. The magnetic configuration of the

FIG. 2.—Yohkoh SXT images show the coronal structures before (left column), during, and after the development of the large loop arcade over the southern polar crown on 1994 April 14.

faint structure looks the same as in the SXR loop arcade. The images in the left column show changes of coronal structures before the SXR arcade formed.

Figure 3 shows four daily magnetograms measured at the Wilcox Solar Observatory between April 12 and 15. The dashed lines denote the polarity reversal lines, i.e., the zero contour of the line-of-sight component of the photospheric magnetic field. The solid and dotted lines denote contours of ± 2 , ± 5 , ± 10 , ± 20 , and ± 50 Gauss. All coronal structures in Figure 2, both arcade and faint, are located over polarity reversal lines in the southern hemisphere. There is only a slight change in the photospheric magnetic field below the arcade before and after the arcade formation (between 1994:04:12 21:18 UT and 1994:04:14 18:17 UT). This is not surprising because flux concentrations do not emerge near the polar crown in the declining phase of solar activity.

To model the coronal magnetic field in the well-developed SXR arcade we begin with the appropriate “monthly” synoptic chart centered at 1994:04:14 18:17 UT. We then use the data from the 1994:04:14 18:17 UT WSO magnetogram to replace the composite synoptic chart values within $\pm 65^\circ$ latitude and $\pm 55^\circ$ longitude of the center. This synoptic frame is used to determine the expansion coefficients and compute the coronal magnetic field.

The spherical harmonic order N in equation (2) is taken as 9 in all computations. Figure 4 shows the magnetic lines of force over the southern polar polarity reversal line (*thick dashed line*) computed with various combinations of parameters a and α , as shown on the top of each panel. Among these combinations, the middle-left panel agrees best in both shape and size with the well-developed SXR arcade. This shows that field-aligned currents may be absent in the well-developed SXR arcade, though there are horizontal currents.

There are bright east-west features superposed on the well-developed SXR arcade, as shown in the 0414.1426 UT image of Figure 2. The bright features lasted for tens of hours in the well-developed state. These features are assumed to be formed by heating at the sites of magnetic reconnection of newly-opened magnetic lines of force (Koop & Pneuman 1976). A simple projection analysis locates the bright axial features at the apexes of the SXR loops (McAllister et al. 1994). By matching the loci of the apexes of computed closed magnetic lines of force with the bright axial features, the range of heights where the bright features are located may be inferred. Because the magnetic field during reconnection is dynamically changing (say, from cusp-like to inverse U-like) the bright features in the well-developed state are probably below the site of recon-

FIG. 3.—Daily magnetograms measured at the Stanford Wilcox Solar Observatory

nection at the time reconnection is going on. Accordingly, the inferred lowest apex may indicate whether there is a lower limit for the real site of reconnection and thus whether the pre-eruption closed lines of force open up completely during the eruption.

Figure 5 shows four magnetic arcades identical to the middle-left panel of Figure 4. Filled circles in panels of Figure 5 denote apexes of the magnetic lines of force. The phrase “lowest brightening height” on the top of each panel refers to the lowest level of all displayed apexes in the panel. The loci of the apexes appear to be similar in thickness to the observed bright features when the lowest brightening height is $1.3 R_{\odot}$, and they are wider than the thickness of the observed bright axial features if it is lower than $1.3 R_{\odot}$. This may suggest that the magnetic reconnection of newly opened lines of force started above $1.3 R_{\odot}$ and thus that the pre-eruption closed lines of force are not fully opened up during the eruption.

In order to search for observational evidence of the opening up of pre-eruption closed lines of force, we closely examine the SXT images before the SXR loop formation. The faint diffuse structure in the 0412.1711 UT and 0413.0224 UT images (see the left column of Fig. 2) is

similar to the diffuse component in the 0415.1815 UT image, implying that they consist of large-scale closed lines of force, even though no loop structure detected in these images. The faint structure faded continuously as time went on. This may be caused by cooling or density decreasing because of a helmet streamer distending before eruption (Illing & Hundhausen 1986; McAllister et al. 1996). The faint structure at 0413.1717 was basically the same in thickness as the faint structure at 0414.0125 UT. These faint structures are much thinner than the structure at 0413.0224 UT, suggesting that significant dimmings occur between 0413.0224 UT and 0414.0125 UT. To search for the onset time of the dimmings, we made a movie using 258 SXT images between 940412.101728 UT and 940416.230927 UT. The movie clearly shows that the transition of the faint structure from thick to thin took place near 0413.0935 UT and that before the transition its thickness was decreasing slightly with time. The dimming is believed to be associated with opening up of initially closed lines of force and thus associated with the ejection of coronal mass. The existence of the thin faint structure suggests the opening is not completely. The wide region of nearly radial structure over the SE limb in the Mauna Loa white-light image observed at

FIG. 4.—1994:04:14 18:17 UT magnetic arcade computed over the southern polar polarity reversal line using various combinations of the two free parameters (a and α) of the non-force-free sheared field model.

0413.2019 UT showed the coronal mass ejection just before the arcade loop formation, instead of the helmet-streamer distending before the CME as McAllister et al. (1996) suggested. Because of the similar shape and size of the faint structures observed at 0414.0125 UT and 0414.0246 UT (see Fig. 2) the reconnection may have started at roughly the altitude indicated by the cusp of the first arcade loop. Based on the position of the cusp point we estimate the altitude to be 1.5 solar radii.

4. SUMMARY AND DISCUSSION

We used the “instantaneous” global photospheric magnetic field distribution with the non-force-free sheared field model to compute the large-scale coronal magnetic field in the well-developed large-scale SXR loop arcades observed on 1994 April 14. The model contains effects of both horizontal and field-aligned currents. Various magnetic configuration may be computed on the basis of observations of the

FIG. 5.—The loci of apexes of closed magnetic lines of force computed to have a lowest brightening heights above the indicated altitude. The computed magnetic arcade is the same as middle-left panel of Fig. 4.

photospheric magnetic field. The well-developed SXR arcade is found to be best produced with $\alpha \rightarrow 0$ and $a = 0.9$. This suggests that the magnetic arcade is basically potential-like without field-aligned currents. How can this be explained? Suppose a nonpotential field structure opens and then recloses. The shear or twist on initially closed magnetic lines of force would propagate along the newly open magnetic lines of force out of the corona as Alfvén waves; in this way the field structure rapidly becomes poloidal with zero magnetic helicity. On the other hand, the large-scale coronal field must not be current-free, even though it looks nearly potential, since if it were current-free the coronal plasma would be spherical-symmetrically distributed. The homogeneous horizontal current assumed here is, of course, an simplified approximation for understanding the real coronal plasma distribution.

The method may be used to model the large-scale coronal magnetic field in other structures evolving on timescale of a day or less. It should be noted, however, that all magnetic lines of force computed using the non-force-free sheared field model are useful only when their apexes are lower than the cusp point of helmet streamers, since the solar wind velocity beyond the cusp point is no longer negligible and the quasi-static approximation cease to be valid. If $\alpha = 0$, the “source surface” technique that assumes all magnetic field at the source surface are radial may be used. In that case one can determine the another set of unknown coeffi-

cients in equations (2) and (4) and roughly mimic the effect of the interaction between the solar wind and coronal magnetic field (Zhao & Hoeksema 1994, 1995).

The loci of computed magnetic arcade apexes above 1.3 solar radii have similar shape and size to those of the bright axial features over the well-developed SXR arcade. Since the bright features in the well-developed SXR arcade state are probably lower than the sites of reconnection at time reconnection is going on, the heliocentric distance of 1.3 solar radii inferred here may suggest that the pre-eruption closed lines of force do not open up completely during the eruption. The SXT images do show partially “transient” coronal openings before the appearance of the first SXR arcade loop. The dimmings began near 940413.0935 UT and lasted for 15 hours. If the onset of the CME occurred at the time when significant dimmings started to appear and its ending time is defined at the time when coronal mass ceases to eject, the SXR arcade formation is the aftermath of the CME. The delay between the onset of CME and the onset of SXR arcade formation must be considered in predictions of geoeffectiveness when taking the SXR arcade as the signature of solar disturbances.

CMEs are generally believed to be a physical process involving the release of magnetic energy stored in coronal electric currents. During the free energy release, the magnetic field must be reconfigured into a lower energy state. The reconfigured field must be fully or partially opened to

provide an avenue for the frozen-in plasma to escape the Sun. It is usually assumed that initially closed lines of force are fully opened up during eruption (e.g., Low 1996; Antiochos, DeVore, & Klimchuk 1999). For a bipolar magnetic system, force-free magnetic fields with all lines of force anchored to the coronal base cannot have an energy greater than any fully open field having the same flux distribution at the coronal base (Aly 1991; Sturrock 1991). Therefore, unless the magnetic system is multipolar (Antiochos et al. 1999), the free magnetic energy must be stored in cross-field currents as well as field-aligned currents (Low & Smith 1993). In particular, a detached magnetic flux rope held down by anchored magnetic fields and the weight of plasma may have sufficient energy (Low 1996). Based on this idea, Wu, Guo, & Andrews (1997) have successfully simulated a streamer coronal mass ejection with a magnetohydrodynamic model of the interaction of a helmet streamer and an emerging flux rope.

The 1994 April 14 event suggests another kind of CME, in which the initially closed lines of force open only partially during eruption. It seems unlikely that changes in the polarity reversal line under the SXR arcade caused the event (McAllister et al. 1996). Nor was any emerging flux rope observed before the eruption. The characteristics of the interplanetary counterpart of the event detected by *Ulysses* (Gosling 1994) suggests that the event is indeed a mass ejection, rather than a mass expansion as Antiochos et al. (1999) proposed for the cause of high-latitude CMEs.

The CME of April 13 and the subsequent appearance of the SXR loop arcade occurred between two coronal holes of opposite polarity: the large negative-polarity south polar hole and a significant equatorial hole of positive polarity. After the event, the southern boundary of the equatorial

hole had moved northward and the northern boundary of the polar hole had moved southward (see Fig. 1 of McAllister et al. 1996). This implies that some pre-eruption open lines of force became closed during the development of the SXR arcade. Before the sudden dimmings associated with the eruption, there was slight expansion of the coronal hole boundary corresponding to a slight decrease of the faint structures. Slight changes of a coronal hole boundary are frequently observed and may be caused by global physical processes other than CMEs (Zhao & Hoeksema 1999).

The corona is controlled by a competition between two effects: the tendency of the million-degree corona to expand into the solar wind and the opposing tendency of a bipolar magnetic field in a highly conducting plasma to seek a closed configuration and resist the solar-wind flow. In helmet streamer arcades the tension force of closed magnetic fields confines high-density plasmas in quasi-static equilibrium (Low 1990). It may be interesting to study the possibility that changes of the coronal holes' boundaries reduce the tension force of the closed magnetic field and thus trigger the CME.

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