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Evidence Supporting Quadruple Magnetic Source Model of Arcade Flarings, and Implications

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Abstract

Taking advantage of high sensitivity, wide dynamic range observations by Yohkoh, we have investigated the structures and their changes in the still faint pre-event coronal region around a dark filament which is going to be involved in arcade flarings (arcade flares or high latitude arcade formations). It becomes clear that what we find from the observations is quite different from what we expect from the classical "Re-closing of Once Opened-up Simple Magnetic Aracde Model" for arcade flarings. The observations, instead, indicate that the quadruple magnetic source model advocated by Uchida (1980), for which definitive support from observations was not possible at that time, turns out to be a likely model that explains the observations.

Key words: Sun – arcade flares; Sun – X-rays; Sun – filaments

1. Introduction

Arcade flares were known as two-ribbon flares in Hα observations. Those two ribbons take place just on both sides of the border of the regions of opposite magnetic polarities where an Hα dark filament existed and disappeared. It was proposed that the destabilization of the dark filament that had been supported at the top part of magnetic arcade connecting those opposite polarity field regions caused them: The rise of the destabilized dark filament stretches the magnetic arcade that supported it until then, and eventually cut the magnetic arcade open. Magnetic reconnections between the opposite polarity parts on the legs of the thus stretched arcade may occur, and the reformation of the closed magnetic arcade releases the difference of the magnetic energies of the opened and re-closed fields, and forms a heated X-ray arcade and the two-ribbon Hα flare at its footpoints (Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp and Pneuman 1976, Priest and Forbes 1990). Some people (eg., Shibata 1995) call this process as CSHKP model after the names of the above authors.

This type model, that we here refer to as "classical model", however, has a serious problem as Uchida (1980) noted, and Aly (1991) pointed out independently later: Namely, if flares are due to the liberation of the magnetic energy increased due to the stretching by the dark filament rise, the dark filament rise should have greater energy than the flare itself. Therefore, this simply shifts the problem of the large flare energy to the problem of "large energy" of the dark filament rise. This may be justified if the dark filament is actually a highly energetic entity, but the observations indicate that the dark filaments are generally quiet, and they are not likely to be in a high-tensioned states as assumed in some models worked out along such a suggestion (Moore et al. 1992).

In the "classical model", there is *no neutral sheet* unless the initial magnetic arcade is *torn open*, and no flare due to magnetic reconnection can occur unless this takes place first. It is generally seen, however, that the rising dark filaments have low velocity first, and therefore the kinetic energy is smaller compared with the magnetic energy of the arcade field that supported it against gravity before the rise of it. Deceleration, rather than acceleration, of the rising motion should be expected if the dark filament rise stretches the magnetic field, but what is observed is the opposite, and the dark filament rise is accelerated in reality.

The "classical model", although it has such an intrinsic argument against it, may be said to be a simplest possible idea if the magnetic situation below is truly *bipolar*. There are, however, many other pairs of magnetic sources in the neighborhood at least in active regions. If we take the effect of a second pair of magnetic sources nearby into account, the situation can become very much more reasonable, and a magnetic neutral line (a magnetic neutral sheet if squeezed) can pre-exist in the magnetic structure in the corona above them. The strongest part of the field is, so-to-say, already open due to the effect of the second pair of magnetic sources, not by the dynamical opening up by the rising dark filament. This was claimed by Uchida at the Skylab Flare workshop in 1980 (Uchida's contribution on pp67, 110 with calculated Figures of a realistic quadruple magnetic source model in magnetohydrostatic equilibrium which already indicated important features revealed later by the observations from Yohkoh).

In the period soon after the successful launch of Yohkoh, there was a flood of new information, and while there were not sufficient discussions, some young colleagues of the Yohkoh team reported the finding of the cusped arcade event of Feb 21, 1992, associating it with the "classical model" that had been cited in most of the textbooks as the standard model, without noting the debate about the energies mentioned above. This association, however, was a bit too hasty, because just a similar cusped arcade with the widening of the footpoints (Hα two ribbons) could be explained also in the quadruple source model. Important differences between the "classical" and the quadruple magnetic source models should be (a) the difference in the pre-event coronal structure in the region *above* the top of the cusp, and (b) the difference in the theoretical aspect of the energy as mentioned above.

We have been trying to make these points clear. The energy problem already posed a crucial question for the type of simple bipolar models like the "classical model", but the argument (ours, and a clearer one by Aly 1991) has not been realized by many people as crucial. We thus have sought direct observational evidence for (a) that is likely to be detectable by using a large dynamic range high sensitivity observations of Yohkoh.

Actually, we could readily find it in the pre-event structure of the Feb 21, 1992 arcade flare event itself (Uchida 1996), and also in another arcade flare of Dec 2, 1991, both seen favorably axis-on at the north-east limb (Tsuneta et al.1992, Tsuneta 1993), and we became convinced of the presence of high structure above the cusp, indicating the non-bipolarity.

We, however, should also be able to show similar evidence in high latitude arcade formation events if they are "week field versions" of arcade flares outside active regions. We, however, foresaw some difficulties in this, because most of the previous reports described the magnetic field surrounding the related dark filaments as bipolar! With all these, we tried to investigate directly the *pre-event coronal structure* in their environment making use of high sensitivity, wide dynamic-range observations by Yohkoh/SXT, together with the re-examination of the magnetic situation in the photospheric level more closely ourselves (Uchida et al. 1999b). We summarize the unexpected results of our closer examinations of those.

2. Observational Results

2.1. Cases of Flares in Active Regions

The faint structure above the flaring regions is most easily seen along the axis of the arcade at the limb. Actually, we could find them in such cases. We show the faint pre-event structure of Feb 21, 1992, and Dec 2, 1991 flares in Fig. 1.

We see in the frames in the pre-event phase that there exist high loops connecting the top region of the pre-flare cusp back to the photosphere on both sides in the Feb 21 flare case. Also a brightening low structure near the axis of the dark tunnel is seen. We readily find that a brightening structure near the axis of the dark tunnel existed also in the Dec 2, 1991 flare case, and the structure connecting the top of the cusp back to the photosphere on both sides are also seen clearly especially in the later phase. These large scale loops and the brightenings in the tunnel have no model counterparts in the "classical models", while they can be naturally explained in the quadruple source model (Uchida 1980, Uchida et al.1999a).

2.2. Cases of High Latitude Arcade formation Events

We searched pre-event faint structures also in the cases of high latitude X-ray arcade formation events. For this purpose, we use the data with the longest exposure, and the thinnest filter, and concentrate our attention to the dark coronal region by sacrificing the bright active regions. We further use an Unsharpened-Image Masking technique to enhance the faint structures in the pre-event frames surrounding the relevant dark filament. We make a detailed comparison by rotating the Kitt Peak magnetograms and Hα pictures properly to the time of the X-ray observations, since observed times of those generally differ from those of SXT. Since the Hα dark filaments have their own heights, we draw the locus of the top of them, and project it on a larger sphere with $R_\circ + h$ (by assuming a constant height, h, along the top as an approximation), and rotate this large sphere to the time of the SXT observation. The rotation of the magnetogram is more straight forward, though the inclusion of the solar differential rotation is necessary in both. h is determined so that the locus of the white line down-projected to the photospheric surface after rotation matches best with the polarity-reversal line in the photospheric field.

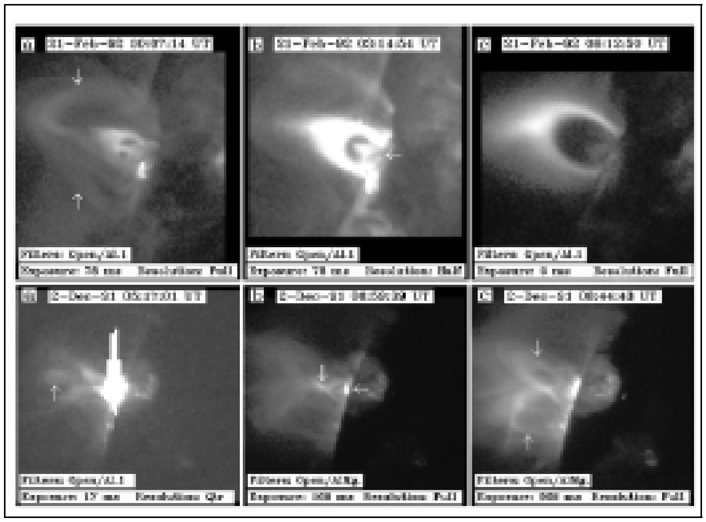

Fig. 1.. Pre-event Structure of Arcade Flares Seen on Axis (Uchida 1996): Upper panel: Feb 21, 1992 Flare. There are two large scale back-connections from the top of the pre-flare cusp to the photosphere on both sides. Also, there exists a bright feature at the axis of the dark tunnel. Lower panel: Dec 2, 1991 Flare. The back connections to both sides, as well as the bright feature at the axis of the tunnel also exist in this case.

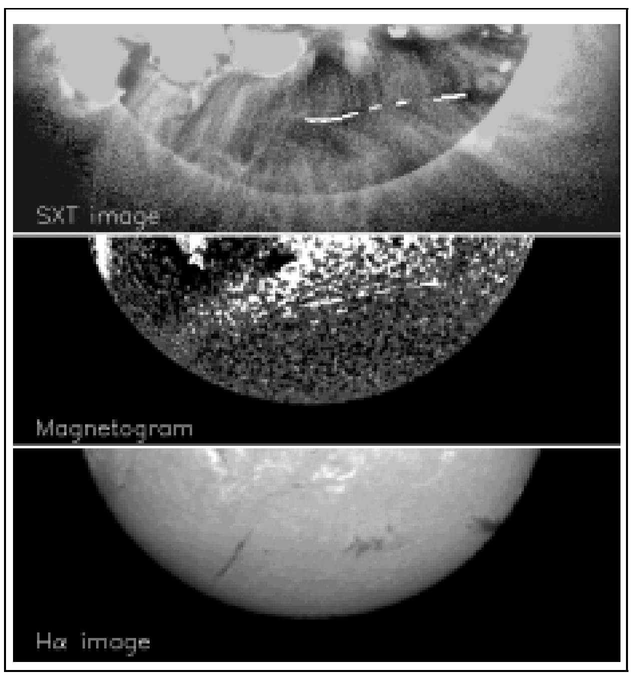

Fig. 2.. The Coronal Structure Surrounding a Quiescent Dark Filament (Namely, the Pre-event Coronal Structure before a High Latitude X-ray Arcade Formation)(Uchida et al. 1999b): (a) The structure seen in X-ray is a "dual arcade" type structure. (b) Kitt Peak magnetogram rotated to the time of (a). (c) Big Bear Hα filtergram (not rotated). The locus of the top of the dark filament is shown in white line, and this is rotated to compare with (a) and (b), down-projected in the case of (b). The loops in "dual arcades" in (a) cross with each others in the middle, and the photospheric magnetic field has a mixed polarity belt there as seen in (b).

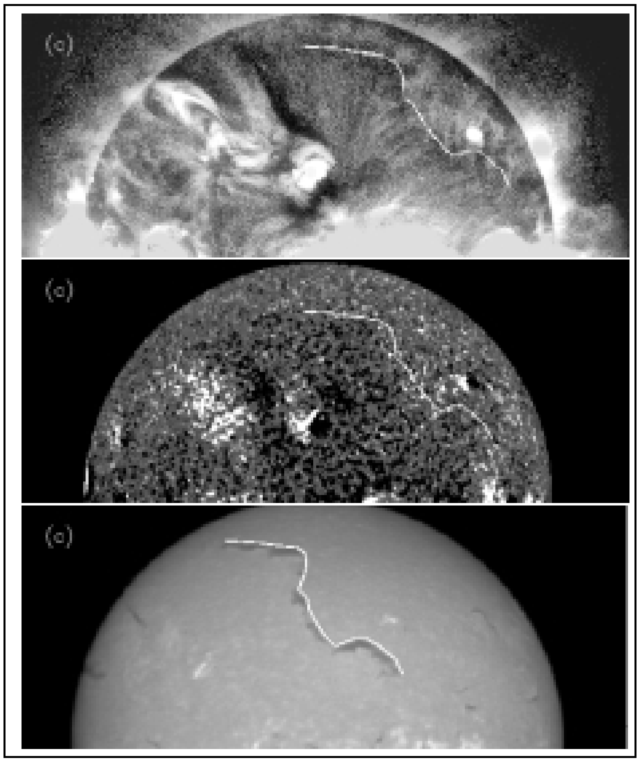

Fig. 3.. Coronal Structure Surrounding Another Dark Filament (Uchida et al. 1999b): (a) The structure seen in X-ray is a "dual arcade" type structure connecting the left to the middle, and the middle to over-the west limb. Note that the regularity is disturbed around the active region (the bright dot). (b) Kitt Peak magnetogram rotated to the time of (a). (c) Big Bear Hα filtergram (before rotated to the time of X-ray). The locus of the top of the dark filament is shown in white line, and is rotated to compare with (a) and down-projected in the case of (b). The loops in "dual arcades" in (a) cross with each others in the middle, and the photospheric magnetic field has a mixed polarity belt there as seen in (b), also in this case.

The most noticeable points we find in the procedure are,

1. The so-called field-polarity reversal line is *not at all clearly-definable*, but what we find there is a broad mixed polarity belt having a width sometimes amounting to hundred-thousand kilometers or more. This important fact was either not noticed or ignored in the previous reports, but J. Harvey has endorsed this is an intrinsic feature.

2. The height h determined from the procedure of matching the down-projected locus of the top of the dark filament with the middle of the mixed polarity belt is indeed in the range of the height of the dark filament observed at the limb, when possible.

3. The X-ray structure seen in the dark filament environment has, very unexpectedly, a "dual arcade" type structure, the inside legs of which cross with each other, and the locus of these crossing points match well with the rotated locus (*not* the down-projected one in this case) of the top of the dark filament. The above results were quite unexpected from the "classical model", but we examined a number of cases to confirm this. We have reported the results (Uchida et al. 1999b) since we are convinced in this conclusion by examining a number of cases. The crossing angle of the legs of "dual arcades" in many cases is large, and the structure can not be explained as a projection of the hammocking structure considered in the "classical" model. The grounding of the threads in the middle is necessary. Furthermore, the structure is seen in some cases in different projection angles (Fig. 3), and the structure proves to be like the MacDonald's logo grounded in the middle with the crossed legs (corresponding to the "barbs", Martin et al. 1990).

4. The threads coming from both sides seem to point towards the magnetic patches transported to the opposite sides of the border of the magnetic polarity. This, again contradicts the expectation, and suggests that the

threads in the observed "dual arcades" are *not* the usual magnetic lines of force, since the normal lines of force can not connect the same polarity points. The conclusion we reached is that they are "critical lines" of force on the flux separatrix surfaces (Uchida et al. 1999b). Since the crossing line of the two separatrix surfaces in the quadruple source model is the "neutral line", some heat and mass may well be supplied from the neutral line to the separatrix surfaces to give them higher visibility in X-rays already in the preflare stage.

3. Conclusion and Discussion

We presented in the above the pre-event structures of both arcade flares and high latitude arcade formation events that we found in the faint structure-enhanced images from Yohkoh/SXT.

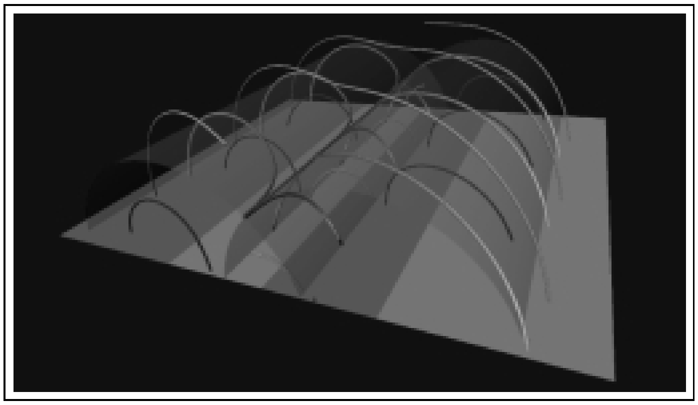

Fig. 4.. The Separatrix Surfaces of a 2.5D Potential Field with a Quadruple Array Sources.

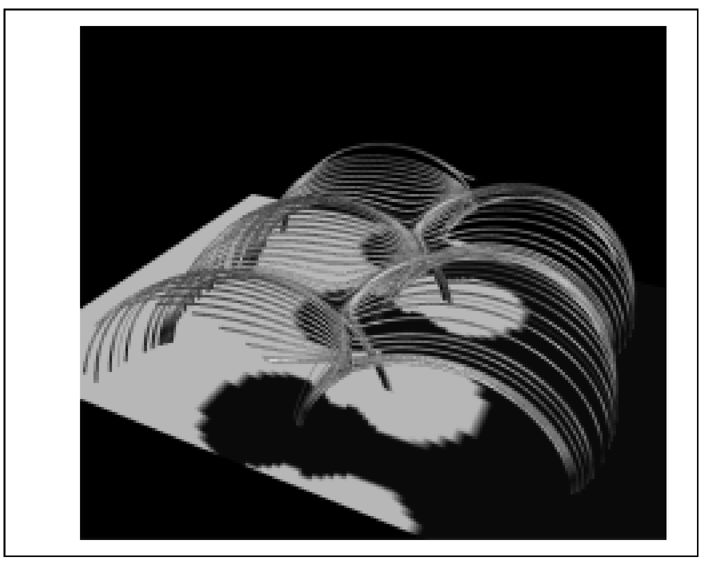

Fig. 5.. The Separatrix Surfaces for More Realistic 3D Potential Field with Small Patches of Field Transported to the Opposite Sides.

What we found can not be explained by the so-called classical "re-closing of a once opened-up simple arcade" model, and the structures and their development can be interpreted with the quadruple source model (Uchida 1980). In the quadruple magnetic source model, the model counterpart for the "dual arcades" structure is the flux separatrix surfaces, and is pre-heated and supplied mass, since the crossing line of these two surfaces is the magnetic neutral line. In the 2.5D approximation, those separatrix surfaces and the crossing line of them are given in Fig. 4 (Uchida et al. 1999b). In the cases of arcade flares, we argued that the quadruple characteristics in the arcade flare case can be explained by including some other pair of the magnetic sources in the same active region, and the actual connectivity can be seen in the soft X-ray observation as seen in Fig. 1. The 3D structure for the February 1992 homologous flare series was reduced in Morita et al. (1999) by using the information given by three different lines of sight at the time of the consecutive flares occurring roughly three days apart.

In the high latitude arcade formation cases, however, it was claimed in previous reports that the photospheric magnetic field distribution in the relevant region is a simple bipolar. This widely accepted point has been questioned here, as seen in Figs. 2 and 3, and many corresponding cases of the pre-event region of arcade formation showed that the magnetic field below is not a simple bipole. The photospheric field in the region surrounding the arcade formation site in the pre-event period has a wide mixed-polarity belt near the border of the extended opposite polarity regions. Our interpretation is that the patches of one polarity transported into the opposite sides may play the role of the inner pair of quadruple sources, if averaged along the length of the dark filament (2.5D approximation). In other words, if we smear the patches transported into a belt of that polarity, the field distribution results in a + - + - belts in case the total flux of the exchanged patches exceeds the local flux. In such a case, the separatrix surfaces are shown in Fig. 4.

If we further consider a more precise model with the exchanged patches as they are, the critical field lines, or the lines spanning the separatix surfaces are seen as in Fig. 5 (Uchida et al. 1999a). This is more like the observed X-ray structure, and we think that this may represent the observed “dual arcade structure”.

The rest of the story, namely, the dynamic MHD simulations of the reconnection process in the quadruple source model will be given in Hirose’s paper (Hirose et al. 1999) following this.

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