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X-RAY OBSERVATIONS OF MOTIONS AND STRUCTURE ABOVE A SOLAR FLARE ARCADE

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ABSTRACT

In this Letter, we describe a solar flare that was observed by *Yohkoh* in 1999 January 20. This long-duration event is notable because the *Yohkoh* images show not only the formation of the arcade associated with the coronal mass ejection but also a considerable amount of motion above the arcade in the region normally identified with a large-scale current sheet or the outflow from magnetic reconnection in the current sheet. A number of arcade events of this morphological type (i.e., a fan of spikelike "rays" above the posteruption loops) have been seen by *Yohkoh*, but in this case we have a much clearer view of mass motions in the region above the arcade. The motions indicate field-line retraction without the formation of long-lasting cusps during the rise phase of the flare, and a downward flow above the arcade during the decay phase. The late-phase downward motion is in the form of X-ray dark voids moving at 100–200 km s^{-1}, i.e., at velocities much smaller than the free-fall speed or the assumed Alfvén speed. We interpret the voids as cross sections of evacuated flux tubes resulting from intermittent reconnection following the associated coronal mass ejection. We believe these data represent the first direct evidence of high-speed flows in the region immediately above the flare loops.

Subject headings: Sun: flares — Sun: magnetic fields

1. INTRODUCTION

In 1999 January 20, a flare occurred on the northeast limb of the Sun in association with a coronal mass ejection. The X-ray flux from the flare reached a level of M5.2 on the *GOES* scale, as depicted in Figure 1. Images from the *Yohkoh* soft X-ray telescope (SXT; Tsuneta et al. 1991) show the formation of a large arcade of magnetic loops, similar to many arcades observed by SXT.

The creation of an arcade in association with a coronal mass ejection (CME) has been treated theoretically by many authors (e.g., Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp & Pneuman 1976). In the current standard picture, magnetic field lines stretched out by the ejection surround a current sheet. The field lines diffuse through the current sheet and reconnect; the tops of the reconnected loops are sharply cusped initially and then retract downward to form an arcade of potential-field loops. The plasma is heated at the reconnection site and by the annihilation of the magnetic field in the slow-mode shocks formed in this process.

The arcade of 1999 January 20 is one of a minority of flare arcades, in that during its decay phase, the arcade displays a "fan" of bright spikelike rays protruding from its top. These rays can be seen in Figures 1 and 2. To date, *Yohkoh* has made observations of about 20 arcades with obvious fan structures (see Švestka et al. 1998 for a description of one such arcade fan). Additionally, and perhaps more importantly, the rays are not static. In the example described here, we observe violent lateral motion and downward-traveling dark voids. These dark voids appear in the X-ray images as coherent blob-shaped depressions in X-ray intensity, moving downward through the arcade fan.

2. OBSERVATIONS

The flare was in 1999 January 20, beginning at about 19:00 UT on the northeast limb. The rise phase of the flare is quite slow, taking approximately 1 hr from onset to peak flux in the *GOES* light curve. *Yohkoh* switched into its automatically triggered flare-observing mode almost immediately after the flare onset; SXT recorded images for the first 25 minutes from 19:05:57 to 19:30:17 UT. The flare peak was at about 20:03 UT, while *Yohkoh* was in orbital nighttime. The next orbit of *Yohkoh* observations was also in flare mode and caught the first part of the decline phase, from 20:36:01 to 21:32:17 UT. SXT made images with three different spatial resolutions ("full," "half," and "quarter," at 2″.46, 4″.91, and 9″.82 pixel^{-1}, respectively) and in four analysis filters; the data were all prepared using the standard SolarSoft software (Freeland & Handy 1998) and *Yohkoh* databases. The flare arcade seen by SXT appears to be exactly on the limb, with an angle of approximately 50° between the main axis of the arcade and the line of sight. Figure 1 marks the times of the images considered in this Letter, which show the creation of the arcade and the motions present during both the rise phase and the period immediately after. Although the present Letter discusses primarily data from the rise phase and the early decline phase of this flare, we note that images even 17 hr after the flare onset show motion and structure in the region above the arcade (see right-hand side of Fig. 1).

2.1. *First Orbit: Rise Phase*

The images from the first orbit show the brightening of the flare arcade, where it is apparent that many of the arcade loops had formed as early as 19:06 UT, although they were not initially very bright. The brightening of these extant loops in the first few minutes appears as a "front" propagating upward from the footpoints of the loops; we believe this is consistent with the common interpretation of loop-filling by chromospheric evaporation (e.g., Acton et al. 1982). Some of these initial loops appear to retract or "shrink" (cf. Forbes & Acton 1996; Hiei & Hundhausen 1996), but the motions are com-

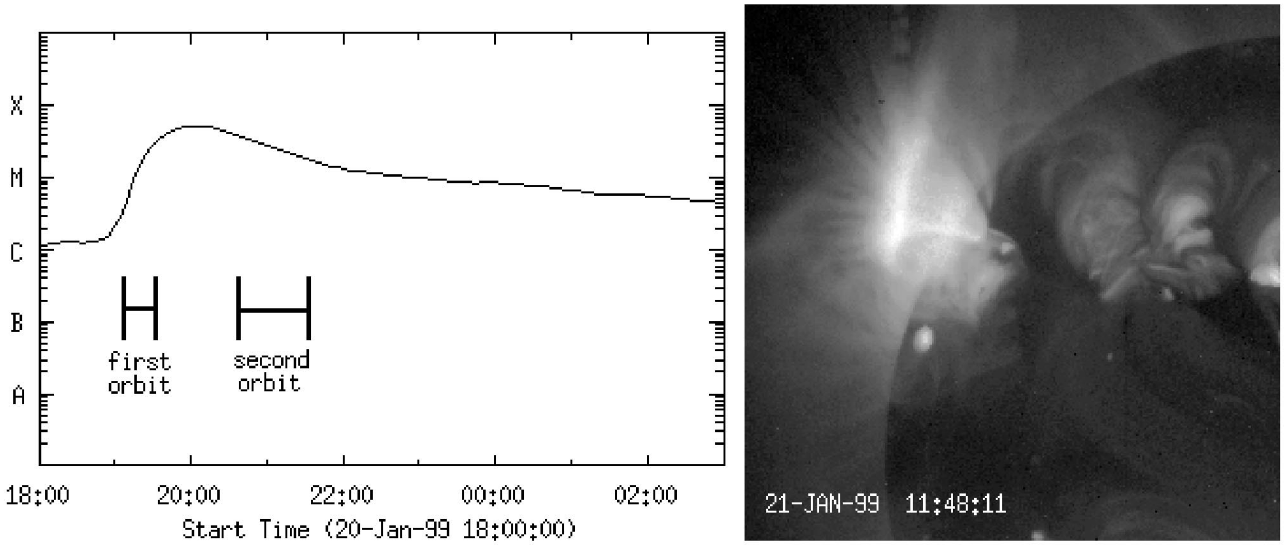

FIG. 1.—Plot of X-ray flux measured by the *GOES* spacecraft. The times of *Yohkoh* data discussed in the present Letter are noted; the right-hand panel shows the appearance of the arcade and fan at a time 17 hr after the onset of the flare.

plicated. The quarter-resolution images evince the removal of a large mass of material from the north part of the region. This coronal dimming (cf. Hudson & Webb 1997) is presumably related to the CME proper, which was observed by the Mauna Loa coronagraph. In the full-resolution images, we observe the brightening of successive footpoints along the arcade; the *Yohkoh* hard X-ray telescope (Kosugi et al. 1991) received photons from a source on the near side of the limb that coincides (spatially and temporally) with the brightest footpoint observed by SXT.

2.2. *Second Orbit: Early Decay Phase*

After a brief pause, SXT began making images again at 20:36:01 UT. The data from this second orbit show the arcade just after the peak soft X-ray brightness of the flare. By this time, the arcade fan is fully formed, its rays protruding high above the top of the arcade. We note particularly that the rays are not static: they exhibit "waving" motions and apparent responses to perturbations by dark blobs moving downward between (and occasionally through) the rays. More than 10 of these "X-ray voids" appear in the images from the second orbit; two are noted in Figure 2. The white arrows in Figure 2 are stationary at the positions of the two dark objects at 21:08:49, while the later two frames of Figure 2 show (with black arrows) the positions of the same two dark objects at the respectively later times. Measurements of the changing positions of several of these X-ray voids imply speeds of 100–200 km s^{-1} and sizes of a few half-resolution pixels (i.e., approximately 10^9 cm in width). The voids exhibit a range of speeds substantially smaller than the gravitational free-fall velocity of 619 km s^{-1}, or the assumed Alfvén speed, and are much higher than the velocity inferred for field-line shrinkage by Hiei & Hundhausen (1996) and Forbes & Acton (1996). However, Forbes & Acton point out that the speeds of retraction can theoretically vary over a wide range, from sub- to supermagnetosonic, depending on the plasma beta.

The arcade fan remains visible for many hours after the onset of the flare. At 11:48 UT on January 21, the rays can be seen to stretch almost two-thirds of a solar radius above the photosphere. Interestingly, the rays do not appear to be static at any time, exhibiting lateral motion and downfalling voids even 17 hr after flare onset. The images imply a measurable regu-

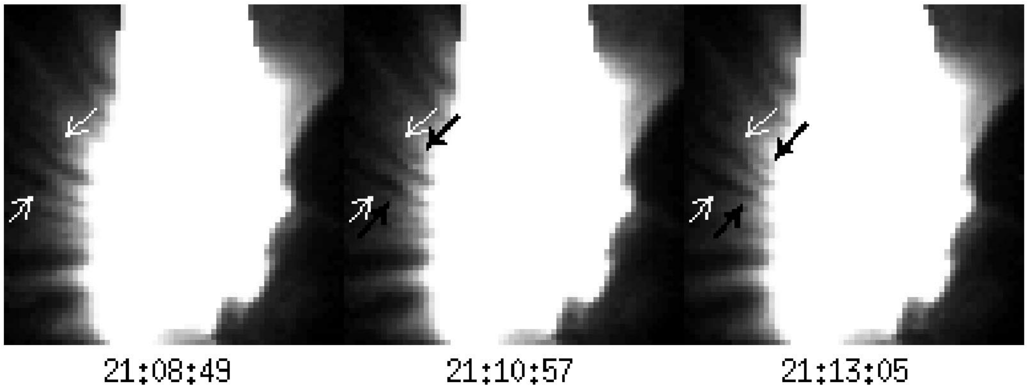

FIG. 2.—Sequence of images showing motion of two dark voids. The white arrows show the locations of these two voids at 21:08:49 UT; the black arrows show the positions at later times. The main body of the arcade is not discernible in these half-resolution images because of pixel saturation.

larity of the rays: at 11:48 UT on January 21, at a height of ≈5×10^9 cm above the top of the arcade (i.e., ≈15×10^9 cm above the photosphere), the rays appear to be spaced approximately 3×10^9 cm apart. (Projection effects due to the angle of the main axis with the line of sight—approximately 50°—have been taken into account in this estimation.)

3. DISCUSSION

In this section, we describe the physical conditions as measured from the SXT images and offer some possible interpretations. We estimate the temperatures and densities in the arcade fan from ratios of images made in the Al12 and AlMg analysis filters (Tsuneta et al. 1991). An attempt was made to correct for scattered light within the telescope via a deconvolution of the raw image and the measured instrumental point-spread function. Although SXT suffers from vignetting for target regions near the edge of the field of view, a satisfactory vignette correction was not available at the time of this writing. The calculation of temperatures from the image-ratio method carries the assumption that each pixel in the images is isothermal, that changes in temperature within the region are negligible between the two exposures (an interval of 32 s in this case), and that the two images can be precisely aligned.

The temperatures thus derived for a selected ray, lane, and void are 7.9, 8.6, and 9.1×10^6 K, respectively. In order to estimate the density of the plasma in each of the regions, we assumed that the line-of-sight depth was the same as the apparent width of the dark voids, approximately 10^9 cm; this yields densities of 2.3, 1.4, and 1.3×10^9 cm^{-3}. Because of the assumptions and limitations listed above, we have more confidence in the qualitative characteristics of the image ratio than in the absolute temperature estimates. In particular, the *relative* temperature comparisons are more robust. For example, we note that if the column depth of the bright ray is as much as 1.5×10^9 cm, the density of the ray is approximately 2.0×10^9 cm^{-3}; similarly, if the void is determined to represent the cross section of a flux tube linking through the current sheet (see § 3.2), then a width and column depth of 1.0 and 2.0×10^9 cm yield a density of ≈1×10^9 cm^{-3} in the X-ray void. A void column depth of 1.0×10^{10} cm implies a density of 4×10^8 cm^{-3}. Variations of the amplitude of scattered light and of the amount of "vignette correction" do not reorder the relative temperatures: the data support the conclusion that the lanes are warmer than the rays, and the voids appear to be warmer still. Consequently, we are led to conclude that the rays are markedly denser than the lanes, with the X-ray voids being less dense than the lanes and rays through which they move.

3.1. *Rays of the Arcade Fan*

The low relative temperature of the rays is reminiscent of the magnetically unipolar polar plumes detected by the *Solar and Heliospheric Observatory* EUV Imaging Telescope and reported by DeForest & Gurman (1998), a comparison suggested by Švestka et al. (1998). An interesting complication to the identification of the rays is that several of the rays can be traced continuously from their tops all the way down to the footpoints of arcade loops, and thus they appear to be associated one to one with individual loops. There are no clear examples of a fan ray that can be associated with a footpoint on *both* sides of the arcade. Gosling, Birn, & Hesse (1995) have demonstrated how such unipolar structures might be created, in a three-dimensional picture of the reconnection in a CME event.

Through a comparison of the time of flare eruption and synoptic interplanetary scintillation data, Švestka et al. (1998) were led to conclude that the arcade fan might be considered a possible source of matter injected into the solar wind. In the present case, we find no unambiguous evidence for material flow outward along the fan rays or in the lanes between the rays, and in fact the presence of a downward velocity field (the dark voids) between the rays suggests that at least the field lines threading the dark voids do not open out into the solar wind.

3.2. *X-Ray Voids*

The voids in Figure 2 are dark in X-ray emission and are moving downward toward the top of the arcade. The images indicate that a few of these voids appear to be compressed from the sides as they approach the top of the arcade. That is, the width of some voids seems to decrease as if responding to an increase in the ambient pressure. In the X-ray images, we were unable to detect any of these voids moving *below* the top of the arcade; in fact, some of the voids were observed to slow down as they approached the top of the arcade, as if coming to a stop. Hα images also showed no evidence of material above the arcade. Based on this information and the temperature analysis, we can start to introduce arguments about the nature and identity of the voids.

The darkness of the X-ray voids almost certainly does not result from the absorption of X-rays, since the temperature analysis implies a density that is too low to account for such absorption. The velocity measurements suggest gravity-driven infall, as with coronal rain in postflare Hα loops, but this identification is problematic since the voids are observed *above* the arcade rather than *below* it. Moreover, we have noted that the movie representation of the data strongly suggests that the ray structures respond to the infalling blobs, as if pushed aside by the blobs rather than obscured by them. This would argue for a regime in which the lower density voids can push the denser rays out of the way. If the rays of the arcade fan trace out the magnetic field lines, and the voids are magnetic features, this would be consistent with low plasma beta.

Here we see two possibilities. The first identifies the blobs with "magnetic islands" formed as a result of resistive instabilities (such as might result from variations in plasma density, magnetic diffusivity, or a tearing-mode instability) in the current sheet during the reconnection process (see the sketch, for example, in Fig. 7.13 of Priest 1982, p. 275). However, the observation of compression as the blobs move downward suggests motion into a domain of higher ambient pressure, which is contrary to the idea that the current sheet squeezes the islands outward.

A separate possibility, which we prefer, is that the voids represent the cross section of flux tubes linking through the arcade fan. Their downward motion would thus be interpretable as shrinkage of the field lines due to magnetic tension, and the observation that some of the voids slow down and stop as they approach the top of the arcade is consistent with the interpretation of flux tubes reaching their equilibrium position in the potential-field arcade configuration. It is uncertain whether the "shrinking linking flux tubes" are field lines that have been reconnected or whether they have simply been "dropped" from the CME after having been stretched upward. The three-dimensional reconnection picture of Gosling et al. (1995) suggests that either possibility is allowed. In the standard two-dimensional reconnection picture, the lower lying field lines are supposed to reconnect first, and then the outer ones later.

The presence of several reconnected flux tubes linking through the current sheet seems to require that the outer field lines have reconnected before the inner ones, or at least that they are retracting faster. This is not a problem if the flux tubes are being lifted, stretched, and then dropped prematurely. Figure 3 sketches this scenario.

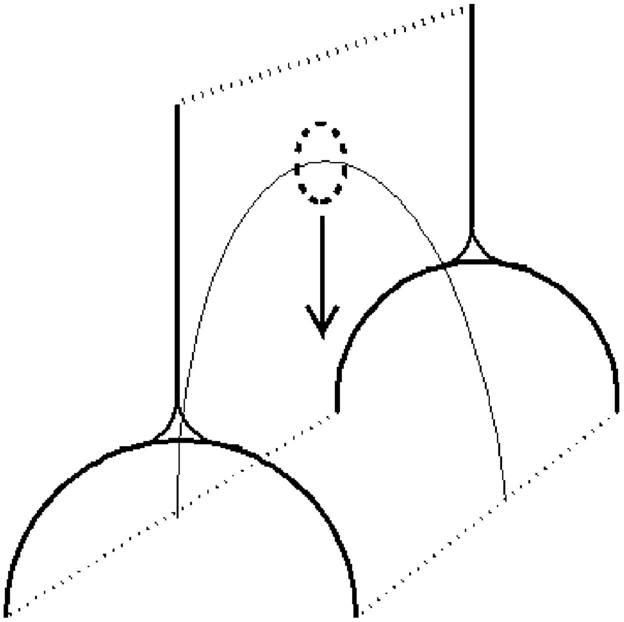

FIG. 3.—Sketch of the proposed scenario. An evacuated flux tube links through the arcade fan (which supposedly contains the current sheet), creating a local depression in X-ray emission. As the flux tube shrinks because of magnetic tension, the void apparently moves downward.

4. CONCLUSIONS

The observations presented in this Letter are rich in motions and structures in the region above the flare arcade. The temperature measurements of the arcade fan suggest that the rays of the fan are cooler than the lanes between the rays, implying a similar configuration to the polar plumes reported by DeForest & Gurman (1998). However, several of the rays of the arcade fan appear to be associated one to one with bright X-ray loops in the arcade and thus would seem to be related to the loop-top cusps expected from reconnection theory. Furthermore, although long-lasting, the rays are clearly not static, as they exhibit violent motions seemingly in response to downward-moving dark voids during the entire decay phase of this flare. The fan structure calls to mind the folds of the quiescent aurora borealis, an effect largely caused by geometry. The observation that some rays are forked, aligned one to one with loop legs, and that in two or three cases, there are rays that are displaced and/or deformed by voids moving down through the rays makes a purely geometrical interpretation unlikely.

The nature of the dark voids remains enigmatic. They appear to have densities similar to (or slightly less than) the inter-ray lanes but to have temperatures that are greater. Interpretations considered include (1) cool, dense blobs of falling material, (2) magnetic islands resulting from resistive instabilities in the current sheet, and (3) shrinking flux tubes linking the current sheet. Based on the available data, the latter interpretation appears to be the most easily supportable.

Finally, we ask what these observations imply for the standard reconnection picture. We believe these data represent the first direct evidence of high-speed flows in the region immediately above flare loops. If our identification of the moving voids in terms of shrinking linking flux tubes holds, we will note that it represents a feature not commonly included in the standard picture. The motion of these flux tubes is much slower than the assumed Alfvén speed and thus might not form either a fast termination shock or a set of slow shocks. This in turn may explain the lack of significant X-ray emission in the voids: the absence of plasma heating by shocks reduces the chromospheric evaporation, which is needed to fill the flux tubes with emissive plasma. The persistence of these flows until late in the decay phase suggests that the reconnection process in this case may have only an indirect relationship to the important flare energy release. We note that this class of events (arcade events surmounted by rays) comprises a minority of the arcade events, themselves a minority of flares in general, and that these conclusions about the nature of large-scale magnetic reconnection in a flare may therefore not apply to all flares.

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