

# Rapid Penumbra Decay Following Three X-Class Flares

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## ABSTRACT

We show strong evidence that penumbral segments decayed rapidly and permanently right after three X-class flares. Two of the three events occurred very recently in solar active region NOAA 10486, an X17 flare on 2003 October 28 and an X10 flare on 2003 October 29, 2003. The third X2.3 flare was observed in solar active region NOAA 9026 on 2000 June 6. The locations of penumbral decay are closely related to hard X-ray flare kernels or coincide with the central region of flare ribbons seen in extra-ultraviolet (EUV) images obtained by the Transition Region and Coronal Explorer (TRACE). We present difference images highlighting the rapid changes between pre- and post-flare states of the flaring active region, which show distinct decaying penumbral segments and neighboring umbral cores becoming darker. This indicates that magnetic fields change from a highly inclined to an almost vertical configuration within approximately one hour after the flares, i.e., part of the penumbral magnetic field is converted into umbral fields.

*Subject headings:* Sun: activity – Sun: sunspots – Sun: magnetic fields – Sun: flares

## 1. Introduction

Only recently rapid and permanent changes of photospheric magnetic fields have been associated with large solar flares. Spirock et al. (2002) studied the X20 flare on 2001 April 2, the largest solar flare in the last few decades. They found that the magnetic flux of the leading polarity increased by approximately  $6 \times 10^{20}$  Mx after the flare, whereas no obvious change in the magnetic flux of the following polarity was detected. Wang et al. (2002a) summarized the study of six X-class flares and found that unbalanced, rapid, and permanent flux increase might be a common property of major solar flares. Advances in ground and space observations now provide data sets with high cadence of about one minute and high-spatial resolution magnetic field observations with a spatial resolution of about  $1''$  to  $2''$ . Therefore, sudden flux changes associated with flares are more likely to be identified for many of the larger events and possibly also for less energetic events. All six events studied by Wang et al. (2002a) have flare associated coronal mass ejections (CMEs), i.e., studying flare related magnetic field changes will also shed light on the magnetic mechanism that cause CMEs. Two additional papers described the appearance of unbalanced magnetic flux that is associated with flares (Yurchyshyn et al. 2003; Wang et al. 2003). However, magnetic flux can also decrease, while parts of an active region are decaying, e.g., the rapid disappearance of a small sunspot associated with a flare was reported by Wang et al. (2002b). Kosovichev & Zharkova (2001) studied high resolution Michelson Doppler Imager (MDI) magnetogram data from the Solar and Heliospheric Observatory (SoHO) for the 2000 July 14 “Bastille Day Flare” and found regions with a permanent decrease of the magnetic flux, which were related to the release of magnetic energy.

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This study was motivated by the recent work of Deng et al. (2003), who found two rapidly decaying penumbral areas, which were associated with an X2.3 flare in solar active region NOAA 9026 on 2000 June 6. Therefore, it is only natural to look for the same signature in the two exceptional flares in solar active region NOAA 10486, classified as X17 and X10, on 2003 October 28 and 2003 October 29, respectively, which received extended media coverage and are likely to be extensively scrutinized by the solar physics and space science community. In this study, we focus on difference images illustrating the penumbral decay and darkening of umbral cores, which will subsequently be related to the energetics of the flare.

## 2. Observations and Data Reduction

All three events in this study were observed by TRACE, which was designed to link observations of dynamic phenomena from the chromosphere through the transition region to the corona (Handy et al. 1999). In the present study, TRACE obtained data sets at different wavelengths before and after the flares (white-light, 1600 Å and 195 Å) due to the fact that the flare triggered its coronal observing mode. In the following section, we concentrate on the analysis of white-light observations. For the X2.3 event on 2000 June 6, TRACE provided data coverage with a one minute cadence. For the X10 and X17 flares, the cadence of white-light images is significantly reduced to about one hour. However, this cadence is sufficient for our purpose of comparing pre- and post-flare states, since we expected to find the tell-tale sign of decaying penumbra based on our previous experience.

Much of the energy released during a flare is used to accelerate electrons, which emit primarily X-rays, upto very high energies. The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) combines for the first time high-resolution imaging in hard X-rays and  $\gamma$ -rays with high-resolution spectroscopy, so that a detailed energy spectrum can be obtained at each point of the flare emission (Lin et al. 2002). This new approach to

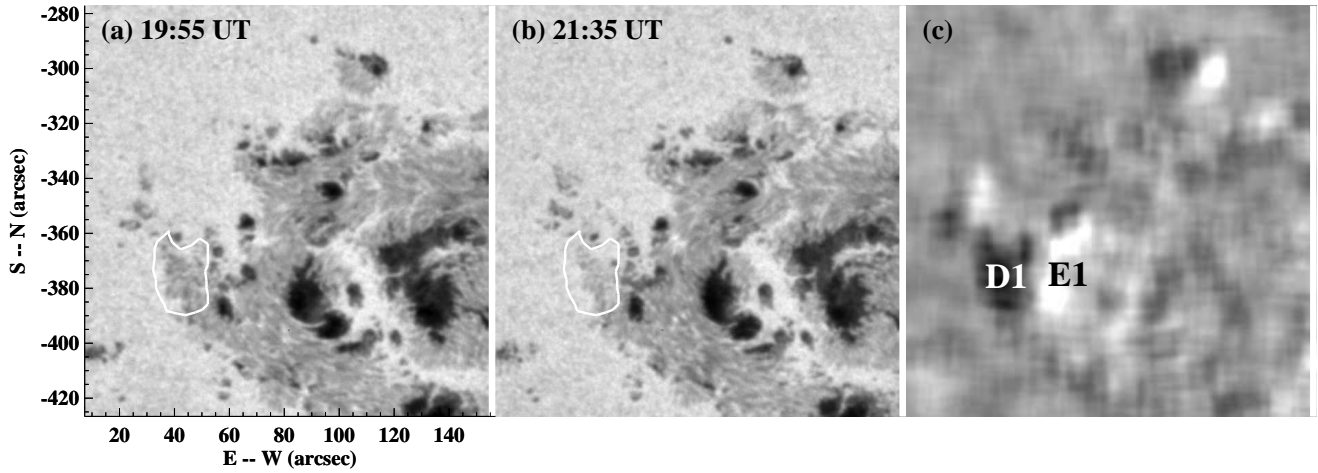


Fig. 1.— Comparison of pre-flare (a) and post-flare (b) TRACE white-light images for the X10 flare on 2003 October 29. The right panel (c) shows the difference image of these two images. The field-of-view is  $150'' \times 150''$ . The annotation D1 refers to the decaying penumbra. The solid white lines in the left and middle panels outline the area of the decaying penumbra.

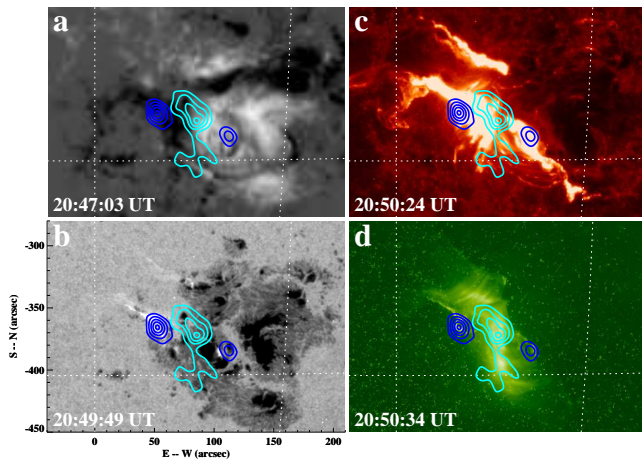


Fig. 2.— RHESSI hard X-ray contours corresponding to the 15-20 keV channel (azure) and 50-100 keV channel (blue) for the X10 flare on 2003 October 29 superimposed on (b) TRACE white-light, (c) 1600 Å, and (d) 195 Å images and an MDI magnetogram (a). Counts were accumulated from 20:49:42 UT to 20:50:42 UT. Contour levels correspond to 35%, 55%, 75%, and 95%, respectively. The two footpoints and a loop top source are clearly discernible.

high-energy solar physics will advance our understanding of the fundamental high-energy processes at the core of the solar flare problem. RHESSI had coverage of X10 and X17 flare peaks. We concentrate our study on the morphology of the flares. In particular, we will study the relationship between the flare kernels as observed by RHESSI and the areas of penumbral decay.

### 3. Results

In Figures 1 and 2, we show the images on the X10 flare from 2003 October 29. According to GOES X-ray report, the flare peaked at 20:49 UT. Figure 1 compares two white-light

images, one before and the other after the flare. We also include the corresponding difference image (pre-flare minus post-flare state), which was smoothed by a window of  $10'' \times 10''$ . Any dark feature in the difference image indicates a brightening in the post-flare image, e.g., an area of decaying penumbra, whereas any bright feature corresponds to a darkening in the post-flare image, e.g., the darkening of an umbral core. Figure 2 shows RHESSI contour maps of the same X10 flare, superimposed on TRACE white-light, 1600 Å, and 195 Å maps and a MDI magnetogram. A two-ribbon flare is clearly visible in the 1600 Å image. The other two X-class flares are also two-ribbon flares. In all the figures, we corrected image shift due to solar rotation.

Figures 3 and 4 show similar results for the X17 flare on 2003 October 28. The flare emission peaked at 11:10 UT. Figure 5 shows the result of the X2 flare on 2000 June 6, peaked at 15:25 UT. Most of the contents in Figure 5 were described by Deng et al. (2003). However, the difference image was not presented in the previous paper.

These three events were all observed near the solar disk center, where the evolution of sunspot structure can be easily and reliably studied, since geometric foreshortening does not have to be taken into account. Three common features are found in all three events: (1) Penumbral decay was found for each event on a time scale of about one hour or less. For the X10 and X17 flares, only one area each was found. They are marked by D1 and D2 in Figures 1 and 3, respectively. Two decaying areas were found for the 2000 June 6 event. They are indicated as D3 and D4 in Figure 5 corresponding to opposite magnetic polarities. The peak intensity reduction (umbral cores) or enhancement (penumbral segment) is of the order of 15% of the continuum intensity and is well above the noise level of about 3%. (2) The locations of the penumbral decay are at or very close to flare footpoints. Comparing Figures 1 and 2, the strongest penumbral decay area coincides with the strongest higher energy hard X-ray source for the X10 event. For the X17 event,

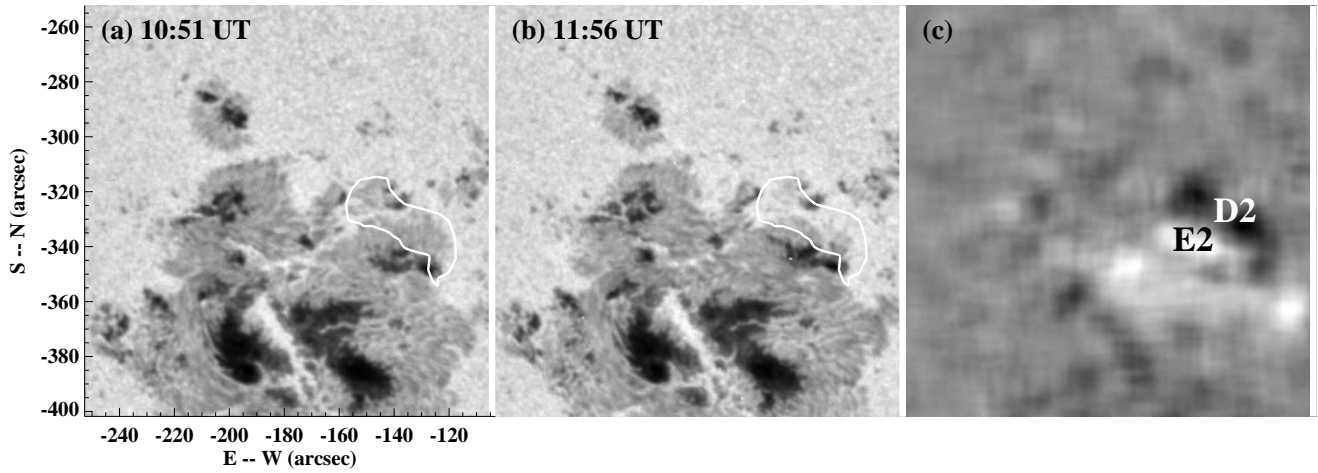


Fig. 3.— Same as Figure 1, however, for the X17 flare on 2003 October 28. The annotation D2 refers to the decaying penumbra.

the area of the decay is not associated with the strongest hard X-ray source, however, it is related to the central part of one of the two TRACE 1600 Å ribbons. There were no hard X-ray images available for the X2.3 event. However, as Deng et al. (2003) found, two penumbral decay areas were very closely associated with two TRACE white-light ribbons marked by two rectangles in Figure 5. (3) For each of the decaying areas, there is a darkening of adjacent umbrae marked as E1, E2, and E3, respectively. The darkening of the umbral cores E3 is shared by D3 and D4. This indicates that the magnetic fields turned from a more inclined direction to a more vertical direction (see Deng et al. 2003). As the penumbra weakens, the umbra becomes stronger.

#### 4. Discussion

The results presented in this letter are straightforward: a section of a penumbra can disappear rapidly and permanently right after a major flare. The location of such a disappearance coincides or is closely related with flare kernels. The adjacent umbra cores are darkening, indicating that the magnetic fields are turning to be more vertical after the flares.

A natural first question is, if such a penumbral decay is associated with the heating of the lower atmosphere by flares. Since the penumbra is not restored even after 10 hours in each case, we conclude that heating is not responsible for decaying penumbrae. Besides, flare emission cannot cause part of the photosphere to be cooler. Magnetic flux in the decaying penumbrae obviously decreased based on the MDI measurements of the X2.3 event (Deng et al. 2003). However, we did not find changes in the magnetic flux in the adjacent umbral areas. We recognize the limitation of filter-based magnetograph systems, since they are not well suited for measurements of strong magnetic fields in the sunspot umbrae due to the well-known Zeeman saturation. Accurate measurements of sunspot magnetic fields can only be achieved by spectro-polarimetry.

We have one likely interpretation of the results: magnetic fields become more vertical after the flares, which causes penumbrae to decay. Deng et al. (2003) presented a sketch

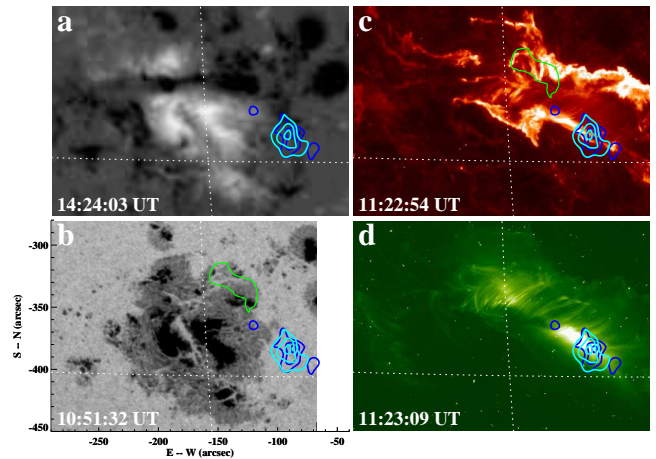


Fig. 4.— Same as Figure 2, however, for the X17 flare on 2003 October 28. RHESSI hard X-ray contours corresponding to the 15-20 keV channel (azure) and 30-50 keV channel (blue) for the X10 flare on 2003 October 29, superimposed on TRACE white-light, 1600 Å, and 195 Å images and an MDI magnetogram. Counts were accumulated from 11:22:22 UT to 11:23:22 UT. Contour levels correspond to 55%, 75%, and 95%. The hard X-ray sources are outside of the active region, but the decaying penumbra coincides with the kernel of a TRACE 1600 Å flare ribbon. The decayed penumbra is indicated by the green contour in panels (b) and (c).

of what might happening under the framework of the break-out model proposed by Antiochos et al. (1999), where magnetic reconnection transfers flux from the central and overlying systems to bilateral arcades.

A more detailed study of the three-dimensional magnetic structure of the three events described in the previous sections will be presented in a forthcoming paper, which will be based on multi-wavelength studies combining ground and space observations.

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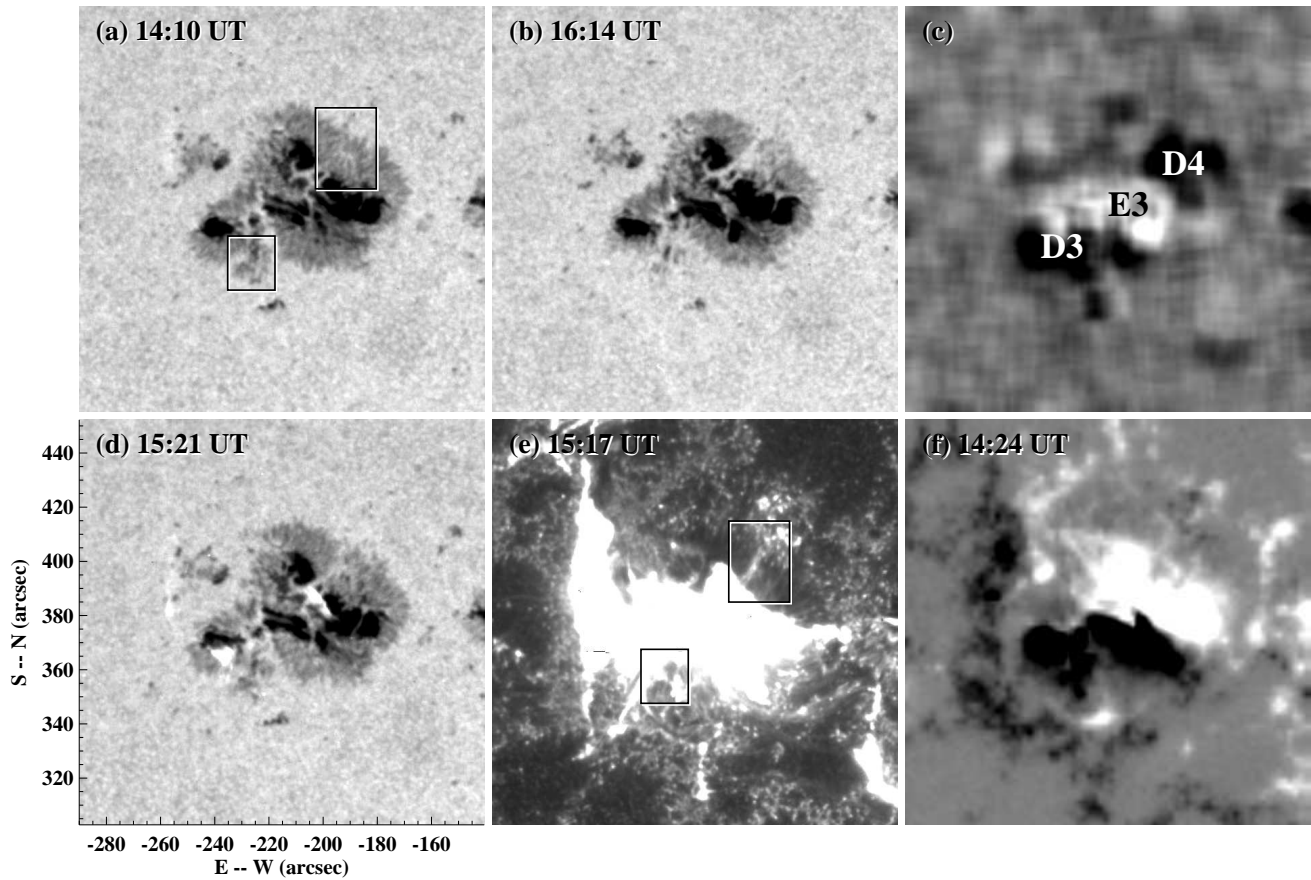


Fig. 5.— The top three panels are the same as in Figures 1 and 3, however for the X2.3 flare on 2000 June 6. The two decaying penumbral segments are marked as D3 and D4. The bottom panels show the flare morphology observed in TRACE white-light and 1600 Å images, as well as an MDI magnetogram. The two rectangles mark the areas of decaying penumbrae and one white-light kernel is located inside each box.

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