

Rapid Penumbra Decay Following Three X-Class Solar Flares

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ABSTRACT

We show strong evidence that penumbral segments decayed rapidly and permanently right after three X-class solar 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. The third X2.3 flare was observed in solar active region NOAA 9026 on 2000 June 6. The locus of penumbral decay is related to flare emission, although with distinct differences for each event. 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.

Because of the lack of spectroscopic data, we cannot exclude the possibility that the observed changes are due to changes in the temperature structure of the flaring atmosphere, or to a corresponding reduction in opacity for a section of both umbra and penumbra (which would cause an increase in the penumbral intensity and a darkening of the umbra). However, we argue against this possibility because the observed intensity changes are permanent, not transient. We instead propose a possible explanation that magnetic fields change from a highly inclined to a more 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 observed to be associated with large solar flares. Spirock et al. (2002) studied the X20 flare on

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2001 April 2, one of the two largest solar flares in the last few decades. They found that the magnetic flux of the leading polarity increased by approximately 6×10^{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 detected for many of the larger events and possibly also for less energetic events. 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.

More recently, we have started to pay attention to the changes of white-light structure in flaring active regions, as the interpretation of white-light observations are more straightforward than the polarization measurements of magnetograms. 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 extensive 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 at three different wavelengths (white-light, 1600 \AA and 195 \AA). 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 penumbrae based on our previous experience.

Much of the energy released during a flare is used to accelerate electrons, which emit primarily X-rays, up to very high energies. The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is advancing our understanding of the fundamental high-energy processes at the core of the solar flare problem (Lin et al. 2002). RHESSI had coverage of the X10 and X17 flare peaks. We concentrate our study on the morphology of the flares. In particular, we will study the relationship between flare emission as observed by RHESSI/TRACE and areas of penumbral decay.

3. Results

In Figures 1 and 2, we show the images of the X10 flare on 2003 October 29. According to the 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 of Figure 5 were described by Deng et al. (2003). However, the difference image was not presented in the previous paper. Please note that in both Figures 2 and 4, TRACE 1600 Å and 195 Å intensities are presented as negative images, in order to optimize the color table.

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 over only a few hours. 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 decayed area was found for each case. 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%. We note that the decaying segments are all located at the outer edge of the active regions. (2) The locations of the penumbral decay are associated with flare emissions, but with distinct differences for each event. Comparing Figures 1 and 2, the strongest penumbral decay area coincides with one of the two 50 to 100 keV hard X-ray sources for the X10 event. For the X17 event, the core of the hard X-ray emission is outside the sunspot region and the area of the penumbral decay is not associated with any hard X-ray source. However, the decaying segment is related to a section of one of the two TRACE 1600 Å flare 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 adjacent to but did not coincide with two TRACE white-light kernels inside 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 core E3 is shared by D3 and D4.

4. Discussion

The observational results presented in this letter are straightforward: a section of penumbra can disappear rapidly and permanently right after a major flare. The location of such a disappearance is related to flare kernels differently in each case. The adjacent umbral cores are darkening in all cases. The physical interpretation of our finding is difficult. In particular, it is hard to understand the nature of the different relationships between decaying penumbral segments and flare emissions.

A natural first question is if such a penumbral decay is associated with heating of the lower atmosphere due to the flare. We have the following arguments against such an explanation. (1) Since the decaying penumbra is not restored even after 10 hours in each case, it is hard to argue that transient heating causes a permanent change in the temperature structure. (2) Flare emission cannot cause part of the atmosphere (in this case the umbrae) to be cooler. We can not absolutely rule out the possibility of temperature change due to a lack of spectroscopic observations. However flare heating and/or mass ejection may cause a reduction of opacity in the overlying atmosphere; i.e. the decaying penumbral would become more transparent, so the underlying photosphere can be seen, which has higher intensity. In the umbral core, one can see deeper into the photosphere, which is darker because of stronger

magnetic fields in deeper layers. However, formulating a precise model of this hypothesis is beyond the scope of this paper.

We therefore put forward another interpretation of the results: magnetic fields become more vertical after flares, which cause penumbrae to decay. The umbrae become darker due to enhancement of longitudinal magnetic field. Deng et al. (2003) presented a sketch of what might happen in 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. Evidence to support such a theory is that the magnetic flux in the decaying penumbrae obviously decreased based on 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 Zeeman saturation. Accurate measurements of sunspot magnetic fields can only be achieved by high-resolution two-dimensional spectro-polarimetry.

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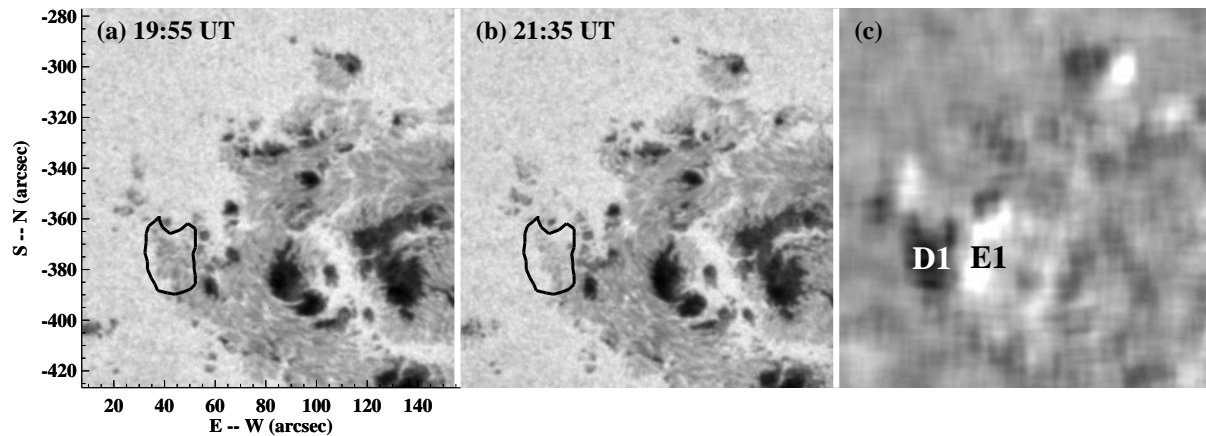


Fig. 1.— Comparison of pre-flare (a) and post-flare (b) TRACE white-light images for the X10 flare on 2003 October 29. The right panel (c) shows the difference image (the pre-flare image minus post-flare image). Therefore, the darkening area represents decayed penumbra segment and brightening area represents an enhanced umbra. The field-of-view is $150'' \times 150''$. The annotation D1 refers to the decaying penumbra. The solid dark lines in the left and middle panels outline the area of the decaying penumbra.

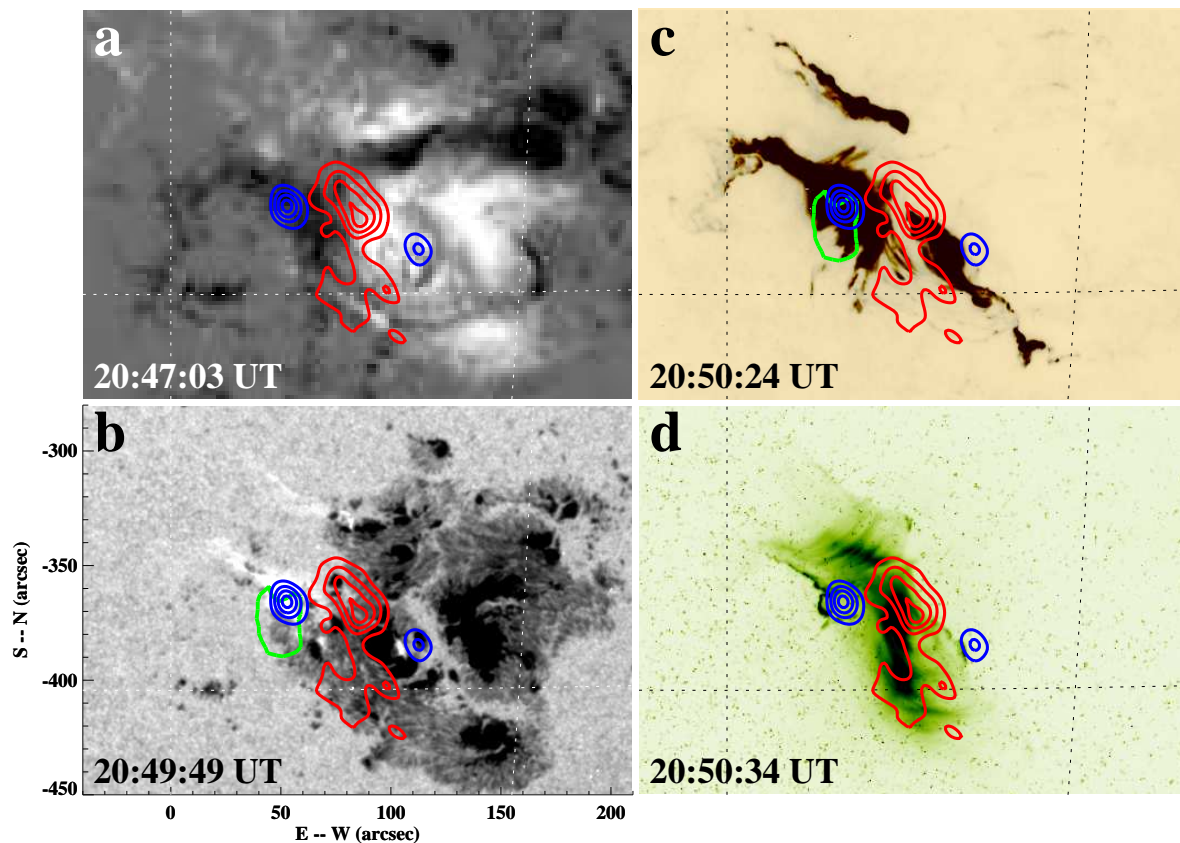


Fig. 2.— RHESSI hard X-ray contours corresponding to the 15-20 keV channel (red) and 50-100 keV channel (blue) for the X10 flare on 2003 October 29 superimposed on (b) TRACE white-light, (c) 1600 Å, and (d) 195 Å images and an MDI magnetogram (a). Note that TRACE 1600 Å and 195 Å intensities are presented by negative images. RHESSI maps were accumulated from 20:49:42 UT to 20:50:42 UT. Contour levels correspond to 30%, 50%, 70%, and 90%, respectively. The two footpoints and a loop top source are clearly discernible. The decayed penumbra is indicated by the green contour in panels (b) and (c).

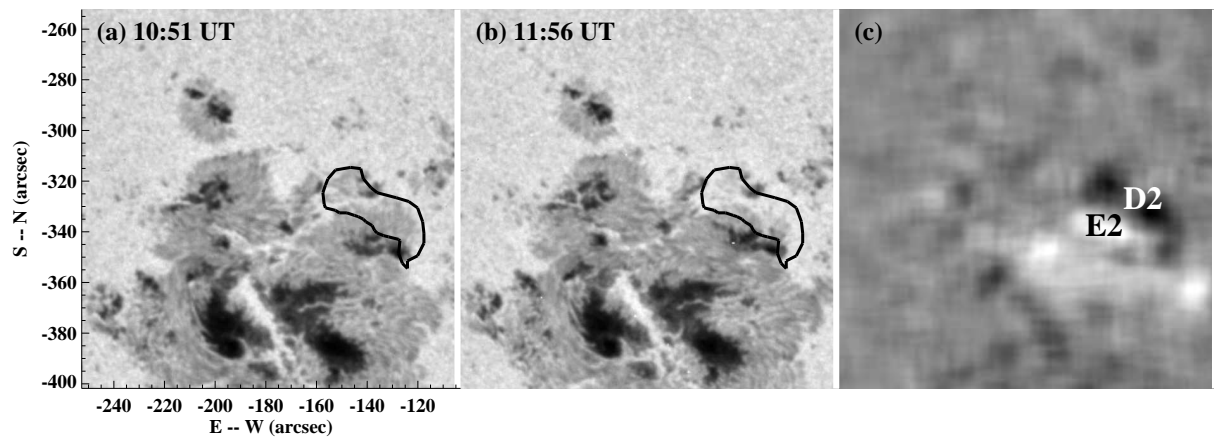


Fig. 3.— Same as Figure 1, however, for the X17 flare on 2003 October 28. The annotation D2 refers to the decaying penumbra. Again, the difference image is the pre-flare image subtracted by the post-flare image.

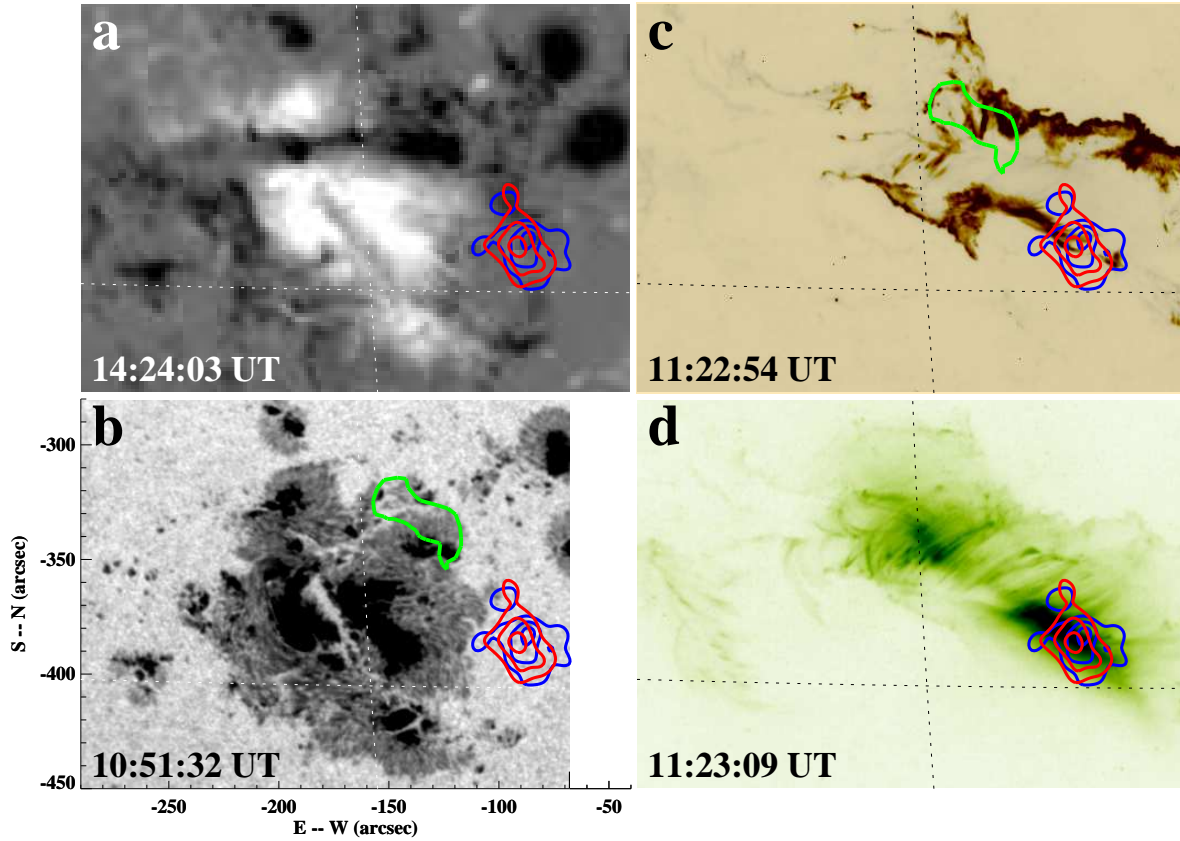


Fig. 4.— Same as Figure 2, however, for the X17 flare on 2003 October 28. RHESSI hard X-ray contours corresponding to the 15-20 keV channel (red) and 30-50 keV channel (blue) for the X10 flare on 2003 October 29, superimposed on TRACE white-light, 1600 Å, and 195 Å images and an MDI magnetogram. RHESSI counts were accumulated from 11:22:22 UT to 11:23:22 UT. Contour levels correspond to 50%, 70%, and 90%. The hard X-ray sources are outside of the active region, but the decaying penumbra coincides with a portion of a TRACE 1600 Å flare ribbon. The decayed penumbra is indicated by the green contour in panels (b) and (c).

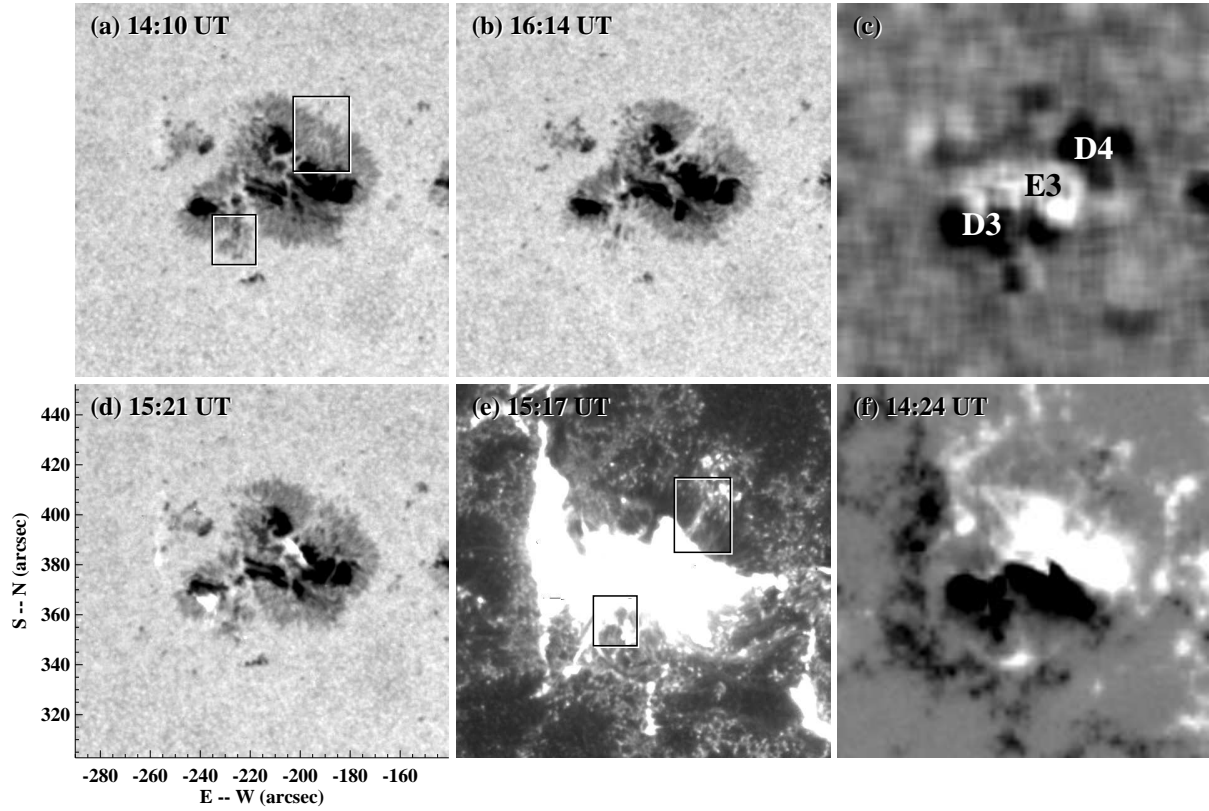


Fig. 5.— The top three panels are the same as in Figures 1 and 3, however for the X2.3 flare on 2000 June 6. The two decaying penumbral segments are marked as D3 and D4. The bottom panels show the flare morphology observed in TRACE white-light and 1600 Å images, as well as an MDI magnetogram. The two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