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A Statistical Study of Rapid Sunspot Structure Change Associated with Flares

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Abstract We reported recently some rapid changes of sunspot structure in white-light (WL) associated with major flares. We extend the study to smaller events and present here results of a statistical study of this phenomenon. In total, we investigate 403 events from 1998 May 9 to 2004 July 17, including 40 X-class, 174 M-class, and 189 C-class flares. By monitoring the structure of the flaring active regions using the WL observations from the Transition Region and Coronal Explorer (TRACE), we find that segments in the outer sunspot structure decayed rapidly right after many flares; and that, on the other hand, the central part of sunspots near the flare-associated magnetic neutral line became darkened. These rapid and permanent changes are evidenced in the time profiles of WL mean intensity and are not likely resulted from the flare emissions. Our study further shows that the outer sunspot structure decay as well as the central structure darkening are more likely to be detected in larger solar flares. For X-class flares, over 40% events show distinct sunspot structure change. For M- and C-class flares, this percentage drops to 17% and 10%, respectively. The results of this statistical study support our previously proposed reconnection picture, i.e., the flare-related magnetic fields evolve from a highly inclined to a more vertical configuration.

Key words: Sun: activity — Sun: flares — Sun: magnetic fields — sunspots

1 INTRODUCTION

The evolution of photospheric magnetic fields associated with solar flares, being one of the most important subjects for understanding how the magnetic energy is stored and released during the flare process, has long been studied in the past (Severny 1964; Zvereva & Severny 1970; Moore et al. 1984; Kosovichev & Zharkova 1999, 2001; Wang & Tang 1993; Wang et al. 1994). Notable progress has been made recently in observing rapid and permanent changes of photospheric magnetic fields associated with large flares (Kosovichev & Zharkova 2001; Spirock et al. 2002; Wang et al. 2002a,b, 2004b; Yurchyshyn et al. 2004; Sudol & Harvey 2005). These studies have demonstrated that high cadence (∼1minute) and high spatial resolution ($\sim 1''$–$2''$) magnetic field observations are able to reveal sudden flux changes associated with major flares, when present.

As an alternative way, we very recently started to pay attention to changes in the white-light (WL) structure of flaring active regions, as the WL observations are more readily interpreted than the polarization measurements of magnetograms. Wang et al. (2004a) studied two X-class flares in the active region NOAA 10486 and found that the penumbral segments decayed rapidly right after the flares; meanwhile, the adjacent umbral cores became darker. The location of such a disappearance of penumbral structure coincides with, or is close to, the flare kernel. Moreover, these changes are permanent, i.e., they remained well after the flares and did not go back to the preflare level. Deng et al. (2005) found very similar penumbral decay and neighboring umbral core darkening when they studied the X2.3 flare of 2000 June 6 in the active region NOAA 9026. Liu et al. (2005) further studied this type of short-term evolution of sunspot structure associated with seven major flares, and proposed accordingly a reconnection picture to interpret the findings. They also understood further that the decay in the outer sunspot structure tends to be more obvious for larger events. We have since noticed that, in an early brief note to the Astrophysical Journal, Howard (1963) indicated that the penumbral areas of sunspots decreased appreciably after major flares.

The studies mentioned above primarily targeted on sunspot structure change associated with X-class flares. It is therefore worthwhile to investigate this phenomenon more systematically and in a statistical manner by analyzing a large unbiased sample of flares. In the present study, we investigated a total of 403 events and extended our study to M- and C-class flares. We use two events to illustrate our method of analysis, and then present our statistical results for all the events studied.

2 OBSERVATIONS AND DATA PROCESSING

We used the Flare Catalog[1] based on the observations obtained with the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) as the starting point for our selection of events. The TRACE 5000 Å WL images are our key data, which we processed using standard TRACE calibration procedures and further aligned with respect to the co-temporal intensitygrams from the Solar and Heliospheric Observatory (SOHO) Michelson Doppler Imager (MDI). We then identified the change in sunspot structure associated with each event by comparing the preflare and postflare TRACE WL images, taken about half to one hour before and after the flare peak time. Care was also taken to make sure that there was no other flare during the time period between the chosen WL images. We made movies using co-aligned WL images from well before to well after the flare, which enabled us to unambiguously trace the evolution of sunspot structure and pin down the location of any structure changes associated with the flare. Furthermore, to aid the investigation of the relationship between the structure change in WL and flare energy release, we used TRACE 1600 Å images near the flare peak time to determine the location of the flare emissions.

To investigate how the magnetic field evolved with changes in WL, we used the high-resolution, high-cadence line-of-light magnetograms of SOHO MDI. For the events we studied, the MDI had obtained full-disk longitudinal magnetograms with a cadence of 1 minute and a pixel resolution of $\sim 2''$. Combined with the corresponding TRACE WL images with $1''$ spatial resolution and typical temporal resolution of 1.5–2.5 minutes, we could derive the time profiles of intensity and magnetic flux of the specific regions.

3 RESULTS

For each event, we constructed a difference image by subtracting the preflare WL image from the postflare WL image. We smoothed the difference image by a window kernel of $10'' \times 10''$ to reduce the background noise caused by granulation and by the five-minute oscillation. In the difference image, a bright area indicates a region of sunspot structure decay, meaning that the sunspot in this area becomes less dark after the flare. This area is always located in the outer part of the sunspot group. On the other hand, the dark area in the difference image indicates the enhancement of sunspot in the postflare image. After identifying the areas of structure change of the difference images, we can further trace them in the time-lapse WL movies, which finally led to the identification of the decaying and darkening structures. We use the following parameters to characterize changes in the sunspot structure:

First, we choose a $20'' \times 20''$ area in a quiet-Sun region outside the sunspot. Let the average intensity of this area be I_0. Then for each event we calculate the integrated decay I_d and the integrated darkening I_e, which are the integrated difference intensity normalized by I_0. For example, the following formula is used to calculate the integrated decay I_d:

$$I_d = \int \frac{I_a - I_b}{I_0} ds , \tag{1}$$

where I_a and I_b are the intensities of the decaying area in the postflare and preflare images, respectively. We used a similar equation to calculate the integrated darkening. Furthermore, we define the mean value of top 5% in the decaying or darkening regions as the peak value and the peak contrast change is then the peak

[1] *http://hea-www.harvard.edu/trace/flare_catalog/index.html*

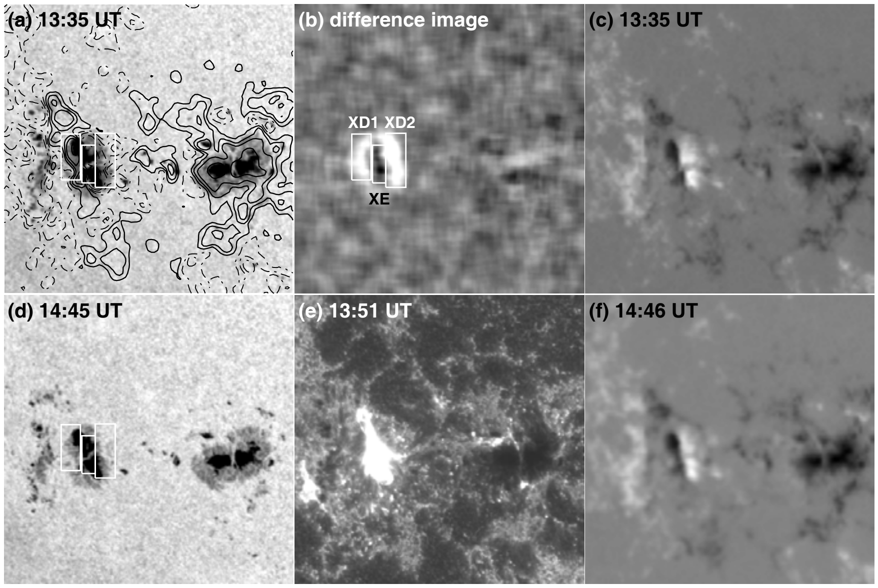

Fig. 1 Comparison of preflare (a and c) and postflare (d and f) states for the X3.6 flare on 2004 July 16. (a and d) and (c and f) are TRACE WL and MDI magnetograms, respectively. (b) is the WL difference image (the postflare image minus the preflare image). MDI longitudinal magnetic field is superimposed onto (a), with black line and dash-dot line representing positive and negative fields, respectively. The magnetic contour levels are ± 50, 150, 300, and 700 G. (e) is the TRACE 1600 Å image near the flare peak time. The FOV of (a)–(f) is $195'' \times 195''$.

value divided by I_0. Finally, the average intensity change is defined as the average intensity of a decay or darkened region in the difference image normalized by I_0.

For each event, we plot the mean intensity of TRACE WL images for both the decayed and darkened regions as a function of time. We also study the evolution of the line-of-sight magnetic fluxes associated with these regions. To mark the timing of the flare, we further superimpose the derivative of the GOES soft X-ray light curve onto the time profiles of the intensity and the magnetic flux.

3.1 Detailed Case Study

To demonstrate our analysis procedure, we present our studies of two typical flares in detail: one X-class flare and one M-class flare. Table 1 provides an overview of these two events. It includes the time of the flares, the NOAA active region number, the flare class in the X-ray classification, and the location of the event on the solar disk.

Table 1 Overview of the Sample Events

Date	Starting time (UT)	Peak time (UT)	AR No.	Class	Location (deg)
2004 July 16	1349	1355	10649	X3.6	S10E26
2002 July 29	1027	1044	10039	M4.7	S15W17

3.1.1 The 2004 July 16 X3.6 Event

This X3.6 flare is one of the X-class flares in the active region NOAA 10649. It started at 13:49 UT and peaked at 13:55 UT in GOES soft X-ray flux. Figure 1 compares the morphology between the postflare and preflare states in the TRACE WL and MDI magnetogram. Note that there are two sunspot groups in the

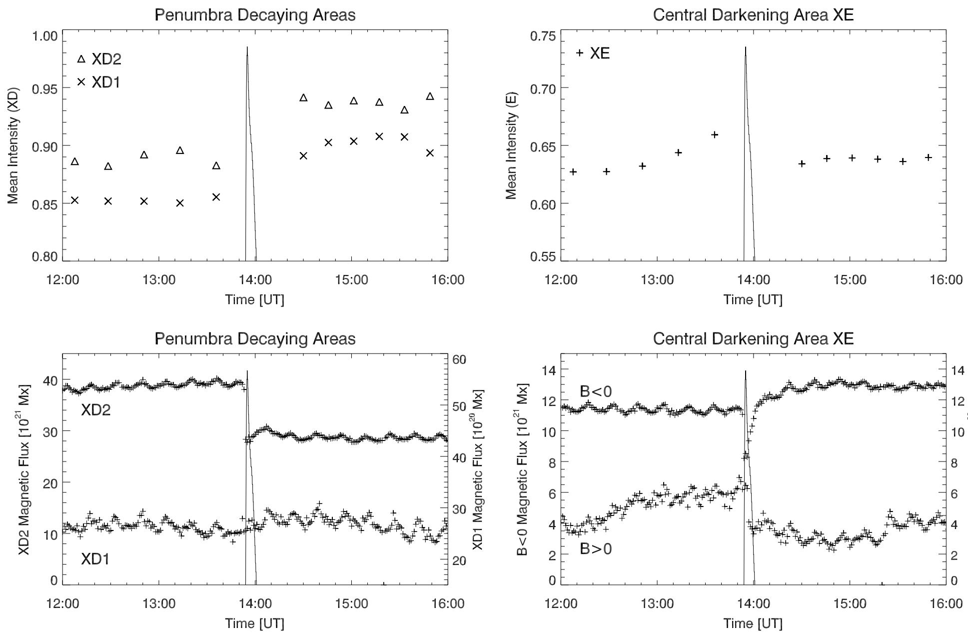

Fig. 2 Top two panels: Mean intensity of the outer sunspot structure decay areas XD1 and XD2 and the central darkened area XE as a function of time on 2004 July 16. Bottom two panels: Evolution of the absolute value of the longitudinal magnetic flux in each area. The curve of vertical spikes represents the derivative of GOES soft X-ray flux.

TRACE field of view (FOV), while the TRACE 1600 Å image near the flare peak time (Fig. 1e) shows that the flare occurred in, and thus was only related to, the eastern group that has a δ configuration (see Fig. 1a). From the WL difference image shown in Figure 1b, we identify two outer sunspot structure decay areas XD1 and XD2, and a central darkened region XE that is close to the flare-associated magnetic neutral line. It can be seen that these decay/darkened areas are co-spatial with the flare emission (cf.Figs. 1b and 1e). As a comparison, no obvious change in WL was found for the western sunspot group where there was no flare. In fact, in all the events that we studied, changes of sunspot structure, if there are any, are always associated with the flaring region. This kind of change closely associated with flare activities is different from the long-term evolution of sunspots that was previously studied (see more discussions in Liu et al. 2005).

In Figure 2, we plot the time history of intensity and magnetic flux of the detected decay and darkened areas. An intensity of 1.0 represents that of the quiet Sun, thus a higher value represents a smaller and/or lighter sunspot in the area. For the areas XD1 and XD2, it is obvious that their mean intensity increases very rapidly after the flare (3.56% and 5.87%, respectively within $\sim$1 hour), representing the rapid sunspot structure decay in these two regions. We monitor this change up to 5 hours after the flare and find that the decayed outer sunspot structure remains un-restored. Similar results are obtained for all the "clear change" events (see discussion in Sect. 3.2), which indicate that the outer sunspot structure decay is not only rapid, but also permanent, relative to the flaring period. For the area XD2, the magnetic flux decreases by about 10^{22} Mx after the flare (c.f. Figs. 1c and 1f) while there is no obvious change in the area XD1. Meanwhile, there are also pronounced changes in the WL intensity and magnetic fields of the central darkened region XE, which includes both umbra and inner penumbra structure as we previously reported (e.g., Liu et al. 2005). We further note that the persistence of these changes suggests that the transient flare emissions do not account for the observed structure changes of sunspots (Wang et al. 2004a).

Because there is a special UV-sensitive coating on TRACE's CCD, the question naturally arises whether the TRACE WL data are sensitive to the UV chromospheric emission. The TRACE 1700 Å channel can be used to detect any UV continuum that is possibly present in the WL images, since it uses the 1600 Å analysis

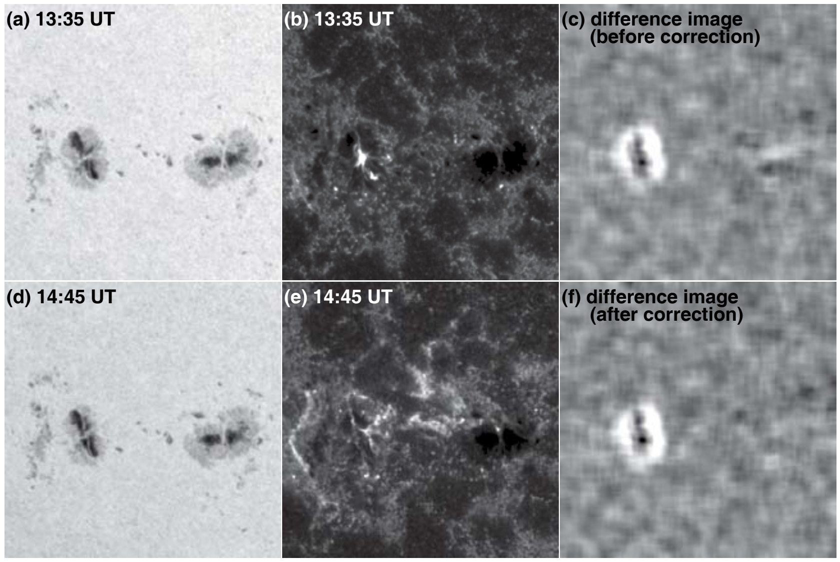

Fig. 3 (a) Preflare WL image with the 1700 Å channel (shown in b) subtracted. (d) Postflare WL image with the 1700 Å channel (shown in e) subtracted. (c and f) WL difference images before and after the UV channel correction, respectively.

filter in series with the fused silica WL filter. For this purpose, we follow the procedure used by Metcalf et al. (2003) to subtract the 1700 Å channel from the TRACE WL images of this X3.6 event and present the results in Figure 3. Compared with Figure 1, it can be seen that for both the WL and the WL difference images, there is little difference with or without the UV channel correction. Therefore, what we found based on WL difference images for this event and most probably for all the other events should reveal the real changes of sunspot structure with negligible impact from the UV emission.

3.1.2 The 2002 July 29 M4.7 Event

This flare occurred in active region NOAA 10039. Similarly, we find decaying outer sunspot structure areas MD1 and MD2 shown in the WL difference image (Fig. 4b) by comparing the preflare image (Fig. 4a) and the postflare image (Fig. 4d). Different from the 2004 July 16 event, the decay regions MD1 and MD2 have the same polarity located to one side of the magnetic neutral line. Also, a darkened region, ME, is clearly seen which includes both an umbral core and an inner penumbral structure. Since the TRACE 1600 Å and WL images at the flare maximum are not available, we present a TRACE 1600 Å image before the flare peak time in Figure 4e to confirm that these changes of sunspot structure occurred in the flaring region.

In Figure 5, we plot the WL intensity and magnetic flux of these decayed and darkened areas as a function of time. For the areas MD1 and MD2, the mean intensity increases very rapidly after the flare (1.91% and 2.0%, respectively, in about 30 minutes), representing the rapid outer sunspot structure decay in these two regions. Meanwhile, for the central region ME, the mean intensity decreases by 1.91%, indicating that the feature becomes darker. These observed structure changes were still not restored several hours after the flare. Noticeable changes of magnetic fields are also found in these regions; however, we remark that the measurement of strong magnetic field in sunspot umbrae may not be accurate due to Zeeman saturation. The implications of the associated magnetic field change in the decay/darkened sunspot structure are further discussed by liu et al. (2005).

3.2 Statistical Results

Following a similar analysis, we investigated 403 events in total from 1998 May 9 to 2004 July 17 including 40 X-class, 174 M-class, and 189 C-class flares. We divide all the events into three categories based on eval-

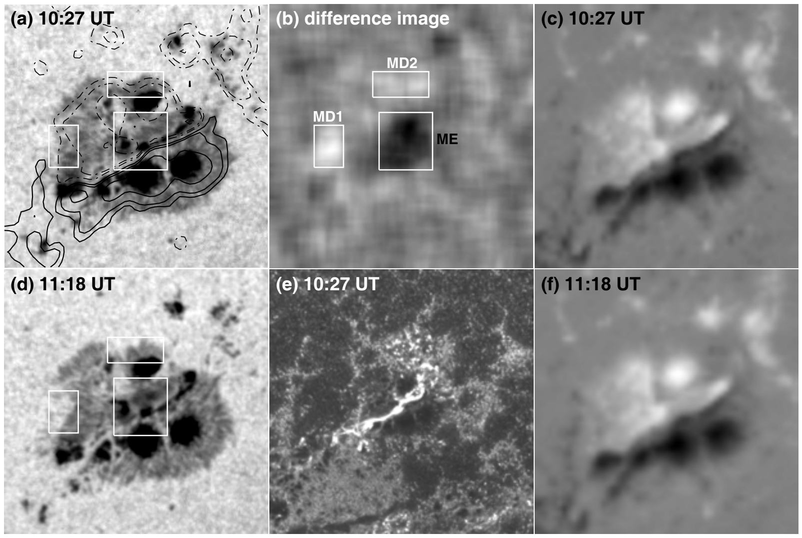

Fig. 4 Same as Fig 1, but for the M4.7 flare on 2002 July 29. The magnetic contour levels are $\pm$ 150, 300, 700, and 1200 G. (e) A TRACE 1600 Å image before the flare peak time. The FOV is $103'' \times 103''$.

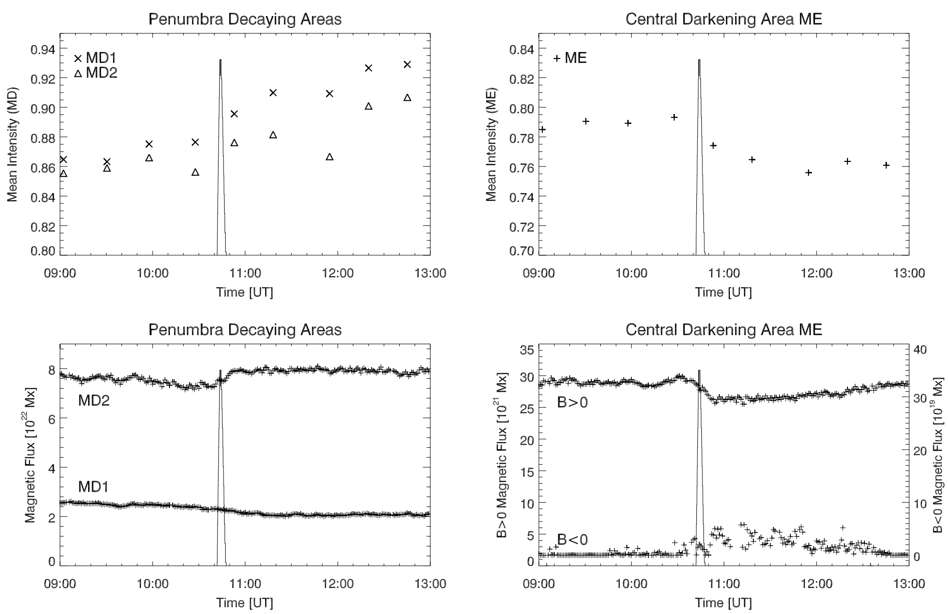

Fig. 5 Same as Fig. 2, but for the M4.7 flare on 2002 July 29.

uating their difference images: "clear change", "uncertain change", and "no change". When we examine the difference image, we mark the event as "clear change" if it is obvious that the change is associated with the flare both spatially and temporally. For other events, we further classify them as "uncertain change", which might be due to the sunspot's proper motion, or "no change". The statistical results are listed in Table 2. For X-class flares, over 40% of events show distinct changes, while for M- and C-class flares, this percentage drops to 17% and 10%, respectively. This indicates that the change of sunspot structure is more likely to be detected when associated with larger flares, which is consistent with the result of Liu et al. (2005). As the

Table 2 Statistical Results of Sunspot Structure Change

			Percentage of Events (Number of Events)		
Flare Type	Total Events	Date	Clear change	Uncertain	No change
X	40	11/22/1998–07/17/2004	42.5% (17)	7.5% (3)	50% (20)
M	174	07/14/1998–06/17/2003	17% (30)	20% (34)	63% (110)
C	189	05/09/1998–11/16/2002	10% (18)	29% (54)	62% (117)

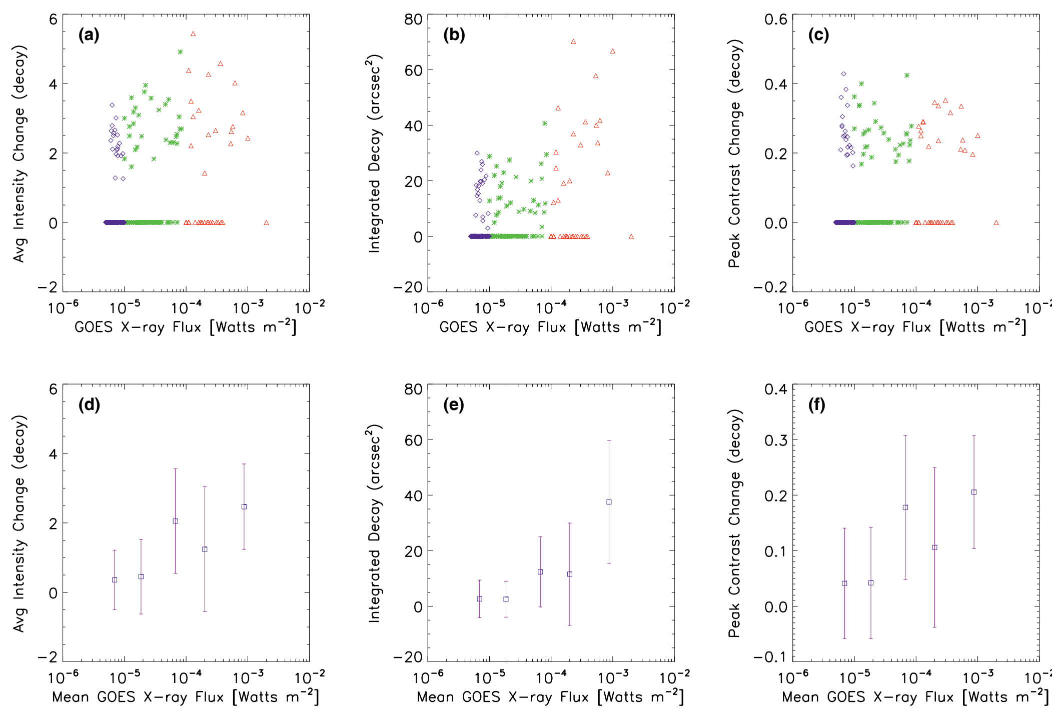

Fig. 6 Scatter plots (top panels) and the averaged plots (bottom panels) between GOES X-ray flux and decay parameters. (a) Average intensity change vs. the GOES X-ray flux. (b) Integrated decay vs. the GOES X-ray flux. (c) Peak contrast change vs. the GOES X-ray flux. The triangles are for X-class flares, stars for M-class, and diamonds for C-class. Panels (d), (e) and (f) are the averages of the data in panels (a), (b) and (c), respectively. From right to left, the squares stand for upper-X, lower-X, upper-M, lower-M, and upper-C class, respectively (see text for explanation). The error bars are the standard deviations determined individually for each subclass.

next step, it is scientifically meaningful to investigate whether there is a quantitative relationship between the parameters of sunspot structure change and those of flares and furthermore, whether there is a better parameter to evaluate sunspot structure change.

For both the decayed and the darkened regions, we calculated the average intensity change, the integrated intensity change, and the peak contrast change as defined in the beginning of Section 3. When making scatter plots, we discarded the "uncertain change" events and put a zero sign for each "no change" event. We further divided the X-class flares into two classes: upper-X (with magnitude larger than X5) and lower-X (with magnitude lower than X5). The M- and C-class flares were also divided in a similar way. Then we calculated the average values of each subclass and plotted them. In all the plots of average values (bottom panels of Figs. 6 and 7), the squares in each panel stand for, from right to left, upper-X, lower-X, upper-M, lower-M, and upper-C class, respectively.

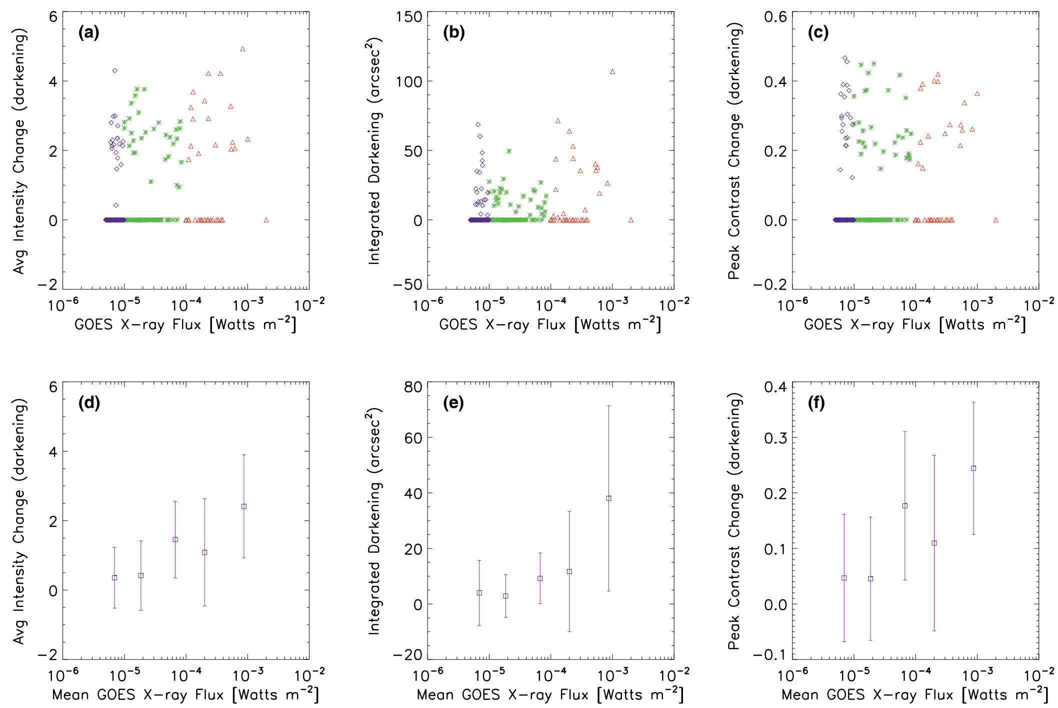

Fig. 7 Same as Fig. 6, but for the darkened areas. Panels (d), (e), and (f) are the averages of the data corresponding to panels (a), (b) and (c), respectively.

3.2.1 Decayed Sunspot Features

A plot of the decay parameters against the GOES X-ray flux is shown in Figure 6. Some similar result was presented by Liu et al. (2005) for a limited set of seven events. Panels (a,b,c) are the scatter plots of the decay parameters and panels (d,e,f) are the averaged values. The error bars are standard deviation determined individually for each subclass from the fluctuations in the parameters. These panels show a general trend that the larger structure decays are associated with the more intense flares. We observe the same trend in all the three different parameters: the average intensity change, the integrated decay, and the peak contrast change.

3.2.2 Darkened Sunspot Features

We analyzed the parameters for the darkened sunspot features in a similar way. In order to compare with the decay features, we used absolute values of all the parameters describing the darkened features. The plots of these parameters against the GOES X-ray flux are shown in Figure 7. Again Panels (a,b,c) and (d,e,f) show the scatter plots and their averaged values, respectively. As for the decayed features, the bigger the flare, the larger the darkening parameters are. Therefore, we conclude that the central feature darkening is also more notable when associated with larger flares.

3.2.3 Flare Duration Versus Decay Parameters

We further investigated the relationship between flare duration and the decay parameters to see if there is any difference between impulsive and long-duration flares. We define the flare duration as the time period when the GOES soft X-ray flux level in the 1–8 Å range remains one magnitude above the background. We plot the flare duration versus the decay parameters in Figure 8 for all the "clear change" events. Only a weak correlation between the flare duration and the integrated decay is found (see Fig. 8b).

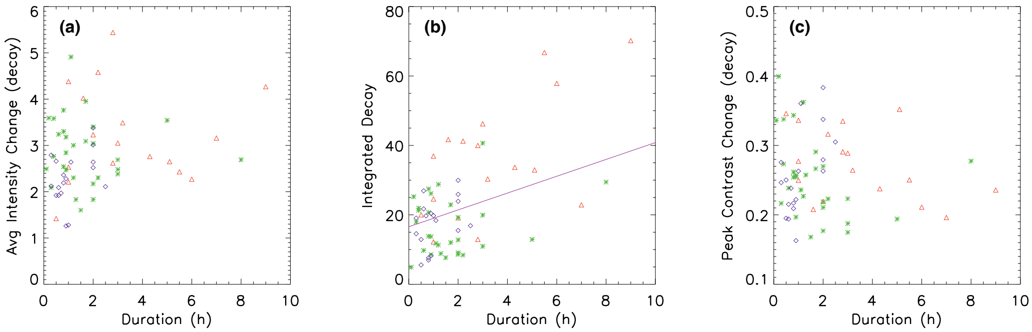

Fig. 8 (a) Average intensity change vs. the flare duration. (b) Integrated decay vs. the flare duration. The correlation coefficient is ∼0.4. (c) Peak contrast change vs. the flare duration.

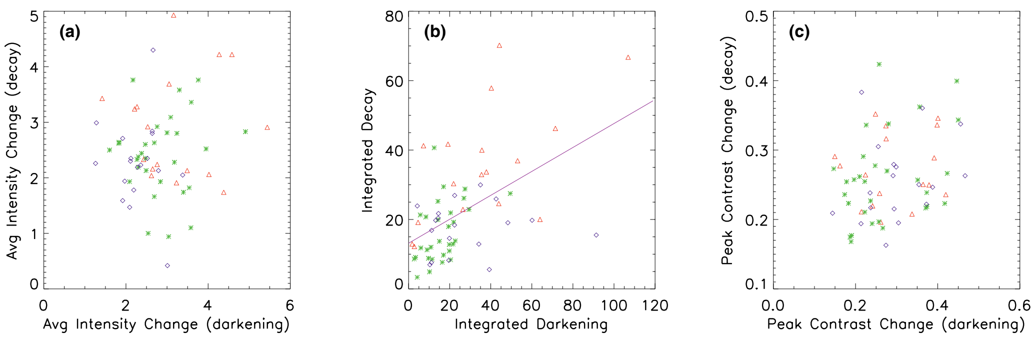

Fig. 9 Relationship between the parameters of structure darkening (X-axis) and decay (Y-axis). (a, c) Average intensity change and peak contrast change, respectively. (b) A moderate correlation between the integrated decay and integrated darkening, with a correlation coefficient of ∼0.52.

3.2.4 Relationship Between Outer Sunspot Structure Decay and Central Feature Darkening

Scatter plots between the parameters of sunspot structure decay and darkening are shown in Figure 9. Panels (a,b,c) are the plots for the average intensity change, the integrated intensity change, and the peak contrast change, respectively. A mild, positive trend is found between the integrated decay and the integrated darkening, i.e., larger integrated decays go with larger integrated darkenings. However, correlation is not clear for the other two parameters. Since both the decay and darkening parameters are correlated with the flare magnitude (see Sects. 3.2.1 and 3.2.2), the trend mentioned above indicates that the integrated intensity change might be a better parameter to quantitatively describe sunspot structure change.

4 SUMMARY AND DISCUSSION

We have presented results of a statistical study of rapid sunspot structure changes closely associated with flares using TRACE WL images. In total, we investigated 403 events from 1998 May 9 to 2004 July 17, including 40 X-class, 174 M-class and 189 C-class flares. Our results and conclusions are summarized as follows.

1. For the outer sunspot structure decay, normalized by the quiet sun intensity I_0, the average change of mean intensity is about 1%–6%, the integrated decay is about 5–70 arcsec^2, and the peak contrast change is around 0.15–0.45. For the central darkened regions, the change of mean intensity is about 1% – 5%, the integrated darkening is about 1–110 arcsec^2, and the peak contrast change is

around 0.1–0.5. These rapid decay/darkening changes that can be identified in the time profiles of WL mean intensity are permanent, not transient, therefore they are not likely caused by the flare emissions (Wang et al. 2004a).

2. Our results indicate that the changes of sunspot structure, in terms of outer structure (mainly penumbra) decay and central umbra/penumbra darkening, are more likely to be detected when associated with larger flares. For X, M, and C class flares, the percentage of events that have clear structure changes is 42.5%, 17%, and 10%, respectively.
3. We find that the longer the flare duration, the bigger the integrated decay is, indicating that the sunspot structure change is associated with the flare reconnection process. In addition, we find a correlation between the parameters of integrated decay and integrated darkening.

For all the "clear change" events, we find that the sunspot structure changes are closely associated with flare activities within hours. We did not find such short-term changes of sunspot structure when there was no flare. To explain these observations, Liu et al. (2005) proposed a reconnection picture in which the outer penumbral fields change from a highly inclined to a more vertical configuration. In this scenario, the change of the orientation of penumbral field lines resulted from magnetic reconnection, which subsequently leads to the outer penumbra decay. Meanwhile, the central umbra/inner penumbral region close to the flare-associated magnetic neutral line becomes darkened as a result of increased field strength there, mainly in the transverse field. Therefore, the parameter of integrated decay in our statistical study should be related to the amount of reconnected fluxes, and hence, to the amplitude of the flare. Combining our results, we conclude that the integrated intensity change could be a better parameter to quantify the sunspot structure change due to flares.

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