Research in Astron. Astrophys. **2009** Vol. **9** No. **2**, 127–132
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

LETTERS

Study of white-light flares observed by Hinode

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Received 2008 November 12; accepted 2008 November 27

Abstract White-light flares are considered to be the most energetic flaring events that are observable in the optical broad-band continuum of the solar spectrum. They have not been commonly observed. Observations of white-light flares with sub-arcsecond resolution have been very rare. The continuous high resolution observations of Hinode provide a unique opportunity to systematically study the white-light flares with a spatial resolution around 0.2 arcsec. We surveyed all the flares above GOES magnitude C5.0 since the launch of Hinode in 2006 October. 13 of these kinds of flares were covered by the Hinode G-band observations. We analyzed the peak contrasts and equivalent areas (calculated via integrated excess emission contrast) of these flares as a function of the GOES X-ray flux, and found that the cut-off visibility is likely around M1 flares under the observing limit of Hinode. Many other observational and physical factors should affect the visibility of white-light flares; as the observing conditions are improved, smaller flares are likely to have detectable white-light emissions. We are cautious that this limiting visibility is an overestimate, because G-band observations contain emissions from the upper atmosphere. Among the 13 events analyzed, only the M8.7 flare of 2007 June 4 had near-simultaneous observations in both the G-band and the blue continuum. The blue continuum had a peak contrast of 94% vs. 175% in G-band for this event. The equivalent area in the blue continuum is an order of magnitude lower than that in the G-band. Very recently, Jess et al. studied a C2.0 flare with a peak contrast of 300% in the blue continuum. Compared to the events presented in this letter, that event is probably an unusual white-light flare: a very small kernel with a large contrast that can be detected in high resolution observations.

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

1 INTRODUCTION

White-light flares (WLFs) are defined as flares that have visible emission in the optical continuum. The first such event was noted by Carrington (1859). They are thought to be the most energetic flaring events. The observations of WLFs are rare, and observations of them under sub-arcsecond conditions hardly exist except for a few cases. Neidig & Cliver (1983) surveyed all the WLFs observed up to then, with a total of 60 of them. This number increased to 86 in their later survey (Neidig et al. 1993). Among other conditions, they found that one necessary condition of WLF occurrence is that the GOES X-ray class is greater than or equal to X2. Note that all the events in their studies were observed with a spatial resolution substantially greater than 1 arcsec.

In the past decade, the advanced space observations and ground-based observations with adaptive optics made the higher quality WLF observations possible. Matthews et al. (2003) surveyed WLFs observed by the Soft X-ray Telescope on Yohkoh. Although the spatial resolution of these observations was 5 arcsec, they were able to detect 28 events in the G-band and found a strong association with hard X-ray emissions. Hudson et al. (2006) used white-light observations onboard the Transition Region and Coronal Explorer (TRACE) that has a spatial resolution of 1 arcsec (pixel resolution of 0.5 arcsec) and detected white light emissions for events as weak as GOES C1.6. Therefore, they concluded that the white-light continuum may essentially occur in all flares. However, because TRACE WLFs have higher contrast than the traditional WLFs, it is unclear if the TRACE continuum is affected by UV emission although careful contamination removal was performed by the authors. Fletcher et al. (2007) discussed the mechanism of white-light emissions and believe that they come from moderate depths in the chromosphere.

The first sub-arcsecond resolution observations of WLFs were carried out with AO-corrected observations at the Dunn Telescope of NSO/SP (Xu et al. 2004, 2006). The principal observing wavelength was near infrared at 1.6 μm, which is formed at an opacity minimum, and is therefore the deepest layer observable by direct imaging. The flares were also covered by observations of the G-band and continuum around 520 nm. The maximum intensity enhancements of the two flares were 25% and 66%, compared to the quiet-Sun NIR continuum. The likely explanation of the observed emission is back-warming as the non-thermal electrons cannot penetrate to the lower photosphere (Hudson 1972; Metcalf et al. 1990; Ding et al. 1999, 2003; Liu et al. 2001).

In a very recent paper (Jess et al. 2008), white-light emission in the blue continuum was detected for a C1.6 flare on 2007 August 24, with a peak contrast of 300%. The flare was studied with the diffraction limited observations using the 1-meter Swedish Solar Telescope. They concluded that the white-light emissions might be visible in all the flares, as long as the data have sufficient spatial resolution. Motivated by the work of Jess et al., in this letter, we present a systematic study of WLFs observed by Hinode that has a spatial resolution of 0.2 arcsec. The G-band WLF of 2006 December 13 was analyzed carefully by Isobe et al. (2007), where they found the structure in the form of a core-halo, confirming what was reported by Xu et al. (2006). Jing et al. (2008) studied this event further, and found that the white-light emissions correspond to the location of a process with a strong magnetic reconnection rate. Different from the approaches of previous works, in this letter, we study all the flares with a GOES magnitude above C5.0 that were covered by the Hinode observations, to analyze the visibility of white-light emission as a function of GOES X-ray flux.

2 DATA DESCRIPTION AND ANALYSIS

Hinode is the follow-up mission to the very successful Japan/UK/US Yohkoh mission. The mission consists of a coordinated set of optical, X-ray, and EUV telescopes (Kosugi et al. 2007). The 0.5 meter Solar Optical Telescope (SOT) provides angular resolution of $0.2''$ to $0.3''$. The focal plane package of SOT consists of a Broadband Filter Imager (BFI), Narrowband Filter Imager (NFI) and Spectro Polarimeter (SP). After surveying the Hinode data archive, we realized that the SOT coverage of flares is primarily in the CaII H band, and that the next most common data sets are in the G-band centered on 430.50 nm with a bandwidth of 0.8 nm. The typical pixel resolution of the G-band images is 0.109 arcsec. The observing cadence varies, but nominally, it is around 2 minutes. Since the launch of Hinode in October 2006, in the last two years, there have been 29 flares with GOES classification C5 or larger. SOT G-band observations covered 13 of them that were all disk events. Strictly speaking, G-band observations do not represent the true white-light emission of a flare, as it is contaminated by the emissions in the upper atmosphere due to the complicated CH band (e.g., Langhans & Schmidt 2002). Therefore, its measured emission would be larger than the pure white-light continuum. In particular, the G-band contrast is enhanced in the areas corresponding to fine magnetic flux tubes. One of the 13 events in our study had near simultaneous observations in the G-band and blue continuum (450.45 nm with a bandwidth of 0.4 nm), giving us the opportunity to compare the flare emissions in these two bands. This event was the M8.9 flare on 2007 June 4, in AR 10960. Table 1 lists the key properties of these 13 events.

In the table, the peak contrast is defined as the maximum of $\frac{I-I_0}{I_0}$, where I_o is the local intensity before the flare and I is the intensity at the observed peak of the flare. The pre-flare image is taken between 2 to 4 minutes before the time of the flare peak, depending on the duration of the flare and

Table 1 Properties of Flares

Date	Peak Time	AR number	Location	GOES	Peak Contrast	Equivalent Area
2006 Dec 6	1013UT	10930	S07E68	X9.0	3.82	100.4 arcsec^2
2006 Dec 13	0240UT	10930	S06W23	X3.4	3.52	68.9
2006 Dec 14	2215UT	10930	S06W46	X1.5	1.51	46.5
2007 Jun 4	0513UT	10960	S05E51	M8.9	1.75	49.3
2007 Jun 3	0641UT	10960	S06E63	M4.5	1.79	16.8
2007 Jun 2	1035UT	10960	S09E73	M1.0	0.74	1.26
2007 Jun 9	1348UT	10960	S10W23	M1.0	0.0	0.0
2007 May 2	2348UT	10953	S14W17	C8.5	0.0	0.0
2007 Jul 10	0240UT	10963	S04E47	C8.2	0.51	0.61
2007 Jun 5	1613UT	10960	S07E30	C6.6	0.0	0.0
2006 Dec 7	0445UT	10930	S07E52	C6.1	0.0	0.0
2006 Dec 11	0818UT	10960	S04W02	C5.7	0.0	0.0
2007 Jul 10	1753UT	10963	S07E45	C5.2	0.0	0.0

the availability of the data. Consequently, a contrast value of 1.0 means that the excess brightness is 100% of the pre-flare value. The equivalent area is the contrast integrated over the flare area, in units of arcsec^2. This has an analogy to the "equivalent width" used in line spectrum analysis. We chose a contrast threshold of 30% when we calculated the equivalent area. This threshold is about 3 times the background noise in the difference image, e.g., if a flare kernel has a size of 5 arcsec, the mean contrast is 100%, and according to our definition, the equivalent area is 25 arcsec^2. In addition, GOES flare classification, flare peak time, NOAA active region number and disk location of each event are also described in Table 1. The weakest event having white-light emission in our list is a C8.2 flare, which has a contrast of 51% and kernel size of about 1 arcsec.

3 OBSERVATIONAL FINDINGS

As we mentioned earlier, only the M8.7 flare of 2007 June 4 had simultaneous observations in the blue continuum–a more accurate way to measure the white-light emission than in the G-band. As a comparison, the measured peak contrast in the blue continuum for this flare is 0.944 while the equivalent area is 5.10 aresec^2, about a factor of two and an order of magnitude smaller than the corresponding numbers from the G-band. This contrast ratio between the G-band and the visible continuum is between the values for the two flares presented by Xu et al. (2006). Figure 1 compares the flare morphology in the G-band and blue continuum. For this event, the maxima of flare emissions were observed at 051243 UT and 051249 UT for the G-band and blue continuum, respectively, while the pre-flare images were taken at 050944 UT and 050951 UT. The flare kernels are clearly visible in the G-band as marked by 4 dark boxes. The blue continuum emission can be identified in these boxes, however, with a much narrower margin above the background noise. In the same figure, we show much extended flare emissions as observed in CaII H band. The H band image is saturated in part of the strong flare emissions, resulting in voids inside boxes marking G-band flare kernels. The available magnetogram closest to the time of the flare was obtained by Hinode/SP 7 hours after the flare. We rotate the image of the line-of-sight magnetogram to the location of flare time and include it in Figure 1. It roughly gives locations of flare kernels relative to the magnetic structure; however, no serious analysis of magnetic topology can be done based on this magnetogram because of the huge time gap. The properties of the G-band flare emissions are similar to those in all the events presented in this Letter. There are at least two kernels; the kernels are observed inside sunspots; typically in the penumbrae.

From prior studies, it is reasonable to believe that larger flares (higher GOES X-ray flux) would give a higher white-light emission (e.g., Neidig & Cliver 1983). Figure 2 quantitatively describes the correlation between GOES X-ray flux and the observed emission in the G-band. The top panel plots the peak contrast vs. GOES X-ray flux while the bottom panel plots the equivalent area. Due to the small number of data points, it is meaningless to fit the data points to empirical curves to further quantify the correlations. We estimated that the error of contrast measurement is 30% (3 times the background noise

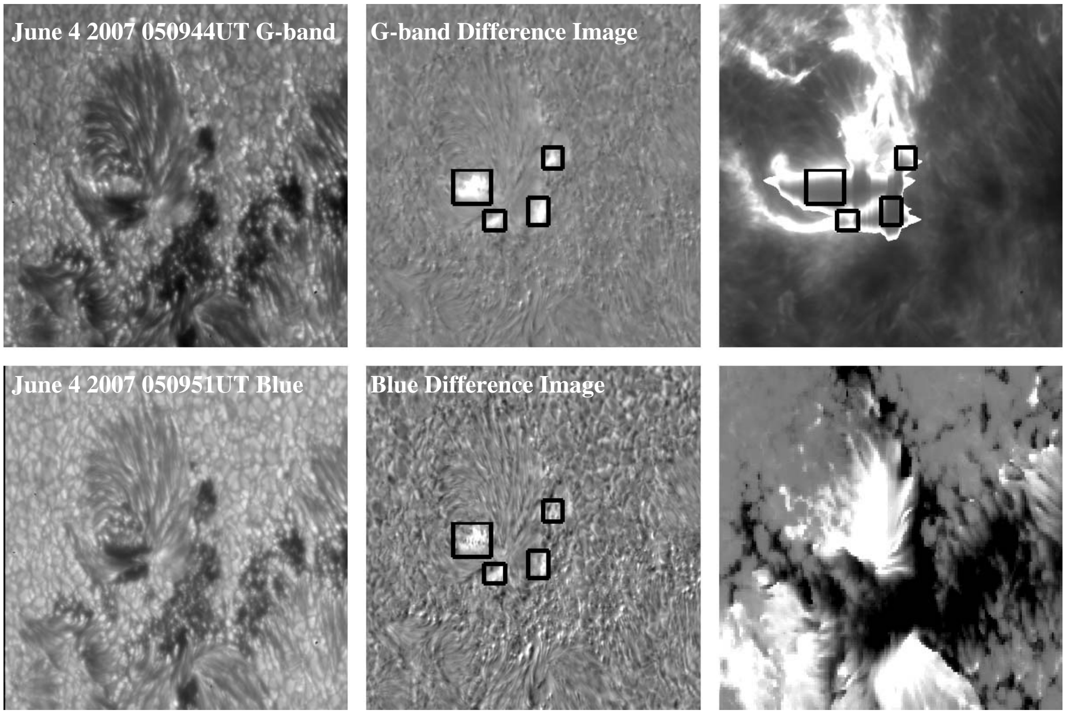

Fig. 1 Comparison of white-light emissions in the G-band and blue continuum of the M8.7 flare on 2007 June 4. Top panels: pre-flare image in G-band, difference image at the peak of the flare and corresponding image in CaII H band. Bottom panels: pre-flare image in the blue continuum, difference image at the peak of the flare and the corresponding line-of-sight magnetogram obtained at 12 UT. Four flare kernels are marked by dark boxes. The flare images were obtained at 051243 UT and 051249 UT for the G-band and blue continuum, respectively, while the pre-flare images were at 050944 UT and 050951 UT. The field of view is 43.6 by 43.6 arcsec.

in difference images), and that of the equivalent area is 10% of measured values. These errors are marked in the vertical direction of the data points. Based on Table 1 and this figure, it is not hard to conclude that the cut-off of the G-band emission appears at M1 GOES level under the observing condition of Hinode. The cut-off of the blue continuum would occur at an even higher GOES magnitude. This is evidenced by the comparison of the G-band and blue continuum for the M8.7 flare on 2007 June 4: the peak contrast drops by about half, and the equivalent area drops about an order of magnitude in the blue continuum.

As we mentioned in Section 1, in a very recent paper of Jess et al. (2008), high contrast (300%) blue continuum emissions were reported for a small C2.0 flare. Therefore, we compare the properties of this flare with Hinode flares. The flare was only observed by the 1-m Swedish Telescope. Unfortunately, Hinode did not cover this event. We include two data points in Figure 2 which indicate the contrast and integrated flux. We believe that with the adaptive optics system on the telescope and the post-facto image processing, the spatial resolution of the 1-m telescope has a comparable, perhaps even slightly better, spatial resolution than that of the Hinode SOT. The contrast of 300% in the blue continuum is extremely high. However, using the kernel size given in their paper, the equivalent area is estimated to be 0.3 arcsec^2. We use the triangles to mark the contrast and equivalent area of the blue continuum, in the top and bottom panel of Figure 2. Furthermore, we extrapolated the G-band contrast and equivalent area based on the scaling information of the 2007 June 4 flare, and mark them as squares in Figure 2. It is obvious that the peak contrast does not follow the trend of the plot in the top panel, while the equivalent area is considered as normal in the bottom panel. The visibility of this WLF is due to an extremely small

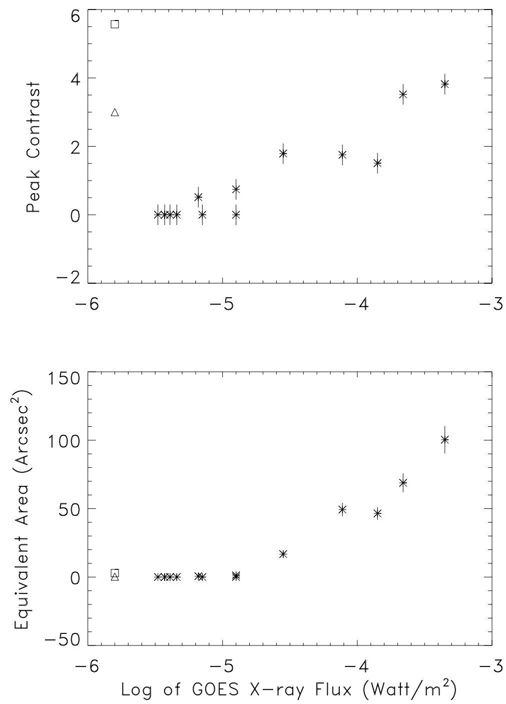

Fig. 2 The correlation between GOES X-ray flux and the flare emission in the G-band. The top panel plots the peak contrast while the bottom panel plots the equivalent area. The triangles and squares mark the corresponding emission of the C2.0 flare of 2007 August 24 observed by Jess et al. (2008) for the blue continuum and the extrapolated G-band emissions. The values of –6, –5 and –4 on the X-axis mark the beginning of the C, M and X-class flares.

flare kernel (0.4 arcsec) with high emission contrast, that should be detected easily by either Hinode or the Swedish Telescope.

4 SUMMARY AND DISCUSSION

We surveyed all the flares above the GOES magnitude of C5.0 since the launch of Hinode in October 2006. This is a flare-quiet period in the solar cycle. Only 13 of them were covered by the Hinode G-band observations among a total of 29 events. We analyzed the peak contrast and integrated excess emission (in term of equivalent area) of these flares, and found that the cut-off visibility is likely around M1 flares under the Hinode observing conditions. As many other factors can affect the appearance of WLFs, some smaller flares may have white-light emissions that were not detected by Hinode. Among the 13 events, only the M8.7 flare of 2007 June 4 had observations in both the G-band and blue continuum. The blue continuum has a peak contrast of 94% vs. 175% in the G-band. The equivalent area in the blue continuum is an order of magnitude lower than that in the G-band. The 300% peak emission contrast in the blue continuum of a C2.0 flare as observed by Jess et al. might be a special case. We speculate the following reasons for this unusual event. (1) The flare kernel is confined in a small area (0.4 arcsec in size) so that the peak contrast can be high while the equivalent area can be comparable to other events. (2) The higher cadence of Jess et al.'s observation may increase the chance of catching the exact time of the peak of the flare. The cadence of the SOT G-band observation is nominally 2 minutes, therefore the peak of the flare emissions may be missed so the visibility of the white-light emission is reduced. Furthermore, we are cautious that this limiting visibility is an overestimate by us, as the G-band observations contain emissions from the upper atmosphere.

Summarizing the previously published WLF observations, it is known that the visibility of WLF depends on the observing wavelength. The order is: TRACE WL, G-band, blue continuum and red-continuum. In addition, it is possible to detect the flare emission at the opacity minimum (Xu et al. 2004, 2006) in near infrared, although with even weaker emission. Of course, the flux and hardness of electrons precipitating to the surface is another important factor affecting the visibility of WLFs. Therefore, studying the contrast of WLFs as a function of hard X-ray flux will be extremely important in understanding the mechanism of WLFs, such as direct precipitation or back-warming. Back-warming has been considered by a number of authors (Jess et al. 2008; Xu et al. 2004, 2006) for various reasons. The data present in this letter cannot distinguish between these two emission mechanisms. As we found in this letter as well as the work of Jess et al. (2008), WLF kernels are found inside sunspots. No kernel in the quiet areas of the sun was detected. Furthermore, we speculate that the disk position of flares affects the visibility of WLFs. The events closer to the limb would have a better chance to have observed white-light emissions, consistent with the comparison of Xu et al. (2006). However, we do not have enough events to present a statistically significant study.

As new instruments are being developed for higher resolution observations, including 1.5 class telescopes such as the New Solar Telescope (NST) of Big Bear Solar Observatory and the GREGOR telescope in Germany, as well as the 4-m Advanced Technology Solar Telescope, it will be likely that we can extend the observational limit beyond what we discussed in this letter, e.g., if flare emission is confined to the size of 0.1 arcsec, these new observations will detect flare emissions when the peak contrast is above the noise level. Furthermore, the high cadence observations will cover the true flare emission peaks, increasing the visibility of WLFs. The higher cadence data will likely reduce the noise level (e.g. from the current 30% to 10%). Using adaptive optics equipped NST as the example, the threshold of equivalent area would drop to 0.001 arcsec^2, at least two orders of magnitude lower than the threshold found in this letter. The high-cadence high-resolution multi-wavelength observation will also be important for studying the evolution of fine structures in flares.

Acknowledgements We thank the referee for his/her comments to improve this paper. The work is supported by NSF under grant ATM 07-45744, and by NASA under grants NNX07AH78G, NNX08AJ23G and NNX08AQ90G. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as the domestic partner and NASA and STFC (UK) as the international partners.

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