Characteristics that Produce White-light Enhancements in Solar Flares Observed by Hinode/SOT

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Abstract

To understand the conditions that produce white-light (WL) enhancements in solar flares, a statistical analysis of visible continuum data as observed by Hinode/Solar Optical Telescope (SOT) was performed. In this study, approximately 100 flare events from M- and X-class flares were selected. The time period during which the data were recorded spans from 2011 January to 2016 February. Of these events, approximately half are classified as white-light flares (WLFs), whereas the remaining events do not show any enhancements of the visible continuum (non-WLF; NWL). To determine the existence of WL emission, running difference images of not only the Hinode/SOT WL (G-band, blue, green, and red filter) data, but also the Solar Dynamics Observatory/Helioseismic and Magnetic Imager continuum data are used. A comparison between these two groups of WL data in terms of duration, temperature, emission measure of GOES soft X-rays, distance between EUV flare ribbons, strength of hard X-rays, and photospheric magnetic field strength was undertaken. In this statistical study, WLF events are characterized by a shorter timescale and shorter ribbon distance compared with NWL events. From the scatter plots of the duration of soft X-rays and the energy of non-thermal electrons, a clear distinction between WLF and NWL events can be made. It is found that the precipitation of large amounts of accelerated electrons within a short time period plays a key role in generating WL enhancements. Finally, it was demonstrated that the coronal magnetic field strength in the flare region is one of the most important factors that allow the individual identification of WL events from NWL events.

Key words: Sun: flares – Sun: particle emission – Sun: X-rays, gamma rays

1. Introduction

Solar flares are often associated with enhancements of visible continuum (white-light; WL) radiation. The first white-light flare (WLF) recorded was the Carrington flare of 1859 (Carrington 1859). WLFs are largely associated with energetic events such as GOES X-class flares and are rarely observed. However, using recent high-precision observations obtained from spacecraft (Yohkoh, TRACE, Hinode, etc.), WLFs have been observed in weaker flares such as GOES C-class flares (Matthews et al. 2003; Hudson et al. 2006; Jess et al. 2008; Wang 2009).

Although 150 years has passed since the discovery of WLF, the mechanism of WL emission is still not fully understood. One of the most famous correlations with WL emission is that of hard X-ray emission, which originates from accelerated electrons. Observationally, WL emission is well correlated with hard X-ray and radio emission, both in the time profile and emission location (e.g., Neidig 1989; Ding et al. 2003; Fletcher et al. 2007; Watanabe et al. 2010; Krucker et al. 2011; Kuhar et al. 2016). As a result there is some consensus that the origin of WL emission is non-thermal electrons. By comparing the total energy of WL and hard X-ray emission, the energy range characterizing WL emission can be estimated as a few tens of keVs (Neidig 1989; Fletcher et al. 2007; Watanabe et al. 2010; Kuhar et al. 2016). The total energy of the observed WL emission is therefore similar to the total energy of the accelerated electrons with energies typical of hard X-rays.

There are questions relating to the emission height of WLF. Theoretically, WL is emitted near the photosphere. However, non-thermal electrons in the energy range of 50–100 keV are almost thermallyized by the time they reach the lower chromospheres, whereas hard X-rays are emitted from the lower chromosphere. To reach the photosphere, accelerated electrons need energies in excess of 900 keV (Neidig 1989). Even if such high-energy electrons exist, this is still not enough to explain the total energy of WL emission.

Observationally, the emission height of WL and hard X-rays and the relationship between them are measured by limb flares (e.g., Battaglia & Kontar 2011, 2012; Martínez Oliveros et al. 2012; Watanabe et al. 2013; Krucker et al. 2015). Some events show that WL emission takes place in the photosphere (Martínez Oliveros et al. 2012; Watanabe et al. 2013), whereas other events show that it occurs in the chromosphere (Battaglia & Kontar 2012; Krucker et al. 2015). Even in the same flare, different results were reported. For the 2011 February 24 flare, one paper reported there was a significant difference in source height between hard X-rays and WL (Battaglia & Kontar 2012), however, others showed no difference between them with a different analysis method (Martínez Oliveros et al. 2012). Determining the height of WL emission is therefore not a straightforward problem and at present its exact nature remains unsolved.

The emission height relationship between WL and hard X-rays reflects the emission mechanisms of WL emissions. Theories explaining WL emission mechanisms fall into two general categories, namely, one involves direct heating and the other indirect heating. A simple model for the direct heating case is that very high-energy (>100 keV) electrons precipitate directly into the photosphere, thereby increasing the temperature of the photosphere and resulting in the emission of WL (Aboudarham & Henoux 1986; Neidig 1989). A further model involving the direct heating approach is that WL emission results from an optically thin source in the mid-chromosphere.
that is directly heated by non-thermal electrons (Kerr & Fletcher 2014). An indirect heating model of WL emission may be outlined as follows: The WL emission region/layer differs from the energy deposition layer/region for non-thermal electrons. Relatively low-energy (<100 keV) electrons precipitate into the chromosphere wherein they dissipate energy. Energy is then transported from this heated region to the lower atmosphere. This energy transport is termed back-warming and the exact transport mechanism remains the topic of debate (Machado et al. 1989; Metcalf et al. 1990; Isobe et al. 2007). The resulting WL emission is thought to be caused by the photoionization of hydrogen atoms and recombination of associated photoelectrons. The excited neutral hydrogen atoms lead to Balmer Paschen continuum emission (Machado et al. 1986; Metcalf et al. 2003).

Although these emission mechanism models highlight the relationship between WL and hard X-ray emission, there are many flare events that do not have any WL enhancements even if they have hard X-ray emission. There are many reports of WLFs that discuss the correlation between hard X-rays and emission mechanisms. However, there are no studies that compare events without WL enhancements even if the flare itself is observed by continuum bands. To understand the conditions that produce enhancements of WL in solar flares, a statistical analysis was performed on WL data observed by the Solar Optical Telescope (SOT; Ichimoto et al. 2008; Shimizu et al. 2008; Suematsu et al. 2008; Tsuneta et al. 2008) on board Hinode and the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012) on board Solar Dynamics Observatory (SDO; Pesnell et al. 2012). We compared these WL data with the data of the GOES soft X-rays, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) hard X-rays, and the strength of the photospheric magnetic fields, as observed by SDO/HMI. An investigation of the relationships between the many physical parameters recorded was completed and the results presented in this work provide some constraints on the mechanism of WL emission.

2. Event Selection

The Hinode/SOT provides high-resolution photometric and magnetic observations of various features in the photosphere and chromosphere and has the capability of observing WLFs. The broadband filtergraph imager on SOT contains interference filters to acquire images of the Ca II H (3968.5 Å, width 3 Å), G-band (4305.0 Å, width 8 Å), blue filter (4504.5 Å, width 4 Å), green filter (5550.5 Å, width 4 Å), and red filter (6684.0 Å, width 4 Å). From 2011, SOT performed a flare observation program that obtained continuum images of the G-band and the red, green, and blue filters when a solar flare was automatically detected (Kano et al. 2008) by the X-Ray Telescope (XRT; Golub et al. 2007) and the flare position was inside the SOTs field of view (FOV).

Not all flares are observed by SOT, due to restrictions related to SOTs FOV. Among the Hinode instruments, XRT has the capability to observe the full solar disk. SOT has a much smaller maximum FOV size of 328″ × 164″. Therefore, only flares that occur while Hinode is observing and are located inside the FOV may be observed by Hinode. It is important to determine which flares were observed by Hinode to analyze the flare data. Flare events that occurred while Hinode was observing were listed and checked to determine whether the event was inside the Hinode FOV. These results are available on the web site in the Hinode Flare Catalogue (Watanabe et al. 2012). In this catalog, the number of images obtained by the Hinode instruments is shown along with the RHESSI and Nobeyama radio heliograph information.

In this study, events were selected for the period 2011 January to 2016 February. To select flare events, the Hinode Flare Catalogue (Watanabe et al. 2012) was used. This catalog lists 11,387 flare events during the study period. M- and X-class flares were chosen for investigation because WLFs are usually associated with relatively large flares. Of the total 11,387 events, 721 events satisfied these selection criteria. From these 721 events, we selected those that were observed using Hinode/SOT in the visible continuum bands (G-band, blue, green, and red filters) during flare observation mode. This gave a revised total of 101 events. These 101 events were classified into WLF and NWL events using running difference images in the SOT continuum data. The criterion for classification of WL was the existence of WL enhancements under the Ca II H ribbon. All images through the flare evolution were searched for a WL signature. This resulted in the identification of 36 WL events and 65 NWL events. However, it is possible that even if an event is classified as NWL from SOT data, WL emission may exist outside the SOTs FOV. To account for this factor, the SDO/HMI continuum data were checked and 13 further WLF events were identified (these WL enhancements were located on the 1600 Å ribbons). The final sample consisted of 49 WLF events (11 X-class and 38 M-class flares) and 52 NWL events (five X-class and 47 M-class flares). The event lists for WLF and NWL events are given in Tables 1 and 2, respectively. Statistical analysis was performed for the Hinode/SOT, SDO/HMI, and GOES data sets and the method of analysis and results are discussed in Sections 3.1–3.4.

Statistical analysis for the hard X-ray data observed by RHESSI was also performed. Among the 101 events, 27 were simultaneously observed with RHESSI and were shown to have greater than 50 keV emissions. Among them, 17 WLF events (six X-class and 11 M-class flares) and 10 NWL events (two X-class and nine M-class flares) were observed. An event list for the RHESSI data is available in Table 3. An analysis of hard X-ray data is described in Section 3.5.

3. Statistical Data Analyses

3.1. Flare Duration

In general, WL enhancements were found to be associated with large flares. However, some NWL events are associated with X-class flares. From these observational facts, it can be inferred that WLFs are associated with impulsive flares. Using this inference, correlations with flare duration were sought. The soft X-ray duration is easily obtained from GOES flare information (GOES flare start to end time). However, some flares occurred consecutively over a short time period and it was not possible to identify the start time and/or end time from soft X-ray light curves. It was therefore decided to use soft X-ray derivative data to determine flare duration. The soft X-ray derivative profile is almost the same as the hard X-ray profile from the Neupert effect (Neupert 1968). Although the Neupert effect is not always present for all flare events, this relationship was employed in this study because it is a very good index of flare duration.
### Table 1

| GOES Flare Start YYYY/MM/DD hh:mm | GOES Derivative | 1600 Å Ribbon |
|----------------------------------|-----------------|---------------|
|                                  | Start           | Positive (G)  |
|                                  | GOES Derivative | Negative (G)  |
|                                  | X-Ray Class     |               |
|                                  | Sunspot Location|               |
|                                  | Duration (s)    | ME (10^8 cm^-3) | Distance (x 10^6 km) |
|                                  | Temperature (MK)|               |                      |
|                                  | @Derivative End |               |                      |
|                                  | X                                     |               |
| 2011 Feb 15 01:44                | X2.2 S20W10     | 21.3          | 9.85                  | 12.0                  |
|                                  | X1.9 N21E64     | 20.9          | 5.68                  |                      |
| 2011 Nov 03 20:17                | X1.7 N33W85     | 16.0          | 8.88                  |                      |
| 2012 Jan 27 17:37               | X1.1 S13W59     | 20.0          | 5.07                  | 38.6                  |
| 2012 Jul 06 23:01               | X1.8 S13E58     | 24.6          | 6.42                  | 17.5                  |
| 2012 Oct 23 03:13               | X1.4 S14E13     | 20.2          | 5.99                  | 22.1                  |
| 2014 Feb 22 14:02               | X1.6 S14E13     | 20.2          | 5.99                  | 22.1                  |
| 2014 Oct 24 20:50               | X3.1 S16W21     | 22.3          | 9.00                  | 34.3                  |
| 2014 Oct 26 10:04               | X2.0 S18W40     | 21.2          | 8.41                  | 51.1                  |
| 2014 Oct 27 14:12               | X2.0 S17W52     | 20.9          | 6.72                  | 81.4                  |
| 2014 Dec 20 00:11               | X1.8 S21W24     | 18.9          | 8.05                  | 51.8                  |
| 2015 Mar 11 16:11               | X2.1 S17E22     | 21.5          | 9.38                  | 18.2                  |
| 2015 Nov 03 20:17               | X2.2 S20W10     | 21.5          | 9.38                  | 18.2                  |
| 2016 Feb 18 09:55               | X1.1 S13W59     | 15.4          | 1.22                  | 8.9                   |
| 2016 Feb 18 10:07               | X1.2 S12W55     | 20.4          | 3.25                  | 13.8                  |
| 2016 Feb 18 12:59               | X1.4 S13E31     | 16.2          | 0.78                  | 16.2                  |
| 2017 Nov 12 13:09               | X1.2 S12W55     | 16.2          | 0.78                  | 16.2                  |
| 2018 Dec 06 12:23               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2019 Dec 03 20:11               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2020 Mar 10 20:20               | X1.2 S12W55     | 16.2          | 0.78                  | 16.2                  |
| 2021 Oct 22 14:02               | X1.1 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2022 Mar 14 08:02               | X1.2 S12W55     | 16.2          | 0.78                  | 16.2                  |
| 2023 Jan 07 12:21               | X1.4 S13E31     | 16.2          | 0.78                  | 16.2                  |
| 2024 Oct 26 19:24               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2025 Oct 28 15:07               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2026 Dec 22 14:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2027 Dec 23 08:59               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2028 Jan 31 21:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2029 Jan 18 00:10               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2030 Mar 13 19:03               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2031 Dec 22 14:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2032 Dec 23 08:59               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2033 Dec 31 21:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2034 Jan 18 00:10               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2035 Mar 13 19:03               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2036 Dec 22 14:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2037 Dec 23 08:59               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2038 Dec 31 21:45               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |
| 2039 Jan 18 00:10               | X1.6 S13W59     | 16.2          | 0.78                  | 16.2                  |

*Note: The values are in Table 1 from the Astrophysical Journal, 880, 2017, December 1.*
Table 1
(Continued)

| GOES Flare Start YYY/MM/DD hh:mm | GOES Derivative Start | GOES Derivative Peak | GOES Derivative End | GOES X-Ray Class | Sunspot Location | GOES Derivative Duration (s) | GOES Derivative Temperature (MK) | GOES Derivative EM (10^9 cm⁻³) | GOES Derivative Distance (x 10ⁱ km) | GOES HMI Field Strength@1600 Å Ribbon | GOES Positive (G) | GOES Negative (G) |
|----------------------------------|----------------------|---------------------|---------------------|------------------|-----------------|-----------------------------|-------------------------------|--------------------------------|----------------------------------|----------------------------------|----------------|----------------|
| 2015 Jun 22 17:23                | 2015 Jun 22 17:49    | 2015 Jun 22 17:58   | 2015 Jun 22 18:00   | M6.5             | N12W08          | 639                         | 19.1                          | 2.38                           | 24.7                             | 520.0                           | −511.8         |
| 2015 Jun 25 08:02                | 2015 Jun 25 08:04    | 2015 Jun 25 08:14   | 2015 Jun 25 08:14   | M7.9             | N09W42          | 594                         | 18.3                          | 2.66                           | 13.7                             | 242.7                           | −190.5         |
| 2015 Sep 29 19:08                | 2015 Sep 29 19:22    | 2015 Sep 29 19:23   | 2015 Sep 29 19:24   | M1.1             | S20W36          | 117                         | 12.5                          | 0.76                           | 16.3                             | 75.5                            | −77.8          |
| 2015 Sep 30 13:14                | 2015 Sep 30 13:18    | 2015 Sep 30 13:19   | 2015 Sep 30 13:20   | M1.1             | S23W59          | 62                          | 15.8                          | 0.74                           | 6.2                              | 221.2                           | −156.9         |
| 2015 Oct 01 13:03                | 2015 Oct 01 13:05    | 2015 Oct 01 13:09   | 2015 Oct 01 13:10   | M4.5             | S23W64          | 311                         | 17.9                          | 2.27                           | …                               | …                               | …              |
| 2015 Oct 02 00:06                | 2015 Oct 02 00:07    | 2015 Oct 02 00:10   | 2015 Oct 02 00:13   | M5.5             | S19W67          | 349                         | 18.1                          | 2.71                           | …                               | …                               | …              |
| Date            | Start Time | Peak Time | End Time | GOES Flare Start Time | GOES Derivative | X-Ray | Sunspot | Duration | Temperature | Distance | NWL Event List | Physical Parameters from GOES and SDO Data | 1600 Å Ribbon | HMI Field Strength @1600 Å Ribbon |
|----------------|------------|-----------|----------|-----------------------|-----------------|-------|---------|-----------|-------------|-----------|----------------|------------------------------------------|---------------|-------------------------------|
| 2012 Mar 05    | 03:30      | 03:45     | 05:03    | 2012 Mar 05 03:45     | X1.1            | N19E58| 1483    | 18.7     | 4.55        | 33.0      | 539.2          | 522.3                                    |               |                  |
| 2012 Jul 12    | 15:37      | 16:26     | 17:05    | 2012 Jul 12 16:32     | X1.4            | S13W03| 2011    | 17.9     | 6.47        | 46.7      | 975.8          | 436.5                                    |               |                  |
| 2013 May 15    | 01:24      | 01:45     | 02:00    | 2013 May 15 01:43     | X1.2            | N12E66| 1366    | 16.3     | 6.57        | 26.6      | 399.4          | 413.7                                    |               |                  |
| 2014 Oct 25    | 16:55      | 17:07     | 17:07    | 2014 Oct 25 17:03     | X1.0            | S10W22| 1214    | 19.8     | 4.79        | 40.4      | 521.6          | 383.5                                    |               |                  |
| 2014 Nov 07    | 16:53      | 17:22     | 17:25    | 2014 Nov 07 17:17     | X1.6            | N14E36| 475     | 17.5     | 7.83        | 26.6      | 399.4          | 413.7                                    |               |                  |
| 2011 Feb 16    | 07:35      | 07:40     | 07:43    | 2011 Feb 16 07:47     | M1.1            | S19W29| 358     | 16.1     | 0.58        | 23.3      | 521.3          | 591.7                                    |               |                  |
| 2011 Sep 23    | 21:54      | 22:03     | 22:10    | 2011 Sep 23 23:19     | M1.6            | N12E56| 700     | 13.3     | 0.88        | 58.2      | 274.8          | 890.5                                    |               |                  |
| 2011 Nov 03    | 10:58      | 11:07     | 11:10    | 2011 Nov 03 11:07     | M2.5            | N20E70| 647     | 16.8     | 0.94        | 26.0      | 397.4          | 292.4                                    |               |                  |
| 2011 Nov 05    | 03:29      | 03:30     | 03:32    | 2011 Nov 05 03:32     | M3.7            | N20E47| 197     | 14.9     | 2.00        | 27.3      | 492.4          | 345.4                                    |               |                  |
| 2011 Nov 05    | 20:31      | 20:35     | 20:37    | 2011 Nov 05 20:35     | M1.8            | N21E37| 258     | 17.2     | 0.89        | 11.5      | 391.1          | 327.5                                    |               |                  |
| 2012 Dec 31    | 16:21      | 16:24     | 16:26    | 2012 Dec 31 16:21     | M1.5            | S25E42| 262     | 15.6     | 0.85        | 27.1      | 248.6          | 353.7                                    |               |                  |
| 2012 Jan 17    | 04:41      | 04:54     | 04:52    | 2012 Jan 17 04:45     | M1.0            | N18E53| 547     | 13.8     | 0.59        | 11.3      | 199.2          | 140.5                                    |               |                  |
| 2012 Jan 18    | 19:04      | 19:09     | 19:11   | 2012 Jan 18 19:06     | M1.7            | N17E32| 138     | 14.6     | 0.91        | 11.1      | 391.1          | 327.5                                    |               |                  |
| 2012 May 07    | 14:03      | 14:19     | 14:26   | 2012 May 07 14:22     | M1.9            | S20W49| 1224    | 14.1     | 1.00        | 41.1      | 166.8          | 241.4                                    |               |                  |
| 2012 May 09    | 14:04      | 14:06     | 14:08   | 2012 May 09 14:04     | M1.8            | N06E22| 280     | 14.8     | 1.04        | 20.7      | 223.2          | 594.1                                    |               |                  |
| 2013 Aug 01    | 07:55      | 08:00     | 08:05   | 2013 Aug 01 07:58     | M1.5            | S17W40| 319     | 15.4     | 0.84        | 13.7      | 809.5          | 291.3                                    |               |                  |
| 2014 Oct 26    | 19:59      | 20:05     | 20:12   | 2014 Oct 26 20:16     | M2.4            | S15W45| 848     | 16.7     | 1.06        | 107.0     | 315.0          | 768.5                                    |               |                  |
| 2014 Dec 04    | 07:36      | 08:01     | 08:08   | 2014 Dec 04 07:53     | M1.3            | S24W27| 403     | 13.9     | 0.91        | 17.7      | 470.3          | 177.8                                    |               |                  |
| 2014 Dec 19    | 09:31      | 09:39     | 09:43   | 2014 Dec 19 09:43     | M1.3            | S19W27| 619     | 13.1     | 0.79        | 31.3      | 244.1          | 219.3                                    |               |                  |
| 2015 Mar 12    | 12:09      | 12:11     | 12:13   | 2015 Mar 12 12:13     | M1.4            | S18E05| 314     | 12.3     | 0.69        | 68.5      | 481.5          | 380.5                                    |               |                  |
| 2015 Mar 12    | 13:45      | 14:02     | 14:04   | 2015 Mar 12 13:45     | M4.2            | S15E06| 361     | 17.4     | 2.07        | 24.0      | 417.0          | 298.8                                    |               |                  |
| GOES Flare Start  | GOES Derivative | GOES | Derivative | @Derivative End | 1600 Å Ribbon | HMI Field Strength @1600 Å Ribbon |
|-------------------|----------------|------|------------|-----------------|---------------|----------------------------------|
| YYYY/MM/DD hh:mm  | Start          | Peak | End        | Class           | Location      | (s)       | (MK)       | (10⁶ cm⁻³) | (× 10³ km) | Distance       | Positive (G) | Negative (G) |
| 2015 Mar 13 05:49 | 2015 Mar 13 06:00 | 2015 Mar 13 06:03 | 2015 Mar 13 06:07 | M1.8           | S14W02        | 385       | 16.0       | 0.96       | 10.4         | 317.5           | −400.0       |
| 2015 Mar 14 04:23 | 2015 Mar 14 04:33 | 2015 Mar 14 04:36 | 2015 Mar 14 04:40 | M1.3           | S14W12        | 383       | 14.4       | 0.77       | 39.8         | 144.4           | −655.1       |
| 2015 Mar 15 22:42 | 2015 Mar 15 22:45 | 2015 Mar 15 22:46 | 2015 Mar 15 22:47 | M1.2           | S19W32        | 131       | 14.2       | 0.20       | 55.0         | 304.0           | −586.6       |
| 2015 Mar 16 10:39 | 2015 Mar 16 10:41 | 2015 Mar 16 10:50 | 2015 Mar 16 10:56 | M1.6           | S17W39        | 876       | 15.1       | 0.86       | 28.9         | 165.5           | −342.2       |
| 2015 Mar 17 22:49 | 2015 Mar 17 23:28 | 2015 Mar 17 23:30 | 2015 Mar 17 23:32 | M1.0           | S21W56        | 270       | 12.0       | 0.66       | 43.4         | 107.7           | −106.4       |
| 2015 Jun 21 01:02 | 2015 Jun 21 01:22 | 2015 Jun 21 01:27 | 2015 Jun 21 01:37 | M2.0           | N12E13        | 895       | 15.2       | 0.94       | 29.3         | 803.1           | −681.8       |
| 2015 Aug 30 02:01 | 2015 Aug 30 02:54 | 2015 Aug 30 02:56 | 2015 Aug 30 03:01 | M1.4           | S17W80        | 445       | 13.9       | 0.61       | ...          | ...             | ...           |
| 2015 Sep 27 20:54 | 2015 Sep 27 20:55 | 2015 Sep 27 20:57 | 2015 Sep 27 21:00 | M1.0           | S21W16        | 287       | 14.6       | 0.57       | 10.8         | 378.9           | −286.7       |
| 2016 Jan 01 23:10 | 2016 Jan 01 23:30 | 2016 Jan 01 23:37 | 2016 Jan 01 23:44 | M2.3           | S25W82        | 811       | 13.0       | 0.95       | ...          | ...             | ...           |
Figure 1 shows sample light curves of GOES soft X-ray flux and their time derivative. The left panels show an X2.1-class flare on 2015 March 11 as a sample of impulsive flare. The right panels show an X1.4-class sample of long duration event. Flare duration for the X1.4 class flare was four times longer than that of the X2.1 class flare. From these soft X-ray derivative data, the derivative start, peak, and end time and derivative duration were obtained, as shown in Tables 1 and 2. The derivative peak time is defined as the time of the peak in derivative data from the start of the GOES flare to its peak. The derivative start time is defined as the time when the derivative data has a continuous positive value till the derivative peak. The derivative start time is defined as the time from the first negative value from the derivative peak time. In some events (flares on 2012 June 13, 2014 December 05, and 2015 March 15), no GOES data could be obtained and so no derivative data information appears in Tables 1 and 2.

The relationship between the GOES soft X-ray peak flux and the derivative duration is shown in the left-hand side panel of Figure 2. WLF events (represented by blue diamonds) show shorter duration compared with NWL events (represented by red crosses). It appears that the flare derivative duration is roughly correlated with the GOES soft X-ray flux. As a result, the average of both groups could not be compared directly. The average duration of WLF events was 419 s, whereas the average duration for NWL events was 619 s. The average duration of NWL events is therefore 1.5 times longer than that of WLF events.

Because there is a relationship between the GOES X-ray peak flux and the flare derivative duration, the GOES X-ray peak flux was divided by the derivative duration and this number was used to represent the impulsivity of the flare. This impulsivity reflects the increase in rate of hard X-ray emission. If there are RHESSI data for all flare events, we do not need to use the GOES X-ray derivative data, only the one-third of flare events were observed by RHESSI in fact, so we used this method. The right-hand side panel of Figure 2 shows a histogram of flare impulsivity. Figure 2 clearly shows two separate peaks, namely, WLF events (blue), which exhibit a shorter duration and larger flare class (impulsive flare) compared with NWL events (red). This result indicates that the impulsivity of the flare is one of the causative factors of WL enhancement.

### 3.2. Temperature and Emission Measure

The temperature and emission measure of each flare was calculated using the CHIANTI model. These values were measured at the derivative end time because this time characterizes the end of the energy release from the flare. Figure 3 is a scatter plot of the temperature and emission measure for all events and this graphically indicates there is a relationship between the temperature and electron temperature has been reported by Shibata & Yokoyama (2002). Figure 2 in Shibata & Yokoyama (2002) shows four theoretical curves for coronal magnetic field strengths of 5,

| GOES Flare Start YYYY/MM/DD hh:mm | GOES X-Ray Class | Sunspot Location | Derivative Duration (s) | 50–100 keV HXR Peak (counts s⁻¹ cm⁻² keV⁻¹) | Power-law Index | Energy Deposition Rate (>30 keV) (erg s⁻¹) |
|---------------------------------|-----------------|-----------------|-------------------------|---------------------------------------------|----------------|---------------------------------------------|
| **WLF events**                  |                 |                 |                         |                                             |                |                                             |
| 2011 Feb 15 01:44               | X2.2            | S20W10          | 631                     | 0.74                                        | −4.3           | 1.34E+28                                    |
| 2012 Oct 23 03:13               | X1.8            | S13E58          | 170                     | 7.67                                        | −3.1           | 3.66E+28                                    |
| 2014 Oct 22 14:02               | X1.6            | S14E13          | 850                     | 2.93                                        | −4.7           | 9.36E+28                                    |
| 2014 Oct 24 20:50               | X3.1            | S16E21          | 783                     | 1.03                                        | −5.9           | 1.06E+29                                    |
| 2014 Oct 27 14:12               | X2.0            | S17W52          | 1237                    | 0.26                                        | −6.2           | 3.85E+28                                    |
| 2015 Mar 11 16:11               | X2.1            | S17E22          | 512                     | 64.2                                        | −7.1           | 3.77E+28                                    |
| 2011 Feb 18 09:55               | M6.6            | S21W55          | 233                     | 0.43                                        | −3.0           | 1.84E+27                                    |
| 2011 Dec 31 13:09               | M2.4            | S24E46          | 254                     | 0.11                                        | −3.4           | 3.97E+26                                    |
| 2012 May 09 12:21               | M4.7            | N13E31          | 268                     | 0.12                                        | −3.4           | 7.44E+26                                    |
| 2012 May 10 20:20               | M1.7            | N12E12          | 263                     | 0.20                                        | −4.6           | 5.10E+27                                    |
| 2012 Jul 05 03:25               | M4.7            | S18W29          | 90                      | 0.34                                        | −4.7           | 3.16E+27                                    |
| 2012 Jul 06 01:37               | M2.9            | S18W41          | 156                     | 1.27                                        | −3.3           | 4.18E+27                                    |
| 2013 Oct 28 15:07               | M4.4            | S06E28          | 315                     | 0.18                                        | −3.3           | 1.14E+27                                    |
| 2013 Dec 22 14:45               | M3.3            | S19W56          | 278                     | 0.08                                        | −3.1           | 3.47E+26                                    |
| 2014 Oct 22 01:16               | M8.7            | S13E21          | 733                     | 2.15                                        | −3.7           | 2.38E+28                                    |
| 2015 Mar 12 04:41               | M3.2            | S15E11          | 246                     | 1.02                                        | −5.1           | 1.20E+28                                    |
| 2015 Mar 12 21:44               | M2.7            | S15E01          | 252                     | 0.47                                        | −4.5           | 6.92E+27                                    |

| **NWL events**                  |                 |                 |                         |                                             |                |                                             |
| 2013 May 15 01:24               | X1.2            | N12E64          | 1366                    | 0.53                                        | −3.2           | 3.09E+27                                    |
| 2014 Oct 25 16:55               | X1.0            | S10W22          | 1214                    | 0.07                                        | −8.3           | 5.97E+28                                    |
| 2011 Dec 31 16:16               | M1.5            | S25E42          | 262                     | 0.12                                        | −2.7           | 2.56E+26                                    |
| 2013 May 02 04:58               | M1.1            | N10W26          | 553                     | 0.67                                        | −2.8           | 1.02E+27                                    |
| 2013 May 03 16:39               | M1.3            | N10W38          | 529                     | 0.12                                        | −3.9           | 8.04E+26                                    |
| 2013 Oct 22 00:14               | M1.0            | N06E17          | 356                     | 0.06                                        | −4.5           | 5.46E+26                                    |
| 2013 Dec 22 08:05               | M1.9            | S20W49          | 235                     | 0.07                                        | −2.0           | 3.58E+25                                    |
| 2014 Jan 04 10:16               | M1.3            | S05E48          | 350                     | 0.15                                        | −3.6           | 1.28E+27                                    |
| 2014 Feb 14 12:29               | M1.6            | S15W36          | 580                     | 0.04                                        | −2.4           | 6.20E+25                                    |
| 2015 Mar 15 22:42               | M1.2            | S19W32          | 131                     | 0.21                                        | −6.6           | 4.35E+25                                    |
events. To determine the difference between the WLF and NWL events and the coronal magnetic field strength, this result suggests that there is a rough correlation between the ribbon distance and soft X-ray class, i.e., intense flares have a relatively large size. However, the ribbon distance of NWL events is located in the upper part of the left-hand side panel of Figure 4 compared with that of WLF events. The average separation for WLF events was determined as $2.2 \times 10^3$ km and that for NWL events as $3.3 \times 10^3$ km. The separation of WLF events is therefore significantly less than that of NWL events. This result indicates that the flare formal size of WLF events is relatively more compact than that of NWL events.

This flare ribbon distance is an index of flare size. When the emission measure is divided by flare volume (distance$^3$) and the square root taken, an index of flare loop density can be obtained. The right-hand side panel of Figure 4 shows the histogram of event number for flare density. In this figure, it is just possible to see two peaks for WLF events (blue) and for NWL events (red). This result indicates that the plasma density of the flare is one of the causative factors of WL enhancement.

### 3.4. Field Strength Under the Flare Ribbons

From Section 3.2, it was suggested that there is a relationship between WLF and NWL events and the coronal magnetic field strength. However, no coronal magnetic field strength data exist in the observational data used in this study. Instead, the...
photospheric magnetic field strength under the flare ribbons as obtained in Section 3.3 is employed.

The SDO/HMI field strength data under the 1600 Å flare ribbons is therefore used in this analysis. For the two flare ribbons associated with each flare, positive field strength is taken from one flare ribbon and negative field strength taken from the other ribbon. Most of the event, these flare ribbons were located on the plage region, not umbrae. We calculated the average field strength under the 1600 Å flare ribbons.

Figure 5 shows the relationship between the GOES soft X-ray peak flux and the field strength under the 1600 Å flare ribbons as estimated from SDO/HMI data (taken from around the derivative peak time of GOES soft X-ray data). Unfortunately, there was a high degree of scatter in the data and no relationship could be determined between these two parameters.

### 3.5. Hard X-Ray Data Analysis

As mentioned in Section 2, a statistical analysis of hard X-ray data as observed by RHESSI was performed. Among the 101 Hinode/SOT events, 46 flare events were simultaneously observed with RHESSI. Among the 46 flare events, 21 events were associated with the WLF events and 25 events were the result of NWL events. Among them, 17 WLF events (6 X-class and 11 M-class flares) and 10 NWL events (2 X-class and 9 M-class flares) have emission greater than 50 keV. Physical parameters for these events are given in Table 3. Based on these events, hard X-ray photon counts and spectra could be analyzed.

#### 3.5.1. Maximum Photon Counts of Hard X-rays

The maximum photon count of 50–100 keV hard X-ray photons during the flares was investigated. The photon count of each flare is given in Table 3. A scatter plot of the photon count and GOES soft X-ray flux is shown in Figure 6. Consideration of Figure 6 shows that hard X-ray photon count is roughly correlated with the GOES soft X-ray flux. The average photon count of the hard X-rays was calculated and found to be approximately 4.6 counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\) for WLF events and 0.2 counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\) for NWL events. Although the standard deviation is larger than the above mentioned values, the maximum photon count of WLF events is significantly larger than that of NWL events. This is directly related to the fact that the GOES soft X-ray flux for WLF events is larger than that for NWL events.

#### 3.5.2. Hard X-Ray Spectra and Non-thermal Energy

Spectral fitting was performed for 27 events using a single power law to describe each hard X-ray spectrum in the region of the hard X-ray peak time and in the range of 30–100 keV. Indeces for the power laws obtained are given in Table 3 and the correlation of spectral index and GOES soft X-ray flux are shown in Figure 7. The average power-law indices are \(-4.3\) for WLF events and \(-4.0\) for NWL events. Because the standard deviation is smaller than \(-1.0\), there is no significant difference in the power-law indices.

The deposition rate of non-thermal energy was then calculated assuming a thick target model with a low-energy cutoff of 30 keV (Brown 1971). This was done using the same method as described in Watanabe et al. (2010). The calculated deposition rate of the non-thermal energy and GOES soft X-ray flux are given in Table 3. The corresponding scatter plot is
Figure 4. Left: relationship between GOES soft X-ray peak flux and flare ribbon distance as estimated from SDO/AIA 1600 Å images (taken around derivative peak time of GOES soft X-ray data). The diamond (blue) and cross (red) symbols correspond to WLF and NWL events, respectively. Right: histogram of event number for flare density.

Figure 5. Relationship between GOES soft X-ray peak flux and field strength under the 1600 Å flare ribbons, as estimated from SDO/HMI data (taken around derivative peak time of GOES soft X-ray data). The diamond (blue) and cross (red) symbols correspond to WLF and NWL events, respectively.

Figure 6. Relationship between GOES soft X-ray peak flux and 50–100 keV hard X-ray peak count obtained from RHESSI data. The diamond (blue) and cross (red) symbols correspond to WLF and NWL events, respectively.

Figure 7. Relationship between GOES soft X-ray peak flux and spectral index of hard X-ray, as estimated from RHESSI data. The diamond (blue) and cross (red) symbols correspond to WLF and NWL events, respectively.

Figure 8. Relationship between GOES soft X-ray peak flux and energy deposition rate of >30 keV emission, as estimated from RHESSI data. The diamond (blue) and cross (red) symbols correspond to WLF and NWL events, respectively.
found in Figure 8. There is one NWL event in Figure 8 with very high-energy deposition. That is the X1.0-class flare on 2014 October 25, which is due to the very soft power index for this event. The average deposition rate of non-thermal energy was found to be \((2.34 \pm 3.05) \times 10^{28} \text{ erg s}^{-1}\) for WLF events and \((6.68 \pm 1.77) \times 10^{27} \text{ erg s}^{-1}\) for NWL events. The deposition rate of WLF events is significantly larger than that of NWL events and this is because the GOES soft X-ray flux for WLF events is larger than that for NWL events.

The X-axis from the GOES soft X-ray flux is then plotted as the derivative duration, and the results are shown in Figure 9. In Figure 9, WLF events are located on the upper left-hand side of the dashed line and NWL events are located on the lower right-hand side of the dashed line. It is important to note that these data occupy separate regimes in Figure 9. This result suggests that the injection rate of non-thermal electrons is one of the causative factors of WL enhancement.

### 4. Discussion

The results described in the previous sections can be summarized as follows.

1. The derivative duration of GOES soft X-rays during WLF events is relatively short.
2. WLF events are characterized by stronger magnetic fields at the energy-release site compared with NWL events from the relationship between the temperature and emission measure.
3. The separation between two ribbons is shorter for WLF events.
4. No significant difference exists in field strength under the flare ribbons.
5. The hard X-ray photon count in the energy range of 50–100 keV and the deposition rate of non-thermal energy \((>30 \text{ keV})\) are correlated with the GOES soft X-ray flux.
6. No significant difference exists between the power-law indices of hard X-ray spectra for WLF and NWL events.
7. WLF events are characterized by larger deposition rates of non-thermal energy compared with NWL events. WLF events are characterized by a shorter derivative duration for a given deposition rate.

From results (1) and (3), WLF events appear to be small in terms of spatial extent and have a relatively short duration. WLF events are therefore short-lived and exhibit a rapid enhancement phase, whereas NWL events show a gradual enhancement phase. The short separation of flare ribbons implies that the magnetic field structure related to WLF events is compact. During the evolution of a flare, the separation between flare ribbons increases as a function of time, which is consistent with the short duration. Result (3) suggests that the magnetic loop related to WLF events occurs at low altitudes. In general, the magnetic field is stronger at low altitudes than at high altitudes. The energy release of WLF events therefore appears to occur in the lower corona wherein the magnetic field is relatively strong.

Result (2) suggests the existence of strong magnetic fields at the energy-release site for WLF events. The scatter plot of the emission measure and electron temperature reported in Figure 2 of Shibata & Yokoyama (2002) shows four theoretical curves for coronal magnetic field strengths of 5, 15, 50, and 150 G at the energy-release site of the flare. The scatter plot of emission measure and electron temperature reported in this investigation (Figure 2) shows that WLF events are distributed toward the right-hand side of plot, whereas NWL events are located on the left-hand side of the plot. The difference in the distribution of these data may be due to differences in coronal magnetic field strength at the energy-release site. The magnetic field is weaker for NWL events than for WLF events. This finding is consistent with result (3) as the magnetic field is stronger at lower altitudes in the corona.

An attempt was made to check the field strength of the photosphere. However, due to lack of field strength data at the energy-release site, an alternative analysis was undertaken, as described in Section 3.4. No significant difference was observed in the field strength under the flare ribbons.

Results (5) to (7) relate to the hard X-ray observations. As described in Section 1, WL enhancement is correlated with hard X-ray sources in time, location, and energy. Contrary to the expectations of this study, no significant difference was observed in the power-law indices of WLF and NWL events. It therefore follows that the energy distribution of accelerated electrons is similar in both WLF and NWL events. Only very high-energy \((>100 \text{ keV})\) electrons can reach the photosphere (Aboudarham & Henoux 1986; Neidig 1989). Results presented in this work do not show that the fraction of electrons with such high energies is larger in WLF events compared with NWL events. This result does not support the model whereby electrons penetrate directly into the photosphere and emit WL. However, as the conclusions presented here are the result of a statistical analysis, it is possible that some WLF events may result from this process.

The results presented in this investigation indicate that to enhance WL emissions, a large number of accelerated electrons must precipitate within a short period, thereby allowing very rapid heating of the atmosphere. Result (7) suggests that rapid heating is important and that a threshold exists in terms of the injection rate of non-thermal electrons required to generate WL emission.

Through this statistical study, it has been shown that WLF events are characterized by stronger magnetic fields at the energy-release site compared with NWL events. This strong
magnetic field may be a factor in the enhancement of WL emission. It is important to consider how a strong magnetic field may be related to WLF events. Two models explain WL emission and indicate that the energy-release region is characterized by a strong magnetic field. In the solar flare model based on magnetic reconnection, the energy-release rate increases if the energy-release region has a strong magnetic field and electrons are accelerated. Hard X-ray sources appear at the region wherein the magnetic field is strongest along the flare ribbon (Asai et al. 2002). Large numbers of electrons are accelerated and this leads to the enhancement of WL emission. The strong magnetic field may also be considered in terms of the trapping efficiency of accelerated electrons in the flare loop. If the top part of the loop is characterized by a stronger magnetic field than that of the foot-point region, the magnetic mirror ratio between the top and the foot-point becomes small and the loss-cone angle is large. Because of this effect, a larger number of accelerated electrons can precipitate into the foot-point region within a short period of time. The trapping efficiency of the loop is therefore lower and most of the accelerated electrons precipitate directly into the foot-point region. This scenario is consistent with results obtained in this study.

Investigating the magnetic structure of a flare region could prove interesting and may reveal how and why the magnetic field strength at the energy-release site is related to the generation mechanism of WLF events.

5. Conclusion

A statistical study has been presented comprising 101 solar flares observed using the visible continuum filter of Hinode/SOT and SDO/HMI for GOES M- and X-class flares occurring during the period from 2011 January to 2016 February. Of these 101 events, 49 WLF events and 52 NWL events were identified on the basis of the existence of an enhancement of the visible continuum images obtained using Hinode/SOT and SDO/HMI. The WLF events are characterized by short duration, a high temperature in the GOES soft X-ray data, and short distance between two flare ribbons in the SDO/AIA 1600 Å observations. No significant difference was observed between WLF and NWL events in terms of power-law indices, flux of non-thermal photons (50–100 keV), or in the deposition rate of the non-thermal energy. However, a clear relationship between the injection rate of non-thermal energy and duration was observed. These results indicate that during WLF events, accelerated electrons precipitate in a short time period, thereby leading to rapid heating of the atmosphere. The similarity in the power-law index of hard X-ray spectra, as well as the similar deposition rate of non-thermal energy, does not indicate that the fraction of electrons with very high energies (>100 keV) is larger in WLF events compared with NWL events. Relatively low-energy (<100 keV) electrons appear to contribute to the enhancement of WL. This finding is consistent with studies detailing the energy budget between non-thermal electrons and WL emission (Watanabe et al. 2010).

The statistical analysis presented here suggests that the non-thermal energy deposition rate and the magnetic field strength at the energy-release site are significant in WL emission in solar flares. In future work, investigating the magnetic field structure around the energy-release site would be interesting to describe more fully the environment of non-thermal electrons. The physical relationship between the magnetic field structure and the energy of electrons should therefore be the subject of a detailed investigation. Such a study would be expected to provide insight into not only the process of WL emission but also into the acceleration of electrons in solar flares.

It is useful to derive the color temperature of WL when its energy source is studied (Watanabe et al. 2013; Kerr & Fletcher 2014). However, we did not derive it in this paper because we focused on the difference of WL and NWL events. In the future, we would like to perform this kind of detailed WL analyses that would provide unique constraints for radiative-hydrodynamic flare models and might reveal lower atmospheric heating differences in impulsive flares and non-impulsive flares. Moreover, Kowalski et al. (2013) showed how the NUV and optical continuum spectral properties of M dwarf flares vary from impulsive flare events to gradual flare events, where the type of flare (impulsive versus gradual) is determined from a similar quantity as the “impulsivity.” It would also be interesting to discuss how their results for M dwarf WLFs connect with our study.

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