Solar Physics (2006) 234: 79–93
DOI: 10.1007/s11207-006-0056-y

WHITE-LIGHT FLARES: A TRACE/RHESSI OVERVIEW

H. S. HUDSON, C. J. WOLFSON and T. R. METCALF
Space Sciences Laboratory, University of California, Berkeley, CA 94720 Lockheed Martin Advanced Technology Center, Palo Alto, CA NWRA/CORA, Boulder, CO

(Received 2 September 2005; accepted 19 October 2005)

Abstract. The Transition Region and Coronal Explorer (TRACE) instrument includes a "white light" imaging capability with novel characteristics. Many flares with such white-light emission have been detected, and this paper provides an introductory overview of these data. These observations have 0.5″ pixel size and use the full broad-band response of the CCD sensor; the images are not compromised by ground-based seeing and have excellent pointing stability as well as high time resolution. The spectral response of the TRACE white-light passband extends into the UV, so these data capture, for the first time in images, the main radiative energy of a flare. This initial survey is based on a sample of flares observed at high time resolution for which the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) had complete data coverage, a total of 11 events up to the end of 2004. We characterize these events in terms of source morphology and contrast against the photosphere. We confirm the strong association of the TRACE white-light emissions - which include UV as well as visual wavelengths – with hard X-ray sources observed by RHESSI. The images show fine structure at the TRACE resolution limit, and often show this fine structure to be extended over large areas rather than just in simple footpoint sources. The white-light emission shows strong intermittency both in space and in time and commonly contains features unresolved at the TRACE resolution. We detect white-light continuum emission in flares as weak as GOES C1.6. limited by photon statistics and background solar fluctuations, and support the conclusion of Neidig (1989) that white-light continuum occurs in essentially all flares.

1. Introduction

White-light flares (WLF), first noted by Carrington (1859), are typically thought of as the most energetic of solar flares; see Neidig (1989) for a review based on traditional ground-based observations. "White light." refers to continuum emission in excess of the photospheric background, and for extreme cases (such as Carrington's) the local intensity may actually double. The energy implied by this emission exceeds that observed in any of the flare effects observed in the much more tenuous corona. In recent decades it has become clearer that the WLF continuum formation has a strong association with particle acceleration, specifically the weakly relativistic electrons of the impulsive phase (Rust and Hegwer, 1975; Hudson et al., 1992; Neidig and Kane, 1993). Thus, the oldest observations of solar flares pointed already to the key elements of flare physics recognized only in recent decades. In this respect it is also interesting to note that the first observed flare was also the first "geoeffective" flare recognized (see Chapman and Bartels, 1940, for a reproduction of the original data of the geomagnetic effects).

In the meanwhile research on the actual optical spectrum of white-light flares, and an understanding of its physics, has proceeded rather slowly because of the great difficulty of capturing a flare at the right time and location for a spectroscopic observation. Stellar flares have striking similarities to solar flares, and exhibit optical continuum spectra characterized by effective temperatures of $\sim 10^4$ K, roughly resembling an A0-class star embedded in the atmosphere of an M-class star (e.g.. Gurzadyan, 1980). Neidig (1989) provides a review of the literature on the optical spectra of WLFs.

The white-light continuum is usually a phenomenon of the impulsive phase (Švestka, 1970; Hudson, 1972), although the literature (and this paper, see below) contains examples of other kinds (e.g., Neidig *et al.*, 1993; Matthews *et al.*, 2003). In general the emission occurs near sunspots where seeing conditions strongly affect photometry at low contrast (but again, there are exceptional WLFs that occur withot large sunspots; see the example of 1992 January 26 event in Hudson *et al.*, 1992). Because of the strong association with sunspots, though, high time resolution and good seeing (image stability) have paramount observational importance. The difficulty of the observations is underscored by the fact that Neidig and Cliver (1983) could only list about 60 events prior to that time – from an extremely heterogenous set of observations – and that a dedicated multispectral program over the next decade increased that number only to 86 (Neidig, Wiborg and Gilliam 1993).

Our knowledge of white-light flares prior to the first observations from space (Hudson *et al.*, 1992) have been concisely summarized by Neidig (1989) in four conclusions: "(1) WLFs are not fundamentally different from ordinary flares, (2) WLFs are located in the chromosphere and upper photosphere, with no evidence for strong heating near the quiet Sun $\tau = 1$ level, (3) the WLF light curve approximately follows the hard ($\sim$50 keV) X-ray emission regardless of whether the hard X-rays are associated with the impulsive or gradual phase of the flare, and (4) heat conduction, irradiation by soft X-rays, and heating by high-energy protons are not sufficient to power the WLF at the time of its peak luminosity." The results in this survey support all of these conclusions and mainly serve to extend our knowledge of this most, energetic flare component, making use of the higher resolution and spectral breadth of the TRACE (Handy *et al.*, 1999) observations. Specifically we find this component to reside in fine structures that are intermittent in space and time and are often not resolved at the TRACE angular resolution of $\sim 1''$.

2. Data

2.1. Instrument properties

The TRACE white-light observations are a part of the general UV response of the instrument, and different observing sequences typically interleave them with

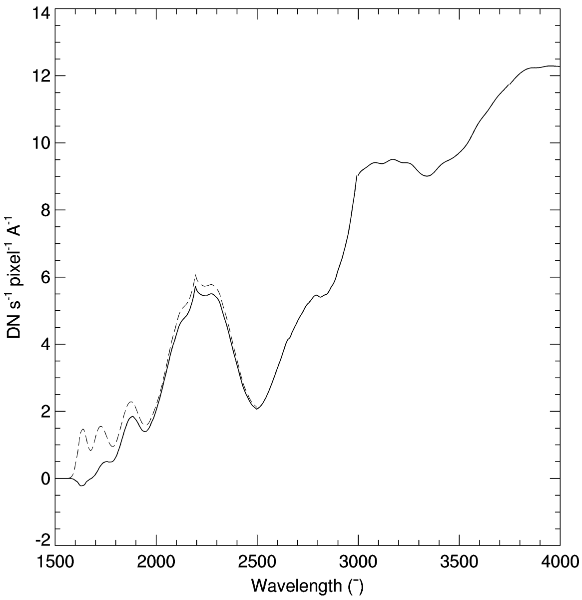


Figure 1. TRACE spectral response for white light plus UV (*dotted*), and the WL alone after subtraction of the UV response (*solid*). The spectral response is largely determined by the Lumogen-coated CCD and the transmission of the fused silica window. See Handy *et al.* (1999) for fuller details.

exposures in the 1700Å or another UV band. The individual exposures in white light are a few msec duration, separated in time by at least a few sec, so they represent a sparse set of snapshots of the true solar intensity. This should be borne in mind when comparing with RHESSI (Lin *et al.*, 2002) images or light curves, which essentially integrate over the 4-sec rotation period. The TRACE pixel size is $0.5''$ and the finest features in the images presented here suggest that the resolution achieved typically approaches the Nyquist limit of $1''$ (FWHM). Figure 1 shows the spectral response of the white-light filter, which is primarily the response of the Lumogen-coated CCD itself plus the transmission of a fused silica window (Handy *et al.*, 1999). In comparison with previous observations of solar white-light flares, this response function distinctively has a much stronger response in the UV. The UV response of the TRACE white-light channel can be at least partially corrected by use of the 1700Å channel (Metcalf *et al.*, 2003).

The RHESSI instrument consists of a set of nine high-purity Ge spectrometers viewing the Sun through a set of nine modulation collimators with different pitches, mounted on a spacecraft rotating around the solar direction with a period of about 4 sec. The highest angular resolution is about $2.1''$ (FWHM). RHESSI observes in the hard X-ray and γ-ray spectral bands with spectral resolution on the order of 1 keV (FWHM) in the X-ray band. For full information see Lin *et al.* (2002).

TABLE I
TRACE/RHESSI white-light flare list.

Date	Flare start	GOES	NOAA	Location	Peak WL[a]
25-JUL-02	03:55:00	C2.7	0039	S13E46	0.10 ± 0.015
26-JUL-02	18:57:00	M1.0	0044	S21E21	1.55
4-OCT-02	05:34:00	M4.0	0137	S19W09	1.58
5-OCT-02	10:39:00	M1.2	0137	S20W24	0.56
12-NOV-02	17:58:00	C9.9	0180	S11W75	0.23 ± 0.017
12-JUN-03	01:04:00	M7.3	0375	N13W65	1.97
23-OCT-03	02:35:00	M2.4	0484	N03E15	3.39
9-JAN-04	01:33:00	M3.2	0537	N02E49	1.78
22-JUL-04	00:14:00	M9.1	0652	N03E17	4.14
24-JUL-04	00:34:00	C1.6	0652	N12W03	0.08 ± 0.017
24-JUL-04	13:31:00	C4.8	0652	N04W16	1.46 ± 0.025

[a]Excess intensity normalized to local quiet Sun values, peak pixel.

2.2. Data selection

TRACE observational programs have a great deal of flexibility in choice of wavelength, exposure time, pixel binning, etc., and thus there is no homogeneous database. Instead the available data reflect the preferences of individual observers. For this survey we have restricted the time range to the RHESSI observing period, from 2002 Feb. 11 (RHESSI launch) through 2004. We selected only the events for which the TRACE WL[1] channel had an average white-light image cadence of ten seconds or less. These criteria resulted in a "shopping list" of 33 events, and the additional requirement of full coverage for both RHESSI and TRACE through the GOES time range resulted in a final list of 11 events as detailed in Table I. TRACE has obtained WL observations of many other events that do not meet these criteria, which unfortunately did not result in any GOES X-class flares. Note that most prior studies of white-light flares have emphasized X-class events, whereas ours are all in the C and M ranges.

Faint white-light flare emission may get "lost" against the highly structured image field of a sunspot group within a solar active region likely to produce a flare. Accordingly we study the TRACE images by forming differences against a chosen pre-event image. This works well on short time scales, but various effects (TRACE pointing jitter, solar rotation, feature proper motion, p-modes, granulation) result in a gradual degradation of the flatness of the difference images. Figure 2 shows the resulting background fluctuations in a representative example.

[1]We use "WL" to designate the TRACE white-light channel, and "UV" for the 1700Å channel.

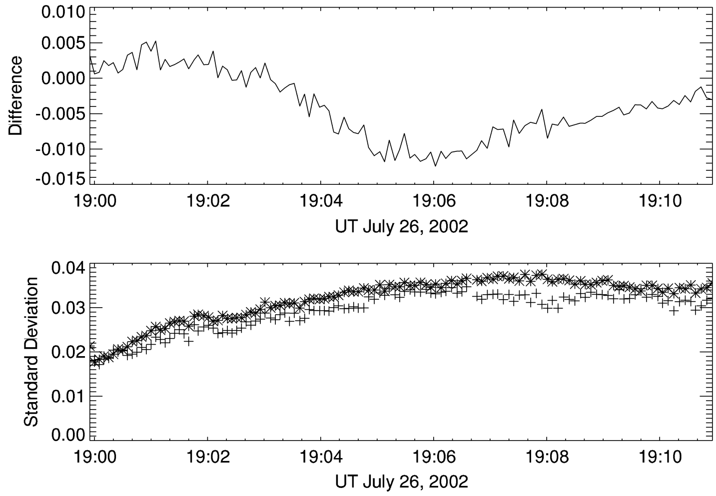


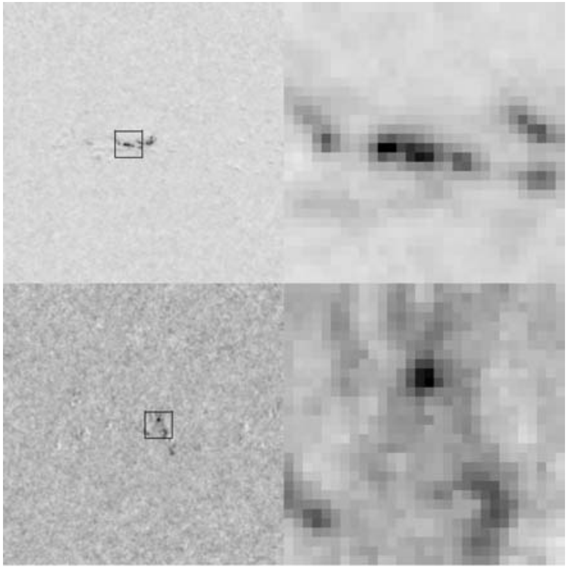
Figure 2. Statistics of the difference images for one of the events, 2002 July 26; *upper*, the excess in a 20 × 20-pixel region away from the flare; *lower*, the standard deviations of two such regions. Both are normalized units, i.e. excess divided by the quiet-Sun intensity. The slow variation of the intensity is apparently due predominantly to the *p*-modes.

The pixel-to-pixel fluctuations observed in quiet-Sun regions, for the example shown in Figure 2, amount to 2–4% of the total signal. This fluctuation includes both solar terms and photon statistics. We estimate the photon statistics, using the gain calibration of 12 electrons per data unit (Handy *et al.*, 1999), to be on the order of 1–2%, and this probably dominates the error for short time differences.

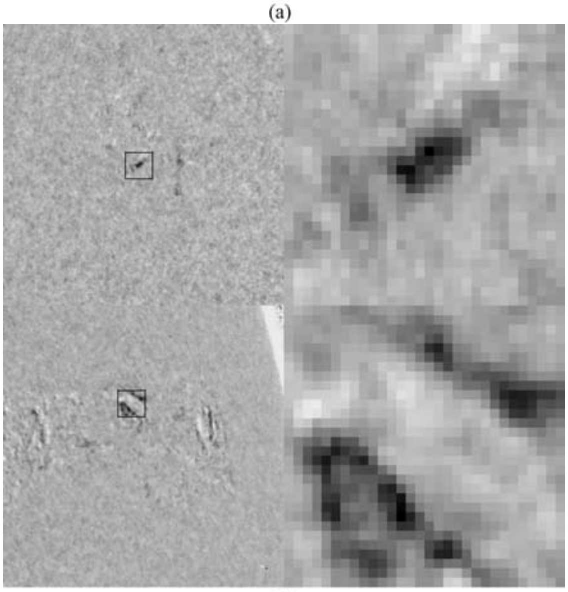
3. TRACE Morphology

A major objective of this paper is to describe this new data set, which has the unique properties described earlier, and to draw the obvious conclusions from the morphology. Ten of the individual events are shown in Figures 3a–3e at two magnifications, in reversed color table for clarity. The remaining event of Table I, namely the C1.6 flare of 2004 July 24, is too faint to illustrate well; its maximum excess contrast was only 0.08 ± 0.017 and it persisted for only about three images (note that we are defining the excess contrast as $(I_f - I_p)/I_p$, with I_f the flare intensity and I_p the intensity of the neighboring quiet photosphere).

Table I gives uncertainties based on the statistics of fluctuations in a 25 × 25-pixel corner region of the difference image used for the contrast determination for one of the M-class flares.

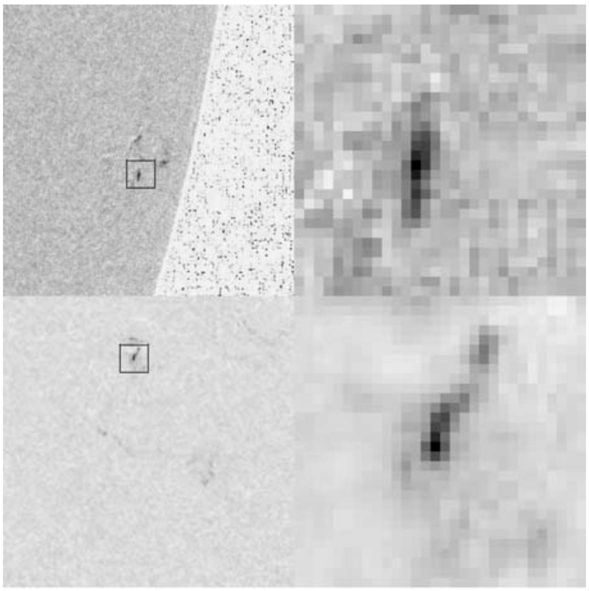


(a)

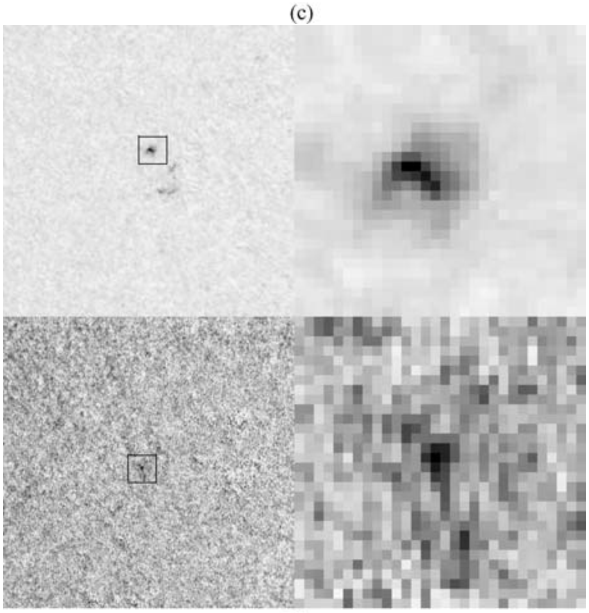


(b)

Figure 3(a). TRACE white-light snapshots at the peak times of two of the events of the sample. *Above*: 2002 October 4, 05:35:49 UT: *below*: 2002 October 5, 10:41:58 UT. *Left-hand panels* have dimensions of 150″ × 150″. The *right-hand panels* show the indicated regions blown up to display the full TRACE pixel contents, 15″ × 15″. This figure and the next four below are all in reversed color table for clarity: WL emission appears black. (b) Same as Figure 3a, for 2004 January 9, 01:40:17 UT, and 2003 June 12, 01:27:01 UT (note the solar limb at the *upper right corner* of the large-scale image). (c) Same as Figure 3a, for 2002 November 2 18:16:04 UT and 2004 July 22 00:29:56 UT. (d) Same as Figure 3a, for 2003 October 23 02:39:49 UT and 2002 July 25 03:59:04 UT. (e) Same as Figure 3a, for 2002 July 26 19:00:25 UT and 2004 July 24 13:34:38 UT. (*Continued on next page*)



(c)

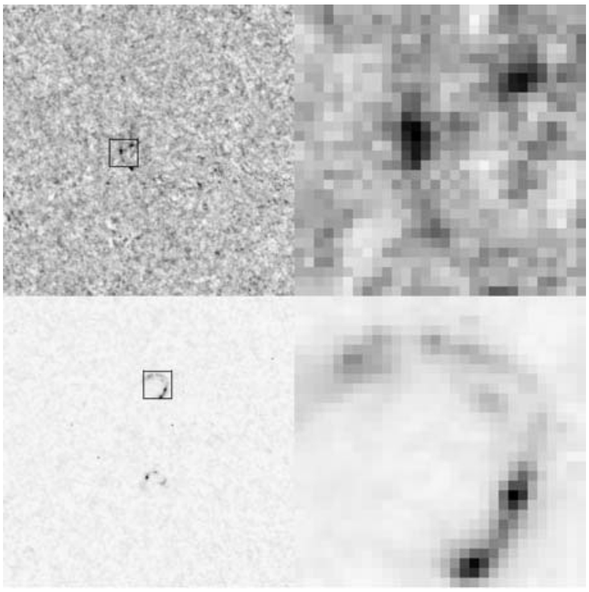


(d)

Figure 3. (*Continued*)

3.1. IMAGES

These events typically show white-light emission broken up into small patches, which occur within the general outline of the flare ribbons as seen in the contemporaneous UV images. The high-resolution snapshot, images (right panels of Figures



(e)

Figure 3. (*Continued*)

3a-3e) show that often the patches are unresolved at the TRACE pixel resolution of 0.5″. We show X and Y cuts across the brightest pixels in each sub-image in Figure 4 and these confirm this impression, showing many sharp spikes well above the background background fluctuations. The scales observed match the TRACE angular resolution, which would include any residual focus error as well as the pixel sampling. There is no evidence that this resolution is sufficient to determine the true dimensions of these features. Figure 5 illustrates the temporal intermittency, a striking characteristic of the TRACE white-light flare emissions. At an 8-sec image cadence and $\sim 1''$ spatial resolution, TRACE does not resolve the spatial or temporal variability of these sources. Thus precise comparisons between white light and UV cannot be made except on a statistical basis.

In all cases the data show the flare more clearly in the UV filters, as we illustrate in Figure 6 for an M4.0 event of 2002 October 4. This increased contrast is qualitatively explainable by a higher effective temperature in the flare continuum. The differences between the WL and UV emission regions may reflect different radiation-transfer properties as well as different excitation mechanisms, since the emissions may be formed in different regions.

In at least one event from the sample the TRACE white-light emission extends into loops, as illustrated in Figure 7. This is presumably a "white-light prominence" (e.g., Leibacher *et al.*, 2004) as seen above the limb in major flare events, and also presumably related to the high densities inferred from flare loop systems driven into

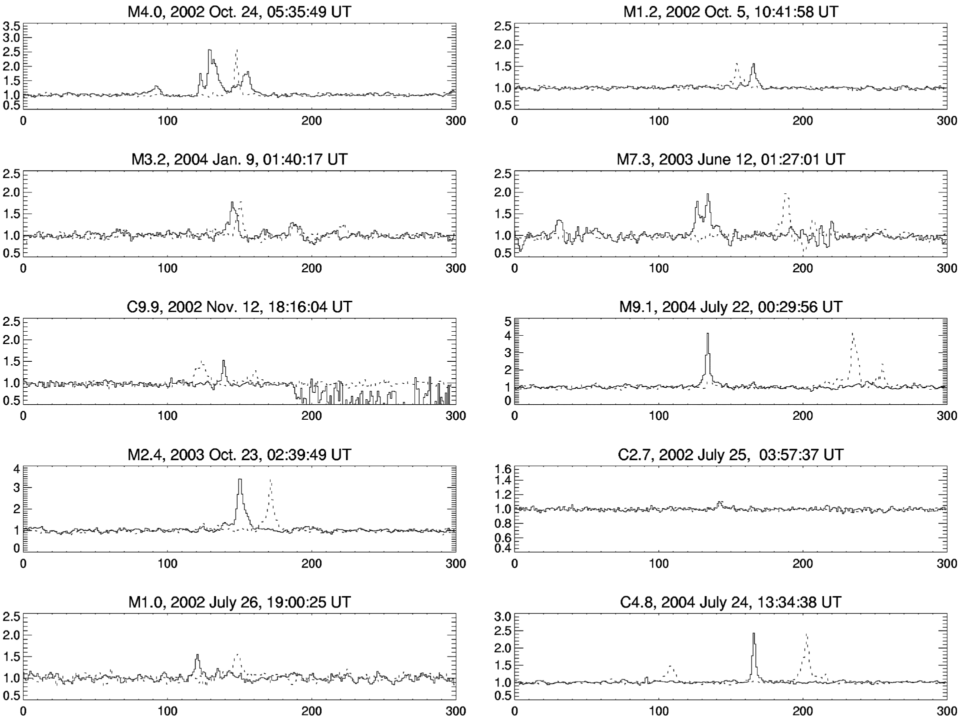


Figure 4. X,Y scans at the brightest pixels of the magnified images, showing intensity relative to quiet Sun vs. pixel number. Each scan is 150″, with *solid lines* for the X cuts and *dotted lines* for the Y cuts. The sequence (*left to right, top to bottom*) follows the order of Table I. Note that the intensity scales differ.

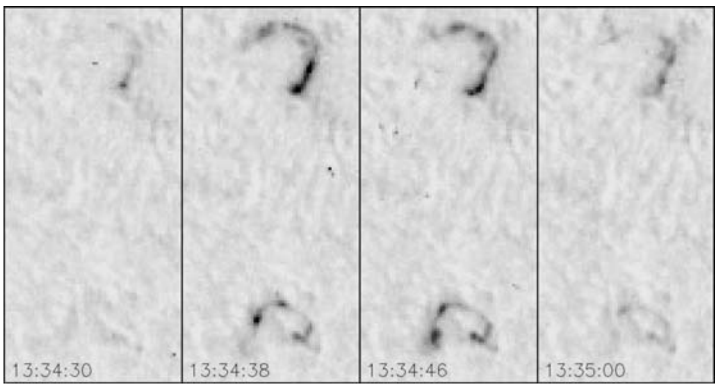


Figure 5. Illustration of the rapid flickering seen in TRACE white-light images, taken from fixed difference images of the C4.8 flare of 2004 July 24 13:31 UT. The four consecutive WL exposures span a total time range of 30 sec, with time for each frame as indicated: frame dimensions are $32'' \times 68''$; The contrast range is [−.05, 1.00] relative to the reference image brightness. Close inspection shows the WL emission to consist of unresolved patches that differ from frame to frame: the WL emission is intermittent both in space and in time at this resolution.

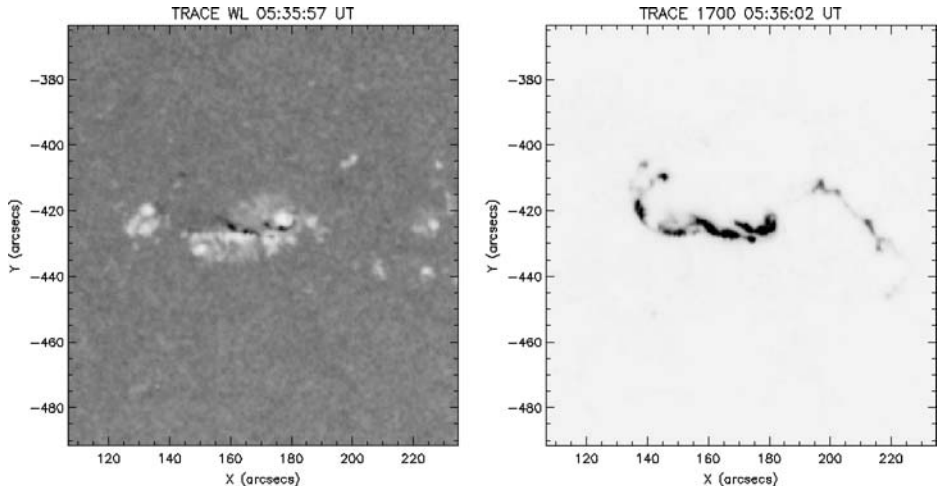


Figure 6. Comparison of TRACE white-light image with a UV 1700Å image taken 5 sec later at the hard X-ray peak of the M4.0 event of 2002 October 4. Again, a reversed color table, so that the white features on the left are the sunspots. See Figure 7 for another comparison.

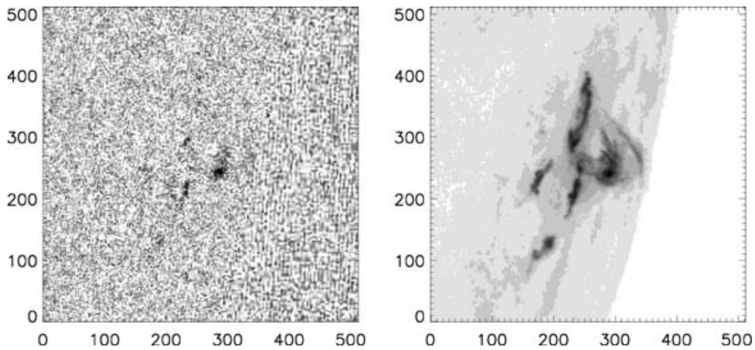


Figure 7. Illustration of loop-top emission seen in TRACE white light, for the event of 2002 November 12 17:58 UT. The *right panel* shows the loops more clearly via the TRACE 1700Å response. Color tables are reversed; WL image is scaled between (−2, 10)% and UV image is log-compressed. Note the location of the limb in the UV image. Image scales are in TRACE pixels (0.5″).

emission in Hα (e.g., Švestka, 1976). Figure 8 shows lightcurves from the footpoint and loop-top sources for this event. The lightcurves show that the footpoint and looptop emissions have impulsive and gradual character, respectively, consistent with the latter arising in flare-driven density increases in the loops.

3.2. Spectrum

The spectral response shown in Figure 1 differs substantially from traditional ground-based observations of white-light flares, upon which most of our experience

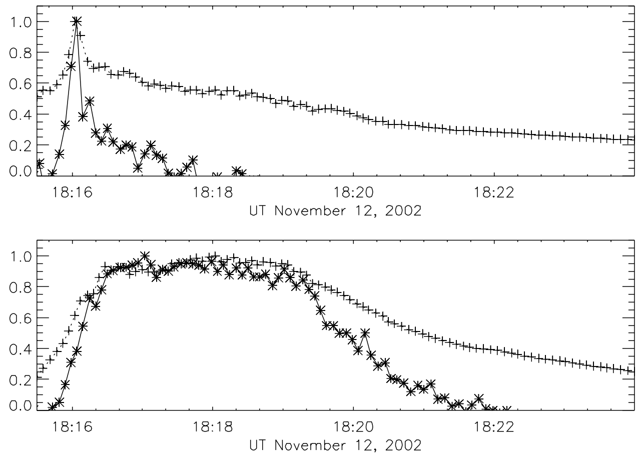


Figure 8. Light curves from the loop flare of Figure 7, showing the impulsive variation of the footpoint sources and the gradual behavior of the loop emission. *Upper*, a selected footpoint region; *lower*, a looptop region. In both plots WL is shown as $*$ and UV as $+$. Each light curve is normalized to its maximum and shows only excess fluxes.

is based, as discussed above in Section 2.1. The image excesses detected in our event sample are often large, exceeding the quiet-Sun intensity even in a sample not including X-class flares. For reference Carrington described his flare, which was probably as energetic as a flare ever is, as having a "... brilliancy... fully equal to that of direct sunlight." Thus on this basis the broader UV passband of the TRACE white-light continuum suggests a higher effective temperature than the photosphere. The recent 1.56 μ infrared observations by Xu *et al.* (2004) continue this trend, exhibiting contrasts of a few tens of percent for major flares. This is roughly consistent with the nominal flare continuum temperature of about 10^4 K (e.g., Machado *et al.*, 1989), given the great uncertainties in anecdotally comparing such disparate observations. The larger contrasts that we see presumably result from the difference in the passband involved, since TRACE WL includes so much UV response. In a future paper we intend to compare TRACE WL response, and WL with UV correction, with simultaneous MDI or ground-based observations of common flares.

Can we distinguish white-light emission from UV continuum emission, for example in the TRACE 1700Å passband? If so, the TRACE images and time series will provide information about the excitation mechanisms of these different continua. Metcalf *et al.* (2003) showed that one can effectively correct for the UV response by subtracting a multiple of the 1700Å data from the WL data; by so doing they suggested for their flare that the "true" WL response behaved differently from the UV and could be distinguished from it. We have compared images and lightcurves for all of the events in Table I and present an example in Figure 9. The sharp spike in the corrected WL lightcurve (lower left in Figure 9) matches the

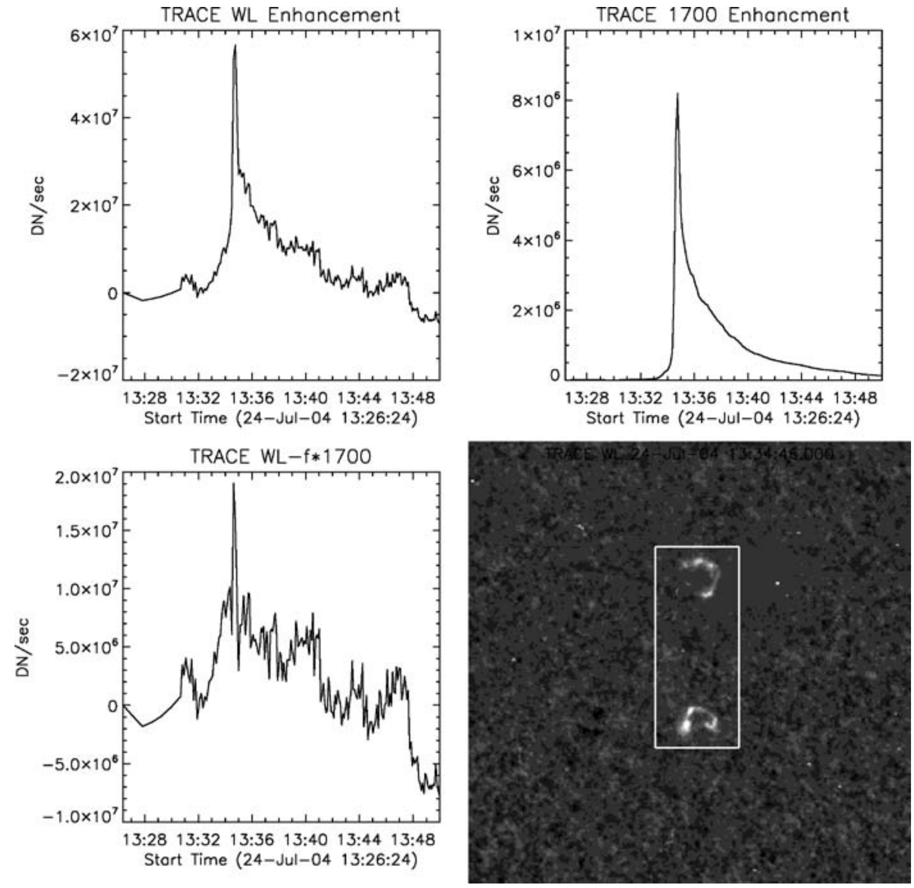


Figure 9. Comparison of TRACE white-light and 1700Å UV data for the C4.8 flare of 2004 July 24 13:31 UT. The light curves look substantially similar, although with much better signal-to-noise for the 1700Å data because of the relative faintness of the Sun in the UV. The box on the image panel shows the integration region for the light curves. The corrected light curve at the *lower left* shows a suggestion of a distinct white-light peak at about 13:34:50 UT. This time exactly matches the peak of the RHESSI impulsive hard X-ray burst. The image spatial dimension is 150″.

time of the RHESSI hard X-ray burst, but unfortunately the image sampling time interval (3 to 8 sec for TRACE; 4 sec for RHESSI) do not adequately resolve the time variations. Thus this flare does not provide unambiguous evidence for a distinct and separate WL emission component without a corresponding UV emission. Figure 10 provides a better example distinguishing the WL and UV components, using only a part of the image to make a sharper comparison.

3.3. Comparison with Hard X-rays

The TRACE white-light emission generally correlates well with hard X-ray fluxes observed by RHESSI. Figures 11 illustrates this (cf. Figure 10) for one

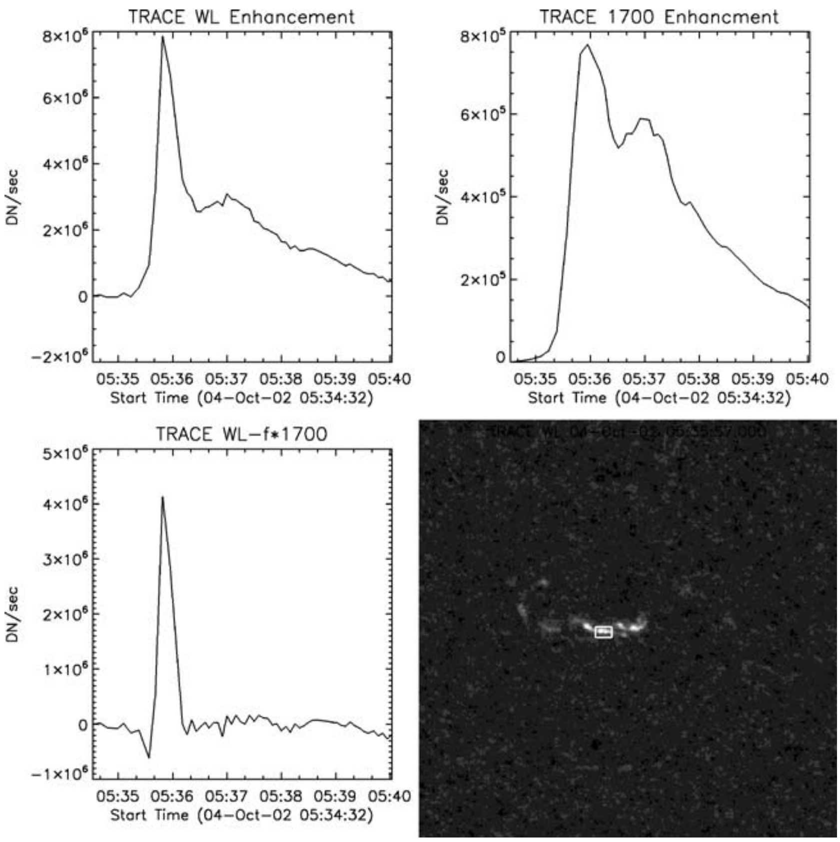


Figure 10. Comparison of TRACE white-light and 1700Å UV data for the M4.0 flare of 2004 October 4 05:34 UT, same format as Figure 9. Here the lightcurves show only a small region of flare emission. This kernel, and others in this flare, show clear distinctions between WL and UV emission components. The image spatial dimension is 150″.

event; the hard X-ray timing matches the true WL signature inferred from the TRACE data quite well during the impulsive phase. Outside this time no clear WL signal appears, even though the correction involves a simple subtraction of a fixed multiplier (7) of the 1700Å signal and hence may contain spectrum-dependent effects. We take this as evidence that "true" white light differs physically from the broad-band emission seen by the TRACE WL response.

We defer detailed analysis of these relationships, especially including spatial relationships, to a future paper. This will involve time series of HXR imaging as obtained from RHESSI, by which we will hope to define the temporal relationships suggested by Neidig *et al*. (1993).

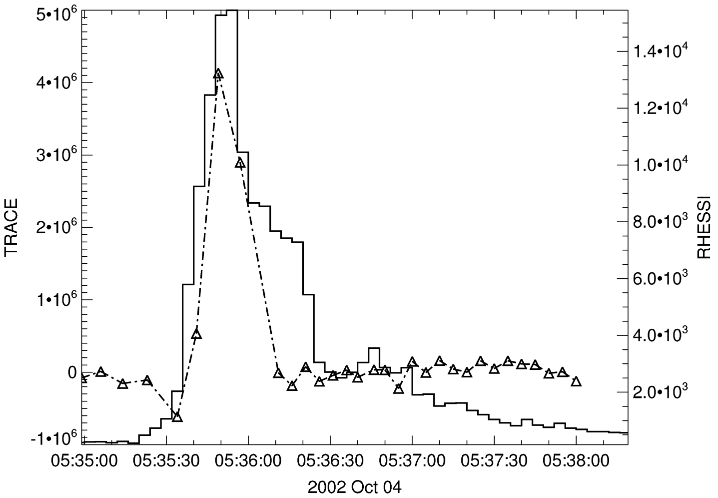


Figure 11. Comparison between UV-corrected TRACE white light (*dash-dot line*) and RHESSI hard X-rays (25-100 keV; *solid histogram*), for the event of 2002 October 4. The area for WL photometry is that defined in Figure 10. The peaks are simultaneous within the time resolution of the instruments, but the different light curves suggest complexity in the relationship, possibly spatial in origin.

4. Conclusions

In this survey of TRACE white-light flare observations we have used the complete sample of events for which RHESSI hard X-ray data were available through 2004. In the event morphology and behavior we find nothing to contradict the basic conclusions of Neidig (1989). We find as well a new and important property of the white-light emission: its inherent intermittency within the envelope of the flare structure (i.e., the ribbons). The importance of this finding is that these white-light emission patches may show the sites of the most significant flare energy. These then could also be the sites of energy deposition by non-thermal electrons, as envisioned in the standard thick-target picture, and we will explore this relationship with more detailed RHESSI image studies in a future paper. We summarize our findings in as follows:

(1) For a given GOES class, the TRACE white-light flare emission in the TRACE appears brighter (higher contrast) than that seen in narrower bands, e.g., from ground-based observations.
(2) TRACE UV images (1700Å continuum) resemble the white-light images, but have far greater contrast. In some cases the white light may be distinguishable from the UV and have a stronger association with hard X-ray time profiles.
(3) White-light emission is higly localized (intermittent) both in space and time, even with the superior TRACE resolution and sampling.
(4) White-light emission correlates well in detail with hard X-ray emission.

(5) In some cases, white-light emission can clearly be seen from loop tops, as well as ribbon/footpoint structures.

Among these results we feel that the most important may be the degree of intermittency. There is no clear evidence that the TRACE angular resolution actually resolves the white-light kernels. These kernels closely reflect the main luminous energy of a flare. The intermittency in the time domain matches that of the space domain. Future observations with another order of magnitude of resolution both in space and in time would therefore be highly interesting.

Acknowledgments

This work has been supported by NASA under grant NAG5-12878 and contract NAS5–38099.

References

Carrington, R. C.: 1859, *MNRAS* **20**, 13.

Chapman, S. and Bartels, J.: 1940, *Geomagnetism*. Oxford: University Press.

Gurzadian, G. A.: 1980, *Flare Stars*. International Series in Natural Philosophy, Oxford: Pergamon Press.

Handy, B. N., Acton, L. W., Kankelborg, C. C., Wolfson, C. J., Akin, D. J., Bruner M. E. *et al.*: 1999, *Solar Phys*. **187**. 229.

Hudson, H. S.: 1972, *Solar Phys*. **24**, 414.

Hudson, H. S., Acton, L. W., Hirayama, T., and Uchida, Y.: 1992, *Publ. Astron. Soc. Japan* **44**, L77.

Leibacher, J. W., Harvey, J. W., Kopp, G., Hudson, H., and GONG Team: 2004, *American Astronomical Society Meeting Abstracts* **204**.

Lin, R. P., Dennis, B. R., Hurford, G. J., Smith, D. M., Zehnder, A., Harvey P. R. *et al.*: 2002, *Solar Phys*. **210**, 3.

Machado, M. E., Emslie, A. G. and Avrett, E. H.: 1989, *Solar Phys*. **124**, 303.

Matthews, S. A., van Driel-Gesztelyi, L., Hudson, H. S., and Nitta, N. V.: 2003, *Astron. Astrophys*. **409**, 1107.

Metcalf, T. R., Alexander, D., Hudson, H. S., and Longcope, D. W.: 2003, *Astrophys. J*. **595**, 483.

Neidig, D. F.: 1989, *Solar Phys*. **121**, 261.

Neidig, D. F. and Cliver, E. W.: 1983, *NASA STI/Recon Technical Report N* **84**, 24521.

Neidig, D. F. and Kane, S. R.: 1993, *Solar Phys*. **143**, 201.

Neidig, D. F., Kiplinger, A. L., Cohl, H. S., and Wiborg, P. H.: 1993, *Astrophys. J*. **406**, 306.

Neidig, D. F., Wiborg, P. H., and Gilliam, L. B.: 1993, *Solar Phys*. **144**, 169.

Rust, D. M. and Hegwer, F.: 1975, *Solar Phys*. **40**, 141.

Švestka, Z.: 1970, *Solar Phys*. **13**, 471.

Švestka, Z.: 1976, *Solar Flares*, Dordrecht: Reidel.

Xu, Y., Cao, W., Liu, C., Yang, G., Qiu, J., Jing, J., Denker, C., and Wang, H.: 2004, *Astrophys. J. (Lett.)* **607**, L131.