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ENERGETICS AND TIMING OF THE HARD AND SOFT X-RAY EMISSIONS IN WHITE LIGHT FLARES

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LETTERS · LETTERS · LETTERS

Abstract. By comparing the light curves in optical, hard x-ray, and soft x-ray wavelengths for 8 well-observed flares, we confirm previous results indicating that the white light flare (WLF) is associated with the flare impulsive phase. The WLF emission peaks within seconds *after* the associated hard x-ray peak, and nearly two minutes *before* the 1-8 Å soft x-ray peak. It is further shown that the peak power in nonthermal electrons above 50 keV is typically an order of magnitude *larger*, and the power in 1-8 Å soft x-rays radiated over 2π strdn at the time of the WLF peak is an order of magnitude *smaller*, than the peak WLF power.

In determining the stage of flare development associated with the production of optical continuum, or white light flare (WLF), it is necessary to compare the time development of the WLF in relation to other emissions that define, for example, the impulsive and thermal phases of the flare. A further question, relating to the mechanisms of energy transport in WLFs (cf. Canfield et al. 1986, Neidig 1989), requires quantitative measurements of emissions from which the rate of energy deposition in various forms can be derived. Although it is recognized that optical continuum often occurs in intense flares, the emission processes and sources of energy are not well understood. Whereas one interpretation explains the WLF in terms of energy deposited in the chromosphere by nonthermal electrons (cf. Kane et al. 1985, Neidig 1989), another interpretation involves backwarming of the photosphere by coronal soft x-rays produced during the flare (cf. Rust 1986). This ambiguity in interpretation is partly due to the relatively small number of well-observed WLFs. In this letter we compare the timings and energetics of hard x-rays, soft x-rays, and optical continuum in eight well-observed WLFs.

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These eight events constitute the entire currently available sample of WLFs satisfying the selection criteria of two-dimensional photometric imaging, wavelength integrated optical output as a function of time, and simultaneous measurements in full disk hard and soft x-rays.

The data are shown in Table I, where, for the purposes of comparison with x-rays, three of the flares show double peaks in optical continuum which are sufficiently well defined and separated in time so that we treat them here as individual events. Six of the flares were photographically recorded at Sacramento Peak Peak in either two or five wavelength bands (always including Balmer continuum); the 1980 Feb 11 event was observed in one band at Big Bear Solar Observatory, and the 1989 Mar 7 event was recorded on CCD arrays in one continuum band at Sacramento Peak (Neidig et al. 1992). The total optical power was obtained by integrating over wavelength using a model WLF spectrum consistent with imaging observations between 3600 and 6000 Å (the assumed spectrum extends into the near UV and near IR; see Kane et al. 1985, Neidig et al. 1992).

For the first six WLFs in Table I, the general similarity of the optical light curves with those in hard x-rays is demonstrated in graphs shown in Canfield et al. (1986), although quantitative measurements of any time delays are not presented there. The seventh (as yet unpublished) and eighth WLF also show close similarity with hard x-rays. In Table I we present the time difference between the peaks in ≈50 keV x-rays and WLF power; we compare only those peaks whose times are well defined, not multiple on short (<60 s) time scales, and not adversely affected by noise. The result shows a mean lag in the WLF peak, relative to hard x-rays, of 8.4 s (σ = 8.3 s). This is comparable to the time resolution of the photographic measurements, and is therefore consistent with the more precisely determined lag of 2.5 s (1989 Mar 7 event) measured with a CCD array at 0.5 s time resolution. From Table I it was further determined that the ratio of the power in thick target electrons above 50 keV at the time of the WLF peak, to the peak WLF power, has a mean of 7.9 (σ = 8.3). In only one case (1982 Jun 5) was the ≥50 keV power less than the WLF power—and only by a factor of 2.

By using GOES 1-8 Å x-ray light curves (original plots with 3 s resolution were kindly provided by H. Garcia) it was found that the WLF peaks preceded the soft x-ray peaks by a mean of 111 s (σ = 71 s). In order to explore the possibility that the optical continuum might arise from radiative backwarming of the chromosphere or photosphere by coronal soft x-rays, we calculated the ratio of 1-8 Å power (over 2π strdn and assuming no solar surface albedo) at the time of the WLF peak to the peak WLF power. The result showed a mean ratio of 0.085 (σ = 0.075), and in no case was the 1-8 Å power closer than a factor of 4 less than the optical power.

The results presented here lead to two conclusions. First, the relatively close temporal association between the white light and hard x-ray emissions indicates that the WLF is identified primarily as an impulsive phase phenomenon, as was concluded previously by Svestka (1970). Nevertheless, the WLF may show a gradual component in cases where the hard x-ray emission also has a gradual

TABLE I

Optical, Hard X-ray, and Soft X-ray Data for Eight WLFs

Date and UT[a]	Log P_w/Log P_e/Log $P_{1\text{-}8}$[b] (erg/s)	Δt[c] (s)	$t_h - t_w$[d] (s)	$t_{1\text{-}8} - t_w$[e] (s)
80/2/11 20:37:35	26.75/27.79 I/25.51	15	-7	+50
80/7/1 (16:27:00)	27.36/27.81 S/25.45	90/10		—
80/7/1 (16:28:30)	27.65/27.67 S/26.38	90/10		0
81/4/24 13:47:40	27.15/28.16 I/25.71	30/5	-15	+80
81/4/24 (13:57:10)	27.85/28.45 I/26.79	30/5		+170
82/6/5 (15:29:40)	26.53/26.22 I/25.90	20/10		+110
82/6/26 (19:12:45)	27.11/27.50 I/26.30	30/15		+135
82/12/17 18:53:45	27.38/28.73 I/26.46	30/15	-1	—
82/12/17 18:55:45	27.82/29.16 I/27.04	30/15	-15	+95
84/4/25 00:00:50	29.32/— S/26.54	30/5	-10	(+250)
89/3/7 14:55:15	28.19/28.65 S/26.19	0.5	-2.5	+105

[a]Two times of WLF maximum are given in cases where two distinct WLF peaks occur; times in parentheses are not precisely determined, due to noise in the data.

[b]P_w is the peak WLF power. P_e is the power in ≥50 keV thick target electrons at the WLF peak, derived from ISEE data (I) or SMM (S); electron power for the 1984 Apr 25 event could not be measured due to pulse pile-up effects. $P_{1\text{-}8}$ is the irradiating power in 1-8 Å x-rays.

[c]Time resolution of the optical data. The first number refers to the time required for a complete cycle of wavelengths, the second to the time between individual measurements.

[d]Time difference between the peak in hard x-ray flux (at ≈50 keV) and the associated peak in WLF power. Due to pulse pile-up effects at 50 keV, the time of peak hard x-ray flux in the 1984 Apr 25 event was measured at ≥100 keV.

[e]Time difference between the peak in 1-8 Å soft x-ray flux and the associated WLF peak. The entry for the 1984 Apr 25 event is an estimate, due to saturation of the 1-8 Å detector between 0003 and 0009 UT.

component (Kane et al. 1985, Neidig et al. 1992); and, as shown further in Canfield et al. (1986), the WLF power tends in general to track the hard x-ray light curve.

Second, it can be argued that the temporal association between the WLF and hard x-rays may be more than coincidental, as the power in nonthermal electrons above 50 keV (in a thick target interpretation) is sufficient to balance the WLF radiative losses. While this is suggestive of direct heating of the optical continuum emitting layers by nonthermal electrons, it does not by itself prove this to be the case; additional evidence, showing that the continuum emitting layers are indeed located at the atmospheric levels where the nonthermal electrons are being collisionally degraded, is required. Nevertheless, because electrons with energies above 50 keV can penetrate well into the chromosphere, and because lags of several seconds may be consistent with the time scales of lower atmospheric heating, ionization, and recombination (Canfield and Gayley 1987) as well as with additional processes originating in the chromosphere (e.g. optical irradiation, condensations) which may further transport energy downward, it is therefore reasonable to conclude that electrons are fundamentally involved in transporting energy from the corona to the WLF. In effect, the large radiative outputs of WLFs have not succeeded in overturning the thick target nonthermal electron model of solar flares.

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