IMPLICATIONS OF THE SOFT X-RAY VERSUS HARD X-RAY TEMPORAL RELATIONSHIP IN SOLAR FLARES

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ABSTRACT

We have calculated the time profiles of spatially integrated hard X-ray (30–500 keV) and soft X-ray (1–8 Å) emission in both thick-target electron-heated models, and bulk heated thermal models, of the impulsive phase of solar flares. For the thermal model, we find a serious difficulty: the time profiles of the 30–500 keV hard X-ray emission do not peak at the same time as those for the higher energy component (40–500 keV) of this emission, a result that manifestly disagrees with the observations. In the thick-target model, however, the hard X-ray light curves at all energies >30 keV peak at the same time, lending considerable support to this model.

Observations also suggest that the relationship between the hard X-ray and soft X-ray emission is that of “derivativity,” that is, the hard X-ray time profile corresponds not so much to the instantaneous soft X-ray flux, but rather its temporal derivative. We have explored the relationship between the hard X-ray (30–500 keV) and soft X-ray (1–8 Å) time profiles in the thick-target model. Typically we find that the temporal derivative of the soft X-ray emission does indeed correspond well to the instantaneous soft X-ray emission, particularly during the rise phase of the event. The cause of this behavior is a combination of heating and density enhancement processes, and we assess the relative roles of each process for a variety of simple hard X-ray time profiles, ranging from short (5 s rise time) to long (60 s rise-time). As expected, temperature enhancements dominate the behavior for the shortest bursts, with density enhancements becoming important for bursts of greater than approximately 15 s duration. It also appears that some other form of gradual heating (e.g., slow reconnect) persists through the decay phase of the event.

Subject headings: radiation mechanisms: miscellaneous — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

It is well known that solar flare hard X-rays are produced by energetic electrons through bremsstrahlung. One of the most pressing problems in flare physics is determining whether the released electrons are predominantly thermal or nonthermal. Resolution of this issue could lead to a better understanding of the flare energy release itself, that is, how much energy goes to accelerate electrons versus heating of the plasma, etc. Since an in situ measurement of these energetic electrons is not possible, their nature can be inferred only through observations of their radiative signatures, such as hard X-ray emission.

Both thermal and nonthermal models of hard X-ray bursts have been developed for some time now. In thermal models (e.g., Brown, Melrose, & Spicer 1979; Smith & Lilliequist 1979; Cheng et al. 1983; Emshie & Nagai 1985) the bulk of the hard X-rays are produced through collisional bremsstrahlung of a thermally relaxed distribution of electrons (T > 10^7 K), which cools through diffusion into the cooler surroundings. On the other hand, in a nonthermal model (e.g., Brown 1971, 1973; Lin & Hudson 1976; Emshie 1981), the hard X-rays are produced when a suprathermal distribution (“beam”) of electrons interacts with a relatively cold target. Various authors, such as Emshie & Vlahos (1980) and Holman & Benka (1992), have suggested hybrid thermal/nonthermal models, in which the high-energy electrons are either accelerated by a large-scale electric field or form the suprathermal high-energy “tail” of a predominantly thermal distribution, in turn formed by bulk (e.g., joule) heating of the ambient medium. Over the years various workers have compared the hard X-ray burst characteristics (e.g., Temporal behavior, spatial structure, directivity, polarization) of the various models and compared these predictions with observations (see, e.g., Tandberg-Hanssen & Emshie 1988 for a review).

Here we extend this diagnostic effort to include the relationship between the hard X-ray emission and the corresponding soft X-ray emission associated with the flare. The plasma that emits the soft X-rays is produced either through bulk heating in the primary release (thermal models) or collisional heating of the ambient medium by the passage of the accelerated electrons (nonthermal models; see Li & Emshie 1990).

Observationally, it is well known that EUV broad-band emission (10–1030 Å) correlates well in time with hard X-ray (HXR) emission (e.g., Kane & Donnelly 1971; Donnelly & Kane 1978; Emshie, Brown, & Donnelly 1978; McClymont & Canfield 1986). At optical wavelengths, observations indicate that the flare Hz wings have a temporal behavior similar to hard X-rays (e.g., Canfield & Gunkler 1985). In addition, the hard X-ray and the microwaves time profiles are similar to one another (e.g., Arnoldy, Kane, & Winkle 1968; Kane 1983; Cornell et al. 1984; Starr et al. 1988). However, not all temporal correlations between impulsive phase emissions follow such a pattern. For example, it was first pointed out by Neupert
(1968) that the time integral of the microwave emission rather than the microwave profile itself more closely matches the soft X-ray light curve. Motivated by this result, and in view of the similarity between microwave and hard X-ray light curves, comparisons between the soft X-ray time derivative and the hard X-ray light curve have been carried out (e.g., Tanaka, Nitta, & Watanabe 1982; Antonucci, Gabriel, & Dennis 1984). These later observations verified the early results of Neupert. Using a large sample of Solar Maximum Mission (SMM) data, Dennis (1991) has demonstrated that this “derivativeness” relationship between soft X-ray and hard X-ray time profiles is in fact a common feature for impulsive flares, confirming the early studies by Neupert. We note, however, that there exists some debate on whether this “derivativeness” relationship is causal or noncausal (Karpen, Doschek, & Seeley 1986; Feldman 1990).

There remains a need for a theoretical study of the soft X-ray versus hard X-ray temporal correlation. In this paper, therefore, we study such correlations within the context of both thermal and nonthermal models. We begin in § 2 by summarizing recent observations of the relationship between hard X-ray and soft X-ray emissions. We point out that the observed synchronism of hard X-ray emission at all energies in the 30–500 keV range argues against a thermal interpretation of the hard X-ray burst, and in favor of a nonthermal interpretation. In § 3 we discuss detailed results from numerical simulations of thick-target electron-heated models, with particular attention to the “derivativeness” relationship between soft and hard X-ray emissions. Our conclusions are presented in § 4.

2. OBSERVATIONS AND THERMAL MODEL ANALYSIS

Dennis (1991) has studied the temporal relationship between soft X-ray and hard X-ray emission using hard X-ray observations from the Hard X-Ray Burst Spectrometer (HXRBS) on the SMM and soft X-ray observations from the Geostationary Operational Environmental Satellite (GOES). As a measure of hard X-ray flux, he used the HXRBS total count rate covering the energy range of 30–500 keV, while for the soft X-ray flux, he used GOES channel 1 data covering the range 1–8 Å. He initially studied 12 flares (Dennis 1991). Since then, at least 40 additional flares have been examined (B. Dennis 1991, private communication). These studies show that for most impulsive flares studied (which are type “B” in the scheme of Tanaka 1983 and Tsuneta 1983), the soft X-ray time derivative matches the hard X-ray time profile, strengthening the conclusions made by Neupert (1968) and Tanaka et al. (1982). Figure 1 shows one example of the flares studied. The soft X-ray time profile, its time derivative, and the hard X-ray time profile are plotted. It can be seen that the soft X-ray time derivative and the hard X-ray time profiles are closely related with $I_{sx} \sim I_{sx}$.

It is also well established (Forrest & Chupp 1983) that hard X-ray time profiles over the energy range from 30 to 500 keV are similar and, in particular, that they peak at the same time. Such an observation offers us an additional constraint on the models, since in a thermal model, one might expect the higher energy channels to peak earlier while lower energy channels peak later as the plasma cools.

To explore this suggestion, we examined the predicted hard X-ray signature of the thermal model first considered by Nagai (1980) and developed by Emslie & Nagai (1985). Similar heating models can also be found in Cheng et al. (1983) and Craig & Davys (1984). The model assumes that the flare occurs in a loop with a uniform cross-sectional area. Through some unspecified heating mechanism, the corona is heated. The energy input $Q_\text{I} \text{erg s}^{-1} \text{cm}^{-2} \text{s}^{-1}$ has a Gaussian spatial distribution:

$$Q(z, t) = \frac{1}{\sqrt{\pi}} \frac{g(t)}{\sigma} \exp \left( -\frac{z^2}{\sigma^2} \right),$$

where $z$ is the loop length variable, $\sigma$ is a scale length (equal to $2 \times 10^6 \text{cm}$), and $g(t)$ is the energy input profile per cm$^2$ of cross-sectional area, assumed to have a triangular time profile (see Fig. 2).

The dynamics of this thermal model have been discussed in detail by Emslie & Nagai (1985); here we give only a brief summary. After the flare start, the heating in corona generates downward-moving conduction fronts. When these fronts impinge on the upper chromosphere, an upward motion (“chromospheric evaporation”) commences, which brings the chromospheric material into the corona, enhancing the density there. The coronal atmosphere is heated to about $4 \times 10^7 \text{K}$ within 20 s, forming a “super-hot” region there. The chromospheric evaporation continues to drive material up, causing the coronal density to increase from $2 \times 10^9 \text{cm}^{-3}$ at the beginning to about $10^{11} \text{cm}^{-3}$ at the end of the flare. The enhanced coronal temperature and density imply that thermal bremsstrahlung is substantial.

For simplicity, we assume that the electron distribution is locally Maxwellian, and neglect the possible nonthermal component produced by escaping high-energy tail energetic electrons (Brown et al. 1979). The soft X-ray (1–8 Å) emission is then composed of emission from both the free-free and free-bound continua, and from various spectral lines formed at these energies. The evaluation of the spectral lines is troublesome and may be uncertain (Mewe & Gronenschild 1981). However, continuum emission dominates over spectral line emission over the entire 1–8 Å energy band (Culhane & Acton 1970). Thus, the thermal hard X-ray emission at photon energy $\epsilon$ from a segment $l$ of the flare loop, with the Gaunt factor $g$ included, is to a good approximation given by (see, e.g., Allen 1973)

$$I_{th} = 1.2 \times 10^{-11} \frac{n^2 l}{\epsilon^{3/2}} \exp \left( -\frac{\epsilon}{kT} \right) g(\epsilon, T),$$

where $T$, $n$, and $l$ are the density, temperature, and the length of that segment. We used a Gaunt factor (Gorenstein, Gursky, & Garmire 1968) of the form $g(\epsilon, T) = (kT/e)^{2/5}$, which is applicable to high temperatures (>7 × 10^5 K).

Differentiating equation (2), we obtain

$$I_{sx} = \frac{\epsilon}{kT} \left( \frac{1}{10} \right) \frac{T}{T} + 2 \frac{\epsilon}{n},$$

from which we see that the thermal emission at each point in the flare generally (i.e., except at very low photon energies $\epsilon < 0.1kT$) increases with both temperature and density. Equation (3) is important for examining the relative roles of temperature and density changes to the total soft X-ray emissivity, both here and in the discussion of the thick-target model in the next section.

For the purposes of comparing the model results with spatially unresolved observations, we integrated equation (2) over the flare loop structure and the appropriate range in photon energy (wavelength), namely 30–500 keV (hard) and 1–8 Å (soft), using the Emslie & Nagai (1985) hydrodynamic profiles.
The results are shown in Figure 2. Looking first at the soft X-ray results, it is easy to see that soft X-ray flux $I_{sx}$ continues to increase during the entire event. At $t = 10$ s, the conduction fronts have not yet reached the upper part of the chromosphere, so that no evaporation has begun. Therefore, only the temperature controls the behavior of the soft X-ray emission at such times, and the growth rate is slow. However, after 10 s, chromospheric evaporation begins to occur, and the greatly enhanced coronal density causes the soft X-ray emission to increase more rapidly after 10 s. Although the temperature in the corona begins to decrease after 20 s (see Figs. 7–9 of Emslie & Nagai 1985), the evaporation continues to enhance the coronal density. This overcomes the drop in temperature (eq. [3]), causing $I_{sx}$ to keep increasing after 20 s. After 45 s, the evaporation decreases because of the high coronal over-pressure already produced (Emslie & Nagai 1985). Consequently the rate of increase of $n$ drops off ($\dot{n} < 0$). Since by this time the density term in equation (3) is dominant over the almost vanishing $T'/T$ term ($T$ has saturated at around $2 \times 10^7$ K), $I_{sx}$ starts to decline. It is clear from Figure 2 that $I_{sx}$ does not well match the energy input time profile $g(t)$.

The lower panel of Figure 2 shows that the (thermal) hard X-ray emission ($I_{ht}$) in the 30–500 keV range does not match the energy input time profile $g(t)$ either. The behavior of $I_{ht}$ is controlled by the physics of the evaporation process in the highest temperature region of the loop. This can also be seen by looking at the rapid increase in $I_{ht}$ after $t = 10$ s. $I_{ht}$ has a first peak around 20 s, corresponding to the formation of a “super-hot” component in the corona as the upward-moving fronts of the material collide (Fig. 7 of Emslie & Nagai 1985). The temperature in this region increases by several tens of percent in 10 s, causing a rapid increase in $I_{ht}$ (eq. [3]). This region is, however, short-lived: thermal conductive losses to the cooler surroundings rapidly cool the region. The large negative $\dot{T}$ during the cooling phase just overcomes the modest density increase, so that $I_{ht}$ actually undergoes a slight decrease between $t = 20$ and 30 s. After this brief transient, steady evaporation resumes, causing $I_{ht}$ to increase again; it reaches a main peak around 40 s. After 40 s, the density saturates at $\sim 10^{11}$ cm$^{-3}$. However, the temperature begins to decrease, causing $I_{ht}$ to decline (eq. [3]). Because of the fundamentally different physics affecting the highest temperature plasma (that produces $I_{ht}$) compared to the loop as a whole (that produces $I_{sx}$), we do not expect a close correlation between the two emissions. This is indeed the case. First, $I_{ht}$ and $I_{hx}$ do not peak at the same time. Second, there is no double peak structure in $I_{hx}$. Furthermore, neither matches the energy input time profile $g(t)$.

We also calculated the hard X-ray emission at higher energies. In Figure 2 we compare $I_{ht}$ (40–500 keV) and $I_{hx}$ (30–500 keV) and find that the two peaks (at $t = 20$ and 40 s) are switched in relative intensity. For $I_{hx}$, the main peak is at $t = 40$ s, while for $I_{ht}$, the main peak occurs at 20 s, with a subpeak at 40 s. Since the high-energy hard X-ray emission is predominantly controlled by the coronal temperature through the exponential term in equation (2), significant emission above 30 keV is produced only in the very hot corona. Thus the peak at $t = 20$ s due to the super-hot region is exaggerated in the higher energy (40–500 keV) emission.

The lack of similarity between $I_{sx}$, $I_{hx}$, $I_{ht}$, and $g(t)$ indicates that the thermal model fails to reproduce the basic “derivativity” trend of Figure 1. We note that the thermal model also fails to reproduce the observed differential emission measure (DEM) in the transition region (Emslie & Nagai 1985). The lack of synchronism of the hard X-ray emission at different energies is also in sharp disagreement with observa-
lations (Forrest & Chupp 1983). We calculate that the thermal model, despite its appealing simplicity, fails to reproduce the hard X-ray and soft X-ray behaviors that are observed. Let us now, therefore, turn to the thick target model to see if it can satisfactorily account for the hard X-ray and soft X-ray temporal relationships.

3. THICK-TARGET MODEL ANALYSIS

An apparently straightforward explanation of the derivativity effect in thick-target models can be obtained from simple energy arguments. Since the nonthermal emission is a prompt indication of the beam energy deposition power $P_e$ (ergs s$^{-1}$), it follows that $I_{\alpha} \propto P_e(t)$. On the other hand, the soft X-ray emission is an indicator of the cumulative energy deposited by electron beams up to time $t$: $I_{\alpha, \propto \int_0^t P_e(t')dt'}$, so that $I_{\alpha} \propto I_\alpha$. Whether this simple argument holds in a rigorous hydrodynamic model, with energy terms due to conduction, radiation, and mass motions, is the subject of this investigation.

3.1. The Model

Many modifications and advances in the study of the nonthermal thick-target hard X-ray model have been made since Brown (1971) first proposed the idea. Although all models assume suprathermal electrons as the principal mode of flare energy input, they differ in model parameters and assumptions. In general, there are two types of model parameters. The first type concerns electron parameters, such as the total flux $F$, spectral index $\delta$, lower energy cutoff $E_\gamma$, and pitch angle distribution. The second type concerns the initial flare atmosphere, including the density $n$, temperature $T$, and the flare magnetic loop geometry.

Motivated by 3MM Bent Crystal Spectrometer (BCS) observations of the Ca xix line profile in the impulsive phase, Li, Emslie, & Mariska (1989) and Emslie, Li, & Mariska (1992) have modeled this line profile in the framework of a thick-target model. They discovered that only a nonthermal model with high initial coronal pressure $P_0$, a small amount of magnetic loop tapering, and a moderately large beam flux could reasonably reproduce the observed Ca xix line profiles. In particular, they have found that a model with electron beam parameters of $F = 5 \times 10^{10}$ ergs cm$^{-2}$ s$^{-1}$, $E_\gamma = 15$ keV, and $\delta = 6$, and an initial atmosphere with $P_0 = 100$ dyn cm$^{-2}$ and a near uniform loop geometry, could indeed satisfactorily predict the observed behavior of the Ca xix line profiles. Furthermore, the model can also quantitatively predict the observed EUV/HXR and Hx/HXR correlations (Li 1991).

Since the main objective of this paper is to study the soft X-ray and hard X-ray temporal relationship, it is important to extend the model of Emslie et al. (1992) to different temporal profiles. We keep the symmetrical (triangular) form of the energy unchanged but allow the rise (or decay) time to vary from 5 to 60 s. Note that the peak flux is the same in all models. This implies that (1) the instantaneous flux in longer duration events has a more gradual rise and fall, and (2) the total energy deposited is proportional to the duration of the event.

3.2. Method of Calculation

In considering a so-called nonthermal model, it is important to realize that hard X-ray emission is produced not only through the "direct" collisional bremsstrahlung of the primary electrons, but also through the thermal bremsstrahlung from the "hot" plasma energized by the same electrons through Coulomb collisions. The relative importance of these thermal and nonthermal components has been studied by Li & Emslie (1990). It was found that the thermal component could dominate over the nonthermal component at energies up to several tens of keV (depending on the model parameters). Hence, a so-called nonthermal model does not in fact guarantee a predominance of nonthermal hard X-ray emission. Both components were self-consistently included in the present calculation of the hard X-ray yield.

The nonthermal hard X-ray yield from a segment of a flare loop is given by (Li & Emslie 1990)

$$I_{\alpha}(\epsilon, N) = \frac{1140}{(\delta + 2)[\delta - 1]} F_\delta(\epsilon) \epsilon^{-\delta - 2} e^{\epsilon^{-\delta}} [j(x + \Delta x) - j(x)],$$

(4)

where $F_\delta$ is the electron input time profile (a triangle with rise and fall times both equal to $\tau$), $\epsilon$ is the photon energy in keV, $N$ is column depth (cm$^{-2}$), $x = 2KN/\epsilon^2$ is a dimensionless column depth, $K = 2.6 \times 10^{-18}$ keV cm$^2$, $\Delta x$ is the change in $x$ within the segment, and $j(x)$ is the normalized nonthermal emission function (see, e.g., Fig. 1 of Li & Emslie 1990). $I_{\alpha}$ is in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at the Sun. The thermal (soft X-ray) yield is calculated using equation (2), in a similar manner to the thermal model.

3.3. Results

Using equations (2) and (4), and flare hydrodynamic simulation results for flares with rise times of $\tau = 5, 15, 30, 60$ s,
respectively, we calculated the soft X-ray time profile $I_{sx}$, its time derivative $\dot{I}_{sx}$, and the hard X-ray time profile $I_x$. In Figure 3 we show the time profile of the energy input, the resulting hard X-ray fluxes, and the time derivative of the soft X-ray flux for all four cases. Also shown in this contribution of the evaporative $\langle \dot{n}/n \rangle$ term (eq. [3]) to the total logarithmic derivative $\dot{I}_{sx}/I_{sx}$. The quantity $\langle \dot{n}/n \rangle$ is a spatial average over all parts of the loop with temperature in excess of $10^5$ K and typically varies by less than 5% over the relevant part of the loop.

We first note that in all cases the hard X-ray profile follows faithfully the electron energy input. Since only the "direct" bremsstrahlung hard X-ray yield is strictly proportional to the nonthermal energy input, we infer (and have in fact verified) that the hard X-ray (30–500 keV) yield from this model must be dominated by this nonthermal component. Because of this dominance of direct bremsstrahlung emission, it is easy to see that the 40–500 keV, or even higher energy emissions, should be also dominated by the direct component. Since this component is directly proportional to the electron energy input, we would expect (and indeed have found) that the hard X-ray emission from different energy bands have similar profiles and peak at the same time (i.e., at the energy input maximum). Let us now discuss the relationship between the hard X-ray flux and the soft X-ray flux time derivative, as shown in Figure 3, for each case in turn.

3.3.1. $\tau = 5$ s

This short time profile corresponds to a "spiky" impulsive event with a total hard X-ray duration of 10 s. The soft X-ray flux continues to increase even after the peak of hard X-ray flux $I_x$. Its time derivative $\dot{I}_{sx}$, on the other hand, increases up to the peak of the hard X-ray flux and then begins to decline. During the hard X-ray rise phase, $I_x$ and $\dot{I}_{sx}$ both increase linearly. During the decay phase, they both decrease linearly. The overall similarity between $I_x$ and $\dot{I}_{sx}$ is good during the entire event. Since the energy deposited during such a short burst cannot heat the chromospheric material to temperatures great enough for the onset of radiative instability and so induce explosive chromospheric evaporation (e.g., Fisher, Canfield, & McClymont 1985), there is little contribution from chromospheric evaporation to the soft X-ray flux in this model. As seen in the lower left panel of Figure 3, throughout the event $\langle \dot{n}/n \rangle$ is negligible, so that the temperature change is the dominant term controlling the variation of the soft X-ray emission.

3.3.2. $\tau = 15$ s

Since we keep the electron peak flux unchanged, an increase in heating rise time flattens the slope of the heating time profile,
this event is less impulsive than the $\tau = 5$ s case. The soft X-ray emission flux $I_{\mathrm{sx}}$ increases monotonically until 26 s, after which it begins to decline. Its time derivative $I_{\mathrm{sx}}$ increases up to $t \sim 18$ s, then begins to decrease. After $I_{\mathrm{sx}}$ peaks at $t \sim 26$ s, $I_{\mathrm{sx}}$ becomes negative and the $I_{\mathrm{sx}} \sim \dot{I}_{\mathrm{sx}}$ relationship clearly breaks down. The lowest panel shows that initially the time profile of $I_{\mathrm{sx}}/I_{\mathrm{x}}$ is completely determined by temperature changes (i.e., the first term in eq. [3]). However, at $t \sim 15$ s, the density begins to increase due to chromospheric evaporation. At about 22 s, the $I_{\mathrm{sx}}/I_{\mathrm{x}}$ and $2\langle \dot{h}/n \rangle$ curves cross over; at this time the temperature increase term in equation (3) is zero. After this time, the temperature begins to drop ($\dot{T} / T < 0$). At $t \sim 25$ s, the positive density increase $2\langle \dot{h}/n \rangle$ cannot balance the temperature decrease anymore, so that $I_{\mathrm{sx}}/I_{\mathrm{x}}$ becomes negative. Comparison between $I_{\mathrm{x}}$ and $I_{\mathrm{sx}}$ shows that the overall time profiles are qualitatively similar, but $I_{\mathrm{sx}}$ peaks about 5 s later than $I_{\mathrm{x}}$ (note that $I_{\mathrm{sx}}/I_{\mathrm{x}}$ peaks earlier than $I_{\mathrm{sx}}$) and becomes negative after 26 s. The 5 s peak time lag in $I_{\mathrm{sx}}$ is within the uncertainties in the observations (Fig. 1). However, soft X-ray observations show that the soft X-ray emission continues to increase even after the hard X-ray burst diminishes, so that $I_{\mathrm{sx}}$ should be positive during the entire event. Our results after 26 s are not consistent with this feature and imply that additional heating, not associated with hard X-ray emission, takes place during this phase. We return to this point in § 4.

3.3.3. $\tau = 30$ s

This is the case which has been discussed extensively by Emslie et al. (1992). From Figure 3 we see that $I_{\mathrm{sx}}$ is similar to $I_{\mathrm{x}}$ during the rise phase. From the beginning of the flare to the time when the hard X-ray emission peaks, the soft X-ray emission is mainly due to the heating of the flare plasma, in other words, the first term of equation (3). After $t \sim 15$ s until well after the hard X-ray peak, conduction-driven evaporation drives chromospheric material in to the corona, and the density change term in equation (3) dominates.

During the decay of the hard X-ray light curve, the soft X-ray time derivative does not monotonically decrease. Instead, we observe a "bump" in $I_{\mathrm{sx}}$ at about $t = 42$ s. The similarity between $I_{\mathrm{x}}$ and $I_{\mathrm{sx}}$ during the decay phase apparently is poor. The hydrodynamic simulation results show that at about $t = 40$ s, the upward-moving evaporating components reach the top of the loop and collide with each other, forming a region of strongly enhanced density and temperature. One would suspect that the excess soft X-ray emission corresponding to this hot dense region leads to the second peak in $I_{\mathrm{sx}}$, and in fact sustains a positive $I_{\mathrm{sx}}$ throughout the entire decay. To test this idea, we replaced the density profile by one with the density excess in the top of the loop removed. The revised density profile was obtained by extending, via a linear extrapolation, the density profile of the relatively smooth part of the corona into the upper part of the corona. We then recalculated $I_{\mathrm{sx}}$. This resulted in the disappearance of the shaded regions in the appropriate panels of Figure 3. As expected, the second "bump" in $I_{\mathrm{sx}}$ indeed vanishes; the revised behavior of $I_{\mathrm{sx}}$ and $I_{\mathrm{x}}$ are shown in dot-dashed lines in the middle panel of the $\tau = 30$ s column. With the uncorrected model, $I_{\mathrm{x}}$ and $\dot{T}$ remain positive throughout the hard X-ray burst; with the smoothed model, $I_{\mathrm{x}}$ instead increases monotonically up to $\tau \sim 30$ s, then begins to decline due to cooling. $I_{\mathrm{sx}}$ increases monotonically up to $t = 30$ s, the peak in the hard X-ray light curve, and then begins to decline, becoming negative at $t = 43$ s, at which time, as for the $\tau = 15$ s case, the positive density enhancement cannot balance the cooling term. The overall similarity between $I_{\mathrm{sx}}$ and $I_{\mathrm{x}}$ is much better in the "corrected" model. We shall return to this in § 4.

3.3.4. $\tau = 60$ s

As previously noted, with an increase in rise time comes a decrease in the slope of the heating rate. Consequently, the hot high-density region that produced the anomalous feature in the $\tau = 30$ s case is absent here, because of the more gentle evaporation induced. $I_{\mathrm{sx}}$ continues to increase until the very late decay phase ($\tau \sim 110$ s). Its time derivative $I_{\mathrm{sx}}$ increases up to $t \sim 65$ s, and decreases until $t \sim 110$ s. The quantity $I_{\mathrm{sx}}/I_{\mathrm{x}}$ has a profile similar to the previous models, with the density enhancement commencing at $t \sim 15$ s, and becoming dominant by the early decay phase. The coronal temperature begins to decrease slightly after the peak of the heating. As in the $\tau = 15$ s and $30$ s cases, the soft X-ray emission enhancement is dominated by temperature changes during the rise phase, but by density structure during the decay phase.

The following trends in Figure 3 are evident. The peak value of the hard X-ray flux $I_{\mathrm{x}}$ is, by design, constant. However, as $\tau$ increases (i.e., the event becomes more gradual) the contribution of chromospheric evaporation becomes more prominent later in the event, and the peak soft X-ray flux $I_{\mathrm{sx}}$ becomes larger, from $1.5 \times 10^{15}$ cm$^{-2}$ s$^{-1}$ ($\tau = 5$ s) to $4 \times 10^{16}$ cm$^{-2}$ s$^{-1}$ (a factor of 24 larger) at $\tau = 60$ s. The rate of change of $I_{\mathrm{sx}}$ still increases with $\tau$, but much less dramatically because of the larger event duration. At $\tau = 5$ s, $I_{\mathrm{sx},\mathrm{max}} \approx 2.3 \times 10^{14}$ cm$^{-2}$ s$^{-1}$, increasing to $7.2 \times 10^{14}$ cm$^{-2}$ s$^{-1}$ (only a factor of 3 larger) for the $\tau = 60$ s case. Consequently the peak value of the logarithmic derivative $I_{\mathrm{sx}}/I_{\mathrm{x}}$, decreases with $\tau$. The contribution to $I_{\mathrm{sx}}/I_{\mathrm{x}}$ due to evaporation is relatively constant $2\langle \dot{h}/n \rangle = 0.04$ s$^{-1}$ after the onset of evaporation, which occurs at $t > 15$ s in all cases. In fact, the onset time is a slowly increasing function of burst duration, due to the more gradual heating associated with larger time-scale bursts. $I_{\mathrm{sx}}$ becomes negative later in the decay phase of simulations, except for the shortest (temperature-dominated) events. This is because, in events in which evaporation plays an important role, the growing coronal overpressure created by the primarily evaporated material eventually suppresses further evaporation. After this, the reduced $2\langle \dot{h}/n \rangle$ contribution cannot offset the decrease in $I_{\mathrm{sx}}$ due to cooling, and $I_{\mathrm{sx}}$ becomes negative. Clearly some form of additional energy input is necessary to prevent this cooling and to maintain the observed derivative relationship throughout the decay phase of the event.

We note that the evaporation term $2\langle \dot{h}/n \rangle$ is only significant later in the events; in fact, in no case does $I_{\mathrm{sx}}/I_{\mathrm{x}}$ increase at a time when evaporation is significant (the $2\langle \dot{h}/n \rangle$ term only slows the decrease from the cooling $\dot{T} / T$ term). This is a consequence of the high coronal overpressure $P_{\mathrm{o}}$ in these models, introduced deliberately to suppress evaporation and yield predominantly stationary principal components of the Ca xix line during the impulsive phase (Emslie et al. 1992). For lower values of $P_{\mathrm{o}}$ (e.g., Mariska, Emslie, & Li 1989) we would expect the $2\langle \dot{h}/n \rangle$ term to become significant earlier in the event and to play a greater role in the behavior of $I_{\mathrm{sx}}/I_{\mathrm{x}}$, particularly during the rise phase. (Of course, such a behavior would not be consistent with the vast majority of soft X-ray line profiles observed.)

4. SUMMARY AND DISCUSSION

We have calculated the soft X-ray (1–8 Å) time profile, its time derivative, and the hard X-ray (30–500 keV) time profile,
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in both thermal and nonthermal models of hard X-ray production in solar flares. In a simple conductively heated thermal model, no simple correspondence is found among the hard X-ray profile, the derivative of the soft X-ray profile, and the energy input itself. Moreover, the model manifestly fails to account for the observed simultaneity in the hard X-ray emission peaks at various energies above 30 keV. Although in our thermal modeling we have neglected the nonthermal component produced by escaping very high energy electrons, it is not expected that the inclusion of this component will significantly affect our conclusions. This component is still a complicated function of atmospheric structure, does not contain electrons with energies < 3.5kT (Brown et al. 1979), and does not relate to the energy input (S) in a simple way (see, e.g., Emslie & Vlahos 1980). Hence, it is not likely that this component could match the soft X-ray time derivative either. In short, it appears that such a thermal model cannot reproduce the observed temporal correlations among these quantities. The general failure of the thermal model in predicting these major impulsive flare radiative signatures leads us to conclude that the impulsive energization is not likely to be thermal in origin.

In all the thick-target nonthermal models studied, the hard X-ray emission is dominated by direct (beam-target) bremsstrahlung emission, with the thermal emission produced in the hot plasma created by the beam heating being in fact negligible at these energies (Li & Emslie 1990). Thus the hard X-ray flux at all energies is more proportional to the nonthermal electron energy input. The soft X-ray time derivative is found to be roughly proportional to the hard X-ray time profile during the rise phase. During the decay phase, however, of larger (∼15 s) events, the similarity between the soft X-ray time derivative and the hard X-ray time profile breaks down, with the soft X-ray emission decreasing once the evaporation-driven density enhancements cannot overcome the cooling of the hot plasma. As the energy deposition become more gradual, the ratio of soft X-ray flux I_{\alpha} to hard X-ray flux I_{\beta} generally increases. The time derivative I_{\alpha}' also increases, but by a much smaller factor. Generally the straightforward derivative I_{\alpha}'/I_{\alpha} peaks after the peak in the hard X-ray flux, whereas the logarithmic derivative I_{\alpha}'/I_{\alpha} peaks before the hard X-ray peak. Because of the simple physical relationship of this logarithmic derivative to the physical processes taking place (eq. [3]), we encourage observers to consider this quantity instead of, or in addition to, the straightforward derivative in future work.

It is interesting to consider whether or not the localized density and temperature enhancement at the top of the loop, that leads to the second “bump” in I_{\alpha} in the τ ≈ 30 s case, is real. On one hand, the exact form of the feature in our simulations is strongly dependent on the assumption of strict symmetry between the two halves of the loop—the upward momentum of the two evaporating masses exactly cancels, giving a dense concentration, while the kinetic energy is 100% transformed into thermal energy. Many criticisms can be made of this feature of the modeling. For example, an asymmetry in the loop geometry, or in the injected electron flux or spectrum, would diminish the apex-localized enhancement. Indeed, it is possible (and perhaps even probable) that electron acceleration into different halves of the loop occurs on distinct sets of field lines, so that the evaporating fronts pass right over the apex without ever colliding. In view of these uncertainties at this time we view the “corrected” data, which conform better to the “derivativeness” principle, as being perhaps more representative of the true physical situation.

In summary, it appears that a thick-target electron-heated model not only reproduces the synchronism of hard X-ray emissions of different energies (as observed), but also adequately explains the “derivativeness” relationship between the soft X-ray and hard X-ray fluxes, particularly during the rise phase. During the decay phase, the saturation of the evaporation process (at least in loops with an initially high pressure) means that the slowly rising density (and hence emission measure) cannot overcome the rapid cooling due to thermal conduction. Consequently, some additional form of energy input is necessary to maintain a positive I_{\alpha} during this phase, as is observed. Other authors (e.g., Moore et al. 1980) have previously stressed the need for such an additional energy input (such as gentle, nonexplosive, magnetic reconnection), and our results here serve to reinforce this conclusion.

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