THE NEUPERT EFFECT
AND THE ELECTRON-BEAM-DRIVEN EVAPORATION MODEL

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ABSTRACT

Based on a sample of \(\sim 1100\) solar flares observed simultaneously in hard and soft X-rays, we performed a statistical analysis of the Neupert effect. For a subset of \(\sim 500\) events, supplementary H\(\alpha\) flare data were considered. The timing behavior of \(>50\%\) of the events is consistent with the Neupert effect. A high correlation between the soft X-ray peak flux and the hard X-ray fluence is obtained, being indicative of electron-beam-driven evaporation. However, about one fourth of the events (predominantly weak flares) reveal strong deviations from the predicted timing, with a prolonged increase of the thermal emission beyond the end of the hard X-rays. These findings suggest that electron-beam-driven evaporation plays an important role in solar flares. Yet, in a significant fraction of events there is also evidence for an additional energy transport mechanism from the energy release site other than electron beams, presumably thermal conduction.

As a consequence of the rapid energy deposition, a strong pressure gradient develops between the top of the chromosphere and the bottom of the corona. The heated plasma explosively expands into the corona in a process termed “chromospheric evaporation” (Antonucci et al. 1984, Fisher et al. 1985, see also the recent study by Cauzzi et al. 2002), and gives rise to enhanced SXR emission via thermal bremsstrahlung.

In this scenario, the hard X-ray flux is linked to the instantaneous rate of energy supplied by electron beams, whereas the soft X-ray flux is related to the accumulated energy deposited by the same electrons up to that time. Thus, we can expect to see the Neupert effect:

\[
F_{\text{P, SXR}} = k \cdot F_{\text{HXR}},
\]

with \(F_{\text{P, SXR}}\) the SXR peak flux and \(F_{\text{HXR}}\) the HXR fluence, i.e. the HXR flux integrated over the event duration. The coefficient \(k\) depends on various factors (e.g., magnetic field geometry, viewing angle), and thus may vary from flare to flare (Lee et al. 1995). However, if \(k\) does not depend systematically on the flare intensity, then the relationship between the SXR peak flux and the HXR fluence is linear. Deviations from the Neupert effect suggest that the hot SXR emitting plasma is not heated exclusively by thermalization of the accelerated electrons responsible for the HXR emission. Therefore, investigations of the Neupert effect provide insight into the role of nonthermal electrons for the flare energetics.

Various aspects of the Neupert effect have been investigated in previous studies: correlations between SXR and HXR light curves, relation between thermal and nonthermal energies, comparison of spatially resolved X-ray emissions, relation to hard X-ray spectra, temperature dependence of the Neupert effect, etc. (see, e.g., Dennis & Zarro 1993, Hudson et al. 1994, Färnike et al. 1997, McTiernan et al. 1999, Tomczak 1999). On the basis of flare frequency distributions, Lee et al. (1995) and Veronig et al. (2002a) inferred inconsistencies with the linearly formulated
Neupert effect expressed in Eq. (1). A possible explanation for this finding is that the HXR and SXR emissions are not directly indicative of the nonthermal and thermal energies involved, in the sense that the energies are not simply linearly related to the emissions. Another possibility is that the Neupert effect interpreted in the frame of the electron-beam-driven chromospheric evaporation model does not hold for the majority of flares. Most observational evidence of the Neupert effect is provided for large flares (see Dennis & Zarro 1993, McTiernan et al. 1999). In the present paper, we study the Neupert effect and its relevance for the flare energetics on a statistical basis, considering a large sample of solar flares that covers large as well as small events.

2. DATA SELECTION

We utilize the SXR data from the Geostationary Operational Environmental Satellites (GOES) and the HXR data from the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma Ray Observatory. The X-ray sensor aboard GOES consists of two ion chamber detectors, which provide whole-sun X-ray fluxes in the 0.5–4 and 1–8 Å wavelength bands. BATSE is a whole-sky HXR flux monitor that, in part, consists of eight large-area detectors. From each detector there are hard X-ray measurements in four energy channels, 25–50, 50–100, 100–300 and >300 keV (e.g., Schwartz et al. 1992).

We use the 1-min averaged 1–8 Å GOES data, and the HXR data collected in the BATSE Solar Flare Catalog, archived in the Solar Data Analysis Center at NASA/Goddard Space Flight Center for the period 01/1997–06/2000. The peak and total count rates are background subtracted for the flux below 100 keV. For the SXR events, we used the flux just before the flare start for background subtraction. To be identified as corresponding events we demand that the start time difference between a SXR and a HXR event does not exceed 10 min. Overlapping events are excluded. Applying these criteria, we obtained 1114 events that were observed in both hard and soft X-rays. Supplementary, we use Hα flare data compiled in the Solar Geophysical Data. For the considered period, we identified 503 Hα flares that started within the same 10-min window as the corresponding HXR and SXR events (for details see Veronig et al. 2002b,c).

3. RESULTS

3.1. Timing analysis

Figure 1 shows the histogram of the difference of the peak time of the SXR emission and the end time of the HXR emission, which are expected to occur simultaneously. We derived the time differences in absolute values, \( \Delta t \), as well as normalized by the HXR event duration, \( D \), i.e. \( \Delta t_{\text{norm}} = \Delta t / D \). Both distributions of the SXR–HXR time differences have their mode at zero. 49% of the events lie within the range \( |\Delta t| \leq 1 \) min, and 65% within \( |\Delta t| \leq 2 \) min. For the normalized time differences, we obtain that 44% lie within \( |\Delta t_{\text{norm}}| \leq 0.5 \) HXR units, and 59% within \( |\Delta t_{\text{norm}}| \leq 1 \) HXR unit. This outcome suggests that certainly a considerable part of the events coincides well with the expectations from the Neupert effect regarding the relative timing.

24% of the events have \( \Delta t < 0 \), i.e. the SXR maximum occurs before the HXR end. These events are preferentially of long duration (see the sharp decline of the normalized time differences for negative values in Figure 1). 56% of the events have \( \Delta t > 0 \). In principle, the fact that the SXR emission is still increasing although the HXR emission, i.e. the electron input, has already stopped indicates that an additional agent besides the HXR emitting electrons contributes to the energy input and prolongs the heating and/or evaporation. However, McTiernan et al. (1999) have shown that the SXR time profile depends on the temperature response of the used detector, and the low-temperature SXR emission may increase beyond the end of the hard X-rays due to cooling of high-temperature plasma. Thus, we cannot attribute all events with \( \Delta t > 0 \) as inconsistent with the electron-beam-driven chromospheric.
evaporation model, but only those with strong deviations from it.

The Hα emission during the main phase of a flare is also related to the evaporation process, and a similar coincidence in the timing of the Hα maximum – HXR end is expected than for the SXR maximum – HXR end. However, the Hα emission is not affected by the above argument of McTiernan et al. (1999). In Figure 2, we plot the distribution of the Hα – HXR time differences. 51% of the events lie within $|\Delta t| \leq 1$ min, and 65% within $|\Delta t| \leq 2$ min. For the normalized time differences, we obtain that 42% lie within $|\Delta t_{\text{norm}}| \leq 0.5$ HXR units, and 65% within $|\Delta t_{\text{norm}}| \leq 1$ HXR unit. This outcome is similar to the SXR–HXR timing, but the partitioning among events with positive and negative time differences is quite different: 40% belong to $\Delta t < 0$, and 36% to $\Delta t > 0$. This may indicate that indeed a part of the events with increasing SXR emission beyond the hard X-rays is due to cooling of high-temperature plasma that is seen in the GOES 1–8 A detector.

We have applied the following criterion to identify events with strong deviations from the expected timing: ($|\Delta t| > 2$ min AND $|\Delta t_{\text{norm}}| > 1.0$ unit). 24% fulfill this criterion considering the SXR–HXR timing, and 21% with regard to the Hα–HXR timing. These events are predominantly characterized by $\Delta t > 0$, indicative of increasing thermal emission beyond the end of the nonthermal emission.

Figure 3 shows the scatter plot of the SXR peak flux ($F_{\text{p, SXR}}$) versus the HXR fluence ($F_{\text{HXR}}$), clearly revealing an increase of $F_{\text{p, SXR}}$ with increasing $F_{\text{HXR}}$. However, the slope is not constant over the whole range but it is larger for large HXR fluences than for small ones. For very large fluences, the slope approaches the value of 1, indicative of a linear relation between the SXR peak flux and HXR fluence (see the line of constant $k$). We stress that the slope at small fluences might be affected by missing events with small SXR peak fluxes (due to selection effects), and thus appear flatter than it is in fact. A distinct interdependence exists between the importance of an event and the sign of the SXR–HXR time difference (see Figure 4). Basically all large flares have $\Delta t < 0$, i.e. the SXR peak occurs before the HXR end, whereas events with $\Delta t > 0$ are preferentially weak events. Moreover, flares with $\Delta t < 0$ reveal a strong tendency to be of long duration.

We obtain a high cross-correlation coefficient for the SXR peak flux and HXR fluence relationship, $r = 0.71$. This coefficient is higher than those for the SXR peak flux and HXR peak flux, $r = 0.57$. This indicates that the correlation is primarily due to the HXR fluence – SXR peak flux relationship, as predicted from the Neupert effect, and not, e.g., due to the fact that flares with large HXR peak fluxes also tend to have intense SXR counterparts. Furthermore, it is important to note that the HXR fluence – SXR peak flux correlation is higher for the events with negative time differences, $r = 0.82$, than for the events with positive time differences, $r = 0.54$.

Li et al. (1993) have calculated time profiles of soft and hard X-ray emission from a thick-target electron-heated model, finding that, in general, the time derivative of the SXR emission coincides with the time profile of the HXR emission, as stated by the
Neupert effect. However, for gradual events (long HXR duration) they obtained that this relationship breaks down during the decay phase, in that the SXR maximum occurs before the end of the HXR emission. This outcome is due to the fact that the SXR emission starts to decrease if the evaporation-driven energy supply cannot overcome the instantaneous cooling of the hot plasma, which is likely to happen in gradual flares (Li et al. 1993). These results from simulations together with our findings that events with Δt < 0 are predominantly of long duration and reveal a high correlation between $F_{P, SXR}$ and $F_{HXR}$ ($r \approx 0.8$), suggest that most of the events with Δt < 0 are consistent with the electron-beam-driven evaporation model. We infer that, on average, the cooling dominates over the evaporation-driven energy supply for ~0.4 times the HXR duration.

4. CONCLUSIONS

For a considerable fraction of events (>50%), the relative timing of the nonthermal and thermal flare emission coincides well with the predictions from the Neupert effect, which lends support to the importance of nonthermal electrons for the flare energetics. However, about 20–25% of the events show strong deviations from the expected timing. These flares are characterized by increasing thermal emission beyond the end of the hard X-rays, and are preferentially weak events. For these flares, an additional energy transport mechanism from the energy release site other than electron beams is suggested, prolonging the heating and/or evaporation (see also Veronig et al. 2002b,c). Since the energy release site is strongly heated, a promising candidate is thermal conduction, which is supported by various observations as well as simulations (e.g., Czyzakowska et al. 2001, Yokoyama & Shibata 2001, and references therein).

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