THE NEUPTERT EFFECT

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Abstract. The Neupert effect describes the empirical result that for many solar flares the soft X-ray time derivative resembles the hard X-ray time profile. The Neupert effect suggests a causal relation between nonthermal and thermal flare emissions, and can be explained by a model in which the flare energy goes primarily into accelerated electrons and the electrons are the heating agent for the soft X-ray emitting plasma. We discuss recent efforts in trying to quantify the validity of the Neupert effect and to understand its relevance in the frame of the flare energetics.

Key words: Sun – flares – X-rays – chromospheric evaporation – electron beams

1. Introduction

In the standard flare scenario, electrons and ions are accelerated in the solar corona as a consequence of magnetic reconnection. According to the thick-target model, the flare energy goes primarily into the acceleration of nonthermal electrons (Brown, 1971). The kinetic energy of the electrons is transferred to the lower corona and chromosphere, where electron-ion collisions cause hard X-ray (HXR) emission due to nonthermal bremsstrahlung. In the frame of this model only a small fraction of the energy is lost by radiation. The bulk energy goes into plasma heating via Coulomb collisions between the beam and the ambient electrons, producing an overpressure in the chromosphere as the plasma is heated beyond its ability to radiate away the deposited energy. As a consequence, the preflare hydrostatic equilibrium gets lost and the heated plasma explosively expands up into the coronal loops in a process termed “chromospheric evaporation” (see Hudson, 1972; Brown, 1973; Antonucci et al., 1984; Fisher et al., 1985). The hot
dense plasma which was convected into the corona gives rise to enhanced soft X-ray (SXR) emission in the form of thermal bremsstrahlung.

Under these model assumptions, the hard X-ray emission \( F_{\text{HXR}}(t) \) is related to the instantaneous number of electrons and therefore to the power \( dE/dt \) injected into the system, while the soft X-ray emission \( F_{\text{SXR}}(t) \) is linked to the accumulated energy \( E \) deposited by the same nonthermal electrons up to that time, therefore:

\[
F_{\text{HXR}}(t) \propto \frac{d}{dt} F_{\text{SXR}}(t).
\]  

(1)

Neupert (1968) first proposed the hypothesis that the SXR emission might be related to the energy lost by nonthermal electrons up to that time. The relation expressed in Eq. (1), i.e. that the time derivative of the SXR light curve in the rise phase resembles the hard X-ray light curve, was observed in many flares (Dennis and Zarro, 1993; McTiernan et al., 1999), and was named “Neupert effect” by Hudson (1991). Figure 1 shows an example of the Neupert effect, by comparing the hard X-ray emission observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the derivative of the soft X-ray emission recorded by GOES.

2. The Neupert effect and the link to the flare energetics

The Neupert effect suggests that there is a causal relation between the nonthermal (hard X-ray or microwave) and the thermal (soft X-ray) flare emission. From the above argumentation it follows that, if the Neupert effect is observed, it can be considered as evidence of electron-beam-driven chromospheric evaporation. In recent years, the Neupert effect has been observed also in stellar flares, which suggests the existence of the chromospheric evaporation process also in stellar activity (Hawley et al., 1995; Güdel et al., 1996, 2002).

Dennis and Zarro (1993) pointed out that the Neupert effect must exist virtually for any flare model if the hard X-rays are electron-ion bremsstrahlung and the plasma cooling time is long compared to the characteristic duration of the hard X-ray burst. In principle any deviation from the Neupert effect suggests that the hot SXR emitting plasma is not heated exclusively by thermalization of the accelerated electrons responsible for the HXR emission. Thus, by investigating the Neupert effect it should be possible to determine what fraction of the plasma heating results from the accelerated
electrons and what fraction comes from any other heating agent, as, e.g., direct plasma heating in the energy release process itself (see Dennis et al., 2003).

Comparing SXR and HXR flare frequency distributions, Lee et al. (1995) inferred inconsistencies with the Neupert effect. When a linear relation between the SXR peak flux and the HXR fluence, i.e. the HXR flux integrated over the burst duration, is assumed (which is equivalent to Eq. (1)), it is expected that the SXR peak flux distribution is described by the same slope $\alpha$ as the HXR fluence distribution. However, the slope derived from HXR fluence distributions is found in the range $1.4 \lesssim \alpha \lesssim 1.6$, while that of SXR peak fluxes is in the range $1.8 \lesssim \alpha \lesssim 2.0$ (cf. Lee et al., 1995; Veronig et al., 2002a).

There are two basic possibilities to interpret this discrepancy. One is

that in the bulk of solar flares the Neupert effect is not valid but another
form of plasma heating in addition to electron beams is acting. The other
possibility is that HXR and SXR emissions are not directly indicative of
the energies involved, in the sense that the energies are not simply linearly
related to the emission (see Veronig et al., 2002b). Lee et al. (1995) empha-
sized that the Neupert effect interpreted as a consequence of electron-beam
heating should not exist necessarily between the X-ray emissions but be-
tween the related energies. The energy deposited by accelerated electrons
should equal the maximum thermal energy contained in the plasma that is
heated by those electrons, i.e.

\[ E_{\text{e}} = E_{\text{th, max}}. \]  \hspace{1cm} (2)

Several attempts have been made to investigate the relation between
energies associated with HXR and SXR bursts by estimating the total en-
ergy contained in accelerated electrons from measured HXR spectra and
the thermal energy of the heated plasma from SXR observations (e.g., An-
tonucci et al., 1984; Wu et al., 1986; Starr et al., 1988). However, neither
the thermal nor the nonthermal energy can be estimated to better than
an order of magnitude. The uncertainties of the nonthermal energy cal-
culations arise from the fact that the low energy cut-off in the electron
spectrum is unknown and may vary from flare to flare. The thermal energy
calculations are uncertain mostly due to the estimates of the volume, filling
factor and density of the emitting plasma (see Wu et al., 1986; Dennis et
al., 2003). In the following we address the Neupert effect, i.e. compare the
directly observable X-ray emissions to study the energetic importance of
accelerated electrons. If nonthermal electrons carry the major fraction of
the total flare energy, the Neupert effect should be observed.

3. Statistical approach to the Neupert effect

We compare SXR data from GOES with HXR data from the Burst and
Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray
Observatory for the period January 1997 to June 2000. For the analysis,
the 1-min averaged 1–8 Å GOES data and the 25–100 keV data compiled
in the BATSE Solar Flare Catalogue archived in the Solar Data Analysis
Center at NASA/GSFC are used. The peak and the total count rates of the
HXR bursts are background subtracted for the flux below 100 keV. For the
SXR bursts, the flux just before the flare start is applied for background subtraction. For identifying corresponding events, we basically demand that the SXR and HXR burst start within a 10-min time window. Applying this criterion, 1114 corresponding SXR–HXR bursts are selected for which all the relevant parameters are available (for details see Veronig et al., 2002b).

One aspect of the analysis is the relative timing of related SXR and HXR events. The interpretation of the Neupert effect in the frame of the electron-beam-driven evaporation model implies that the maximum in soft X-rays should be contemporaneous with the end of the HXR burst: when the electron input stops, also the HXR emission must stop, and the SXR emission does not increase further. The other aspect is to analyse the HXR fluence – SXR peak flux relation. A simple prediction of the Neupert effect is that there should be a high correlation among these two parameters (cf. Eq. (1)).

Figure 2 shows the histogram of the difference of the peak time of the SXR emission and the end time of the HXR emission. The time differences are represented in absolute values $\Delta t$ (left panel), as well as normalized by the HXR event duration $D$, $\Delta t_{\text{norm}} = \Delta t / D$ (right panel). Both distributions of the SXR–HXR time differences have their mode at zero. Almost half events (49%) lie within the range $|\Delta t| \leq 1$ min. This outcome suggests

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that certainly a considerable part of the events is in good agreement with the expectations from the Neupert effect regarding the SXR–HXR timing. Based on the relative timing, two subsets of events are extracted. Events of set 1 are roughly consistent with the timing expectations of the Neupert effect, while events of set 2 are inconsistent with it. The two sets are defined by the following criteria:

\[
\text{Set 1: } (|\Delta t| < 1 \text{ min}) \quad \text{OR} \quad (|\Delta t_{\text{norm}}| < 0.5 \text{ unit}), \\
\text{Set 2: } (|\Delta t| > 2 \text{ min}) \quad \text{AND} \quad (|\Delta t_{\text{norm}}| > 1.0 \text{ unit}).
\]

The applied conditions represent a combination of absolute and normalized time differences in order to avoid as much as possible any a priori independence with the flare duration and/or flare intensity. 44% of the events fulfilled the timing criterion of set 1, 24% belong to set 2, and 32% are neither attributed to set 1 nor to set 2.

![Figure 3: Scatter plot of SXR peak flux versus HXR fluence. Regions outside the detection limits are grey shaded. For each event, the sign of the time difference between SXR peak and HXR end is indicated: “+” symbols denote events with positive (i.e. SXR peak delayed), “−” symbols events with negative, “o” symbols events with “zero” (i.e. SXR peak and HXR end take place within 1 min) time difference. The straight line indicates a linear relation between SXR peak flux and HXR fluence.

Figure 3 shows the scatter plot of the SXR peak flux versus HXR fluence, clearly revealing a distinct correlation between both quantities. From the figure it can also be inferred that the slope is not constant over the whole range but that it is larger for large HXR fluences than for small ones. It has to be stressed that the slope at small fluences might be affected by missing
events with small SXR peak fluxes, and thus appear flatter than it actually is (the estimated detection/sensitivity limits are indicated by grey shading). The cross-correlation coefficient between SXR peak flux and HXR fluence gives $r = 0.71$. This coefficient is higher than that for the SXR peak flux – HXR peak flux correlation, $r = 0.57$. This indicates that the correlation is primarily due to the HXR fluence – SXR peak flux relation, as predicted from the Neupert effect and not, e.g., due to the fact that flares with high HXR 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 events with negative, $r = 0.82$, than for those with positive time differences, $r = 0.54$.

Figure 3 also reveals an interdependence between the importance of an event and the relative SXR–HXR timing. Basically all intense flares belong to the group of events with $\Delta t < 0$ (SXR peak before HXR end). On the other hand, this group distinctly covers fewer weak flares than the group of events with $\Delta t > 0$. Figure 4 shows the distributions of HXR peak fluxes (left panel) and HXR duration (right panel) for events with $\Delta t < 0$ together with those of the total sample. It can be seen that these events, in which the SXR emission is already decaying while still hard X-rays are detectable, are mostly intense and long-duration events. Figure 5 shows the same distributions for events of set 2 (indicating violations of the Neupert effect timing), which reveal a predominance of low intensities and short
Figure 5: Histograms of the HXR peak flux (left panel) and the HXR burst duration (right panel). The histograms of the total sample are represented in light grey, those of events belonging to set 2 in dark grey.

4. Discussion and Conclusions

In long-duration events, instantaneous losses (conductive and radiative) during the burst lifetime can no longer be neglected, and deviations from the Neupert effect are to be expected. 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 SXR time derivative coincides with the HXR time profile, as stated by the Neupert effect. However, for gradual events (long HXR duration) they obtained that this coherence breaks down during the decay phase, in that the SXR maximum occurs before the end of the HXR emission: 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 \( \Delta t < 0 \) are predominantly of long duration and show a high correlation between the SXR peak flux and HXR fluence \( (r \approx 0.8) \) suggest that many of the events with \( \Delta t < 0 \) are consistent with the electron-beam-driven evaporation model (see also Veronig et al., 2002b,c).

We conclude that about half of the events can be considered as consistent with the Neupert effect and its interpretation by the electron-heated

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evaporation model, while about 25% (set 2) show strong deviations indicative of an additional agent besides electron beams prolonging the heating/evaporation. These percentages are consistent with those derived by McTiernan et al. (1999) with a different criterion (measuring the instantaneous correlation between the SXR derivative and the HXR flux).

The finding that in about 25% of the events there is increasing thermal emission beyond the end of the HXR emission might be evidence for a prolongation of chromospheric evaporation by thermal conduction (– however, see also the finding by McTiernan et al., 1999, that consistency with the Neupert effect depends on the temperature sensitivity of the SXR detectors used). As the energy release site is strongly heated, thermal conduction is a feasible candidate for energy transport in flares (see Vršnak, 1989; Somov, 1992). Various observations lend support for prolonged evaporation beyond the impulsive flare phase caused by thermal conduction fronts (e.g., Zarro and Lemen, 1988; Schmieder et al., 1990; Czaykowska et al., 2001). Simulations of chromospheric evaporation driven by thermal conduction have been presented by Yokoyama and Shibata (1998, 2001).

It is worth noting that the statistical study indicates that the Neupert effect cannot be described as a linear relation between SXR and HXR emissions (besides probably for the most intense events, see Figure 3). A deviation from a linear relation between the SXR peak flux and the HXR fluence is to be expected when any of the relevant physical quantities involved in relating the X-ray emissions to the thermal/nonthermal energies (viz. plasma density and temperature; low energy cut-off of the electron spectrum, electron spectral index) depends systematically on the flare intensity (see Lee et al., 1995; Veronig et al., 2002b). In that case, the amount of SXR emission per HXR electron may differ between weak and intense flares (note also the different SXR response relative to the HXR emission for the bursts shown in Figure 1). In further studies, it should be worth to disentangling this effect from differences in the relative SXR/HXR productivity due to violations of the correspondence between the energy in accelerated electrons and the energy in the hot plasma.

Dennis et al. (2003) summarized that in many solar flares the total energy in precipitating electrons is derived to be substantially higher (up to an order of magnitude) than the thermal energy in the heated plasma. This discrepancy becomes even bigger when considering recent results from RHESSI (Lin et al., 2002), which measures hard X-rays and soft X-rays
down to 3 keV with high sensitivity and spectral resolution. RHESSI observations indicate that in many flares the nonthermal spectrum extends down to about 10 keV (e.g., Krucker and Lin, 2002; Saint-Hilaire and Benz, 2002) instead of the previously assumed limit of ≈25 keV (see Dennis et al, 2003). The large amount of energy found in nonthermal electrons possibly indicates that the whole flare energy is channeled through accelerated electrons into other forms, such as plasma heating, mass motions and radiation (Hoyng et al., 1976). Deeper insight into the thermal/nonthermal energy budget in solar flares can be expected from the combination of RHESSI observations with data from the Soft X-ray Imager (SXI) aboard the GOES 12 spacecraft which will become operational within the year 2003.

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References

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Izlaganje sa znanstvenog skupa

Sažetak. Neupertov efekt opisuje empirijski rezultat da u velikom broju bljeskova derivacija po vremenu toka mekog rendgenskog zračenja nalikuje vremenskom profilu tvrdog rendgenskog zračenja. Neupertov efekt upućuje na uzročnu vezu između netermalne i termalne emisije bljeska i može se objasniti modelom u kojem energija bljeska prvo bitno odlazi u ubrzane elektrone koji zatim zagrijavaju plazmu koja emitira meko rendgensko zračenje. Diskutiraju se nove potvrde važenja Neupertovog efekta i razumijevanja njegove relevantnosti u okviru energetike bljeskova.

Ključne riječi: Sunce - bljeskovi - kromosfersko isparavanje - snopovi elektrona