STATISTICAL STUDY OF SOLAR FLARES OBSERVED IN SOFT X-RAY, HARD X-RAY AND Hα EMISSION

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Abstract. Correlations among statistical properties of solar flares observed in soft X-rays, hard X-rays and Hα are studied. We investigate corresponding HXR flares measured by BATSE, SXR flares observed by GOES and Hα flares reported in the SGD for the period 1997–2000. Distinct correlations are found among the SXR peak flux and Hα area, as well as between the SXR peak flux and HXR fluence. This can be comprehended in the frame of the chromospheric evaporation model of flares.

Key words: solar flares - correlations - chromospheric evaporation

1. Introduction

Flares represent an abrupt release of magnetic energy stored in the solar corona. This energy release causes a wealth of phenomena including plasma heating, acceleration of particles, plasma motions, shock waves, and a sudden increase of radiation almost at all wavelengths. In this paper, we investigate correlations among statistical properties of solar flares observed in soft X-rays (SXR), hard X-rays (HXR) and Hα. Such multi-wavelength correlation studies are especially of interest with respect to the problem of energy transport during flares. In
particular we investigate correlations among the SXR peak flux, the Hα area, the HXR peak flux and the HXR fluence, i.e. the flux integrated over the duration of the burst.

In this paper we do not concentrate on correlations among the various properties characterizing flares within a single wavelength. For statistical investigations of Hα flares see Wilson (1987), Yeung and Pearce (1990) and Temmer et al. (2001). Extensive statistical studies of HXR flares have been made by Dennis (1985), Pearce et al. (1993) and Crosby et al. (1998). Recent studies of SXR flare properties can be found in Pearce et al. (2001) and Veronig et al. (2001a).

2. Data Set

We utilize the SXR data from the Geostationary Operational Environment Satellites (GOES), the HXR data observed by the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray Observatory (CGRO) and the Hα flare data collected by the Solar Geophysical Data (SGD).

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. A description of the GOES X-ray sensor can be found in Donelly and Unzicker (1974) and Garcia (1994). BATSE is a whole-sky HXR flux monitor that consists of eight large-area wide-field detectors. From each detector there are hard X-ray data in four energy channels, 25–50, 50–100, 100–300 and >300 keV. For characteristics of the BATSE instrument and its application to solar flare studies see Fishman et al. (1989, 1992) and Schwartz et al. (1992).

For the analysis, the 1-minute averaged GOES SXR data measured in the 1–8 Å channel, the HXR data from the BATSE Solar Flare Catalog archived in the Solar Data Analysis Center at NASA Goddard Space Flight Center, and the Hα flare reports from the SGD for the period 1997–2000 are used. In the BATSE Flare Catalog, the peak and the total count rates reported for the flux below 100 keV are already background subtracted. For the SXR events observed by GOES we apply the flux just before the flare start for background subtraction.

The identification of corresponding HXR – SXR, HXR – Hα and
SXR – Hα events is primarily based on temporal coincidence. Two events are considered to be associated if the difference of starting times between the events observed in different wavelengths does not exceed 10 minutes. For corresponding SXR – Hα events it is additionally required that the reported heliographic coordinates do not differ more than 1° in latitude and longitude. Moreover, events that overlap in time with any other event observed at the same wavelength as well as events for which a multiple assignment to flares observed at other wavelengths is possible are excluded from the analysis. Applying these selection criteria, we obtain 1114 HXR – SXR, 735 HXR – Hα and 1486 SXR – Hα events, for which all the relevant parameters are available.

3. Results

In Figure 1 the correlation scatter plot of the SXR peak flux versus the Hα area measured at the time of maximum Hα intensity is shown.

*Figure 1:* Scatter plot of the SXR peak flux versus the Hα flare area (given in millionths of the solar disk). Only flares within the heliographic longitude range $-20^\circ$ to $+20^\circ$ are considered.
Figure 2: Scatter plot of the HXR peak flux versus the Hα flare area. Only flares within the heliographic longitude range $-20^\circ$ to $+20^\circ$ are considered.

To avoid the uncertainties and problems related to the correction of the Hα area for foreshortening (for an extensive discussion of this issue see Sawyer, 1967), we considered only events near the disk center, i.e. within a heliographic longitude range $-20^\circ$ to $+20^\circ$, amounting to 405 (out of 1486 corresponding SXR–Hα) events. Figure 1 reveals a distinct increase of the SXR peak flux with increasing Hα area, even if the scatter is rather large. For the cross-correlation coefficient, determined in log-log space, we obtain $r = 0.65$. The correlation is considerably better than the one found in a previous study (Veronig et al., 2001b), in which events from the whole disk were considered and no background subtraction was applied to the SXR emission.

In Figure 2 the scatter plot of the HXR peak flux versus the Hα flare area is shown. Again, only events within the heliographic longitude range $-20^\circ$ to $+20^\circ$ are selected, comprising 194 events (out of 735 identified HXR–Hα events). The scatter plot does not reveal a distinct relationship between both parameters. For the cross-correlation coefficient we obtain $r = 0.23$. In Figure 3 the HXR fluence against
Figure 3: Scatter plot of the HXR fluence versus the Hα flare area. Only flares within the heliographic longitude range $-20^\circ$ to $+20^\circ$ are considered.

the Hα flare area is plotted for the same sample of events. The cross-correlation coefficient is $r = 0.34$. Thus, the HXR fluence as well as the HXR peak flux reveal only a very low correlation with the area of the corresponding event observed in Hα.

Figure 4 shows the scatter plot of the SXR peak flux versus the HXR peak flux for the total sample of identified SXR–HXR events. The cross-correlation coefficient is $r = 0.57$. In Figure 5 the SXR peak flux is plotted against the HXR fluence, revealing a very distinct relationship. For the cross-correlation coefficient we obtain $r = 0.71$.

For the correlation between the SXR peak flux and the SXR event duration we obtain $r = 0.40$, for the Hα area and Hα event duration $r = 0.56$, for the HXR peak flux and the HXR event duration $r = 0.53$. Thus, the quantities that characterize the flare maximum at a certain wavelength are correlated with the event duration at this wavelength. We investigated also the relation between these quantities and the event duration at the other wavelengths.

Only for the relation between the SXR peak flux and the Hα duration, and the SXR peak flux and the HXR duration, a significant
Figure 4: Scatter plot of the SXR peak flux versus the HXR peak flux.

correlation was found \( r = 0.50 \) and \( r = 0.66 \), respectively). In all other cases the correlation coefficients were \( r < 0.3 \). Figure 6 shows the scatter plot of the SXR peak flux versus HXR duration.

4. Summary and Discussion

A distinct correlation between the SXR peak flux and the H\( \alpha \) area is found, \( r \approx 0.7 \). In particular, as it can be seen in Figure 1, there are practically no flares with small H\( \alpha \) areas and large SXR peak fluxes, and vice versa. From the linear least squares fit to the data in log-log space, minimizing the orthogonal distance of the points from the fitted line, we obtain a slope \( \approx 1.4 \). This value, which is close to the value 3/2, suggests that the measured H\( \alpha \) area can be considered as an intersection of the volume of evaporated plasma responsible for the enhanced SXR emission at the chromospheric level. Moreover, it has to be noted that the scatter in the figure is quite large. Ruždjak et al. (1989) have shown that spotless flares (indicative for small magnetic fields) reveal distinctly lower SXR emission at a given H\( \alpha \) flare importance than spot group flares. However, for both types of flares the SXR peak flux
Figure 5: Scatter plot of the SXR peak flux versus the HXR fluence.

increases with increasing Hα importance. These findings suggest that the scatter of the SXR peak flux versus Hα area may be related to different magnetic field strengths involved in different flares.

Only a very weak correlation is found between the Hα flare area and the HXR peak flux as well as the HXR fluence, $r \approx 0.3$ (cf. Figures 2 and 3). According to the so-called thick-target model (Brown, 1971), the HXR emission is due to electron-ion bremsstrahlung produced by electron beams encountering the dense layers of the transition region and chromosphere. Only a small fraction of the energy of the nonthermal electrons is lost through radiation; most of the energy is transferred into heating of the ambient plasma. Due to the rapid energy deposition a strong pressure imbalance develops and the heated plasma explosively expands upwards into the corona, in a process known as chromospheric evaporation (e.g., Antonucci et al., 1984; Fisher et al., 1985), where this hot dense plasma gives rise to the enhanced SXR emission via thermal bremsstrahlung. The Hα flare area at the main phase is linked to the SXR emission by the intersection of the volume of evaporated plasma at chromospheric levels. The HXR emission is related to the kernels, where the accelerated electrons mov-
Figure 6: Scatter plot of the SXR peak flux versus the HXR event duration.

...ing along the magnetic field lines encounter the chromosphere. This may explain the weak correlation between Hα area and HXR emission in contrast to the high correlation between Hα area and SXR emission.

Very distinct correlations among the SXR peak flux and the various parameters characterizing the HXR emission are found (see Figures 4–6). The highest correlation is obtained for the SXR peak flux and the HXR fluence, $r \approx 0.7$. Since the fluence can be approximated by the product of peak flux and duration, this indicates that the correlations among SXR peak flux – HXR peak flux and SXR peak flux – HXR duration are secondary phenomena with respect to the SXR peak flux – HXR fluence relationship. Indeed, a high correlation between the HXR fluence and the SXR peak flux is expected in the frame of the chromospheric evaporation model, in which the hard X-ray emission is related to the time profile of the accelerated electrons and the soft X-ray emission is linked to the energy deposited by the same electrons up to a given time. Further studies of the HXR–SXR relationship during flares and its implication to the chromospheric evaporation model can be found in Dennis and Zarro (1993) and Veronig et al., (2001c).
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References

STATISTIČKA ANALIZA SVOJSTAVA SUNČEVIH BLJESKOVA U MEKOM I TVRDOM X-ZRAČENJU TE Hα EMISIJI

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Sažetak. Statistički se istražuju korelacije među svojstvima Sunčevih bljeskova u mekom (SXR) i tvrdom (HXR) X-zračenju te Hα emisiji. U analizi se koriste HXR mjerenja instrumentom BATSE, SXR mjerenja sa satelita GOES, te podaci o Hα bljekovima objavljenim u SGD, u periodu 1997-2000. Ustanovljena je jaka povezanost vršne vrijednosti toka SXR zračenja i površine Hα bljeska te ukupnog protoka HXR zračenja. Rezultati su objašnjeni u okvirima modela kromosferske evaporacije.

Ključne riječi: Sunčevi bljeskovi - korelacije - kromosfersko isparavanje