TEMPORAL CHARACTERISTICS OF SOLAR SOFT X-RAY AND Hα FLARES

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ABSTRACT

Temporal aspects of solar soft X-ray and Hα flares for the period 1997–2000 are investigated. For the considered time span about 8 400 SXR and 11 400 Hα flares are reported in the SGD. Related flares observed in Hα as well as in SXR are identified amounting to about 2 100 events. Correlations among corresponding SXR and Hα events are analyzed and their relative timing is investigated. From the timing analysis we infer that for most of the events (84%) the start of the Hα emission is delayed with respect to the SXR emission. On average, the Hα flare starts 3 minutes after the SXR flare. The peaks occur preferentially simultaneously with a slight tendency that the Hα peak precedes the SXR peak.

Key words: Sun – flares; Sun – X-rays; Sun – Hα; Methods – statistical.

1. INTRODUCTION

Solar flares are energetic eruptions on the Sun caused by the release of magnetic energy in the solar atmosphere. They are associated with a rapid increase of emission and a longer decay phase, whereas the detailed temporal behavior is dependent on the specific wavelength in which the event is observed. The temporal behavior of flares observed in different wavelengths is in particular of interest with respect to the question how the released energy is transported through the solar atmosphere before escaping in form of radiant energy that is observed.

In the frame of the thick-target model (Brown 1971), the HXR flare emission is electron-ion bremsstrahlung produced by accelerated electrons encountering the much denser plasma of the lower corona or chromosphere. Due to the rapid deposition of energy by the electron beams, which cannot be radiated away at a sufficiently high rate, a strong pressure imbalance develops and the heated plasma expands up into the corona by a process called chromospheric evaporation (e.g., Antonucci et al. 1984; Fisher et al. 1985). The relative dense and hot plasma convected upwards into the loop gives rise to the SXR emission. The Hα emission in this picture is due to heating of the chromospheric plasma via conduction of the SXR emitting plasma in the flare loop (see, e.g., Dennis & Schwartz 1989; Phillips 1991; and references therein). However, the Hα emission, in particular the emission of the Hα flare kernels, may also be directly excited by the fast electron beams impinging on the chromosphere (see, e.g., Canfield et al. 1989).

In the present analysis, statistics of the duration, rise and decay times with respect to the different soft X-ray (SXR) and Hα flare classes is derived. Moreover, corresponding events observed in SXR and Hα are identified and correlations among distinct flare parameters are investigated. Special emphasis is placed on the relative timing of corresponding events measured in SXR and Hα.

A few papers investigate the timing of SXR and Hα flares, whereas the outcomes of the different studies are rather contradicting. The obtained differences may be related to different criteria that define the onset and maximum time of an event. Moreover, apart from the studies of Thomas & Tsike (1971) and Datlowe et al. (1974), covering ≥ 200 events, rather small data sets have been used for the analysis, which may induce large statistical errors. Thus, in the present analysis we re-examine the question of the timing of SXR and Hα flares on the basis of an extensive (≈ 2 100 events) and homogeneous data set, as for the Solar Geophysical Data (SGD) flare reports a constant and well-defined methodology to derive start and maximum times is in use.

2. DATA

In the present analysis we make use of GOES SXR flare observations in the 0.1–0.8 nm band and Hα
Table 1. Median values with 95% confidence interval for the different SXR flare classes (B, C, M, X) and the total number of flares (T). (Note that due to the nonlinear characteristics of the median the sum of rise and decay time may not exactly render the duration.)

<table>
<thead>
<tr>
<th>SXR class</th>
<th>Duration (min)</th>
<th>Rise time (min)</th>
<th>Decay time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>10.0 ± 0.3</td>
<td>5.0 ± 0.1</td>
<td>5.0 ± 0.2</td>
</tr>
<tr>
<td>C</td>
<td>13.0 ± 0.3</td>
<td>6.0 ± 0.1</td>
<td>6.0 ± 0.1</td>
</tr>
<tr>
<td>M</td>
<td>20.0 ± 1.3</td>
<td>10.0 ± 0.8</td>
<td>9.0 ± 0.9</td>
</tr>
<tr>
<td>X</td>
<td>22.0 ± 3.8</td>
<td>12.0 ± 2.6</td>
<td>9.0 ± 1.8</td>
</tr>
<tr>
<td>T</td>
<td>12.0 ± 0.2</td>
<td>6.0 ± 0.1</td>
<td>6.0 ± 0.1</td>
</tr>
</tbody>
</table>

Table 2. Median values with 95% confidence interval for the different Hα flare classes (S, 1, >1) and the total number of flares (T).

<table>
<thead>
<tr>
<th>SXR class</th>
<th>Duration (min)</th>
<th>Rise time (min)</th>
<th>Decay time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>10.0 ± 0.2</td>
<td>2.0 ± 0.1</td>
<td>7.5 ± 0.1</td>
</tr>
<tr>
<td>1</td>
<td>29.5 ± 1.9</td>
<td>5.0 ± 0.4</td>
<td>23.0 ± 1.5</td>
</tr>
<tr>
<td>&gt;1</td>
<td>58.5 ± 8.1</td>
<td>9.0 ± 2.0</td>
<td>46.0 ± 7.1</td>
</tr>
<tr>
<td>T</td>
<td>11.0 ± 0.2</td>
<td>2.0 ± 0.1</td>
<td>8.0 ± 0.2</td>
</tr>
</tbody>
</table>

3. RESULTS

3.1. Statistics of duration, rise and decay times

In Table 1 and 2 we list the duration, rise and decay times for SXR and Hα flares, respectively. The quantities are derived from the total number of flares as well as separately from the different flare classes. For the Hα flares, importance classes 2, 3 and 4 have been merged into one group, denoted as >1, due to the rareness of these events. As statistical measure we use the median, which in general is a better representation of asymmetric data distributions than the arithmetic mean.

Tables 1 and 2 reveal that the characteristic times increase with the flare class, i.e. the peak flux (SXR) and the flare area (Hα), respectively. In a recent paper, Veronig et al. (2001) studied correlations among SXR flare parameters, reporting that the peak flux of an event and its duration, rise and decay time are weakly correlated.

Comparing the present study with the results obtained by Temmer et al. (2001), who analyzed an extensive data set of Hα flares occurring from 1975 to 1999, we note that in the present study distinctly shorter duration, rise and decay times for subflares are found. For flares of importance 1 and >1 the obtained values are basically the same, i.e. the differences lie within the confidence limits. This phenomenon can be explained by the fact that the time
gives $r = 0.46$, indicating a weak correlation between the duration of corresponding SXR and Hα flares.

The bottom panel of Figure 1 shows the scatter plot of the SXR peak flux versus the apparent Hα flare area, given in millionths of the solar disk. Since not only the Hα flare area but also the measured flux of the corresponding SXR event is affected by the flare position on the solar disk, no correction for foreshortening was applied to the flare areas. From the cross-correlation analysis we obtain $r = 0.56$, indicating that the SXR flare class (defined by the peak flux) and the Hα flare importance (defined by the flare area) are correlated. However, as the large scatter in the figure shows, the relation is far from being one-to-one.

3.3. Relative timing of SXR and Hα flares

In several papers the relative timing of SXR and Hα flares is investigated, whereas the different studies revealed rather contradicting results. Thomas & Teske (1971) figured out that the SXR flare starts before the corresponding Hα event, on average about 2 minutes, and peaks about 3 minutes later, whereas Falconi et al. (1977) and Zirin et al. (1981) report that the SXR flares start about 2 minutes later than the Hα flares. Similarly is the finding of Datlowe et al. (1974) that the Hα onset on average precedes the SXR flare by 1 minute. Verma & Pande (1985) report that the SXR flare starts simultaneously with the Hα flare or up to 2 minutes earlier; the peak of the SXR emission occurs preferentially in the range 2 minutes before and 3 minutes after the Hα flare. The conflicting outcomes obtained by different authors may be related to different criteria that define the onset and maximum time of an event as well as to the rather poor event statistics.

In the present paper, we derived the differences of the start and peak time of 2100 corresponding SXR and Hα events, defined as $\Delta t = t_{SXR} - t_{Hα}$, i.e. negative values indicate that the Hα flare is delayed with respect to the SXR flare, for positive values it is vice versa. The top panel of Figure 2 shows the histogram of the time difference of the flare onset in SXR and Hα. In the bottom panel the histogram of the difference of the SXR and Hα peak times is plotted.

3.2. Correlations among SXR and Hα flare parameters

The top panel of Figure 1 shows the scatter plot of the SXR flare duration versus the Hα flare duration. The solid line indicates the linear regression fit in logarithmic space. The cross-correlation coefficient

\[ \Delta t < 0, \text{ i.e. the Hα flare is delayed with respect to the SXR flare}, \quad \Delta t > 0, \text{ i.e. the Hα flare precedes the SXR flare, and } \Delta t = 0, \text{ i.e. simultaneity of occurrence, for the flare onset and maximum time.} \]

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>Start</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0$</td>
<td>84.4%</td>
<td>22.2%</td>
</tr>
<tr>
<td>$&gt; 0$</td>
<td>11.2%</td>
<td>54.6%</td>
</tr>
<tr>
<td>$= 0$</td>
<td>4.4%</td>
<td>23.2%</td>
</tr>
</tbody>
</table>

In the following we summarize the main results concerning the relative timing of the SXR and Hα emission of solar flares (see also Figure 2 and Table 3):
• For most of the events (84.4%), the start of the \( \text{H}_\alpha \) emission is delayed with respect to the SXR emission. For the median and the mode of the difference of SXR and \( \text{H}_\alpha \) start times we obtain \( \Delta t_{\text{start}} = -3 \text{ min} \).

• The histogram of the peak time differences has its mode at \( \Delta t_{\text{peak}} = 0 \text{ min} \), i.e. the most frequently occurring value indicates simultaneity. However, a tendency exists that the \( \text{H}_\alpha \) flare peaks before the SXR flare (cf. Table 3). For the median we obtain \( \Delta t_{\text{peak}} = +1 \text{ min} \).

• The distinct phenomenon that the \( \text{H}_\alpha \) flare onset is delayed with respect to the SXR flare is even more pronounced for small flares (class B: 90.3% of \( \text{H}_\alpha \) events are delayed).

• The tendency that the \( \text{H}_\alpha \) flare reaches its maximum before the SXR flare enhances with increasing flare class.

4. CONCLUSIONS AND FUTURE PROSPECTS

A distinct delay of the onset of the \( \text{H}_\alpha \) emission with respect to the SXR emission during solar flares is found, on average \( \Delta t_{\text{start}} = -3 \text{ min} \). Thermal preheating prior to the impulsive particle acceleration may be an explanation for the preceding SXR emission. Since such a delay was found for 84% of the investigated events (for class B flares it is even 90%), this would imply that the presence of preheating is the typical case in solar flares. Observational evidence for a frequently strong SXR emission before the impulsive phase is reported, e.g., by Machado et al. (1986) and Tappin (1991) analyzing data from the Solar Maximum Mission. In numeric simulations, Emslie et al. (1992) have shown that preheating of the flare atmosphere affects the evaporation process as it reduces the upward flow speed of the evaporated plasma.

From the current data set we cannot draw a definite conclusion how the found delay of the \( \text{H}_\alpha \) flare onset with respect to the SXR flare can be interpreted in terms of the chromospheric evaporation picture (for reviews see Doschek et al. 1989; Antonucci et al. 1999), in which the SXR emission comes from the dense and hot plasma that convected upward the loop and the \( \text{H}_\alpha \) emission is excited by heat conduction of the SXR emitting plasma in the flare loop. Also for the investigation if the found delay is consistent with direct excitation of the \( \text{H}_\alpha \) flare onset by particle beams, complementary data of nonthermal flare emission, such as hard X-rays (HXR) or microwaves is needed.

Thus, for the future analysis, it is planned to extend the timing analysis to corresponding events observed in \( \text{H}_\alpha \), SXR and HXR, in order to obtain deeper insight into the flare energy transport mechanisms.

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