High time resolution observations of solar Hα flares. I.*

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ABSTRACT

We present here the first results of a search for fast changes of solar flare Hα emission correlated in time with variations of hard X-ray fluxes recorded with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Using the Large Coronagraph (LC), Multi-Channel Subtractive Double Pass (MSDP) spectrograph and the Solar Eclipse Coronal Imaging System (SECS) at the Białkow Observatory, we collected a total of 23 sets of high time resolution (0.04–0.075 s) observations of Hα bright flare kernels during two observational seasons (2003 and 2004). For the first time, several-minute-long high-resolution observations of the H-alpha line profiles as well as simultaneous two-dimensional images have been obtained with time resolution much better than 1 s. Detailed observations of four flares recorded on 2003 July 16 and 2004 April 23 are described. We found examples of good time correlations between X-ray flux variations and variations of the Hα emission of the selected bright flaring kernels. In some events particularly, small but impulsive variations of the hard X-ray (20–50 keV) flux and of the Hα emission are well correlated. The Hα emission follows the 20–50 keV X-ray emission by ~2 s and ~3 s for two of the flares, longer for a third. The 3–10 keV and 10–20 keV X-ray emission, generally characterizing the thermal emission, follow these impulsive changes. There are, however, several examples of impulsive increases in 10–20 keV which appear to be of nonthermal origin. These results are consistent with previous observations and with theoretical studies in which the chromospheric response to energetic beamed electrons is calculated, provided that the chromospheric hydrogen densities are relatively high (~1014–1015 cm−3).

Key words. Sun: flares – Sun: X-rays, gamma rays – Sun: chromosphere – Sun: magnetic fields

1. Introduction

Solar flares have been observed over the entire electromagnetic spectrum for many years, from γ-rays up to long-wavelength radio waves. Despite immense progress over the years, there are still many unsolved observational and theoretical problems in our understanding of flares, e.g. the identification of processes involved in the primary energy release in loop-top sources and the subsequent heating and chromospheric evaporation processes arising from energy that is either conducted from hot plasma contained in loops or transferred by non-thermal particle beams.

Satellite-borne hard X-ray instruments reveal the location and time variations in the flare primary energy release rate occurring in the corona. The chromospheric response to sudden impulses of energy contained in these electrons may be observed with ground-based instruments observing in chromospheric lines such as the hydrogen Hα line at 6563 Å. Hard X-ray data generally have very high time resolution but until recently have been rather limited in spatial resolution; on the other hand Hα observations collected with state-of-the-art instruments on large ground-based telescopes have both high spatial and time resolution, so providing important data for investigations of the solar flares.

Theoretical models indicate that a conduction front reaches the chromosphere about 10–20 s after the onset of the hard X-ray (HXR) emission (Trottet et al. 2000). Beamed non-thermal, high-energy electrons reach the lower corona and upper chromosphere in <1 s, where they are stopped and their kinetic energy reappears as HXR bremsstrahlung and plasma heating. Model atmosphere calculations made by Heinzel (1991) predict a strong correlation of HXR and Hα emission, with a short time lag of the Hα emission compared with the X-ray that depends on the target density. According to Heinzel’s numerical models, if the heating time ∆t of the chromosphere by the electron beam is about 0.1 s, the cooling time of the chromosphere is of the order of ∆t ~ 1 s and its brightness variations, observed in strong chromospheric lines, should also be of the order of 1 s. Indeed, the HXR fluxes observed during the impulsive phase of flares are generally highly variable in time, with characteristic time scales of <1 s. There is hence a need for high-cadence observations in the Hα line.

Flare observations in both Hα and X-rays have been discussed by several other workers. Starting in the early 1980s, Kurokawa and his co-workers made numerous observations of solar flares using a narrow-band Hα filter (Kurokawa et al. 1986; Kurokawa et al. 1988; Kitahara & Kurokawa 1990). The best time resolution achieved in their observations was ~1 s. They found that the time lag between Hα and either hard X-ray or microwave emission was <10 s. Wang et al. (2000) made Hα observations of solar flares with a time resolution of 0.033 s. They found that during a 7-s-long period the Hα emission of a flare kernel showed fast (0.3–0.7 s) fluctuations correlated with variations of the HXR flux. Also, Trottet et al. (2000) found a strong time correlation between HXR and Hα emission from a GOES X1.3 class flare on 1991 March 13. The HXR emission showed

* Figures 12 to 17 are only available in electronic form at http://www.aanda.org
pulses with rise times ranging from 0.4 s to 1.5 s, the cross-

correlation coefficient of the Hα and HXR fluxes being about 0.84 for a 0.5 s time lag of the Hα emission. In 2002, Hanaoka
et al. (2004) began a programme of moderate-cadence Hα ob-
servations of solar flares, collecting images taken at line-centre as well as off-band images for velocity measurements and linear

polarization measurements, with data acquisition rates of 1–2 s, 1 min and 45 s. Recently, McAteer et al. (2005) presented new
results of very high cadence (0.08 s) Hα blue wing observations of
a C9.6 solar flare. The authors used wavelet transformations and time-distance methods to study oscillatory power along a
flare ribbon. They found 3% damped brightness oscillations with
periods of 40–80 s. According to them, the measured properties
of the Hα emission changes can be identified with flare-induced
acoustic waves within the overlying loops.

This paper describes an investigation of Hα flare emis-

sion with observations having very high time cadence
(between 0.075 and 0.04 s, i.e. about 13 to 25 images s⁻¹) us-
ing the Large Coronagraph (LC), Multi-Channel Subtractive
Double Pass spectrograph (MSDP) and fast CCD cameras, part
of the Solar Eclipse Coronal Imaging System (SECIS), at the
Białkow Observatory of the University of Wrocław, Poland. It
discusses the correlation of these data with hard X-ray emis-

sion recorded with the Reuven Ramaty High Energy Solar

Spectroscopic Imager (RHESSI). Unlike previous work, the

observed data with the MSDP spectrograph allow us to make
a comparison of the emission observed simultaneously at several
specifiable wavelengths across the Hα line profile, including the
line centre and blue and red wings. The observations are time-
tagged with atomic clock information. The Hα data are com-

pared with RHESSI data with 4-s time resolution, determined
by the period of the spacecraft rotation, and with data demod-

ulated with recently developed software, giving a time reso-

lution of 0.25 s. From data collected over two observing sea-
sons (2003 and 2004), we selected four flares observed on two
days for detailed discussion. Some preliminary results of this
work have already been presented (Radziszewski et al. 2005;
Radziszewski et al. 2006). More recent observations of a num-

ber of other flares will be described in a future work (Paper II).

2. Instrumentation and data reduction

The Hα spectral-imaging data were collected with the LC
equipped with the MSDP spectrograph and SECIS CCD cameras
at the Białkow Observatory of the Wrocław University. The LC
has a 53 cm diameter main objective, its effective focal length
is 1450 cm, and spatial resolution, normally limited by seeing
conditions, about 1 arcsec or better. The MSDP spectrograph has a
rectangular entrance window, which covers an equivalent area of
325 × 41 arcsec² on the Sun (Mein 1991; Rompolt et al. 1994).
The spectrograph has a nine-channel “prism-box”, enabling
restoration of the Hα line profiles in the range ±1.2 Å from the
line centre using the emission measured in nine wavelengths
separated by 0.4 Å. The spectra-images created by the MSDP
spectrograph were recorded with one of a pair of fast CCD cam-

eras of SECIS. The SECIS cameras, manufactured by EEV (UK),
have a 512 × 512 pixels (px) image format, and images are ac-
quired with frequencies of up to 70 images s⁻¹. The data are
digitized to effectively 10 bits, so that the dynamic range is ap-
proximately 1000:1. SECIS was originally designed and used
by British-Polish expeditions for investigation of fast intensity
changes in solar coronal features during the total solar eclipses in
The image scale for the present work was such that the camera
pixel size was close to 1 arcsec. The SECIS camera software
allows the collection of 10 000 images for each set of obser-
vations, but the time cadence can be adjusted according to the
light intensity. For the observations discussed here, the time ca-
dence selected was between 0.04 s (25 images s⁻¹) and 0.075 s
(~13 images s⁻¹).

The raw MSDP/SECIS data were photometrically corrected
in a standard way, using flat-field and dark current images.
Additionally the data taken on 2003 July 16 were corrected
for Newton’s fringes, accidentally superimposed on the im-
ages. As a result of the numerical reduction of the collected
spectra-images, for each flare we obtained a series of 10 000 sets
consisting of thirteen two-dimensional, quasi-monochromatic
(band-width = 0.06 Å) images, separated by 0.2 Å, at wave-

lengths ±1.2 Å from the Hα line centre. To show all the struc-
tures visible in entire Hα line profile, we constructed compoun-
d images consisting of all quasi-monochromatic images taken
across the line profile. Using these data we were also able
to restore the Hα line profiles for each pixel in the field of view.
The collected data allow us to investigate not only the local time
changes of the Hα emission in the laboratory (zero motion) and
Doppler-shifted (associated with the emitting material) wave-

lengh systems, but also to measure true velocities and emission
profiles of the emitting material.

A permanent characteristic feature of the MSDP quasi-
monochromatic images is a series of parallel strips of slightly
different brightness extending along the whole image, caused
by uncertainties of the spline interpolation of the observed pro-

files. In order to compensate for this (and the variation of at-
mospheric transmittance), each measured signal was normalized
using the average emission of an adjacent region of the quiet
chromosphere lying along the same brightness strip.

Despite the massive nature of the LC, its 10-meter-long
main frame is sensitive to wind gusts. During very windy days
the solar image moved across the camera detector by up to
about 10 arcsecs, showing slow, large-magnitude drifts and small,
noise-like changes. For this reason, on such days the LC was
replaced by a Horizontal Telescope with a compact Jensch-type
coolostat, the main objective of which has an aperture of 15 cm
and focal length 5 m. When the LC was used during less windy
days, the wind-induced residual motions of the field of view
were corrected by shifting all images to a common, reference
position by means of 2-D correlations of well defined chromo-
spheric structures with an accuracy of about 1 px. It was our
intention to improve the co-alignment of the images by evalu-
ing the residual shifts to less than 0.25 px. To do so, we attempted
to evaluate such sub-pixel shifts using a 2-D correlation of the chro-
mospheric structures at the reference and actual images, both
rebinned to 10-times-smaller pixels. Unfortunately, after some
numerical experiments we found the reliable improvement of
the pointing below 1 px was impossible, while the seeing, act-
ing in an unpredictable, stochastic manner, caused some local
deformations of the images, visible as changes of the shape and
brightness of the observed structures.

As a result, for each Hα source we evaluated only the mean
emission calculated inside a rectangular area big enough to en-
compass the source during a particular sequence of images. The
averaged intensities obtained were plotted as a light curve for
each Hα emission source. The disadvantage of this method is
that the emission of the source is averaged with some emission of
the surrounding chromosphere, significantly lowering the frac-
tional variations of the signal. An example of the evolution of
high-cadence Hα line spectra obtained with MSDP-SECIS
Fig. 1. An example of the high-cadence spectral observations collected with the LC, MSDP spectrograph and SECIS system (see main text for details). The graph shows the time evolution of the Hα line profiles emitted by the B9.1 class solar flare on 2004 April 23. The time resolution of the observations was 0.075 s, and the bandwidth of the profiles was limited to ±0.8 Å. For comparison the mean profile of the nearby quiet solar chromosphere in the range ±1.2 Å is shown.

system is shown in Fig. 1. Each spectrum in the series is measured for the rectangular area covering a bright kernel of the B9.1 class solar flare on 2004 April 23 (marked as K4 in Fig. 2). For comparison, the mean profile of the nearby quiet solar chromosphere is also shown.

Our observations are the first ever obtained of a long (several-minute) series of Hα line spectra and images of flaring kernels with time resolution as fine as 0.04 s. Such high-time-resolution spectra allow the investigation of time variations of the flare emission at different parts of the Hα profile simultaneously, and so can assist in modelling the chromospheric response to electron beams during the flare impulsive phase (e.g. Heinzel 2003).

The Hα light curves were compared and correlated with X-ray light curves recorded with RHESSI. Imaging of X-ray flares with RHESSI is accomplished through the use of rotating modulation collimators (Lin et al. 2002; Hurford et al. 2002) located in front of the detectors. Each collimator consists of a pair of grids made up of parallel slats and slits. As the spacecraft rotates (with a period of about 4 s), the flare X-ray signal is modulated in time. Grids with smallest pitch modulate the incoming flux fastest and their output leads to images with the finest spatial resolution (2.3 arcsec). Image reconstruction from the modulated light curves is via various algorithms such as “back projection” in software packages written by the RHESSI team. At increasing photon count rates during flares, sets of attenuators are inserted in front of the detectors to avoid detector saturation; the attenuator states used are A0 (no attenuator), A1 (thin attenuators) and A3 (thick and thin attenuators together). Attenuator changes occurred during two of the four flares studied here, but only one (see Fig. 9) affects the analysis of the Hα and RHESSI data.

X-ray light curves from RHESSI are generally limited to a time resolution of –4 s, this being the spacecraft spin period, but it is possible to get finer time resolution by “demodulating” the output. A test version of a demodulation program was written in Interactive Data Language (IDL) and made available to us by G. J. Hurford (Hurford 2004). The program takes the modulated output from the detectors and performs a demodulation with a time resolution selected by the user, which in the present version of the program is between 0.05 and 0.25 s. A sufficiently large count rate (≥150 counts summed over the detectors used per finest time interval of interest) is required. No particular detector combinations are needed by the program, but for energies <8 keV we used data from all detectors except detectors 2 and 7 (which have relatively poor spectral resolution and high energy thresholds); for energies >8 keV we used data from all detectors except detector 2. In our analysis we used the demodulator program to form RHESSI X-ray light curves with 0.25 s time resolution. The energy range of RHESSI is 3 keV to 17 MeV, so includes both soft (≤12 keV) and hard (≥12 keV) X-ray energies as well as γ-rays. For comparison with our Hα data, we integrated RHESSI photon counts in the ranges 3–10 keV, 10–20 keV and 20–50 keV (though the photon count rates at higher energies were sometimes very small).

3. Description of the observed flares

Four flares were chosen for detailed analysis, one on the disk, observed on 2003 July 16, and three near the west limb, observed on 2004 April 23 (see Table 1). Figure 2 shows Hα line centre images of bright emission sources, labelled K1–K8, and of quiet chromosphere reference regions, labelled Q, which were used to compensate the uncertainties of the photometry caused by the variation of the atmospheric transmittance and striped structure of the MSDP images, described in Sect. 2.

The 2003 July 16 flare was a C1.2 GOES class solar flare in active region NOAA 10410 at S12°E38’. The active region appeared close to the east solar limb on July 12 and grew gradually over the next four days, maintaining a β magnetic class. Solar flares were first observed in the region on July 16: at 12:15 UT (C1.3 class flare), at 16:01 UT (C1.2, this flare was observed by us, see Fig. 3) and at 16:28 UT (C2.9 class flare). By this time, its sunspot group consisted of a single large leading spot and a following group of scattered small spots. Enhanced Hα emission was concentrated to the west and to north of the main sunspot, along the magnetic neutral line. We made high-cadence Hα observations of the active region on July 16 between 15:57:45 UT and 16:06:05 UT with a time resolution of 0.05 s (20 images s⁻¹). This flare was also observed by RHESSI. For this active region we also made some low time-resolution context MSDP observations before and after the flare.

On 2004 April 23, we observed three solar flares in active region NOAA 10597. This active region was first observed on April 21 as a small, bipolar sunspot group of β magnetic class. It grew slightly during the next two days, but did not produce any flare. On April 23 the active region was located at S06°W83’, very close to the Sun’s west limb. It had become very active by then, producing 18 C-class and 2 M-class flares during a single day. Our first set of Hα observations was taken on April 23 between 05:49:17 UT and 06:01:48 UT, during a B9.1 GOES class flare which started at 05:47 UT, peaked at 05:50 UT, and ended at 05:52 UT (see Fig. 4). Our second set of Hα observations was taken between 09:28:50 UT and 09:41:19 UT, during a C4.4 GOES class flare which started at 09:25 UT, peaked at 09:30 UT, and ended at 09:32 UT. Both the Hα flares were compact with bright kernels. Unfortunately, for both these flares, the emission sources were partially obscured by an elongated structure perpendicular to the solar limb, possibly the lower part of a loop structure, filled by absorbing material (see Figs. 4 and 5). During the 09:30 flare a surge was ejected along this structure. In the Hα compound images (see Fig. 5, right column) the flaring...
Table 1. High cadence Hα observations made on 2003 July 16 and 2004 April 23 at the Białkow Observatory.

<table>
<thead>
<tr>
<th>Data</th>
<th>NOAA region</th>
<th>GOES class</th>
<th>GOES Flare start-peak-end [UT]</th>
<th>Hα observations start-end [UT]</th>
<th>Number of images</th>
<th>Cadence [s]</th>
<th>Białkow Obs.</th>
<th>RHESSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 April 23</td>
<td>10 597</td>
<td>C4.4</td>
<td>09:25–09:30–09:32</td>
<td>09:28:50–09:41:19</td>
<td>10 000</td>
<td>0.075</td>
<td>LC-MSDP-SECIS</td>
<td>yes</td>
</tr>
</tbody>
</table>

Fig. 2. Hα line centre images of the solar disk flare on 2003 July 16 and the three limb flares on 2004 April 23 observed with the LC-MSDP-SECIS system at the Białkow Observatory. The Hα emission sources referred to in the text are marked K1-K8, while relevant reference quiet-chromosphere regions are marked Q. Flare characteristics are given in Table 1.

Fig. 3. Left column A): Hα line centre images of the flare (kernels K1, K2 and K3) in the active region NOAA 10 410 on 2003 July 16. Right column B): compound images (sum of eleven quasi-monochromatic images taken in range ±1 Å, including Hα line centre) of the same flare. The images were taken during the rise of the flare, including the impulsive phase, with the LC-MSDP-SECIS system at Białkow Observatory.

kernels marked K5 and K6 are evident, but in the Hα line centre images (left column) the K5 kernel is not very conspicuous. The time resolution of the Hα data obtained during these flares was 0.075 s (about 13 images s⁻¹). The spatial resolution of the images was limited by seeing to about 1 arcsec. Both events were observed by RHESSI (no other flares occurred on the disk, as was checked from GOES-12 SXI images).

A final set of Hα observations on 2004 April 23 was taken between 11:49:38 UT and 11:56:18 UT, during the M1.5 GOES class solar flare in the same active region. This flare, the largest of the four described here, started at 11:41 UT, peaked at 11:50 UT and ended at 11:52 UT. In Hα the flare appeared as a bright, compact loop located near the lower part of an elongated structure perpendicular to the limb, filled by rising material (see Fig. 6). The footpoints of the bright low loop, marked as K8 in Fig. 2, are co-spatial with the two structures marked as K5 and K6 during the 09:30 UT flare and are better seen in the compound images presented in Fig. 6, right column. Unfortunately, there is very little coverage (approximately 100 s) of this flare by RHESSI observations as RHESSI had just emerged from
spacecraft night at the start of our observations and then immediately entered the South Atlantic Anomaly.

4. Results

The \( \text{H} \alpha \) and \textit{RHESSI} X-ray light curves of the four solar flares are shown in Figs. 7–11. Further plots, showing more detail, are given in Figs. 12–17 in on-line material associated with this paper. For each \( \text{H} \alpha \) emission source (K1–K8) the \( \text{H} \alpha \) data are shown with integration periods of 4 s and 0.25 s as well as with the full time resolution (0.04 s–0.075 s). To reduce the noise in the higher-cadence light curves, the data were smoothed with a box-car filter to 1 s (shown as dark lines); as with the \( \text{H} \alpha \) data, the unsmoothed data are plotted in each case (light grey lines). The \textit{RHESSI} light curves are shown with integration times of 4 s (no de-modulation: top panels) and 0.25 s (de-modulated data: middle panels) for three energy bands (3–10 keV; 10–20 keV and 20–50 keV). The 0.25 s integrated data, smoothed with a 2 s box car filter, were shown as dark lines; as with the \( \text{H} \alpha \) data, the unsmoothed data are plotted with light grey lines. The \textit{RHESSI} fluxes are plotted logarithmically, the \( \text{H} \alpha \) fluxes linearly, the scales being relative in each case. For X-ray energies less than 20 keV, discernible variations in the \textit{RHESSI} light curves may be considered real and of solar origin as the count rates are very high. For the highest energy range (20–50 keV) the count rates are lower, and the Poisson uncertainties in the rates are appreciable. We estimated the latter (from an algorithm supplied to us by R. A. Schwartz of the \textit{RHESSI} team) and illustrate their magnitude by the error bars shown in each of the four figures for the largest count rates.

4.1. C1.2 flare on 2003 July 16

The 3–10 keV and 10–20 keV X-ray light curves (4 s integration) for this flare show a gradual rise over the period 16:02:30–16:05:30 UT, with the 10–20 keV showing a maximum at 16:04:16 UT. These gradual changes most likely follow the flare’s thermal emission but the 10–20 keV energy channel also includes many short-lived intensity increases that appear to be of nonthermal origin. The 20–50 keV X-ray emission has an impulsive main peak at 16:03:54 UT, of high statistical significance, with a ∼20 s rise and ∼10 s fall (Figs. 7 and 11). It is still discernible in the demodulated data (0.25 s integration), with the possibility of a small peak corresponding to it on the rise in the 10–20 keV X-ray emission, though this has low significance. The impulsive peak has a clear counterpart in the \( \text{H} \alpha \) emission from the K1 kernel. For the \( \text{H} \alpha \) line centre and wing emission, the K1 peak occurs at 16:03:57 UT, so a ∼3 s time lag between the hard X-ray and \( \text{H} \alpha \) line emission is indicated (Fig. 11). Hardly any response to the hard X-ray peak is indicated in the K2 or K3 kernel \( \text{H} \alpha \) line emission with the possible exception of a slight decrease in \( \text{H} \alpha \) red wing emission at 16:04:10 UT, just after the 20–50 keV X-ray peak. The maximum of the thermal emission in the 10–20 keV X-ray range occurs ∼25 s or more after the 20–50 keV and \( \text{H} \alpha \) K1 peaks. At the softer energy of the GOES 1–8 Å channel, there is a peak at the still later time of 16:10 UT, some 6 minutes after the 20–50 keV impulsive peak. We note that the K1 kernel is relatively faint in \( \text{H} \alpha \) compared with the K2 and K3 kernels (Figs. 2 and 3) but has the clearest indication of the flare impulsive phase shown at high-energy (20–50 keV) X-rays.

In addition, we observed differences in the timings in the first increases of the \( \text{H} \alpha \) emission from the three kernels of this flare, and even between different parts of the \( \text{H} \alpha \) line profile from the same kernel. Of particular note is a 26-s difference in the start time of the \( \text{H} \alpha \) red and blue wing emission in the K1 kernel (see Figs. 7, 11, and 12 (on-line material)). There is also a 38-s time difference between the time of increase in the K1 and K3 kernels in the \( \text{H} \alpha \) blue wing and a 22-s difference in the red wing (Figs. 7 and 12–14 (on-line material)). Some variations in emission occurring between 16:04:10 and 16:04:50 UT are more marked in the \( \text{H} \alpha \) red wing and line centre emission than in the \( \text{H} \alpha \) blue wing.

4.2. B9.1 flare on 2004 April 23

The 3–10 keV and 10–20 keV X-ray light curves show a 30-s rise to a maximum at 05:50:26 UT, followed by a more gradual fall. The peak is also evident at the same time in higher (20–50 keV) energy emission, followed by a sharper fall, still just discernible in the demodulated (0.25 s) data in the 3–10 and 10–20 keV ranges. The demodulated data at these energies show an earlier maximum, at 05:50:15 UT. There is an \( \text{H} \alpha \) response to the flare maximum at 05:50:29 UT in kernel K4 at the \( \text{H} \alpha \) line centre but not in the \( \text{H} \alpha \) line wings (Figs. 8, 11, and 15 (on-line material)). The maximum in the K4 \( \text{H} \alpha \) line centre emission is thus ∼2 s later than the 20–50 keV X-ray peak. Only a very small time lag of \( \text{H} \alpha \) emission is therefore indicated, identical to that for lower X-ray energies (3–10 keV, 10–20 keV) for which one normally expects thermal emission to be dominant and so a later maximum time which is not observed. Our interpretation is that the impulsive, nonthermal peak at 05:50:26 UT apparent at high X-ray energies also extends to soft X-ray energies, as has been noted several times for other flares (Hudson et al. 1994; Lin et al. 2001; Mrozek & Tomczak 2004).

4.3. C4.4 flare on 2004 April 23

\textit{RHESSI} observations of this flare extend from 09:29 UT to 09:38 UT, though there is an attenuator change (from A1 to A0) at 09:33 UT – the data are consequently noisier before this time owing to higher count rates in the A0 state. The 20–50 keV X-ray emission shows a strong peak at 09:29:48 UT, still visible in the demodulated data, which precedes by a few s the corresponding maximum in the 3–10 keV and 10–20 keV light curves (Fig. 9). Two small emission kernels (K5 and K6) and a larger source...
Fig. 7. The time-series of the RHESSI X-ray and LC-MSDP-SECIS Hα fluxes of the flaring kernels K1, K2, K3 (shown in the three columns of the figure) recorded during the C1.2 flare in NOAA active region 10 410 on 2003 July 16. The Hα data are shown for line centre and ±0.6 Å using a linear scale. The integration times are equal to 4 s, 0.25 s, and 0.05 s in top, middle and bottom panels respectively. The data were smoothed using 1 s box-car filter (shown as dark lines; the unsmoothed data are shown as grey lines). The RHESSI data are photon count rates and are plotted logarithmically with 4 s integration times in the top panel and with 0.25 s integration times (i.e. with de-modulation) smoothed with 2 s box-car in the middle panel. The error bars indicate Poisson uncertainties in the RHESSI 20–50 keV count rates; the uncertainties for 3–10 keV and 10–20 keV count rates are too small to be shown. The vertical scales are arbitrary. The vertical arrows in the middle panels indicate the times of the four flare images in Fig. 3.
maximum at 09:30:05 UT, ~17 s later than the peak of the 20–50 keV X-ray emission (Figs. 9, 11 and 16 (on-line material)). The dip in the Hα line centre light curve incidentally confirms the findings of Kurokawa (1983) that Hα line centre emission is more susceptible to absorption by chromospheric material than that in the line wings. Within the K5 Hα line centre emission dip is a small but significant peak at 09:29:54 UT, or ~6 s later than the 20–50 keV X-ray peak. There is a similarly small peak in the K6 Hα line centre light curves at this time, followed by a further maximum at 09:30:20 UT.

For the emission source K7, there is little in the Hα emission that can be easily related to the X-ray light curves. The increase of the 20–50 keV X-ray emission at times after 09:33:48 UT is coincident with an Hα surge.

### 4.4. M1.5 flare on 2004 April 23

Kernel K8 was located in the same small magnetic loop that is presumed to have footpoints at K5 and K6 in the 09:30 UT flare, two hours earlier (see Fig. 6). Unfortunately, RHESSI data are only available after the flare maximum, and there are no features apparent in the X-ray light curves that are recognizable in the Hα emission for the period of overlap (11:52:16–11:53:56 UT; (Fig. 10)).

### 5. Discussion and conclusions

In this study, the time variations in the Hα flare emission as observed by our MSDP/SECIS instrumentation have been compared with hard X-ray emission as observed by RHESSI. Of particular interest are short-lived, impulsive variations in both the Hα and hard X-ray emission, since a correlation would indicate the possibility of excitation of the Hα emission in bright flare kernels by electron beams or by conduction fronts proceeding along flare loop structures during the flare impulsive stage. We have identified three possible candidate features in the Hα light curves for which there are close correlations with impulsive hard X-ray peaks. These are shown in Fig. 11.

The clearest case is the correlation of RHESSI 20–50 keV X-ray emission and Hα emission from the K1 kernel during the 2003 July 16 (16:04 UT) flare. The Hα emission features of this flare, located on the disk, do not suffer from obscuration by absorbing features. The peak in 20–50 keV X-ray emission at 16:03:54 UT closely corresponds to a peak in the light curves of the Hα emission at line centre and in the blue and red wings some ~3 s later. The K1 kernel is comparatively faint in Hα compared with the K2 and K3 kernels for which there is either no or very little response to the impulsive burst seen in hard X-rays.

Another case is the correlation of RHESSI 20–50 keV X-ray emission with Hα line centre emission from the K4 flare during the limb flare of 2004 April 23 (05:50:26 UT). There is apparently no response in the Hα line wing emission. The K4 emission is affected by absorbing chromospheric material, but notwithstanding this there appears to be good correlation of the Hα line centre feature some ~2 s after the 20–50 keV X-ray peak.

A third case is provided by the limb flare from the same active region a few hours later, with a peak in the RHESSI 20–50 keV emission at 09:29:48 UT The Hα line centre emission from the K5 kernel shows a dip over the period of the X-ray maximum, indicating absorption by chromospheric material, but the line wings show a maximum which is ~17 s later than the 20–50 keV X-ray emission. Within the Hα line centre dip there is a small but significant peak which is ~6 s later than the X-ray peak.
Fig. 9. The time-series of the RHESSI X-ray and LC-MSDP-SECIS Hα fluxes of the flaring kernels K5, K6 and emission sources K7 (shown in the three columns of the figure) recorded during the C4.4 flare in NOAA 10 597 active region at 09:30 UT on 2004 April 23. The observations are arranged as in Fig. 7. The gap in the RHESSI data at about 09:33 UT is due to a change of the attenuation from A1 (thin attenuator) to A0 (no attenuator); this explains the decrease in scatter as the count rate is higher in the A0 state. The raw Hα data were taken with 0.075 s time resolution. Error bars are the same as in Fig. 7. The vertical arrows indicate the times of the flare images shown in Fig. 5.
Broadly similar lag times of the Hα emission peaks compared with those in hard X-ray emission, particularly those observed for the K1 and K4 kernels (∼3 s and ∼2 s), have been observed before, e.g. Wang and co-workers (2000) found Hα flare emission to lag hard X-rays by 2–3 s, Kurokawa with co-workers (1988) found the lag to be ∼1 s, and Trotter with co-workers (2000) found the Hα and X-ray emission to be “nearly coincident”. The time lag for the K5 kernel, either ∼17 s (line wings) or ∼6 s (line centre), are a little longer.

We may compare our results with the several theoretical studies that have been made of the chromospheric response to intense beams of nonthermal electrons accelerated at the flare impulsive stage and the consequent intensity of the Hα line emission. Using a set of dynamic model atmospheres and solving NLTE radiative transfer equations, Canfield & Gayley (1987) found Hα line profiles with rapid response to a single pulse of energy resulting from an input electron beam. The emission in the Hα blue wing was found to be slightly delayed (up to 1 s) because of ionization imbalance. Karlický (1990) has similarly studied the response of a model atmosphere which is heated by a single electron beam pulse using hydrodynamic and energy balance equations. The work of Heinzel (1991) builds on this. He found that the response of the Hα source function to very short (<1 s) pulses was first a dip then an enhancement lasting approximately 1 s for a large range of chromospheric hydrogen number densities, \( n_H \sim 10^{13} - 10^{15} \text{ cm}^{-3} \). For the densities of the order of \( n_H \sim 5 \times 10^{13} - 10^{14} \text{ cm}^{-3} \) a gradual increase of Hα emission can be observed during several pulses, while for higher densities \( n_H \sim 10^{14} - 10^{15} \text{ cm}^{-3} \) the Hα intensity impulsively increases. Later calculations (Karlický et al. 2004; Kasparová et al. 2005) are an improvement on this work, including, e.g., the effects of a return current associated with the electron beams, but their conclusions are very similar.

Our observations of small time lags, 2–3 s, in the Hα line emission with respect to hard (20–50 keV) X-ray emission for the K1 and K4 kernels are clearly compatible with the models of Heinzel (1991) and others. This assumes that the hard X-ray variations seen by RHESSI are a proxy for electron beam pulses.

We note that conduction fronts passing down flux loops following the initiation of energy release at the loop top would give rise to slightly longer delay times of the Hα emission. The conduction front velocity is approximately that of the ion sound speed, \( \sim (1.5 k_B T / m_p)^{1/2} \) (where \( T \) is the electron temperature of the plasma in the loop, \( k_B \) Boltzmann’s constant, and \( m_p \) the proton mass). For \( T = 20 \text{ MK} \), the ion sound speed is \( \sim 1000 \text{ km s}^{-1} \). For a loop length of 15 000 km, as suggested by the images in Figs. 2–6, time lags of ∼15 s can be expected. Possibly such a time lag would apply to the observation of the K5 kernel in the 09:30 UT flare on 2004 April 23, but for the much smaller time lags of the K1 and K4 kernels the conduction front model is inappropriate.

In summary, we have used our equipment, a combination of the LC, MSDP spectrograph, and the SECIS fast-frame CCD cameras, to observe the Hα line in nine wavelength bands across its profile during four small flares. Our observations, lasting several minutes in each case, have a time resolution as fine as 0.04 s, better than what has been achieved in any previous study. This has allowed the detailed comparison of the Hα emission at various wavelength positions across the line profile to be compared with high-time-resolution observations made in X-rays with RHESSI. Comparison of Hα and hard (20–50 keV) emission for three small kernels K1, K4 and K5 indicates that the Hα emission lags the X-ray emission by ∼2–3 s (K1, K4), and either ∼17 s (line wings) or ∼6 s (line centre) for the K5 kernel. The
Fig. 11. Three examples of Hα light curves taken in the line centre and wings (LC-MSDP-SECIS data) and corresponding X-ray fluxes (20–50 keV X-ray RHESSI data) showing time correlations. Upper row: X-ray and Hα light-curves (line centre and ±0.6 Å) of the flaring kernel K1 recorded during the C1.2 flare in NOAA active region 10 410 on 2003 July 16. Middle row: X-ray and Hα light-curves (line centre and ±0.6 Å) of the flaring kernel K4 recorded during the B9.1 flare in NOAA active region 10 597 on 2004 April 23. Bottom row: X-ray and Hα light-curves (line centre and ±1.2 Å) of the flaring kernel K5 recorded during the C4.4 flare in NOAA active region 10 597 on 2004 April 23. The X-ray light curves are plotted logarithmically while the Hα data are shown using a linear scale. The variation ranges of the all light curves were scaled to unity except Hα ± 0.6 Å of the K4 kernel and Hα line centre for K5 kernel, where the observed signals were scaled to the quiet chromosphere. Supplementary information is given in captions of Figs. 7, 8 and 9.

values for the K1 and K4 kernels are in agreement with previous observations, and are compatible with electron beam models of Heinzel (1991) and others in which the electron beam is incident on chromospheric material. Possibly a conduction front model can explain the time lag of the K5 kernel.

In future work (Paper II), we will analyze data for several more flares observed in 2004–2005 and investigate the correlation of Hα emission (observed with the LC-MSDP-SECIS set-up) with RHESSI X-ray emission.

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Fig. 12. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K1 flaring kernel recorded during the C1.2 flare on 2003 July 16. The Hα data, collected with 0.05 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±0.6 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 4 s box-car). The vertical axes have arbitrary units. See main text for details.
Fig. 13. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K2 flaring kernel recorded during the C1.2 flare on 2003 July 16. The Hα data, collected with 0.05 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±0.6 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 4 s box-car). The vertical axes have arbitrary units. See main text for details.
Fig. 14. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K3 flaring kernel recorded during the C1.2 flare on 2003 July 16. The Hα data, collected with 0.05 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±0.6 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 4 s box-car). The vertical axes have arbitrary units. See main text for details.
Fig. 15. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K4 flaring kernel recorded during the B9.1 flare on 2004 April 23. The Hα data, collected with 0.075 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±0.6 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 0.5 s box-car). The vertical axes have arbitrary units. See main text for details.
Fig. 16. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K5 flaring kernel recorded during the C4.4 flare on 2004 April 23. The Hα data, collected with 0.075 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±1.2 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 2 s box-car). The vertical axes have arbitrary units. See main text for details.
Fig. 17. RHESSI X-ray and MSDP-SECIS Hα fluxes of the K6 flaring kernel recorded during the C4.4 flare on 2004 April 23. The Hα data, collected with 0.075 s time resolution and smoothed with a 1 s box-car filter, are shown for line centre and ±1.2 Å line wings in a linear scale. RHESSI data are plotted logarithmically in the energy ranges 3–10 keV (bottom row), 10–20 keV (middle row) and 20–50 keV (upper row). The integration times of the X-ray data are equal to 4 s in upper row and to 0.25 s in both lower rows (data are de-modulated and smoothed with 2 s box-car). The vertical axes have arbitrary units. See main text for details.