# FINE STRUCTURE INSIDE FLARE RIBBONS AND ITS TEMPORAL EVOLUTION

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## ABSTRACT

We observed an X2.3 flare, which occurred on 10 April 2001, in H$\alpha$ with the Sartorius Telescope at Kwasan Observatory, Kyoto University. Thanks to the short exposure time used for the flare, the H$\alpha$ images showed the fine structure in the flare ribbons. First, we examined the temporal and spatial evolution of the H$\alpha$ kernels. We identified the conjugate footpoints in each flare ribbon by calculating cross-correlation functions of the light curves of the H$\alpha$ kernels. We found that these footpoints are really connected by the flare loops seen in extreme-ultraviolet images obtained with the *Transition Region and Coronal Explorer*. We also followed the evolution of the energy release site during the flare. Then, we compared the spatial distribution of the hard X-ray (HXR) sources with those of the H$\alpha$ kernels. While many H$\alpha$ kernels are found to brighten successively in the development of the flare ribbons, the HXR sources are locally confined to some special H$\alpha$ kernels where the photospheric magnetic field is sufficiently strong. We estimated the energy release rates at each radiation source, and found that they are high enough at the HXR sources to explain the difference of appearance between the H$\alpha$ and HXR images.

## INTRODUCTION

Non-thermal particles are considered to be accelerated near the flare energy release site, and to flow with very high speed along the flare loops. The speed is as high as about one-third of the speed of light ($\sim 10^5$ km s$^{-1}$). Due to this high speed, they bombard the chromospheric plasma at both the footpoints of the flare loops almost simultaneously. The temporal evolutions of the intensities of both the footpoints are very similar (Kurokawa *et al.* 1988; Sakao 1994). Although the mechanism responsible for the particle acceleration remains open to debate, the location and time of the acceleration and/or the energy release can be determined by identifying the highly-correlated pairs of footpoints and the precipitation times of the non-thermal particles.

First, in this paper, we determine the precise location and precipitation times using H$\alpha$ data of the 10 April 2001 flare, and examine the evolution of the energy release sites. The locations and light curves of

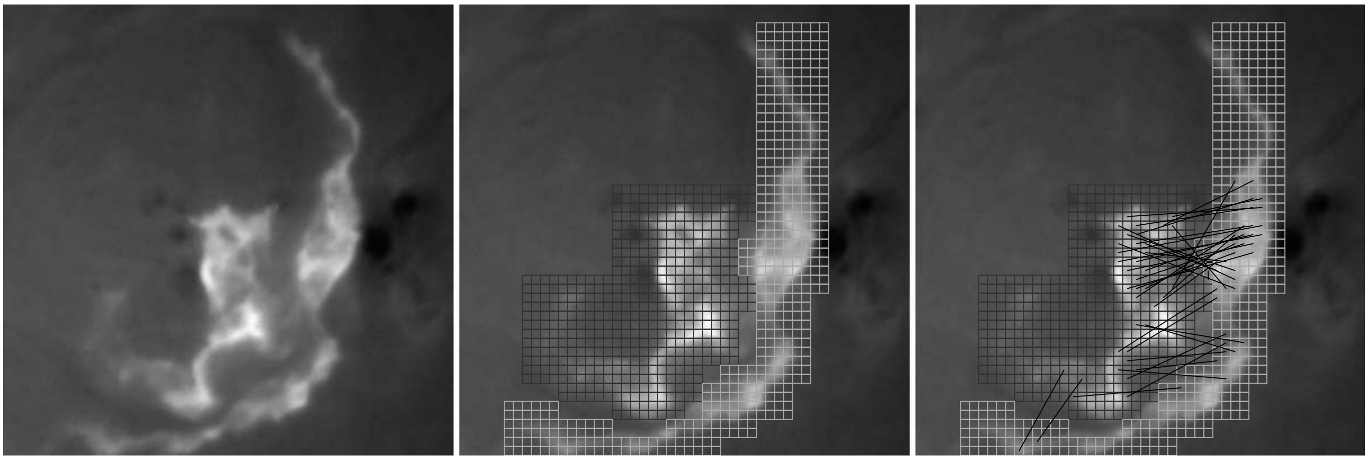

Fig. 1. Method for analyzing the H$\alpha$ data. Each image is $164'' \times 164''$ in area. (The color images are available on the URL site "http://isass1.solar.isas.ac.jp/nuggets/2002/020125/020125.html")

the HXR sources show high correlations with those of the H$\alpha$ kernels, because the bombardments stimulate the excitation and ionization of hydrogen atoms which in turn cause enhanced H$\alpha$ emissions in a short time (Kurokawa *et al.* 1988; Trottet *et al.* 2000; Wang *et al.* 2000; Qiu *et al.* 2001). Furthermore, flare observations with higher spatial resolution are achieved by using H$\alpha$ images rather than by using HXR and/or microwave images. Therefore, we can investigate the precipitation sites of the particles with higher spatial resolution using H$\alpha$ images (Kitahara & Kurokawa 1990).

Second, we compare the locations of the HXR sources with those of the H$\alpha$ kernels and discuss what is essential for the energy release at the HXR sources. HXR images obtained with the hard X-ray telescope (HXT; Kosugi *et al.* 1991) aboard *Yohkoh* (Ogawara *et al.* 1991) often show only a few HXR sources, except in the case of the HXR flare ribbons in the Bastille Day event on 14 July 2000 (Masuda 2001, private communications). HXR sources are accompanied by H$\alpha$ kernels in many cases, but many H$\alpha$ kernels are not accompanied by HXR sources. This difference of spatial distributions between H$\alpha$ and HXR sources can be explained by the difference of the amount of released energy at each source and the low dynamic range of the HXT. The energy release rate in solar flares is considered to depend on magnetic field strength. To check the idea, we measured the photospheric magnetic field strength at each source and investigated its relation with the amount of released energy.

## CONJUGATE FOOTPOINTS

The X2.3 flare occurred in the active region NOAA 9415 at 05:10 UT, 10 April 2001. The flare showed a typical two-ribbon structure. The H$\alpha$ images of the flare were obtained with the Sartorius Telescope (*Sartorius*) at Kwasan Observatory, Kyoto University. The left panel in Figure 1 shows an H$\alpha$ image of the flare. During the observation the exposure time was properly regulated so that the fine structure inside the flare ribbons, like H$\alpha$ kernels, can be clearly seen without saturating.

To find the highly-correlated pairs of H$\alpha$ footpoints, we devised a new method for analyzing the H$\alpha$ data. Firstly, we divided both the H$\alpha$ flare ribbons into fine meshes (see the middle panel in Figure 1). The two ribbons have opposite polarities to each other. The dark gray mesh in Figure 1 shows positive polarity and the light gray mesh shows negative polarity. Secondly, using cross-correlation functions of the light curves, we identified the conjugate points in each mesh. The black lines in the right panel in Figure 1 connect these highly-correlated pairs. Figure 2 shows two examples of the light curves of the highly-correlated pairs. The solid lines and dotted lines in Figure 2 show the light curves from the positive side and from the negative

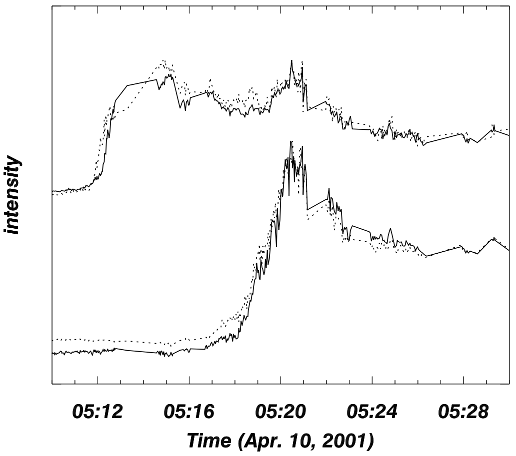

Fig. 2. Examples of the light curves of the highly-correlated pairs (scaled arbitrarily). Solid lines show the light curves with positive polarity and dotted lines show those with negative polarity.

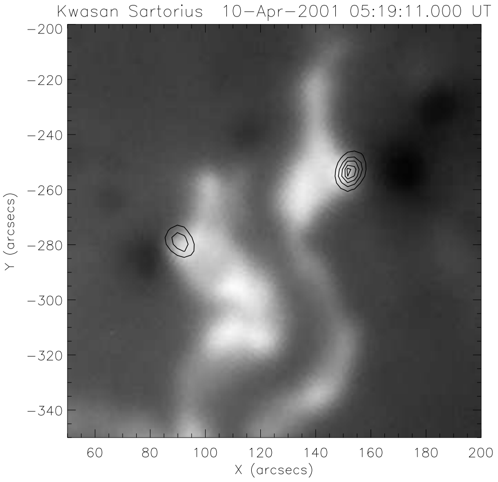

Fig. 3. Comparison of the spatial distribution between H$\alpha$ kernels and HXR sources. A contour image of HXT (H band; 53 - 93 keV) is overlaid on an H$\alpha$ image obtained with the *Sartorius*. Contour levels are 20%, 40%, 60%, 80%, and 95% of the peak intensity.

side, respectively. Thirdly, we confirmed whether the highly-correlated pairs were really connected by the flare loops seen in the extreme-ultraviolet (EUV) images obtained with the *Transition Region and Coronal Explorer* (*TRACE*; Handy *et al.* 1999; Schrijver *et al.* 1999). The *TRACE* 171 Å images clearly show the post-flare loops which confine 1 MK-plasma. We found that 171 Å flare loops really connected almost all the pairs of H$\alpha$ kernels.

From the times and the locations of the brightenings of each H$\alpha$ pair we know where and when the flare loops were connected, that is where and when the energy release occurred. This gives us information about the site and the time of energy release. Thus we can follow the whole history of the energy release.

## H$\alpha$ KERNELS AND HXR SOURCES

Figure 3 shows images of the flare in H$\alpha$ and HXR. In the H$\alpha$ images we can see many H$\alpha$ kernels all over the flare ribbons. On the other hand, the HXT images show only one or two sources (see the contour images in Figure 3). The HXR sources correspond to one of the H$\alpha$ pairs. This difference of appearance is due to the low dynamic range of the HXT images. Only the strongest sources are seen. The weaker sources are buried in the noise of the HXT images. The dynamic range of the HXT images is about 10. If the released energy at the HXR sources is at least 10 times larger than that at the H$\alpha$ kernels without accompanying HXR emission then the difference of appearance can be explained.

To examine the difference in the amount of the released magnetic energy, we measured the photospheric magnetic field strengths of each H$\alpha$ kernel with the Michelson Doppler Imager (MDI; Scherrer *et al.* 1995) aboard the *Solar and Heliospheric Observatory* (*SOHO*; Domingo *et al.* 1995). The magnetic field strengths in the H$\alpha$ kernels are higher than in the other regions, 400 G on average, and those at the HXR sources are especially high ($\sim$ 1200 G). The photospheric magnetic field strength in the HXR sources is about 3 times larger than the field strength in the H$\alpha$ kernels without accompanying HXR emission.

Here, we assume that the HXR intensity observed with the HXT is proportional to the energy release rate $\frac{dE}{dt}$ due to magnetic reconnection. This rate is proportional to the product of Poynting flux into the reconnection region and the area of the region (Isobe *et al.* 2002). The area of the reconnection region is not thought to change so much and is thought to be independent of the magnetic field strength. Therefore, $\frac{dE}{dt} \propto B^2 v_i$, where $B$ is the magnetic field density in the photosphere and $v_i$ is the inflow velocity into the reconnection region. $v_i$ has some dependence on $B$. The Sweet-Parker type reconnection suggests $v_i \propto B^{0.5}$, which is the smallest dependence. On the other hand, the largest dependence is attained if the reconnection rate is constant implying $v_i \propto B$. Therefore, $\frac{dE}{dt} \propto B^\gamma$ where $2.5 \leq \gamma \leq 3.0$. Since $B$ at the HXR sources is 3 times larger, the energy release is 16 - 27 times stronger for the H$\alpha$ sources accompanied by HXR sources than for the other H$\alpha$ kernels. This is sufficiently larger than the dynamic range of the HXT data, and can explain the difference of appearance.

## SUMMARY

We have developed a new method for analyzing H$\alpha$ data. Using the H$\alpha$ images, we have investigated the precipitation of non-thermal particles into the chromosphere with higher spatial resolution than actually possible with hard X-ray and microwave data. This method enabled us to follow the evolution of the energy release sites. We have also examined the difference between the magnetic field strength of the HXR sources and of the ordinary H$\alpha$ kernels. The magnetic field strengths in the H$\alpha$ kernels accompanied by HXR sources are sufficiently higher than those at the other H$\alpha$ kernels, and the energy release rates are also stronger enough, to explain the difference between the appearance of the H$\alpha$ and HXR images.

## ACKNOWLEDGEMENTS

We first would like to acknowledge the anonymous referee for his/her careful reading and useful comments that have improved this paper. We wish to thank all the members of Kwasan and Hida observatories for their support during our observations. We also would like to thank all the members who attended the *Yohkoh* 10th Anniversary Meeting for fruitful discussions. We made extensive use of the *TRACE* Data Center, *Yohkoh* Data Center and *SOHO* MDI Data Service.

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