DIFFERENCE BETWEEN SPATIAL DISTRIBUTIONS OF THE Hα KERNELS AND HARD X-RAY SOURCES IN A SOLAR FLARE

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ABSTRACT

We present the relation of the spatial distribution of Hα kernels with the distribution of hard X-ray (HXR) sources seen during the 2001 April 10 solar flare. This flare was observed in Hα with the Sartorius telescope at Kwasan Observatory, Kyoto University, and in HXRs with the hard X-ray telescope (HXT) on board Yohkoh. We compared the spatial distribution of the HXR sources with that of the Hα kernels. While many Hα kernels are found to brighten successively during the evolution of the flare ribbons, only a few radiation sources are seen in the HXR images. We measured the photospheric magnetic field strengths at each radiation source in the Hα images and found that the Hα kernels accompanied by HXR radiation have magnetic strengths about 3 times larger than those without HXR radiation. We also estimated the energy release rates based on the magnetic reconnection model. The release rates at the Hα kernels with accompanying HXR sources are 16–27 times larger than those without HXR sources. These values are sufficiently larger than the dynamic range of HXT, which is about 10, so that the difference between the spatial distributions of the Hα kernels and the HXR sources can be explained.

Subject headings: Sun: activity — Sun: chromosphere — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

In the impulsive phase of a solar flare, precipitations of nonthermal electrons from the corona generate radiation from denser layers, such as the transition region and/or the upper chromosphere. This radiation is often observed in hard X-rays (HXRs) or microwaves. Precipitations of nonthermal electrons also cause radiation sources in Hα because of rapid thermalization or other mechanisms. Therefore, Hα kernels and HXR sources show a high correlation in their locations and light curves (Kitahara & Kurokawa 1990). However, the difference between the spatial distributions of Hα kernels and HXR sources is also well known. Hα images sometimes show elongated brightenings, called Hα flare ribbons, with many Hα kernels within them. The size of elemental Hα kernels is considered to be about 1° or even smaller (Kurokawa 1986), which is larger than the spatial resolution achieved with Hα instruments (~0′′2) but is smaller than that with HXR instruments of about 5″. On the other hand, HXR images show very few sources, sometimes only one. HXR sources are accompanied by Hα kernels in many cases, but many Hα kernels are not accompanied by HXR sources. The only exception to this “lack of radiation sources in HXRs” that is known is the Bastille Day event on 2000 July 14 (Masuda, Kosugi, & Hudson 2001). This event shows a clear two-ribbon structure in HXRs such as in Hα.

This difference of spatial distributions may be explained by the difference in radiation mechanisms between HXRs and Hα. The HXR intensity is proportional to the number of accelerated electrons and is thought to be proportional to the energy release rate (Hudson 1991; Wu et al. 1986). Therefore, only compact regions where the largest energy release occurred are observable as HXR sources. On the other hand, the mechanisms for Hα radiation are much more complicated than those for HXR radiation, and to derive the effect of electrons is quite difficult (Ricchiazzi & Canfield 1983; Canfield, Gunkler, & Ricchiazzi 1984). Some weaker Hα kernels may be caused by a secondary effect of precipitation or thermal conduction. However, as we mentioned above, the light curve of each Hα kernel has a high correlation with that of the total HXR intensity, even if their intensity is not so strong and they do not have an HXR counterpart. We suggest that the difference between the spatial distributions of Hα kernels and HXR sources is caused by the low dynamic range of the HXR data. In the HXR images, only the strongest sources are seen, and the weaker sources are buried in the noise. We use the HXR data taken with the hard X-ray telescope (HXT; Kosugi et al. 1991) on board Yohkoh (Ogawara et al. 1991) in this Letter. The dynamic range of the HXT images is about 10. Therefore, if the released energy at the Hα kernels associated with HXR sources is at least 10 times larger than that at the Hα kernels without HXR sources, then the difference of appearance can be explained.

In this Letter, we measure the photospheric magnetic field strengths at each radiation source seen in Hα images that have much higher spatial resolution than HXR images. We also estimate the energy release rates based on the magnetic reconnection model (Isobe et al. 2002) at each radiation source. Then we compare the energy release rates with the spatial distribution of radiation sources in an HXR image since they suggest the site where the strong energy release occurred. To examine the difference of the amount of the released magnetic energy, we measure the photospheric magnetic field strengths at each radiation source. In § 2, we summarize the observational data and the results. In § 3, we discuss the amount of energy release at each radiation source. In § 4, the summary and the conclusion are given.

2. OBSERVATIONS AND RESULTS

We observed a large two-ribbon flare (X2.3 on the GOES scale), which occurred in the NOAA Active Region 9415 (S22°, W01°) at 05:10 UT, 2001 April 10, with the Sartorius Refractor.
Fig. 1.—Hα image of the flare at 05:19 UT. Solar north is up, and west is to the right. (a) Hα image taken with Sartorius in which 10 Hα bright kernels are numbered from E1 to E6 and from W1 to W4. (b) Hα image overlaid with the HXR contour image to compare the spatial distribution of Hα kernels with that of the HXR sources. Contour levels are 95%, 80%, 60%, 40%, 20%, and 10% of the peak intensity.

On the other hand, the HXR image (Fig. 1b) shows only two sources even at the contour level of 10% of the peak intensity. These HXR sources are associated with the Hα kernels E2 and W2. We confirmed that those Hα kernels, E2 and W2, are conjugate footpoints in a previous paper (Asai et al. 2002). The soft X-ray images of the flares taken with the Soft X-Ray Telescope on board Yohkoh also show the flare loops that connect E2 and W2. Such differences between the spatial distributions of the Hα kernels and the HXR sources may be caused by the differences in energy release rates at each radiation source. We measured the magnetic field strengths at each Hα kernel, both with and without HXR sources, and estimated their energy release rates. Then we compared these rates with the spatial distribution of the HXR sources. The estimation is discussed in § 3. Here we examine the relation between the photospheric magnetic field strength and the radiation sources.

Figure 2 shows the Hα image in which the flare ribbons are clearly seen (left panel) and the photospheric magnetogram of the same region obtained with MDI (right panel). The outer edges of the Hα flare ribbons are plotted by crosses in both panels.
In this section, we examine the energy release rates in the flare ribbons and discuss the relation between the rates and the spatial distribution of the Hα kernels and HXR sources. We assume that the HXR intensity observed with the HXT is proportional to the energy release rate owing to magnetic reconnection. The energy release rate is written as the product of the Poynting flux into the reconnection region \((4\pi)^{-1}B_{\text{corona}}^2 v_\text{in} A\) and the area of the reconnection region \(A\) (Isobe et al. 2002) as follows:

\[
\frac{dE}{dt} = \frac{B_{\text{corona}}^2}{4\pi} v_\text{in} A,
\]

where \(B_{\text{corona}}\) is the magnetic field strength in the corona and \(v_\text{in}\) is the inflow velocity into the reconnection region. For simplicity, we assume that the area of the reconnection region does not change much during the flare and is independent of the magnetic field strength. Therefore, the energy release rate is simply written as \(dE/dt \propto B_{\text{corona}}^2 v_\text{in}\).

Here we use magnetic field strengths at the photosphere \(B_{\text{photos}}\) instead of those at the corona \(B_{\text{corona}}\) to estimate the energy release rates, since to measure \(B_{\text{corona}}\) directly is difficult. We assume that \(B_{\text{corona}}\) is proportional to \(B_{\text{photos}}\) in the same ratio all over the flaring region. If this assumption is true, the differences of the energy release rates estimated with \(B_{\text{photos}}\) are the same as those with \(B_{\text{corona}}\). From now on, we estimate the energy release rate by using the photospheric magnetic field strength, and we write it simply as \(B\).

If \(v_\text{in}\) has no dependence on \(B\), the energy release rate is directly proportional to the square of the magnetic field strength, \(dE/dt \propto B^2\). Since the Hα kernels accompanied by HXR radiation have magnetic field strengths about 3 times larger than those without the HXR radiation, the energy release rates at the former are about 9 times larger than those at the latter. The difference in the energy release rates is just comparable to the dynamic range of the HXT (~10) but is not enough for weaker radiation sources to be buried in noise. At other Hα kernels, HXR sources should be observed. Therefore, under this assumption the spatial distribution of radiation sources cannot be explained.

This result suggests that \(v_\text{in}\) may have some dependence on \(B\) as some authors have suggested. Sweet (1958) and Parker (1957) give the relation \(v_\text{in} = R_m^{-1/2} v_\text{A}\), where \(R_m\) is the magnetic Reynolds number and \(v_\text{A}\) is the Alfvén velocity. Here \(v_\text{A}\) is expressed as \(v_\text{A} = (4\pi\rho)^{-1/2} B_{\text{corona}} \propto B_{\text{corona}}^2\), where \(\rho\) is the mass density; \(R_m\) is defined as \(R_m = L v_\text{A}/\eta \propto B\), where \(L\) and \(\eta\) are the characteristic length of the flare region and the magnetic diffusivity, respectively. Therefore, we can derive the relation \(v_\text{in} \propto B^{1/2}\) and then \(dE/dt \propto B^{3/2}\). On the other hand, Petschek (1964) suggests that \(v_\text{in}\) hardly depends on \(R_m\) and indicates \(v_\text{in} \propto (\log R_m)^{-1/2} v_\text{A} \approx v_\text{A} \propto B\). Hence, we can derive the relation \(dE/dt \propto B^3\). Since \(B\) at the HXR sources is 3 times larger, these two models of magnetic reconnection predict that the energy release is 16 and 27 times stronger for the Hα sources accompanied by HXR sources than for the other Hα kernels.

### Table 1

| Magnetic Field Strength (G) | HXR Association |
|---------------------------|-----------------|
| E1                       | 260             | No |
| E2                       | 960             | Yes |
| E3                       | 240             | No |
| E5                       | 230             | No |
| E6                       | 220             | No |
| W1                       | −500            | No |
| W2                       | −1050           | Yes |
| W3                       | −260            | No |
| W4                       | −300            | No |

**Fig. 3.—** Magnetic field strength along the outer edges of both flare ribbons (see Fig. 2). Left gray plot shows the east (positive) ribbon, and the right black plot shows the west (negative) one. Note E1–E6 (except for E4) and W1–W4 indicate the position of Hα kernels. E2 and W2 are associated with HXR sources.
kernels, respectively. This is sufficiently larger than the dynamic range of HXT, and the difference between the spatial distributions can be explained.

4. SUMMARY AND CONCLUSION

We have examined the difference between the spatial distributions of Hα kernels and HXR sources. The HXR sources indicate where large energy release has occurred, while the Hα kernels show the precipitation sites of nonthermal electrons with higher spatial resolution. We measured the photospheric magnetic field strength at each Hα kernel and found that the magnetic field strengths at the Hα kernels accompanied by HXR sources are about 3 times higher than those at the other Hα kernels (without any HXR sources). We also estimated their energy release rates, by using the photospheric magnetic field strengths and by considering the dependence of $v_i$ on $B$ as derived by some authors (e.g., Sweet 1958; Parker 1957; Petschek 1964). The estimated energy release rates at the HXR sources are large enough to explain the difference of appearance of the Hα and HXR images.

The gap in our understanding of large-scale structure such as Hα flare ribbons and compact radiation sources has been well known not only in HXRs but also in microwaves. Even in soft X-rays, flare loops often appear only in a part of the whole flaring region and/or seem to connect only a few radiation sources. The lack of radiation sources does not mean that no energy release occurs there. We just cannot “observe” the radiation because of the dynamic ranges of the instrument for those wavelengths.

We compared the photospheric magnetic field strengths at each Hα kernel with the spatial distribution of HXR sources and found that HXR sources appear at strong magnetic regions. However, our result was based on only one event, and the statistical studies about the relation between HXR intensities and magnetic field strengths are needed. We will be able to perform more detailed analysis in the near future by using HXR images, with a higher dynamic range, obtained with the Reuven Ramaty High Energy Solar Spectroscopic Imager.

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