Evolution of Flare Ribbons and Energy Release

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Abstract

We examined the relation between evolutions of flare ribbons and released magnetic energies at a solar flare which occurred on 2001 April 10 in the active region NOAA 9415. We successfully evaluated the released energy quantitatively, based on the magnetic reconnection model. We measured the photospheric magnetic field strengths and the separation speeds of the fronts of the Hα flare ribbon, and estimated the released magnetic energy at the flare by using those values. Then, we compared the estimated energy release rates with the nonthermal behaviors observed in hard X-rays and microwaves. We found that those at the Hα kernels associated with the HXR sources are locally large enough to explain the difference between the spatial distribution the Hα kernels and the hard X-ray sources. Their temporal evolution of the energy release rates also shows peaks corresponding to hard X-ray bursts.

1. Introduction

The energy release rate is written as the product of the Poynting flux carried into the reconnection region $S = 2(4\pi)^{-1}B_c^2 v_i$ and the area of the reconnection region A [5] as follows;

$$\frac{dE}{dt} = SA = 2\frac{B_c^2}{4\pi}v_i A, \tag{1}$$

where B_c is the magnetic field strength in the corona and v_i is the inflow velocity into the reconnection region. It is very difficult to measure B_c and v_i directly. Therefore, an indirect method is needed to evaluate the energy release rate quantitatively by using observable values, such as the magnetic field strengths at the

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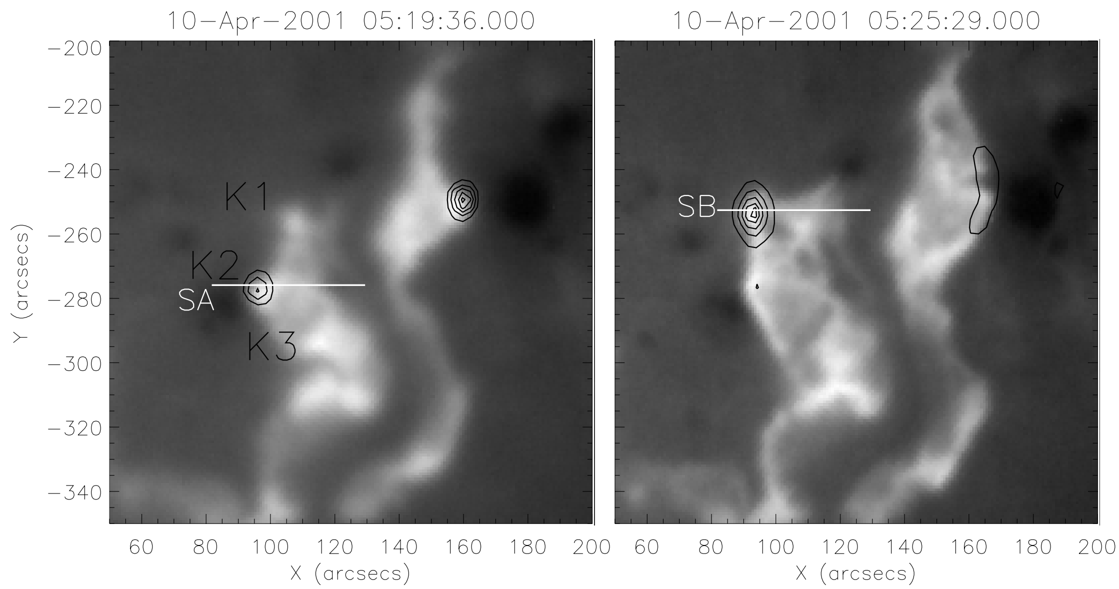

Fig. 1. Hα image taken at 05:19 (*left*) and 05:26 UT (*right*) with *Sartorius*. Solar north is up, and west is to the right. The HXR/M2 band (33 - 53keV) contour image is overlaid on it. Contour levels are 95, 80, 60, 40 and 20% of the peak intensity. In the *left panel* K2 is the Hα kernel associated with the HXR source, and K1 and K3 are those without any HXR sources. White lines numbered SA and SB are the slit lines along which we estimated the energy release rates.

photosphere (B_p) and the separation speed of the flare ribbons (v_f). On the other hand, the hard X-ray (HXR) intensity which is emitted in bremsstrahlung is proportional to the number of accelerated electrons, and is thought to be proportional to the energy release rate [4, 7]. The nonthermal microwave synchrotron emission is also thought to be well correlated with the energy release rate. In this paper we estimated the released magnetic energy at a solar flare, by using the B_p and v_f. Then we compared the temporal evolution of the estimated energy release rates with the light curve of the HXR total intensity.

A large two-ribbon flare (X2.3 on the GOES scale) occurred in the NOAA 9415 at 05:10 UT, 2001 April 10. The details of the flare were reported in several papers [1, 2, 3, 6]. We observed the flare in Hα center with the Sartorius Refractor Telescope (*Sartorius*) at Kwasan Observatory, Kyoto University. Figure 1 shows an Hα images obtained at 05:19 and 05:26 UT with *Sartorius*. Along the outer edges of both the flare ribbons, we can see many Hα kernels, and those numbered from K1 to K3 are the examples. On the other hand, we can see only one or two HXR sources associated with the Hα kernels in the HXR images taken with the hard X-ray telescope (HXT) aboard *Yohkoh*. The contour images are overlaid on

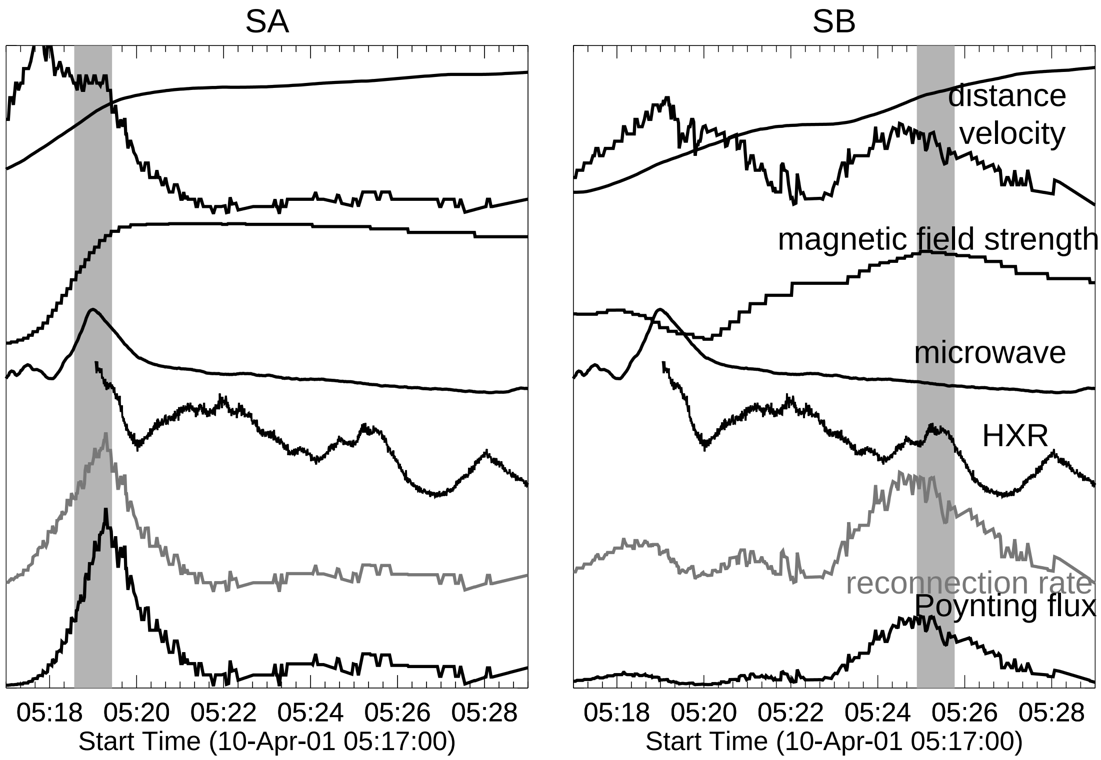

Fig. 2. Temporal evolutions of the flare ribbons and estimated energy release rates which are derived along the slit A (*left*) and the slit B (*right*). All are plotted scaled arbitrarily. *From top to bottom*: Distance from the magnetic neutral line; separation velocity of the flare ribbon (v_f); photospheric magnetic field strength at the ribbon-front (B_p); radio correlation plot taken at 17 GHz with NoRH; HXR count rate measured with HXT; reconnection rate (E); Poynting flux (S).

the Hα image in Figure 1. The Hα kernel K2 is associated with the HXR sources, while K1 and K3 are not. The difference between the spatial distributions of Hα kernels and those of HXR sources is caused by the low dynamic range of HXT (about 10). The energy releases at e.g. K2 are large enough, and other sources are not seen, because they are buried in noise. Radio correlation plot at 17 GHz which was taken with the Nobeyama Radioheliograph (NoRH) was also used to examine nonthermal behavior. We used a magnetogram obtained at 05:18 UT with the Michelson Doppler Imager (MDI) on board *SOHO* to measure the photospheric magnetic field strengths at each Hα kernel.

2. Estimation of Reconnection Rate and Poynting Flux

We estimated the released rate of the magnetic energy via magnetic reconnection, by using photospheric magnetic field strengths B_p and separation speeds of the fronts of the Hα flare ribbon v_f. Here, we assume that A does not change much during the flare and is independent of the magnetic field strength, and then, the energy release rate (eq. 1) is simply proportional to the Poynting flux $S = (4\pi)^{-1}B_c^2 v_i$. First, we estimated the reconnection rate, that is the electric field (E) in the corona. E is defined as the reconnected magnetic flux per unit time, and expressed as $B_c \times v_i$. From the conservation of magnetic flux, it is rewritten as $B_p \times v_f$ [5]. E is one of the most important physical values in reconnection physics, because it shows how violently the magnetic reconnection progresses. Then, we estimated (S). We assumed that B_c is proportional to B_p in the same ratio all over the flaring region, that is $B_c = aB_p$ ($a = constant$). If this assumption is reasonable, $S \propto aB_p^2 v_f$, and it can be derived only with B_p and v_f, instead of with B_c and v_i.

We put the slits on Hα kernels associated with the HXR sources which occurred at 05:19 UT and 05:26 UT. We measured B_p and v_f along the slits, and estimated the reconnection rate E and the Poynting flux S. We compared them with the light curves in HXRs and microwaves. Figure 2 shows the time profiles of estimated E and S, compared with the light curves in HXR and microwave obtained with HXT and NoRH. Those in the *left* and *right* panels are derived along the slit A and B in Figure 1, respectively. The temporal evolutions of the physical values, such as B_p, v_f, and the distance of the front of the flare ribbons from the magnetic neutral line. The evolutions of E and S are well fitted with the HXR and microwave light curves (see vertical light grey lines in Fig. 2). They are enhanced largely enough at the HXR sources so that they can explain the difference between the spatial distribution of the HXR sources and that of the Hα kernels. The reconnection rates (E) at the HXR sources (e.g. Hα kernel E2) are at least 16 times larger than those at the Hα kernels without any HXR sources (e.g. E3). The Poynting fluxes (S) are much more enhanced at the HXR sources, and are about 150 times larger than those at the other sources. Here, we have assumed that $B_c = aB_p$. This assumption is too simple, although the estimated energy release rate well corresponded to the light curves of nonthermal emission. The detailed discussions about the dependence of B_c on B_p is needed to perform the more accurate analyses. We will do it in the future papers.

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