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THE POWER-LAW DISTRIBUTION OF FLARE KERNELS AND FRACTAL CURRENT SHEETS IN A SOLAR FLARE

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ABSTRACT

We report a detailed examination of the fine structure inside flare ribbons and the temporal evolution of this fine structure during the X2.5 solar flare that occurred on 2004 November 10. We examine elementary bursts of the C iv (1550 Å) emission lines seen as local transient brightenings inside the flare ribbons in the ultraviolet (1600 Å) images taken with Transition Region and Coronal Explorer, and we call them C iv kernels. This flare was also observed in Hz with the Sartorius 18 cm Refractor telescope at Kwasan observatory, Kyoto University, and in hard X-rays (HXR) with Reuven Ramaty High Energy Solar Spectroscopic Imager. Many C iv kernels, whose sizes were comparable to or less than 2′′, were found to brighten successively during the evolution of the flare ribbon. The majority of them were well correlated with the Hz kernels in both space and time, while some of them were associated with the HXR emission. These kernels were thought to be caused by the precipitation of nonthermal particles at the footpoints of the reconnecting flare loops. The time profiles of the C iv kernels showed intermittent bursts, whose peak intensity, duration, and time interval were well described by power-law distribution functions. This result is interpreted as evidence for “self-organized criticality” in avalanche behavior in a single flare event, or for fractal current sheets in the impulsive reconnection region.

Key words: acceleration of particles – Sun: chromosphere – Sun: coronal – Sun: flares – Sun: X-rays, gamma rays – turbulence

1. INTRODUCTION

Hard X-ray (HXR) and microwave emissions show fine structures both temporally and spatially during a solar flare, which revealed that a highly fragmented and intermittent particle acceleration occurs (e.g., Benz & Aschwanden 1992; Aschwanden 2002). This fragmented structure of solar flares indicates that a flare is an ensemble of a vast amount of small-scale energy releases. Statistical studies of solar flares have also shown that various kinds of physical parameters of flares, such as peak intensity, flare durations, fluences, waiting time of small X-ray (SXR) emissions between discrete events, are well described with power-law distributions (e.g., Dennis 1985; Wheatland 2000; Veronig et al. 2002). Karlický et al. (2000) examined 12 flares, and showed that microwave spikes seen in each flare show power-law features in the size/timescales (i.e., scale of energy release). In addition, the occurrence of microflares and X-ray bright points is known to follow power-law distributions (Shimizu 1995; Shimojo & Shibata 1999).

Recent development in magnetic reconnection theory also indicates that magnetic reconnection proceeds intermittently, involving repeated formation of magnetic islands and their subsequent coalescence (Finn & Kaw 1977; Tajima et al. 1987). This process is known as the “impulsive bursty” regime of magnetic reconnection (Priest 1985). As Shibata & Tanuma (2001) showed, plasmoids of various scales are generated in the current sheet in a fractal manner. This fractal nature of magnetic reconnection might generate power-law characteristics that are observed in solar flares, as mentioned above, Karlický et al. (2000) and Kliem et al. (2000) discussed similar features seen in the HXR and microwave emissions, based on the theoretical view of dynamic magnetic reconnection. Although the temporal resolutions of HXR and microwave observations were high enough to reveal fragmented features in the temporal scale, the time variability of flare kernels has not been discussed with two-dimensional images with high spatial and temporal resolutions.

Historically, the two-ribbon structure has been observed in Hz and other wavelengths in solar flares. Flare kernels inside the ribbons are well correlated with HXR and microwave emissions temporally and spatially in Hz (Kurokawa et al. 1988; Kitahara & Kurokawa 1990). Also in the ultraviolet (UV), such as in 1550 Å images taken with TRACE, the same properties were observed (Warren & Warshall 2001; Alexander & Couner 2006), indicating that sudden plasma heating occurs in the upper chromosphere and the transition region by nonthermal particles or thermal conduction. Hence, Hz kernels and TRACE 1550 Å (C iv doublet emissions) kernels can also be good tracers of HXR sources.

In this Letter, we examine the fine structures inside the flare ribbons seen in the UV images of the X2.5 flare that occurred on 2004 November 10. We show the fragmented features of the bright emission sources, and that they follow a power-law distribution even in a single event. Finally, we discuss the fractal features of the energy release region (i.e., current sheet) and the avalanching system of the flare that may explain such fragmented structures.

2. OBSERVATIONS: COMPARISON AMONG C iv, Hz, AND HARD X-RAY EMISSIONS

The large flare (X2.5 in GOES class) occurred in the NOAA Active Region 10696 (N08°, W50°) at 02:00 UT, 2004 November 10. This flare was a long-duration event that showed a typical two-ribbon structure preceded by a filament eruption.

5 Transition Region and Coronal Explorer (Handy et al. 1999).
The erupted filament showed a kinking structure (Williams et al. 2005), and a lot of attention has been paid to it because this is a candidate for the source of the geo-effective coronal mass ejection (CME; Harra et al. 2007). We observed the flare with the Sartorius 18 cm Refractor Telescope at Kwasan Observatory, Kyoto University (Asai et al. 2003). The highest temporal and spatial resolutions of the Sartorius data are 1 s and 1"2, respectively. Figures 1(a)–(c) show the images of the flare in Hα at 02:06, 02:08, and 02:10 UT, which correspond to the peak times of the HXR emission (see also Figure 2). We can see some Hα flare kernels inside the ribbon structure.

We overlaid HXR contour images (25–50 keV) on TRACE 1600 Å images to compare the spatial distribution of radiation sources in Hα and HXR emissions (see Figures 1(d)–(f)). The HXR images were taken with RHESSI. 6 We synthesized the HXR image with the Clean algorithm, which is the same method as is commonly used for analyses of radio data, and grids 3–9, which give a spatial resolution (FWHM) of about 10". The integration time is set to be 60 s, and the total photon count was $3.8 \times 10^5$ counts for photons of 25–50 keV. These synthesizing tools are included in the Solar Software. We found that the HXR sources are associated with both Hα and C iv kernels. The location of the HXR sources moves in the southeast direction as the flare progresses, that is, from a mixed polarity region to a strong magnetic field region, indicating a change in the site of the strong energy release. Though the kernels are seen in the southeast of the Hα and TRACE images from 2:05 to 2:08, i.e., before the HXR sources have arrived there, this is probably because the HXR emissions are not large enough to be observed with the dynamic range of RHESSI. Actually small flare kernels in the southeast of Figure 1(d) at around 02:06 UT, which are the components of the ribbons, show small peaks of intensity less than 25% of the later impulsive burst at 02:10 UT, as well as in the Hα time profile (see Figure 2(b)).

We summarize the results of the comparison of the multiwavelength observations in Hα, C iv ($\sim 1550$ Å) and HXR emissions

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6 Reuven Ramaty High Energy Solar Spectroscopic Imager (Lin et al. 2002).
as follows. (1) There are not only good spatial but also temporal correlations among flare kernels observed in Hα and C iv emissions, some of which are associated with the HXR emission. This implies that the C iv and Hα kernels are caused by nonthermal electrons interacting with the ambient thick target plasma as well as HXRs. (2) The C iv flare ribbons are much thinner and sharper than the Hα ribbons. This is because the width of flare ribbons is typically determined by the cooling time via thermal conduction and radiative cooling, and because the thermal conduction timescale in the corona/transition region for C iv is much shorter than that for Hα in the chromosphere. The ratio of the peak intensity of the Hα kernels to the background is not very large, as a result, the integrated Hα emission over the whole active region is similar to the soft X-ray emission (see Figure 2(c)). On the other hand, the integrated C iv emission is still similar to the HXR emission, showing the corresponding peaks in their time profiles.

3. ANALYSIS AND RESULT

As a result of the comparison of the multiwavelength observations, we found that it is easier to identify peaks in the time profile of the C iv emission, rather than in Hα. Moreover, the seeing condition smeared the Hα images in the impulsive phase, and therefore we focused on the temporal variations of the C iv flare kernels here. We measured the intensity, duration, and time interval between each peak from the time profiles. We divided both flare ribbons into fine meshes. Each mesh box is a square with a size of 5′′, 2′′, and 1′′ for comparison. Although this is larger than the elemental Hα kernels, which are considered to be about 1″ or even smaller (Kurokawa 1986), it is small enough for us to determine the essential structures inside the flare ribbons. Next, we examined time variations of the total intensity for each box in the meshes. As the mesh size becomes smaller and smaller, peaks in the time profile become isolated. This means that the light curves with a large (5′′) mesh possibly contain multiple flare kernels that are superposed over each other, while a smaller mesh can cover a single flare kernel alone. We found that a 2′′ mesh is enough to isolate most of the superposed peaks, though some peaks cannot be separated even with a 1′′ mesh. This implies that the size of the heating source is comparable to or smaller than 2′′. Since a 1′′ mesh is too small and too noisy to analyze, we adopted a 5′′ and a 2′′ mesh size for our further analysis.

We defined the maximum intensity of a light curve as the peak intensity (I), and determined the duration (τd) as the full width at the three-fourths maximum intensity of each peak because not all of the peak durations can be measured with the full width at the half-maximum (FWHM). We identified 586 C iv kernels using a 5′′ mesh in the impulsive phase, only with the requirement that the count rate of the detector exceeds 50 counts s−1 to identify the peaks. Figures 3(a) and (b) show the frequency distributions of the peak intensity and the duration of each peak. We also recorded the peak time of the flare kernels across the whole active region. We determined the time interval of the peaks (τint) as the time difference between the peak times and show its frequency distribution in Figure 3(c). The distribution of peak intensities, durations, and time intervals reveal power laws during the impulsive phase. From the slopes of the distributions, we obtain power-law indices α ∼ 1.5 for the peak intensity, α ∼ 2.3 for the peak duration, and α ∼ 1.8 for the time interval between each peak. The lower limit of the time duration of about 10 s comes from the temporal resolution of TRACE. This is, for example, 2–3 s in a flare mode. When we change the mesh size from 5′′ to 2′′, each peak becomes isolated and sharpened so that the number of the peaks with short duration increased.

4. SUMMARY AND DISCUSSION

We found that the distributions of the peak intensity, duration, and time interval well followed power-law distributions with power-law indices of α ∼ 1.5, 2.3, and 1.8, respectively. These power-law indices remain unchanged, even if we change the size of the mesh box from 5′′ to 2′′, and even if we change the threshold of the peak identification. In this individual event, we showed for the first time, the power-law behavior of flare kernels typically seen in studies of large numbers of flares, suggestive of a link between the observations and theoretical modeling of the fractal nature of magnetic reconnection in current sheets. If magnetic reconnection occurs in a fractal manner in the current sheet, one would expect energy release and particle energization/acceleration on a range of different sizes/timescales, such that power-law distributions could be expected in the size, duration, etc., of tracers of the energy release process. Since flare kernels have been shown to be good proxies for the HXR energy release and, furthermore, TRACE C iv kernels can also be good tracers of HXR sources, one would expect to see such behavior in their properties. In fact, the peak intensity
Figure 3. Frequency distributions as function of (a) the peak intensity, (b) duration, and (c) time interval of each burst in log–log space. The circle symbol shows the result in the case of mesh boxes with the size of 5″, and the plus symbol shows that with 2″. All distributions can be approximated with power-law functions through the impulsive phase.

and peak duration could be indicators of the released energy. The peak time also corresponds to the timing when heating of the footpoint plasma occurs, that is the arrival time of released energy at the foot point.

Here, we roughly discuss the relation between the obtained fractal behaviors and the energy release process. The duration of the transition region heating $t_d$ and the time interval $t_{int}$ are roughly characterized by the Alfvén time $t_A$ of the reconnection region,

$$ t_A = \frac{L}{v_A} \propto \frac{L}{B}, \quad (1) $$

where $L$ is the characteristic length of the energy release region (e.g., macroscopic length of a current sheet or plasmoid), $v_A$ is the Alfvén velocity ($\propto B$), and $B$ is a typical magnetic field strength in the corona. On the other hand, the intensity of the flare kernels $I$ can be estimated as,

$$ I \propto \frac{B^2}{t_A} L^3 \propto \frac{B^2}{L/B} L^3 = B^3 L^2. \quad (2) $$

So, if magnetic reconnection occurs in a fractal manner in the current sheet through the repeated formations of magnetic islands and their subsequent coalescence, current sheets become thinner and thinner and as a result, the self-similar structure of current sheet can be formed from macroscopic-scales to microscopic-scales. At that time, the size of the energy release region $L$ can be expected to exhibit power-law behavior, so that power-law distributions can be expected in the energy, duration, etc., of tracers of the energy release process, such as $I$ and $t_A$.

These fractal structures mean that there are no characteristic scales of length, energy, and time in the energy release process. Our results also support the view of the impulsive bursty reconnection (Priest 1985) and the fractal features of the current sheet (Shibata & Tanuma 2001). A power-law distribution for the magnetic energy of the plasmoid is also reported in the magnetosphere by Hoshino et al. (1994). On the basis of the unified view suggested by Shibata (1999), i.e., the plasmoid-induced reconnection model, plasmoid ejection plays a crucial role for energy storage and release, driving the inflow and the reconnection rate enhancement. On a large scale, the flare itself should exhibit these properties. Our results are quite similar to the power-law behaviors typically seen in studies of large numbers of flares (e.g., Dennis 1985), which are often
interpreted as evidence for self-organized criticality (SOC) in an avalanching system. This suggests that the elemental energy release in this individual event may be similar to that in a typical X-ray flare and hence can also be interpreted as SOC in an avalanching system in a single event or as evidence of the fractal nature of the current sheet in the impulsive reconnection region, as discussed above.

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REFERENCES

Alexander, D., & Coyner, A. J. 2006, ApJ, 640, 505
Asai, A., Ishii, T. T., Kurokawa, H., Yokoyama, T., & Shimojo, M. 2003, ApJ, 586, 624
Aschwanden, M. J. 2002, Particle Acceleration and Kinematics in Solar Flares (Dordrecht: Kluwer)
Benz, A. O., & Aschwanden, M. J. 1992, in Lect. Notes in Physics, Vol. 399, Eruptive Solar Flares, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (New York: Springer), 106
Brekke, P., Rottman, G. J., Fontenla, J., & Judge, P. G. 1996, ApJ, 468, 418
Dennis, B. R. 1985, Sol. Phys., 100, 465
Finn, J. M., & Kaw, P. K. 1977, Phys. Fluids, 20, 72
Handy, B. N., et al. 1999, Sol. Phys., 187, 229
Harra, L. K., et al. 2007, Sol. Phys., 244, 95
Hoshino, M., Nishida, A., Yamamoto, T., & Kokubun, S. 1994, Geophys. Res. Lett., 21, 2935
Karlický, M., Jiřička, K., & Sobotka, M. 2000, Sol. Phys., 195, 165
Kitahara, T., & Kurokawa, H. 1990, Sol. Phys., 125, 321
Kliem, B., Karlický, M., & Benz, A. O. 2000, A&A, 360, 715
Kurokawa, H. 1986, in Proc. of NSO/SMM Flare Symp., Low Atmosphere of Solar Flares, ed. D. Neidig (Sunspot: NSO), 51
Kurokawa, H., Takahara, T., & Ohki, K. 1988, Publ. Astron. Soc. Japan, 40, 357
Lin, R. P., et al. 2002, Sol. Phys., 210, 3
Priest, E. R. 1985, Rep. Prog. Phys., 48, 955
Shibata, K. 1999, Astrophys. Space Sci., 264, 129
Shibata, K., & Tanuma, S. 2001, Earth, Planets Space, 53, 473
Shimizu, T. 1995, PASJ, 47, 251
Shimojo, M., & Shibata, K. 1999, ApJ, 516, 934
Tajima, T., Sakai, J., Nakajima, H., Kosugi, T., Brunel, F., & Kundu, M. R. 1987, ApJ, 321, 1031
Veronig, A., Temmer, M., Hanslmeier, A., Otruba, W., & Messerotti, M. 2002, A&A, 382, 1070
Warren, H. P., & Warshall, A. D. 2001, ApJ, 560, L87
Warren, H. P., & Winebarger, A. R. 2000, ApJ, 535, L63
Wheatland, M. S. 2000, ApJ, 536, L109
Williams, D. R., Török, T., Démoulin, P., van Driel-Gesztelyi, L., & Kliem, B. 2005, ApJ, 628, L163