FINE STRUCTURE OF FLARE RIBBONS AND EVOLUTION OF ELECTRIC CURRENTS

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ABSTRACT

Emission of solar flares across the electromagnetic spectrum is often observed in the form of two expanding ribbons. The standard flare model explains flare ribbons as footpoints of magnetic arcades, emitting due to interaction of energetic particles with the chromospheric plasma. However, the physics of this interaction and properties of the accelerated particles are still unknown. We present results of multiwavelength observations of the C2.1 flare of 2013 August 15, observed with the New Solar Telescope of the Big Bear Solar Observatory, and the Solar Dynamics Observatory, GOES, and Fermi spacecraft. The observations reveal previously unresolved sub-arcsecond structure of flare ribbons in regions of strong magnetic field consisting from numerous small-scale bright knots. We observe a red–blue asymmetry of \(\alpha\) flare ribbons with a width as small as \(\sim 100\) km. We discuss the relationship between the ribbons and vertical electric currents estimated from vector magnetograms, and show that Joule heating can be responsible for energization of \(\alpha\) knots in the ribbons.

Key words: Sun: flares – Sun: magnetic fields

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1. INTRODUCTION

Flare energy release in the lower solar atmosphere is usually observed in the form of two parallel ribbons radiating in a broad range of the electromagnetic spectrum. Emission from such ribbons can be stimulated by precipitating accelerated particles, Joule heating by electric currents, electron heat flux from a primary energy release site, or by a combination of these processes operating together. The standard (“thick-target”) flare model (Brown 1971) assumes that the primary energy release occurs due to a magnetic reconnection process high in the corona, and that the low atmospheric phenomena represent a response to this energy release. However, there are evidences that the energy release may occur directly in lower regions of the solar atmosphere (Fletcher et al. 2011). In this case, the flare ribbons may also be generated by initial energy release in the lower solar atmosphere.

Knowledge of the fine structure of flare ribbons and their links to the overlying flare arcade is of great importance for the understanding of solar flares, because the dissipation rate of possible heating sources strongly depends on the value of the so-called “filling factor” of the emitting plasma. The importance of the flare’s fine structure was realized long ago (e.g., Severnyi 1957). Recently, Krucker et al. (2011) discussed the implication of \textit{Hinode} optical observations of flare ribbons for the “thick-target” model. Fluxes of nonthermal electrons per unit area, estimated in the framework of this model, can be explained only by assuming an unexpectedly high density of accelerated electrons. In such a situation, smaller values of the filling factor can result in even more extreme flux densities of nonthermal particles. In addition, loop-like structures (flare arcades) observed in the X-ray and microwave radio emissions clearly consist of multiple organized thin loops (e.g., Zimovets et al. 2013), which are also observed by \textit{TRACE} in the UV range.

Xu et al. (2012) discuss observations of flare kernels observed in the visible and near-infrared continua with characteristic sizes as small as \(0.5\)\,′′. It appears that such fine structuring is an intrinsic property of the flaring plasma at all levels of the solar atmosphere.

In this paper we present analysis of high-resolution observations of flare ribbons in the low atmosphere obtained with New Solar Telescope (NST; Goode & Cao 2012) and simultaneous observations from three NASA spacecraft: \textit{Solar Dynamics Observatory} (SDO), GOES, and Fermi. For the analysis, we selected a C2.1 GOES class flare that occurred on 2013 August 15, at approximately 16:45:00 UT. The main criteria for selecting this event are its weakness (absence of extreme saturation of CCD) and the presence of large flare ribbons with relatively good seeing. The main task is to investigate the fine structure of the flare ribbons and their connection with the properties of electric currents estimated from vector magnetic field measurements from SDO/HMI (Centeno et al. 2014).

2. GENERAL DESCRIPTION OF THE EVENT

The C2.1 flare occurred in the active region NOAA 11818 near the disk center. The absence of coronal mass ejections and type II radio bursts indicates that the flare was non-eruptive. Also, there were no type III radio bursts, indicating the absence of open magnetic field lines or large fluxes of accelerated electrons. Figure 1 presents a summary of the \textit{GOES} and \textit{Fermi} observations. The \textit{GOES} data represent observations of soft X-ray emission integrated over the solar disk in two channels: 1–8\,Å and 0.5–4\,Å with a time cadence of 2 s. These data (Figure 1(A)) reveal a “two-bump” flare starting at \(\sim 16:45\) UT and ending at \(\sim 18:17\) UT (after this time the light curves are influenced by a flare from a different active region). The first \textit{GOES} sub-flare in the long-wave channel peaked at 17:16 UT, and the second one had maximum emission around 17:57 UT. In Figure 1(C) we also show the flare emission measure and temperature, estimated following Thomas et al. (1985). The temperature and emission measure profiles due to the background emission were removed.

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The X-ray data from detector NaI-0 of the Gamma-ray Burst Monitor (GBM) on the Fermi spacecraft are plotted in Figure 1(D) with the time cadence of 0.25 s. We see that the shape of the GOES first peak is different from the Fermi count rate profile. The reason for this is that GBM is more sensitive to the hot plasma than the GOES detectors, which mostly register a relatively low-temperature plasma. The hard X-ray (HXR) emission with photon energies greater than 27 keV (green curve in Figure 1(D)) appears only for the second GOES peak at 17:51:56 UT; it correlates with the maxima of GOES X-ray flux derivatives for both channels. The correlation between the flare HXR emission and the time derivative of the soft X-ray (SXR) emission (Figure 1(B)) is known as the Neupert effect (Neupert et al. 1969). In the framework of the standard model, it corresponds to the initial plasma heating by accelerated electrons (HXR impulse) with subsequent chromospheric evaporation (SXR emission). In our case, the SXR time derivative starts increasing at ~17:40 UT (second peak in Figure 1(B)) at least 10 minutes earlier than the HXR peak (green curve in Figure 1(D)); this may be due to additional energy release in the preheating phase. Moreover, during the first GOES sub-flare around 17:10:00 UT, no HXR emission was observed. It appears that in this phase the plasma was heated to high temperature by some other mechanism different from the thick-target model. This event can be characterized as a confined C2.1 flare with a minor signature of particle acceleration, but with separated extended ribbons.

3. NST DATA

To investigate the spatial structure of the flare we use $H_\alpha$ data obtained with the Visible Imaging Spectrometer (VIS) at the 1.6 m NST (Goode & Cao 2012). The NST data catalog is available from http://www.bbso.njit.edu. The new system of adaptive optics AO-308 and large aperture make it possible to observe the Sun with high spatial resolution. The pixel size of the VIS images is about 0'029, which is approximately three times smaller than the telescope diffraction limit $\lambda_{H\alpha}/D \approx 0'084$. Final images are prepared by using a speckle reconstruction technique (Wöger et al. 2008). The time cadence between two subsequent line scans in 11 wavelength bands (6563 Å ± 1.0, ±0.8, ±0.6, ±0.4 and ±0.2 Å) is 30 s. The NST observations started approximately at 17:10 UT; the data do not cover the beginning of the first sub-flare, but include the entire second subflare.

In Figure 2 we present the evolution of the flare’s $H_\alpha$ emission in comparison with the line-of-sight magnetic field observations from HMI. The time cadence of the magnetograms is 45 s, and their spatial resolution is about 1' (pixel size \~0.5'). To illustrate the structure of the flare emission in the lower solar atmosphere we selected three VIS channels: $H_\alpha$ red wing (+0.8 Å), $H_\alpha$ line center, and $H_\alpha$ blue wing (−0.8 Å). The contour lines mark the regions of strong magnetic field with magnitude > 1 kG for comparison with bright features of the VIS data.
One of the interesting features observed by VIS is a dark filament (marked as $F$ in Figure 2) rooted near a small sunspot embedded into the penumbra of the larger sunspot (marked $Y$ in Figure 2). Near the footpoint of the filament we see very bright sources in the H$_\alpha$ center, in addition to the two-ribbon flare structure. It is important to note that there is a strong incursion (shaped like a snake) of the opposite polarity magnetic field into the sunspot penumbra. This incursion ends near the rooted part of filament $F$, and coincides with the accompanying bright H$_\alpha$ sources.

There was no significant H$_\alpha$ emission near the filament footpoint in both the blue and red line wings, which reflect the conditions in the layers of the solar atmosphere that are deeper than the layer observed in the line core. Generally, images made in the H$_\alpha$ wings show weaker emission than in the line center. The strongest emission in the line wings is observed during
the HXR pulse, in the form of two large-scale ribbons (marked in Figure 2 as R1 and R2). Ribbon R1 has a diffuse structure and located in the region of relatively weak field (<1 kG), while the other ribbon, R2, is very thin and located directly in the sunspot umbra, where the magnetic field reaches 2.3 kG. Since the very strong emission of the ribbons in the Hα center is observed long before the HXR impulse, this means that the initial plasma heating is likely not to be connected with the accelerated particles.

A remarkable property detected in the NST observations is the ultra-fine structure of the flare ribbons. To demonstrate this we present zoomed-in images of the flare ribbon R2 and $Y$-point near the root of filament $F$ in Figure 3 (bottom panels). The observed width of ribbon R2 in the red Hα wing is sometimes as small as 0′′.1 (~70 km). The ribbon has a clear fragmented structure in the form of tiny bright dots with the total area estimated to be $\approx 3 \times 10^{16}$ cm$^2$. The geometry of the flare region marked in Figure 2 as $Y$ is very complex. It consists of many bright filaments and the overlying darker filaments intersecting each other. This is perhaps a site of a very complex magnetic reconnection process involving penumbral flows and filament $F$.

In summary, the high-resolution NST data reveal superfine structuring of the chromospheric flare emission with a characteristic size of $\sim 100$ km, organized in a very thin but long $\sim 10,000$ km ribbon crossing the sunspot region. The other flare ribbon, located in a flare region, is spatially diffused but also

Figure 3. Top panels: structure of the $Y$-region observed in the center of the Hα line. Middle panels: the ribbon R2 in the red wing of the Hα line +0.8 Å. Bottom panels: zoomed-in ribbon R2 in the box marked by yellow rectangles in the middle panels. Contours mark the magnetic field with strengths of 1, 1.5, and 2 kG. Blue contours on the right middle panel display the vertical electric current with levels 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70% and 90% of the maximum. (A color version of this figure is available in the online journal.)
Figure 4. Distributions of the vertical electric current density (top panels) and coronal emission in the AIA 304 Å channel (middle panels), and in the 94 Å channel (bottom panels). Overlaid contours on the images correspond to the absolute values of the line-of-sight magnetic field of 1, 1.5, and 2 kG. White and black contours mark the magnetic field polarity inversion line. (A color version of this figure is available in the online journal.)

displays small-scale structuring. In addition, the chromospheric emission of the flare ribbons starts long before the HXR impulse. The observed heating before the appearance of the HXR emission cannot be explained by accelerated particles precipitating into the chromosphere, as assumed by the standard model. There must be additional heating mechanisms associated with the superfine organized structuring of the flare ribbons. Such fine structuring suggests that the heating mechanism may be related to Joule heating by chromospheric electric currents.

4. SDO DATA, ESTIMATION OF ELECTRIC CURRENTS

In this section we consider the evolution of vertical electric currents at the photosphere level. To calculate the vertical currents we use disambiguated HMI vector magnetic field data (Centeno et al. 2014). The time cadence is 720 s, and the spatial resolution is the same as for the line-of-sight magnetograms (0′.5) per pixel. The vertical electric current density is calculated from Ampere’s law, \( j_z = (\nabla \times B)_z/\mu_0 = (\partial B_x/\partial y - \partial B_y/\partial y)/\mu_0 \).

Figure 4 displays a comparison of the electric current density with the flare images from the AIA (Lemen et al. 2012) EUV data in two channels: He II 304 Å and Fe xvii 94 Å. The first channel has a peak in the temperature response function near 10⁵ K, while for another channel, the response goes up to 10⁶ K. The temporal and spatial AIA resolutions are correspondingly 12 s and 1′.2 (with the CCD pixel size of 0′.6).
The structure of electric currents in the flare region is very complicated. Numerous islands of electric current intensification are located near the polarity inversion line of the magnetic field and correspond to strong field regions. In the vicinity of the region marked $Y$ we observe the strongest electric currents during the whole flare. As we mentioned previously, this is a place of bright Hα sources where the filament $F$ is rooted, and a place of intrusion of the opposite polarity magnetic field. This coincidence indicates that this region is probably heated by electric currents. The AIA 94 Å images show the evolution of the hot plasma with temperatures comparable with the estimations based on the GOES data (Figure 1(C)). High coronal loops are rooted in the region of ribbons, and in the upper image we see a jet-like structure originating from near the $Y$-region.

Ribbon R1 observed in the 304 Å channel does not coincide exactly with the electric currents observed near the line of magnetic polarity inversion, but the emission sources seen in the Hα line center partially correlate with these electric currents. In the region of ribbon R2 the enhanced electric currents correlate with a bright stripe seen in both the AIA 304 Å and VIS Hα images. In Figure 3 (right middle panel) we show the contour map of the vertical electric currents ($j_z$), which shows a spatial correlation of the ribbon R2 with high values of $j_z$. Such a correlation is more pronounced for the Hα emission sources near the $Y$-region.

To analyze the temporal dynamics of the electric currents in the flare region we select three boxes containing the $Y$-region, ribbons R1 and R2 (Figure 5). We calculate the mean value of $j_z$ in the boxes, accounting only for $j_z > \max(j_z)/2$ to reduce the contribution of the background. Errors are estimated as standard deviation of electric currents distribution in the quiet Sun. In Figure 5 we compare the time profiles of the total vertical electric current in all three boxes with the evolution of the SXR emission according to the GOES observations. During the flares we see an intensification of the vertical electric currents in the ribbons, but in the $Y$-region we observe a local minimum. We also display the calculated time derivative of the total $B_z$ magnetic flux through all flare regions, including boxes marked on Figure 5, as:

$$\frac{dF}{dt} = d \left( \int B_z dS \right) / dt.$$

This value is proportional to the circuit’s electric current and can be considered as an indicator of the magnetic flux dynamics in terms of the electric field. It is one of the way to detect magnetic flux emergence or cancellation, events which could trigger a reconnection process. In Figure 5 we see that the main peak of $dF/dt$ corresponds to the HXR sub-flare. This probably means that the flare energy release is associated with the flux emergence.

In our study of the temporal dynamics of electric currents, we use the HMI vector magnetic field data from 15:00 UT up to 21:00 UT. Figure 5 shows that before the flares the electric currents are intensified and accompanied by a high rate of the magnetic flux change. However, the HXR emission appears at ~17:52 UT after the electric currents in ribbons R1 and R2 started increasing.

5. DISCUSSION

The main result of this paper is the detection of extremely fine structuring of the Hα emission of the flare ribbon located in the umbra of the sunspot. The width of the ribbon emission is as small as $0.1 \approx 100$ km. In the case of thin magnetic loops the density of the electric current can reach high values as it depends on the value of the filling factor. In the many works connected with flare studies, the filling factor is usually assumed to be unity (e.g., Saint-Hilaire & Benz 2005; Veronig et al. 2005).

The electric current density estimated from the HMI data reaches $3 \times 10^{10}$ pixel$^{-1}$ or 0.4 A m$^{-2}$. Since the HMI pixel size is 0.5 x 0.5, and the observed size of the ribbon knots is $0.1 \times 0.1$, then the electric current density can be much greater. Assuming five knots in the HMI pixel (shaped like chain) the real density of the vertical electric current and field is five times larger.

In the regime of electric current dissipation the magnetic Reynolds number $Re_m = 4 \pi \sigma_{eff} L^2 / (c^2 \tau) \approx 1$, where $\sigma_{eff}$ is effective electric conductivity, $\tau$ is a characteristic time of electric current dissipation, and $L$ is a characteristic length scale which is taken as the size of the observed Hα knots $\approx 100$ km. From this formula, assuming $\tau \sim 10^2-10^3$ s (the duration of the HXR pulse and SXR flare), we obtain $\sigma_{eff} \sim 7 \times 10^{-5} \Omega$ m$^{-1}$. This value is somewhat lower than the theoretical estimates of electrical conductivity in the sunspot atmosphere, $\sim 10^9$-$10^{10}$ s$^{-1}$ (Kopecký & Kuklin 1966; Oster 1968). However, in the presence of magnetic field, heating by electric currents in the partially ionized chromospheric plasma can be enhanced due to Pedersen conductivity. Also, the current dissipation may be enhanced due to turbulence.

The energy release rate of electric current can be estimated as $Q_j = j_z^2 / \sigma_{eff}$. For the calculated values of $\sigma_{eff}$
and $j = 0.4 \, \text{A m}^{-2}$ we have the volumetric heating rate $Q_j \sim 20-200 \, \text{erg s}^{-1} \, \text{cm}^{-3}$. To estimate radiation losses we use the assumption of optically thin plasma in the heated volume. As the $\text{H}_\alpha$ emission corresponds to a typical temperature of $T = 10^4 \, \text{K}$ the value of the radiation loss function is $f(T) \approx 10^{-21} \, \text{erg s}^{-1} \, \text{cm}^3$ (Rosner et al. 1978). Radiation energy losses are determined by the formula $L_{\text{rad}} = n_e n_H f(T)$, where $n_e$ and $n_H$ are the electron and hydrogen atom number densities. For $n_e n_H \sim 10^{22}-10^{24} \, \text{cm}^{-6}$ (Avrett 1981) $L_{\text{rad}} \sim 0.1-10 \, \text{erg s}^{-1} \, \text{cm}^{-3}$, which is smaller than $Q_j$. Heat conduction losses estimated to be $L_{\text{cond}} = 4 \times 10^{-6} T^{7/2} / L^2 \approx 10^{-5} \, \text{erg s}^{-1} \, \text{cm}^{-3}$ are much less significant than $L_{\text{rad}}$. Thus, the observed emission in the $\text{H}_\alpha$ ribbon knots and plasma heating can be due to the dissipation of electric currents. The largest part of $Q_j$ goes into the internal plasma energy $U_{\text{th}} = (n_e + n_H) k_b T$.

Together with the prominent fine structure in the red wing we observe similarly structured but weaker emission in the blue wing of the $\text{H}_\alpha$ line. In the simplest way, such asymmetry can be explained by the Doppler shift due to plasma downflows.

6. RESULTS AND CONCLUSIONS

The main observational results of the work are the following.

1. The high-resolution NST observations reveal super-fine structuring of the flare ribbon located in the sunspot umbra. Numerous small bright knots as small as 0′′1 ≈ 100 km are organized in a ∼10⁴ km long regular thread-like structure. The second flare ribbon located in a plage region with weaker magnetic field is more diffuse, but also shows fine structuring. The ribbons are stronger in the red wing of the $\text{H}_\alpha$ line than in the blue wing.

2. Vertical electric currents calculated from the HMI vector magnetograms spatially correlate with the observed $\text{H}_\alpha$ ribbons and emission sources. The temporal evolution of the vertical electric currents shows that a probable mechanism of ribbon emission is heating by electric currents in the initial energy release phase.

3. The EUV AIA and $\text{H}_\alpha$ NST observations show enhanced emission long before the appearance of HXR emission, indicating that active heating processes occurred without accelerated high-energy particles.

4. The observed fine structuring of flare ribbons can be explained by Joule dissipation if the electrical resistivity is enhanced in the partially ionized plasma of the lower solar atmosphere, or by turbulent resistivity due to even smaller structuring.

One of the most important open issues of this research is a very regular thread-like organization of the superfine structuring of the observed ribbons. This large-scale organization of the initial energy release needs further observational studies coupled with theoretical modeling.

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