EVIDENCE OF ELECTRON ACCELERATION AROUND THE RECONNECTION X-POINT IN A SOLAR FLARE

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ABSTRACT

Particle acceleration is one of the most significant features that are ubiquitous among space and cosmic plasmas. It is most prominent during flares in the case of the Sun, with which huge amounts of electromagnetic radiation and high-energy particles are expelled into the interplanetary space through acceleration of plasma particles in the corona. Though it has been well understood that energies of flares are supplied by the mechanism called magnetic reconnection based on the observations in X-rays and EUV with space telescopes, where and how in the flaring magnetic field plasmas are accelerated has remained unknown due to the low plasma density in the flaring corona. We here report the first observational identification of the energetic non-thermal electrons around the point of the ongoing magnetic reconnection (X-point), with the location of the X-point identified by soft X-ray imagery and the localized presence of non-thermal electrons identified from imaging-spectroscopic data at two microwave frequencies. Considering the existence of the reconnection outflows that carries both plasma particles and magnetic fields out from the X-point, our identified non-thermal microwave emissions around the X-point indicate that the electrons are accelerated around the reconnection X-point. Additionally, the plasma around the X-point was also thermally heated up to 10 MK. The estimated reconnection rate of this event is $\sim 0.017$.

Key words: acceleration of particles – magnetic reconnection – Sun: flares – Sun: corona

Online-only material: animations

1. INTRODUCTION

Particle acceleration is ubiquitously observed among space and cosmic plasmas, including those around Earth’s magnetotail (e.g., Oieroset et al. 2002), in supernova remnants (e.g., Koyama et al. 1995), and even in distant galaxies (e.g., Mushotzky 1977). For our Sun, acceleration of plasma particles is most prominent in flares, with which vast amounts of electromagnetic radiation from accelerated particles (e.g., Sakao et al. 1996; Yokoyama et al. 2002), as well as the particles themselves (e.g., Lin et al. 1996), are expelled into interplanetary space. Observations from space in the past few decades have established that it is magnetic reconnection during flares that converts magnetic energy in the corona into the kinetic and thermal energies of the plasma particles (e.g., Tsuneta et al. 1992; Masuda et al. 1994; Yokoyama et al. 2001; Hara et al. 2011; Imada et al. 2013; Su et al. 2013). It is thus expected that particle acceleration in flares should also be closely related to the magnetic reconnection process through which as much as half of the liberated energy is converted into acceleration of particles (Lin & Hudson 1976).

There have been a number of theoretical studies made so far that have considered various portions of the reconnecting magnetic structure as the site of electron acceleration in solar flares. These include inside the closed magnetic loop formed by reconnection (e.g., Fletcher & Hudson 2008), in the magnetohydrodynamic fast-shock structure expected to be formed above the closed loop (e.g., Tsuneta & Naito 1998), in the magnetic cusp region where field lines are contracting downward (e.g., Somov & Kosugi 1997), and around the X-point (or in the current sheet; e.g., Litvinenko 1996; Pritchett 2006; Drake et al. 2006; Oka et al. 2010). Meanwhile, some observations have addressed possible sites of the electron acceleration. Aschwanden et al. (1996) studied timing relationship among hard X-ray emissions in different energies and quantitatively estimated locations of electron acceleration above the flaring loops. Sakao et al. (1998) argued that electron acceleration should take place at the reconnection site, which is a common place among the two different magnetic field configurations identified from footprint motions of hard X-ray sources during the impulsive phases. These observations gave us the supposition that the particle acceleration would occur above the flaring loops.

However, there have not been any observations that pinpoint where and how in the flaring magnetic field plasmas are accelerated. This is partly due to the fact that magnetic reconnection in flares takes place in the high corona, where plasma density is low, and hard X-ray fluxes from energetic non-thermal electrons, which are emitted by bremsstrahlung (interaction with ambient coronal plasma), are too weak to be imaged by existing modulation-collimator type hard X-ray telescopes, whose dynamic range is not high, especially for the reconnection region. Meanwhile, there is a possibility that microwaves emitted from the energetic non-thermal electrons by the gyro-synchrotron mechanism (interaction with coronal magnetic fields) can be detected even in the low-density corona including the reconnection region.

In this paper, we report the first identification of energetic non-thermal electrons around the reconnection X-point in a flare, with the location of the X-point identified by soft X-ray imagery and the localized presence of non-thermal electrons identified from imaging-spectroscopic data at two microwave frequencies. This is a strong evidence of the electrons being accelerated around the X-point, providing an observational clue toward understanding the mechanism of electron acceleration in solar flares.
2. OBSERVATIONS

We present soft X-ray and microwave imaging observations, made with the Soft X-ray Telescope (SXT; Tsuneta et al. 1991) aboard the Yohkoh satellite and the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994; Takano et al. 1997), respectively, of the 1999 August 6 UT flare that occurred from around 04:34 UT in NOAA active region 8647 on the west limb of the Sun (S19W91; see Figure 1). The X-ray flux detected by the GOES satellite was almost flat at a level of \(-C6\). The evolution of this flare was not seen in the GOES light curve, probably because this flare was not large enough in soft X-ray flux against the other eight active regions simultaneously located on the solar disk. Hence, we track the evolution of this flare with the soft X-ray intensity from the flaring loop derived from the HXT/SXT data as described in Section 2.1. Though we also check the hard X-ray data taken with the Hard X-ray Telescope (HXT) aboard the Yohkoh satellite, the hard X-ray signal from this flare was very weak against the background level. This is probably because the footpoint of the flaring loop was located behind the solar limb. Hence, we do not discuss the hard X-ray data in this paper.

2.1. Location of the X-point Identified with Soft X-Ray Imagery

Yohkoh/SXT observed the evolution of the flare, from its very early stage, followed by an ejection of a plasmoid structure as seen in animation 1. The corresponding large-scale feature was also observed in an EUV wavelength (195 Å; animation 2; Narukage & Shibata 2006). From around 04:34 UT, the width of the portion connecting the top of the bright soft X-ray loop and the plasmoid started to decrease with time, which eventually led to the plasmoid ejection after \(-04:50 UT\) (see Figure 2(a)). We note that the soft X-ray intensity from the bright soft X-ray loop derived from the SXT data continued to increase as the width decreased, while it turned into a decrease after the ejection, following the peak in the soft X-ray flux (Figure 2(b)). Such behavior in soft X-rays is consistent with what is expected from the well-perceived reconnection picture for flares (Figure 1(a); Shibata & Magara 2011), in which the observed decrease in width is attributed to reconnection inflow (Yokoyama et al. 2001; Narukage & Shibata 2006) toward the X-point while magnetic reconnection is in progress. From the soft X-ray image at the period of ongoing reconnection (Figure 1(c)), we have identified the X-like feature at the apex of the cusp shape structure, i.e., the smallest portion in width in the soft X-ray intensity contour map (see the contours in Figure 1 at 04:45:00 UT), as the location of the reconnection X-point, which is indicated by black circles in Figures 1(b)–(d). We consider that the X-point is located within the fixed black circles from the start of the reconnection to the plasmoid ejection, because the location of the plasmoid gradually moved upward as the flare progressed, but such moving distance is comparable to the diameter of the black circles until the plasmoid ejection at around 04:50 UT. After the plasmoid ejection, the X-point location cannot be tracked, since the plasmoid was ejected outside of the field of view. Additionally, the apex of the cusp shape structure shifted toward the northeast direction after the plasmoid ejection. Hence, we move the black circle along the yellow line in Figures 1(b)–(d) to track the location around the apex of the cusp shape structure (around the edge of the current-sheet-like feature) as seen in animation 3. In the following, quantities referred to as those around the X-point correspond to those averaged over the black circle.

![Figure 1](https://example.com/figure1.png)

Figure 1. Soft X-ray and microwave observations of the 1999 August 6 flare. (a) Schematic illustration of the reconnection picture for the flare. (b)–(d) Soft X-ray images taken with the AlMg filter of Yohkoh/SXT. Each of them is a composite frame made from a pair of full-resolution (2′.46 pixel\(^{-1}\)) and half-resolution (4′.92 pixel\(^{-1}\)) images. The location of the reconnection X-point is indicated by a black circle in each panel, whose diameter is set as 10′′ (\(-7300 km\)), which is approximately the beam size for the 17 GHz maps shown in (h)–(i). The yellow line is drawn to cross the center of the black circle (X-point) and in perpendicular direction to the plasmoid ejection. (e)–(g) Electron temperature derived from soft X-rays, which is approximately the beam size for the 17 GHz maps shown in (h)–(i). The yellow line is drawn to cross the center of the black circle (X-point) and in perpendicular direction to the plasmoid ejection. (e)–(g) Electron temperature derived from soft X-rays. (h)–(i) 17 GHz microwave brightness temperature maps from Nobeyama Radioheliograph (NoRH). (k)–(m) Spatial distribution of power-law index of microwave flux density spectra (alpha index) derived from NoRH 17 GHz and 34 GHz data. Distribution of alpha index with its error less than 1.0 is displayed in each panel of (k)–(m). Black or white contours in (e)–(m) trace soft X-ray intensity levels of 8000 and 30,000 DN s\(^{-1}\) pixel\(^{-1}\) for the full-resolution portion taken with the AlMg filter (thus the vertical feature at the right end of the outer contour level in (e)–(m) is artificial). The accuracy of the co-alignment between soft X-ray and microwave images is better than 2′. In each panel, the white arc represents the solar limb. North is up and east is to the left. (Animations of this figure are available in the online journal.)
2.2. Localized Presence of Non-thermal Electrons Identified with Microwave Imaging Spectroscopy

The flare was simultaneously observed in two microwave frequencies at 17 GHz and 34 GHz with the NoRH. Figures 1(h)–(j) give maps of the brightness temperature at 17 GHz showing a similar spatial distribution as that in soft X-rays. In Figures 1(k)–(m), we present the spatial distribution of the power-law index of the microwave flux density spectra (hereafter referred to as “alpha index”; Dulk 1985) derived from the brightness temperature maps at 17 GHz and 34 GHz. As the 34 GHz maps suffered from aliasing patterns from image synthesis, we carefully removed their effect before evaluating the alpha index; the procedure for this is detailed in Appendix A.

The meaning of the alpha index value is summarized in Table 1, based on Figure 2 in Dulk (1985). The sign of alpha index changes from positive to negative or zero at the frequency where $\tau \sim 1$ ($\tau$ is the optical depth). The degree of alpha index is determined by the emission mechanism of the microwave. As derived by Dulk (1985), for the optically thin gyro-synchrotron emission, the alpha index $\alpha$ is related to the spectral index of the accelerated electrons $\delta_B$ in such a way that $\delta_B = (1.22 - \alpha)/0.9$. Note that there is a difference between the electron spectral indices derived from microwaves $\delta_B$ and hard X-rays $\delta_X$, since each wavelength is emitted from the electrons in different energy ranges by different emission mechanism (i.e., gyro-synchrotron and bremsstrahlung, respectively). According to Asai et al. (2013), the difference between $\delta_X$ derived from Yohkoh/HXT and $\delta_B$ from NoRH is $\delta_X - \delta_B \sim 1.6$ for eight flare examples.

We note that in Figures 1(k)–(m), and also in animation 4, there is a localized distribution of negative alpha index around the X-point for the period of ongoing reconnection (at 04:45 UT; Figure 1(f)) and around the timing of the plasmoid ejection (at 04:50 UT; Figure 1(m)), while the alpha index is around zero in the early stage of the flare (at 04:34 UT; Figure 1(k)). The degree of circular polarization at 17 GHz for the region above the bright soft X-ray (as well as microwave) loop was at most $\sim 2\%$, so the possibility of gyro-resonance emission for this region can be safely ruled out. With this possibility excluded, the negative values of alpha index around the X-point immediately indicate, by themselves, that the microwaves there originate from optically thin (gyro-)synchrotron emission by non-thermal, i.e., accelerated, electrons of (mildly) relativistic energies (see Table 1). We note that, in reality, thermal electrons should also coexist in the corona, and the observed alpha index contains a contribution from both thermal and non-thermal electrons along the line of sight. Even in this case, the negative alpha index indicates the existence of non-thermal electrons, because only the optically thin non-thermal gyro-synchrotron emission can cause the negative alpha index except for the optically thin gyro-resonance emission that was excluded as mentioned above (see Table 1), although $\delta_B$ cannot be estimated correctly from this alpha index. The amount of the non-thermal electrons is discussed in Section 3. The alpha index of $\sim 0$ in the early stage of the flare is likely due to optically thin bremsstrahlung emission from thermal electrons at the initial stage of the acceleration process. Figure 2(c) gives the temporal evolution of the alpha index around the X-point. As the reconnection proceeds toward the plasmoid ejection, the alpha index decreases to larger negative values, increasing the significance of the presence of non-thermal emission there.

| Emission Mechanism                          | Alpha Index |
|---------------------------------------------|-------------|
| Non-thermal gyro-synchrotron $\delta_B = 3^a$ | $+2.9 \pm 0.1$ |
| from mildly relativistic electrons           | $-1.5$       |
| Thermal gyro-synchrotron (gyro-resonance)   | $+2$         |
| Thermal Bremsstrahlung                      | $+2$         |

Notes. This table is the summary of Figure 2 in Dulk (1985). $^a \delta_B$ is the electron spectral index.
After the ejection, the alpha index in the black circles of Figure 1 (that show the location of the X-point before the plasmoid ejection, and now around the edge of the current-sheet-like feature) returned toward zero, suggesting thermalization there or evacuation of the accelerated electrons from the region.

3. ESTIMATE OF THE NON-THERMAL COMPONENT

In addition to the non-thermal (gyro-)synchrotron component discussed above, the observed microwave brightness temperature contains another component from bremsstrahlung emission by thermal electrons along the line of sight. Since we can infer the temperature and column emission measure of the thermal electrons from the SXT images with the filter ratio method (Tsuneta et al. 1991; Takeda 2011) as shown in Figure 3, the brightness temperature at 17 GHz expected from soft X-ray-emitting thermal plasmas, $T_{B}^{th}$, can then be calculated (Dulk 1985) as shown in Figure 2(d). By subtracting $T_{B}^{th}$ from the measured brightness temperature at 17 GHz, we obtain the residual brightness temperature $T_{B}^{NT}$ that may be a good measure of the emission from non-thermal electrons. The “non-thermal brightness temperature” $T_{B}^{NT}$ thus derived around the X-point rapidly increased to $\sim$7000 K in the early stage of the reconnection process at around 04:34 UT (see Figure 2(e)). It stayed around this level throughout the reconnection process until the ejection of the plasmoid. This may indicate that the electron acceleration process continued to be in operation during this period. Since the temporal evolution of the alpha index and $T_{B}^{NT}$ clearly synchronize with the reconnection process, it is most likely that the acceleration process of electrons around the X-point closely traces the progress of magnetic reconnection. After the ejection, we see a drastic decrease in $T_{B}^{NT}$. This indicates that the electron acceleration either ceased or weakened significantly around the edge of the current-sheet-like feature where the X-point was located before the plasmoid ejection.

4. DISCUSSION

We have shown that there is microwave emission from non-thermal electrons most clearly seen around the X-point. This indicates that there are energetic electrons present around the X-point during the course of the magnetic reconnection. Meanwhile, the soft X-ray observations of the flare were in good agreement, in a morphological sense, with the canonical reconnection picture (Figure 1(a)) from which we expect, in addition to the inflow, bi-directional outflow of plasma particles and magnetic fields away from the X-point toward the bright soft X-ray loop and in the opposite direction (Shibata & Magara 2011). Assuming the presence of the expected reconnection outflow, it would be reasonable to conclude that the energetic non-thermal electrons are supplied from, namely, accelerated at, the region around the X-point rather than assuming that they travel from a region lower in altitude than the X-point against the counter-streaming downward outflow, or that they come from a region higher in altitude beyond the X-point against the counter-streaming upward outflow from the X-point. The observed decreasing trend in the column emission measure (Figure 3(c)), i.e., a decrease in density of soft-X-ray-emitting thermal electrons, would be due to the ambient electrons being swept away from the X-point by the reconnection outflow and/or them departing from thermal equilibrium due to collisions with accelerated electrons (Krucker et al. 2010). Furthermore, as seen in animation 4, the negative alpha signal traveled from around the X-point to the footpoint of the flare loop along the northern outer edge of the flare loop around the timing of the plasmoid ejection. This gives further support that the accelerated electrons manifesting themselves as the negative alpha signal are originated from around the X-point, although the traveling negative alpha signal does not immediately correspond to the individual energetic electrons. Hence, we argue that electron acceleration around the X-point is the initial (first-stage) acceleration in a flare that immediately follows the onset of reconnection.

We further take a closer look into the region around the X-point. The spatial extent of the negative alpha index in the lateral direction (parallel to the solar surface) is possibly caused by the inclined configuration of the flaring loop to the line of sight as reported by Narukage & Shibata (2006). Meanwhile, the length of the localized negative alpha index, i.e., the region where the energetic non-thermal electrons exist, has a spatial extent of $\sim$20,000 km along the direction of the height and is located at the topmost of the cusp structure, for the period of ongoing reconnection (see Figure 1(l)). Considering this spatial extent along the direction of the height, the possible scenarios of the electron acceleration around the X-point are as follows: (1) An X-point alone can produce energetic electrons with the inductive reconnection electric field (e.g., Pritchett 2006). Such energetic electrons can easily escape from the X-point and emit microwaves from a spatially extended region as seen in our data. (2) Multi-island coalescence along a single current sheet should also be considered as an electron acceleration scenario (e.g., Oka et al. 2010). (3) Fragmented islands scenario with multiple current sheets (e.g., Drake et al. 2006; Shibata & Tanuma 2001) is also possible, since, considering the spatial resolution of our microwave data ($\sim$10′), the multiple current sheets cannot be resolved, and the non-thermal signals in microwaves should be observed as only one source as seen in the presented data.
We note that the hot thermal electrons (> 10 MK) spatially co-exist with the energetic non-thermal electrons (Figures 1(e)–(g)) around the X-point. Since the coronal temperature below the X-point is cooler than around the X-point, we can say that the hot plasmas around the X-point are not heated by the thermal conduction from the plasmas located below the X-point. These high-temperature plasmas are directly created by the released magnetic energy that would also accelerate the electrons, and/or are the result of the thermalization of the accelerated electrons.

In our flare, we also find microwave non-thermal sources other than around the X-point (see the negative alpha index distribution in Figure 1, especially in Figure 1(m)). One is located at the footpoints of the flaring loop. This negative alpha index is also due to the non-thermal emission, not the gyro-resonance emission, since the sunspots were occulted by the solar disk in this flare. The other non-thermal source is distributed above the top of the flaring loop extending from the X-point region. These two kinds of observed microwave non-thermal sources became noticeable around the X-point region. This is consistent with the timing where intensity enhancement in the hard X-rays was observed around the timing of plasmoid ejections (e.g., Ohyama & Shibata 1998). Hence, these two kinds of sources may have a close relationship with the well-known hard X-ray non-thermal sources, e.g., double-footpoint sources (e.g., Sakao et al. 1996) and above-the-loop-top sources (e.g., Masuda et al. 1994). Considering the spatially smooth distribution of the negative alpha index extending from the X-point region (larger negative alpha index ∼−1) to the above-the-loop-top region (smaller negative alpha index ∼0) at the timing when the microwave non-thermal sources became noticeable (see Figure 1(m)), it is reasonable to expect that no major acceleration site other than around the X-point exists, although some additional sub-accelerations might occur in other locations. The hard X-ray above-the-loop-top source (e.g., Masuda et al. 1994) may appear as a lower part of the spatial distribution of non-thermal electrons from the X-point region to above the loop top manifesting themselves in microwaves (with negative alpha index), and it is detected due to the denser coronal plasmas near the flaring loop with which bremsstrahlung hard X-rays are efficiently emitted.

Meanwhile, the reconnection rate can be estimated to be ∼0.017 from the data set of the following parameters considering the line-of-sight effect (Narukage & Shibata 2006): the inflow velocity (∼16.3 km s⁻¹) derived from Figure 2(a), the footpoint expanding velocity (∼3.3 km s⁻¹) of the flare loop from X-ray data, the averaged magnetic field strength at the sunspot (∼98 G) from the magnetogram, and the coronal column emission measure (∼10²⁸.⁴ cm⁻³, which corresponds to the number density of 10³.⁹ cm⁻³ for the line-of-sight depth of 60,000 km) from the soft X-ray data with the filter ratio method. This reconnection rate supports the Petschek-type reconnection against Sweet–Parker type (Priest 1982).

The solar corona provides a unique opportunity for investigating the acceleration process associated with magnetic reconnection, not only in that the entire view of the reconnecting magnetic structure can be obtained by imaging, but also because the spatiotemporal evolution of any sources with certain spectral features in the dynamically evolving reconnecting structure can be traced by the imaging-spectroscopic approach. With the present result being the first step, progress in theoretical investigations and future observations such as from Atacama Large Millimeter/submillimeter Array (Bastian 2002) with very high spatial resolution and mirror-focusing hard X-ray (Krucker et al. 2013) and soft X-ray (Sakao et al. 2012) telescopes with photon-counting capabilities should help us solve the long-standing questions about particle acceleration in solar flares.

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APPENDIX A

REMOVAL OF THE ALIASING PATTERNS IN 34 GHz BRIGHTNESS TEMPERATURE MAPS

We here explain the method we devised for removing the aliasing patterns in synthesized images at 34 GHz taken with the NoRH. NoRH is a radio interferometer dedicated for solar observations at 17 GHz and 34 GHz microwave frequencies (Nakajima et al. 1994; Takano et al. 1997). A set of raw signals from NoRH gives spatial Fourier components of the two-dimensional brightness distribution across the full Sun, and it is necessary to reconstruct (synthesize) images from the set of raw data to obtain a microwave map of the Sun. NoRH was designed to have its fundamental antenna spacing (smallest antenna spacing) in such a way that it can measure Fourier components corresponding to 40' at 17 GHz. This implies that NoRH is capable of synthesizing full-Sun microwave maps at 17 GHz free from the aliasing effect, while there are inevitable aliasing patterns present in synthesized 34 GHz maps as illustrated in Figure 4. These aliasing patterns (pseudo brightness temperature distribution) drift as the azimuth and elevation of the Sun seen from NoRH change with time (animation 5).
In deriving the microwave alpha index from sets of 17 GHz and 34 GHz maps, it was crucial to correctly remove the aliasing patterns in the 34 GHz maps. In this study, we removed only “aliasing pattern 1” (hereafter AP1) shown in Figure 4 and animation 5, since it is the only aliasing pattern component whose intense part passed over the flare site we analyzed (see animation 5). The effect of other aliasing patterns and residual random fluctuation in brightness temperature maps with image synthesis will be discussed later.

For the removal of AP1, the motion of AP1 should be tracked. However, there was no intense feature in AP1 suitable for tracking its motion. Hence, we first identified the motion of the pseudo flare site produced by the aliasing effect in aliasing pattern 2 (indicated by a blue arrow in Figure 4 and animation 5) using correlation tracking of the real flare site (indicated by a red arrow in Figure 4 and animation 5) and the pseudo one. Then, by making use of the motion of the pseudo flare site and the fact that the motions of aliasing patterns 1 and 2 are symmetric about the center of the solar disk (see animation 5), we identified the motion of AP1.

In order to extract AP1 from the original 34 GHz map, we took the following approach. As we know the relative motion between the real Sun and AP1, instead of looking into the drifting AP1 as we see in animation 5, we fixed the aliasing pattern spatially and let the image of the real Sun drift (Figure 5 and animation 6). At sufficient heights from the microwave disk of the Sun (shown as the green-colored zone on the left-hand side of animation 6), we can expect that any features seen above that height, i.e., inside the green-colored zone, are of non-solar origin, that is, originate from the aliasing. This way, AP1 can be extracted from the brightness distribution in the green-colored zone by utilizing the scanning motion of the real solar disk with an assumption that AP1 was stable over the time of the observations. The resultant patterns of AP1 are shown in green on the right-hand side of Figure 5 and animation 6. Note that each point of the aliasing pattern map gives a brightness temperature for AP1 at a combination of certain time and location on the real Sun. For the X-point structure discussed in the main text, the location of AP1 that passes through the X-point region (from 04:30:30 UT to 05:15:00 UT) is shown in red in Figure 5 and animation 6. An average of 60 consecutive brightness temperature maps (each with 10 s of accumulation time, with a duration of 10 minutes) was taken for determining the brightness at each spatial point in AP1. As can be seen in animation 5, AP1 drifts through the flare site before it moves away from the limb. This means that AP1 determined in the green-colored zone lags behind the time when the corresponding portion of AP1 drifted through the flare site. In order to minimize the effect of any temporal variation in AP1, when determining the brightness temperature at each spatial point in AP1, the first 60 maps after the point entered into the green-colored zone were used. For the final phase of the flare (after 05:08:20 UT), less than 60 maps were available because of a decrease in image quality of the synthesized 34 GHz maps after 05:38:30 UT (which were used to determine AP1 that passed through the flare site after 05:08:20 UT). The relationship between the time that AP1 drifted through the flare site and that of determining AP1 in the green-colored zone is illustrated in Figure 6.

The brightness temperature distribution of AP1 thus derived was subtracted from the original 34 GHz map for each epoch during the observations. Figure 7 and animation 7 illustrate pre- and post-removal of AP1 around the flare site at 34 GHz, where we can see that the bright features in AP1 are successfully removed. After the removal of AP1, however, there are still some flickering features caused by (1) residual random fluctuation due to image synthesis, (2) aliasing patterns other than AP1 (although weak in brightness), and (3) any possible temporal variation in AP1.
Let us now evaluate these effects. Figure 8 indicates the variation in brightness temperature of the aliasing patterns along the red line in the right-hand panel of Figure 5. Note that the horizontal axis (with a label “pixel”) of this figure gives the location along the red line in Figure 5 and also gives (with a label “time”) the time when that location of API passed the site of the X-point. For each point on the horizontal axis, the distribution in colors along the vertical axis gives the fractional distribution of the brightness temperatures among the 60 maps used (until 05:08:10 UT, with fewer numbers of maps after then). This fractional distribution reflects the stability of the brightness temperatures in the drifting aliasing pattern, with the average and standard deviation for each point on the horizontal axis shown in the same figure. The almost constant standard deviation of \( \sim 1000 \) K across the entire horizontal axis location in the figure suggests that random fluctuation due to image synthesis is the main cause of this standard deviation. The amount of the standard deviation in the brightness temperature of API was incorporated when obtaining the real brightness temperature by subtracting API from the original 34 GHz maps. The error in the alpha index derived in the main text (error bars in Figure 2(c)) comes from this standard deviation.

So far we have used the pseudo brightness temperature from API, extracted from the 34 GHz maps in the time range of 04:57:00 UT–05:38:30 UT, for removing the effect of API that passed the X-point between 04:30:30 UT and 05:15:00 UT. There is typically a time gap of \( \sim 30 \) minutes present between the two (the time gap is not constant due to the non-linear drifting motion of API with respect to the real Sun). In order to check whether the pseudo brightness temperature distribution of API was stable enough over this time span, another set of brightness distribution of API was extracted, by utilizing the on-disk portion of the microwave Sun (shown as a blue circle on the left-hand side of Figure 5), where there was little activity (confirmed from EUV images; animation 2). In such a quiet region, an almost flat distribution of 34 GHz brightness temperatures at \( \sim 9000 \) K is expected (Selhorst et al. 2005). 34 GHz maps from 04:05:00 UT to 04:50:40 UT were used for determining API utilizing the on-disk quiet portion, by subtracting the flat disk component at 9000 K. This gives a pseudo brightness temperature distribution from API that passed the X-point from 04:40:40 UT to 05:15:00 UT as illustrated in Figure 6. The quality of the synthesized maps before 04:04:50 UT (which corresponds to the X-point passage before 04:40:30 UT) deteriorated; hence, they were excluded from the analysis. The resultant average pseudo brightness temperature distribution (each derived from 60 consecutive maps closest in time to the X-point passage) is shown by a black line in Figure 8. Throughout the period where API of the pre-flare-site passage was available (after 04:47:30 UT), the overlaid profile falls well within the range of the standard deviation, indicated by thin white lines in the figure. Thus, we conclude that the brightness temperature distribution of API around the flare site can be considered stable during the flare, within the range of standard deviation, supporting the validity of the method we used for removing API from the 34 GHz maps of the flare.

APPENDIX B

DESCRIPTIONS OF THE SUPPLEMENTARY ANIMATIONS

Animation 1. Evolution of the flare observed in soft X-rays with the AlMg filter of Yohkoh/SXT.

Animation 2. Global evolution of the flare observed in EUV 195 Å with the Extreme ultraviolet Imaging Telescope (EIT) aboard Solar and Heliospheric Observatory (SOHO). North is up and east is to the left. The flare site is located in the southwestern part of the Sun, on and above the solar limb.

Animation 3. Evolution of the flare in soft X-rays and in microwave frequencies. Top left panel: the same time–distance plot as in Figures 2(a) and 3(a), with the corresponding time for each video frame indicated by a vertical yellow line. Top middle
panel: soft X-ray images taken with the AlMg filter of \textit{Yohkoh}/SXT. Top right panel: plasma temperature derived by the filter-ratio method from pairs of AlMg and Be119 filter images from \textit{Yohkoh}/SXT. Bottom panels (from left to right): EUV full-Sun images, brightness temperature maps at 17 GHz, brightness temperature maps at 34 GHz, and the spatial distribution of the alpha index derived from 17 GHz and 34 GHz flux densities. The EUV images were observed with \textit{SOHO}/EIT in 195 Å. The white square in the EUV full-Sun image indicates the field of view of the other panels. The microwave data were taken with the NoRH.

\textbf{Animation 4.} Evolution of the flare observed in soft X-rays with the AlMg filter of \textit{Yohkoh}/SXT (orange) overlaid with regions of negative alpha index from 17 GHz and 34 GHz microwave flux densities from the NoRH (green; from 04:30:38 UT to 05:14:58 UT). Negative alpha indices of less than $-0.1$ with a 1σ error less than 0.5 are indicated in green, which saturates at an alpha index of $-0.5$. Negative alpha indices of less than $-0.1$ with a 1σ error less than 0.5 are indicated in green, which saturates at an alpha index of $-0.5$ ($-0.1$: transparent green; $-0.5$: opaque green).

\textbf{Animation 5.} Original brightness temperature maps at 34 GHz from NoRH that contain aliasing patterns. The flare site analyzed in this study is shown with a red arrow. The solar limbs of aliasing patterns 1 and 2 are indicated with orange dotted circles. The pseudo flare site produced by the aliasing effect is shown with a blue arrow.

\textbf{Animation 6.} Aliasing pattern in the 34 GHz maps. The green-colored zone on the left side of the video shows the region used for extracting AP1. The right side shows the extracted AP1. The red line on both sides indicates the trajectory along which the corresponding points on AP1 pass through the X-point.

\textbf{Animation 7.} Pre- and post-removal of AP1 around the flare site at 34 GHz. The left-hand panel presents original 34 GHz maps, while the right-hand panel shows the same maps after removal of AP1.

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