COORDINATED OVRO, BATSE, YOHKOH, AND BBSO OBSERVATIONS OF THE 1992 JUNE 25 M1.4 FLARE

H. WANG, D. E. GARY, AND H. ZIRIN
Big Bear Solar Observatory, Caltech M.S. 264-33, Pasadena, CA 91125

R. A. SCHWARTZ
GSFC NASA, Code 682.2, Greenbelt, MD 20771

AND

T. SAKAO, T. KOSUGI, AND K. SHIBATA
National Astronomical Observatory of Japan, Mitaka, Tokyo 181, Japan

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ABSTRACT

We compare 1–14 GHz microwave images observed at the Owens Valley Radio Observatory (OVRO), 16- and 256-channel hard X-ray spectra obtained by the Burst and Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory (CGRO), soft and hard X-ray images obtained by Yohkoh, and Hα images and magnetograms observed at the Big Bear Solar Observatory (BBSO) for the 1992 June 25 M1.4 flare. We find the following unique properties for this flare: (1) Soft X-ray emissions connect two footpoints, the primary microwave source is located at one footpoint, and hard X-ray emissions are concentrated in the other footpoint. The radio footpoint is associated with an umbral and may have stronger magnetic field. (2) During the period that 256-channel BATSE data are available, the hard X-ray photon spectrum consists of two components: a superhot component with a temperature of $8.4 \times 10^7$ K and emission measure of $2.5 \times 10^{48}$ cm$^{-3}$ and a power-law component with a photon index of 4.2. This is the first time that such a high temperature is reported for the hard X-ray thermal components. It is even more interesting that such a superhot component is identified before the peak of the flare. The microwave brightness temperature spectra during the same period also demonstrate two components: a thermal component near the loop top and a nonthermal component at the footpoint of the loop. The microwave thermal component has the similar temperature as that of the hard X-ray superhot component. These measurements are consistent with the theory that the microwave and hard X-rays are due to the same group of electrons, despite the fact that they are separated by 35,000 km. (3) The soft X-ray emissions brighten the existing loops and co-align with Hα emissions throughout the entire duration of the flare.

Subject headings: Sun: flares — Sun: magnetic fields — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

The scientific motivation and general background of comparison of radio and hard X-ray emissions during solar flares have been discussed in our two previous papers (Wang et al. 1994b, 1995, herein papers I and II). In Paper I, we studied a limb flare in microwaves, BATSE hard X-rays, and Hα. We found that the low-frequency radio emissions come from high in the magnetic flux loops, the microwave brightness temperature spectra at that location are consistent with thermal gyrosynchrotron emissions, and the derived temperature matches well with a superthermal component seen in BATSE hard X-ray spectra; high-frequency emissions come from the footpoint, and the microwave brightness temperature spectral index at that location agrees with that expected from the nonthermal (power-law) component of the hard X-ray photon energy index, assuming that the two emissions arise from the same populations of electrons. In Paper II, we studied a disk flare in soft and hard X-rays, Hα, magnetograms, and microwaves. Paper II represents the first time that we compared spatially resolved microwave, soft, and hard X-ray observations. In addition to confirming that the source location shifts with frequency, we found evidence of interacting between two magnetic loops: a large soft X-ray loop connecting the main p and f spots of the active region, and a compact loop formed by new flux emergence. Low-frequency microwave emissions are found in the big loop, while the high-frequency microwave, hard X-ray, and D3 emissions are confined in the compact loop.

In this paper, we study the 1992 June 25 M1.4 flare, which peaked at 17:54:22 UT. It is one of a few flares for which we have comprehensive data coverage from Yohkoh, BATSE, OVRO, and BBSO. We analyze the burst in detail, concentrating on the short period during the rise of the burst from 17:53:30 to 17:54:00 UT, when 256-channel BATSE spectroscopy data are available and the Yohkoh hard X-ray count rates are sufficient for reliable imaging. Based on the data in this period, we study (1) the morphology of the flare in microwaves, optical, soft X-rays, and hard X-rays; (2) the relationship between microwave brightness temperature spectra and the BATSE hard X-ray photon spectra to understand the flare electron distributions.

2. OBSERVATIONS AND DATA REDUCTION

The M1.4 flare occurred in the active region NOAA No. 7205. The heliocentric coordinates of the region were W71N10 on 1992 June 25. Three hr after this flare, an X3 flare occurred in the same active region, which unfortunately, was not as well observed. The BATSE, OVRO, Yohkoh, and BBSO instruments have been described in detail in Papers I and II. Here we give a brief description of them.
2.1. The OVRO Microwave Observations

The microwave observations were made with the 5-element solar array at OVRO. Among the five antennas, two are 27 m in diameter, and the remaining three are 2 m. We used seven baselines, each of which uses at least one 27 m antenna. The array was operated with an observing sequence that sampled 45 frequencies in the range of 1–18 GHz every 12 s in both right- and left-hand circular polarization (RCP and LCP). The spatial resolution is $99 f_{\text{GHz}}$, where $f_{\text{GHz}}$ is the observing frequency in GHz. The mapping technique was discussed in Paper I and Lim et al. (1994). In order to locate the true sources within the field of view, we first divide all the frequencies into three bins (1–4 GHz, 5–8 GHz, and 9–14 GHz; above 14 GHz, the calibration is not sufficiently reliable for imaging). Maps are constructed by frequency synthesis for these frequency bins and sources are approximately located. Based on the sources located in the frequency synthesis maps, we then construct and clean single-frequency maps. In this way, we obtain radio maps in 34 frequencies from 1.4 to 14 GHz. RCP and LCP maps are combined to obtain the Stokes $I$ maps.

2.2. BBSO Hα and Magnetograms

The flare was observed in both line-center and off-band Hα at BBSO. The movies were recorded on S-VHS videotapes and digitized for comparison with other observations. Digital videomagnetograms (VMGs) were also obtained at BBSO. Since the target is at longitude W71, near the limb, magnetograms are hard to interpret due to the projections. However, we obtained magnetograms a few days prior to the flare, from which we can roughly draw the magnetic neutral lines, and estimate the magnetic field strength of the flare region. The time resolution of the Hα is better than 1 minute; pixel resolution is around 0.5 and the field of view is about 250° by 200°.

2.3. BATSE Hard X-ray Spectra

The BATSE observations and spectral deconvolution procedures were described by Schwartz et al. (1993). The 16-channel Large Area Detector (LAD) data are available for the entire flare duration, with a time resolution of 2.048 s. The 256-channel spectroscopy detector (SD) data are available from 17:53:30 UT to 17:54:00 UT with 1.02 s time resolution.

2.4. Yohkoh SXT and HXT

The flare was a target of both SXT and HXT onboard the Japanese satellite Yohkoh. The flare triggering occurred at 17:53:03 UT. From that time until the end of the flare, SXT was operated in the partial frame image mode (PFM), i.e., higher temporal- and spatial-resolution flare mode. The field of view of SXT is 158° by 158°, time resolution is 2 s, and the pixel resolution is around 2.5.

The SXT was operated with the following sequence: (i) through the thin aluminum (Al) filter (passband 2.4–36 Å), (ii) the thick Al filter (2.4–13 Å), (iii) Mg filter (2–20 Å), and (iv) Be filter (2–10 Å). There is a small aspect optical telescope co-aligned with SXT to take white-light images in the same field of view (Tsuneta et al. 1991), which helps us to align X-ray images with optical images.

The HXT is a Fourier-synthesis imager of 64 elements. Each subcollimator measures a spatially modulated incident photon count (Kosugi et al. 1991). The images are reconstructed by the maximum-entropy technique. The HXT is operated in four energy bands: LO: 13.9–22.7 keV; M1: 22.7–32.7 keV; M2: 32.7–52.7 keV; and HI: 52.7–92.8 keV. We were able to make reasonable maps in the first three energy bands. The last band does not have sufficient counts to allow good mapping.

3. RESULTS

In Figure 1, we plot BATSE hard X-ray time profiles in four energy channels. The duration of the rising phase of this flare is about the same as that of the decaying phase. Most of the hard X-ray flux is confined to the two lower energy channels: 25–50 keV and 50–100 keV. Two fiducial marks show the period for which 256-channel SD data are available.

3.1. The Morphology of the Flare Emissions

Figure 2 (Plate 16) shows the comparison between microwave and X-ray sources. The overlay between microwave and SXT images is based on the coordinates of image centers determined by standard calibration of the instruments. HXT images are aligned with SXT images with the method developed by Masuda (1994). The contours show the OVRO microwave sources at five frequencies; from left to right they are: 2.0, 4.0, 6.2, 9.0, and 14.0 GHz. These are selected single-frequency maps. These same five maps are repeated four times from top to bottom. The underlying grayscale images show Yohkoh.
Fig. 2.—Comparisons between X-ray and microwave emissions. The contours show the OVRO microwave sources at five frequencies; from left to right they are: 2.0, 4.0, 6.2, 9.0, and 14.0 GHz. These same five maps are repeated four times from top to bottom. The underlying grayscale images show Yohkoh X-ray images in four energy channels: SXT soft X-rays with the Be (highest energy) filter, and HXT hard X-rays in LO, M1, and M2 channels.

Wang et al. (see 453, 506)
X-ray images in four energy channels: SXT soft X-rays with the Be (highest energy) filter, and HXT hard X-rays in LO, M1, and M2 channels. From Figure 2, we obtain the following results.

1. There is a substantial shift in the centroid of the microwave source, mostly toward the east (left) and slightly toward the north (up), as frequency increases. If we interpret the brightest part of the SXT emission as delineating a large loop structure, then at lower frequencies the microwave source is higher up in the loop structure; at higher frequencies the source moves to the eastern footpoint of the soft X-ray loop. This interpretation agrees with the early result of Paper I, although for the flare in Paper I the source shifted nearly 100° from 1 to 14 GHz, while for this flare it shifts only 25°.

2. The stronger hard X-ray source in the M2 channel (bottom row of Fig. 2) is located in the western footpoint A of the SXT loop. In all frequencies, the radio emission is located near the eastern footpoint B, where the hard X-ray emissions are much weaker than at footpoint A. As we will see later in this section, the microwave footpoint (B) has stronger magnetic fields. The similar asymmetry was discussed in Paper II. However, for that flare the two flare footpoints are only 10° apart, the results had high uncertainty due to possible alignment errors. Kawabata et al. (1982) compared hard X-ray image obtained by Hinotori and one-dimensional 35 GHz map, and found the evidence of similar asymmetry: the weaker microwave source corresponding to a stronger hard X-ray source. However, our flare demonstrates the first unambiguous example that the hard X-ray and microwave sources come from opposite footpoints.

Note that there are secondary hard X-ray sources, especially in the M1 channel. We do not have a clear understanding of them, but they seem to remind us that flares can have a structure much more complicated than our simple interpretation above, which refers to a single loop.

Hα and VMG images are scaled and aligned with SXT images by using the SXT white-light images as a reference. There are a number of major sunspots in this active region, so the images can be aligned precisely. Figure 3 (Plate 17) compares the off-band Hα emissions with SXT, HXT, and microwave emissions. The image scale is 128° by 128°. The Hα image is shown by the gray scale map, the SXT emissions by thin dark contours, the M2 hard X-ray image by thick white contours, and the OVRO 9.0 GHz microwave map by thick dark contours. The lower SXT loop system (the dominant emission) is obviously very similar to the Hα emission, meaning that the SXT loop is as low as the Hα ribbons. The agreement between dominant SXT emissions and Hα ribbons lasted for the whole period of the flare. This is another unusual aspect of the flare. It has been expected that the soft X-ray emissions usually agree with Hα ribbons in the very early stages (they both come from footpoints). As a flare evolves, two Hα ribbons separate, and soft X-ray emissions become dominant at the loop top (Hudson et al. 1994). For this flare, it is not easy to separate the two Hα ribbons, and the morphology deviation of the Hα and soft X-ray sources did not occur in the later stage. However, there is a weaker SXT emission component (toward the limb) which does not have Hα counterparts. Is this loop similar to the big loop discussed in Paper II? We cannot tell due to foreshortening of the active region. The shape of the Hα emission co-aligns with the magnetic neutral line, so that the magnetic fields might be highly sheared in the flare site.

Because the target is close to the limb, the projection effect prevents us from interpreting the magnetograms accurately. We do not present the magnetogram here because we wish to avoid any possible confusion due to apparent reversal caused by projection effects. However, we have studied the magnetograms of earlier days, June 22, 23, and 24, to track the true polarities of the fields. We found that the footpoint A has negative magnetic polarity and B, positive. B has the stronger photospheric magnetic field and lies near the umbra of one of the trailing sunspots.

3.2. Flare Electron Distribution

The electrons that produce hard X-ray emissions in solar flares have long been considered to be from the same populations as those responsible for the microwave bursts (e.g., Dennis 1988). The accelerated electron distribution can be derived independently from the microwave brightness temperature and hard X-ray photon spectra. In this section, we study the properties of the accelerated electrons of the flare, for a 30 s period when the BATSE/SD data are available. Unfortunately, we cannot obtain the necessary information to study the flare electron distribution outside this period.

3.2.1. Hard X-ray Spectra

Figure 4 presents a hard X-ray photon spectrum (crosses) and the least-square fitting (solid line). The spectrum was accumulated during the rising phase of the burst from 17:53:34 UT to 17:53:59 UT (the intervals between the fiducial lines on Fig. 1), approximately the same time interval for the radio maps shown in Figures 2 and 3. The spectrum is fitted well by a superhot component, with a temperature of $8.4 \times 10^7$ K and emission measure of $2.5 \times 10^{46}$ cm$^{-3}$. The thermal component breaks into a power-law spectrum at energy 59 keV, with a power index of $4.2 \pm 0.5$. The hard X-ray superhot component was first discovered by a balloon flight (Lin et al. 1981) and it was confirmed by the CGRO/BATSE observation (Schwartz et al. 1993). For both cases, the temperature of the superhot component is in the order of $3 \times 10^7$ K. The superhot components in the temperature range of $3 \times 10^7$ to $7 \times 10^7$ K were also reported by Hanyg et al. (1991) and Culhane et al. (1994). However, there are fundamental differences in the data.

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**Fig. 4.**—The hard X-ray photon spectrum observed with SD, accumulated from 17:53:34 to 17:53:59 UT. The solid line is the least-square fit of the observed data, which shows a superhot thermal component and a power-law component with a photon index of 4.2.
Fig. 3.—Comparison of flare emissions in Hα (grayscale), soft X-ray (light dark contours), hard X-ray in M2 channel (thick white contours) and 9.0 GHz microwave (thick dark contours).

WANG et al. (see 453, 507)
analyses. In our observations, because of the high spectral resolution of BATSE, the superhot component came naturally from the least-square fitting and it coexisted with the nonthermal tail; in earlier studies, e.g., in Culhane et al. (1994), the HXT does not have enough spectral resolution to identify if the emission is thermal or nonthermal. They have to assume that it is a thermal component first, then derive the temperature and emission measure. For this flare, it is the first time that such a high temperature for the superhot component is unambiguously measured. It is even more interesting to note that this dominant thermal component exists before the peak of the flare. We believe that the high-energy resolution (< 1 keV) of SD at the low-energy end makes it much easier to detect the thermal component. We have also ruled out the possibility that photon pile-up effect causes a false thermal component for the following reason: The pile-up effect occurs when the detector counts are too high; to minimize this effect, we choose the third most Sun-ward detector, its relative detect area cos θ = 0.566; we then did numerical simulation and proved that with the counts received by this detector, the pile-up effect is negligible. We are also convinced the existence of the nonthermal tail, mainly because the LAD time profile in Figure 1 demonstrates some counts clearly above background in 100–300 keV channel, which cannot be produced by the thermal component only. The flattening after 200 keV is due to inaccurate background subtraction for which we do not have sufficient information to correct.

3.2.2. Microwave Brightness Temperature Spectra

As in Paper I, we construct two-dimensional brightness temperature spectra for the points near the primary sources. Combining the OVRO maps at 34 frequencies in a data cube, we can determine the brightness temperature ($T_b$) spectrum at any point in the field of view. We again use the fitting method described by Stähli, Gary, & Hurford (1989) to derive four parameters from the spectra: the low-frequency slope, the high-frequency slope, the peak brightness temperature, and the frequency at optical depth = 1 ($\nu_{\text{opt}}$). In this paper, we also refer to it as the turnover frequency. Using the same method as in Paper I, we determined that the source is not resolved under 3 GHz. Thus the low-frequency slope is affected by the resolution and should be flatter than the measured value. The spectral points below 3 GHz were excluded to minimize the effect of underresolution. Figure 5 shows the $T_b$ spectra observed at four points 1–4 in Figure 3. Point 1 is located at the peak of the highest frequency (14 GHz map) while point 4 is at the peak of the 2 GHz map. In our interpretation, these represent the eastern footpoint of a large loop structure and a

![Image of graphs showing microwave brightness temperature spectra](image)

**Fig. 5**—Four microwave brightness temperature spectra ranging from footpoint to a point well up the loop leg, during the same period as Fig. 4. The solid lines are the least-square fits of the spectra.
point well up the loop leg, respectively. Points 2 and 3 are intermediate points along the leg of the loop. The Stähli fittings are performed for points 2–4, while for points 1, no reasonable fitting can be achieved with Stähli et al.’s formula, because the optically thin part of the spectrum does not show up in our frequency range. As we have learned from Paper I and Gary & Hurford (1989), the microwave flare emissions are likely due to either thermal or nonthermal gyrosynchrotron radiations. The thermal gyrosynchrotron emission is characterized by its flat brightness temperature spectrum below the turnover frequency, and a steep drop-off (slope ~ 10) above the turnover frequency; the nonthermal gyrosynchrotron emission is characterized by a low-frequency slope of 2.0 and a high frequency slope $\alpha = 0.8 + 0.9\delta$, where $\delta$ is the electron index of the injected power-law–distributed electrons. The brightness temperature spectrum at point 2 fits a typical nonthermal emission with $\alpha = 5.43$, while point 4 shows a more thermal-like spectrum, identified by its steep high-frequency slope and flat low-frequency slope. It is consistent with the results of Paper I that the emission nearer the loop top is dominated by thermal gyrosynchrotron emission and the footpoint emission is dominated by the nonthermal gyrosynchrotron emission. Let us discuss the spectra at points 2 and 4 in more detail.

At point 2, $v_{r=1} = 8.1$ GHz, the peak brightness temperature is $9.7 \times 10^7$ K, and the high-frequency (optically thin) slope ($\alpha$) is 5.43. The measured low-frequency (optically thick) slope is 2.9; however, this number is an upper limit due to the possibility of underresolution, as stated above. If the hard X-rays at high energies ($\geq 100$ keV) are produced by thick-target bremsstrahlung from nonthermal electrons, we can derive electron index as $\delta = \gamma + 1$, where $\gamma$ is the photon spectral index. For this flare, $\delta = 5.2 \pm 0.5$. From the microwave brightness temperature spectrum at this point, we can independently derive an electron index $\delta = (\alpha - 0.8)/0.9$ (Paper I), where $\alpha$ is the high-frequency slope in the microwave brightness temperature spectrum. Therefore, using $\alpha = 5.43 \pm 2.0$ from the point 2 spectrum, we have $\delta = 5.1 \pm 2.2$. These two $\delta$'s agree well within the errors in the measurements. The microwave emission at point 2 and nonthermal component of hard X-ray emissions are likely due to the same group of nonthermal electrons.

We must note that the relationship among $\alpha$, $\delta$, and $\gamma$ is model dependent. Kosugi, Dennis & Kaito (1988) adopt the relation $\delta = \gamma = 1.5$ for a special model for the impulsive flares. So the value of $\delta$ derived from hard X-ray spectra may have to be increased by 0.5, if we use the Kosugi et al. model. However, this small variation does not affect our conclusion significantly.

We can derive the magnetic field strength in the source from a knowledge of electron index and turnover frequency. For the nonthermal gyrosynchrotron radiation, the turnover frequency is (Dulk 1985)

$$v_{r=1} = 2.72 \times 10^3 \times 10^{0.274} \sin \theta^{0.41 + 0.036} \times (NL)^{0.32 - 0.033} \theta^{0.68 + 0.034} \text{ Hz},$$

where NL is the column density $\sim 3 \times 10^{17}$ cm$^{-2}$ (we adopted the value from Paper I, because the hard X-ray photon counts at 100 keV are similar for the two flares; furthermore, the choice of NL is not sensitive for the determination of $B$, because the index above NL is 0.32–0.036 = 0.149); the electron index $\delta$ is 5.2; and $\theta$ is the angle between line of sight and magnetic field line. We estimated that $\theta = 70^\circ$ based on the location of the source on the disk. At point 2, using $v_{r=1} = 8.1$ GHz and $\delta = 5.2$, we derive that $B = 450$ G. At point 1, the turnover frequency is larger than that at point 2, but cannot be determined accurately because the optically thin part does not show well in the spectrum. We can conclude only that the magnetic field of point 1 is stronger than that of point 2.

At point 4, the microwave emissions are due to the thermal gyrosynchrotron mechanism with a brightness temperature of $6.2 \times 10^7$ K, within 25% of the temperature of the superhot component derived from the BATSE hard X-ray spectra. Because of the large scatter in the $T_e$ spectrum, this small discrepancy is not significant. The thermal gyrosynchrotron emission at point 4 and the hard X-ray superhot component may reflect the same population of thermal electrons.

For the thermal gyrosynchrotron emissions, the turnover frequency is

$$v_{r=1} = 475(NL)^{0.035} \sin \theta^{0.067} \theta^{0.5} \theta^{0.095} \text{ Hz}.$$  

If we use $NL = 5 \times 10^{18}$ cm$^{-3}$ from Paper I (however, the choice of NL is even more insensitive than the nonthermal case due to its index of 0.05) and measured values of $T = 6.2 \times 10^7$ K and $v_{r=1} = 8.2$ GHz, we derived $B = 350$ G.

In addition to the two cases presented in Papers I and II, we here show a third case in which the microwave and hard X-ray emissions are consistent with the idea that they are produced by the same group of accelerated electrons. However, it is interesting to note that the microwave and hard X-ray sources are not cospatial. We offer an explanation here: although all the electrons travel freely from one footpoint to the other, stronger magnetic fields at B prevent electrons from penetrating deep, so hard X-ray emissions are weak. At the same time, the strong fields are favorable for gyrosynchrotron emission. So microwave emission is dominant at the footpoint B. At the footpoint A, electrons can efficiently interact with the solar surface, which produced hard X-rays. The magnetic fields are not strong enough to produce microwave emission. This qualitatively agrees with the results and explanation of Sakao (1994), where he finds that the stronger hard X-ray sources correspond to weaker magnetic fields.

Finally, we would like to make some comments about the classification of this flare. If there are only three flare classifications as described by Tanaka (1987), this flare would most likely fit the type A: hot thermal flare. However, there are obvious differences between this flare and classical type A flare: the nonthermal tail of this flare is not soft and the photon index $\gamma$ is 4.2 instead of 8 to 9, described by Tanaka. Its temperature is also much higher than the typical hot thermal flare. So this could be an unusual flare, in the aspect of the flare energy distribution.

4. CONCLUSIONS

We have studied the 1992 June 25 flare in several wavelengths observed with OVRO, BATSE, Yokoh, and BBSO instruments, we draw the following conclusions.

1. Soft X-ray emissions connect two footpoints. The primary microwave source is located in one footpoint, and hard X-ray emissions are concentrated in the other footpoint. The microwave footpoint has the stronger magnetic field.

2. During the period that 256-channel SD data are available, the BATSE hard X-ray photon spectra consist of two components: a thermal component with a temperature of $8.4 \times 10^7$ K and emission measure of $2.5 \times 10^{46}$ cm$^{-3}$ and a power-law component with a photon index of 4.2. The micro-
wave brightness spectra during the same period demonstrate the same two components: a superhot component near the loop top and a nonthermal component at the footpoint of the loop. These measurements are consistent with the theory that the microwaves and hard X-rays are due to the same group of thermal and nonthermal electrons.

3. In addition, we confirmed the results of our previous papers that the centroid of the microwave source shifts toward the strong field footpoint as frequency increases; and we found that the dominant soft X-ray emissions co-align with center-

line and off-band Hα emissions throughout the entire duration of the flare.

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