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DETECTION OF LARGE-SCALE RADIO STRUCTURE AND PLASMA FLOW DURING A SOLAR BRIGHT POINT FLARE

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ABSTRACT

We report on the detection of a large-scale radio structure and plasma flow associated with a bright point flare observed on 1993 July 11. The bright point (BP) flare was simultaneously imaged by the Nobeyama radioheliograph at 17 GHz and the Soft X-Ray Telescope on board the *Yohkoh* mission. The microwave emission consists of a large-scale structure and a compact moving source. The large-scale component seems to be the radio counterpart of large-scale loop structures sometimes observed in association with BP flares in X-rays. The compact source moved from the location of the X-ray BP flare with a speed of about 60 km s^{-1}, which suggests a plasma flow. Spatial comparison between X-ray and radio data shows that the BP flare had different manifestations in the two wavelength domains. The emission peaks in the two wavelength domains did not coincide, which suggests cool plasma flow along the large-scale radio structure. We were able to determine the temperature and emission measure of the BP flare plasma from the X-ray data, and thus we computed the expected radio flux from the X-ray–emitting plasma. We found that the computed radio flux was much smaller than the total observed radio flux.

Subject headings: Sun: corona — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Bright point (BP) flares represent small-scale energy releases on the Sun discovered in X-rays by Golub et al. (1974) and seem to occur as isolated structures away from active regions. After the early studies (Nolte, Solodyna, & Gerassimenko 1979; Webb 1981) using *Skylab* data, detailed studies of BP flares have become possible, thanks to the extensive coverage of the Sun by the *Yohkoh* satellite (Strong et al. 1992). The BP flare may represent an increase in emission measure or temperature, or both. If the BP flare is caused by magnetic reconnection, we expect mass motion and particle acceleration from the reconnection site. Type III radio bursts at meter–dekameter wavelengths, believed to be due to nonthermal electron beams, have been found to be associated with at least 10% of the BP flares observed in X-rays (Kundu, Gergely, & Golub 1980; Kundu et al. 1994b). If the nonthermal electron beams are generated low in the corona where the BP flares occur in X-rays, they may also have radio signatures at higher frequencies such as microwaves. Detection of a nonthermal component at microwaves has important implications for the understanding of the BP flares since nonthermal emission is indicative of particle acceleration similar to regular flares. There is no observational evidence of nonthermal emission from BP flares in microwaves so far. Recently, Kundu et al. (1994a) have concluded that 17 GHz emission from flaring BPs was thermal. According to these authors, a large discrepancy was found between the observed radio flux and the one computed from X-ray observations, which could not be attributed to a nonthermal component. On 1993 July 11, we observed a BP flare in microwaves and X-rays that we use to address some of the above issues in this Letter. Unlike previous observations, this BP flare seems to have different manifestations in X-rays and microwaves. Since our X-ray observations were made with two filters, we were able to determine the temperature and emission measure of the BP flare plasma for an effective comparison with the radio data.

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2. OBSERVATIONS

The 1993 July 11 BP flare was observed simultaneously by the Soft X-Ray Telescope (SXT) aboard the *Yohkoh* mission (Tsuneta et al. 1991) and the Nobeyama radioheliograph at 17 GHz (Nakajima et al. 1994). The SXT was operating in the quiet mode so that only full disk images are available for the present study. Between 00:25 and 03:06 UT, the images have half-resolution (4″.92) and were obtained with Al.1 and AlMg filters. Outside this time range, images were obtained only with AlMg filters. The BP flare occurred in the former period, which enabled us to determine the filter ratios and hence the temperature and emission measure of the BP plasma. The Nobeyama data consist of full disk images in both polarizations obtained every 1 s, with a spatial resolution of ~15″. Since the noise level is high in the high time resolution images, we averaged over 10 consecutive images in the map plane to get an effective time resolution of 10 s, which we use in this Letter.

Figure 1 shows a set of SXT images that show the evolution of a BP located near the west limb of the Sun between 02:02 and 02:49 UT on 1993 July 11. The BP flare in question is seen brightest in the 02:32 UT frame. The BP to the south was a long-lasting one and showed weak flarelike enhancements before and after the BP flare in question. The BP flare started around 02:00 UT, peaked around 02:32 UT, and ended around 02:40 UT. There was no trace of any BP structure at the location of the flare after it had ended. Only after several hours, there occurred another BP flare at the same location at 08:00 UT. The soft X-ray flux with the thin aluminum filter, over an area covered by the flaring BP, is shown in Figure 2. We have also shown the brightness temperature at 17 GHz averaged over an area occupied by the radio BP flare. Note that the flare duration is roughly the same in both wavelength

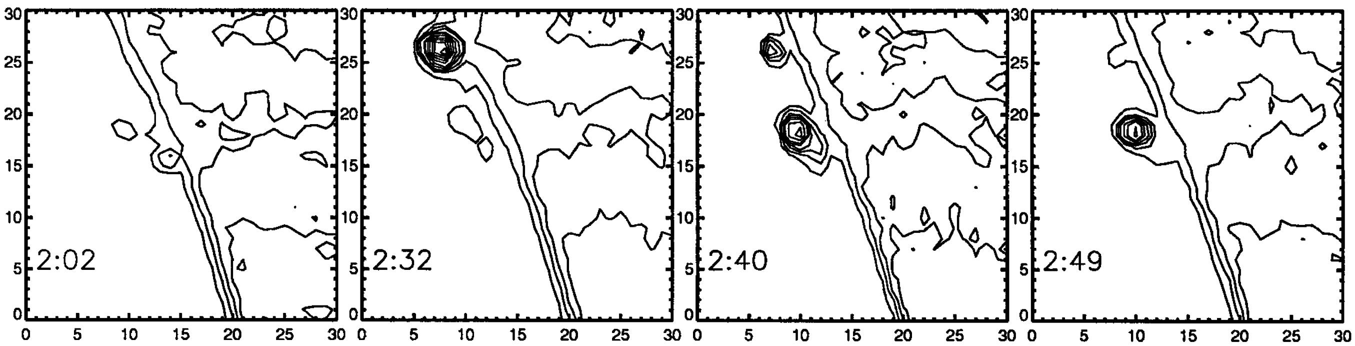

FIG. 1.—A series of *Yohkoh* soft X-ray images of a section of the northwest quadrant of the Sun in contour representation showing the BP flare. The UT of the image is marked at the bottom left-hand corner of each map. The *x*- and *y*-axes are in pixel units (1 pixel = 4."92). The BP flare in question is the northern one, seen brightest in the 02:32 UT frame.

domains. In the 17 GHz images, we see an extended component and a compact source (see Fig. 3). The spatial extent of the extended component is substantially larger (~135") than that of the compact source (~30"). While the extended component remained stationary, Figure 3 shows that the compact source moved southward along the extended component. In order to see the motion of the compact source better, we have plotted in Figure 4 the brightness temperature at each

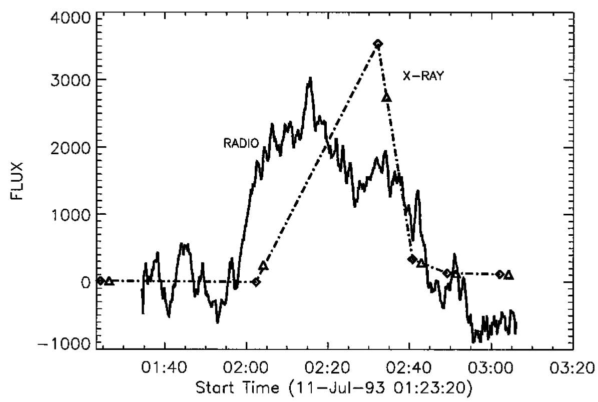

FIG. 2.—Light curves of the BP flare in soft X-rays and in 17 GHz microwaves. The X-ray flux is in units of data numbers per second. The radio data are in units of brightness temperature averaged over the emission region and smoothed over six data points. Both types of data are background subtracted. There was a data gap between 02:02 UT and 02:32 UT, and hence the actual peak in the X-ray data could not be determined. However, the duration of the flare seems to be the same in both wavelength domains.

pixel lying along the axis of the extended component. We see a clear drift of the emission maximum from north to south, away from the location of the BP flare in X-rays. A least-squares fit to the data points gives a speed of about 60 km s^{-1}, which lies in the range of speeds of coronal jets observed in soft X-rays (e.g., Shibata et al. 1992a). This is the speed in the plane of the sky; the actual speed could be much higher if the loop had an east-west extent. The extended component is similar to large-scale loop brightenings observed in X-rays in association with BP flares (see, e.g., Strong et al. 1992). This is the first time such a large-scale structure is detected in microwaves. In addition, the large-scale structure supports a plasma flow.

The peak brightness temperature of the large-scale structure was about 3500 K above the quiet Sun, while the compact source had a brightness temperature of up to ~7000 K. Note that these values may be lower than the actual values because of time averaging. The total flux over the area covered by the radio BP flare (324 pixels) had a peak value of 0.43 sfu. The total flux of the compact source (over 99 pixels) had a peak value of 0.19 sfu at 02:15 UT.

In order to make a positional comparison between the X-ray and radio enhancements during the BP flare, we have superposed the radio contours of the 02:15 UT image onto the 02:30:47 UT SXT image in Figure 5 (Plate L7). The BP flare in X-rays is located at the northern tip of the extended component of the radio source and is of a much smaller size compared to the extended radio component. Figure 5 also shows that the radio and X-ray flares have different manifes-

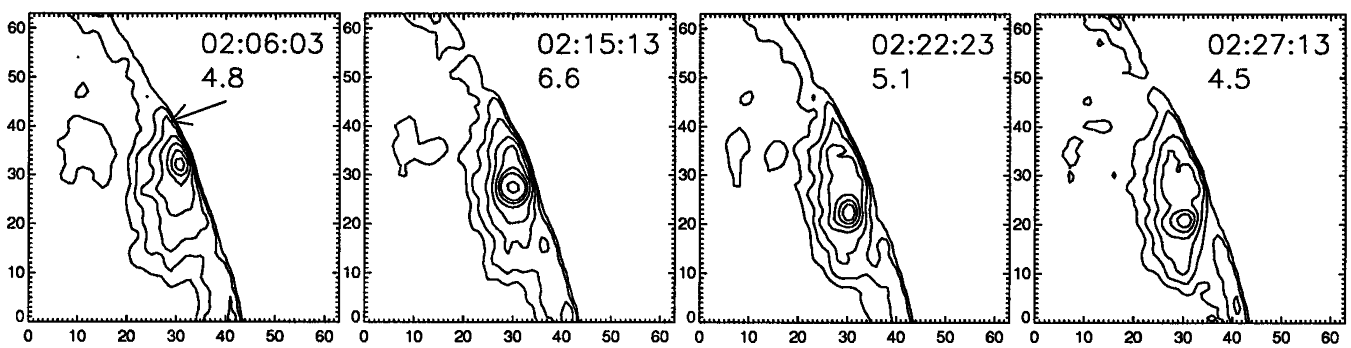

FIG. 3.—A set of Nobeyama radioheliograms at different times showing the large-scale radio structure and a compact source. The *x*- and *y*-axes are in pixel units (1 pixel = 4."91). The contours represent emission exceeding the quiet-Sun level (10,000 K at 17 GHz). The contour levels are at 1500, 2000, 2500, 3000, 3500, 4000, 4500, 6000, 8000, and 10,000 K. The sharp edge is the west limb of the Sun. The UT time and the peak brightness temperature (in units of kilokelvins) are marked at the right-hand top corner of each image. The arrow points to the location of the BP flare in X-rays. North is to the top, and east is to the left.

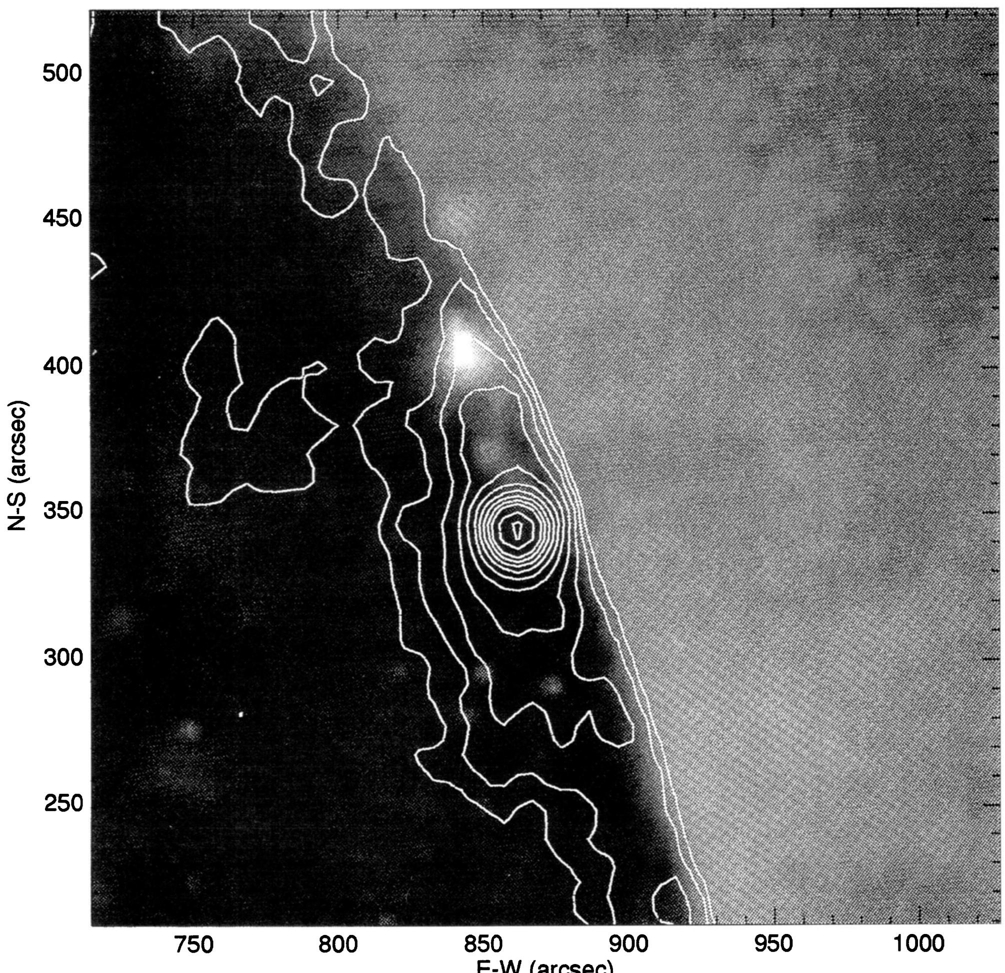

FIG. 5.—Superposition of the SXT image (*gray scale*) of the BP flare on the Nobeyama radioheliogram (*contours*) at 02:32 UT. The radio contours represent brightness temperature in excess of the quiet Sun. The BP flare can be seen at the northern end of the extended radio source. The faint X-ray emission to the south of the BP is from the long-lasting BP. The western limb of the Sun is obvious at both X-ray and radio wavelengths. The compact radio source can be seen as the brightest in the radio image. North is to the top, and east is to the left.

GOPALSWAMY et al. (see 457, L118)

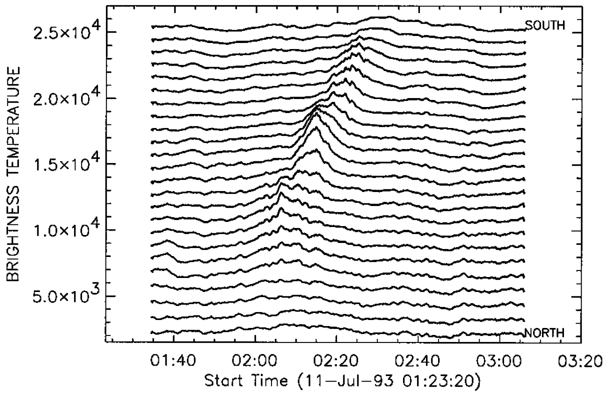

FIG. 4.—Plots of brightness temperature at successive pixels along the axis of the large-scale radio structure. The brightness temperature values are smoothed over six data points to get an effective time resolution of 1 minute. NORTH corresponds to the location of the X-ray BP flare on the radio image. SOUTH corresponds to a pixel close to the southern end of the large-scale structure, 18 pixels away. The *Y*-axis applies only to the bottommost curve. A value of $n \times 1000$ K has been added to the brightness temperature of the *n*th curve from the bottommost curve. Notice the shift of the emission peak to later times as one goes from north to south.

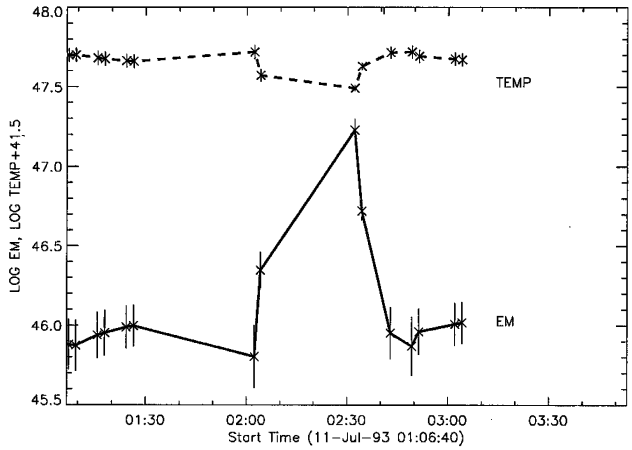

FIG. 6.—Temperature (*dashed curve* [TEMP]) and emission measure (*solid curve* [EM]) of the BP flare plasma determined using SXT filter ratios. Logarithmic scales are employed, and the base value of the temperature is shifted by 41.5. The data points (denoted by crosses) were obtained by interpolating thin Al.1 times to AlMg filter times and vice versa. The error bar at each data point is marked by the vertical line. The actual peak value of the EM is unknown because of a large data gap between 02:02 UT and 02:32 UT. However, the trend suggests that the EM may peak roughly at the same time as the radio peak.

tations: the compact radio source and the extended component do not correspond in the X-ray data. The observed excess brightness temperature at the location of the X-ray emission had a peak value of about 3000 K. The 17 GHz radio flux from the area occupied by the X-ray flare is only about 20% of the radio flux of the extended component. The time evolution of the brightness temperature at the brightest radio pixel within the region of the X-ray BP flare was very similar to the X-ray time variation.

Seventeen pairs of X-ray images are available between 00:25 and 03:04 UT on 1995 July 11 obtained through AlMg and Al.1 filters. Of these, we use only the 10 pairs that were obtained with high exposure time. The combination of Al.1 and AlMg filters provides information about the lowest temperature plasma and hence is very suitable for the present study. Since the BP flare occurred in a quiet region, where there is no high-temperature plasma, we were able to obtain temperature and emission measure diagnostics of plasma with a temperature as low as 10^6 K. The temperature and emission measure (EM) of the BP flare, determined over a box of 80 pixels containing the BP, are shown in Figure 6. The temperature at the location of the BP flare was relatively low and was constant before and after the flare with a value around 1.5 MK. During the flare, the temperature dropped slightly to a minimum of about 1.2 MK (a 20% drop). The actual value of the minimum is unknown because of the data gap. The EM of the BP increased significantly during the flare, reaching a peak value of 1.7×10^{47} cm^{-3} over 80 pixels. We consider this as a lower limit because of the data gap between 02:02 and 02:32 UT. Thus the BP flare was accompanied by an increase in EM and a slight decrease in temperature, the combination of which produced the observed increase in X-ray flux. The error in the determination of EM is about 15% during the BP flare and was higher (up to 40%) outside the flare period. The error in temperature determination was typically less than 10%.

3. DISCUSSION

The primary result of this study is that the BP flare has much different manifestations in microwave and X-ray domains. The radio structure is significantly larger than the compact brightening in X-rays. Thus, a large portion of the BP flare plasma seems to be cooler and less dense so that it is invisible in soft X-rays. The large-scale structure seen in radio is very similar to faint X-ray loops observed in association with some BP flares. The faint X-ray loops are thought to be large-scale magnetic loops connecting the BP to distant quiet-Sun regions with low magnetic field. Strong et al. (1992) have shown examples of a number of such faint loops with lengths in the range 100,000–340,000 km. The large-scale radio structure associated with the BP flare in question has a length of at least 106,000 km, similar to the above values. Note that this is a plane of the sky measurement, and the structure could be longer if it has an east-west extent. From the Mount Wilson longitudinal magnetogram, we found that the large-scale radio structure connects the BP flare to a quiet-Sun region of negative magnetic polarity in the southeast direction from the BP flare. Thus, we may conclude that we have detected the radio counterpart of large-scale X-ray loop brightenings observed in association with BP flares. The physical conditions in the large-scale structure may be such that it is not observed in X-rays.

The BP flare in radio has similarities to the soft X-ray jets observed by Shibata et al. (1992). We infer plasma flow in the large-scale structure using the observed drift rate of the compact sources away from the X-ray BP, with a speed (>60 km s^{-1}) similar to that of X-ray jets (30–300 km s^{-1}) observed by Shibata et al. (1992). The plasma flow can be interpreted as an evaporation flow caused by reconnection between a small loop represented by the X-ray BP and a large-scale loop represented by the large-scale radio structure.

The observed brightness temperature at the location of the X-ray BP (XBP) flare has a maximum value of ~3000 K and has a time variation similar to that in X-rays. The EM of the X-ray–emitting plasma over the area occupied by the XBP is ~1.7×10^{47} cm^{-3} with a temperature of 1.2 MK. This EM would produce a radio emission at 17 GHz with a brightness temperature of 10,000 K, about 3 times larger than the observed value. We must note that the radio spatial resolution is poorer than that in X-rays by a factor of 3, which might have caused some beam dilution. However, the observed radio flux (0.085 sfu) is also smaller than the one computed from X-ray data (0.48 sfu) by a factor of 6. Thus, the smaller filling factor of the hot plasma seems to be the cause of the lower observed value. The presence of cooler plasma can be inferred from the fact that no X-ray emission was seen from anywhere else in the large-scale structure.

The brightness temperatures of the compact source (7000 K) and the large-scale structure (3500 K) can be easily explained as due to free-free emission. However, the absence of soft X-ray emission at the location of these radio sources places constraints on the density and temperature of the plasma that emits radio waves. In the preflare phase, the EM at the location of the XBP flare corresponds to a density of 5.1×10^8 cm^{-3} at a temperature of 1.5 MK and produces a 17 GHz brightness temperature of about 400 K. If the large-scale structure were at this temperature during the BP flare, we need a density of 1.3×10^9 cm^{-3} in order to produce an observed brightness temperature of 3500 K. However, this density is high enough to produce a large X-ray signal, contrary to the observation. Thus, we may conclude that the large-scale structure must be at a lower temperature than the X-ray–emitting plasma. The possibility that the radio structure may be located in the transition region can easily be ruled out since the higher density in the transition region will result in optically thick radio emission ($>10^5$ K), contrary to the observation. To get an estimate of the temperature of the large-scale loop, let us take 10% of the peak EM during the BP flare as the minimum EM needed at 1.2 MK to produce a detectable signal in X-rays. This corresponds to a density of 7.65×10^9 cm^{-3}. If the large-scale structure has this density and a temperature <1.2 MK, then there may not be a detectable X-ray signal. Using the width of the radio structure ($\sim 4.4 \times 10^8$ cm) for its depth along the line of sight, we get a 17 GHz optical depth of $\sim 1.73 \times 10^6 \times T^{-(3/2)}$, where T is temperature in the large-scale structure. In order to produce an observed brightness temperature of 3500 K in the large-scale structure, we need a temperature of 0.24 MK. Of course, slightly higher temperature and density can also explain the observed radio emission, provided these parameters do not result in detectable soft X-ray emission. It must be pointed out that such a long loop with a cool plasma may not be hydrostatically stable. However, if there is a steady flow present in the loop, the density and temperature at the loop apex can be substantially lower than in a static loop of the same length (e.g., Landini & Monsignori Fossi 1981; Foukal 1976).

The above argument applies for the compact source, too. Since there is no soft X-ray emission associated with the compact source, it has to be cooler than the X-ray–emitting plasma. For a temperature of 2.4×10^5 K, we need a plasma density of 1.5×10^9 cm^{-3} to produce the observed brightness temperature. The compact source may represent cool material of enhanced density or a plasmoid from the reconnection region flowing through the large-scale structure. Numerical simulation studies of reconnection show that a cool jet and plasmoids of low temperature are produced in the current sheet (Shibata, Nozawa, & Matsumoto 1992) and hence may flow into the large-scale structure. Alternatively, the compact sources may be produced because of optically thin gyrosynchrotron emission from mildly relativistic electrons produced during reconnection. The emission has to be at very high harmonics since the magnetic field of the large-scale loop in the quiet-Sun region is expected to be low. There are some fast time structures with a duration of a few minutes in Figure 2 that may support a nonthermal process. We need spectral information as well as observations with high temporal and spatial resolution in order to derive a firm conclusion regarding nonthermal emission.

4. CONCLUSIONS

We have detected a large-scale loop structure (length ≥ 106,000 km) that brightens at microwaves in association with an X-ray BP flare. These large-scale structures were previously observed only in X-rays. The X-ray emission was from a compact region at one end of the large-scale radio structure. We have also detected plasma flow along the large-scale structure with a speed of at least 60 km s^{-1}, as inferred from a compact bright source moving away from the X-ray BP flare. The large-scale structure extends from the compact BP flare seen in X-rays to a quiet-Sun region of opposite polarity, similar to large-scale X-ray loops seen during other BP flares. The radio flux from the X-ray–emitting plasma is only a small fraction of the total radio flux. Since there is no X-ray emission from the radio structures, we infer that they may have a temperature less than 1 MK. We suggest that the low-temperature plasma and cool plasmoids may originate during reconnection between a compact loop represented by the X-ray BP flare and a large-scale loop observed as the extended structure in radio.

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