MICROWAVE AND HARD X-RAY OBSERVATIONS OF FOOTPOINT EMISSION FROM SOLAR FLARES

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ABSTRACT

We investigate radio and X-ray imaging data for two solar flares in order to test the idea that asymmetric precipitation of nonthermal electrons at the two ends of a magnetic loop is consistent with the magnetic-mirroring explanation. The events we present were observed in 1993 May by the HXT and SXT X-ray telescopes on the Yohkoh spacecraft and by the Nobeyama 17 GHz radioheliograph. The hard X-ray images in one case show two well-separated sources; the radio images indicate circularly polarized, nonthermal radio emission with opposite polarities from these two sources, indicating oppositely directed fields and consistent with a single-loop model. In the second event there are several sources in the HXT images which appear to be connected by soft X-ray loops. The strongest hard X-ray source has unpolarized radio emission, whereas the strongest radio emission lies over strong magnetic fields and is polarized. In both events the strongest radio emission is highly polarized and not coincident with the strongest hard X-ray emission. This is consistent with asymmetric loops in which the bulk of the precipitation (and hence the X-ray emission) occurs at the weaker field footprint.

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

1. INTRODUCTION

A close connection between the energetic electron’s emission of microwaves and of hard X-rays has been known to exist for a long time. This connection is manifested in two forms: the similarity of the intensity profiles in the two spectral domains (Kundu 1961) and a common flaring loop as the source for both hard X-ray and radio emission, regardless of whether the microwave source is located at the loop top (Marsh & Hurford 1980) or at the footpoints (Shevgaonkar & Kundu 1985). The hard X-ray source is generally at the footpoints. Hoyng et al. (1983) described an event observed with SMM in which, they concluded, the microwaves (2 cm wavelength) came from the loop top and the hard X-rays (≤ 32 keV) from the footpoints. However, their conclusion cannot be generalized. Prior to the launch of Yohkoh, there were few published studies of microwave and hard X-ray sources using simultaneously obtained imaging data; the availability of HXT (Hard X-Ray Telescope) images has increased the number of studies in this area (e.g., Enome et al. 1994; Takakura et al. 1994), but we still have no clear picture of the location of the hard X-ray source relative to the microwave source in a flaring loop.

Sakao (1994; see also Sakao et al. 1994) described the nature of hard X-ray-emitting electrons in the energy bands 14–23 keV (L), 23–33 keV (M1), 33–53 keV (M2), and 53–93 keV (H) using Yohkoh-HXT imaging data, which has significantly advanced our knowledge in this area. In particular, it should be noted that the Yohkoh-HXT energy range goes much higher (up to 93 keV) than was the case for the SMM-HXIS instrument or the Hinotori imager. Using this higher energy range (≥ 33 keV) data, Sakao (1994) and Sakao et al. (1994) were able to characterize the double structure of hard X-ray sources in solar flares. Indeed, Sakao’s study provides important information on the source of solar flare hard X-ray emission, the propagation of accelerated electrons in a flaring loop, and the mechanism of acceleration of energetic electrons. Some important findings are (1) during the impulsive phase, hard X-ray sources are observed on each side of a magnetic neutral line, suggesting that the two sources are the footpoints of a single flaring loop—even in fact, they appear to be spatially coincident with the white-light brightenings observed with the optical Yohkoh-SXT (Soft X-Ray Telescope; see, e.g., Hudson et al. 1993; Sakao et al. 1992); (2) hard X-ray emission from the two sources varies simultaneously to within 0.1 s at the 1σ level, strongly supporting the idea that hard X-rays are emitted from near the footpoints of a flaring loop by energetic electrons streaming downward from near the top of the loop; (3) the footpoint sources often show asymmetry in hard X-ray emission, with the brighter source being located in a weaker magnetic field region than the weaker (or less bright) source. Sakao interpreted the result that the weaker field footpoint has higher electron precipitation as being due to weaker magnetic field convergence, which permits more electrons to reach the...
FOOTPOINT EMISSION FROM SOLAR FLARES

chromosphere than at the stronger field footpoint, where magnetic mirroring is stronger.

Sakao determined the field strength at the footpoints of the loop using line-of-sight magnetogram data. Radio imaging data offer a complementary method for testing the proposal that asymmetric hard X-ray precipitation is connected to the differing field strengths at opposite ends of a flaring loop. Radio emission in flares is generally due to nonthermal gyrosynchrotron emission, which has a strong dependence on magnetic field strength. Thus, we expect that radio emission from a flaring loop will be strongest at the stronger field end. For simple events, with two footpoints of opposite polarity, we would therefore expect that the radio emission will be brightest at the footpoint which is weakest in hard X-rays. This radio technique complements the determination of footpoint field strengths from overlays on magnetograms, which suffer significant uncertainties because of the difficulty of obtaining simultaneous magnetograms and of carrying out accurate overlays.

Microwave imaging data simultaneous with HXT data, with comparable spatial (~5") and temporal (0.5 s) resolution, were not available for the HXT events discussed by Sakao. In this paper, we study two radio events observed simultaneously with the HXT experiment and at 17 GHz with the Nobeyama radioheliograph. These two events were noticed in the course of another study of the evolution of an active region and identified as suitable for this study. Both events show structure which is simple enough to allow us to use them to test whether the connection between radio brightness and hard X-ray brightness is consistent with the asymmetric-loop model.

2. OBSERVATIONS

The two flares under study in this paper were observed on 1993 May 28 and 1993 May 30. They originated in Active Region 7515, which was followed from 1993 May 23 to 1993 June 2 as part of a study of active region evolution and flare productivity. We use data from the Nobeyama radioheliograph, the Toyokawa and Nobeyama microwave patrol telescopes, and SXT and HXT, on the Yohkoh satellite. The properties of these instruments are described below.

The Nobeyama radioheliograph has been carrying out routine operations since 1992 June. Consisting of 88 40 cm diameter dishes in a T-shaped array (east-west dimension of 490 m), it can make snapshot images of the whole solar disk with a spatial resolution of order 10" every 50 ms (Nakajima et al. 1994). Because of the large number of baselines involved, it is not usually feasible to make images at high time resolution for the whole duration of a flare. Here we use fluxes measured from the maps at selected times and "fill in" the time profile with the correlation plots at 1 s time resolution. These consist of the correlation coefficients of visibilities on baselines longer than about 150 m and thus are insensitive to sources larger than about 24". Therefore, they do not represent the variation of total power with time; however, in the impulsive phases of the flares that we will discuss, the source sizes were small, and the correlation plots should be a good representation of the total power. We have calibrated the correlation plots in terms of solar flux units by comparison with fluxes obtained from the full radioheliograph in the impulsive phase of the events discussed. These in turn are normalized to a nominal temperature of 10^5 K for the quiet solar disk at 17 GHz.

The Toyokawa and Nobeyama patrol telescopes are polarimeters operating at 1.0, 2.0, 3.8, 9.4, 17, and 35 GHz (Torii et al. 1979; Nakajima et al. 1985). The data used here have been processed using new software developed by M. Nishio at Nobeyama.

The Yohkoh satellite (Ogawara et al. 1991) is a Japanese satellite carrying joint Japan-US-UK instruments for solar observations. The two instruments which we use are the Soft X-ray Telescope (Tsuneta et al. 1991) and the Hard X-ray Telescope (Kosugi et al. 1991). SXT uses grazing-incidence optics to form images on a 1024 x 1024 pixel CCD in the energy range 0.25-4 keV; a number of filters can be placed in the optical path. The pixel size is 2.5". HXT is a Fourier-synthesis imager consisting of 64 independent subcollimators, forming images in four different energy ranges: 14-23 keV, 23-33 keV, 33-53 keV, and 53-93 keV. Spatial resolution is signal-to-noise dependent but is of order 5". Yohkoh enters its so-called flare mode when the counting rate of one of its spectrometers exceeds an adjustable threshold. In the flare mode, HXT data from all channels become available; otherwise, only the L-band data are recorded. The flare-mode SXT data usually consist of high-cadence (2 s), narrow field-of-view (2.5 x 26) images in three filters, including the two thickest ones in order to measure the temperature of ~10^5 K flare plasma. These are supplemented with wider field-of-view, reduced-resolution images, typically once a minute.

In the following two sections we present the observations of the two events separately. All the images displayed are oriented to place solar north at the top of the image. At 17 GHz, both flares have an impulsive phase of short duration, ~1 minute, followed by a postburst increase phase, which lasts longer. In the hard X-ray domain, the profiles are both "spiky" and of short duration; the spikiness appears to increase with increasing hard X-ray energy.

3. COALIGNMENT OF HARD X-RAY AND RADIO IMAGES

We first coalign the HXT and SXT images using their coordinates relative to disk center, since the alignment between the two instruments is now well understood (Masuda 1994) and the uncertainty is probably of the order of 1". To overlay the radio and X-ray images we make use of the general similarity between Nobeyama and SXT images of the extended active region emission, both of which are produced by thermal bremsstrahlung (Enome et al. 1994). For the 1993 May 30 flare, the estimated coalignment accuracy is 3". For the 1993 May 28 flare, no SXT image of the whole region was available close to the flare time, except for one at 0212:58 UT, which has one quadrant empty (SXT was observing AR 7512 during the flare). Alignment for May 28 was carried out using an SXT image at 0023 UT. The estimated uncertainty is of order 5".

4. EVENT OF 1993 MAY 28, 0202 UT

4.1. Radio and Hard X-Ray Time Profiles and Energy Spectra

Figure 1 shows the HXT time profiles for various energy bands. The hard X-ray flare started at ~0202:08 UT in the L band (14-23 keV), while the flare mode was triggered at 0202:26 UT. For comparison, the 17 GHz Nobeyama patrol data are plotted in the bottom panel, along with the fluxes measured from radioheliograph images at different times during the flare (crosses). We see two spikes in the HXT L- and M1-band time profiles, peaking at 0202:47 UT and 0203:24 UT, respectively (hereafter S1 and S2). While S1 is also present in the M2 and H bands, S2 is not clearly seen in these energy bands, suggesting that S2 has a much softer energy spectrum than S1. Assuming a power-law photon incident spectrum, the
hard X-ray photon index at the peak of S1 is \( \sim 4 \), while that for S2 is \( \sim 6 \) (the ratios M1/L and M2/M1 both give similar results for the indexes). The radio data are consistent with S2's having a softer spectrum: at 17 GHz, S1 is much brighter than S2, as would be expected for a harder electron energy spectrum. Note that the fluxes determined from the radioheliograph images are the same as those obtained from the patrol telescopes to within about 20\%, which is adequate agreement given the differing techniques involved.

S1 has a shoulder in the L, M1, and M2 bands that becomes less conspicuous in the H band. This peak also becomes more spiky with increasing hard X-ray energy. This peak corresponds fairly closely in time to the most prominent peak in the microwave domain (to within a few seconds). However, S2, in the L and M1 bands, corresponds to a rather broad peak in the microwave profile.

4.2. Preflare and Flaring Region in Microwaves

At 17 GHz the active region (AR 7515) in which the flare originated consisted of three main bright features in its immediately preflare stage (prior to 0200 UT). Figure 2 shows a representative selection of 17 GHz images of the region and the flare. (This and all subsequent images displayed are oriented with solar north at the top of the image.) The leftmost panels show the preflare region in total intensity (\( I, \text{ upper} \)) and circularly polarized flux (\( V, \text{ lower} \)). Subsequent images are difference images in which the preflare images have been subtracted: as long as the radio emission is optically thin, which we believe to
be the case, this is appropriate. The only significant polarized radio emission in the preflare region lies over a strong sunspot at the western edge of the radio emission (leftmost bottom panel). The flare occurs in the center of the preflare radio source, well away from the leading spot. The second column of panels shows an enhancement at the flare location more than a minute prior to the impulsive phase, at a time when no hard X-rays were detected. This may be evidence for preflare heating. The middle panels, corresponding to the rise phase of the flare, show a source elongated NNE-SSW, in which the SSW portion is negatively polarized. At the peak of the flare (fourth column of panels) the northern end of the radio source shows positive polarization; the way in which the positive and negative contours are squared together in the polarization map indicates that the center of the positively polarized radio emission is less than 1 beamwidth (~15") away from the negatively polarized emission in the south.

The overall degree of polarization is approximately 10% at the peak of the flare, and it is dominated by the negatively polarized emission from the southern portion of the source. The microwave patrol data indicate that the radio spectral peak is close to 10 GHz; from 17 to 35 GHz the radio flux spectral index is ~2.3, corresponding to a nonthermal electron energy distribution of index ~3.9 in the thick-target model.

4.3. Hard X-Ray Source Structure

Hard X-rays were observed with the Yohkoh-HXT in all energy bands up to 93 keV. Figure 3 shows the hard X-ray images at the peak of S1. During this spike, because of the relatively low count rate, mapping in the M2 band is restricted to the period around the peak (peak count rate 13 counts s^-1 per subcollimator). In the M2 band, we see double sources whose centers are separated by ~23", with the NE source being the brighter. In the L band (and also in the M1 band), the double sources are also clearly seen, with the NE source again being brighter than the SW. The ratio of the peak count rates (SW/NE) is 0.35 in the L band and 0.40 in the combined M1 and M2 bands. The spectral hardness of the NE and SW sources was apparently similar. We suggest that the two sources correspond to the footpoints of a single flaring loop. As the flare evolves, the images show that the whole loop fills in; this is most pronounced (especially in the L band) during the valley between the two peaks and at the second peak (not shown). This filling of the loop is probably due to evaporated plasmas produced by the electron bombardment during the first peak.

Figure 3 also shows the 17 GHz contours superimposed on the hard X-ray flare sources. Figures 3d and 3e show the total intensity and polarization of the 17 GHz source, respectively. Note the cospatiality of the hard X-ray footpoint source. The radio emission is much stronger over the weaker hard X-ray footpoint and extends well south of the hard X-ray emission. No such extension is seen to the north.

4.4. Comparison with Optical Data

No optical data are available at the time of the flare, but magnetograms are available from National Astronomical Observatory of Japan (NAOJ) at 0030 UT, some 2 hr earlier. In Figure 4 (Plate 25) we present a number of overlays with optical data. Figure 4a has contours of the optical continuum (showing the locations of sunspots) overlaid on the only SXT frame (partial) available for the flare. Figure 4b shows HXT contours overlaid on a continuum image. Figure 4c shows the 17 GHz I contours overlaid on a magnetogram, and Figure 4d shows the 17 GHz V contours overlaid on the continuum image. The radio images are not preflare-subtracted, so that the coincidence of the polarized active region emission (westernmost contours, Fig. 4d) with a sunspot may be seen. The northern HXT/radio source is very close to a small spot, which, however, does not appear to display strong magnetic fields in the magnetogram. The southern HXT source apparently lies over a narrow tongue of downward magnetic field that skirts the east of a larger, positively polarized spot. Based on the magnetogram, it is difficult to determine which of the HXT "footpoints" lies over the stronger magnetic field, but
Fig. 4.—(a) Overlay of optical continuum contours on SXT partial-frame image at 02:12:58 UT on 1993 May 28. The contours are chosen to show the spot locations in the active region. (b) Overlay of HXT contours, showing the locations of the two hard X-ray sources, on the optical continuum image. (c) Overlay of 17 GHz total intensity map (not preflare-subtracted) on NAOJ magnetogram. (d) Overlay of 17 GHz circular polarization contours on the optical continuum image. The field of view is 5'2 in each panel.

KUNDU et al. (see 454, 525)
their locations are consistent with being on opposite sides of a netural line.

5. EVENT OF 1993 MAY 30, 0648 UT

5.1. Radio and Hard X-Ray Time Profiles and Energy Spectra

This flare shows a single-spike time profile in the hard X-ray range, peaking at 0648:54 UT (Fig. 5). There is a gradual increase in hard X-ray flux in the L band from ~0648:00 UT, and the flare mode was triggered at 0648:46 UT, after which data from all four energy bands are available. The time profiles are quite similar in all HXT bands, with the burst duration being about 30 s (FWHM) in the L band. There is no significant increase in the H-band count rate. The ratio M1/L of HXT energy bands gives a photon spectral index of 3.3 at the flare peak, increasing to about 4 following the peak. The M2/M1 ratio implies a somewhat softer spectrum, with an index of ~4.5 throughout the hard X-ray spike. The microwave time profiles are very similar to the hard X-ray profiles. Note that in Figure 5 the solid line in the microwave panel is the “correlation” data from the radioheliograph, which is not sensitive to large-scale structure, and the divergence between the map fluxes (crosses) and the solid line during the decay of the flare may be due to large-scale emission, which is not adequately represented by the correlation data.

5.2. Flaring Region in Microwaves

Like the May 28 event, the May 30 event also originated in AR 7515. Prior to the flare, the only significant 17 GHz polarization detected is again over a spot in the leading part of the region (Fig. 6). The difference images in this figure show flare emission from a highly elongated east-west source containing several peaks. Note that the compact source at the eastern end of the region does not change much with time; we believe that it is not associated with the flare. Throughout the flare the strongest radio emission is at the SW edge of the region, close to but not quite coincident with the polarized sunspot source. The brightest microwave flare source was strongly polarized (negative polarity); the flare emission at the eastern end of the extended radio source is unpolarized.

The strongest radio peak has a degree of polarization steady at about ~45% during the impulsive peak. The spectral index

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for this event from 9.4 to 17 GHz is about 2.6, corresponding to a thick-target nonthermal electron distribution of index $-4.2$.

5.3. X-Ray Source Structure

Figure 7 (Plate 26) shows SXT, HXT L, and HXT M1 images at the peak of the flare. The SXT image shows several loops but is dominated by two bright, compact features. The HXT images show peaks nearly at the same locations and also show emission between the bright features as in the SXT images. Figures 7d and 7e present overlays of the microwave images on the X-ray images. In Figure 7d the 17 GHz $I$ contours are shown superimposed on the SXT image, while in Figure 7e the 17 GHz $V$ contours are shown overlaid on the HXT M1 image. As in the previous example, the brightest hard X-ray emission is not coincident with the brightest 17 GHz emission, and the latter probably lies over strong magnetic fields. Since there are more than two hard X-ray sources in this event, it is not clear exactly how the topology of the X-ray sources should be interpreted, which is relevant to determining the degree of asymmetry. The westernmost source has $\sim 40\%$ of the count rate of the bright, easternmost source in the M1 channel, while the next-to-westernmost source has $\sim 30\%$ of the count rate of the brightest source.

Unfortunately, no simultaneous magnetogram is available, so we are not certain of the location of the photospheric neutral line. We have compared two Kitt Peak magnetograms straddling the time of the flare (May 29 and May 30) with nearly simultaneous SXT images (not shown), and we find that a large spot is close to the X-ray emission in the SW, whereas no spot is close to the bright source to the NE. The neutral line...
Fig. 7—X-ray images of the 1993 May 30 flare. (a) SXT image (Be filter) at 06:48:59 UT. (b) HXT L-band (14–23 keV) image for 06:48:46–06:49:09 UT. (c) HXT M1-band (23–33 keV) image for 06:48:46–06:49:02 UT. (d, e) Overlays of radio images (contours) on X-ray images (gray scale). In (d) the 17 GHz total intensity contours at 06:48:57 UT are plotted on the SXT Be-filter image; in (e) the 17 GHz circularly polarized flux contours at 06:48:57 UT are plotted on the HXT M1 image. The field of view is 26 in each frame.

Kundu et al. (see 454, 527)
crosses between the two brightest X-ray sources, and the magnetic shear across this neutral line appears to be increasing at this time.

The SXT observations reveal four compact areas that brightened in the flare. The compactness and the coincidence with hard X-ray emission in the HXT images argue for their identification as footpoints as opposed to upper parts of loops. Indeed, the brightest soft X-ray source is almost exactly co-spatial with the brightest hard X-ray source. Moreover, although the present flare does not show impulsive soft X-ray emission as clearly as the one reported by Hudson et al. (1994), the temporal behavior of the compact soft X-ray sources suggests that they were produced at the same time as the hard X-ray sources, in contrast to the loop emission, which builds up with time due to evaporation from the footpoints. However, we cannot completely rule out the possibility that each of these compact areas represents the top of a small, dense loop. Feldman et al. (1994) argue that soft X-ray emission in a flare tends to be highly localized around the loop top, even in the early phase. In fact, a close look at Figure 7 shows small displacements between soft and hard X-ray sources, which may be due to a height difference between the two sources; the hard X-ray source may represent a footpoint of such a loop, where the magnetic field is weaker. In any case, radio observations with the presently available spatial resolution are not sensitive to such fine structures.

6. DISCUSSION

Asymmetry in hard X-ray emission arises via magnetic mirroring in a magnetic loop as follows (see, e.g., Melrose & White 1979, 1981): Conservation of an adiabatic invariant for an electron gyrating around a magnetic field line means that as an electron propogates toward higher magnetic field strengths, its pitch angle $\alpha$ (the angle between $B$ and the instantaneous velocity of the electron) must increase according to $\sin^2 \alpha \propto B$. Consequently, for a particle with a given pitch angle at the top of the loop, there is a maximum field strength to which it can propagate before conservation of adiabatic invariants forces the electron to “mirror” and reverse direction along the field line. If this maximum field strength lies below the chromosphere, then the electron will first strike the dense chromosphere and precipitate. All electrons pass through the lowest field strength region, usually assumed to be at the top of the loop. If we consider the velocity distribution of electrons passing through the top of the loop, there is a critical pitch angle such that electrons with smaller pitch angles will precipitate, while electrons with larger pitch angles will mirror in the corona. This critical pitch angle is said to define the loss cone, i.e., those pitch angles less than the critical value. Particles with pitch angles lying in the loss cone will precipitate at the footpoints of the loop unless they are scattered as they travel along the magnetic field lines. If the field strengths at the feet of the loop differ, then the loss cones for the two feet will also differ in size. In the situation where there is strong pitch angle scattering in the loop (i.e., on average a particle's pitch angle will change by a large amount in traversing the loop), the loss cones will both be filled at all times (since the pitch angle distribution will be nearly isotropic), and then the ratio of precipitation rates at the two feet ($R_1$ and $R_2$) is just the inverse ratio of the field strengths ($B_1$ and $B_2$):

$$\frac{R_1}{R_2} \approx \frac{B_2}{B_1} \quad (1)$$

(Melrose & White 1979, 1981). The resulting asymmetry in precipitation rates, and hence in hard X-ray emission, can be mild if the two footpoints have similar field strengths.

As mentioned in § 1, the asymmetry in the radio emission is a high power of the ratio $B_1/B_2$, and, thus, unless the asymmetry in precipitation is very strong, the radio emission should be strongest at the footpoint with the weakest hard X-ray emission. This expression only applies to optically thin gyrosynchrotron emission, but it should generally be valid at 17 GHz, which is typically above the spectral peak of flare radio emis-
FOOTPOINT EMISSION FROM SOLAR FLARES

sion. In the optically thin limit, where radio flux \( S \propto N_{\text{nt}} B^{0.908-1.22} \), with \( \delta \) being the spectral index of the electron energy distribution (typically \( \delta \approx 4-6 \)) and \( N_{\text{nt}} \), the number of nonthermal electrons (Dulk & Marsh 1982), the radio fluxes from the two footpoints are in the ratio

\[
S_1/S_2 \propto (B_1/B_2)^{0.908-2.22}
\]

for the strong-scattering limit, where we have used equation (1) to determine the ratio of numbers of nonthermal electrons at the two footpoints. For the typical range \( \delta = 3-6 \), the exponent in equation (2) ranges from 0.5 to 3.2. Unfortunately, equation (2) is of little use by itself because of the additional dependence of the radio flux on the angle \( \theta \) between the line of sight and the magnetic field:

\[
S_1/S_2 \propto (\sin \theta_1/\sin \theta_2)^{0.654-0.43}
\]

The four relevant parameters (\( B, \theta, N_{\text{nt}}, \) and \( \delta \)) required to describe the radio emission completely, and required to evaluate equations (2) and (3), can be determined at each footpoint if we can measure the radio flux and the polarization of each at two frequencies (e.g., Kundu, Velusamy, & White 1987). However, the necessary data are not available for the events we discuss here. Another complication for quantitative analysis is the likelihood that the radio data will be contaminated by emission from weaker field regions lying along the same line of sight as the footpoint but located higher in the loop.

In the limit of weak pitch angle scattering in the loop (little change in a particle's pitch angle as it traverses the loop), the situation is more complicated. The asymmetry in precipitation is generally much greater than in the strong diffusion limit because only the particles initially injected into the loss cone for the stronger field footpoint precipitate at that footpoint: all others, including all particles which are initially outside the loss cones, precipitate at the weaker field footpoint. However, the particles not initially injected into the loop with pitch angles lying in a loss cone are by definition trapped particles, and it will take some time for their pitch angles to diffuse into the (biggest) loss cone. Therefore, the precipitation rates at the two feet at any given instant depend strongly on the history of particle injection into the loop, and there is no simple expression for the instantaneous ratio of precipitation rates in the weak-scattering limit equivalent to equation (1) in the strong-scattering limit. Despite the stronger asymmetry in the precipitation and therefore in the hard X-ray emission, the radio emission from the two sides of the loop is expected to be more symmetric than in the strong-diffusion limit. This is because electrons, as they diffuse slowly in pitch angle, bounce between the same magnetic field strength at both ends of the loop until they eventually precipitate at the weaker field footpoint. Therefore, none of the trapped electrons reaches the stronger fields in the stronger field leg of the loop (although the electrons injected directly into the loss cone for that side of the loop do), and symmetry between the two sides of the loop is maintained.

Since the distribution of electrons with respect to magnetic field strength is approximately symmetric, in the two sides of the loop, the asymmetry in the radio emission will be determined largely by the asymmetry in the viewing angle, as in equation (3). Since comparison of the two footpoints will be most straightforward for events near disk center rather than at the limb, and since the radio source in the stronger field leg will be higher in the corona and therefore is likely to have a larger value of \( \theta \) than a source at the chromosphere for such loops, the radio emission is still likely to appear stronger in the stronger field leg.

How do the two events presented here fit into this picture? In one case, bipolar structure with two footpoint sources of opposite polarity was observed at 17 GHz. These oppositely polarized sources observed in the 1993 May 28 event coincide in position with the double "footpoint" sources observed with the HXT experiment in the high-energy bands up to M2. For the 1993 May 30 event the 17 GHz flaring source is elongated; it is strong and highly polarized (degree of polarization, 45%) where there are strong magnetic fields but weak hard X-ray emission, and it is weaker and unpolarized where the hard X-ray emission is strongest. In both events the strongest 17 GHz emission is not coincident with the strongest hard X-ray emission. The May 28 flare may be the first reported identification of a bipolar microwave flaring source with the two polarities co-spatial with the double "footpoints" of the hard X-ray source, as expected in a single-loop flare model.

Thus, in both events the radio data are consistent with an asymmetric loop in which the bulk of the precipitation occurs at the footpoint which has the weaker magnetic field strength. In the May 28 flare the data are consistent with a single-loop model; in the May 30 flare both the hard and soft X-ray images show that more than one loop is involved. The magnetogram data for May 28, on the other hand, suggest that the line-of-sight photospheric field strength is strongest near the stronger hard X-ray source. However, this magnetogram also illustrates the difficulties of using overlays on magnetograms to determine the magnetic field strength at a footpoint, since a shift of 5" of the hard X-ray sources relative to the magnetogram, which is within the uncertainty of the overlay accuracy, means a very large decrease in the field strength attributed to the northern footpoint. Another effect which is relevant is the inclination of the magnetic field to the line of sight. The mirroring effect depends only on the total magnetic field strength at the footpoint. The longitudinal photospheric magnetogram measures the component of \( B \) along the line of sight, whereas the radio flux is sensitive primarily to the component of \( B \) perpendicular to the line of sight. Thus, neither is strictly a measure of the mirroring field strength.

7. CONCLUSIONS

Sakao (1994) has concluded that, at least for a small sample of events, the ratio of the count rates in the two components of hard X-ray double-source flares is consistent with an interpretation in which the amount of precipitation at the two feet of a loop is determined by the relative magnetic field strengths at the feet. Sakao's study relied on calculating the photospheric magnetic fields at the hard X-ray footpoint locations. In this study we have used an alternative technique to address the same question: the comparison of hard X-ray and microwave images. The asymmetric-loop model predicts that, provided the asymmetry in precipitation is not too strong, the radio emission should be strongest where the magnetic field is strongest, i.e., at the footpoint where hard X-ray precipitation is weakest. That was found to be the case for both events analyzed here. To proceed further and carry out a quantitative analysis of the radio asymmetry, including the role of pitch angle scattering, requires determination of \( B, \theta, N_{\text{nt}} \) and \( \delta \) in each footpoint/leg.
of the radio source. This requires multifrequency data, which are not available for these two events.

This type of study relies on having hard X-ray images with enough dynamic range to see both footpoints. Since current hard X-ray images have limited dynamical range, studies of this type must select against cases in which there is a large ratio in precipitation at the two footpoints, e.g., against any situations in which there is a large ratio $B_1/B_2$, or when there is weak pitch angle scattering in the corona. In such events it will be difficult to identify the stronger field footprint from the X-ray data alone; the addition of radio images may aid in these cases, since we still expect to see a radio source at the stronger field footpoint.

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