LOCATION OF TYPE I RADIO CONTINUUM AND BURSTS ON YOHKOH SOFT X-RAY MAPS

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Abstract. A solar type I noise storm was observed on 30 July, 1992 with the radio spectrometer Phoenix of ETH Zürich, the Very Large Array (VLA) and the soft X-ray (SXR) telescope on board the Yohkoh satellite. The spectrogram was used to identify the type I noise storm. In the VLA images at 333 MHz a fully left circular polarized (100% LCP) continuum source and several highly polarized (70% to 100% LCP) burst sources have been located. The continuum and the bursts are spatially separated by about 100" and apparently lie on different loops as outlined by the SXR. Continuum and bursts are separated in the perpendicular direction to the magnetic field configuration. Between the periods of strong burst activities, burst-like emissions are also superimposed on the continuum source. There is no obvious correlation between the flux density of the continuum and the bursts. The burst sources have no systematic motion, whereas the the continuum source shows a small drift of \( \approx 0.2" \) min\(^{-1} \) along the X-ray loop in the long-time evolution. The VLA maps at higher frequency (1446 MHz) show no source corresponding to the type I event. The soft X-ray emission measure and temperature were calculated. The type I continuum source is located (in projection) in a region with enhanced SXR emission, a loop having a mean density of \( \langle n_e \rangle = (1.5 \pm 0.4) \times 10^9 \) cm\(^{-3} \) and a temperature of \( T = (2.1 \pm 0.1) \times 10^6 \) K. The centroid positions of the left and right circularly polarized components of the burst sources are separated by 15"–50" and seem to be on different loops. These observations contradict the predictions of existing type I theories.

1. Introduction

Solar type I noise storms were the first solar radio events discovered in the metric range, and they are also the most common phenomena at these wavelengths. Type I events last for several hours and sometimes for days. They are associated with active regions, but they are not related to solar flares. Two different components of type I emission can be distinguished: short-lived (0.1–1 s), narrowband (several % of the mean frequency) emissions (type I bursts) are superimposed on a continuous, slowly varying, broadband (50–400 MHz) background emission (type I continuum). Usually, the continuum and the bursts are highly polarized (up to 100%), and the sense of circular polarization corresponds generally to the \( o \)-mode. For a review


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$o$-mode. For a review of the extensive literature on the observational phenomena the reader is referred to Elgarøy (1977).

Imaging observations have located the type I sources in the middle and upper corona (0.1$-$0.5 solar radii) and in connection with new and growing active regions. It is not clear how the energy is brought up and released into the corona. The current ideas may be summarized in three scenarios: (i) Newly emerging magnetic field may interact with the pre-existing coronal field, and reconnection could release free magnetic energy (Benz and Wentzel, 1981). This model is supported by the observed delay of the type I activity in relation to the photospheric changes. The continuum emission is interpreted as caused by trapped electrons exciting upper-hybrid waves. They interact with ion-acoustic waves in the current sheet of the reconnection region producing the bursts. Thus, continuum and bursts would be on the same magnetic field lines. (ii) The emerging magnetic field and the energy may move into the corona by shocks propagating at about the Alfvén speed. Electrons may be accelerated at the shock front and emit bursty radiation at regions of kinetic instability (Spicer, Benz, and Huba, 1981; Wentzel, 1981). (iii) The energy may be released in the low corona and be transported up by particles or waves. This idea originates from observations of soft X-ray and 20 cm radio enhancements before the onset of type I storms. Delays between the maximum X-ray brightness and peak type I activity range between one day (Benz et al., 1984), one hour (Lang and Willson, 1987), 10 min (Lantos et al., 1981), and a few minutes (Willson, Lang, and Liggett, 1990). Raulin and Klein (1994) found that noise storms are systematically accompanied by brightening of the full disk soft X-ray flux. Others, however, have found no consistent pattern in relation to an associated 20 cm source (e.g., Habbal, Ellman, and Gonzalez, 1989).

The relation between the continuum and the burst source has been investigated at lower frequencies: Daigne (1968) and Kundu and Gopalswamy (1990) reported that the positions of continuum sources and burst sources coincide at frequencies below 169 MHz excluding noise storms near the limb. Suzuki (1961) and Daigne (1968) have claimed that most clusters of type I bursts show systematic motions. Apparent source motion up to 15000 km s$^{-1}$ have been noted by van Nieuwkoop (1986) using a two-element interferometer. Willson, Lang, and Liggett (1990) have noted an elongated source in a low-temporal-resolution observation, and Raulin et al. (1993) observed motions across the extrapolated potential field. Kai (1970), and more recently White, Thejappa, and Kundu (1992), have reported bipolar structures in type I storms. Kai has interpreted the observations as two sources having opposite circular polarization and lying on both sides of the same magnetic field loop.

Since the sign of the longitudinal field component changes, but not the magnetotonic mode, the emission would be oppositely polarized. Comparisons between type I sources and EUV loops by Stewart, Brueckner, and Dere (1986) suggest that the projected centroids of the LCP and RCP components are separated along the magnetic field lines. Double or complex burst structures are reported by Daigne.
(1968) and Kerdraon (1979). The different burst sources are separated by distances between $1'$ and $3'$. Here we present the first comparison of high-resolution soft X-ray and noise storm (radio) images. The data of the type I event are classified by spectra, and the simultaneous VLA observations provide spatial images. From the Yohkoh soft X-ray data the emission measure and the temperature images of the active region causing the type I event are calculated and compared with the positions given by the VLA observations.

2. Instruments

2.1. The Spectrometer (Phoenix)

The Phoenix spectrometer of ETH Zürich, Switzerland, was built in 1989 and is described by Benz et al. (1991). The frequency-agile receiver measures digitally the flux density and the polarization of the full solar disk in the frequency range of 100 to 3000 MHz with a selectable time resolution of 0.5 to 250 ms. The operation mode was set to a time resolution of 0.04 s. This allowed us to measure 80 frequency channels per spectrum: 20 frequencies were chosen around 333 MHz, and 60 frequencies around the second frequency of the VLA (1446 MHz). Because of technical reasons, the calibration parameters were determined more than a month later.

2.2. The Very Large Array (VLA)

The VLA*, New Mexico, U.S.A., was used in the D configuration to produce high angular resolution images of the solar disk. Since the 90 cm and 20 cm feeds are located at different points (prime focus and secondary), it is possible to observe simultaneously at 333 MHz and 1446 MHz. For both frequencies the left and right circular polarizations were available. Because of the large volume of data, the calibration parameters were derived for 10-s averaged visibilities. Afterwards, the calibration table was applied to the full-time resolution data ($\Delta t = 0.417$ s). The AIPS calibration package was used. 3C48 was the primary flux calibrator, and 3C196 was the phase calibrator.

The time period of interest was selected and classified with the aid of the spectra. Around the selected period, snapshot maps were made and deconvolved from the dirty beam (clean deconvolution, Clark, 1980). The most intense of these cleaned snapshot maps was used for self-calibration (Pearson and Readhead, 1984; Cornwell and Fomalont, 1989). Again, the solution tables, i.e., the solutions of the complex gain of each antenna calculated by the self-calibration algorithm,

* The Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
were copied and applied to the calibrated data. The cleaned snapshot maps of the self-calibrated data were used for the following analysis.

2.3. **The Yohkoh Soft X-ray Telescope**

The soft X-ray telescope on-board *Yohkoh* (Tsuneta et al., 1991) is designed to produce full and partial disk images with an angular resolution down to 2.45″. The telescope is sensitive in the 0.25–4.0 keV energy range. As type I events are not related to flares, the telescope was not working in the flare mode during the type I event. Full disk images taken a few minutes before the first group of type I bursts are used in this analysis.

Several different metal filters can be positioned in the focal plane of the soft X-ray telescope. From two images with different filters and with the aid of the known filter ratio, it is possible to calculate the emission measure and the temperature for each pixel (cf., Hara et al., 1992). The uncertainties in the temperature, $T$, are about 0.1 in $\log_{10} T$.

3. **Observations and Analysis**

3.1. **Spectral Observation (Phoenix)**

During the entire observing time (15:00 to 18:00 UT on, 1992 July 30), type I bursts appear in the observed frequency band from 300 to 357 MHz. About 250 single bursts occur per hour. Most of them are clustered or appear as drifting chains. Some single bursts can also be observed between two periods of enhanced type I burst activity. Most of the bursts are around the lower limit of the observed frequency band (300 MHz), and only about 5% of the bursts occur at the VLA frequency of 333 MHz. The single bursts have an intensity from a few solar flux units up to 100 s.f.u., a bandwidth of 2 to 4% of the center frequency and a duration of about 0.5 s.

The broadband continuum of the type I event is a component of the background in the spectrograms. Therefore, the continuum emission is removed by the background subtraction.

Two periods are selected for detailed analysis: the first burst group (burst group 1) is around 15:01:45 UT (Figure 1) and the second group (burst group 2) occurs at 15:05:30 UT (Figure 2). The polarization of the bursts is left circular: burst group 1 is $\approx 65(\pm 10)\%$ LCP and group 2 is $\approx 80(\pm 10)\%$ LCP. Figure 1 presents a spectrogram of total flux density with single type I bursts lasting 0.5–1 s. Both the small bandwidth and the high degree of polarization clearly indicate that the emission is of type I.

Around the second frequency of VLA (1447 MHz), no enhanced radiation above 0.4 s.f.u. was detected.
3.2. SPATIAL OBSERVATION (VLA)

To identify the location of the type I emission in the spatial maps, one has to find the VLA source that correlates in time with the Phoenix flux density. Around the occurrence of the two type I burst groups, the VLA maps show two different sources (Figure 3, left), but only the source near the coordinate S30 W05 shows significant intensity variation during this period. After a time integration of the spectral data to the same time resolution as the VLA data, a comparison of the flux densities yields a clear identification of the more southern source as the location of the type I event.

Since the type I source in the VLA maps also exists before and after the type I bursts observed in the spectrogram, a continuum emission is involved. During each type I burst the intensity of the VLA source also increases, and the location of the maximum emission is slightly shifted in the southern direction. This shift of the source can be explained by a superposition of two spatially separated sources: a permanent continuum source and a burst source.

The coordinates of the continuum source and the burst source could be determined, for instance, by fitting the contour levels with a set of gaussian functions. However, the inverse process was already done in the cleaning algorithm: The accumulated point source model was convolved with an elliptical gaussian fit (the ‘clean beam’) to the dirty beam for producing the cleaned image. Thus, to separate the superposed sources, it is more practical to artificially decrease the beam size in the convolution and produce ‘enhanced contrast’ maps, rather than fitting the cleaned maps with a set of single source distributions.

The dependence of the source positions on the choice of the artificially reduced beam size has been investigated: for maps containing only the continuum source, the calculated centroid is stable in position within ±1.5″ for beam sizes down to
Fig. 2. *Top*: spectrogram of type I bursts observed by the Phoenix spectrometer of ETH Zürich on 30 July, 1990. Frequency increases downward, time to the right. Enhanced flux density is shown dark. The frequency range between 340 MHz and 347 MHz is disturbed and therefore omitted. Two groups of type I bursts can be seen: a larger one around around 15:01:45 UT, and a smaller group around 15:05:30 UT. *Middle top*: flux density of the continuum source for the same period as the spectra observed by the VLA at 333 MHz. The component of the quiet Sun is removed. *Middle bottom*: same for the burst sources. The shown curve is the flux density of all burst sources together. *Bottom*: the flux density around the location of the type I event at 1446 MHz. The time resolution is integrated to 2.5 s. In this plot, the range of the flux density is ten times smaller than in the two plots above. No source was found in these maps.
Fig. 3. In both figures the Yohkoh full-disk soft X-ray image with the Al.1 filter (≈ 0.25–4.0 keV) at 14:56:43 UT with an exposure duration of 2.69 s is presented. Enhanced emission is shown dark. Left: the VLA snapshot at 15:01:45.10 UT (Δt = 0.417 s) of the solar disk convolved with the synthesized 'clean' beam is overlayed on the Yohkoh SXR image. The equidistant contour levels show the intensity at 333 MHz. The contours are multiples of 1 × 10⁷ K. Two sources can be seen: the stronger source in the south correlates with the type I bursts observed in the spectra (cf., Figure 2). Right: the same VLA snapshot convolved with an artificially reduced beam size. The more southern source is now separated into two sources. The two sources can be identified as continuum and burst of the type I event. The source at N22 E44 cannot be seen because of the different choice of contour levels.

the pixel size (20″). For maps with both continuum source and burst sources, the sources are well separated using a beam size of three pixels (60″) and smaller. The position of the centroids is again stable within ±1.5″ for beam sizes between one and three pixels. To avoid round-off error in the flux density, an artificial beam size of 60″ is used in the following. Additionally, simulations with model UV data at the appropriate hour angle containing two point sources at different angular separations have been carried out. It is trivial to resolve a source with an angular separation of 3 pixels (60″) or more, whereas smaller separations can only be reconstructed with reduced accuracy.

The type I continuum and single-burst sources have an apparent size at half intensity with a mean major axis of ≈ 290″ and a mean minor axis of ≈ 230″. The beam size (major axis 289″, minor axis of ≈ 207″) suggests that the type I sources have been spatially resolved along the minor axis. The deconvolved source size of about 100″ is in agreement with the previous observations (reviewed by Elgarøy, 1977), corresponding to an averaged brightness temperature of 2.6 × 10⁷ K for the continuum and a peak brightness temperature of 1.9 × 10⁸ K for the bursts. For a symmetric beam with an artificially reduced diameter, the continuum source and the burst source show a separation of their centroids of up to 135″ (Figure 3, right). The observed correlation of the centroid of the combined emissions with flux and the temporal stability of the subsources prove the reality of the subsources (cf., Figures 5 and 6). To calculate the flux density of the separated sources, one has first to account for the different beam of the residual map, because the residual map is
convolved with the dirty beam. The temporal evolution of the flux density of the two sources can be seen in Figure 2, and they are discussed in the following.

3.2.1. The Continuum Source

3.2.1.1. Flux Density. The flux density of the continuum source is around 6 s.f.u. There are significant variations in the flux density (Figure 2). The strongest variation is about 16 s.f.u. and has a duration of about 1.6 s. Two single, narrowband bursts can be found in the spectrogram at 15:03:48 UT, the time when the strongest peak in the continuum source occurs. Since the continuum source position does not vary significantly during this period, the burst-like activities seem to be superposed on the continuum emission.

The variations of the continuum source do not clearly correlate with the flux density of the burst source. Continuum enhancements by about 5 s.f.u. were observed 20–30 s after each burst group (Figure 2). However, more observations are needed to establish the significance of this phenomenon.

In the 60-s-averaged snapshot maps, the long-time evolution of the type I source can be investigated. During the period from 14:30 to 16:00 UT, the flux density of the continuum source is decreasing significantly from about 9 s.f.u. to 3 s.f.u.

3.2.1.2. Polarization. The polarization of the continuum source is, within the
Fig. 5. The evolution in time of the intensity contour levels at 333 MHz of the left circular polarized (LCP) component of the continuum source and the burst sources (cf., Figure 3). An artificially reduced beam size has been used for convolution. The contour levels are equidistant. In a single contour map, the direction from left to right corresponds to the east–west direction, and north is at the top; the coordinates are indicated in the map at the lower-left corner. The first contour map is at 15:01:14.69 UT, and the following maps are each separated by 0.417 s. At the beginning there is no type I bursts activity, and only the continuum source appears. During periods of type I bursts, the emission occurs in more than one source.

uncertainty of the observations, 100% LCP, i.e., no corresponding component was found in the RCP maps. Even in the maps with enhanced flux density no RCP source was found.

3.2.1.3. Location of the continuum source. The location of maximum emission was determined by fitting the source with a gaussian function. No correlation
between the flux density and the location of the emission has been found. Most of the coordinates of the centroid are within a square of 20". The scatter of the location of the centroid is large, but a slow drift in the x-direction can be seen. In the 60-s-averaged maps, the drift is more obvious (Figure 4): in the period before the bursts (14:30–15:01 UT), the continuum source moves slightly to the west with an average velocity of about 0.4" min\(^{-1}\). After the burst episodes (15:14–15:45 UT) the continuum source does not move, within a scatter of ±5", but later on starts to drift westward again. The drift velocity of the continuum source due to the rotation of the sun of 0.16" min\(^{-1}\) has to be subtracted from the above values. Hence, the location of the continuum source is almost stable and moves at a few km s\(^{-1}\) back and forth along the loop outlined by SXR (Section 3.3.1.1).
3.2.2. The Burst Sources

3.2.2.1. Intensity Contours and Flux Density. In Figure 5 the temporal evolution of the intensity contours around the period of the appearance of the first burst group can be seen. In the first maps only the continuum source is active. The burst emission starting later comes from different sources: the burst sources of the most intense maps are separated by about 100" from the continuum source. A quick look at these maps suggests a superposition of two sources lying close together. At the beginning and the end of the burst group also a weak source between the continuum source and the most intense burst source appears. The second burst group shows the same characteristics.

The flux density of the bursts peaks at 35 s.f.u., whereas the mean value is about 20 s.f.u. Before, between and after the two burst groups no source is observed at their location (Figure 2).

3.2.2.2. Polarization. The sense of polarization of the burst source is left circular, the same as the continuum source, but the bursts are not fully polarized: the first group is \( \sim 80\% \) LCP, with extreme values at 70\% and 90\%. For the second burst group, a RCP source can be clearly identified only in 6 maps. The polarization is 90\% LCP or higher. The agreement with the polarization values measured by the spectrometer (Section 3.1) is acceptable considering the different ways the background has been subtracted and the calibration problem of the spectrometer (cf., Section 2.1).

The location of the maximum emission is slightly different for the two polarizations: the separation of the centroids has approximately a Gaussian distribution with FWHP \( \approx 11" \) for the first burst group and FWHP \( \approx 4" \) for the second burst group, and the average separation is \( 25(\pm1)" \) for the first burst group, and about \( 47(\pm1)" \) for the second group. For both burst groups, the RCP sources are displaced in the north-eastern direction. A possible time delay between the LCP and RCP emission can be calculated with the aid of the cross-correlation of LCP and RCP flux density of the Phoenix data. The result shows no delay in excess of the time resolution of 0.04 s. In the following, the LCP source is investigated.

3.2.2.3. Location of the Burst Sources. Again, the sources were fitted with a gaussian function and the location of the maximum burst emission was calculated. For the most intense bursts the results are plotted in Figure 6. The points are connected according to the temporal evolution, and points with an intensity above half of the maximum intensity of the relevant burst group are marked by a symbol (diamonds for the first burst group, triangles for the second).

Both burst groups show a similar behavior. There are two sources in each burst group: a more intense source, around \( 90"/615" \) for the first burst group (source A), respectively around \( 75"/610" \) for the second burst group (source C), and a weak source, around \( 95"/640" \) for the first burst group (source B), respectively.
around \((80''/ -645'')\) for the second burst group (source D). In the first burst group source B sometimes exceeds source A, whereas in the second burst group source C always dominates source D. Therefore, the coordinates of source C and D in Figure 6 are not connected by lines. The scatter of the location is small for the intense sources A and C \((\approx \pm 3'')\), and relatively large for the weak sources B and D \((\approx \pm 8'')\), but the location of the different sources are well separated, and stable in position. Coordinates lying between sources A and B can be explained as a superposition of these two sources. Therefore, the single burst sources in the first burst group are not moving, and no systematic movement of the burst sources is discernible in either group.

3.2.3. **Microwave (1446 MHz) Emission**

In the VLA maps at 1446 MHz no source above 0.2 s.f.u. is found near the active region producing the type I event at 333 MHz. Since the onset of the noise storm is missed in these observations, an already disappeared source at 1446 MHz cannot be excluded. The flux density integrated over a square area with a length of 320'' around the active region is shown in Figure 2 (bottom). There is a slight increase in the flux density of about 0.2 s.f.u. with a maximum about one minute after the first burst group. Since no source can be found, this increase is most probably due to an incomplete Fourier back-transformation of the \(u - v\) data.

3.3. **SOFT X-RAY OBSERVATION (Yohkoh)**

The \textit{Yohkoh} satellite was observing before the two burst groups occurred (14:30–15:00 UT), and resumed the observations about 40 min later. Only full disk images before the bursts are available (Figure 3). These images have an angular resolution of 4.92''.

3.3.1. **Emission Measure and Temperature Maps**

From the two images with different filters (14:56:43 UT with filter Al.1, and 14:58:51 UT with filter AlMgMn) the emission measure per unit area, \(EM\) (Equation (1)), and temperature, \(T\), were calculated for each pixel. The contour levels of these two maps are plotted in Figure 7 (bottom). The combination of these two filters is sensitive in the range of \(4 \times 10^{23} \leq EM \leq 4 \times 10^{28}\) cm\(^{-5}\) and for \(10^6 < T < 10^7\) K. Values above these limits are saturated by the instrument. Because of the poor photon statistics, no emission measure and temperature contour levels are shown in faint regions.

In the SXR emission measure map, the location of the denser magnetic loops can be seen. The high temperature regions are offset from the regions of strong emission measure. This was also found by Hara \textit{et al.} (1992).

3.3.1.1. **The Location of the Continuum Source on the Emission Measure and Temperature Maps.** In the two-dimensional projection, the continuum source lies on a loop with an emission measure in the range of \(2.6 \times 10^{27}\) cm\(^{-5}\) to
Fig. 7. The four images are enlargements of the active region (S20 W10) related to the type I event. On all images the coordinates of the maximum emission of the continuum and the burst are plotted (cf., Figures 4, 5, and 6). Top left: the soft X-ray image (Al.I filter, 14:56:43 UT, cf., Figure 3) is plotted over the contour level of the NSO magnetogram: dashed contours correspond to negative polarity, solid contours to positive polarity. Note that the type I continuum source is located near the apex of the loop structure with a cooler temperature ($T = 2.1 \times 10^6$ K) than the ambient loops ($T = 3.5 \times 10^6$ K). Top right: the same with the soft X-ray image observed with the AlMgMn filter (14:58:51 UT). Bottom left: the emission measure contours are plotted over the soft X-ray map at 14:56:43 UT. The contour levels are multiples of $0.8 \times 10^{27}$ cm$^{-5}$, starting with $1.6 \times 10^{27}$ cm$^{-5}$. Bottom right: the same for the temperature contours. The lowest contour level is $2.3 \times 10^6$ K, and the following contours are separated by $0.2 \times 10^6$ K.

$5.1 \times 10^{27}$ cm$^{-5}$ and a temperature of about $2.0 \times 10^6$ K to $2.2 \times 10^6$ K. Compared to characteristic values for a large-scale loop ($EM \approx 5 \times 10^{25}$ cm$^{-5}$, $T \approx 2.1 \times 10^6$ K) and for an active region ($EM \approx 3 \times 10^{28}$ cm$^{-5}$, $T \approx 2.5 \times 10^6$ K) (cf., Tsuneta et al., 1991), the calculated values for this loop are intermediate: the continuum emission may be related to a loop not too far away from the active region. The slow motion of the continuum source (cf., Section 3.2.1.3) is approximately in the direction along this loop. Also, the short-term scatter of the centroid position is larger along the loop than perpendicular to it.
It is possible to approximate the density of the soft X-ray emitting electrons from the observed emission measure, and from that the plasma frequency follows. The known plasma frequency allows one to study the relation of the SXR loop with the type I radio emission.

The observed diameter $d \approx (25 \pm 10)''$ of the contour level perpendicular to the magnetic field can be used as an approximation of the thickness of the loop. Since the largest part of the SXR emission comes most probably from the magnetic loop and not from below or above the loop, the emission measure per unit area is about

$$EM = \int_{\text{source}} n_e(t)^2 dt \approx \langle n_e \rangle^2 q d,$$

where $\langle n_e \rangle$ is the average density in the loop. For an emission measure of the loop of $(3.9 \pm 1.3) \times 10^{27} \text{ cm}^{-5}$, a diameter of $(1.8 \pm 0.7) \times 10^9 \text{ cm}$ and a filling factor $q \approx 1$, the electron density in the loop becomes $\langle n_e \rangle = (1.5 \pm 0.4) \times 10^9 q^{-1/2} \text{ cm}^{-3}$. This density corresponds to a plasma frequency of $\nu_p = (350 \pm 50) q^{-1/4} \text{ MHz}$.

Since, within the accuracy available, the calculated plasma frequency is comparable to the frequency of the observation (333 MHz), the escape of the radiation does not pose a problem. For the continuum source, most theories predict an emission slightly above the plasma frequency (e.g., Benz and Wentzel, 1981). These observations are thus compatible with fundamental plasma emission.

3.3.1.2. The Location of the Burst Sources on the EM and Temperature Maps. To avoid erroneous results because of the poor photon statistic in the faint SXR emitting region around the type I bursts (cf., Figure 7), only averaged values of the emission measure and the temperature are calculated. For the locations of the LCP and RCP sources, which are separated up to $50''$ (cf., Section 3.2.2.2), the calculated values do not differ significantly. The emission measure is $\langle EM \rangle \approx (5 \pm 2) \times 10^{26} \text{ cm}^{-5}$ and the temperature $\langle T \rangle \approx (1.8 \pm 0.3) \times 10^6 \text{ K}$ around the location of the bursts. The bursts are located just outside the weakest enhanced SXR structure in a region of average ambient temperature. Since the Yohkoh data are from 14:58 UT, these averaged values corresponds to the emission measure and the temperature before the type I bursts occur.

Very surprising is the position of the burst relative to the continuum: the bursts are not on the same X-ray loop as the continuum. Continuum source and burst sources seem to be separated perpendicular to the magnetic configuration. We will further study this points in the following subsection.

3.3.1.3. Comparison of the EM Map with the Extrapolated Potential Magnetic Field. A rough approximation of the magnetic field topology can be calculated with the aid of the potential field extrapolation code by Sakurai (1982). The code calculates the Green’s function, and uses the observed photospheric magnetic field configuration (NSO magnetogram) for the boundary conditions. As the name
implies, the term $\nabla \times \mathbf{B}$ is neglected in the calculation, i.e., the coronal plasma is assumed to be current free. Since currents cannot be ignored in the solar corona, this assumption is certainly not valid. Nevertheless, the extrapolated potential field can be helpful: since the potential field is the configuration with the lowest energy, the extrapolated field is not only a rough approximation of the actual magnetic field, but it also shows what the relaxed magnetic field would be.

In Figure 8 (top) the emission measure contours are plotted over the photospheric magnetogram. Additionally, the locations of the continuum and bursts are shown, and the potential field lines which transverse the continuum source or the burst source in the two-dimensional projection are plotted. The projected positions of the continuum and burst source suggest that they are not on the same magnetic field lines. Both the continuum source and the burst sources are located halfway between the bipolar footpoints, and thus near the apex of the connecting loop.

The altitude of the magnetic field lines can be seen in Figure 8 (bottom). The altitude of the sources is very uncertain, because loops with altitudes of about $0.4-2.0 \times 10^{10}$ cm are found to match the line-of-sight position.

4. Summary of the Observations

Out of a long-lasting solar type I noise storm, an intermediate period of about 4 hours is investigated. The two components of the type I event, the continuum and the bursts, are identified on the VLA maps and compared to the emission measure and temperature maps calculated from Yohkoh soft X-ray data. The results are the following:

- The continuum and bursts are spatially separated by up to 135″.
- The continuum emission comes from a single source and is always fully polarized (in LCP mode).
- The flux density of the continuum source decreases with a rate of 4 s.f.u. per hour. No clear correlation between the flux density of the continuum and the bursts is found.
- Burst-like activities are superimposed on the continuum source as well.
- The projection of the continuum source coincides with an enhanced X-ray loop having a mean density of $\langle n_e \rangle = (1.5 \pm 0.4) \times 10^9$ cm$^{-3}$ and a temperature of $T = (2.1 \pm 0.1) \times 10^6$ K. The density agrees with the observed frequency assuming fundamental plasma emission.
- The position of the continuum is moving slowly ($\approx 0.2$″ min$^{-1}$) along this loop. This suggests that the continuum source is located in the observed X-ray loop.
- The burst emission originates from different sources with a high degree of left circular polarization (70–100% LCP). The position of the RCP burst source differs from the position the LCP source by 15″ to 50″. Between the two periods of burst emission no enhanced emission is observed from the position of the bursts.
Fig. 8. *Top:* on the photospheric magnetogram the SXR emission measure contours (cf., Figure 7, bottom left), the location of the radio sources (continuum and bursts) and the two-dimensional projection of the extrapolated potential field lines are plotted. Only field lines which traverse one of the two radio sources are shown. *Bottom:* the potential magnetic field lines in space. The $x$- and $y$-coordinate are the surface coordinates of the photosphere relative to the solar disk center, and parallel to latitude and longitude. The $z$-coordinate is the altitude above the photosphere. The projections of the field lines on the photosphere are plotted as dashed lines. For a comparison with Figure 8 (*top*), the line of sight is plotted.
The burst source is not on the same loop as the continuum. The burst source seems to be displaced perpendicularly to the continuum in a bipolar active region structure.

No microwave (1446 MHz) emission was found around the active region producing the type I event.

5. Discussion and Conclusions

This first comparison of coronal structures as seen in soft X-ray and type I radio images has revealed some surprising results.

A clear separation of the continuum source and the bursts has been noted. The separation is not only large (up to $10^{10}$ cm), but transverse to the field lines as outlined by dense X-ray loops. This seems to contradict the expectations of both the 'reconnection' (Benz and Wentzel, 1981) and 'shock' (Spicer, Benz, and Huba, 1981; Wentzel, 1981) models: in the former model the electron distribution is unstable to Langmuir waves or upper hybrid waves producing the continuum source in the loop and, by wave-wave coalescence with ion acoustic waves, the type I bursts in the reconnection region. Alternatively, in the 'shock' model the upper hybrid waves produced by the trapped electrons may scatter on lower hybrid waves produced in the shock to emit the type I bursts at the shock front. Hence, in these two models, the continuum source and the burst source are both related to the location of the trapped electrons, i.e., loops connected to the acceleration region. Therefore, additional assumptions are required in these two models to explain the observed spatial separation of the continuum source and the burst source.

An additional problem in the shock model is the stability of the position of the observed burst sources. The 'shock' model for type I storms predicts a systematic motion of the bursts with the Alfvén velocity. For a plasma frequency of 333 MHz, a magnetic field of 2.5 G (potential field extrapolations), a duration of about 45 s for the first burst group and of about 20 s for the second, the displacement of the position during the first and the last burst would be about $9''$ for the first group and $4''$ for the second. Such motion has not been observed. Compared to Figure 6, these predicted separations are considerably larger than the standard deviation of the coordinates of about $2.5''$. This contradicts the prediction of the 'shock' model for type I storms.

The 'bipolar' scenario for type I storms (Kai, 1970; White, Thejappa, and Kundu, 1992) is also problematical in view of these observations. The observed separation of the centroids of the left and right circular mode is transverse to the magnetic field as outlined by the soft X-ray loops. This poses serious difficulties with Kai's model of two sources in the two legs of a loop. Instead, we propose that the separation is a propagation effect. Scattering has been proposed to be the cause of the reduced polarization of the type I sources (e.g., review by Benz, 1993). The
different scattering and propagation properties of the two modes may also cause a shift of the apparent source position.

If one considers only the location of the observed continuum and burst sources and looks for a possible magnetic geometry in which a connection by field lines between these two sources is possible, a ‘helmet streamer’ would be a possible configuration. The continuum sources would be situated below the vertical current sheet, and the burst sources would be located in the neutral sheet above where reconnection takes place. The weak enhancements in the continuum source, occurring about 20 s after the two burst groups, could then be explained by the travel time of the energetic electrons from the burst source to the continuum source. This geometry can only be proposed, if the burst position is always higher than the continuum position. However, multifrequency observations generally find the continuum source higher, the lower the frequency (e.g., Raulin and Klein, 1994).

On the other hand, the continuum source is not free of burst activity at 333 MHz. This may support a model in which the observations are explained by two independent noise storms, one at the position of the continuum source and the other one at the position of the burst source. In this model the lack of a continuum emission at the location of the burst source may be interpreted as an effect of age or loop size. Hence, more investigations on the relative positions and the temporal relation between of the continuum and burst source are needed to understand the geometry: Are the continuum and the bursts most often spatially separated, and is there a causal relation between these sources? What is the position of the continuum and the bursts at lower frequencies? What is the general orientation of the continuum and the bursts relative to the active region and the magnetic field?

The comparison of type I radio storms with soft X-ray structures has produced surprising results and has lead to more questions than answers. More events have to be studied for definite conclusions and the development of new models. The combination of thermal and non-thermal imaged information is an exciting new possibility to study non-flare phenomena of the solar corona.

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