THE STRUCTURE AND INTENSITY EVOLUTION
OF A SOLAR BURST AT 2.8 cm AND THE RELATION
WITH THE SOFT X-RAY EMITTING REGION

MARCELLO FELLI, ROBERTO PALLAVICINI, and GIANNI TOFANI
Osservatorio Astrofisico di Arcetri, Florence, Italy

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Abstract. The decay phase of a microwave burst was observed with a one-dimensional angular
resolution of 16" at 2.8 cm. The structure was found to be composed of several bursting regions with
different evolution. The event was also observed in soft X-rays by full-disk detectors. The joint analysis
of these data suggests that the complete event has thermal origin and that the soft X-ray emission is
associated with the rapidly varying component of the radio structure. From these results the average
values of the electron temperatures and densities were computed for each component.

1. Introduction

In the past the morphological characteristics and the emission mechanisms of the
microwave solar bursts have been investigated with the aid of measurements of total
power and polarization evolution at different frequencies. These measures were
limited by the low instrumental resolving power and only a few high resolution obser-
vations are reported in the literature (Enomé et al., 1969; Tanaka and Enomé, 1970;
Kundu et al., 1974; Lang, 1974).

Indeed, a series of high resolution pictures of the entire active center during the
burst not only would allow us to locate the place of birth of the phenomenon, but
would also allow us to investigate interactions with the neighbouring regions.

In the present work interferometric observations at 2.8 cm are presented for the
decay phase of a burst, obtained with an angular, one-dimensional resolution of
16".

The information derived from the radio angular structure and the soft X-ray
emission, observed simultaneously, is used to investigate the relationships between the
X-ray and the radio sources and the nature of the emission mechanism. The results
indicate that the burst is probably of a thermal nature and that the X-ray emission
is associated with only one component of the flaring radio region.

2. The Radio Observations

The radio data of the present work were obtained with the Five Element Array of the
Stanford Radio Astronomy Institute, during a program of observations on solar
active regions performed during August–September 1973 (Felli and Tofani, 1975).

The instrument (Bracewell et al., 1973) is composed of five parabolic antennas
displaced along the east-west direction and operates as a synthesis interferometer. With observing times of less than a few minutes the radiotelescope is able to give the synthesized one-dimensional brightness distribution. The field of view is 2.1' on each side of the direction to which the instrument is pointed. The direction of the one-dimensional ‘scan’ varies with hour angle as shown, for instance, by Christiansen and Hogbom (1969). The shortest integration time available is about 20 s.

The resolution perpendicular to the ‘scan’ direction is that of the single antenna, equal to 7'.

The interferometer is astronomically calibrated by observing point radio sources.

**Fig. 1.** The development of the radio event. Several one-dimensional observed brightness distributions are shown: (a) before the event, 2054 UT, (b) first observation of the burst, 2154 UT, (c) to (g) samples during the event, from 2158 to 2254 UT, (h) on the following day at 2010 UT. The components A, B and C are indicated. The dotted line is the reference level for each scan (which has zero integral value). The intensity scale is in arbitrary units. The positions are in minutes of arc from the center of the observed fields.
The calibration procedure and the results are described elsewhere (Felli et al., 1974); here we recall concisely the relevant standard errors: \( \pm 2.5^\circ \) in right ascension, \( \pm 20^\circ \) in declination and \( \pm 10\% \) on the fluxes.

The burst was observed on September 2, 1973 from 2154 UT, when the instrument was pointed on the active region McMATH 12512 (S 21°, E 54°).

*Solar-Geophysical Data* (1973) reports the absence of optical patrol during this event. Our observations continue until 2253 UT, except during an interval between 2229 and 2240 UT. All the observations are probably related to the decay phase of the event, as will be shown later. A selected number of the brightness distributions observed at different times are reported in Figure 1. The scans are not deconvoluted from the interferometric beam, which produces a complex sidelobe structure. The procedure of recovering the source distribution will be discussed in the next section. Except for the first scan which has been obtained with an integration time of 2 min, all the other observations result from an integration of 20 s.

In order to track a solar source, the center of the observed field is continuously corrected for the solar motion and rotation; this procedure allows us to compare directly the position of the radio features in the subsequent scans.

The same active region was observed before the event, at 2054 UT, with the same pointing, and the day after at 2000 UT, with heliographic coordinates S 21° and E 37°; these scans are also reported in Figure 1.

### 3. The Deconvolution of the Radio Observations

The observed brightness distributions are the convolution of the interferometer pattern with the true source distributions. The components of these distributions are recovered by the use of a computer program, reported in other works (Felli et al., 1974; Felli and Pampaloni, 1975). Gaussian type sources are convoluted with the interferometer function and the result is compared with the observed distribution until the best least square fit is obtained. The process may be repeated by inserting successively up to six independent Gaussian sources of different intensity, width and position. The recovered brightness distribution is then given by the sum of the Gaussian sources found in the process. The iteration is halted when the residual brightness is of the order of the expected noise level. The radio fluxes are deduced from the data obtained by the fitting program and are calibrated with the flux of known point radio sources.

The method has the intrinsic limitations of any fitting process, i.e. when the separation of the sources is close to the instrumental resolution, only the overall brightness distribution, and the total flux, are valid, while the single component values might be randomly computed.

In the first phase of the burst two components are evident. These will be referred to as component A and B as shown in Figure 1b). When their intensities (Figures 1f and g) are of the same order their separation becomes difficult.

Some examples of the fitting program results are reported in Figure 2.
4. The Description of the Radio Event

The observation at 2054 UT, before the event, indicates the existence of an extended source of half intensity width (HPW) 0.86' and an overall flux 5.3 sfu*, which in the hypothesis of circular symmetry gives a brightness temperature $2 \times 10^5 \text{K}$.

The components A and B contribute significantly to the increase of the total flux of this region during the burst. At the end of the event a third low intensity component C is also identified by the program.

The main features A and B have been separated up to 2110 UT. In Figure 3a and b the following parameters of the fitted Gaussian sources are plotted: the intensity (AMP) and the half intensity width (HPW). The figure does not include the data of the first observation at 2054 UT, when a longer integration time of 2 min was used.

As shown in Figures 3a and b and also directly by the observed data of Figure 1, the component B remains constant in size and intensity while the component A, of greater intensity, has a faster intensity decay and an appreciable increase in width. The fluctuations visible in Figure 3b as for instance for the points at 2159, 2201 UT etc. are caused by the fitting program which might overestimate the size of one component with respect to the other.

* 1 sfu (solar flux unit) = $10^{-22} \text{W m}^{-2} \text{Hz}^{-1}$.
Fig. 3. The parameters of the Gaussian components A (dots) and B (crosses) plotted for the first phase of the burst decay. From top to bottom: intensity (arbitrary units), half power width (minutes of arc) and brightness temperature ($\times 10^6$ K).

In Figure 3c are plotted the brightness temperatures defined by

$$T_b = \frac{\lambda^2 F}{2k1.333\theta_G^2},$$

where $\lambda$ is the wavelength in meters, $F$ is the derived flux density in W m$^{-2}$ Hz$^{-1}$, $k$ is the Boltzmann constant, $\theta_G$ is the HPW of the fitted Gaussian in minutes of arc.
Equation (1) is valid on the assumption of Gaussian sources with circular symmetry. While the component B has an approximately constant value of $2 \times 10^6$ K during a large part of the observed period, that of component A decreases from $2 \times 10^6$ K to $0.7 \times 10^6$ K in the same interval. All these temperatures are well above the pre-burst level.

The positions of the components with respect to the center of the radio scans are constant within $\pm 3.5^\circ$, a value of the same order as our accuracy. The separation between the components A and B is also constant during the event and it is 24.5$^\circ$, which, at a heliographic photospheric longitude of 55$^\circ$ corresponds to a projected linear distance of $3 \times 10^4$ km.

The emission from the active region has appreciable variations up to 2111 UT, then the structure becomes more stable and the component A is barely detectable. Another significant parameter is the total flux of the bursting region, which is plotted in Figure 4 and was derived by subtracting the contribution of the preexisting region.

![Graph](image_url)

**Fig. 4.** The integrated flux density from the bursting region referred to the preburst level of the active region. The crosses indicate those values which have greater errors due to the fitting program.

The total flux has a marked decrease in the first phase, essentially due to the decay of the component A, while in the second phase the flux is almost constant with a value of 8.5 sfu, hence remaining much higher than the preburst level and indicating the presence of a long lived active structure. The scatter of the points in Figure 4 is greater in the last part of the event due to the greater extent and lower intensity of the components. The total error after the subtraction of the preburst level is estimated to be $\pm 1$ sfu.

The last scan, reported in Figures 1g and 2 (at 2254 UT), shows that the region has evolved into three more stable components: a large source of $\text{HPW} = 0.98^\prime$ and $T_b = 3 \times 10^5$ K with superimposed the component B, which has now $\text{HPW} = 0.17^\prime$ and $T_b = 2 \times 10^6$ K, and a third low intensity component C, with $\text{HPW} = 0.52^\prime$ and $T_b = 2.1 \times 10^6$ K. Component A has vanished, while there is a small increase in the flux density of the neighbouring regions. The same active region was observed on September
3, 1973 at 2010 UT, about 24 hr after the event. Two main components were resolved with \( HPW = 0.94' \) and \( HPW = 0.19' \), and \( T_b = 0.73 \times 10^5 \text{ K} \) and \( T_b = 2.6 \times 10^5 \text{ K} \), respectively. The total flux from the region is reduced to 2.6 sfu, a value much lower than the preburst level.

5. The Relationship between the Radio Event and the X-Ray Burst

Solar microwave bursts are generally divided between impulsive and gradual rise and fall (GRF) (Kundu, 1965; Takakura, 1967; Takakura, 1969; Labrun, 1972). While the first type is usually related to the non-thermal process of the gyro-synchrotron emission in localized magnetic fields (Takakura, 1969), the GRF events probably originate in free-free emission from the hot plasma (Hachemberg and Wallis, 1961). Besides the time evolution, the two classes also present fluxes and polarizations with different spectral behaviour. As far as the brightness distribution of microwave bursts is concerned, we remember that a double structure was previously observed for both categories (Enomé et al., 1969); this result was interpreted as a consequence of the bipolar structure of the magnetic field in the active regions.

The event of the present work was not observed with a sufficient spectral range to allow any spectrum analysis: *Solar-Geophysical Data* (Comprehensive Reports, 1974) reports only the observation from Ottawa at 2800 MHz, where the burst was classified as GRF, with a duration of 145 min and a peak intensity of 3.8 sfu at 2210 UT, in the decay phase of our observations.

The gradual decay evolution, observed at our frequency, and the brightness temperatures, which are always less than \( 3 \times 10^6 \text{ K} \), suggest that the emission may be produced by a thermal free-free process. This hypothesis was investigated with the aid of the soft X-ray burst simultaneously observed by the NRL satellite SOLRAD 9 (*Solar-Geophysical Data*, Comprehensive Reports, 1974) in the spectral range 0.5–20 Å.

The analysis of the relationship between microwave and X-ray bursts has been carried out by several authors, who found a high correlation between impulsive radio and hard X-rays bursts (Takakura and Kay, 1966; Arnoldy et al., 1968; Holt and Cline, 1968; Holt and Ramaty, 1969) and between soft X-ray and GRF radio bursts (Chambe and Shain, 1969; Shimabukuro, 1970; Hudson and Okhi, 1972). From these studies however the relations between X-ray and radio emission have not been completely solved and doubts still exist as to whether the emissions originate at the same source.

The soft X-ray emission, observed by the broad band photometers of the SOLRAD satellites, is interpreted for wavelengths \( \geq 1 \text{ Å} \) in terms of a pure thermal process. Horan (1971) and Landini et al. (1972) have shown that the ratio of the X-ray fluxes in two spectral bands is a function only of the plasma electron temperature \( T_e \). Since the X-ray flux is

\[
F_x = E M_x \times \Phi(T_e),
\]

where \( E M_x = \int N_e^2 \text{ d}V \) is the emission measure and \( \Phi(T_e) \) is a known function of the
temperature, once $T_e$ is known the emission measure can also be derived. The region emitting X-rays is assumed to be isothermal and the measure of $T_e$ and $EM_x$ are only effective values over the region. The information from these satellites does not have any spatial resolution.

The burst was investigated in the bands 1–8 Å and 8–20 Å; the electron temperatures and the emission measures were derived by the reduction tables provided by Horan (1973), which are based on the theoretical computation of the solar X-ray thermal spectrum, including free-free and free-bound continuum emission (Culhane, 1969) and line emission (Tucker and Koren, 1971). The electron temperature $T_e$ and the emission measure $EM_x$ are reported in Figure 5 as a function of time, for the period when the X-ray emission was significantly above the background level.

The parameters thus determined include several errors; even if we ignore the errors in computing the theoretical X-ray spectrum and the uncertainties in the evaluation of the pre-burst level, the presence of both systematic and random errors in the observations only allows us an accuracy of 15% for the measured fluxes. The derived electron temperatures are then correct within $0.5 \times 10^6 K$ for values of the order of $10^7 K$ and the emission measures have errors up to 45%.

Fig. 5. The parameters deduced from the X-ray event: electron temperature $T_e$, emission measure $EM_x$ and the expected radio flux $F_R$ in the optically thin approximation.
As shown by the time profile (see Solar-Geophysical Data, Comprehensive Reports, 1974) the X-ray burst has a peak at 2154–2155 UT and returns to the pre-burst level at about 2230 UT; if the X-ray and radio bursts have the same maximum, then our 2.8 cm observations immediately follow the peak phase of the event; we also note that the radio emission remains enhanced for a longer interval than the X-ray one.

According to Kawabata (1960), microwave free-free radiation is emitted by the hot plasma where the X-ray emission originates and the expected radio flux may be computed from the X-ray parameters, under some condition on the microwave thickness of the plasma.

The comparison of the $T_e$ during the decay phase of the X-ray event and the radio brightness temperatures $T_b$ shows that the latter ones are always lower.

If the emission originates from the same plasma, this difference implies an optically thin source at 2.8 cm, with a brightness temperature $T_b = T_e \tau$, where $\tau$ is the optical depth.

If the plasma is optically thin, the theoretical radio flux at 2.8 cm may be derived from the X-ray parameters (Hudson and Ohki, 1972):

$$F_R = 2.5 \times 10^{-6} T_e^{-1/2} \times EM_x \quad \text{W m}^{-2} \text{ Hz}^{-1}. \quad (3)$$

The evolution of $F_R$ is shown in Figure 5; the values have a mean error of about 50% based on the accuracy on $T_e$ and $EM_x$.

The comparison between $F_R$ and the observed radio flux (Figure 4) indicates a discrepancy of a factor between 2 and 4. The disagreement might suggest that the radio event is completely independent from the X-ray source; this hypothesis would imply that the X-ray source does not contribute to the observed flux at 2.8 cm, which means that the electron density is so high that the plasma frequency ($f_p \approx 9000 N_e^{1/2}$) is greater than 10 GHz. The required $N_e$ is $1.4 \times 10^{12} \text{ cm}^{-3}$, which, with an emission measure of $6 \times 10^4 \text{ cm}^{-3}$, gives a source volume $\leq 3 \times 10^{24} \text{ cm}^3$, much smaller than the typical sizes found in the X-ray flares photographs (Vaiana, 1975).

The 2.8 cm emission could be also produced by a non-thermal process. The gyro-synchrotron emission usually explains the impulsive phases of the microwave bursts, while this event is characterized by long, enduring emission (Figure 4) and the enhanced flux is diffused over the entire region (Figure 2), which suggests a gradual heating of the plasma.

In a last, most probable, interpretation, the X-ray source might be smaller than the overall radio region of Figures 1 and 2, coinciding only with a fraction of it. The validity of this assumption will be discussed in the following sections.

5.1. THE COMPONENT A

An inspection of Figures 5 and 4 shows that a similarity exists between the decay of $F_R$ and the observed decrease in the first phase of the radio event, from 2158 to 2210 UT, which is essentially due to the strong variation of the component A.

The radio emission due to this component was isolated by subtracting from the observed values the emission at the end of the burst ($\sim 2254$ UT). The result is that the
variable part of component A decreases between 2158 and 2210 UT from 3.8 to 1.6 sfu; these values are, within the experimental errors, in good agreement with the $F_R$ found from the X-ray parameters.

If we now use radio parameters of this part of the component A in order to obtain the brightness temperature $T_b$, we can check the validity of the assumption of Equation (3). The brightness temperature thus determined varies between 0.6 and $0.26 \times 10^6$ K, which with electron temperatures of the order of $8 \times 10^6$ K clearly indicates a $\tau \ll 1 (\tau_{2.8} \leq 0.08)$. We then interpret the similarity in the evolution and the actual values of the observed and expected radio fluxes as an indication that the flaring X-ray source is associated only with the variable part of the component A. With the derived $EM_x$ and the radio size of the component A the average $N_e$ is $2.5 \times 10^{10}$ cm$^{-3}$.

5.2. THE COMPONENT B

If the X-ray source is completely related to the component A, the component B of the radio region does not produce any detectable X-ray emission at least in the spectral range 1–20 Å. This experimental information, together with the radio data, can be used to determine the limits of $N_e$ and $T_e$ which must be present in the component.

In Figures 3c and 3b we see that the component B, during the decay phase, has quite stable brightness temperature $T_b \approx 2 \times 10^6$ K and angular size HPW $\approx 0.3'$, corresponding to a linear size $L_B = 1.3 \times 10^9$ cm. If we assume an isothermal region with uniform $N_e$ and with depth $L_B$ along the line of sight, from equations

$$\tau = 0.19 \frac{N_e^2 L_B T_e^{-3/2} v^{-2}}{1 - e^{-\tau}}$$

and

$$T_e = T_b (1 - e^{-\tau})^{-1}$$

we have

$$N_e = 13.9 \times 10^{20} \times \frac{\tau}{(1 - e^{\tau})^{3/2}}.$$  

The functions $T_e (\tau)$ and $N_e (\tau)$, determined from Equations (5) and (6), are plotted in Figure 6. Two curves are shown: full lines are computed for the total flux of the component B and dashed lines for the difference between the total flux of this component and its preburst level.

Figure 6 shows that, as expected, the electron temperature decreases with increasing $\tau$ and tends towards $T_B$ for $\tau \gg 1$. The electron density $N_e$ has a minimum for optical depths of about 0.5–1; these minimum values are $4 \times 10^{10}$ and $5.2 \times 10^{10}$, respectively, for the two cases. With the angular size of the component B, we may assume a source volume $\approx 2.2 \times 10^{27}$ cm$^3$ and derive an emission measure of $3.5\text{–}6 \times 10^{48}$. We see from Figure 5 that towards the end of the X-ray burst (~2223 UT) the X-ray emission reaches an $EM_x = 1 \times 10^{48}$ and a $T_e = 6 \times 10^6$ K. The X-ray flux is given by (2) where $\Phi (T_e)$ is a known function of the temperature for each X-ray spectral range. If we assume as an upper limit that the X-ray flux level at the end of the burst is the same for both components A and B and the emission measure for B is greater than for A by a factor 3.5–6, then the $\Phi (T_e)$ must be reduced of the same values and the resulting
Fig. 6. Plots of the functions $T_e(\tau)$ and $N_e(\tau)$ derived from Equations (5) and (6). Dotted lines refer to differences between the total flux of the component B and the preburst level.

electron temperatures are about $4\times 10^5$ K. The absence of observable X-ray emission from the component B implies that this source is a region of optical depth $\tau \approx 1$ and hence greater than that of the component A; the source B has a slightly higher electron density ($\geq 4\times 10^{10} \text{ cm}^{-3}$) and much lower electron temperature ($\leq 4\times 10^6$ K). Although the component B is stable during the first phase of the radio event, we notice a slow intensity decrease in time and, at the end of the observations ($\approx 2254$ UT), its flux is reduced by a factor 3 with respect to the initial value.

In Section 2 it has been remarked that the positions of the two components do not vary during the burst. Considering the heliographic longitude of the region ($55^\circ$), the result mainly indicates the absence of radial movements greater than 3000 km. We remember that changes in source position during bursts were found by several authors (Kundu, 1965). Here, the stable positions of the components are quite consistent with the thermal origin deduced for the event, which implies a local heating of the plasma.

The observed increase in diameter of the component A is about 10" (see Figure 3b) in a time interval of 14 min. This corresponds approximately to an expansion of the emitting region at a mean speed of 10 km s$^{-1}$, which is much less than the velocity of sound and of Alfvén waves within such a region.

5.3. COMPARISON WITH THE MAGNETIC FIELD

The relation between radio active regions and magnetic fields was investigated in another work (Felli et al., 1975b). A comparison between the position of the radio structures and the photospheric magnetic map can be performed for this region only for September 3, 1973 (the day after the burst). The comparison is shown in Figure 7.
Fig. 7. The magnetic field configuration of the active region on September 3, 1973. The lower part is the observed one-dimensional brightness distribution on the same day. Also marked are the positions that the components A, B and C of the burst had respect to the radio active region on the previous day.

The magnetic region appears to be of moderate intensity (photospheric fields $\leq 900$ G) and to have a bipolar structure separated by a neutral line approximately in the north-south direction.

If we suppose that magnetic field configuration has not changed appreciably from the previous day we see that the component A is projected on the region of predominant transverse magnetic field, while the components B and C are projected in regions of predominant longitudinal field. This is consistent with what found from X-ray photographs (Vaiana and Giacconi, 1969; Pallavicini et al., 1975), that X-ray bursts occur across the neutral line.

6. Conclusions

A radio burst was observed at 2.8 cm simultaneously with a soft X-ray event.

The high radio spatial resolution allows us to separate two distinct components with angular sizes of the order of 20″–30″ but with different evolution.

The knowledge of the fine radio structure, although pointing out the complex evolution of the bursting region, is not sufficient to define completely the nature of the event. The comparison with the X-ray event enables us to make a detailed analysis.

The emission mechanism seems to be thermal on the following grounds: gradual rise and fall type of the event, low radio brightness temperatures ($<3 \times 10^6$ K) compared with the electron temperatures derived from the soft X-ray event.
Only the component with rapid decay can be interpreted as associated with the X-ray event, as indicated by the coincidence of the observed radio flux decay and that derived from the expected free-free radio emission from the X-ray source. The more stable component which does not emit X-rays in the band 1–20 Å can be interpreted as a region of plasma with slightly higher electron density and lower electron temperature.

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Solar-Geophysical Data, National Oceanic and Atmospheric Administration, Boulder, Colo.