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# Radio Counterparts to SXR Transients

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## Abstract

By now several studies have been done on small-scale brightenings seen at radio, UV, EUV, and soft X-ray wavelengths. These are to be reviewed by Kundu in these proceedings. In this talk we concentrate on the radio counterpart of a particular type of brightening—the soft X-ray transient brightenings of Shimizu. These brightenings are associated with active regions, and a study of radio counterparts by White et al. (1995) using Nobeyama data found an excellent correspondence between the 17 GHz and SXR brightenings, both spatially and temporally. However, this study found that both the SXR and microwave emissions could be satisfactorily explained as purely thermal emission, and a search of BATSE hard X-ray data showed no nonthermal counterpart. White et al. (1995) were forced to conclude that the events may be different from flares.

A more sensitive search for nonthermal emission was needed, in particular using lower frequency microwaves where the influence of nonthermal electrons would be more easily detected. Gary, Hartl and Shimizu (1997) found 34 SXR transient brightenings over a 10-day period in May 1992, for which OVRO (1-18 GHz) total power data were available. A comparison of the data showed a number of clear nonthermal signatures. In addition, one of the events was seen in the lowest energy (6-9.3 keV) channel of the BATSE SPEC detector, suggesting a connection between the microflares discovered in hard X-rays by Lin et al. (1984). The evidence that SXR transient brightenings are microflares is reviewed in this talk. We also attempt to place other small-scale brightenings in context with regard to SXR transient brightenings and microflares.

**Key words:** Sun: corona — Sun: active regions — intrumentation: interferometers — radio continuum

## 1. Introduction

Shimizu et al. (1992) first called attention to the frequent occurrence of soft X-ray brightenings in solar active regions (hereafter ARTBs). Since then many studies have been undertaken to elucidate their properties in soft X-rays (Shimizu 1994, 1995; Shimizu et al. 1994), radio emission (Gopalswamy et al. 1994; White et al. 1995; Gary et al. 1997; Gopalswamy et al. 1998; Zhang et al. 1998; Nindos et al. 1998), and in hard X-rays (Nitta 1997). Many of these studies sought a connection with the microflares reported in hard X-rays by Lin et al. (1984), by looking for a nonthermal counterpart to the emission. This is an important question, since the soft X-rays are produced by heating of the coronal plasma which could be an entirely thermal process quite different from the nonthermal acceleration needed for microflares. Indeed, the first two searches for nonthermal emission at radio wavelengths (Gopalswamy et al. 1994; White et al. 1995) gave negative results—the radio emission that was seen could be accounted for by thermal processes. (The Gopalswamy et al. 1994 events have since been shown to have unambiguous nonthermal signatures; see Gopalswamy et al. 1998.)

This paper reviews the results of Gary, Hartl, & Shimizu (1997), which was the first to show unambiguous evidence for nonthermal emission associated with ARTBs. The result is based on the presence of weak (0.5 to a few SFU), time-coincident microwave bursts in the range 1-18 GHz that show a number of nonthermal signatures. As we will show, this work made it clear that ARTBs can indeed be considered the same phenomenon as the microflares of Lin et al. Since then, Nitta (1997) has removed any doubt of the link by showing that a number of ARTBs have hard X-ray emission (14-23 keV channel) far in excess of any expected thermal contribution.

Recently, there have been reports of even smaller events (Krucker et al. 1997; Nindos et al. 1998) some located in the network away from active regions, which have radio fluxes two to four orders of magnitude lower than in the White et al. and Gary et al. studies. Despite their small size, they also show nonthermal characteristics.

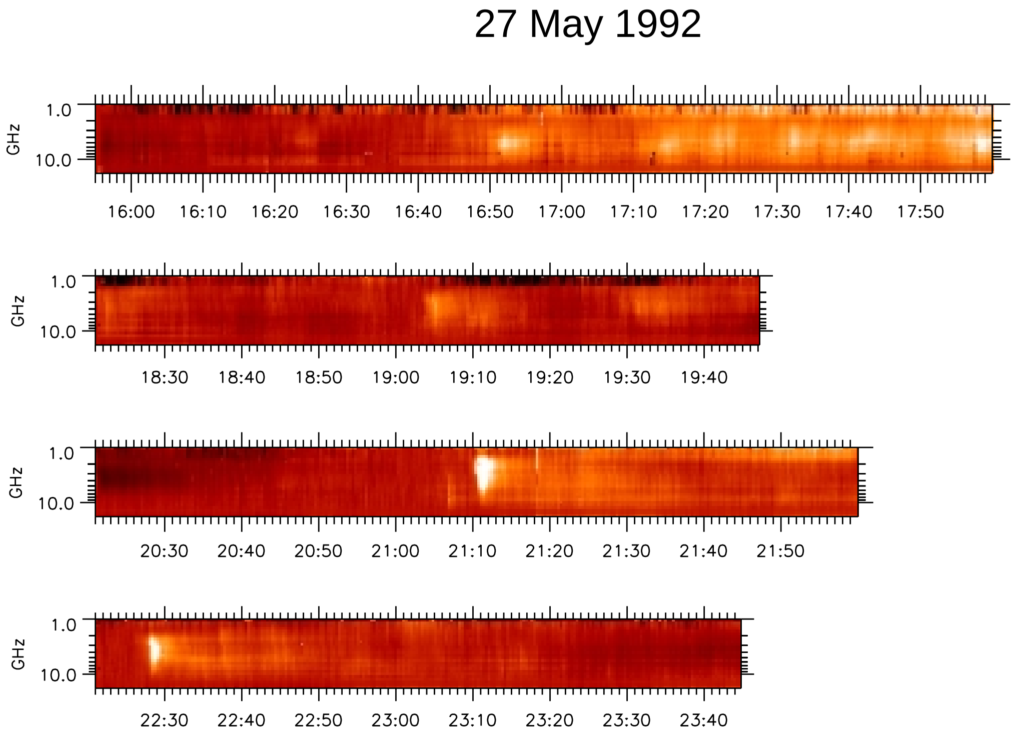

Fig. 1.. An example of dynamic spectra in total power from OVRO, for 1992 May 27. In each row of the figure is a separate 1.5–2 hour segment of data covering a total of approximately 8 hours. The numbers along the bottom of each row give the UT time. The brightness is scaled from -2 to +2 SFU. Similar data were examined on 7 days: 20–22 May and 26–29 May.

## 2. Overview of Observations

White et al. (1995) used 17 GHz observations from Nobeyama in their study of 4 ARTBs obtained with SXT, and although they found nearly perfect spatial co-alignment and good agreement in radio flux expected from thermal emission, they could not find any evidence for nonthermal emission. As they pointed out, low-energy nonthermal electrons would be more easily seen at lower radio frequencies.

We recognized that OVRO data might contain the signatures of nonthermal electrons, and set about examining data from an active region, NOAA 7172, that was known to have produced many soft X-ray ARTBs over a 10-day period in May 1992. The technique was to first identify the ARTBs by visual inspection of the SXT thin AL filter images, then look for evidence of emission in the OVRO total power data taken at 45 frequencies over the range 1–18 GHz. We identified 34 SXT events with peak fluxes ranging from $4\text{–}400 \times 10^4$ DN s$^{-1}$, which is about the same flux range as that for the 291 events reported by Shimizu (1995), so the events can be considered representative of ARTBs as a whole.

Figure 1 shows the OVRO spectra for one of the days, to show the obvious radio spectral activity. ARTBs are associated with the events near 1652, 1714, 1823, 1934, 2111, and 2229 UT. Events such as the one at 1905 UT occurred during *Yohkoh* night, and are not counted in this study.

### *2.1. Statistics of Association*

The 34 events were categorized into three groups depending on whether there was a *positive* correspondence with a radio event, a *possible* correspondence, or *no* correspondence. The assignment into the positive category was stringent, to ensure that only unambiguously corresponding events be counted. We found that 12 of the 34 events (35%) were in the *positive* category, 17 of 34 events (50%) were in the *possible* category, and only 5 of 34 SXT events (15%) clearly had *no* corresponding radio event. Figure 2 shows 8 of the 12 events in the *positive* category.

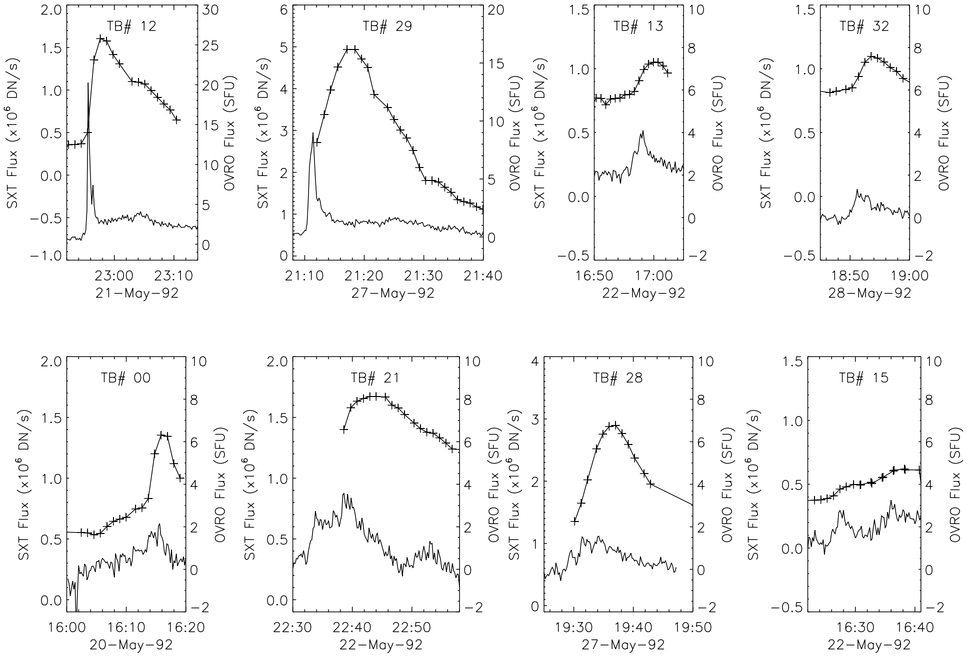

Fig. 2.. Sampling of eight of the 12 events showing *positive* correspondence in microwaves and soft X-rays. The SXT flux time profile is shown with symbols in the upper part of each plot, using the scale at the left. The OVRO flux density is shown in the lower curve of each plot, without symbols, using the scale at the right.

### *2.2. Evidence for Nonthermal Emission*

There are several lines of evidence that the radio emission from many of the events is nonthermal in character. First, the radio flux density of about half of the bursts (19 out of 34) is greater than 1 SFU. Although we have not done a temperature/emission measure analysis, the emission measures and temperatures given in Shimizu (1995) and White et al. (1995) indicate a optically thin radio flux level for thermal bremsstrahlung of about 0.5-1 SFU. Thus, many of the bursts have a clear excess flux above the thermal radio emission.

A second, stronger argument is that the time profiles tend to be very different, with the radio flux peaking typically 1 to 2 minutes earlier than the soft X-ray flux. In fact, there is a suggestion of a Neupert Effect relationship (Neupert 1968; Dennis and Zarro 1993) between several of the profiles in Figure 2, which is expected if the thermal soft X-ray emission is a response to heating by nonthermal particles. We tested this hypothesis by comparing both the radio peak flux and the time-integrated radio flux (the radio fluence) with the soft X-ray peak flux. The result is shown in Figure 3, where the soft X-ray peak flux correlates better with radio fluence than with radio flux, especially for those events with the greatest time delay (filled circles in the figure).

Finally, when we examine the microwave spectral shapes at the peak of each event, as shown in Figure 4, we find that the shapes display all of the variety one comes to expect from flares. They certainly do not uniformly show the flat spectrum characteristic of optically thin thermal bremsstrahlung. For all of these reasons we conclude that ARTBs are associated with the acceleration of nonthermal electrons, and so there is no longer any reason not to identify them with the microflares of Lin et al. (1984).

If these are microflares, then one might be tempted to ask—where are the hard X-rays? White et al. (1995) found none in the 25–50 keV channel of BATSE, for the four events they studied. We found one event (out of 7 with joint coverage) for which hard X-rays could be seen in the lowest energy channel (6–9.3 keV) of the BATSE SPEC detector. However, since then, Nitta (1997) has further demonstrated the existence of weak hard X-rays in the LO (14–23 keV) channel of HXT that are associated with many ARTBs, effectively clinching the link between ARTBs and microflares.

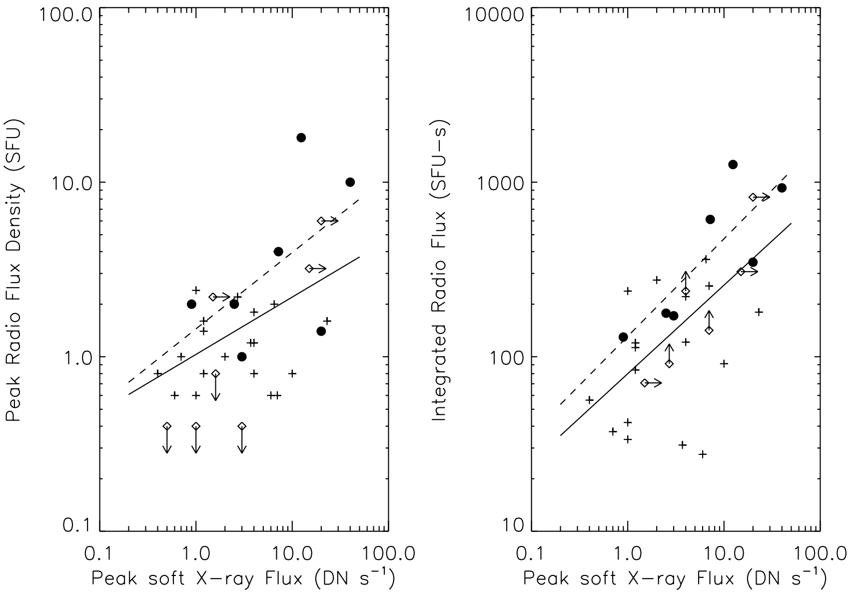

Fig. 3.. Plot of (*a*) peak radio flux density vs. peak soft X-ray flux, and (*b*) peak radio fluence (integrated flux density over time) vs. peak soft X-ray flux. Filled circles mark events with time delays of more than 2 minutes. The solid line in each plot shows the best-fit powerlaw relationship for the points with crosses, while the dashed lines show the same for the events marked with filled circles. The correlation is markedly improved in *b* as discussed in the text.

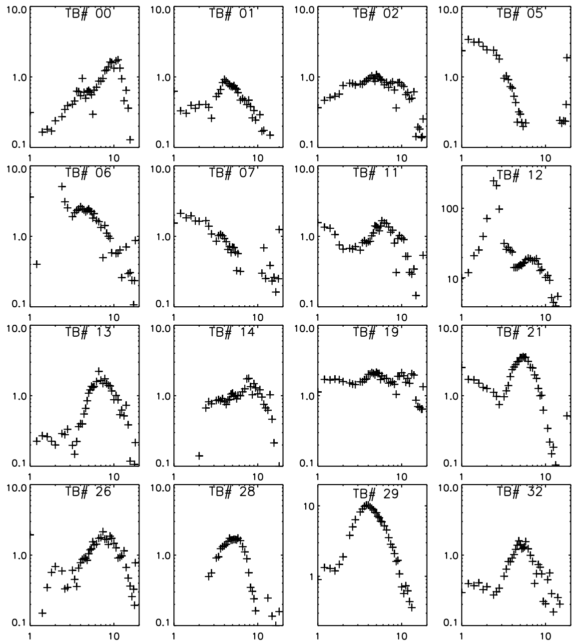

Fig. 4.. OVRO total power spectra for the 16 events for which it could be measured. The spectral shape is highly variable from event to event, but some of the events (e.g. Event numbers 13, 21, 28, 29 and 32) have a low-frequency slope greater than 2, implying that they must be the result of nonthermal electrons.

## 3. Comparison with Other Observations and Implications for Coronal Heating

One important characteristic of ARTBs is that they occur in active regions. Recently, radio observations of much smaller events near the edge of active regions or in the quiet Sun have been reported (Krucker et al. 1997; Nindos et al. 1998), and it is important to put these new observations in perspective. Whereas the SXT fluxes of the events described in this paper (e.g. Figure 2) are on the order of $10^5$–$10^6$ DN s$^{-1}$, the corresponding fluxes of the events reported by Nindos et al. were only a few hundred DN s$^{-1}$, and those of Krucker et al. were yet another order of magnitude smaller. Likewise, the radio peak fluxes in this paper are of order 2 SFU, while those of Nindos et al. were about 0.02 SFU, and those of Krucker et al. about 0.002 SFU. Despite their small size, most if not all of these much weaker events showed evidence for nonthermal emission, so these too appear to be tiny flares—nanoflares. The numbers of events so far observed are too small for us to be definitive about the importance of these events energetically, but Krucker et al. estimate that about one event every three seconds may occur over the entire Sun.

There remains the important question whether microflares and their smaller counterparts can account for the heating of the corona, as suggested by Parker (1988). Shimizu (1995) has already shown that the collective *thermal energy* from the events at least down to about $10^{26}$ erg is *not* sufficient to heat the active region corona, being from 5 to 10 times too low. Krucker et al. (1997) came to a similar conclusion for their smaller events. It is unlikely that the nonthermal component of the events can supply the "missing" energy because according to the Neupert Effect the nonthermal energy ultimately shows up in the thermal response of the plasma and is already counted in the thermal energy. One possibility, of course, is that the rate of occurrence of events per unit energy may increase more steeply at low energies, so that the tiniest events, nanoflares, may supply most of the energy.

Let us assume for the moment that nanoflares do heat the corona. The frequency distribution of events that have so far been measured is known to follow a powerlaw with index $\alpha = 1.5$–$1.6$ for both flares and ARTBs (Shimizu 1995), and a number of studies have shown that merely extending this same distribution to lower energies cannot account for all of the energy needed. Thus, the low-energy end of the frequency distribution must eventually turn upward into a steeper slope. As new, more-sensitive observations push the low-energy end of the observed distribution to lower energies, the powerlaw index of the remaining, unobserved part due to nanoflares must get ever steeper in order to contain enough energy to heat the corona. How steep must the slope be according to the present information? Call $W_0$ the lowest energy we can measure so far ($\sim 10^{26}$ erg), at which energy the rate of occurrence per unit energy is $N_0$. At higher energies, the number per day falls as

$$dN = N_0 \Big(\frac{W}{W_0}\Big)^{-\alpha_1} dW.$$

The total energy of all of the events that we know about (call it $W_{\rm flares}$), is then

$$W_{\rm flares} = \int_{W_0}^{W_{\rm max}} \frac{dN}{dW} W\, dW = \frac{N_0 W_0^2}{2-\alpha_1}\Big[\Big(\frac{W_{\rm max}}{W_0}\Big)^{2-\alpha_1} - 1\Big] \tag{1}$$

where $W_{\rm max}$ is the energy of the largest flares ($10^{32}$ erg). The lower energy events that we do not yet have the sensitivity to see must supply the missing energy

$$W_{\rm missing} = \int_{W_{\rm min}}^{W_0} \frac{dN}{dW} W\, dW = \frac{N_0 W_0^2}{2-\alpha_2}\Big[1 - \Big(\frac{W_{\rm min}}{W_0}\Big)^{2-\alpha_2}\Big]. \tag{2}$$

where $W_{\rm min}$ is the low-energy limit of the smallest possible events and $\alpha_2$ is the quantity we want to estimate—the steeper slope of the low-energy distribution.

The values of $W_{\rm max} \approx 10^{32}$ erg and $\alpha_1 \approx 1.5$ are known from observation, while the values of $W_0$, $W_{\rm min}$, and $\alpha_2$ are not known. However, Shimizu (1995) has shown that $W_0 < 10^{26}$ erg, and Parker (1988) suggested coronal heating by nanoflares with energy $10^{24}$ erg so let us be generous and choose a two orders of magnitude lower value, $W_{\rm min} \approx 10^{22}$ erg. What, then, would $\alpha_2$ have to be in order for the missing energy to at least equal the combined energy of flares? With these values inserted into the above relations, we find that $\alpha_2$ must be greater than about 2.79. If $W_0$ can be pushed to $10^{25}$ erg, $\alpha_2$ becomes at least 3.30. Clearly, as we push the minimum observed energy to lower energies we are "running out of room" for the remaining, unobserved events to supply the missing energy.

Shimizu & Tsuneta (1997) have studied soft X-ray nanoflares in both the active and quiet corona, and have shown that (1) the brighter the background corona, the larger the number of events with a given energy that occur there, and (2) the upper envelope $E_{\rm max}$ of these tiny nanoflare events plotted against background coronal intensity has unit slope—that is, observationally $E_{\rm max} \propto P$, where $P$ is the intensity of the persistent corona. They point out that if nanoflares form a powerlaw of slope greater than 2, the intensity of the persistent corona should be dependent on $W_{\rm min}$ but insensitive to $W_{\rm max}$, the energy of the largest members of the distribution. From this they conclude that the frequency distribution of nanoflares, if they are to account for the persistent corona, cannot be in the form of a powerlaw.

However, this argument assumes that what changes from one place to another to account for differences in the intensity of the persistent corona is the *shape* of the energy distribution of the events. It seems possible that it is instead the rate of occurrence (the normalization factor $N_0$ in the notation above) that varies from place to place (correlated with field strength, say), and that the shape of the distribution (that is, the values of $W_{\rm max}$, $W_{\rm min}$, $\alpha$, etc.) is the same everywhere. In that case, the $E_{\rm max}$ measured by Shimizu & Tsuneta (1997) is not the $W_{\rm max}$ of the actual frequency distribution, but rather the maximum energy of the sampled distribution, which will depend on the sampling time (28 minutes in this case). It is quite natural that parts of the corona with smaller $N_0$ will give a smaller $E_{\rm max}$ over a fixed time interval, quite unrelated to $W_{\rm max}$ of the distribution. Thus, the observations of Shimizu & Tsuneta (1997) do not appear to rule out a powerlaw distribution for nanoflares.

In conclusion, as more sensitive measurements are made, so far the number of small events has continued to fall short. A continuous distribution with a steep enough powerlaw below $W_0$ to account for the heating of the corona is still possible, but becomes increasingly problematic as observations are pushed to lower energy. A large spike (delta function) in the number of nanoflares near, say, $10^{24}$ erg cannot be ruled out, of course, but Shimizu & Tsuneta (1997) correctly argue that such a distribution would imply a relation between maximum energy and intensity of the persistent corona of $E_{\rm max} \propto P^{1/2}$, which does not match their observations. Despite the apparent problems, researchers will continue to search for smaller events in the hope of explaining the heating of the corona. In the meantime, it is at least useful to know that even the smallest events show a similar proportion of nonthermal emission as their larger cousins, and flare physics can be usefully advanced by studying these smaller and perhaps simpler events.

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