SHOCK-ASSOCIATED KILOMETRIC RADIO EMISSION AND SOLAR METRIC TYPE II BURSTS

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Abstract. We present statistics relating shock-associated (SA) kilometric bursts (Cane *et al.*, 1981) to solar metric type II bursts. An SA burst is defined here to be any 1980 kHz emission temporally associated with a reported metric type II burst and not temporally associated with a reported metric type III burst. In this way we extend to lower flux densities and shorter durations the original SA concept of Cane *et al.* About one quarter of 316 metric type II bursts were not accompanied by any 1980 kHz emission, another quarter were accompanied by emission attributable to preceding or simultaneous type III bursts, and nearly half were associated with SA bursts. We have compared the time profiles of 32 SA bursts with Culgoora Observatory dynamic spectral records of metric type II bursts and find that the SA emission is associated with the most intense and structured part of the metric type II burst. On the other hand, the generally poor correlation found between SA burst profiles and Sagamore Hill Observatory 606 and 2695 MHz flux density profiles suggests that most SA emission is not due to energetic electrons escaping from the microwave emission region. These results support the interpretation that SA bursts are the long wavelength extension of type II burst herringbone emission, which is presumed due to the shock acceleration of electrons.

1. Introduction

A promising new source of solar radio information on coronal shocks consists of a class of kilometric radio bursts discussed by Cane *et al.* (1981). These fast-drift bursts observed with the ISEE-3 Radio Astronomy Experiment were identified on the basis of their relatively high intensities and long durations (~ 30 min at 1980 kHz). Sixteen of the 28 bursts identified in a two-year period could not be associated with reported metric type III activity, suggesting that these bursts were not the low-frequency extensions of 'impulsive phase' type III bursts. A good association of these kilometric bursts was found with metric type II bursts, indicative of coronal shocks, and with 'herringbone' structure of the type II bursts in particular. Since the herringbone structure is presumed due to energetic electrons accelerated by the shock, the kilometric bursts were interpreted as the long-wavelength extension of the herringbone structure and referred to as shock-accelerated (SA) bursts. A schematic view of the Cane *et al.* interpretation is shown in Figure 1. In a subsequent discussion of SA bursts Cane and

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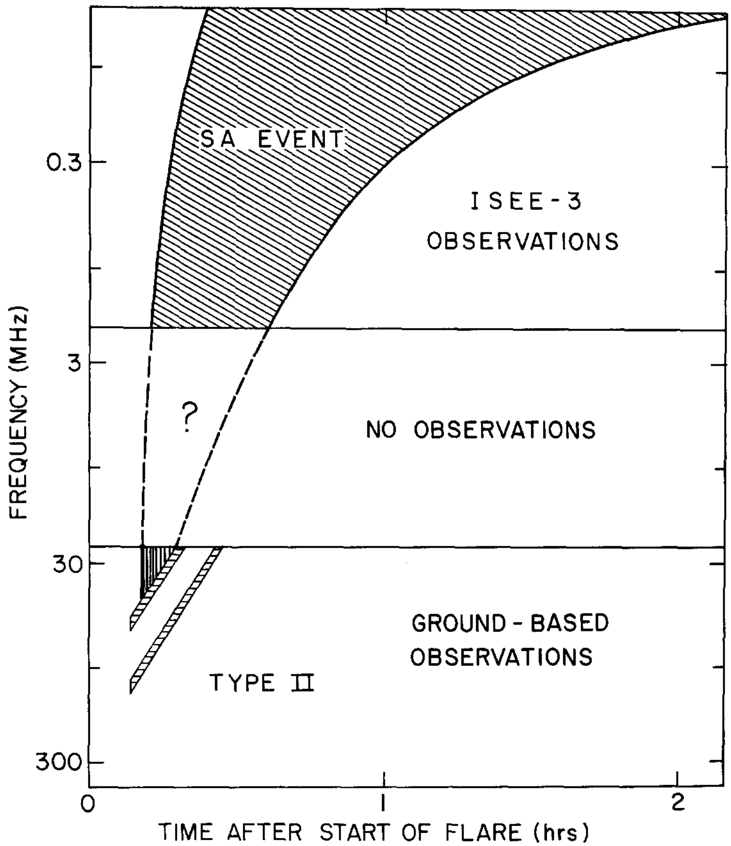

Fig. 1. A schematic representation of the relationship between SA bursts and metric type II herringbone emission as proposed by Cane *et al.* (1981). Both the fundamental and harmonic type II bands are shown, but only the long-wavelength herringbone emission from the fundamental band is included here.

Stone (1984) introduced the term 'shock-associated', a more conservative terminology indicating an association of the SA bursts with shocks but not implying the physical origin of the electrons producing the bursts. We will continue the use of 'shock-associated' here.

An obvious problem in the study of SA bursts is that the burst characteristics discussed by Cane *et al.* are inadequate to identify unambiguously other such events. They described SA bursts as very intense, with long durations, and generally composed of individual bursts so close together in time that the individual profiles could not be resolved. MacDowall, Stone, and Kundu (1987) provided objective criteria for selecting SA bursts which had a high ($>70\%$) probability of association with metric type II and/or type IV bursts. Their most important criterion was that the 1 MHz flux density profile should have a peak $\geq 10^5$ s.f.u. more than 3 min after the end of any reported metric type III burst. Their SA bursts had longer durations, higher peak flux densities and more components than those kilometric bursts associated only with metric type III bursts. Although those properties matched the Cane *et al.* criteria well, they alone were not sufficient to distinguish SA bursts from kilometric type III bursts.

Kundu and Stone (1984), noting that their selected SA bursts started almost simultaneously with the impulsive onsets of microwave bursts, have suggested an alternative interpretation for the origin of the SA electrons. In their view at least some of the energetic electrons producing the impulsive microwave bursts in the lower corona have access to the open field lines of the upper corona and are able to escape, giving rise to the SA emission. Although they provided no details of their analysis, Kundu and Stone claimed to have found no evidence of a correlation between an individual SA burst and a corresponding herringbone burst.

We see, then, that while the SA bursts appear to hold some promise for studies of coronal shocks, we have two problems which must be confronted before we can assess the relationship between SA bursts and metric type II bursts. The first problem is to define an SA burst. While the largest SA bursts as defined by Cane *et al.* (1981) or MacDowall, Stone, and Kundu (1987) may be obvious, we would expect that many SA bursts might be weak and/or short in duration. How can we proceed to select a large sample of SA bursts with a range of peak intensities and durations? The second problem is to determine whether SA bursts are kilometric signatures of electron acceleration in coronal shocks or whether the kilometric emission can all be explained as the long wavelength extension of impulsive type III or microwave bursts. A cursory comparison of the kilometric radio data with reports of metric bursts shows that many, if not most, large 1 MHz bursts are well associated in time with groups of metric and decametric type III bursts. Furthermore, when a metric type II burst is present, it is usually accompanied by type III bursts which may overlap the type II burst in time, so that resolving the origins of the 1 MHz burst is certainly not straightforward.

In this study we investigate the relationship between SA bursts and coronal shocks by using a new definition of SA bursts. Rather than beginning with kilometric SA bursts selected subjectively, as did Cane *et al.* (1981) and Kundu and Stone (1984), or by computer algorithm, as did MacDowall, Stone, and Kundu (1987), we use as the basis of our study reported metric type II bursts, which constitute *a priori* evidence of coronal shocks. We then examine the burst profiles at 1980 kHz, the highest frequency available on the ISEE-3 radio experiment, during the times of the reported metric type II bursts (Section 2.1). These comparisons suggest specific criteria by which the bursts can be sorted into three distinct classes based on their type II and type III burst associations. To learn more about the origins of the SA bursts, we compare in detail metric type II burst records from Culgoora Observatory (Section 2.2) and microwave burst records from Sagamore Hill Observatory (Section 2.3) with the associated 1980 kHz profiles. A preliminary version of this work was presented by Kahler, Cliver, and Cane (1986).

2. Data Analysis

2.1. Comparison of Metric Type II Bursts with 1980 kHz Emission

The metric type II bursts used in this study consisted of all the importance 2 or 3 bursts reported in *Solar-Geophysical Data* by the Culgoora, Harvard, or Weissenau observatories for the period from August 1978 through September 1982. Weak, intensity 1, and 'possible' type II bursts, were not considered, nor were reports from other observatories. When two observatories reported the same burst, the duration of that burst was taken to extend from the earlier reported onset to the later reported end time.

The metric type II bursts were then compared with plots of antenna temperatures at 1980 kHz from the ISEE-3 radio astronomy experiment. That experiment measures the intensity of the received radiation at 23 frequencies over the range from 1980 kHz to 30 kHz and is described briefly in Cane *et al.* (1982) and in detail in Knoll *et al.* (1978). We matched the reported time intervals of each metric/decametric type II burst, as well as those of any time-associated type III bursts, to the 1980 kHz antenna temperature profile. Events reported as 'DCIM', defined to be fast drift spikes close to the decimetric range, were also counted as type III bursts, as were type III storms (III s). Since fast drift bursts are due to electrons travelling with speeds ~ 0.3 c, the delay between the metric activity and the 1980 kHz activity occurring nominally at $\sim 10\,R_0$ is only 1–2 min. The classic situation of a metric type II burst preceded by a group of type III bursts (Wild, Smerd, and Weiss, 1963) was encountered in 77% of the cases.

The general philosophy of the comparison was to attribute as much of the increase in the 1980 kHz antenna temperature profile as reasonably possible to the reported type III bursts. Any remaining portion of the increase of the 1980 kHz profile occurring in good time agreement with the metric type II burst was considered to be SA emission associated with the shock. When SA emission, so defined, was found, we listed the peak antenna temperature and the time duration of enhanced antenna temperature which could be defined as SA emission. Because of the burst complexities we attempted to minimize the subjectivity of this process by adopting certain rules and getting a consensus among the authors for the classification of each event. Among the more important rules were:

(1) Types I and IV metric emission were not considered to be signatures of fast-drift electrons, so no part of the 1980 kHz profile was attributed to such bursts; also, reports of weak, intermittent type III bursts (III N, W) were not considered for association.

(2) If the log of the antenna temperature T_A did not exceed 8.0, no burst was considered to be present. The background $\log T_A$ was usually about 7.6.

(3) SA durations were generally taken only from relatively steep rises to steep falls in the T_A profile.

(4) If the peak T_A of the SA burst profile was partially due to the presence of emission from the decay phase of preceding activity associated with type III bursts, the value of T_A was reduced accordingly.

(5) If a type III burst occurred near the middle of the type II burst and an SA burst was already present, the entire interval was attributed to the SA burst; also, if the SA burst appeared to extend beyond the end of the type II burst, that extension was included as part of the SA burst.

A total of 316 type II bursts were included in this comparison. Enhanced 1980 kHz emission ($\log T_A > 8$) was not observed during any parts of the type II burst intervals for 87 cases (28%). Two prominent examples of what we call the 'null' bursts are shown in Figure 2. In these cases it is clear that the metric shock was not associated with any fast drift activity at 1980 kHz. Another class of bursts, the 'III' bursts, were those in which the type II burst was accompanied by enhanced 1980 kHz emission, but all that emission was attributed to metric/decametric type III activity according to our criteria.

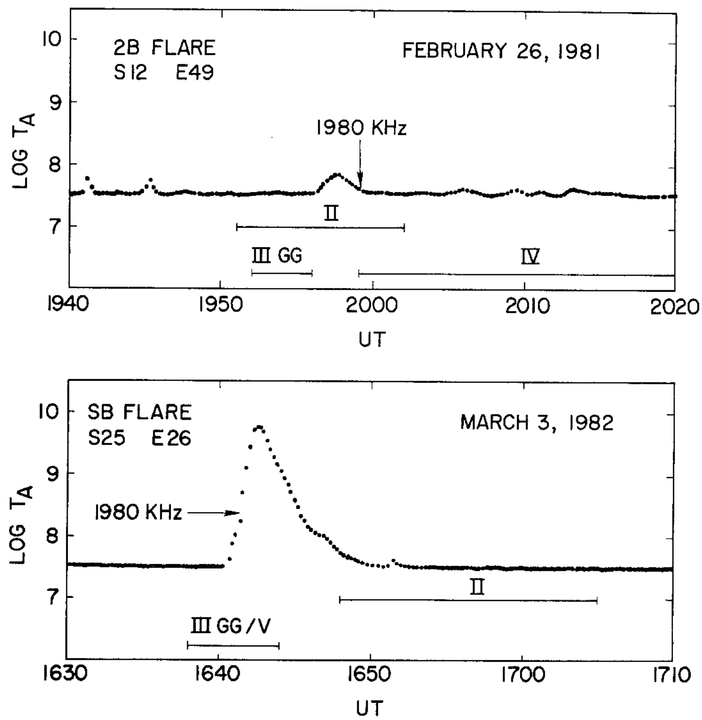

Fig. 2. 1980 kHz profiles of two null bursts. Peaks with $\log T_A < 8$ were not considered to be significant. Metric burst time intervals are from *Solar-Geophysical Data*.

As might be expected, the III group encompasses cases in which the 1980 kHz emission appears to be most closely related to the metric type III bursts as well as cases in which the metric type II burst appears to be more important for the kilometric emission. Figure 3 shows two examples of III bursts, one of each of these two kinds. The 85 events in the III burst class constitute 27% of the total.

The remaining 144 (46%) cases were the SA bursts, of which we show two examples in Figure 4. Another example, on August 21, 1979, was shown in Figure 2 of Cane *et al.* (1981). A peak log T_A, rounded to the nearest 0.5, and a duration, estimated to the nearest minute, characterized each burst. The median peak $\log T_A$ was 9.0, with two thirds of the bursts in the range 8.5–10.0; the median duration was 8 min, with two-thirds of the bursts in the range 3–17 min. Most bursts (103 of 144) also had 1980 kHz components which began during or within 1–2 min of metric type III bursts. These type III components were statistically more intense (median peak log T_A of 10.0) and slightly shorter in duration (median of 6 min) than the SA bursts.

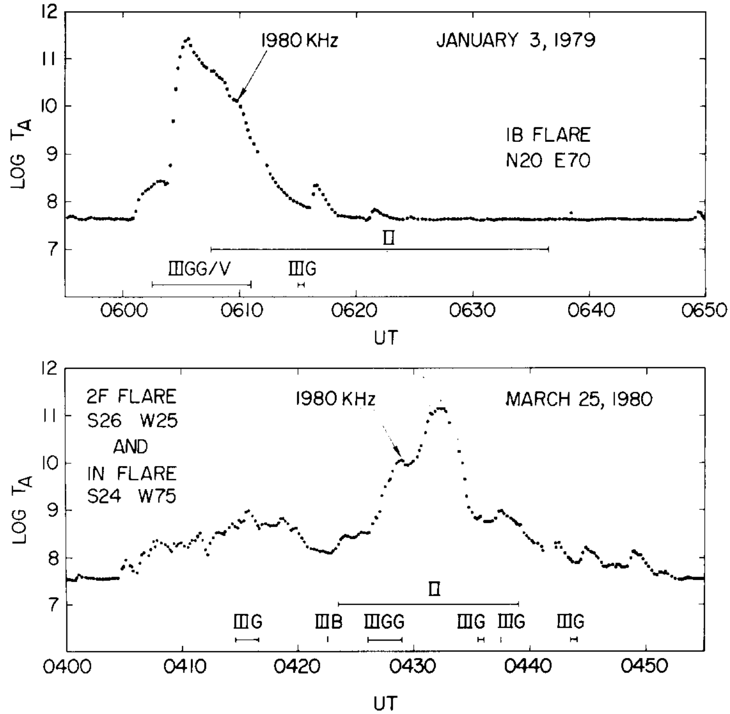

Fig. 3. 1980 kHz profiles of two III bursts. *Top*: The profile is one with no apparent SA bursts; peaks at 06 : 05 and 06 : 16 UT are associated with type III bursts. *Bottom*: The profile is suggestive of an SA burst, particularly the peak at 04 : 32 UT.

2.2. Comparison of SA bursts with Culgoora dynamic spectra

We were able to compare our 1980 kHz profiles with film records of metric dynamic spectra from Culgoora Observatory for 32 SA bursts and 10 III bursts. The film records allowed us to examine the brightness and structural variations of the metric bursts and than look for correlations of these variations with the 1980 kHz profiles. We found as a general result for the SA bursts that the brightest and most structured parts of the metric type II bursts were the most closely associated with enhanced 1980 kHz emission. These parts might be construed to be herringbone structures, but we were not able to make such identifications unambiguously. We found some bursts with apparent herringbone, some without, but many events in a gray area of uncertainty. The longer time scales characteristic of the 1980 kHz emission (cf. Fainberg and Stone, 1974) allowed us to do only a crude time comparison between the two wavebands; we could not examine the 1980 kHz extensions of individual metric herringbone bursts. For three cases of strong, weak, and no preceding 1980 kHz type III bursts, Figures 5, 6, and 7, respectively, show the good association between the brightest parts of the metric type II bursts and the most intense parts of the 1980 kHz profiles.

In their examination of the July 23, 1980 burst shown in Figure 5, Kundu and Stone (1984) considered the entire enhanced 1980 kHz emission profile to be the SA burst.

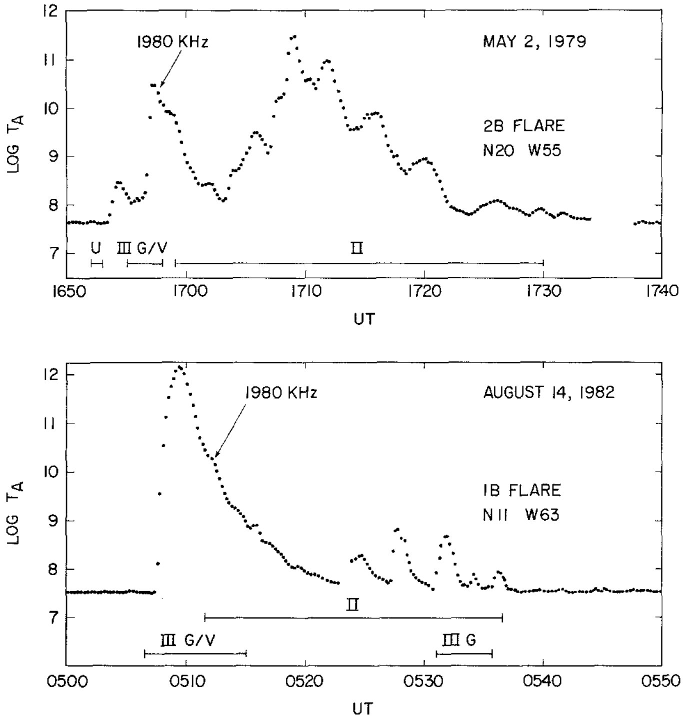

Fig. 4. 1980 kHz profiles of two SA bursts. *Top*: the long duration, high intensity, and fluctuations are characteristic of the SA criteria discussed by Cane *et al.* (1981). The estimated peak $\log T_A$ was 11.5 and the duration 18 min (17 : 04–17 : 22 UT). *Bottom*: the impulsive bursts at 05 : 25 and 05 : 28 UT and the onset of the burst of 05 : 32 UT are not associated with reported type III bursts and so constitute an SA burst. The estimated peak $\log T_A$ was 8.5 and the duration 10 min.

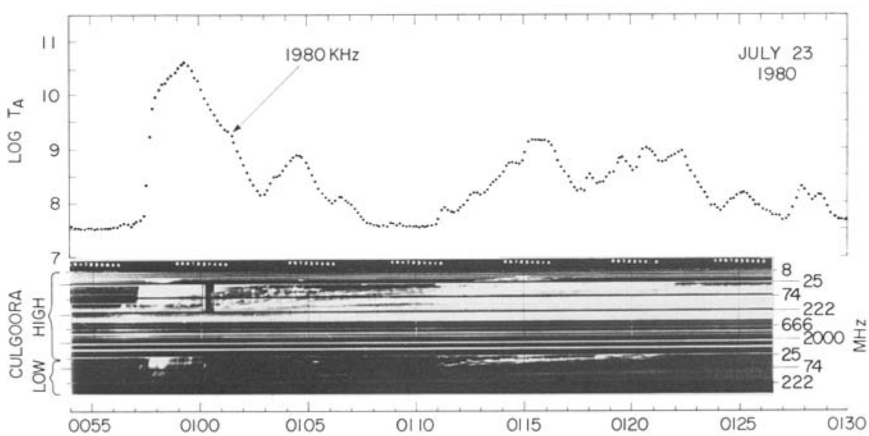

Fig. 5. Comparison of the Culgoora film record of a metric type II burst with the 1980 kHz profile for an SA burst with a strong preceding 1980 kHz type III burst. The most intense part of the SA burst extends from 01 : 12 to 01 : 23 UT in good association with the most intense part of the metric type II burst shown on the low gain part of the film strip.

They argued that the SA burst began well before the metric type II burst and was, therefore, more likely to be associated with the impulsive phase. We see, however, that the 1980 kHz emission profile of this event had two components. The first, from 00 : 57 to ≥01 : 03 UT, was well associated with the type III bursts, but the second, from

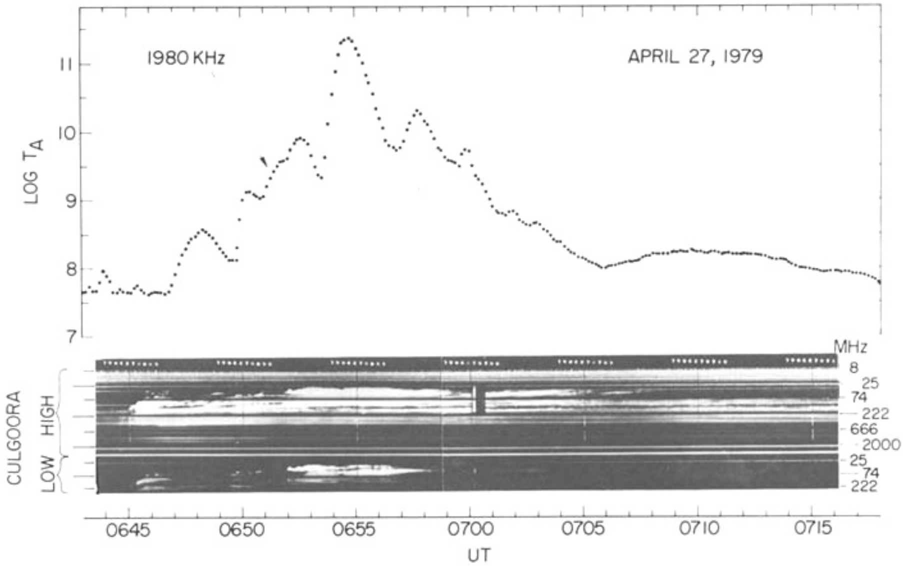

Fig. 6. Comparison of the Culgoora film record of a metric type II burst with the 1980 kHz profile for an SA burst with a weak preceding 1980 kHz type III burst. The 1980 kHz peak at 06 : 48 UT is probably due to type III bursts, but the remainder of the profile until 07 : 05 UT appears as an SA burst. The brightest part of the metric type II burst from 06 : 52 to 06 : 57 UT coincides with the peak of the SA burst.

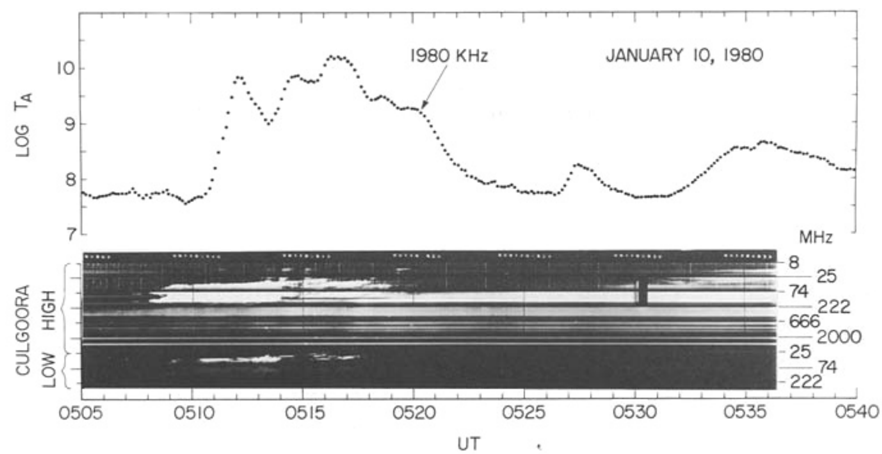

Fig. 7. Comparison of the Culgoora film record of a metric type II burst with the 1980 kHz profile for an SA burst with no preceding type III bursts. Several metric type III bursts are present from 05 : 13 to 05 : 15 UT. The most intense part of the SA burst, from 05 : 11 to 05 : 18 UT, again correlates well with the most intense part of the metric type II burst, shown on the low-gain profile.

01 : 12 to 01 : 24 UT, is in good agreement with the brightest part of the type II burst and is the only part described as an SA burst in our analysis.

In Figure 8 we show a case in which no 1980 kHz emission occurred during the brightest part of the type II burst. This is a III burst as discussed in the figure caption.

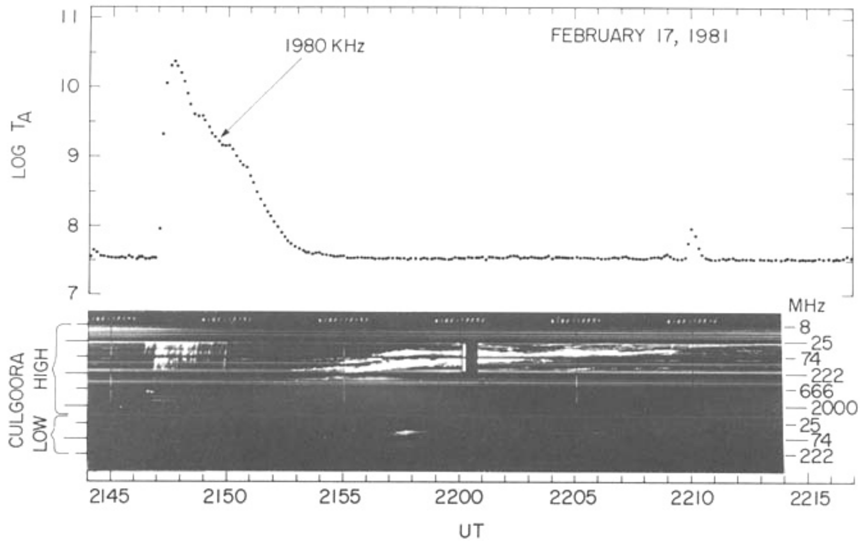

Fig. 8. Comparison of the Culgoora film record of a metric type II burst with the 1980 kHz profile with no associated SA burst. The start time of the type II burst was reported as 21:51 UT by Ft. Davis Observatory; hence, the burst was classified in our analysis as a III rather than a null. The peak at 21 : 48 UT is well associated with the type III bursts.

2.3. Comparison of SA Bursts with Sagamore Hill Microwave Profiles

To test the Kundu and Stone (1984) hypothesis that the SA bursts result from the escape of microwave-emitting electrons accelerated low in the corona, we have compared SA burst flux-density profiles with simultaneous microwave profiles from Sagamore Hill Observatory. The microwave data consisted of time profiles of flux densities in the centimeter (2695 MHz) and decimeter (606 MHz) ranges. We chose these frequencies because, if the Kundu and Stone hypothesis is correct, the 1980 kHz SA time profiles might be expected to agree best with those of lower frequency microwave bursts. Of the 21 total cases available for comparison we found no microwave emission during 8 SA bursts and only a gradual decay of a previous microwave burst during 5 additional SA bursts. Twelve of these 13 SA bursts were of short duration (≤ 9 min) and low peak $\log T_A$ (≤ 9.5), and, as a result, may not be considered particularly convincing counter-examples to a correlation between microwave and SA profiles. Of the remaining 8 SA bursts accompanied by microwave emission, 6 had durations > 10 min. For two of these 6 bursts (August 18, 1979 and June 8, 1980 (Figure 9)) the 1980 kHz and microwave profiles were well correlated. In each case a pair of 2695 MHz peaks was roughly matched in time by 1980 kHz peaks, as shown in Figure 9. Another well correlated burst

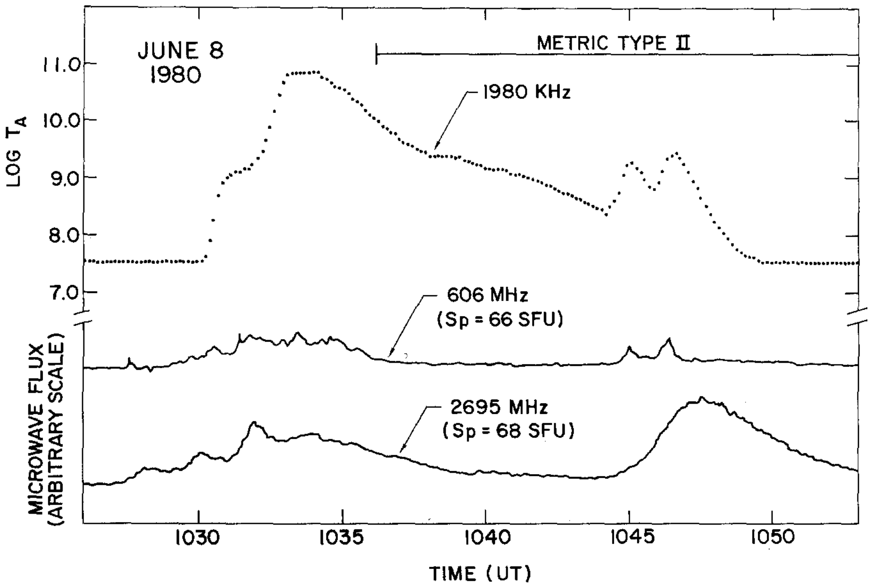

Fig. 9. Comparison of the Sagamore Hill 606 and 2695 MHz flux density profiles during the corresponding 1980 kHz SA burst of June 8, 1980. In this case a rough correspondence is seen between the two peaks at ~ 10 : 34 and 10 : 46 UT. Note that the flux density scale is logarithmic for the 1980 kHz burst and linear for the 606 and 2695 MHz bursts. Sp is the maximum flux density of the burst.

not in our sample is that of August 21, 1979. The 1980 kHz flux profile of that burst was shown in Figure 2 of Cane *et al.* (1981) and the Toyokawa Observatory microwave records in Figure 3 of Cliver *et al.* (1983). The broad SA peak from ~06 : 10 to ~06 : 30 UT is roughly matched by the accompanying microwave burst, although the microwave burst ends at ~06 : 30 UT, about 15 min before the end of the SA burst.

In the remaining four SA bursts lasting > 10 min (May 2, 1979 (Figure 10); April 4, 1980; May 3, 1980; and April 20, 1981 (Figure 11)), the association between individual peaks in the microwave emission and structure in the SA profile was poor. In each of these four bursts, we found some agreement early in the burst profiles, but later microwave activity generally was low and declining when new peaks were observed in the 1980 kHz profiles, as shown in Figures 10 and 11. A similar case not in our comparison sample is that of July 23, 1980, published in Figure 9 of Kundu and Stone (1984). The SA emission from 01 : 10 to 01 : 25 UT (Figure 5) is accompanied by a relatively weak 3750 MHz burst which smoothly declines to background from a peak at 01 : 12 UT.

To summarize, we found evidence for a correlation between the peaks of the microwave profiles and those of the 1980 kHz SA profiles for a few cases, but in other cases the correlation was poor. The fact that most of the SA bursts in our sample were not accompanied by any 2695 MHz emission contradicts the view that the microwave-emitting electrons are the sources of SA bursts.

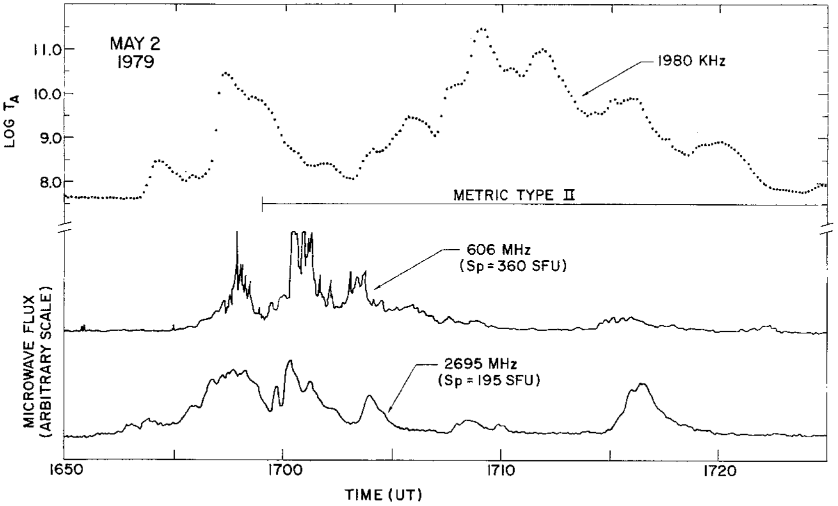

Fig. 10. A comparison similar to that of Figure 9. In this case some early agreement is seen between the microwave and 1980 kHz profiles at ~16 : 57 UT, but after 17 : 05 UT the correspondence is quite poor. The 606 MHz flux densities at ~17 : 01 UT are saturated on the plot used for the figure.

3. Discussion

In their discovery paper Cane *et al.* (1981) discussed SA bursts in terms of intense 1980 kHz bursts that correlated well with the occurrence of metric type II herringbone emission. They reported that 16 of their 28 SA bursts were not accompanied by metric

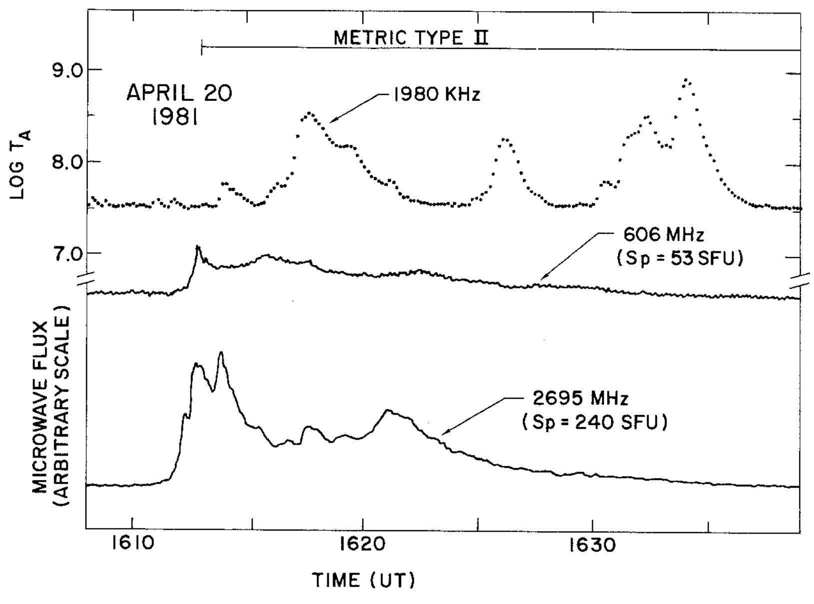

Fig. 11. Another comparison similar to Figure 10 showing poor agreement between the Sagamore Hill microwave flux densities and the 1980 kHz profile.

type III activity. In addition, the smoother profiles and lower average intensities they found for the type III profiles at 1980 kHz suggested further criteria for isolating the SA bursts from type III bursts. However, the lack of a precise operational definition for selecting SA bursts has left ambiguity in the selection of the bursts by other workers, and this, in turn, has raised questions (Kundu and Stone, 1984) about the validity of the shock acceleration hypothesis (Cane *et al.*, 1981) proposed for the SA events.

In this study we have assumed that Cane *et al.* (1981) examined only the high-intensity end of a spectrum of such bursts and that, as with other transient solar phenomena (Hudson, 1978), most SA bursts are substantially weaker and less obvious in the 1980 kHz records. Since, by definition, SA bursts must occur with coronal shocks, we have used as the basis of our study 1980 kHz emission occurring at the times of reported metric type II bursts. We find that about one quarter (28%) of the metric type II bursts of this study, the null bursts, were not matched during their durations by 1980 kHz emission. Another quarter (27%), the III bursts, were accompanied by 1980 kHz emission, but this was attributed to type III bursts based on their temporal associations with metric type III bursts. The remaining 46% of the metric type II bursts were associated with SA bursts. Half of our SA burst sample had durations ≤ 8 min and peaks of $\log T_A \leq 9.0$, values far lower than those of the SA bursts discussed by Cane *et al.* (1981).

With our definition of an SA burst as any 1980 kHz burst occurring during a metric type II burst and not attributable to a type III burst, we must expect *a priori* that random coincidences between metric type II bursts and unassociated 1980 kHz bursts will constitute some fraction of all SA bursts, particularly at the small burst end of the size spectrum. Consequently, we have no assurance that any given 1980 kHz burst meeting our definition of an SA burst is, in fact, physically associated with the coronal shock (cf. MacDowall, Stone, and Kundu, 1987). From this point of view, one can doubt whether SA bursts have been established as a distinct phenomenon. On the other hand, our comparison of a sample of SA burst profiles with the Culgoora metric profiles (Figures 5, 6, and 7) shows a close correspondence between the SA emission and the brightest, most structured parts of the metric type II burst, implying that in these cases the SA emission is truly shock-associated. Furthermore, our examination of the Sagamore Hill microwave data during 21 SA bursts does not support the contention of Kundu and Stone (1984) that SA bursts result from the escape of impulsive phase energetic electrons that produce microwave bursts in the lower corona.

Cane *et al.* (1981) interpreted SA bursts to be the long wavelength extension of herringbone emission (Figure 1). In a detailed analysis of herringbone bursts Cairns and Robinson (1987) found radial velocities of the burst exciters similar to those of type III bursts. Unlike type III bursts, however, the deduced range of herringbone bursts was limited to $\leq 0.5\ R_0$. The results of our study support the hypothesis of Cane *et al.* (1981) that the radio emission from the shock-accelerated electrons can also be detected in the kilometric range.

Since we considered in our analysis only type II bursts of greater intensities (2 and 3), which are probably better associated with SA bursts than are the weaker type II bursts, we can conclude, as did MacDowall, Stone, and Kundu (1987), that a majority of all metric type II bursts are *not* associated with SA bursts. The fact that impulsive 2–100 keV electrons detected at 1 AU are essentially always accompanied by kilometric fast-drift bursts (Lin, 1985) implies that if energetic electrons are produced in those shocks, they are not able to escape the corona in sufficient numbers to produce a detectable burst.

4. Conclusions

We have used new criteria to select and study the properties of SA bursts. Nearly half of all intense metric type II bursts were temporally associated with 1980 kHz emission which was not attributable to metric type III bursts. A quarter of all intense type II bursts are not associated with any significant 1980 kHz emission and another quarter are accompanied by 1980 kHz emission presumed due to type III bursts. The SA bursts are generally not well correlated with microwave flux-density profiles but compare more closely with the most intense and structured parts of the profiles of metric type II bursts. These results imply that the SA emission is due primarily to energetic electrons accelerated at the associated shock.

Acknowledgements

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