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SOFT X-RAY EMISSIONS, METER-WAVELENGTH RADIO BURSTS, AND PARTICLE ACCELERATION IN SOLAR FLARES

H. V. CANE[1] AND D. V. REAMES
Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center
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ABSTRACT

A detailed study of the relationship between metric radio bursts and soft X-ray flares has been made using an extensive data set covering 15 yr. We find that type IV emission is mainly associated with long-duration 1–8 Å events that are known to be well associated with coronal mass ejections. In contrast, type II and type III bursts originate primarily in impulsive soft X-ray events that are not necessarily accompanied by mass ejection. Strong type III bursts, in particular, appear to occur only in association with relatively impulsive flares. We suggest that coronal shocks responsible for type II bursts are blast waves generated in impulsive energy releases.

Subject headings: particle acceleration — Sun: flares — Sun: radio radiation — Sun: X-rays

I. INTRODUCTION

Recently, the time scales of soft X-ray flares have been used to further our understanding of solar particle acceleration and meter-wavelength phenomena. Cane, McGuire, and von Rosenvinge (1986) (hereinafter CMvR) have suggested that there are two classes of solar energetic electron events observed in the interplanetary medium. One class is associated with impulsive flares and the other class with long-duration flares. One distinguishing characteristic delineated was the types of metric radio bursts associated with each of the two classes. For the electron events associated with impulsive flares, the associated metric radio events included strong type III/V bursts and type II emission. Very few included type IV emission. Electron events associated with long-duration flares were frequently associated with type IV emission and infrequently with type III emission. The results of CMvR motivated us to investigate further the relationship between meter-wavelength radio emission and the time scales of flares.

In this study, as in that of CMvR, the duration of the associated soft X-ray flare is defined using 1–8 Å emission. It has been shown by Pallavicini, Serio, and Vaiana (1977) that soft X-ray emission defines two classes, with impulsive events occurring low in the corona in compact regions and long-duration events occurring higher in the corona in extended regions. All prior studies which considered the soft X-ray characteristics of flares associated with radio bursts have dealt with a particular subset of radio events. Apart from being less general, such studies have suffered from insufficient statistics. For example, Robinson, Stewart, and Cane (1984) examined the properties of metric radio bursts associated with 16 interplanetary type II events; Robinson *et al.* (1986) considered 45 events which had type II and coronal mass ejections (CMEs) and 19 events with type II and without CMEs. In our study, we use the entire Culgoora observations of type II and type IV bursts for the years 1968–1983. This data set comprises several hundred radio events. In a separate paper (Cane and Reames 1988, hereafter Paper II) we document some of the general properties of the radio events.

[1] Also Department of Physics and Astronomy, University of Maryland.

II. DATA ANALYSIS

We began by determining the 1–8 Å soft X-ray characteristics of flares associated with radio events in the Culgoora catalog (Robinson *et al.* 1983). This catalog consists of all "major metre-wavelength solar events recorded by the Dapto and Culgoora solar radio observatories (1961–1981)." Nearly all the events (97%) in the catalog include type II or type IV bursts. The remaining events were "the stronger" short-wave fadeout events and these were not of interest for our study. For the years 1968 onward the catalog includes morphological properties of the bursts (e.g., intensities, starting frequencies of the type II) and our study commenced here. However, we only had X-ray data available for 1969 onward, so the data for 1968 were used only in deriving the general statistics presented in Paper II. Our study continued beyond the extent of the catalog, to the end of 1983, by using type II and type IV events reported by the Culgoora Observatory in *Solar Geophysical Data* (*SGD*). The total number of radio events studied was 685, of which 458 were type II only, 28 were type IV only, and the remainder included both.

Soft X-ray data were obtained from *SGD* and from two NOAA technical memoranda (Donnelly 1981; Donnelly and Bouwer 1981). For ~20% of the events there were gaps in the X-ray data. For each event with data we recorded the peak flux and the duration at 10% of the peak. The logarithmic CMX flux scale was used. In this system C1, M1, and X1 correspond to fluxes of 10^{-6}, 10^{-5}, and 10^{-4} W m^{-2} respectively. Durations were measured to the closest decimal part of an hour. For many small events we could not determine a duration because 10% of the peak was in the background noise.

Most radio events could be associated with an isolated X-ray event. Excluding periods of high activity and missing X-ray data, about 15% of the radio events clearly did not have an associated X-ray event. Since it was also not possible to associate Hα activity with these radio events it is probable that the solar sources were behind the limb.

Our study included positional information using Hα observations where available. Robinson *et al.* (1983) included Hα identifications in the catalog, and these were supplemented by our own identifications. The associations between type II bursts and Hα flares are usually unambiguous. The radio emis-

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sion begins near the maximum of the flare (Roberts 1959). Moreover, the majority (63%) are associated with flares of importance 1 or greater (Wright 1980). In our study, 74% of all type II bursts were associated with a flare which compares well with the 79% obtained by Dodge (1975).

Note that the Culgoora Observatory divides radio bursts into four intensity classes. Radio events are classified in order of increasing intensity as 0, 1, 2, or 3. Events of intensity either 0 or 1 are minor events. In *SGD*, events of intensity 0 are classified as "weak." Note also that we only included type III bursts as being part of the radio event if they preceded the type II burst by no more than 25 minutes. Type III emission that commenced after type II bursts was not included in our study. However, there were only six events listed in the Culgoora catalog in which type IIIs followed type II bursts.

Since the Culgoora event list excluded essentially all type III bursts that were unaccompanied by type II or type IV emission, a second small sample of type III bursts was obtained from *SGD*. This sample consisted of all type III/V bursts of intensity class 2 or 3 in the years 1979 and 1980 for which there was useful soft X-ray data.

As a final comment, there are a number of different classes of type IV emission (see Robinson 1985), one of which is related to the impulsive phase. Robinson (1985) calls this "early flare continuum" and comments that this class of type IV emission may in fact be the same as type V. The Culgoora catalog does not distinguish the different classes, and our study treats all type IV bursts equally.

II. RADIO EMISSION VERSUS SOFT X-RAYS

a) Type IV

The X-ray events associated with type IV emission are intense; 56% have peak fluxes greater than M3. The majority of the associated X-ray events (53%) have durations greater than 1 hr and 26% are greater than 2 hr. These properties can be seen in Figure 1*a*.

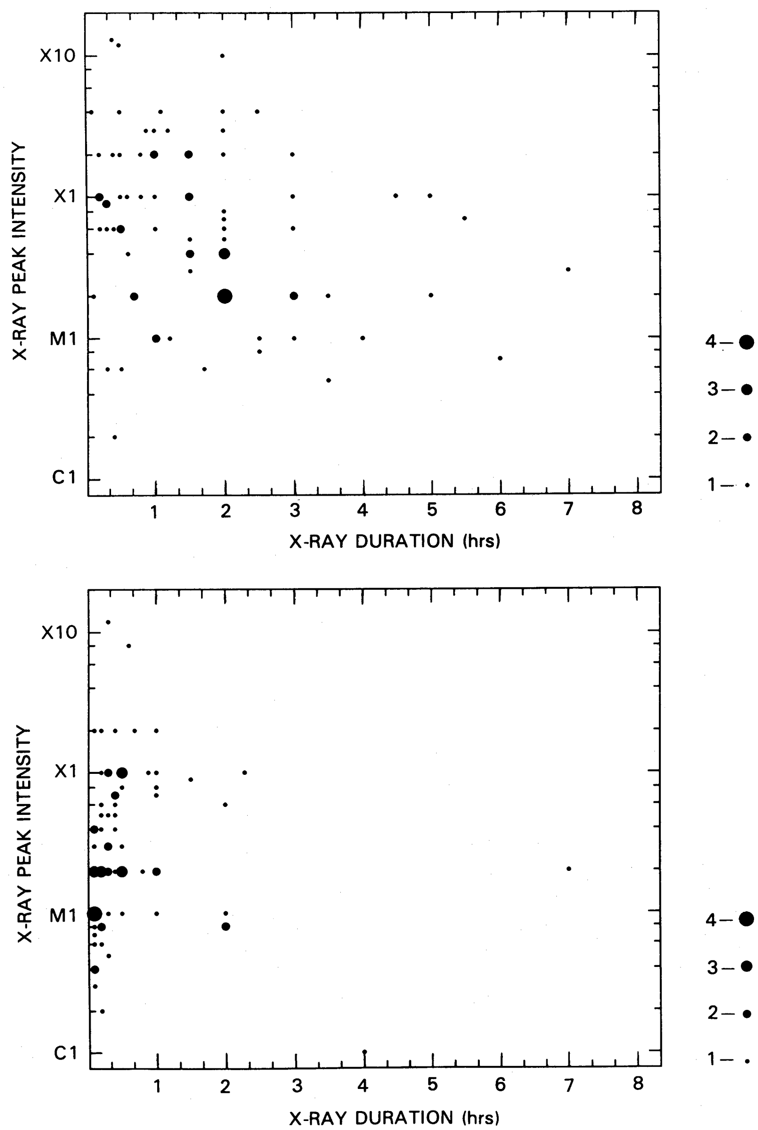

FIG. 1.—Soft X-ray intensities and durations of flares that occurred within 60° of central meridian and were associated with (*a*) type IV bursts and (*b*) type II bursts without associated type IV emission. Larger circles are used when several events have the same properties.

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b) *Type II*

More than half (66%) of all the type II bursts are associated with X-ray events with durations of 1 hr or less. The distribution of the peak fluxes shows more weaker flares than does the distribution for X-ray events associated with type IV emission. Thirty-two percent (128/397) have a peak less than M1, as against 18% (32/176) for type IV. The X-ray properties of events with type II bursts but *no* type IV emission are shown in Figure 1*b*. Only events occurring within 60° of central meridian are included, since otherwise it would be possible that type IV emission might have gone undetected. The observability of type IV emission decreases near the limbs (see Paper II). For consistency the longitude restriction was also applied for the events displayed in Figure 1*a*. Since essentially all type IV events are associated with type II bursts, Figure 1 contrasts the X-ray properties of flares with type II bursts, with and without type IV emission. Clearly the latter are less intense and more impulsive.

The frequency at which a type II burst commences is a measure of the altitude in the corona at which conditions are favorable for the production of radio emission. Figure 2 shows the starting frequencies of type II bursts as a function of X-ray duration. There is a trend that starting frequency is related to the duration of the flare. For example, it can be seen that all the events with starting frequencies above 100 MHz are associated with flares with durations less than 2 hr. The correlation coefficient for the 182 events studied was 0.41. The probability that starting frequency and X-ray duration are uncorrelated is less than 0.001. The lower panel of Figure 2 shows histograms of the starting frequencies. The dark section is the histogram of starting frequencies of events associated with flares with durations longer than 1 hr.

c) *Type III*

Figure 3 shows the distribution of type III activity as a function of flare duration. Remember that the radio events

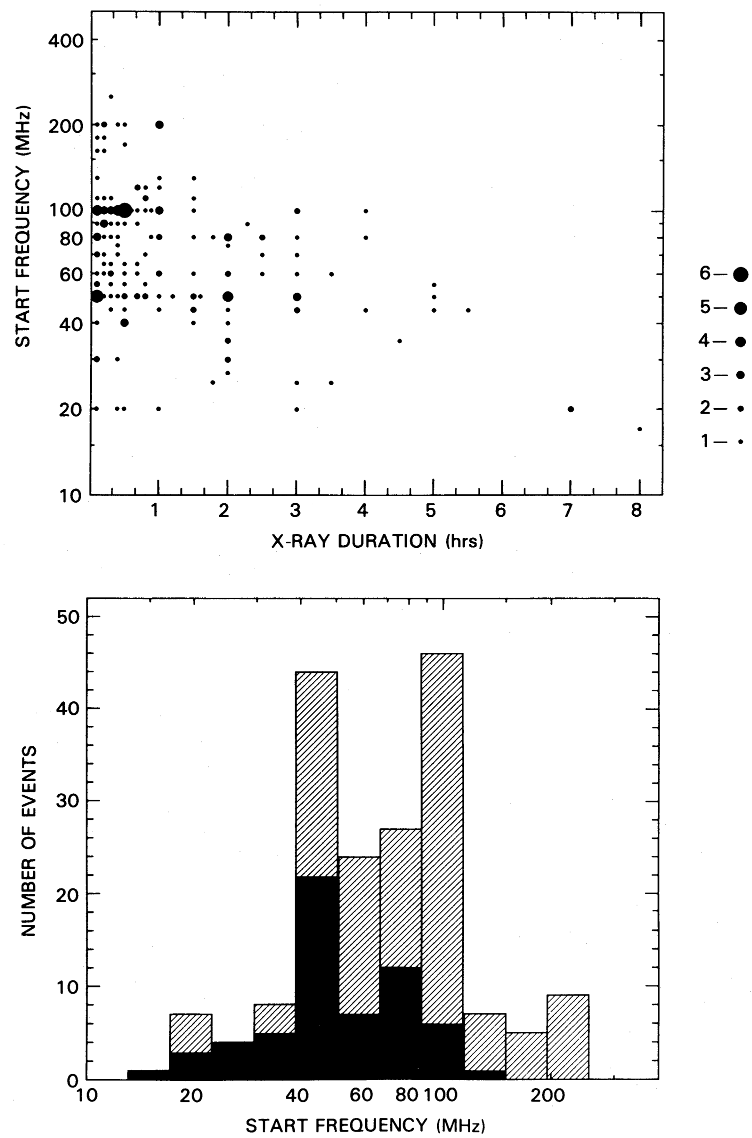

FIG. 2.—Distribution of starting frequencies of all type II bursts as a function of the duration of the associated soft X-ray flare. Histogram in lower panel shows all events and darker bars show the fraction associated with flares with durations greater than 1 hr.

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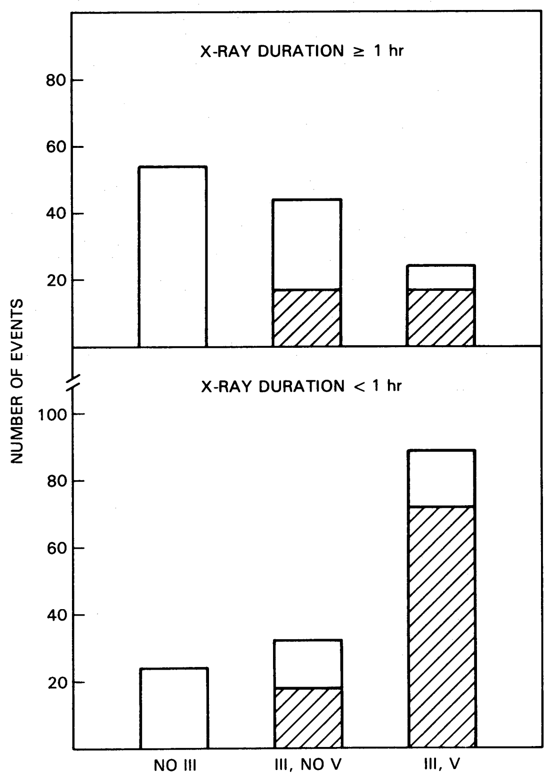

FIG. 3.—Type III activity associated with long-duration (≥ 1 hr) and (< 1 hr) short-duration flares. Shaded sections represent those events with intensities of 2 or 3.

considered in this study are those which include type II or type IV emission. Thirty-seven percent of these have no associated type III emission. The fraction with no type III activity represented in Figure 3 is less ($\sim 30\%$), but this is because for only about half of all events in this study was it possible to measure an X-ray duration.

The association of type III activity with type II bursts is independent of whether or not there is type IV emission (see Table 1). About 63% of all type II bursts are preceded by some type III activity and 37% are preceded by intense (intensity class 2 or 3) type III activity. It is clear from Figure 3 and Table 1 that nearly half of long-duration flares have no preceding type III emission. Any type III emission associated with long duration flares tends to be weak. Note that in Table 1 the numbers in the last column are considerably more than the sums of the numbers in the preceding columns because of the many events for which durations could not be estimated.

Figure 3 shows that only 21% of the type III/V bursts are associated with X-ray flares of durations longer than 1 hr. Noting that these type III bursts are a select group, i.e., those associated with type II or type IV events, we sought to check if this statistic was true of all type III/V bursts by examining the X-ray characteristics of the sample of type III events for years 1979 and 1980 as described. Most of these type III bursts did not have associated type II or IV bursts. Ten out of 71 (14%) associated X-ray events had durations greater than 1 hr. Only one event was greater than 2 hr. This occurred on 1980 June 21 and was associated with type IV emission, energetic protons, and an interplanetary shock. We note furthermore that only 20% of the flares associated with the intense type III/V bursts had peak intensities above C9 and, of these, 52% had associated type II bursts. Although these statistics were generated with events including type V we believe that similar numbers would have been generated if all type III bursts of intensity class 2 or 3 had been considered. This is because the majority (65%) of intense type III bursts include type V continuum (CMvR). We conclude that the majority of all intense type III bursts are associated with impulsive flares.

TABLE 1

THE FRACTIONS OF TYPE II AND TYPE IV BURSTS WITH VARIOUS TYPE III ASSOCIATIONS[a]

TYPE	TYPE III INTENSITY	EVENTS WITH X-RAY DURATION <1 hr	EVENTS WITH X-RAY DURATION ≥1 hr	ALL EVENTS
A. Type II, No Type IV				
Type III	3 or 2	0.62 (61)	0.32 (12)	0.38 (175)
	1 or 0	0.20 (20)	0.19 (7)	0.25 (113)
No Type III ...	...	0.18 (18)	0.49 (18)	0.37 (170)
B. Type IV				
Type III	3 or 2	0.63 (29)	0.25 (21)	0.32 (73)
	1 or 0	0.24 (11)	0.33 (28)	0.31 (69)
No Type III ...	...	0.13 (6)	0.42 (35)	0.37 (85)

[a] Actual numbers of events shown in parentheses.

III. SOFT X-RAY EMISSION AND RADIO EMISSION

In a separate study, we listed all soft X-ray events with peak fluxes above X1 which occurred between the hours 2100–0700 UT, the approximate Culgoora observing range, during the years 1969–1983. About half of these intense events had durations less than 1 hr. Using the Culgoora catalog the events which had associated radio emission of types II and IV were determined. For the remaining events the reports in *SGD* were used. The majority (103/139, i.e., 74%) of intense soft X-ray events had associated metric radio bursts; although only 60% (62/103) of these associated events included a type II burst. Of the remainder, most (30/41) were associated with type III activity, with more than half being of intensity 1 or 0.

IV. DISCUSSION

We have shown that, like CMEs (Sheeley *et al.* 1983), type IV bursts are predominantly associated with long duration flares, but that some are associated with impulsive flares. The similar distribution of intensities and durations of type IV–associated X-ray events and X-ray events associated with CMEs, suggests that type IV radio emission (excluding early flare continuum) occurs with CME events. Robinson *et al.* (1986) have found an association between the occurrence of type IV activity and the presence of CMEs and, in fact, the association is probably better than that suggested by these authors since they did not consider the decrease in detectability of type IV for events that occur close to the solar limbs. Of 35 CMEs associated with flares and type II bursts in the Robinson *et al.* study, 20 had associated type IV. Of the remaining 15 events, 10 originated within 40° of the limbs, in which case type IV may have been undetectable. Probably type IV emission arises in the upper loop structures created by the ejection of coronal material as suggested by Cliver (1983) (see also Kahler 1982).

The distribution of X-ray flare properties for all type II

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bursts is not the same as that for type IV burst/CME events. Type II bursts originate with both impulsive and long-duration flares, with the majority being impulsive. Whereas CME events (the less energetic ones) can originate in solar events with no Hα flares, type II bursts are clearly flare related; greater than 70% can be associated with flares (see § II), and the start time is close to the Hα maximum (Roberts 1959). For events in which there are type III bursts, these precede the onset of type II emission by typically 2–10 minutes, and the delay increases with decreasing starting frequency (see Paper II). Extensions back in time of the drift curves of type II bursts appear to intercept the onset of preceding type III activity. (The relationship between delay and starting frequency is consistent with a disturbance moving at ~ 1000 km s^{-1}, with the usually assumed density models of the corona; see, for example, Maxwell and Thompson 1962.) Thus, Wild, Smerd, and Weiss (1963) suggested that type II–producing disturbances are blast waves generated at the time of impulsive energy release in flares. It is currently believed that the source of energy is magnetic and that this energy is released during reconnection. This process does not require that a CME be involved. Other arguments that type II shocks are blast waves and not closely related to CMEs have been given by Wagner and MacQueen (1983), Cane (1984), and Gary *et al.* (1984).

Certain conditions are apparently necessary for the shock wave to generate radio emission so that it "turns on" at some time after the onset of the impulsive energy release. Uchida (1974) suggests that the shocks strengthen in regions of low Alfvén speed. The higher in the corona that radio emission turns on, the lower the starting frequency of the type II burst. We have shown that the starting frequencies of type II bursts associated with impulsive flares are higher than those associated with long-duration flares.

Cane and Stone (1984), Robinson *et al.* (1983), and Robinson *et al.* (1986) have pointed out that type II bursts associated with CMEs and with interplanetary type II events have lower starting frequencies than do type II bursts not associated with these phenomena. We have shown data suggesting a more general result that applies to all type II bursts. The lower starting frequencies associated with the above-mentioned phenomena reflect the fact that CMEs and interplanetary shocks are usually associated with long-duration flares. When we look at all type II bursts associated with impulsive flares, the distribution of starting frequencies for the events associated with type IV emission is not different from that for type II bursts without type IV emission. This suggests that the starting frequency of a type II burst is not related to the presence or absence of a CME.

Robinson *et al.* (1986) invoke the low starting frequency of CME–associated type II bursts to suggest a physical relationship between metric type II bursts and CMEs. We suggest that the starting frequency of a type II burst is related to the time scale of the event. The higher starting frequencies of type II bursts associated with impulsive events are probably related to the smaller spatial scales and resultant higher energy densities in these events.

The suggestion that type IV emission is generated only in CME events explains why type IV is well associated with interplanetary proton events (Maxwell and Thompson 1960; Maxwell, Defrouw, and Cummings 1964; Kahler 1982). CMEs appear to be necessary for second-phase particle acceleration which produces high fluxes of protons in the interplanetary medium (see CMvR and references therein). Note that, since CMEs sometimes are associated with impulsive flares, one does expect high fluxes of interplanetary protons in this small subset of impulsive flares. In the majority of impulsive flares, one expects that only the first phase of acceleration operates. If particles escape, the radio event will include a type III burst.

The absence of type III bursts in association with the majority of long-duration flares implies that in these events first-phase particles generally do not escape to the interplanetary medium. The lack of escaping first-phase particles does not appear to be related to the presence of the CMEs which we associate with long-duration flares, since CMEs associated with impulsive flares do have associated type III bursts. Recall also that the fractional association of type III bursts with type II bursts was the same for events with and without associated type IV emission.

V. CONCLUSIONS

Type IV emission occurs in intense flares, the majority being of long duration. The distribution of X-ray intensities and durations of the flares associated with type IV emission are the same as those of flares associated with coronal mass ejections. This suggests that type IV emission occurs only in flares associated with mass ejections.

The majority of type II bursts are associated with impulsive flares. The starting frequencies are higher for more impulsive events. Type II bursts are associated with flares both with and without mass ejections. The coronal shocks responsible for type II bursts are probably blast waves having their origins in impulsive energy releases.

Type III bursts (particularly intense ones) occur primarily in association with impulsive flares. In more energetic events the type III bursts are followed by type II bursts.

Since, for particles escaping to the interplanetary medium, the radio signatures of the two phases of particle acceleration are type III and type IV bursts, it is apparent that the phases will generally dominate in flares with different (i.e., impulsive or long-duration) time scales.

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H. V. Cane and D. V. Reames: NASA/Goddard Space Flight Center, Laboratory for High Energy Astrophysics, Code 661, Greenbelt, MD 20771

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