SOLAR CYCLE VARIATION OF LONG DURATION 10.7 CM AND SOFT X-RAY BURSTS

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Abstract. Gradual rise-and-fall (GRF) microwave bursts and long duration soft X-ray events (LDEs) are generally accompanied by solar coronal mass ejections (CMEs). We use reports from the Ottawa and Penticton stations to examine the annual variations from 1965 to 1985 of 10.7 cm GRF bu[illegible] with total durations of at least 4 hr. The annual numbers of such bursts are well correlated with the q[illegible] n 10.7 cm flux densities. This result is in contrast with the finding of Koomen *et al.* (1985) that the annual numbers of ≥ 4 hr GOES soft X-ray events are not well correlated with sunspot numbers. We show that the latter result is biased by the large variation of the quiet-Sun X-ray background throughout the solar cycle. Four-hour events are more easily detected in X-ray data than in 10.7 cm data at solar minimum, but, conversely, these events are much more easily detected in 10.7 cm data around solar maximum. About 70% of the most energetic CMEs are associated with ≥ 4 hr X-ray or 10.7 cm bursts. A one-to-one relationship does not exist between CMEs and either LDEs or GRF bursts viewed in full-Sun detectors.

1. Introduction

Long-duration soft X-ray events (LDEs) and microwave bursts are characteristically accompanied by coronal mass ejections (CMEs) (Sheeley *et al.*, 1975, 1983). Skylab X-ray observations of LDEs (Kahler, 1977; MacCombie and Rust, 1979) have supported the model of Kopp and Pneuman (1976) in which a loop prominence system is formed by magnetic reconnection of field lines torn open by the eruptive CME. In the model the loop prominence system emits both soft X-rays and microwave emission by thermal bremsstrahlung. Comparisons of X-ray and microwave fluxes for a number of gradual flare events have shown that the fluxes are consistent with this thermal bremsstrahlung hypothesis (Hudson and Ohki, 1972; Shimabukuro, 1972).

The association of CMEs with LDEs motivated Koomen *et al.* (1985) to examine the occurrence frequency of LDEs observed with the Solrad and GOES X-ray detectors from 1969 through 1982. They found that the annual variation of LDEs lasting ≥ 4 hr was poorly correlated with the annual sunspot numbers. This result was due primarily to LDEs of durations ≥ 6 hr, which were slightly anticorrelated with sunspot numbers. Since the ≥ 6 hr LDEs are almost certainly associated with CMEs (Sheeley *et al.*, 1983), and the occurrence rate of CMEs follows that of the solar activity cycle (Howard *et al.*, 1986), the anticorrelation with sunspot number was not expected. However, some CMEs are associated with ≤ 4 hr X-ray events (Sheeley *et al.*, 1983) and some frontside

TABLE I

Peak flux densities of ≥ 4 hr gradual 10.7 cm bursts

Year	Flux density (s.f.u.)						Average annual background (s.f.u.)
	0–4.9	5.0–9.9	10–19.9	20–39.9	≥ 40	Total ≥ 5 s.f.u.	
1965	4	1	1	0	0	2	75.9
1966	6	10	6	2	0	18	102.2
1967	5	15	11	4	0	30	143.2
1968	2	7	5	1	2	15	149.1
1969	1	12	7	4	1	24	151.2
1970	4	16	14	9	3	42	156.1
1971	8	12	6	1	0	19	118.3
1972	22	18	11	1	3	33	121.0
1973	19	16	9	1	1	27	93.4
1974	15	9	3	4	1	17	86.6
1975	6	2	1	0	0	3	76.1
1976	5	3	2	1	0	6	73.4
1977	15	1	0	0	0	1	86.9
1978	20	17	16	3	5	43[a]	143.5
1979	14	15	23	7	3	48	191.7
1980	12	21	31	14	2	69[a]	198.4
1981	8	15	32	19	9	75	202.6
1982	13	13	25	17	12	67	175.1
1983	14	19	5	4	0	28	119.8
1984	10	9	7	3	0	19	101.1
1985	1	3	2	0	0	5	74.7

[a] Three large (> 30 s.f.u.) bursts in threse years were not completely observed and are not listed in the bins of flux density.

bin (1979–1982). One generally expects the size distribution of 10.7 cm bursts to increase toward smaller flux densities, so we now ask why, in times of enhanced solar activity, the lowest bin is apparently underreported.

One possibility is that during periods of high activity the daily variations of the background solar 10.7 cm flux density are greater than around solar minimum and thus mask small burst increases. We have tested this possibility by examining the changes in quiet-Sun flux densities occurring between the daily 14 : 00 and 20 : 00 UT measurements at Ottawa for two groups of bursts. The first group were those during 1973 through 1977, when the largest numbers of events were in the smallest size bin and the annual 10.7 cm quiet-Sun fluxes ranged from 73 to 94 s.f.u. The other group were those bursts during 1979 through 1982, when the largest numbers of bursts were reported in the third (10–19.9 s.f.u.) bin and the annual 10.7 cm quiet-Sun fluxes ranged from 175 to 203 s.f.u. For each burst in these two groups we calculated the difference between the two daily Ottawa quiet-Sun flux densities, if measured. If either measurement was compromised by the presence of a burst, we used the difference from the last previous 'uncontaminated' day. These differences are plotted in the two histograms of Figure 1.

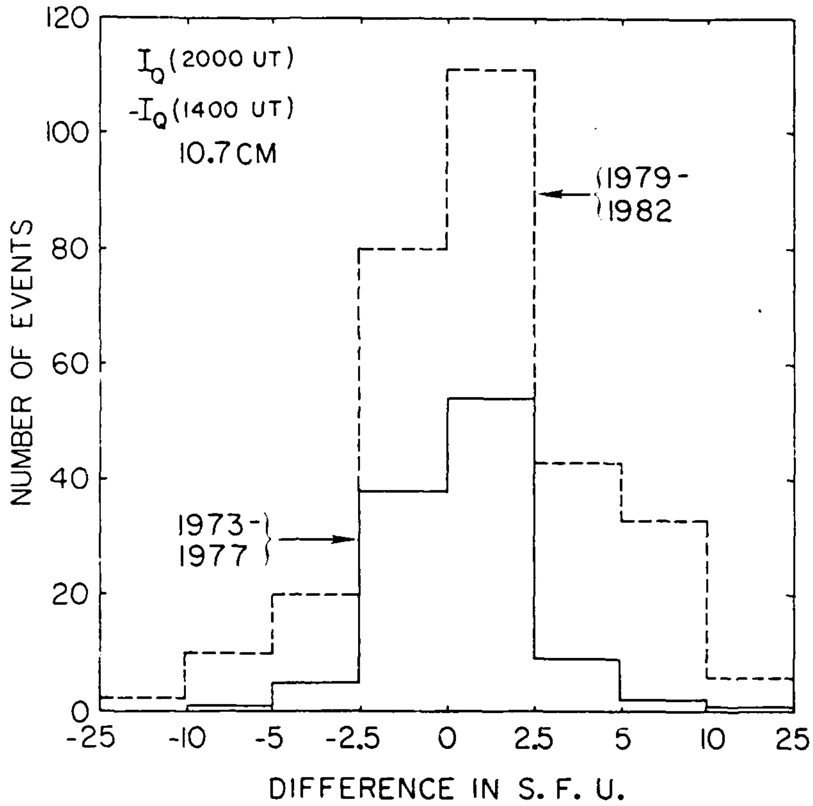

Fig. 1. Histograms of the differences in 10.7 cm quiet-Sun flux densities measured at 14 : 00 and 20 : 00 UT at Ottawa for bursts of Table I. The two histograms compare the period of low solar activity (1973–1977) with that of high activity (1979–1982). These small differences indicate that 10.7 cm bursts of $S_p \geq 5$ s.f.u. should be readily detected during both epochs of solar activity. The slight positive bias in the differences is not understood.

The distribution of differences is only slightly broader during the period of higher quiet-Sun flux densities, and for both periods most differences are less than 2.5 s.f.u. in magnitude. Even during the 1979–1982 period 83% of all differences were less than 5 s.f.u. in magnitude. We interpret these small differences to indicate that bursts of $S_p \geq 5$ s.f.u. should be equally discernable at all times during the solar cycle.

Another possible explanation for the unexpected size distribution during 1979–1982 in Table I is that the PBI bursts were more numerous than the GRF bursts at that time and the S_p values of the PBI bursts are generally large. We find, however, that during the 1973–1977 period 11 of the 114 total bursts (10%) were PBI bursts and that during 1979–1982 28 of 306 total bursts (9%) were PBI bursts. Thus the PBI burst contribution to the statistics of Table I is small and is independent of the level of solar activity. The reason for the maximum occurrence numbers to lie in the 10–19.9 s.f.u. bin rather than in a lower bin during 1979–1982 is, therefore, unclear.

For the period 1965–1985 we have calculated correlation coefficients between the annual mean values of 10.7 cm flux density and the numbers of bursts per year above fixed flux density thresholds. We found $r \geq 0.8$ for all cases, with a maximum value of $r = 0.90$ for the burst threshold of $S_p \geq 5$ s.f.u. The numbers of bursts with $S_p \geq 5$ s.f.u.

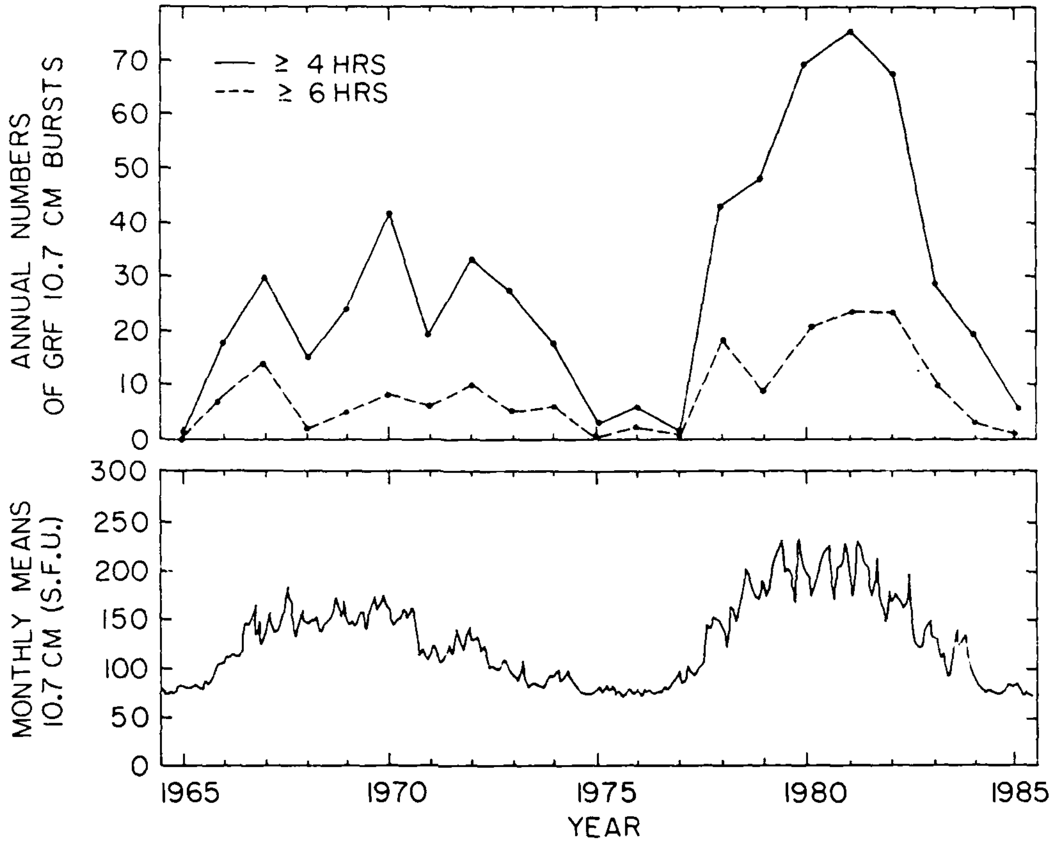

Fig. 2. *Top*: the annual numbers of GRF and PBI bursts of ≥ 5 s.f.u. reported at 10.7 cm by Ottawa and Penticton. Solid line: all bursts with ≥ 4 hr durations. Dashed line: all bursts with ≥ 6 hr durations. *Bottom*: the monthly means of the 10.7 cm quiet-Sun flux densities measured at Ottawa and corrected to a distance of 1 AU. The fiducial marks on the abscissa indicate the midpoint of each year.

are plotted in Figure 2, where the good correlation between burst numbers and solar activity throughout the 21-year period is obvious.

2.2. Reexamination of the Results of Koomen et al.

A surprising result of the LDE study by Koomen *et al.* (1985) was that the yearly numbers of their 1–8 Å LDEs with durations of 6 hr or more were weakly anticorrelated ($r = -0.23$) with sunspot number during the 1969–1982 period. However, in their LDE selection procedure Koomen *et al.* did not take into account the considerable solar-cycle variation of the full-Sun X-ray background, a variation of about two orders of magnitude from minimum to maximum (Kreplin *et al.*, 1977). For a given size distribution of LDE peak fluxes, we would expect the high background flux level at solar maximum to mask many small events, leading to an artificial dearth of LDEs at that time.

To test this effect in the Koomen *et al.* study we compared ≥ 6 hr LDEs during the 1975–1977 period around solar minimum with those during the 1979–1982 period around solar maximum. Using the LDE event list supplied by M. Koomen (private communication) and daily plots of GOES 1–8 Å fluxes (Donnelly, 1981; Donnelly and Bouwer, 1981; *Solar-Geophysical Data*, 1979–1983), we tabulated both the peak 1–8 Å

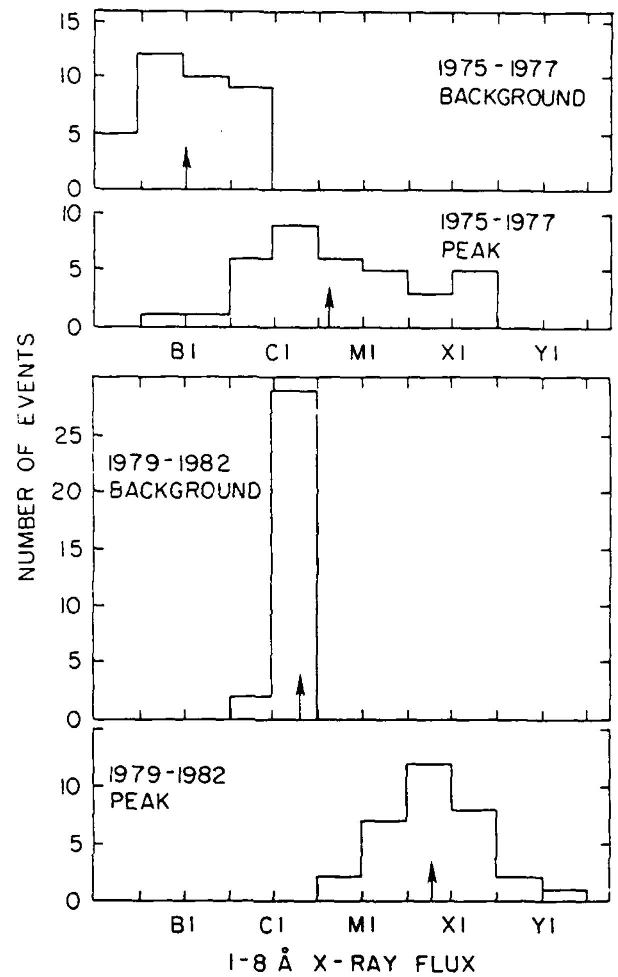

Fig. 3. Histograms of the pre-event backgrounds and peak fluxes of the ≥ 6 hr LDEs for the periods around solar minimum (*top*) and solar maximum (*bottom*). Events are those compiled by Koomen *et al.* (1985). The logarithmic X-ray flux scale is as follows: $B1 = 10^{-7}\,W\,m^{-2}$, $C1 = 10^{-6}\,W\,m^{-2}$, $M1 = 10^{-5}\,W\,m^{-2}$, $X1 = 10^{-4}\,W\,m^{-2}$, $Y1 = 10^{-3}\,W\,m^{-2}$. The median values of each distribution are shown by the arrows.

flux and the preceding background flux of each event. The histograms of these fluxes in the CMX classification system are shown in Figure 3. It is obvious that the background levels of 1975–1977 are substantially lower than those of 1979–1982. The median background values of the two epochs differ by a factor of 20, and the median value of the 1979–1982 LDE peak fluxes is higher by a factor of 15 than that of the 1975–1977 period. If we assume that at all times the distribution of LDE peak fluxes increases monotonically with decreasing peak fluxes, as is generally the case for energy parameters of solar flares (Hudson, 1978), it is clear that in comparison with the 1975–1977 period a substantial number of low-flux LDEs were unobserved in 1979–1982 due to the high backgrounds. We suggest that the apparent lack of a correlation between annual numbers of ≥ 6 hr LDEs and sunspot number is a result of the variation of background X-ray flux and is not a good measure of the solar cycle variation of those events. As another test of this conclusion we show in Figure 2 the annual numbers of ≥ 6 hr radio bursts. These bursts also appear well correlated ($r = 0.78$) with the 10.7 cm quiet-Sun flux densities.

2.3. Comparison of long-duration X-ray and 10.7 cm profiles

In the preceding sections we have assumed that the X-ray LDEs and the 10.7 cm GRF events are signatures of the same coronal phenomena. In this section we compare the two signatures for common events to establish the close relationship between the signatures and to gain an insight into the relative sizes of the two flux densities. We selected 21 radio bursts with reported durations at 10.7 cm of at least 6 hr. For each of these bursts we used the Ottawa strip chart records (supplied by M. Bell) to determine the flux densities 3 hr after the burst onsets. The 3 hr time was chosen to exclude completely the effects of impulsive phase bursts. One of these bursts is shown in Figure 4. For an additional 13 Koomen *et al.* (1985) X-ray LDEs during the solar minimum period of 1976 and 1977 we used the reports of Covington, Gagnon, and Moore (1977) and Bell, Gagnon, and Moore (1980) to estimate the 10.7 cm flux densities at comparable times during the decay.

The results are shown in Figure 5, where a rough proportionality is evident. As discussed in Section 2.1, we consider the 10.7 cm bursts with flux densities ≥ 5 s.f.u.

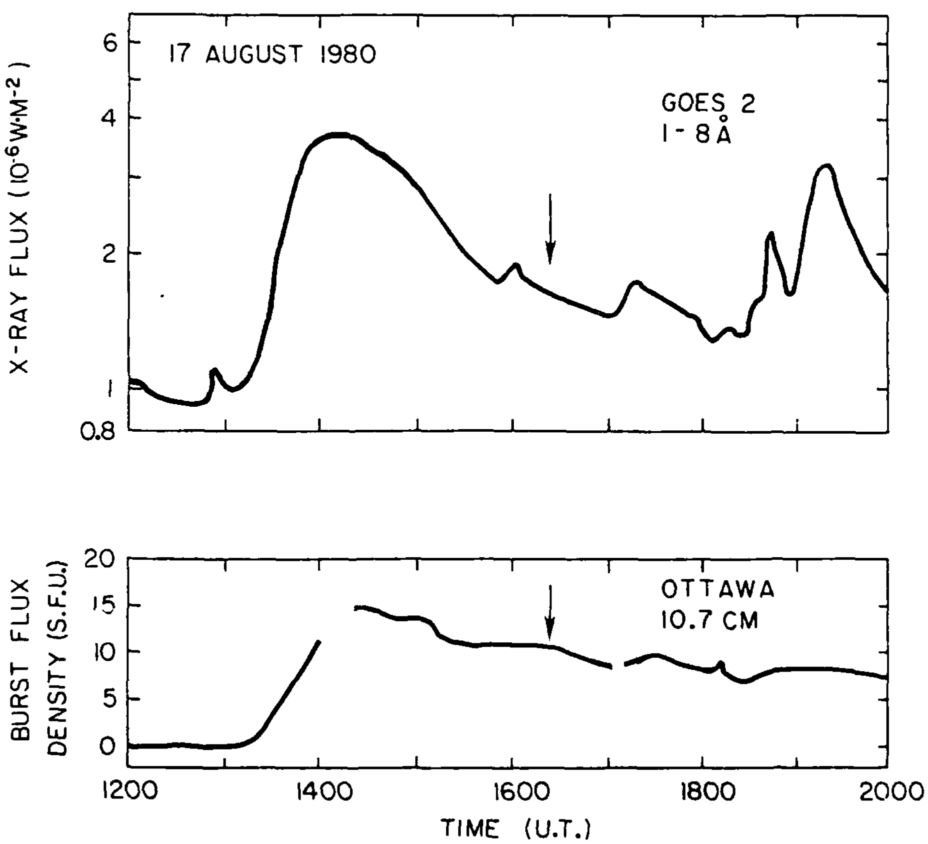

Fig. 4. The flux profiles of the LDE/GRF of 17 August, 1980. The event onset occurred at $\sim 13:20$ UT; the data points for the decay phase 3 hr later are shown by the arrows. The Ottawa 10.7 cm profile has been expanded in scale and redrawn from the original strip chart.

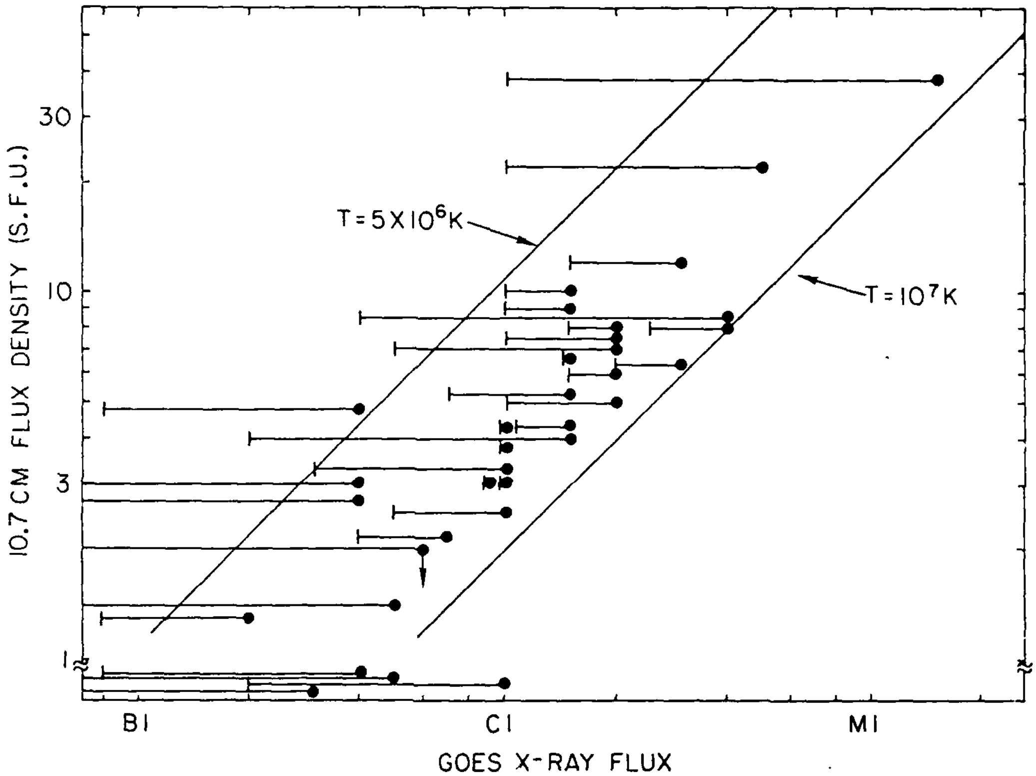

Fig. 5. 10.7 cm flux densities and GOES 1–8 Å X-ray fluxes measured 3 hr after the onsets of GRF/LDE events. Bars to the left of the data points indicate background X-ray fluxes. Four X-ray bursts were not accompanied by reported 10.7 cm bursts; these are shown below the break in the scale. The two diagonal lines show the relationship expected between the 10.7 cm and 1–8 Å fluxes for a thermal bremsstrahlung source, according to Equations (1) and (2).

to be reliably reported. At the 5 s.f.u. level the corresponding expected X-ray fluxes in the B8–C2 range are close to the usual quiet-Sun fluxes around solar maximum as shown in Figure 3. In those cases the 10.7 cm observations should provide a better diagnostic of gradual solar events than do the 1–8 Å X-ray fluxes. On the other hand, at solar minimum the substantially lower X-ray background levels (Figure 3) allow the clear observation of faint LDEs which have essentially undetectable 10.7 cm signatures. We can test this conclusion by comparing the total numbers of ≥ 4 hr 10.7 cm and 1–8 Å X-ray events during solar minimum and maximum. During 1975–1977, the period around solar minimum, 10 bursts with $S_p \geq 5$ s.f.u. were reported at 10.7 cm (Table I). To convert from the 9 hr effective observing window to an equivalent 24 hr window, we multiply by 2.67 to get a total of 27 bursts at 10.7 cm during that period. During the same period Koomen *et al.* reported 46 X-ray bursts. On the other hand, during 1979–1982, around solar maximum, the number of 10.7 cm bursts corrected for a 24-hr window was $2.67 \times 259 = 691$, substantially larger than the 93 X-ray bursts reported by Koomen *et al.* The X-ray waveband is, therefore, somewhat better as a diagnostic of gradual solar events around solar minimum, but the 10.7 cm waveband is definitely superior around solar maximum.

The two diagonal lines of Figure 5 show the expected response in the two wavebands for isothermal bremsstrahlung sources at $T = 5 \times 10^6$ K and 10^7 K. To calculate the microwave flux f at 10.7 cm we have used the Equation (A-12) of Webb and Kundu (1978) and interpolated values of the Gaunt factor g from their Table III. Values of the GOES 1–8 Å fluxes, B_8, are taken from Equation (10) of Thomas *et al.* (1985). We calculate that

$$B_8\,(\mathrm{W\ m^{-2}}) = 9.3 \times 10^{-8} f\,(\mathrm{s.f.u.}) \quad \text{at} \quad T = 5 \times 10^6\ \mathrm{K}, \quad \text{and} \tag{1}$$

$$B_8\,(\mathrm{W\ m^{-2}}) = 5.5 \times 10^{-7} f\,(\mathrm{s.f.u.}) \quad \text{at} \quad T = 10^7\ \mathrm{K}. \tag{2}$$

The data of Figure 5 are clearly consistent with a thermal bremsstrahlung source in this temperature range (cf. Hudson and Ohki, 1972; Shimabukuro, 1972). X-ray observations of Skylab LDEs have shown a similar temperature range (MacCombie and Rust, 1979).

2.4. Comparison between strong interplanetary shocks and LDE/GRF bursts

Although Sheeley *et al.* (1983) have shown that some CMEs are accompanied by short duration (≤ 4 hr) X-ray events, we might ask whether the most energetic CMEs result

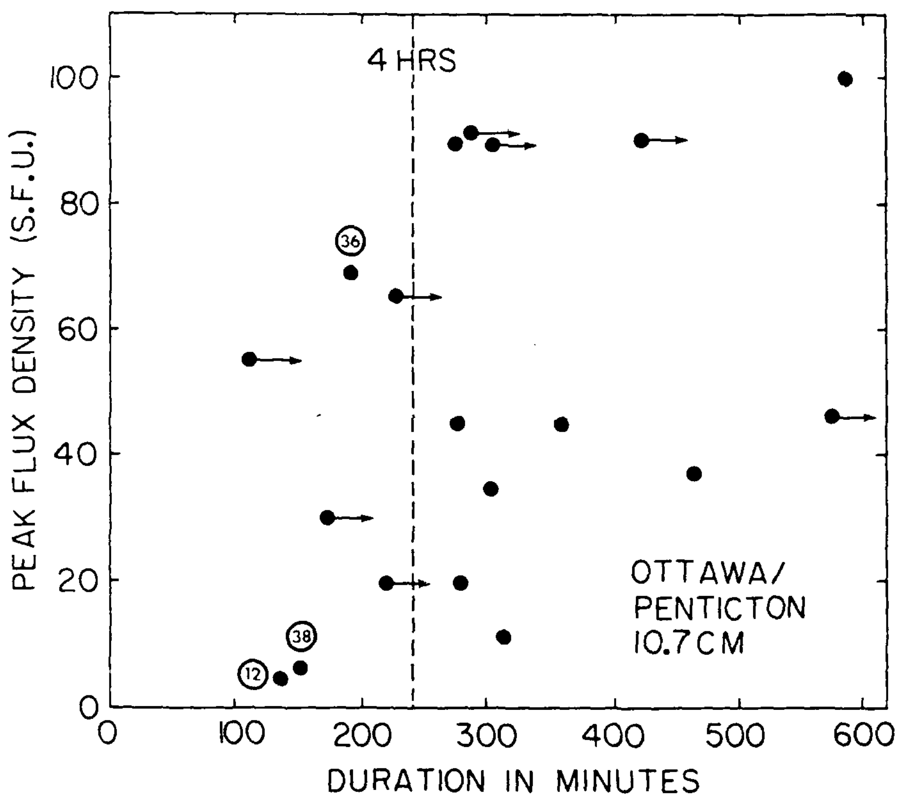

Fig. 6. Ottawa and Penticton 10.7 cm bursts associated with the interplanetary type II bursts of Cane (1985). Bursts with durations ≥ 4 hr are included in Table I. Bursts with arrows are lower limits due to incomplete observations. Most of these bursts are PBI events for which we use the peak flux density of the PBI component only. The circled numbers accompanying three data points refer to the event numbers in Table I of Cane: 12 is 18 August, 1979; 36 is 9 November, 1981; and 38 is 5 December, 1981.

in both X-ray LDEs and microwave GRF bursts. Since Cane, Sheeley, and Howard (1987) have shown that the most energetic CMEs are the ones resulting in strong interplanetary shocks, we can answer this question by examining the 1–8 Å and 10.7 cm observations for these shocks. A list of 48 interplanetary shocks during the period 1978–1983 strong enough to produce kilometric type II emission has been published by Cane (1985). All but two of those shocks were associated with solar flares, and those two, on 23 April, 1979 and 5 December, 1981, have subsequently been associated with the eruption of quiescent filaments (Cane, Sheeley, and Howard, 1986). For each of the 48 associated X-ray events, which range from C1.5 to X7, we estimated the duration of the 1–8 Å burst using the Koomen *et al.* (1985) criterion of a flux level about 10% above background for the cutoff. Thirty-five of the 48 had durations ≥ 4 hr.

Nineteen of the 48 solar events of the Cane (1985) study were observed at 10.7 cm at Ottawa or Penticton. The peak flux densities and burst durations are shown in Figure 6. The bursts of Figure 6 are quite intense; 14 of the 19 bursts are PBIs. In comparison, only 7% (57 of 795) of the bursts of Table I are PBIs, the remainder being essentially GRF bursts. In four cases of burst durations < 4 hr, incomplete observations allowed only lower limits to be determined. Twelve of the remaining 15 (80%) bursts exceeded 4 hr in duration, yielding a slightly better association with the strong shocks than did the ≥ 4 hr X-ray LDEs (35 of 48, or 73%). This result shows that 70–80% of the most energetic CMEs are accompanied by ≥ 4 hr X-ray and 10.7 cm bursts.

3. Discussion

A good association of X-ray LDEs and microwave GRF bursts with erupting filaments and CMEs was first established by Sheeley *et al.* (1975). Since that time, however, microwave observations have generally been neglected in favor of the X-ray observations in studies dealing with coronal eruptive events. This may be due to the convenience of the daily plots of GOES X-ray fluxes published in SGD. We have shown that the substantial variation of quiet-Sun 1–8 Å X-ray fluxes, which can exceed two orders of magnitude between the minimum and maximum of the solar cycle (Kreplin *et al.*, 1977), probably precludes the detection of faint events around solar maximum. At least part of this variation in the detection threshold must be due to the use of a logarithmic scale to display the X-ray fluxes. In general one can detect a variation of $\Delta \log F \geq \alpha$, where α might be 0.3, say, in the log plot. Since $\Delta \log F = 0.4343\ \Delta F/F \geq \alpha$, the minimum detectable flux of the X-ray LDE, ΔF, is directly proportional to the quiet-Sun flux F and will be greatest at solar maximum. This is not to imply that linear plots of X-ray fluxes would necessarily be more advantageous for detection of LDEs, because it appears that the fluctuations in the flux profiles due to numerous short-duration bursts also scale roughly with F. Thus the log scale and/or the background fluctuations result in a variable threshold for ΔF which is higher by a factor of 20–100 at solar activity maximum than at minimum.

The averaged 10.7 cm quiet-Sun flux densities, on the other hand, vary by a factor of only ~ 4 throughout the solar cycle, and we find that the quiet-Sun variation during a given day rarely exceeds 5 s.f.u. This means that bursts with peak flux densities of at least 5 s.f.u. should be reliably detected throughout the solar cycle. We find empirically (Figure 5) that this level corresponds to about a C1 X-ray flux. Since quiet-Sun X-ray fluxes around solar maximum generally exceed C1, the 10.7 cm data should be a more sensitive indicator of LDEs at that time. This is borne out by our finding that the number of ≥ 4 hr bursts detected at 10.7 cm during 1979–1982 exceeded those observed in soft X-rays by a factor of ~ 7.

The detection and occurrence rates of LDEs and GRFs is of interest for their possible use as proxies of at least some CMEs. Let us ask whether an X-ray LDE is a sufficient condition for a CME. Sheeley *et al.* (1983) has shown that X-ray flares with ≥ 6 hr durations are always associated with CMEs. Their result was based on 15 events, all of which had peak X-ray fluxes of at least C6. The longest and largest LDEs, therefore, appear to be a sufficient condition for the occurrence of a CME. Previously, Sheeley *et al.* (1975) and Kahler (1977) used Skylab data to establish that LDEs of various peak fluxes are well associated with CMEs. In Kahler's study we find that 9 of 12 LDEs with peak fluxes between B3 and C5 and lying $\geq 50°$ from central meridian were associated with observed CMEs. We are not aware of any more comprehensive study relating LDEs and CMEs. Therefore, in answer to our question, it is not yet clear that all weak ($\leq$ C1) X-ray LDEs are necessarily associated with CMEs. Some LDEs may be due to variations in active region brightness (Krieger *et al.*, 1972; Vaiana and Rosner, 1978). It is also plausible that some LDEs may result from non-eruptive filament disappearances (Martin, 1973).

A ≥ 4 hr LDE or GRF viewed in a full-Sun detector is not a necessary condition for the observation of a CME. We discussed in Section 2.4 the result that only 70–80% of the energetic CMEs producing interplanetary type II bursts (Cane, 1985) are associated with LDEs or GRFs. In addition, Sheeley *et al.* (1983) found that the probability for a given X-ray event to be associated with a CME increases monotonically with the duration of the X-ray event. The 50% value occurs at ~ 3 hr, showing that a ≥ 4 hr LDE is not necessary for the occurrence of a CME. Finally, Webb and Hundhausen (1987) found that about one quarter of all the SMM CMEs observed in 1980 and found to have some near-surface signature did not have an X-ray event association of any time-scale. It should be pointed out, however, that all three of these studies considered only events occurring around the period of 1978–1982, during solar maximum, and the existence of long duration tails on initially impulsive events might be masked by higher background levels at those times. We note that Koomen *et al.* (1985) found a relative dearth of LDEs during these years. Given this state of affairs, the use of LDEs as a proxy for all CMEs is unwarranted, as Koomen *et al.* (1985) suggested earlier.

To determine in further detail the relationship between GRF/LDEs and CMEs, it will be necessary to carry out a one-to-one correspondence study beginning both with GRF/LDEs and CMEs. There are several difficulties with such a study. First, one has to consider thresholds of detections for both events. Secondly, CMEs near central meridian are difficult to observe but are well observed from behind the limbs where GRF/LDEs are poorly observed. Also, one generally has no spatial information about the source position of a GRF/LDE event. Thus far, these factors have prevented a detailed understanding of the association between CMEs and GRF/LDE events.

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Solar Cycle Variation of Long Duration 10.7 CM and Soft X-Ray Bursts

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Abstract. Gradual rise-and-fall (GRF) microwave bursts and long duration soft X-ray events (LDEs) are generally accompanied by solar coronal mass ejections (CMEs). We use reports from the Ottawa and Penticton stations to examine the annual variations from 1965 to 1985 of 10.7 cm GRF bursts with total durations of at least 4 hr. The annual numbers of such bursts are well correlated with the quiet-Sun 10.7 cm flux densities. This result is in contrast with the finding of Koomen *et al.* (1985) that the annual numbers of ≥ 4 hr GOES soft X-ray events are not well correlated with sunspot numbers. We show that the latter result is biased by the large variation of the quiet-Sun X-ray background throughout the solar cycle. Four-hour events are more easily detected in X-ray data than in 10.7 cm data at solar minimum, but, conversely, these events are much more easily detected in 10.7 cm data around solar maximum. About 70% of the most energetic CMEs are associated with ≥ 4 hr X-ray or 10.7 cm bursts. A one-to-one relationship does not exist between CMEs and either LDEs or GRF bursts viewed in full-Sun detectors.

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