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COMMENTS ON THE DURATION – PEAK-FLUX-DENSITY DIAGRAM FOR 2800 MHz SOLAR BURSTS

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ABSTRACT

The existence of an essentially two-pronged distribution in the duration–peak-flux-density scatter plot for simple 2800 MHz solar bursts (Covington and Harvey, 1958) was verified for a more recent data set. An investigation was made of events that fall between the impulsive and gradual rise and fall branches of the T-S_p Diagram. Such events are rare, with only 51 observed at Ottawa during the 11 year period studied. A relatively high percentage of these bursts were associated with proton flares. (This fact may aid in the prediction of some otherwise difficult-to-forecast proton events.) Smaller subgroups in the sample include bursts from behind-the-limb flares and events associated with "spotless" flares (Dodson and Hedeman, 1970).

Introduction. Covington and Harvey (1958) noted that approximately 90 per cent of all 2800 MHz bursts could be classified as simple, single-maximum, events. Furthermore, they found that a scatter plot of burst peak-flux density versus duration for these events resulted in a two-pronged distribution representing the impulsive bursts on the one hand and the gradual rise-and-fall events on the other (figure 1(a)). This diagram remains the basic formalism for the classification of simple microwave events. Historically, the impulsive events have been attributed to gyrosynchrotron emission from non-thermal electrons while the gradual bursts have been characterized as thermal bremsstrahlung from a Maxwellian distribution of electrons (Švestka, 1976).

Wefer (1973) constructed the duration – peak-flux-density diagram from a sample of 1502 simple 2700 MHz bursts observed at Pennsylvania State University during a six-year period (July 1964 – June 1970) and found that the two-pronged distribution was not as well defined as in the earlier Ottawa observations, with a number of events falling in the "zone of avoidance" between the two branches. Wefer concluded that if the bifurcated distribution of points should have been evident in his data, then the most likely reason that it was not was differences in burst classification between Pennsylvania State and Ottawa. (Neither differences in absolute calibrations affecting the measured burst peak-flux densities nor differ-

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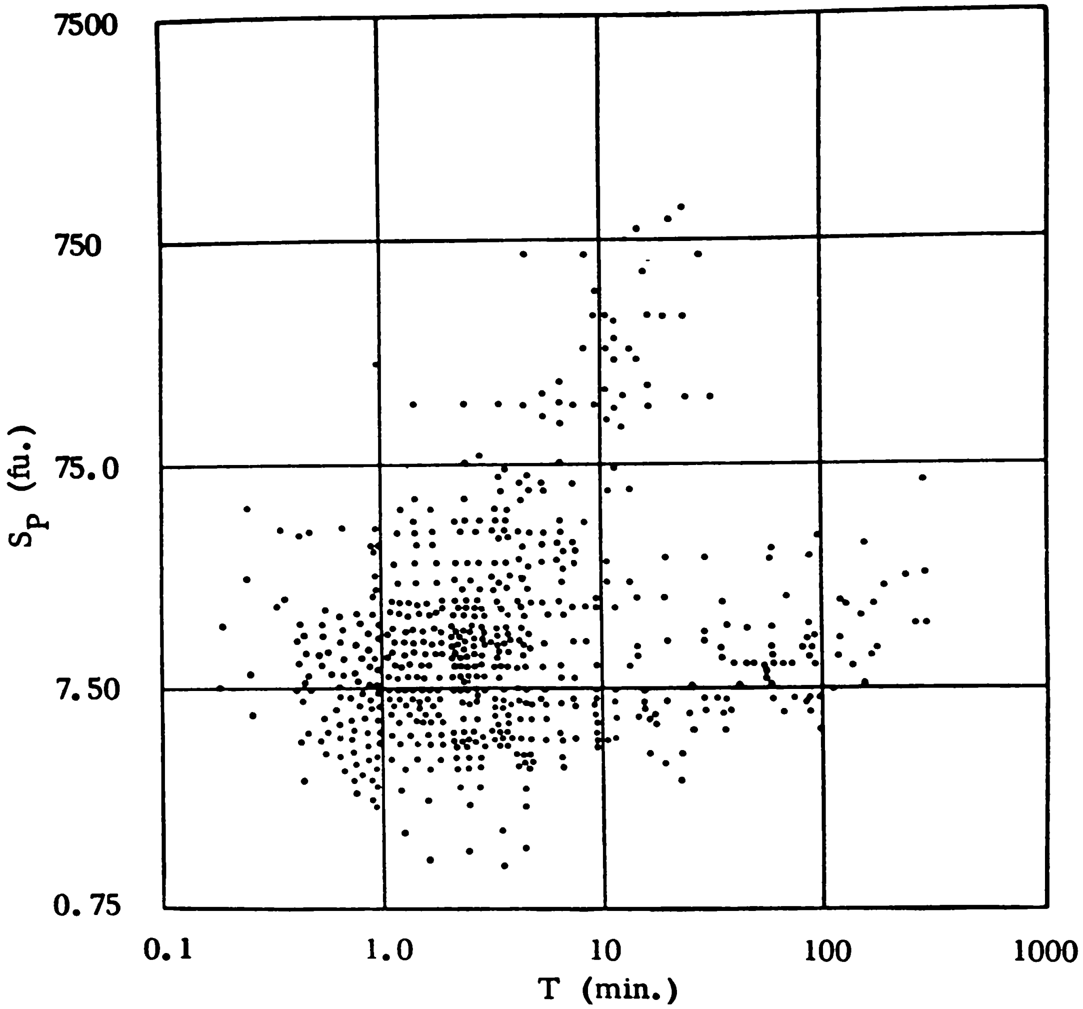

FIG. 1(a)—The duration – peak-flux-density scatter plot for simple 2800 MHz bursts observed at Ottawa during 1956 (Covington and Harvey, 1958).

ences in radiometer sensitivities affecting the determination of burst start and end times were large enough to account for the discrepancy.) To check this hypothesis, we compared all the simple 2700 MHz bursts observed at Pennsylvania-State during this period with durations (T) ≥ 10 minutes and peak-flux densities (S_p) ≥ 20 Sfu (1 Sfu = 1 solar flux unit = 1×10^{-22} watts $m^{-2}Hz^{-1}$) with the corresponding Ottawa observations. There were 133 bursts which satisfied these criteria in the Pennsylvania-State data. According to the published Ottawa burst summaries, however, only 36 of these events met the criteria and, of these, only seven fell clearly between the two branches. The resultant T-S_p diagram thus retained its basically two-pronged character.

As Wefer had correctly surmised, the chief difference between the Ottawa and Pennsylvania-State observations lay in the burst-classification procedures. In comparison with Ottawa, Pennsylvania-State observers were less likely to use "underlying" (codes 21 and 23) burst types or to assign Post-Burst Increases (PBI's) to events, tending rather to consider these long-enduring components as part of the principal burst. In either case, the net effect was to increase the duration of the principal burst and to push these events toward the zone of avoidance on the T-S_p scatter plot. An additional classification difference concerned distinguishing between simple events with fluctuations, where the maximum intensity of secondary peaks is less than 20 per cent of the peak-flux density of the burst, and complex events, where secondary peaks meet or exceed the 20 per cent criterion. The simple events with fluctuations are included in the T-S_p diagram while the truly complex events are not. In all, Ottawa classified 19 of the 133 simple (PSU classification) events in the above sample as complex.

Because seven events with uncharacteristic (T, S_p) points were found in the above search and because Covington (private communication in Wefer, 1973) had noted a much less distinct separation between the impulsive and gradual branches on a T-S_p diagram for data obtained at Ottawa during the period July 1957 through December 1960, it was decided to search for further examples of these bursts that seemingly do not fall neatly into either a thermal or non-thermal category. This was done in an attempt to determine what characteristics, if any, these unusual events might have in common.

Data Sources and Considerations. Because of the precision and the consistency of the Canadian observation, it was decided to use only the Ottawa and Penticton burst-data as reported monthly in *Solar Geophysical Data* and yearly in the National Research Council reports by Covington, Gagnon, and Moore. The search criteria employed were as follows:

(a) for simple bursts with

$$30 \text{ Sfu} < S_p \leq 200 \text{ Sfu}, \quad T > 20 \text{ min}$$

(b) and for simple bursts with

$$S_p > 200 \text{ Sfu}, \quad T > 3.2\, S_p^{0.35}$$

These relationships correspond to the heavy black lines drawn in figure 1(b). A search of data for the years 1966–1976, corresponding roughly to the 20th solar cycle, uncovered 51 examples of these events (including the seven from above). Their relative rarity is apparent if we consider that in

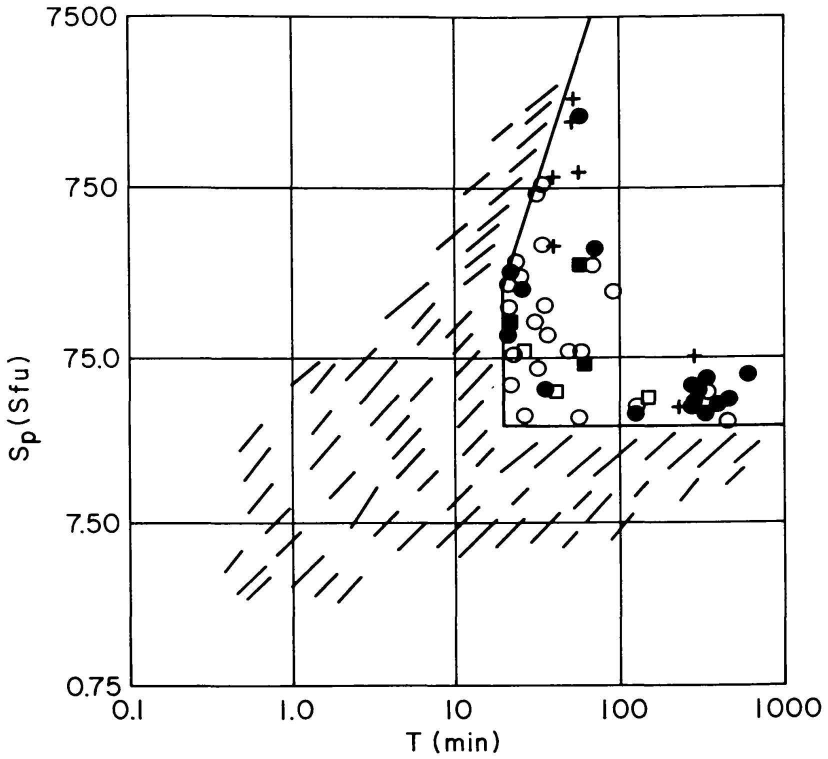

FIG. 1(b)—A stylized T-S_p diagram showing the positions of the 51 events in Table I. The boundary of the "zone of avoidance" is indicated by the heavy line. The symbols are explained in the text.

1972, for example, Ottawa and Penticton observed more than 500 long-enduring events with $T > 20$ min and 56 simple bursts with $S_p > 30$ Sfu but only three events which satisfied the above-listed search criteria. Early on in the investigation it was noted that a relatively high percentage (51 per cent or 26/51) of these events had proton association. The pertinent proton data along with the radio-burst and Hα-flare data are listed in Table 1 for each of the 51 events. Several comments on this table are in order:

1 For gradual-rise-and-fall events with superimposed burst(s) (classification code 21 or 23), the burst parameters for the largest superimposed event are given on the line immediately following the long-enduring burst entry.
2 In the burst-classification column, code 47 refers to a Great Burst ($S_p \geq$ 500 Sfu). Such events may be intrinsically simple (single maximum) or complex. We checked published photographs or the Sagamore Hill records for each of these bursts to determine which category they fell into.
3 The Proton column lists either the 30-MHz riometer-absorption value in

TABLE I

SIMPLE 2800 MHZ BURSTS OBSERVED AT OTTAWA AND PENTICTON DURING THE PERIOD 1966–1976 WHICH FALL IN THE "ZONE OF AVOIDANCE" ON THE T-SP DIAGRAM

Event No.	Date	Burst Start Time	Burst Peak Time	2800 MHz Class	Duration (T) (min)	Peak Flux Density (S_p) (Sfu)	Hα Class	McMath Region	Location	Protons	Ref.	Comments	Symbol
1.	01 Feb 67	2304	2321	4	34	157	–N	8680	N28E60	—	—		○
2.	04 Feb 67	1644	1654	4	24	270	2B	8682	N11E40	—	—		○
3.	13 Feb 67	1753	—	21	127	33	3	8687	N21W10	0.5db	C&T	"Spotless" Flare	●
		1759	1804	3	16	50							
4.	18 May 67	2346	2400	4	30	120	–N	8818	N23E71	—	—		○
5.	19 May 67	1525	1533	4	35	345	1B	8818	N24E64	—	—		○
6.	20 May 67	1513	1521	3	32	730	1B	8818	N24E50	—	—	Great Burst	○
7.	26 May 67	1532	1602	4	72	256	1N	8818	N30W04	—	—		○
8.	30 Oct 67	1738	1754	3	45	45	—	9034	E limb	—	—	Flare on disk ends before burst peaks	□
9.	01 Feb 68	1442	1444	4	60	82	1N	9184	N14W25	—	—		○
10.	01 Feb 68	1917	1918	4	50	78	1B	9184	N16W16	—	S&S	Pure Electron event	○
11.	07 Jul 68	1758	1802	3	23	52	1N	9503	N12E70	—	—		○
12.	09 Jul 68	1807	1819	4	26	200	2B	9503	N13E40	1.1db	S&S	Contributed to PCA	●
13.	12 Jul 68	1344	1402	3	75	320	2N	9499	N11W19	3db	C&T		●
14.	01 Oct 68	0035	0049	4	22	260	1N	9687	N13W34	SAT	S&S	Unconfirmed proton event; flare assoc. uncertain	●
15.	24 Oct 68	2045	2135	4	95	180	1B	9740	S15E52	—	—		○
16.	27 Oct 68	1232	1332	23	290	74	2N	9740	S17E18	SAT	C&B	2 Flares	+
		1232	1236	47	20	570	1B	9740	S17E16			Great Burst	
		1306	1320	47	25	610	2N	9740	S17E18			Great Burst	
17.	30 Oct 68	1235	1340	23	275	50	2B	9740	S18W25	SAT	S&S		●
		1235	1250		50	32							

TABLE I (Continued)

Event No.	Date	Burst Start Time	Burst Peak Time	2800 MHz Class	Duration (T) (min)	Peak Flux Density (S_p) (Sfu)	Hα Class	McMath Region	Location	Protons	Ref.	Comments	Symbol
18.	21 Mar 69	1240	1400	21	290	46	2B	9994	N19E09	0.8db	S&S	Contributed to proton event.	●
		1316	1334	47	40	1875						Great Burst	
19.	13 June 69	1545	1750	23	455	31	2B	10146	S24E69	—	—	"Spotless" Flare	○
		2024	2025	1	8	4							
20.	18 Nov 69	1600	1725	21	240	38	2B	10432	N14E40	SAT	C&B		+
		1635	1655	4	35	1070						Great Burst	
21.	28 Nov 69	1950	2135	21	150	42	—	10432	W limb	—	—	Behind-the-limb	□
		2059	2102	3	13	50							
22.	18 Dec 69	1445	1515	4	60	76	—	10481?	W limb	0.6db	C&T	Behind-the-limb	■
23.	30 Jan 70	1458	1506	4	22	142	1B	10544	S06W33	—	—		○
24.	31 Jan 70	1510	1600	21	330	33	2B	10542	S23W62	3db	C&T	2 flares	●
		1648	1649	1	2	5	−B	10544	S02W42				
25.	11 Feb 70	1900	2115	23	300	45	−N	10568	N18W13	—	—	2 flares ?	○
		2104	2104	8		9	2B						
26.	29 Mar 70	0035	0041	4	40	870U	2B	10641	N13W37	1.8db	C&B	Great Burst	+
27.	06 Apr 70	1134	1150	21	60	32	1N	10669	S11E35	—	—		○
		1139	1144	3	8	15							
28.	15 Jun 70	1055	1330	23	290	41	2B	10781	N15E04	SAT	DHM	Contr. to proton event; several flares, two largest listed.	●
		1315	1319	4	13	595	1N	10789	N18E22			Great Burst	
29.	22 Aug 70	0044	0051	3	21	98	−F	10887	N21W02	SAT	C&T	Unconfirmed flare	●
30.	15 Nov 70	1755	1815	21	280	37	2B	11029	N16W18	SAT	DHM	Contr. to proton event	●
		1802	1804	3	7	48							

TABLE I (*Concluded*)

Event No.	Date	Burst Start Time	Burst Peak Time	2800 MHz Class	Duration (T) (min)	Peak Flux Density (S_p) (Sfu)	Hα Class	McMath Region	Location	Protons	Ref.	Comments	Symbol
31.	21 Nov 70	1300	1337	21	390	37	1B	11035	N06W46	SAT	DHM	At least two flares	●
		1515	1522	4	20	336	1B	11035	N08W41				
32.	24 Jan 71	1805	1817	4	27	33	1B	11128	N17W46	—	—		○
33.	20 Apr 71	1924	1945	4	40	45	1B	11250	S06W53	0.9db	C&T		●
34.	13 May 71	1904	1923	4	60	260	—	11294	W limb	SAT	C&T	Behind-the-limb	■
35.	01 Sep 71	1928	1941	4	22	120	—	11482	W limb	5.2db	C&T	Behind-the-limb	■
36.	22 Nov 71	1511	1526	47	60	940	1B	11621	N15E72	SAT	C&B	Great Burst	+
37.	15 Jun 72	1230	1515	20	590	57	1F	11922	S12W02	2.2db	C&T	2 Flares ?	●
38.	11 Aug 72	1313	1320	3	27	84	—	11976	W limb	—	—	Behind-the-limb	□
39.	29 Oct 72	1520	1805	21	440D	40	−B	12094	S15W02	2db	C&T		●
		1612	1615	4	6	152							
40.	22 Apr 73	2144	2151	4	25	81	−N	12322	N13E20	—	—		○
41.	05 May 73	1705	1755	21	130	36	1B	12336	S15E19	—	—		○
		1713	1717	4	11	355							
42.	29 Jul 73	1312	1350	21	335	55	3B	12461	N14E45	<0.5db	C&T	"Spotless" Flare	●
		1319	1334	46	30	98							
43.	08 May 74	0008	0016	3	22	248	1N	12906	S16E03	—	—		○
44.	13 May 74	2120	2125	4	25	262	2N	12906	S13W65	—	—	"Spotless" Flare McMath 12915 ?	○
45.	04 Jul 74	2048	2058	4	38	350	1N	13043	S16W12	?db	C&B		+
46.	10 Sep 74	2126	2147	47	53	2520	2B	13225	N10E61	3.0db	C&B	Great Burst	+
47.	19 Sep 74	2221	2240	47	51	1880	2N	13225	N09W62	2.6db	C&B	Great Burst	+
48.	22 Sep 74	2327	2341	47	34	850	?	13225	W limb	—	—	No Flare Patrol Behind-Limb Event? Great Burst	○
49.	05 Oct 74	1618	1632	4	32	63	−F	13280	N10E88	—	—	Unconfirmed flare Behind-the-limb?	○
50.	25 Mar 76	1309	1318	4	40	96	1N	14143	S05E69	—	—		○
51.	28 Mar 76	1914	1936	47	59	1965	1B	14143	S07E28	SAT	C&T	Great Burst	●

decibels for Polar-Cap Absorption (PCA) events or says simply "SAT" for events detected only by satellites in the vicinity of the earth.

4 The Reference column refers to the study in which the given flare was associated with a proton event. "S & S" refers to the *Catalog of Solar Particle Events, 1955–1969*, edited by Švestka and Simon (1975); DHM refers to extensions of this *Catalog* by Dodson *et al.* (1977, 1978) for the years 1970–1972; "C & B" refers to the published list of Castelli and Barron (1977) of proton flares with classical "U-Shaped" radio spectra; and "C & T" refers to Castelli and Tarnstrom's (1978) catalog of proton events associated with flares which did not have a U-shaped peak-flux-density spectrum.

5 The key to the symbols in the last column is: C & B (+); C & T or S & S (●); behind the limb events with and without proton association respectively (■, □); and all remaining bursts without proton association (○).

The scatter points for the 51 events are plotted in figure 1(b) with the above symbols.

Classical versus Non-Classical Proton Flares. Castelli *et al.* (1967) reported that the peak-flux-density spectra of significant proton flares have a characteristic U-shape – with a high flux-density response at meter wavelengths, a pronounced dip in the decimeter range, and intensities approaching or greater than 1000 Sfu at frequencies ≥8800 MHz. The validity of this forecast tool has long been established (O'Brien, 1970). Seven of the events in Table I are associated with such classical proton flares (+). Five of these had peak-flux densities ≥350 Sfu. The position of these five events in figure 1(b) reveals their basically impulsive nature.

The two remaining "classical" events (Nos. 16 and 20) were actually long-enduring events with a superimposed Great Burst. Four other events in Table I (Nos. 18, 28, 31 and 41) are similar to Nos. 16 and 20 in that the superimposed event dominates the long-enduring component even though the radio peak flux density spectra of these flares were not U-shaped. From the point of view of burst classification, it is difficult to distinguish these events from a large burst preceded by a precursor and followed by a post-burst increase. In fact, this is how events Nos. 16 and 18 were classified at Sagamore Hill.

If we do not consider the above 11 events, then, and ignore for the moment the six bursts from behind-the-limb flares, we are left with a sample of 34 events. Thirteen of these (or 38 per cent) had proton association. This is a high percentage considering that none of the 34 events had the classical U-shaped radio spectrum and only three were Great Bursts at

2800 MHz. Castelli and Tarnstrom (1978) investigated 76 proton events, occurring between 1966 and 1976, that could be attributed to visible disk flares with non-classical radio emission. They found that the most important of these (in terms of measured riometer absorption) came from flares which had associated microwave bursts with durations on the order of an hour or more and with peak-flux densities on the order of 100 Sfu across the spectrum from 1000 to 9000 MHz. Obtaining average values of T and S_p for the 13 events in our sample with proton association and the 21 events without reveals some interesting, and perhaps significant, differences between the two groups. If we eliminate the largest event in each parameter group and average the remainder, we obtain

$$S_{p_{\mathrm{avg}}} = 102 \text{ Sfu}$$

$$T_{\mathrm{avg}} = 169 \text{ min}$$

for the proton related events, and

$$S_{p_{\mathrm{avg}}} = 165 \text{ Sfu}$$

$$T_{\mathrm{avg}} = 52 \text{ min}$$

for the non-proton events. If we assume a simple triangular burst-shape, we can use the approximation that the mean flux-density $(S_m) \approx \frac{1}{2} S_p$ to compute the average burst-integrated flux-density (E) in each case,

$$E_{\mathrm{avg}}(\text{proton}) = S_m \times T \approx \tfrac{1}{2} S_p \times T = 5.2 \times 10^{-17} \text{ Joules m}^{-2}\text{Hz}^{-1}$$

and

$$E_{\mathrm{avg}}(\text{non-proton}) = 2.6 \times 10^{-17} \text{ Joules m}^{-2}\text{Hz}^{-1}.$$

Thus the proton-flare bursts in the sample have, on the average, significantly longer durations and larger integrated flux-densities than the 2800 MHz bursts from the non-proton flares. We note that the average integrated fluxes from both groups, however, exceed the 10^{-17} Joules m^{-2}Hz^{-1} value cited by Castelli and Tarnstrom as a prerequisite for a flare associated >10 Mev proton flux of 1 proton cm^{-2}s^{-1}ster^{-1}. A histogram of the solar longitudes of the 34 flares is given in figure 2 where the well known Archimedean-spiral propagation effect, (Smart *et al.*, 1976), favouring observation at the earth of protons accelerated on the western hemisphere of the sun, is apparent. From this figure it appears likely that more events in the sample may have had proton association, especially when one considers that several of these flares (Nos. 5, 6, 11, 15 and 40) came from proton-prolific regions.

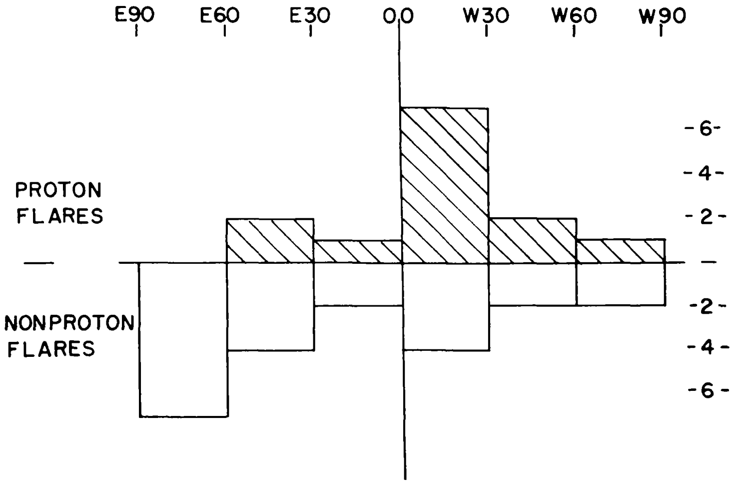

FIG. 2—The longitudinal distribution of the 34 flares, distinguishing between proton (upper) and non-proton (lower) events.

While the proton events from flares with non-U-shaped radio spectra tend to be small in size (Castelli and Tarnstrom, 1978), they can, on occasion, be significant. Four of the events in our sample (Nos. 13, 24, 37 and 39) were principal (≥2.0 db) PCA's. Because the radio emission from these flares is unspectacular, the ensuing proton events are particularly difficult to predict. Plotting the point for the associated 2800 MHz burst on the T-S_p diagram may help to identify certain flares as proton producers. From figure 3 we note that 10 of the 18 (56 per cent) western-hemisphere events that fell in the zone of avoidance had proton association. Also, from figure 1(b) it appears that the observation of a 2800 MHz burst with $T > 100$ min and $S_p > 30$ Sfu is a strong indicator that a proton event will occur.

2800 MHz Bursts from Behind-the-Limb Flares. Six of the events in Table I (Nos. 8, 21, 22, 34, 35 and 38) cannot be confidently linked to flares observed in Hα and are assumed to have come from active regions behind the solar limb. For five of the six cases a likely candidate region was located behind either the east or west limb. A possible explanation to account for the (T, S_p) points of these events falling in the zone of avoidance is that the source of the impulsive microwave component is located low in the solar atmosphere and is occulted by the disk; what is observed, then, is either the extended source of the gradual thermal burst in small flares or, more likely, the extended source of the smooth Type-IV microwave emission from large flares. This picture is consistent with the emerging model of solar flares in which the nonthermal impulsive-emission source is taken to lie relatively low in the corona below heights ranging from 6000 km (Vorpahl, 1973) to 15000 km (Böhme *et al.*, 1976).

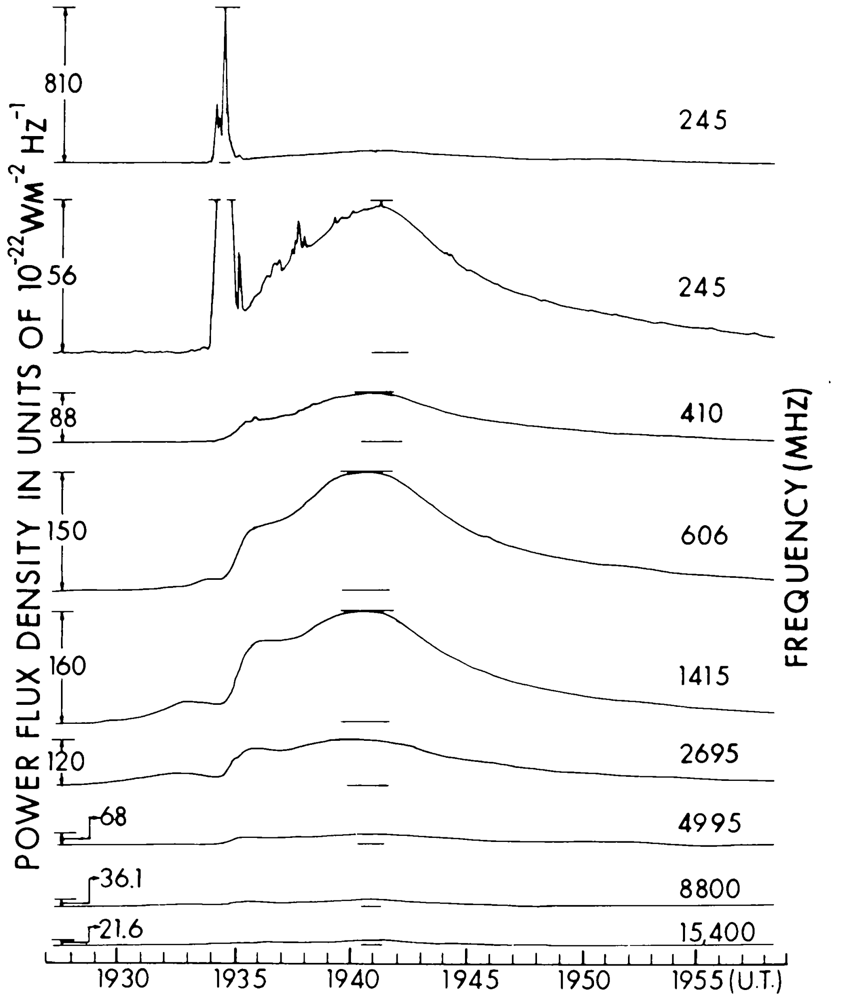

FIG. 3—The Sagamore Hill multi-frequency observations of the behind-the-limb flare on 01 Sept. 1971.

The absence of an impulsive component in behind-the-limb flares has been noted by several investigators. Teske (1967) pointed out the lack of an impulsive component in soft X-Rays for certain limb events. Unusual gradual hard X-Ray events associated with behind-the-limb flares have been reported by Frost and Dennis (1971), Kane and Pick (1976), and Hudson (1978b). Křivský and Krüger (1973) noted the lack of an impulsive component in the higher-frequency observations of the event of 01 Sep 1971 (figure 3) but, because the responsible flare was $\gtrsim 30°$ beyond the limb, were unable to make a more definitive statement than "the emission height (of the impulsive microwave component) must be smaller than about 1.5×10^5 km". Further studies of such partially occulted bursts might serve to better delineate the vertical structure of the microwave source.

It must be mentioned that examples of impulsive 2800 MHz events from behind-the-limb flares also exist (Badillo and Salcedo, 1969; Kane *et al.*, 1979). For these events it is possible that ejecta carry flare plasmas and fields to great heights. The radio emission of the event of 30 March 1969 reported by Badillo and Salcedo gave evidence of such outward motion.

''Spotless'' Flares. Dodson and Hedeman (1970, 1975) reported the occurrence of flares from regions with small spots or none at all. They found that the microwave emission from these flares is characteristically of the gradual-rise-and-fall type. The four such events in Table I (Nos. 3, 19, 42, and 44) represent only about 10 per cent of the major (Hα importance ≥2) spotless flares observed between 1966 and 1974. In Hα, these flares appear as parallel ribbons at the location of a previously existing quiescent dark filament.

Closing Comments. This study has reiterated the fact that solar microwave bursts fall into two basic categories, impulsive and long-enduring. These two branches of the T-S_p diagram merge in the region of short durations and low peak flux densities. For longer durations, the number of gradual-rise-and-fall events greatly exceeds the number of impulsive events. This latter statement follows almost by definition and is apparent in figure 1 (a). The long-enduring events rarely have peak-flux densities greater than 30 Sfu and, in the Ottawa records, events with peak fluxes less than 5 Sfu predominate. For the events listed in Table I, the largest of the long-enduring events (No. 37) had an integrated flux density a factor of three less than that of the largest of the impulsive events (No. 46), 1.0×10^{-16} Joules $m^{-2}Hz^{-1}$ *vs* 3.0×10^{-16} Joules $m^{-2}Hz^{-1}$.

We view the impulsive events listed in Table I as the ''rough edge'' of the upper branch of the T-S_p diagram, i.e., as having the same basic character as the events on this branch. We are less certain that the events whose (T, S_p) points fall near the lower branch of the diagram (figure 1(b)) can be viewed as the normal upward extension of the gradual-rise-and-fall events. In particular, many of the longer-duration ($T >$ 120 min) events without a dominant impulsive component seem to be of the ''magnetic-storm type'' discussed by Sakurai (1974), even though the peak fluxes are somewhat lower. Several (≥5 of 10) of these events had associated Type II and/or Type IV emission. It is difficult to reconcile this dynamic behaviour with the smaller gradual rise and fall events that are generally thought to be short-lived sources of the slowly varying component.

The high percentage of proton association for the events in Table I is perhaps explained by Hudson's (1978a) finding that an absolute total flare-energy threshold may exist beyond which the second-stage acceleration process becomes very efficient. This parallels Castelli and Tarnstrom's (1978) establishment of a single-frequency (at centimeter wavelengths) integrated-burst flux-density of 10^{-17} Joules $m^{-2}Hz^{-1}$ as a necessary condition for a $>$ 10 Mev proton flux of 1 proton $cm^{-2}s^{-1}ster^{-1}$, a condition that applies independently of the nature of the energy release – either rapid or slow. (Earlier investigators (Pick 1961; Harvey 1965) had suggested similar values of the 2800 MHz burst energy as a favourable condition for the observation of an associated Type IV or Type II/IV event at meter wavelengths.) The smallest event that our selection criteria allowed (No. 40) had an integrated flux-density approaching this threshold ($\sim 0.2 \times 10^{-17}$ Joules $m^{-2}Hz^{-1}$).

The traditional interpretation of the two burst classes has recently come into question. For the impulsive events, Mätzler (1978) and Dulk *et al.* (1979) have presented theoretical evidence that allows for an interpretation of these events in terms of gyrosynchrotron emission from a thermal (quasi-thermal) distribution of electrons. For the gradual-rise-and-fall events, Guidice and Castelli (1975) reported that only 20 per cent, at most, of a sample of nearly 400 long-enduring events observed at Sagamore Hill between 1968–1971 had peak-flux-density radio spectra that were consistent with a thermal bremsstrahlung emission mechanism. This is at marked variance with the widely held view that these events are of thermal origin and more work is needed to resolve the discrepancy.

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