PROPERTIES OF METRE-WAVELENGTH SOLAR BURSTS ASSOCIATED WITH INTERPLANETARY TYPE II EMISSION

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Abstract. A statistical analysis is used to determine the properties of metre-wavelength events which are associated with interplanetary type II bursts. It is found that the likelihood of an interplanetary type II burst is greatly increased if: (a) an associated metre-wavelength type II has a starting frequency less than 45 MHz; (b) a strong metre-wavelength continuum is present; (c) the type II contains herringbone fine structure; and (d) the metre-wavelength activity is accompanied by strong, long-lasting Hα and soft X-ray events.

1. Introduction

Dodson *et al.* (1953) first pointed out that solar flares associated with sudden outbursts of great intensity at 200 MHz were frequently followed several days later by geomagnetic storms, whilst other large flares (importance 2 or 3) without radio outbursts were not related to geomagnetic activity. The radio emission was later identified as type II, often followed by type IV continuum, and the idea arose that the geomagnetic disturbance was created by a piston-driven shock wave. Shocks were later detected directly by spacecraft and showed a close association with type II–IV bursts (Hundhausen, 1972). For many years observers speculated that the interplanetary shocks were extensions of the shock which produced the type II radio event. Supporting evidence for this assertion was initially provided by Malitson *et al.* (1973) from low-frequency radio observations using the IMP-6 satellite and more recently by ISEE-3 results (Cane and Stone, 1982). However, the direct extension of the type II burst from the metre-wavelength range to the kilometre range cannot be unambiguously shown because of the lack of frequency coverage between ~ 20 and 2 MHz.

During the interval September 1978 to December 1981 the low-frequency radio experiment on ISEE-3 detected 37 interplanetary type II bursts at frequencies < 2 MHz (Cane and Stone, 1983), 16 of which occurred during the observing hours of the Culgoora radiospectrograph. All of these events were associated with metre-wavelength activity of type II, type IV or both. During this interval 240 type II bursts and 76 type II–IV burst pairs were seen on the Culgoora radio spectrograph in the 20 to 200 MHz range. This indicates that only a small fraction (7%) of metre-wavelength type II bursts are followed by detectable interplanetary radio events.

In this paper we examine the physical properties and associations for the 16 metre-wavelength events preceding interplanetary type II bursts. To check the significance of

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these associations in producing interplanetary events, we compare the results statistically with a large sample of events taken from the Culgoora catalogue of major solar events (Robinson *et al.*, 1983).

2. Observations

2.1. Dynamic spectra

The 16 Culgoora events associated with the interplanetary type II bursts are listed in Table I. Three examples of the dynamic spectra are reproduced in Figure 1. The first example is a very energetic event containing the usual sequence of type III–II–IV bursts. Unusual features are the low starting frequency for the fundamental type II component (35 MHz) and the herringbone fine structure. The second example is another energetic event with a high type II starting frequency (130 MHz) and containing intense herringbone structure. The third example is a less energetic event with a weak, gradual type IV burst and a low starting frequency (25 MHz). This type II event also contains appreciable herringbone fine structure.

2.2. Type IV continuum

A broad-band continuum event occurred in 14 of the 16 interplanetary events. In most cases this continuum started during the type II burst and is the variety termed type-II-related flare continuum, or FCII (Robinson and Smerd, 1975; Robinson, 1978). In contrast, only 31% of all type II bursts are followed by a continuum.

The continuum associated with interplanetary events tended to be strong. In nine of the 14 cases observed (64%) it had an importance of 2 or greater, whereas only 36% of all continua associated with type II bursts reach these intensity levels.

It is interesting to note that whereas 88% of the interplanetary events in our sample were preceded by type II–IV bursts the inverse relation is not as good. In all, a total of 76 type II–IV pairs occurred in Culgoora observing hours during the ISEE-3 period, so that only 21% were followed by interplanetary type II bursts. The association improves somewhat when only strong continuum (importance ≥ 2) events are considered. In this case nine of 24 (or 38%) had an interplanetary type II.

2.3. Type II starting frequencies

The starting frequency for a type II burst is defined as the plasma frequency at which the burst starts. Hence, if the event first appeared in the harmonic, this frequency was divided by 2. If only one band appeared we could not unambiguously determine the starting frequency and the event was not used in the analysis. Fortunately, most of the type II bursts showed fundamental/harmonic structure during at least part of their lifetime.

In Figure 2a we present a histogram of the starting frequencies of the metre-wave type II bursts associated with interplanetary type II events. For comparison we show in Figure 2b the starting frequencies for 156 type II bursts accompanied by a type IV

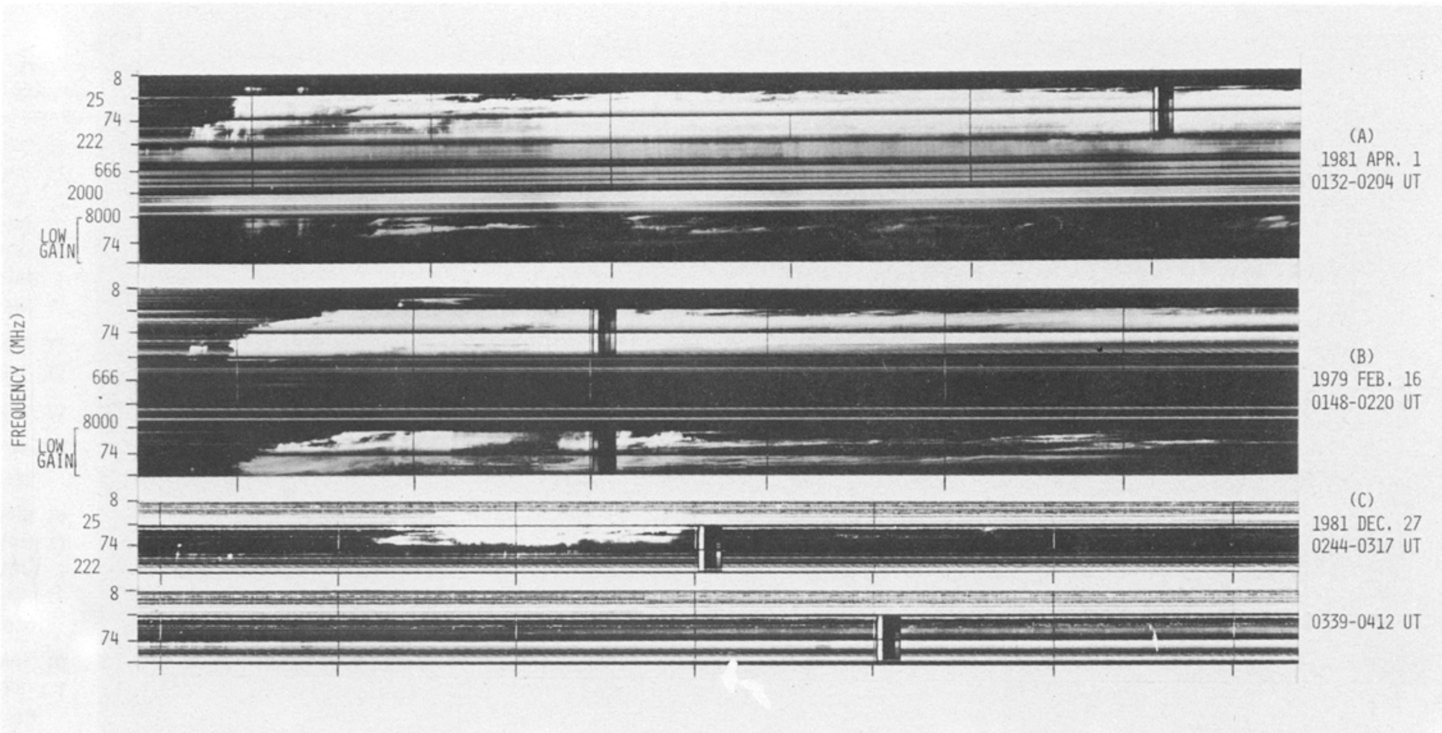

Fig. 1. Examples of dynamic spectra of type II–IV bursts recorded on the Culgoora radio spectrograph for events associated with interplanetary type II bursts detected at the ISEE-3 spacecraft. Time runs along the horizontal axis, with an interval of 5 min between the tick marks. In the top example the type II burst commences at 01 : 38 UT after an intense type III(V) burst. The type II burst is accompanied by strong flare continuum. Herringbone bursts can be seen as sharp spikey structure in the type II burst especially from 01 : 39–01 : 40 UT. In the middle example the type II burst is preceded by a small group of type III(V) bursts. Herringbone structure can be seen throughout the type II burst in the low-gain record, especially from 01 : 54–02 : 03 UT. Flare continuum is also present. In the bottom example the type II burst is preceded by only weak type III bursts. The herringbone structure can be seen clearly from 03 : 48–03 : 55 UT. A weak gradual type IV continuum follows the type II burst.

TABLE I

Properties of Culgoora events associated with interplanetary type II bursts[a]

Date of event	Hα flare			Type III class[b]	Type II burst				Type IV burst Imp.	X-ray event	
	Maximum (UT)	Imp.	Position		Imp.	HB	F–H	S.F. (MHz)		Imp.	Duration (hours)
1978											
Oct. 1	07:18	2N	S 13 E 57	–	3	s	Yes	80	2	M9	5
Nov. 10	01:10	2N	N 17 E 01	–	2	w	Yes	45	2	M2	4
1979											
Feb. 16	01:50	3B	N 16 E 59	IIIG, U	3	s	Yes	130	1	No data	
April 3	01:10	1N	S 25 W 14	IIIs	–	–	–	<20	2	M4	8
April 23	01:56	?	W 100 ?	IIIG	w	?	?	45?	–	–	0
Sept. 14	07:00	?	E 90 ?	–	2	s	Yes	90	1	X2	5
1980											
July 17	06:04	2N	S 11 E 06	IIIs	–	–	–	<20	2	M5	3
July 23	01:00	3B	S 19 E 17	IIIG, V	3	w	Yes	90 35	3	M9	2
Oct. 15	05:20	2B	N 19 E 54	IIIs	1	–	Yes	20	–	M2	4
Nov. 22	05:44	1B	S 17 E 40	IIIs	–	–	–	<20	1	M2	3
1981											
April 1	01:38	2B	S 43 W 52	IIIGG, V	3	s	Yes	35	2	X2	4
May 8	22:33	1B	N 09 E 42	–	3	s	Yes	45	2	M7	9
May 13	03:57	2B	N 12 E 58	IIIs	w	?	?	30?	1	X1	8
Oct. 7	22:59	1B	S 13 E 90	IIIG, V	2	?	Yes	35	1	X4	5
Oct. 12	06:27	3B	S 17 E 30	–	3	?	Yes	37	3	X3	6
Dec. 27	02:51	SN	S 13 E 16	IIIN, U	1	s	Yes	25	2	C7	6

[a] Symbols: –, no event; s, strong; w, weak; ?, uncertain; F, fundamental; H, harmonic; HB, herringbone; S.F., starting frequency.
[b] As defined in *Solar Geophysical Data*.

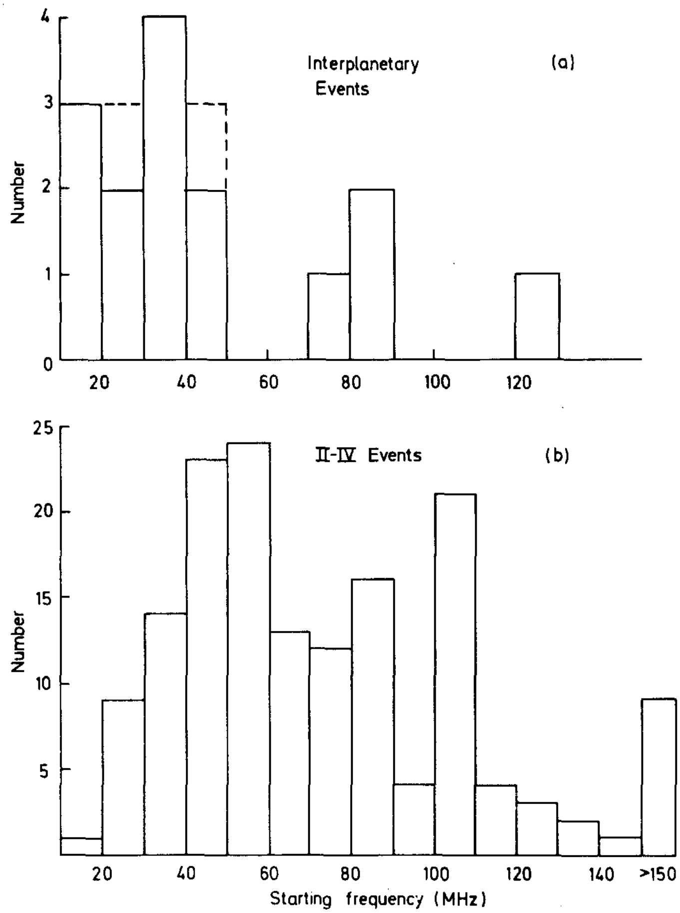

Fig. 2. Histograms of the starting frequencies of type II fundamental radiation (a) for those events associated with interplanetary type II bursts and (b) for 156 type II–IV burst pairs recorded by the Culgoora radio spectrograph between January 1968 and December 1981.

continuum. This represents all of the events from the Culgoora catalogue (Robinson *et al.*, 1983) for which the starting frequency could be unambiguously determined.

Note the rather broad distribution of starting frequencies in Figure 2b, with a mean near 60 MHz. In contrast, the starting frequencies in Figure 2a are mostly restricted to frequencies <50 MHz and the mean is near 30 MHz. The three events with starting frequencies less than 20 MHz in Figure 2a refer to interplanetary type II events which were not associated with a metre-wavelength type II burst. The starting frequencies of the other 13 type II bursts are listed in Table I. Note that two events were weak (April 23, 1979 and May 13, 1981) with doubtful starting frequencies. These events have been represented by dashed lines in Figure 2a. The event of July 23, 1980 had two type II bursts, one starting at 90 MHz and the other at 35 MHz. We give a weight of 0.5 to each of these bursts in determining the statistics (see Section 2.8) and a weight of 1 in producing Figure 2a.

TABLE II

Probabilities of associations and their statistical significance

Property	Interplanetary events				All type II		Type II–IV	
	Samples [a]	P	F_{r1}	F_{r2}	Samples [a]	P1	Samples [a]	P2
Start <40 MHz	10.5/14	75%	0.0004%	0.025%	105/519	20%	47/156	30%
Start <80 MHz	13/16	81%	30.4%	8.8%	375/519	72%	96/156	62%
Herringbone structure	8/13	62%	0.13%	1.48%	109/540	20%	50/175	29%
Type IV bursts	14/16	88%	0.0007%	–	175/553	32%	175/175	100%
Type IV importance >2	9/14	64%	0.0001%	1.31%	56/553	10%	56/175	32%
F–H structure	11/13	85%	18.1%	20.2%	377/546	69%	122/175	70%
Type III bursts	11/16	69%	52%	65%	364/553	66%	121/175	70%
Flares of importance >2	9/14	64%	0.0037%	0.83%	83/553	15%	53/175	30%
X-ray importance >M5	8/13	62%	0.02%	22%	27/191	14%	28/60	47%
X-ray duration >3 hr	12/13	92%	0.00001%	0.0002%	36/191	19%	17/60	28%

[a] Number of events with specified association / total number of events in the sample.

In summary, we see that 10.5 out of 14 events (75%) or possibly 12.5 of 16 events (78%) had starting frequencies less than 45 MHz, in contrast with 20% of all type II bursts and 30% for all type II–IV bursts pairs (see Table II).

2.4. Herringbone structure

Table I shows that a common feature of the interplanetary type II events in our sample is the occurrence of appreciable herringbone fine structure (see Roberts, 1959, for description). Of the 16 events, six had strong herringbone structure, with intensities of 2 or greater and lasting for 3 min or more. In two other cases the herringbone fine structure was present, but much less pronounced. Of the remaining eight events three started at a very low frequency and were not seen on the Culgoora radio spectrograph. In two events (October 7, 1981 and October 12, 1981) the type II fine structure may have been masked during most of the event by a broad-band radiation which saturated the spectrograph. In the final three events (April 3, 1979, October 15, 1980, and May 13, 1981) the bursts were weak or the spectral record was of poor quality so that we were uncertain about the presence of herringbone structure. We conclude that between 62% and 100% of the interplanetary type II events were preceded by metre-wavelength type II bursts showing herringbone fine structure. In contrast, only 20% of all type II bursts and 30% of II–IV bursts contain discernible herringbone emission.

2.5. Type II importance

The interplanetary type II events were associated with a metre-wavelength type II burst having an importance of 2 or greater in nine of the 13 events observed (68%). This compares with 69% for all type II–IV bursts and 50% for all type II bursts. Clearly the intensity of the metre-wavelength type II radiation does not influence the probability of detection of an interplanetary type II burst. Note however that the importance classification for an event refers only to the maximum flux attained within the burst. Since this maximum normally occurs near the start of the event it is possible that the interplanetary events (which start at low frequencies) have a significantly higher intensity at decametre wavelengths (<30 MHz) than normal type II bursts. An examination of this possibility is under way.

2.6. Type III associations

The classic model of a large metre-wavelength event is of a group of type III bursts, followed by a type II and a continuum. We have already established that a close association exists between type IV bursts and interplanetary events, and we now look at the type III association. In only three cases was the type III activity the well-developed, impulsive phase phenomenon expected in a strong event. The remaining interplanetary events either had no type III association (five events), were preceded by weak groups or single bursts (three cases) or were accompanied by type III storms lasting for 15 min or more (five cases). Combining all varieties of type III association, we see that the relation is comparable with other type II events (see Table II). However, the class of type III activity associated with the interplanetary events appears to be different from those in other events.

2.7. Flare characteristics

The properties of associated Hα and soft X-ray flares are given in Table I. In two cases the events occurred at or beyond the limb and were not considered. Of the remaining 14 interplanetary events nine (64%) had an associated Hα flare importance of 2 or 3, compared with 15% for all type II events and 26% for type II–IV events. The Hα flare intensity for the interplanetary events was normally 'bright'.

Soft X-ray emission was also intense for the interplanetary events. In eight out of 13 cases (62%) for which reliable data are available the soft X-ray classification (in the range 1–8 Å) exceeded intensity class M5 (equal to 5×10^{-2} erg cm^{-2} s^{-1}). The duration of the events was abnormally long, exceeding 2 hr in all cases and reaching as much as 9 hr. In Table I the X-ray duration is defined as the time between the impulsive start of the event and the point in the decay phase when the intensity decreased to 5% of its peak value (after subtraction of background flux and contributions from other bursts). Comparison with a sample of 191 type II events observed between January 1979 and December 1981 shows that type II events are normally accompanied by only a moderate soft X-ray burst, with only 14% exceeding intensities of M5 and only 19% having durations over 3 hr. Combining these properties, only 11 (6%) of the 191 type II events had both intensities greater than M5 and duration over 3 hr. Ten of these 11 had an associated type IV continuum and seven were in our sample of interplanetary type II bursts.

It is evident that the interplanetary type II events are accompanied by extremely energetic flares, even in comparison with normal type II–IV events.

2.8. Statistical significance of associations

Because of the small sample (16 events) it is necessary to test whether or not a selected association occurred by chance. To do this we first established the overall probability (P1) of an association occurring using a sample of 553 type II events observed by the Culgoora radio spectrograph during the period of January 1968 to December 1981 (Robinson *et al.*, 1983). Because of the close relationship between type II and type IV events in the interplanetary sample, we also deduce the probability (P2) of the association occurring in a subset of 175 type II–IV events.

Using the binomial distribution we then established the probability, F_r, that a particular association occurs by chance at least r times out of n trials through random selection from one of the classes of events. Here r represents the number of times a particular association is observed in the interplanetary events. If F_r is less than 1%, we reject the null hypothesis and assume that the probability of this association is significant.

The results of the analysis are presented in Table II. F_{r1} refers to F_r in relation to the total sample of type II events and F_{r2} represents a comparison with only type II–IV bursts.

3. Discussion

It has been suggested by Cane and Stone (1983) that there are two separate shock disturbances responsible for the metre-wavelength and the interplanetary type II bursts. In this study however we have been able to statistically define several properties which separate metre-wave type II events associated with interplanetary type II bursts from those not associated. This suggests that the two events are produced from a single disturbance. Further evidence for this conclusion has been supplied by Sheeley *et al.* (1983), who found a close relationship between metre-wavelength type II bursts, fast coronal mass ejections and interplanetary shocks. In the following discussion therefore we make the assumption that the interplanetary type II burst is simply a low-frequency extension of the metre-wave type II event.

The large intensities of associated Hα and soft X-ray flares and the observed connection with continuum radiation both suggest that the energy of a flare event is important in the production of interplanetary type II bursts. However, the fact that only 21% of all type II–IV bursts are seen in the interplanetary medium suggests that other factors are important in producing an interplanetary event.

One such factor appears to be the presence of a long-duration soft X-ray source. Many flare events lacking such a source failed to produce an interplanetary type II, even though they were otherwise strong with intense type II and IV radiation and a large Hα flare.

Another factor is the occurrence of herringbone fine structure in the metre-wavelength type II. This fine structure indicates that the initiating disturbance was effective in accelerating electrons and that these electrons had access to open field lines. The association of type II herringbone bursts and shock accelerated events observed at kilometre wavelengths (Cane *et al.*, 1981) confirms that electrons can escape from the shock, presumably along open field lines, out to distances ~1 AU. The angular extent of the shock wave would thus be an important factor. Interplanetary shocks, being associated with more energetic flare events, would perhaps have larger angular extents and be more likely to satisfy the conditions required for the excitation of herringbone bursts. One such condition could be electron access to open field lines, another might be the orientation of shock front to the field lines (Holman and Pesses, 1983).

One of the most interesting results of the present study is that metre-wavelength events which start at frequencies less than 45 MHz are more closely associated with interplanetary type II events than those starting at significantly higher frequencies. Since type II events are unlikely to be seen until the initiating disturbance exceeds the local Alfvén velocity, this observation implies that MHD shocks which are formed high in the corona are more likely to produce an interplanetary type II than those generated at lower heights. We can suggest two possible implications of this observation, dependent upon whether the shock is driven by a coronal mass ejection or is a blast wave.

(1) The direct association between interplanetary type II events and coronal white-light mass transients (Cane and Stone, 1983), as well as the association of these coronal transients with type II–IV bursts (Gosling *et al.*, 1976; Munro *et al.*, 1979) and with long-decay soft X-ray events (Sheeley *et al.*, 1975; Kahler, 1977) strongly suggests that the interplanetary events are produced by piston-driven shocks. The low starting frequency observed for these events could imply that the disturbance was initially slow and was accelerated to super-Alfvénic velocities by an energy source. The close association with long-duration soft X-ray flares points to the presence of such a source in these events. It is unclear however why the disturbance should be preferentially slow at the start.

(2) If the shock is created by a blast wave, then dissipative processes associated with the formation of the shock, including particle acceleration, plasma heating and generation of magnetic turbulence, tend to drain energy from the disturbance as soon as the local Alfvén speed is exceeded. For this reason, blast waves which do not produce shocks until they are high in the corona are more likely to escape into the interplanetary medium than those of comparable energy which produce shocks at low heights. Theory suggests that the type II burst is created when the initiating disturbance encounters a coronal structure having a low Alfvén velocity (e.g. Uchida, 1974). It is possible then that the interplanetary type II events are produced when a suitable low Alfvén velocity region did not exist near the flare site or when the initiating disturbance was prevented from entering suitable nearby structures.

4. Conclusions

The investigation of 16 metre-wavelength events associated with interplanetary type II bursts suggests that the presence of strong flare phenomena, intense continuum radiation, a low starting frequency and herringbone fine structure are all important features. We suggest that the interplanetary type II is most probably produced in a strong flare event in which energy is continuously supplied to the outwardly moving disturbance by an intense, long-lasting source at the flare site. The disturbance normally reaches a height of 1.6 to 2.0 solar radii before becoming a shock.

To check this model more interplanetary events should be investigated. It is also important to obtain dynamic spectra in the region between 20 and 2 MHz separating the present groundbased and satellite measurements. Such spectra would enhance our ability to follow the disturbance out from the Sun. Investigations should also be carried out using white-light coronal data to search for the presence of an accelerating piston in association with interplanetary type II shocks.

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