FINE STRUCTURE IN THE SPECTRA OF SOLAR RADIO BURSTS

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Summary

Observations are described of solar radio burst spectra in the frequency range 25–100 MHz with a time resolution of $0 \cdot 02$ sec. The types of bursts that were observed included (1) fast drift storm bursts with a mean frequency–time slope of $1 \cdot 9\ \mathrm{MHz\,sec^{-1}}$, a mean bandwidth $\Delta f \sim 0 \cdot 03$ MHz, and a mean duration ΔT of $0 \cdot 6$ sec; (2) drift pair bursts with $df/dt = 1 \cdot 2\ \mathrm{MHz\,sec^{-1}}$ and $\Delta f = 0 \cdot 45$ MHz; and (3) split pair bursts with $df/dt = 0 \cdot 08\ \mathrm{MHz\,sec^{-1}}$, $\Delta f = 0 \cdot 05$ MHz, and $\Delta T = 1 \cdot 4$ sec. In addition, chains of split pair bursts were frequently observed, the chain resembling a type I burst with fine structure.

Diffuse radiation with a positive frequency–time slope was observed to follow fast drift bursts and drift pairs on some occasions.

Introduction

The existence of transient solar radio events with a time scale much less than 1 sec has been known since 1955 (Reber 1955), but the only extensive series of observations of their spectral properties so far reported has been by Elgaroy (1961) for the frequency range 190–210 MHz. He found many subtypes of the well-established types of solar radio bursts normally observed in this frequency range and, in addition, discovered much new spectral fine structure. However, the remainder of the solar radio spectrum remains essentially unexplored at high time resolution.

The observations described here were made mainly between 20 and 100 MHz, over the period March 1966 to December 1967, as part of a general investigation of the spectrum between 10 and 1000 MHz.

Description of Equipment

Four spectrographs were used, each of which was capable of scanning a frequency range of 8–240 MHz in a single sweep with a scan rate up to 500 Hz, and with a variety of bandwidths from 2 to $0 \cdot 02$ MHz. A fifth spectrograph for high frequency resolution observations was used between 27 and 28 MHz with a bandwidth of 2 kHz. In addition, the right- and left-handed circular polarization components were recorded between 28 and 34 MHz, and some information on the direction of the source was provided in the same frequency range. The general purpose antennas were double log-periodics directed obliquely onto the ground screen. The polarimeter used a cross log-periodic on an altazimuth mounting, while the directional information was

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provided by an east–west linear array of 32 broad-band dipoles. The east and west halves of the array were connected alternately in phase and antiphase every $0 \cdot 5$ sec.

Recording was on 35 mm film moving continuously at 2 in. min^{-1} from 1030–1330 hr local time each day, with four separate cathode ray tubes, one for each spectrograph, all the spectra being recorded side by side on the one film. For most of 1967, the recording configuration for the four channels was respectively (1) 24–34 MHz direction finding, bandwidth 20 kHz; (2) 28–34 MHz polarization, bandwidth 20 kHz; (3) 28–34 MHz intensity; and (4) 28–60 MHz intensity; the bandwidths of the (3) and (4) channels were 25 and 50 kHz respectively. More recently, the polarization observations were discontinued and the frequency ranges have been 27–28, 26–35, 35–50, and 25–200 MHz, with bandwidths 2, 25, 25, and 50 kHz respectively. The sweep times in all cases have been $0 \cdot 02$ sec except for the 27–28 MHz receiver, for which it was $0 \cdot 04$ sec. The direction-finding system has since been modified to provide a 12′ to 20′ fan beam swept across the Sun five times per second, while the frequency range 30–50 MHz is simultaneously swept at 400 Hz. Observations made with this modified instrument will be described elsewhere.

Observations

(*a*) *Fast Drift Storm Bursts*

Figures 1 and 2 show examples of narrow bandwidth bursts that had a frequency–time slope in the range $1 \cdot 0$–$2 \cdot 1$ MHz sec^{-1}. They occurred during noise storms, usually in groups of 10 to 20 bursts, although some single isolated bursts were observed. In many of the records they appeared to be paired, i.e. two similar bursts occurred successively, the second component of the pair at a distinctly higher frequency. However, the time and the frequency intervals between the two components varied considerably, $0 \cdot 5$ to 2 sec and $0 \cdot 1$ to 2 MHz for bursts near 30 MHz. No characteristic time interval such as exists for drift pairs was seen. Figures 3(*a*) and 3(*b*) illustrate the ranges of the frequency and time intervals between the components respectively, while Figures 4, 5, and 6 show their duration, bandwidth, and frequency range of occurrence.

The most noticeable properties of the bursts were their narrow bandwidth, approximately $0 \cdot 03$ MHz, and the narrow range of their frequency–time (f–t) slopes, the measured values of which were slightly greater than for drift pairs occurring during the same noise storm (Fig. 12). Their bandwidth was much less than for drift pairs and frequently appeared to be smaller than that of the spectrograph (20 kHz). The absence of echo-like traces for many of the bursts is also interesting since they were observed sometimes concurrently with drift pairs. No modulation due to circular polarization components was observed on the polarimeter records.

These transient fast drift bursts were probably similar to those identified near 200 MHz by Elgaroy (1961) and called type I(fd), although those he observed were of proportionately much greater bandwidth ($\sim$ 2 MHz). He also reported similar bursts with reverse as well as forward frequency drift. In the present observations, a few reverse drift bursts were observed, although these were much more diffuse and of greater bandwidth. Figure 2(*c*) shows an example.

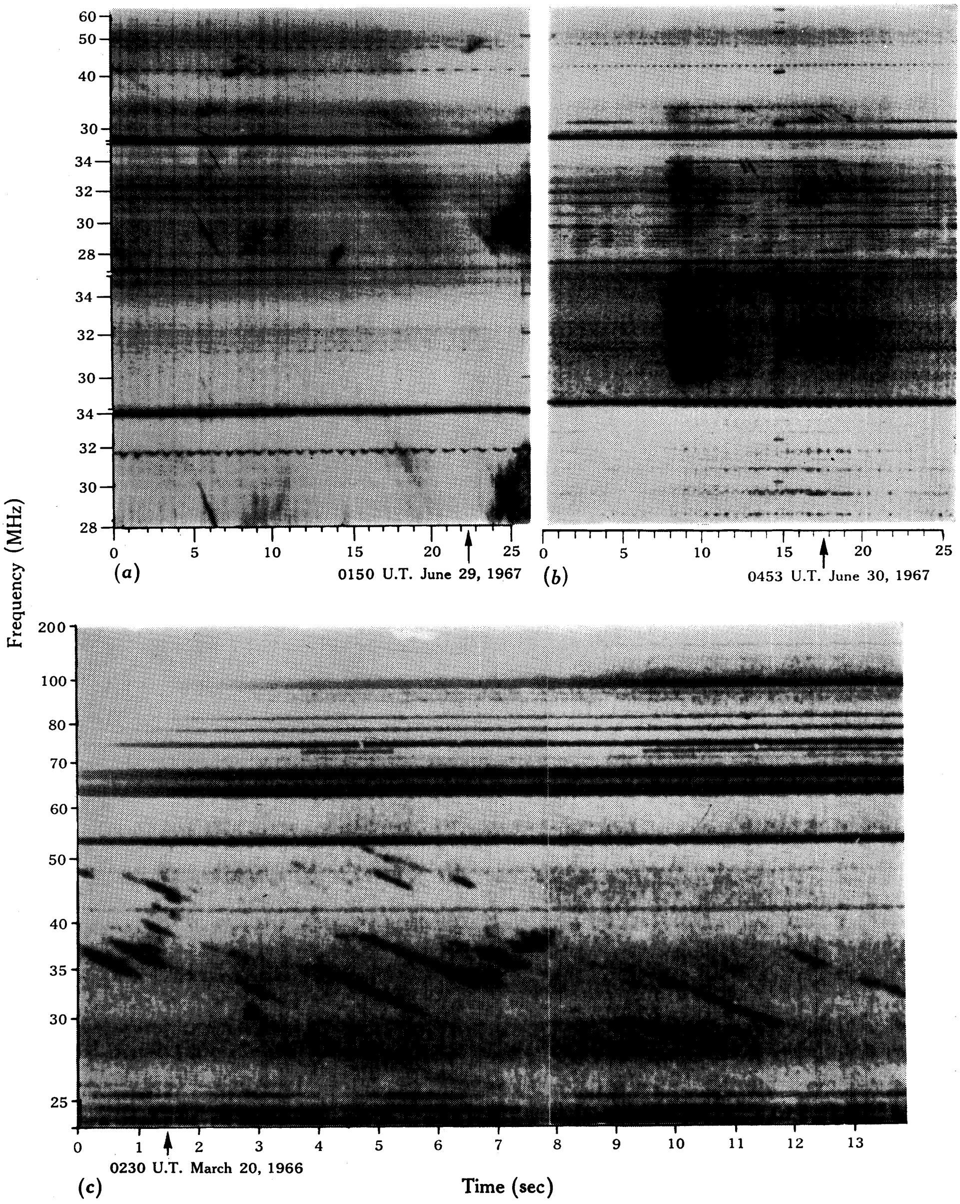


Fig. 1.—Spectra of fast drift storm bursts showing intensity versus frequency in each section of (*a*), (*b*), and (*c*).

(*b*) *Drift Pairs*

Many drift pair bursts were observed during several solar outbursts. These in general showed the features discussed in detail by Roberts (1959). On the f–t plane, they appeared as a trace with a bandwidth of approximately $0 \cdot 5$ MHz, and f–t slope of approximately 1–2 MHz sec^{-1} followed by an apparent echo trace 1–2 sec later

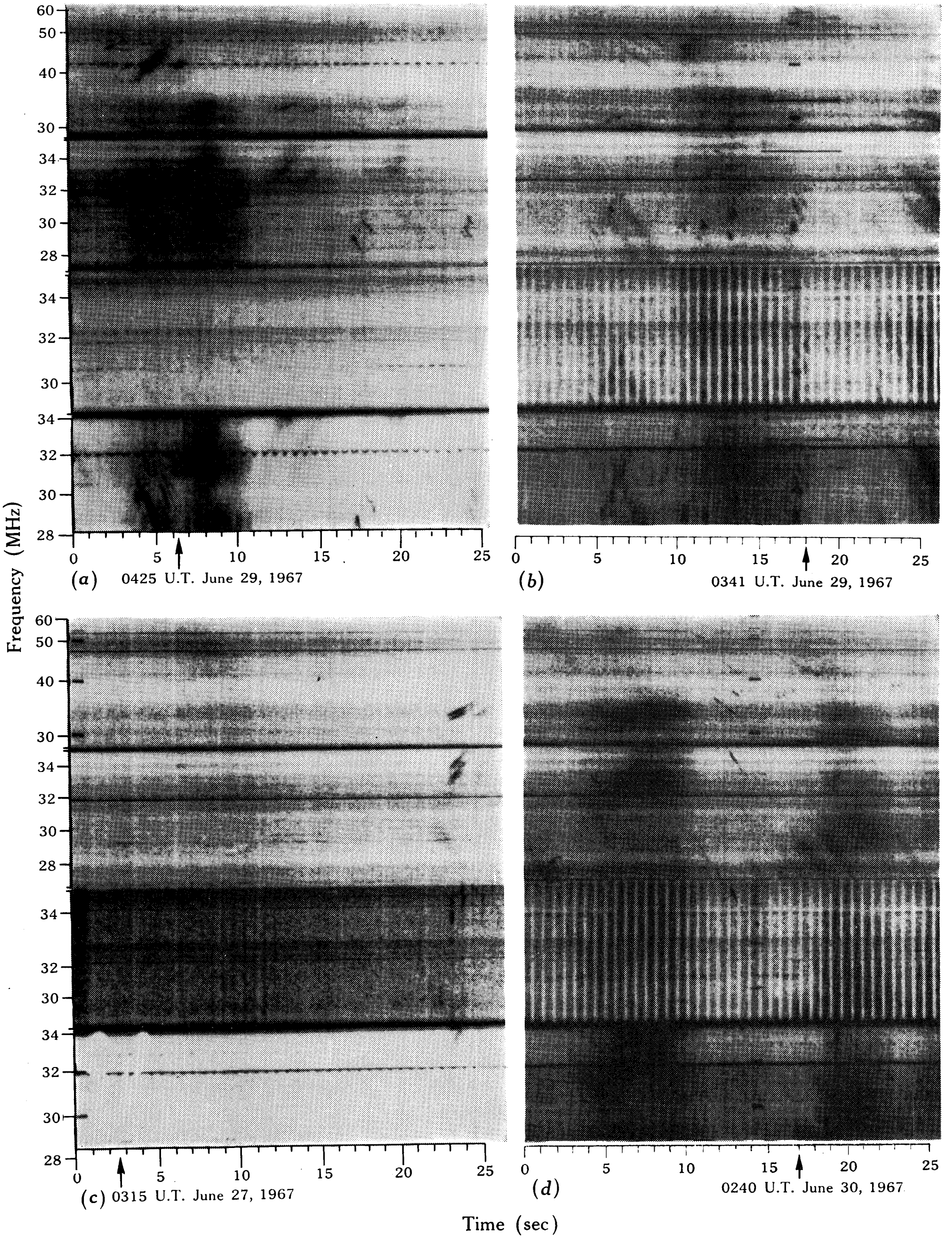


Fig. 2.—Spectra of fast drift storm bursts. In each of (*a*), (*b*), (*c*), and (*d*) the lower section shows the polarimeter record, the next section the direction-finding record, and the two upper sections the burst intensities versus frequency and time.

(examples are shown in Fig. 7). Figure 5 shows a histogram of the bandwidths of the first traces of drift pairs. It can be seen that the bandwidth is generally much greater than that of the type I(fd). The f–t slopes occupied a very narrow range, the mean value of 1·4 MHz being significantly less than that of the type I(fd) (Fig. 12).

Roberts (1959) suggested that the trace doubling in drift pairs was due to echoing with propagation of the radiation along two rays paths to the observer, one direct and one involving reflection at a lower level in the corona. This process would

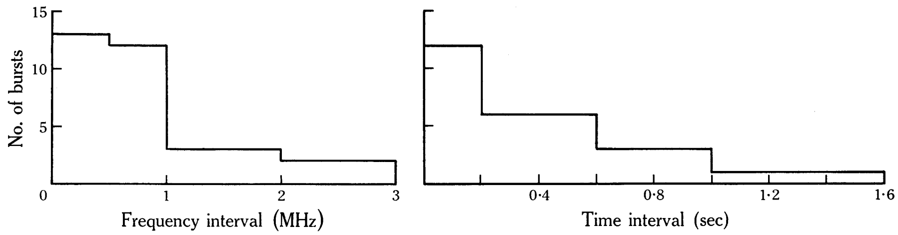


Fig. 3.—Distribution of (*a*) the frequency intervals and (*b*) the time intervals between pairs of fast drift storm bursts.

be expected to lead to two similar traces, one displaced in time with respect to the other. In addition, the emission frequency would necessarily be higher than the local plasma frequency in order to allow the initial inward propagation of the echo.

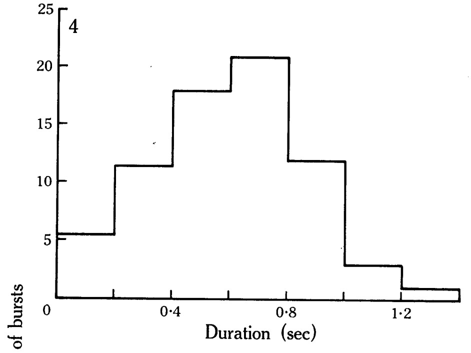
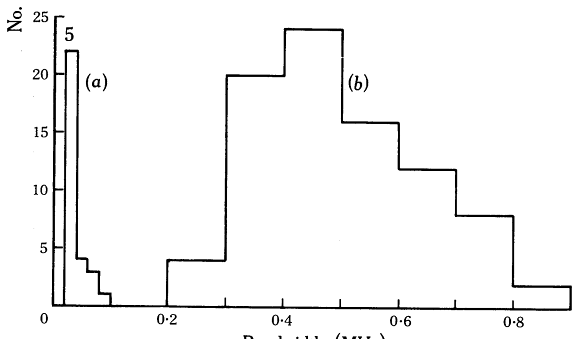


Fig. 4.—Duration of fast drift storm bursts at a constant frequency.



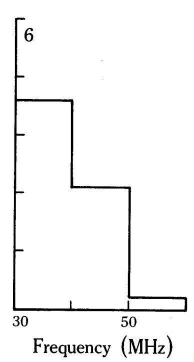


Fig. 5(*left*).—Bandwidth distribution of (*a*) fast drift storm bursts and (*b*) drift pairs.

Fig. 6(*right*).—Occurrence of fast drift storm bursts as a function of wave frequency.

Close examination of the records obtained in the present observations showed that the second component of a forward drift pair frequently occurred at a higher frequency as well as at a later time than the first. In the record shown in Figure 7(*b*), both the beginning and end of the traces can be seen. The second trace is displaced

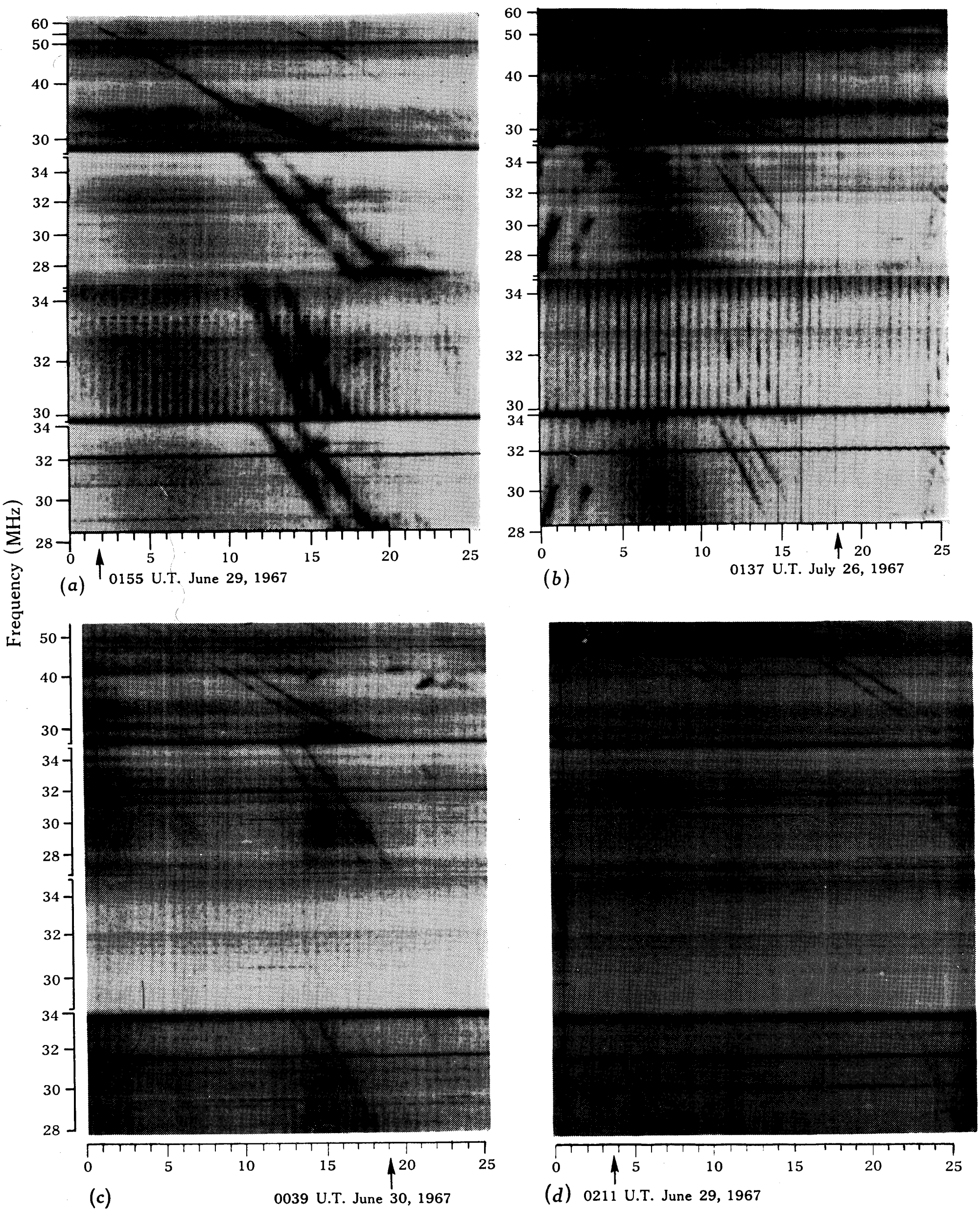


Fig. 7.—Records of drift pairs: (*a*) drift pair with breaks in the two traces near 30 MHz showing a frequency shift in the second trace with respect to the first; (*b*) and (*c*) drift pairs with weak midpoint traces; (*d*) drift pair extending upwards in frequency to 60 MHz and showing an absence of a subharmonic trace near 30 MHz. A second drift pair on (*d*) also shows a weak midpoint trace.

diagonally on the f–t plane. This was a characteristic feature of all the short drift pairs observed. Figure 7(*a*) shows another example, where the intensity of the first trace suddenly decreased between 29 and 28·5 MHz. The second trace showed a similar decrease between 30·1 and 29·6 MHz, i.e. the discontinuity was not displaced in time only as would be expected for a simple echo. It should be noted that variations in receiver sensitivity with frequency will often produce the appearance of displacement in time only. The mean frequency displacement near 30 MHz was 0·8 MHz, and the mean time difference 1·2 sec.

In the echo theory of drift pairs, it would be expected that the delay time Δt, and hence the time interval between the burst components at the same frequency, would decrease with increasing wave frequency since the geometrical scale of the ray paths would become smaller at lower levels in the corona (Roberts 1959). Although some individual examples of drift pairs do show this sort of variation in time interval, the mean time interval does not vary with frequency (Roberts 1959), some pairs actually showing an increase in Δt with frequency (Fig. 8). However, where there is

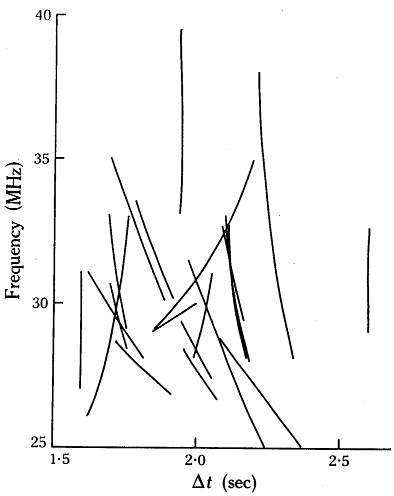


Fig. 8.—Time interval Δt at a constant frequency between the two components of drift pairs plotted against wave frequency.

a frequency as well as a time displacement between the components as indicated by the present observations, the time interval measured at the same frequency would not be a straightforward measure of the delay, and the absence of the expected variation of delay with frequency need not therefore be taken as contradictory to the echo hypothesis. The present observations of the properties of the drift pairs point to an emission mechanism in which the backward radiation from the source is at a slightly higher frequency than radiation emitted in the same direction as the source motion. At the same time, there is no evidence that the mean emission frequency is twice the local plasma frequency as suggested by Roberts (1959). In this case, it might be expected that a burst would sometimes be observed corresponding to the emission at the fundamental frequency, i.e. a single trace at about half the frequency of the pair. This has never been observed.

Figure 7(*b*) shows a feature of drift pairs occasionally found during the present observations, namely, a fine single or double *f–t* trace midway between the two normal traces. A similar midpoint burst may be seen in the example of a double type I(fd) shown in Figure 2(*a*). Neither of the drift pair traces usually observed showed significant polarization.

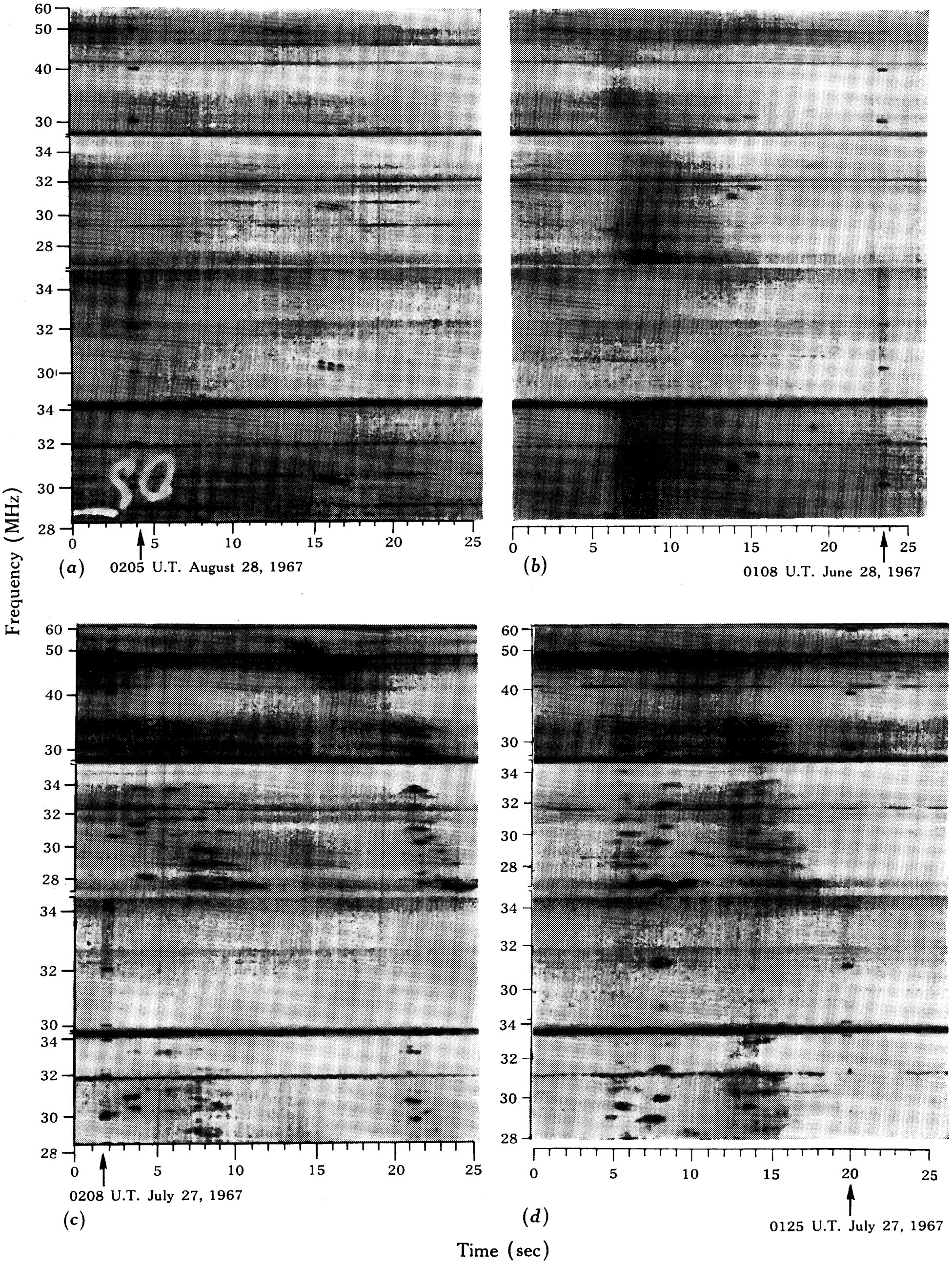


Fig. 9.—Records of individual split pair bursts ((*a*) and (*b*)), and chains of split pair bursts ((*c*) and (*d*)).

(*c*) *Split Pair Bursts*

Short duration bursts of narrow bandwidth that showed frequency splitting were recorded during most periods of solar activity. Their mean duration was 1·5 sec,

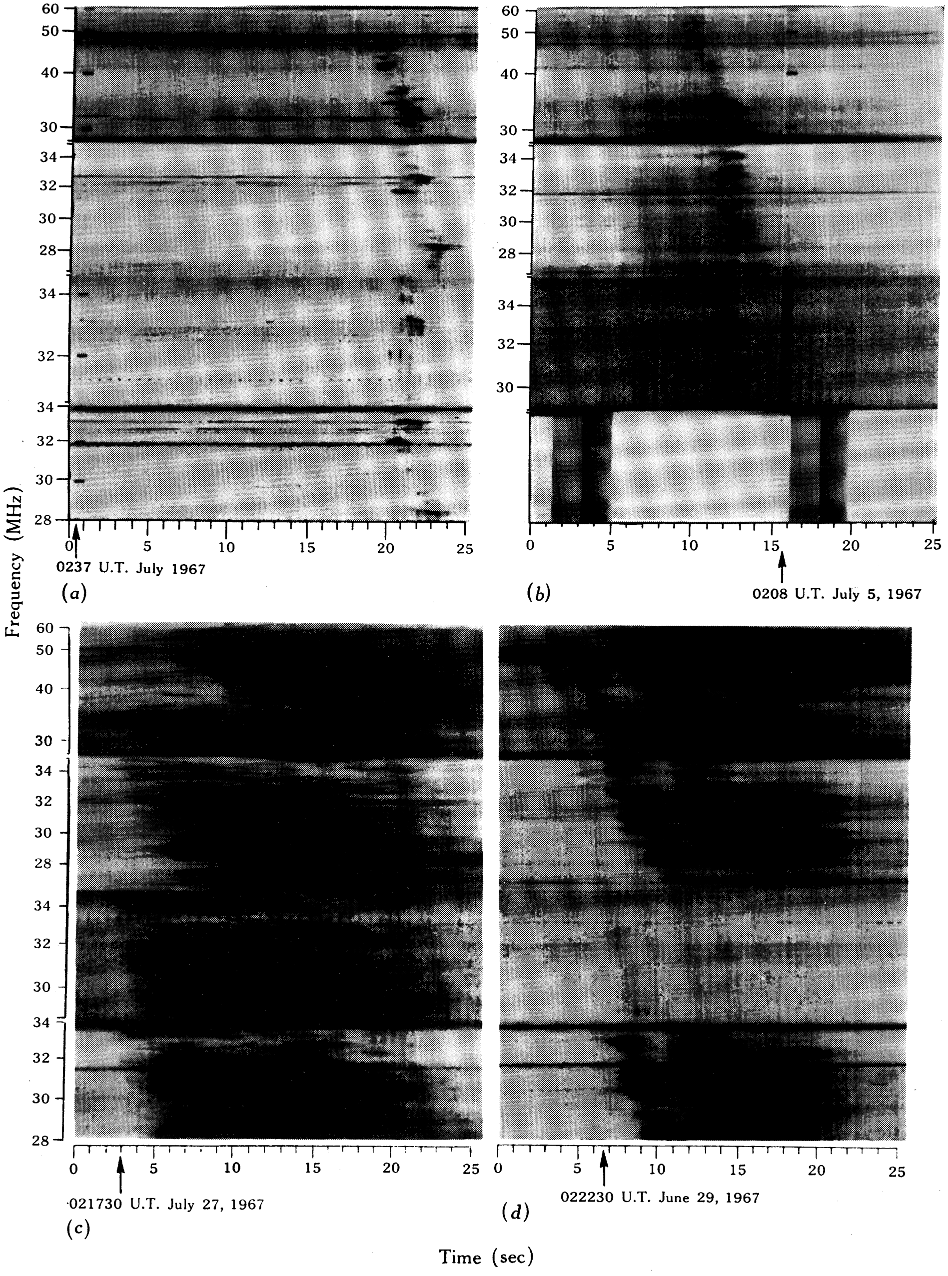


Fig. 10.—Records of chains of split pair bursts and type III bursts showing fine structure.

mean bandwidth 0·08 MHz, and the mean frequency interval between their components 0·15 MHz at 30 MHz. Figure 10 shows some examples. Their properties have been discussed in detail by Ellis and McCulloch (1967). The present series of observations provided information about their polarization. Both components were found

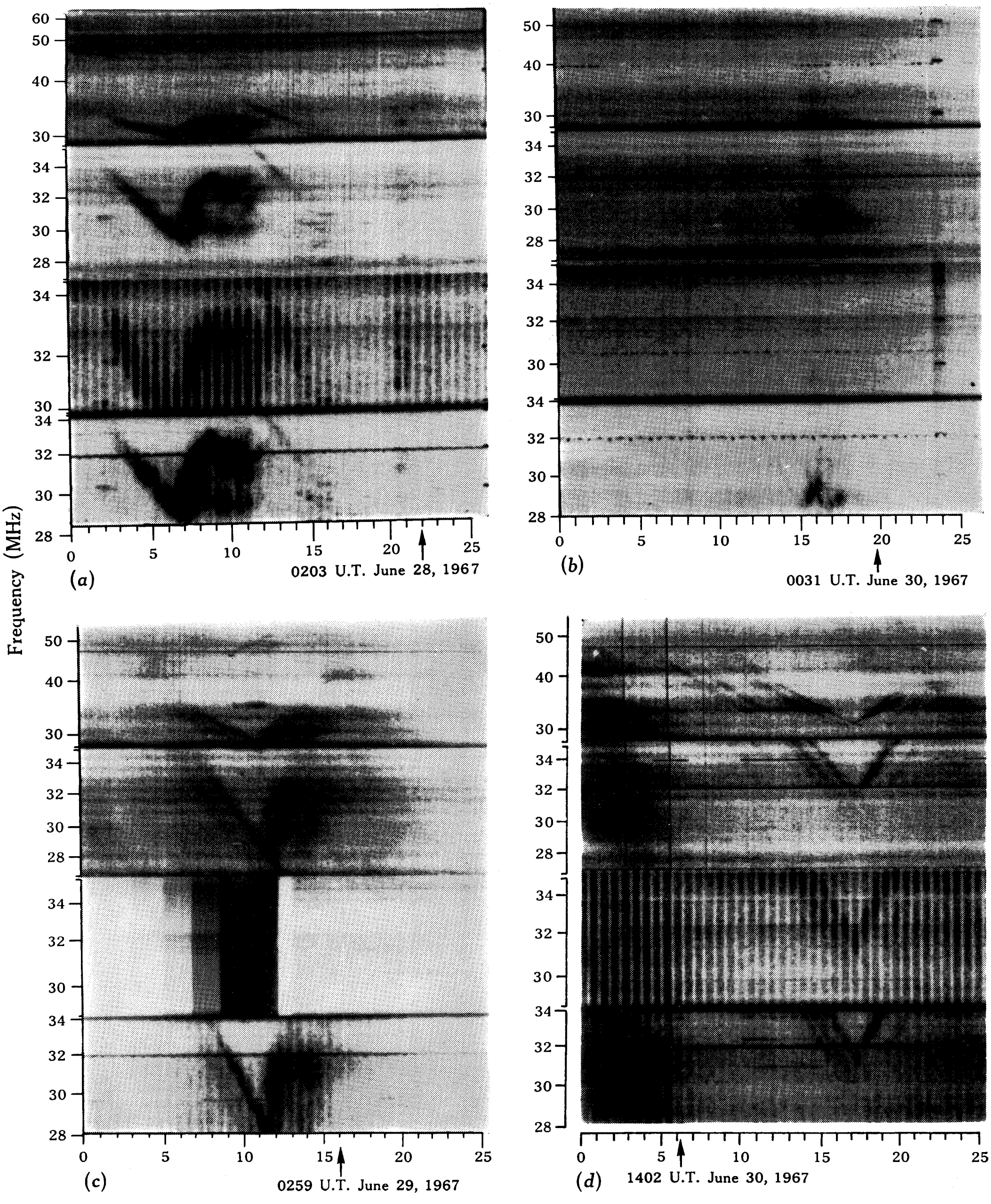


Fig. 11.—Records of hook bursts. In (*b*) a weak drift pair apparently led to a double burst in which the second component did not appear as an echo of the first.

to be polarized in the same sense, namely, right-handed looking along the direction of propagation. This corresponded to ordinary polarization with respect to the leading sunspots of the group. No bursts showed pure circular polarization. The mean intensity of the signal received in the right-handed mode was $2 \cdot 1$ times that in the left-handed mode. The polarimeter was unable to distinguish between circular plus random polarization and opposite circular polarizations. Nevertheless, the observation of similar polarization in the two components would seem to indicate that magnetoionic splitting is unlikely to be responsible for the frequency splitting. This was one of the possible mechanisms considered by Ellis and McCulloch (1967). The polarization measurements do not exclude another mechanism suggested by Ellis (1967), namely the excitation of plasma radiation by moving electrons at the plasma frequency f_p and the upper hybrid plasma resonance frequency $(f_p^2+f_H^2)^{\frac{1}{2}}$. Indeed, other evidence to be reported elsewhere now supports this latter interpretation.

Split pair bursts were observed to occur in isolation (Fig. 9(*a*)), in storms (Fig. 9(*b*)), or in chains (Figs. 9(*c*) and 9(*d*)). The chains often had the appearance of type III bursts with fine structure and their *f–t* slope was similar to that of the type III, although normally slightly greater in magnitude. Figure 12 shows a comparison of the *f–t* slopes of burst chains and type III.

(*d*) *Type III*

The properties of the type III bursts observed were in general agreement with those previously reported. Fine structure was observed in their leading edges on some occasions (Fig. 10(*d*)) and there appeared to be a continuous transition from normal type III through the development of fine structure of split pair chains. Where a type III with fine structure was observed together with a second harmonic component, the latter was normally diffused and did not show any fine structure.

(*e*) *Hook Bursts*

An unusual type of burst analogous to a U-burst but associated with drift pairs is illustrated in Figure 11. This showed an *f–t* trace which had a slope and bandwidth similar to that of a drift pair, but which suddenly reversed, producing a characteristic curved trace of increasing frequency. The spectrograms were remarkably similar to those of v.l.f. hooks generated by electron streams in the Earth's magnetosphere.

The rising trace was frequently diffuse and had the appearance of a burst of radiation triggered by the initial drift burst. It appeared to be somewhat similar to the type V radiation that follows a type III burst. Figure 11(*b*) shows a double burst associated with a drift pair. It is interesting to note that in this case the second diffuse component does not have the appearance of an echo of the first and has a different *f–t* slope.

Discussion

The bursts reported here may be divided into four classes on the basis of their frequency–time slopes. Figure 12 shows plots of $\mathrm{d}f/\mathrm{d}t$ for the split pairs, drift pairs, type I(fd), type III, and split pair chains. Also shown is the distribution of *f–t* slopes for type II bursts observed in 1967.

The relatively broad range of $\mathrm{d}f/\mathrm{d}t$ for the type III has been explained by the range of velocities available for electrons travelling through the corona, limited on the one hand by the velocity of light and on the other by opacity of the corona for electrons travelling at less than the thermal speed (approximately 2×10^9 cm sec^{-1}). At the other extreme in the observed values of df/dt, the type II with df/dt near $0\cdot03$ MHz sec^{-1} is thought to be produced at the shock front associated with a mass of ionized gas travelling slightly faster than the Alfven velocity in the corona, which is about 5×10^7 cm sec^{-1} (Zaitsev 1966).

The narrow range of df/dt for the drift pairs and type I(fd) and split pairs would seem to imply different and highly specific velocity-dependent emission processes. The quite different properties of the drift pairs and type I(fd) associated with a small decrease in df/dt is particularly striking. The velocities implied by the values of df/dt for the burst chains and their component split pairs frequently appear to be in the

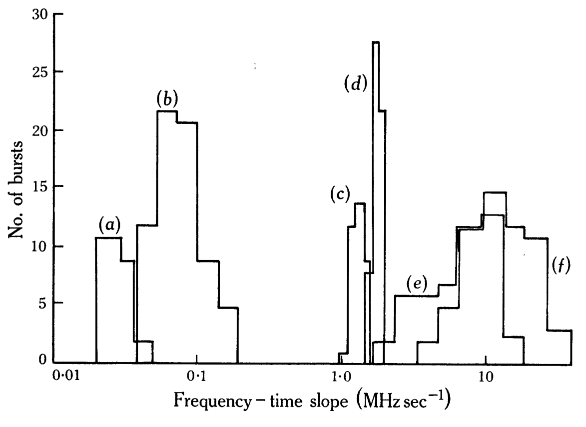


Fig. 12.—Distribution of frequency–time slopes for (*a*) type II bursts, (*b*) split pair bursts, (*c*) drift pair bursts, (*d*) fast drift storm bursts, (*e*) type III bursts, and (*f*) chains of split pair bursts.

ratio of approximately 50 : 1, and it is possible that they are respectively associated with electrons and protons. The existence of a chain, i.e. a series of isolated bursts, implies that the fast moving agency responsible for the overall *f–t* slope of the chain does not itself radiate directly, but excites in succession the radiation seen in the individual components, which themselves may well indicate the existence of irregularities in the corona.

Acknowledgments

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