FREQUENCY SPLITTING OF SOLAR RADIO BURSTS

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Summary

Solar radio bursts showing frequency splitting have been observed regularly below 60 MHz. The bursts have a duration of 1–2 sec and a frequency interval between their elements of 0·1–1·0 MHz. Their wave frequency generally decreases with time at about 0·1 MHz/sec. The bursts may occur either in isolation, in chains associated with type III bursts, or in large numbers during noise storms. Triple splitting is observed in about 10% of the bursts. The properties of the bursts are not inconsistent with those expected from magnetic splitting of the radiation.

I. Introduction

From time to time, solar radio bursts have been observed with a double frequency structure in the frequency–time plane; i.e. the bursts consist of two similar elements separated in frequency by an interval that is small compared with the wave frequency. Such bursts have been observed rather infrequently either as fine structure associated with type II solar bursts (Wild 1950; Roberts 1959) or in storm bursts of short duration at metre wavelengths (Elgaroy 1961).

It has been recognized for many years that frequency splitting is of considerable potential importance since it may be caused by the effect of magnetic fields on the emission process (Wild, Murray, and Rowen 1954; Roberts 1959; Sturrock 1961; Tidman, Birmingham, and Stainier 1966). A number of theoretical mechanisms have been considered in which the frequency interval between the elements is a measure of the magnetic field intensity at the point of emission. Nevertheless, uncertainty with respect to the emission process has meant that it has not been possible to establish this technique for investigating coronal magnetic fields.

In the present paper, solar bursts showing frequency splitting are shown to be observable in large numbers in the frequency range 25–60 MHz, providing radio spectrographs with a sufficiently fast response are used (Ellis and McCulloch 1966; Ellis 1967).

II. Observations

Observations of the spectra of solar radio bursts were made over the period June 1965 to March 1967 in the frequency range 8–240 MHz. Several spectrographs were used in a variety of frequency ranges, bandwidths, and scan-rate configurations. The system found most useful for observing the bursts described here incorporated four separate spectrographs scanning the frequency ranges 24–28, 28–36, 36–46, and

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46–60 MHz respectively. The scan rate of each was 50 sweeps/sec and the bandwidths were 30, 30, 30, and 50 kHz respectively. The antenna was a fixed double log periodic directed obliquely into a horizontal ground screen. Its beam was 30° wide in altitude and 90° in azimuth. The receiver noise factors varied from 2 dB at 25 MHz to 2·5 dB at 60 MHz. Recording was on 35 mm film moving at 2 in/min between 0900 and 1500 local time each day. Two separate cameras were used to record the four spectra.

Bursts with frequency splitting were first observed in large numbers between 24 and 28 MHz on March 17, 1966. Typical examples are shown in Figures 1 and 2 (Plates 1 and 2 respectively). It is seen that in the frequency–time plane they had two similar elements separated in frequency by 0·1–0·2 MHz. The wave frequency generally decreased with time at 0·05–0·2 MHz/sec, and the lower frequency element was usually the weaker of the two.

(*a*) *Occurrence*

From March 1966 to March 1967 the bursts were recorded during most periods of solar radio activity, either in groups of 5–10 or in isolation. In January 1967, for example, they were recorded on the days 4, 5, 6, 7, 10, 15, 26, 27, 30, and 31. The greatest numbers of bursts were recorded on March 17–20, 1966, and on March 9–12, 1967, when the hourly rate reached 200. The March 17–20 bursts were observed when the associated spot group was near the limb of the Sun (Fig. 3). The bursts were frequently observed in groups or chains distributed in the frequency–time plane like a type III burst; that is, a succession of bursts occurred at progressively lower wave frequencies with the frequency–time slope of the whole group in the range 5–10 MHz/sec (Fig. 2, Plate 2). The group was sometimes observed to occur within a type III burst.

The distribution in frequency of the bursts is illustrated in Figure 4. They were observed predominantly in the frequency range 24–40 MHz, the rate of occurrence increasing steadily from 60 to 24 MHz, the lower limit of the observations. None of the bursts was observed above 60 MHz.

(*b*) *Frequency Interval between Elements*

The frequency interval Δf between the elements increased with wave frequency from a mean value of 0·1 MHz at 25 MHz to 1·0 MHz at 60 MHz (see Figs. 5 and 6). There was considerable variation of Δf from minute to minute for bursts occurring near a given wave frequency (Fig. 7), although the mean value of Δf did not vary much during a particular solar event. During a single chain of bursts, the frequency interval between the elements was usually observed to increase monotonically with increasing frequency.

Approximately 10% of the bursts recorded during noise storms had three elements. An example of a triple burst is shown in Figure 1(*a*). In these, the mean frequency interval measured between the centre frequency of the two lowest frequency elements was almost the same as that between the upper two, and the middle element

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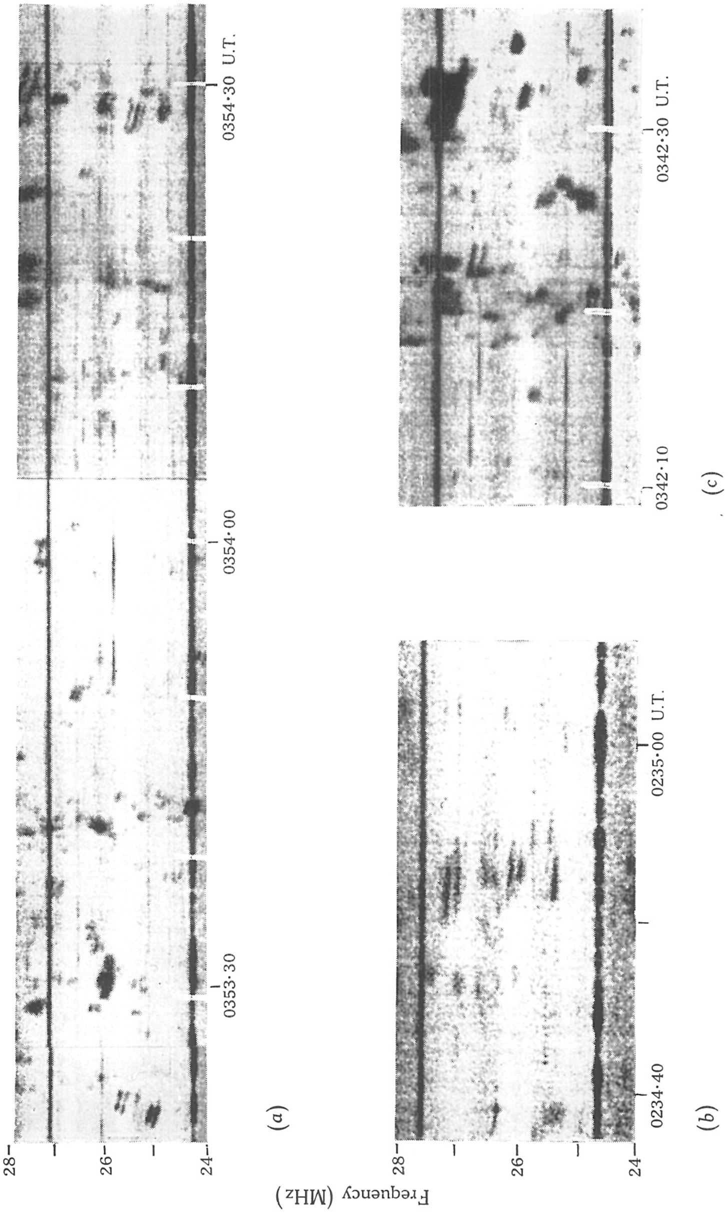

Fig. 1.—Records of chains of bursts observed on March 17, 1966; (*a*) is a typical sequence of bursts showing frequency splitting. Triple splitting is observable on the burst at 0354·28 U.T.

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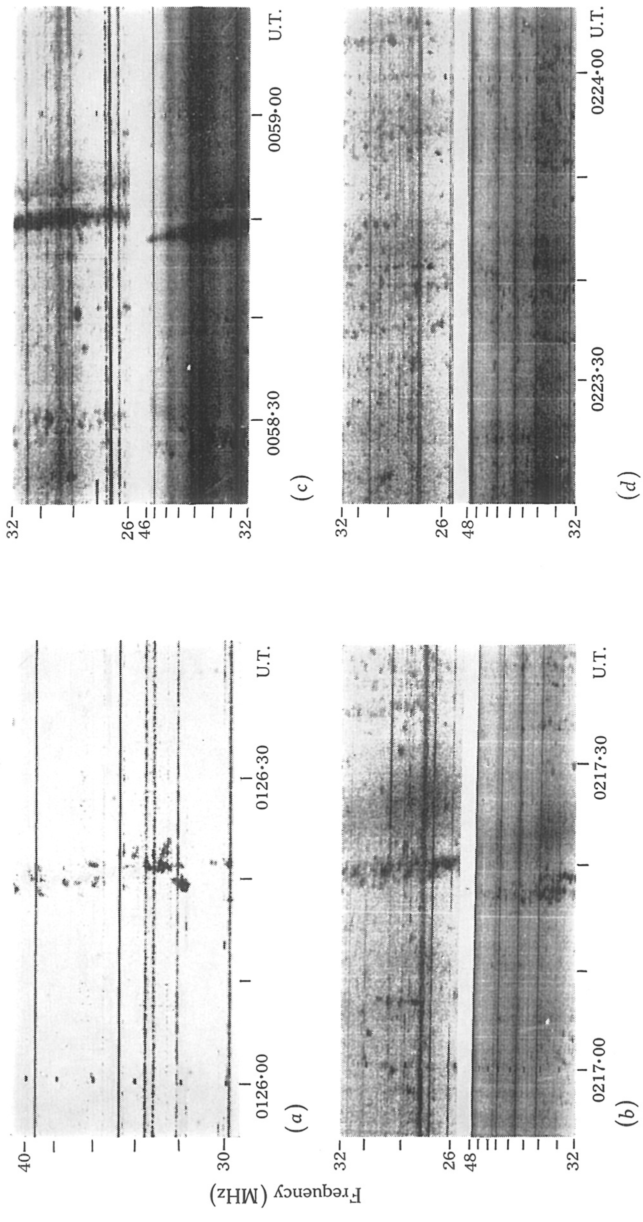

Fig. 2.—Records of chains of bursts observed on (*a*) February 28, 1967, over the frequency range 30–40 MHz; (*b*) March 10, 1967, showing chain with associated diffuse harmonic emission; (*c*) March 10, 1967, showing chain with harmonic trace containing burst pairs (resolved on original film); (*d*) March 10, 1967, showing typical occurrence of bursts during noise storm.

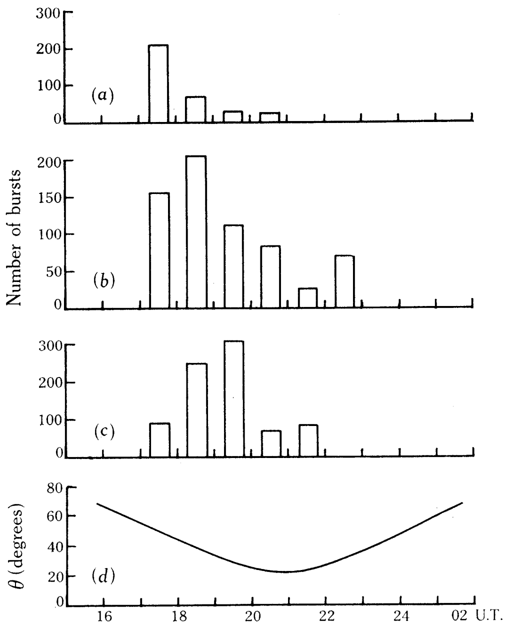

Fig. 3.—Daily occurrence of (*a*) double bursts for the solar event March 17–24, 1966. Also shown for comparison are the occurrence of (*b*) type III bursts and (*c*) drift pairs. The angle between the radius through the associated spot group and the direction of the observer is shown in (*d*).

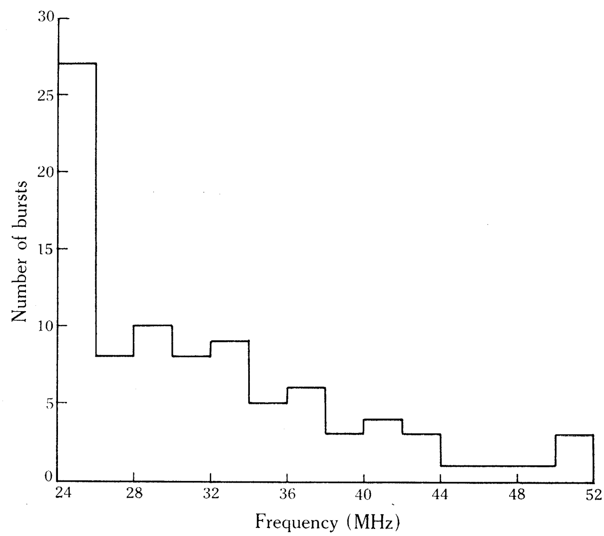

Fig. 4.—Occurrence of bursts on January 30–31, 1967, as a function of wave frequency for a single event.

was usually the strongest. Seventeen such bursts were recorded, for example, between 0230 and 0330 U.T. on March 17, 1966, between 25 and 27 MHz. The mean upper and lower frequency intervals for these bursts were 0·13 and 0·133 MHz respectively. A microphotometer scan of one of these bursts is shown in Figure 8 at 0354·28 U.T. It can be seen that the two lower elements resemble those of a double burst, with the third and highest frequency element appearing as an additional one.

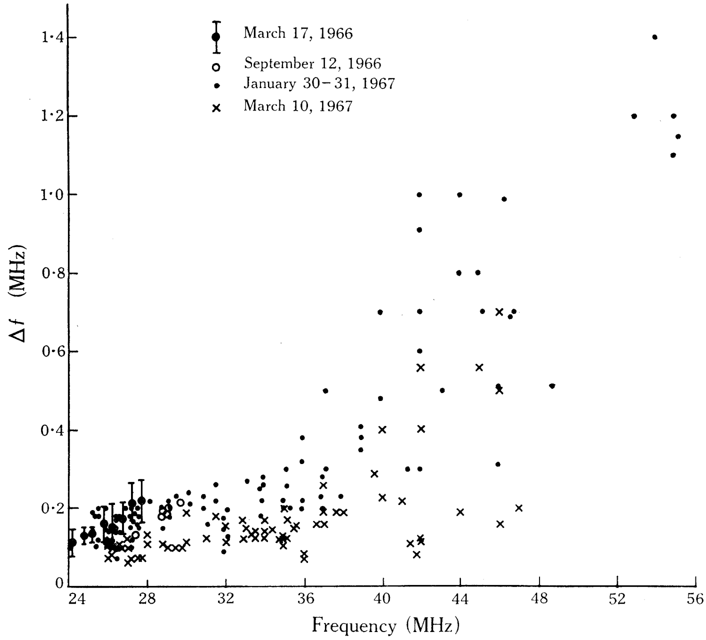

Fig. 5.—Scatter diagram of the variation of the frequency interval between the burst elements with wave frequency for different solar events.

(*c*) *Time Delay between Elements and their Duration*

The two elements did not usually begin at exactly the same time. Figure 9 shows that the lower frequency element began about 0·1 sec before the other, although there was considerable variation in the time interval. The mean duration of the elements was 1·2 sec (Fig. 10).

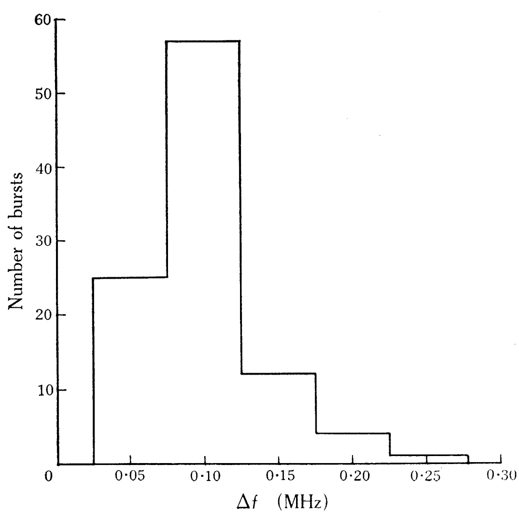

Fig. 6.—Distribution of the frequency interval for bursts on March 17, 1966, with wave frequencies in the range 24–26 MHz.

(d) *Rate of Frequency Drift*

The centre frequency of each element was generally observed to decrease with time at about 0·1 MHz/sec, although zero drift rates occurred (Fig. 11). The mean value of the frequency–time slope was greater for bursts at higher frequencies (Fig. 12), increasing with frequency at about the same rate as the frequency interval between the elements (Fig. 5). However, for bursts occurring in a narrow frequency interval, the slope does not appear to be correlated with Δf (Fig. 13).

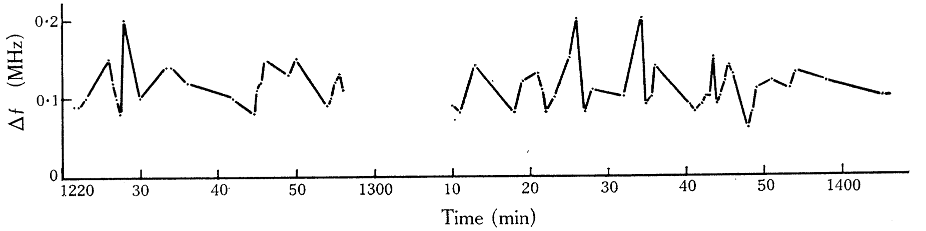

Fig. 7.—Variation in the frequency interval for successive bursts occurring on March 17, 1966, at almost the same wave frequency (25·75–26·25 MHz).

(e) *Bandwidth*

The bandwidth of the lower frequency element of the bursts was usually about 0·05 MHz, that is, slightly greater than the bandwidth of the equipment for the frequency range 24–28 MHz. The bandwidth of the upper frequency element, on the other hand, varied between 0·04 and 0·3 MHz. Figure 14 shows the distribution of bandwidths of the lower frequency elements of bursts occurring near 25 MHz. The

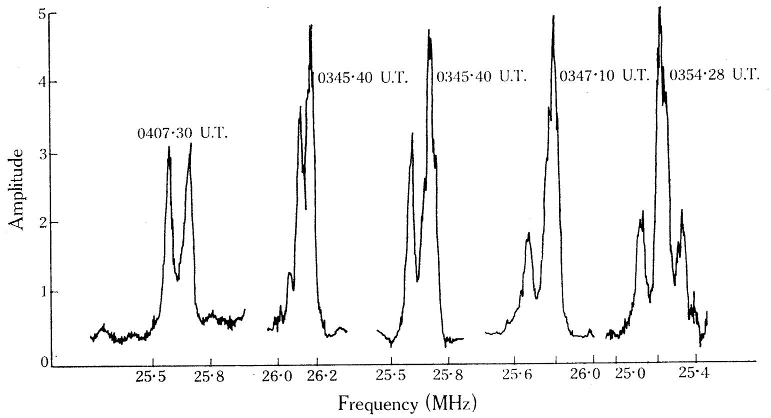

Fig. 8.—Microphotometer scans showing the variation of amplitude with wave frequency for individual bursts on March 17, 1966. The burst at 0407·30 U.T. shows one with equal elements while that at 0354·28 U.T. shows an example of triple frequency splitting.

difference between the element bandwidths is illustrated clearly in the microphotometer tracings of individual bursts shown in Figure 8. The characteristically smaller amplitude of the low frequency element is also shown. Approximately 20% of bursts were observed to have equal amplitudes and bandwidths in each element. An example is shown in Figure 8 at 0407·30 U.T.

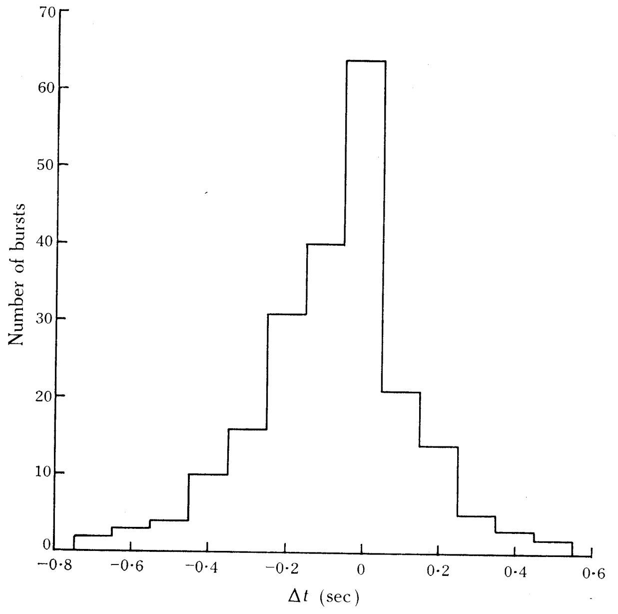

Fig. 9.—Time differences Δt from the beginning of the upper element to the beginning of the lower element for bursts in the frequency range 24–28 MHz recorded on March 17, 1966.

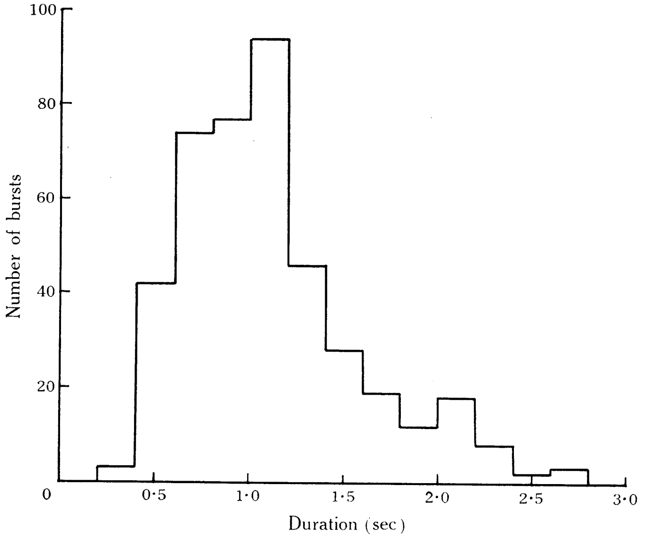

Fig. 10.—Distribution of the durations of elements of bursts in the frequency range 24–28 MHz recorded on March 17, 1966.

(*f*) *Harmonic Properties*

In the present observations, almost all the bursts occurred between 24 and 50 MHz and very few were observed above 48 MHz, where the second harmonic radiation of bursts near 24 MHz might be expected. No clear example of isolated

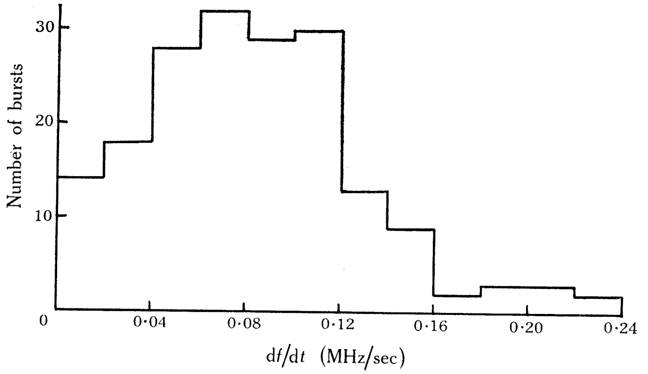

Fig. 11.—Distribution of frequency–time slopes for bursts in the frequency range 24–28 MHz recorded on March 17, 1966.

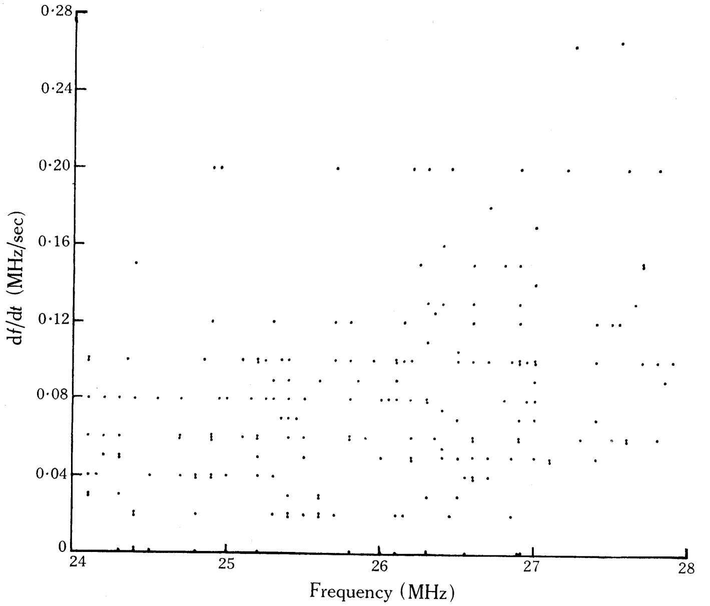

Fig. 12.—Scatter diagram of the variation of frequency–time slopes with frequency for bursts occurring at different frequencies on March 17, 1966.

pairs of double bursts occurring at harmonically related frequencies was found. However, in the frequency range 26–48 MHz, double chains of bursts were observed in which the chains appeared to be harmonically related. The bursts in both chains were double, not triple. An example is shown in Figure 2(*b*), Plate 2. The record was

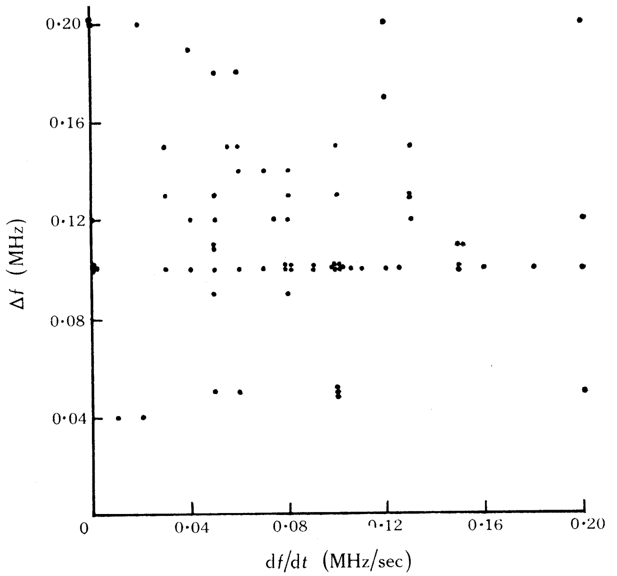

Fig. 13.—Scatter diagram of the variation of the frequency intervals between bursts against their frequency–time slopes for bursts in the frequency range 26–27 MHz recorded on March 17, 1966.

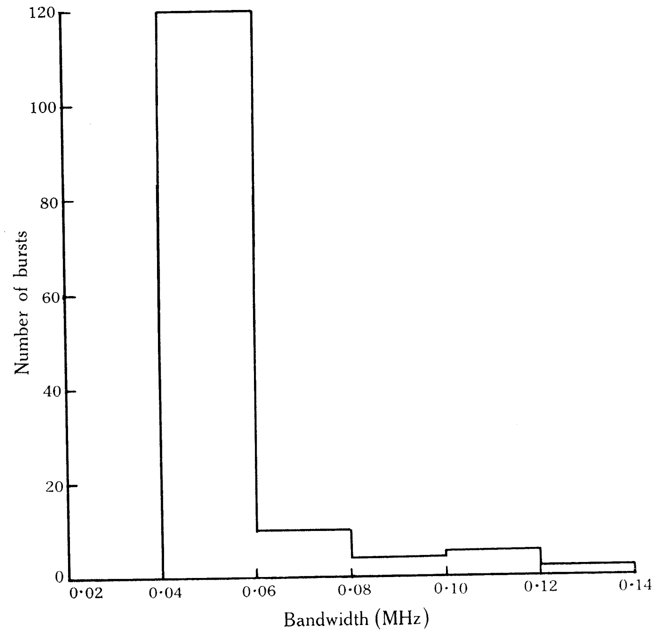

Fig. 14.—Bandwidth of the lower frequency elements for bursts near 25 MHz recorded on March 17, 1966.

made with the frequency range 26–32 MHz displayed above the range 32–48 MHz. Any type III burst or chain of bursts then produced a trace displaced in time between the two sections of the record. Where harmonic emission existed, the trace in the 26–32 MHz section was almost collinear with that due to the harmonic radiation in the 32–48 MHz band, and harmonically related chains could be immediately recognized. About 25% of all chains observed showed harmonic structure.

III. Discussion

(a) *Source of Bursts*

The close resemblance between chains of the double bursts and type III bursts strongly suggests that the electron clouds moving at $0 \cdot 3$–$0 \cdot 5c$ thought to excite type III bursts may also be responsible for the double bursts. The small frequency–time slope of the individual double bursts, on the other hand, points to electron velocity components less than $0 \cdot 05c$ in the direction of the coronal magnetic field, and it would seem that some electrons from the rapidly moving cloud may be scattered by irregularities in the corona, subsequently emitting the radiation observed as double bursts, while moving with large pitch angles. The chain structure also implies that a rapidly moving exciting agency can move out through the corona without radiating continuously and, possibly in the absence of suitable coronal irregularities, without radiating observable electromagnetic radiation at all. The existence of invisible type III sources could then account for the observation of isolated double bursts without nearby bursts in a chain.

(b) *Frequency Splitting*

The similarity between the elements of the bursts and their almost simultaneous occurrence suggests that the radiation is produced in a common source emitting at two, and sometimes three, different frequencies. It seems reasonable to assume that these frequencies are associated with resonance conditions in either the coronal plasma or electron streams travelling through it. As discussed by Tidman, Birmingham, and Stainier (1966), several plasma resonances may be expected in the presence of a weak magnetic field. In general, these are in the vicinity of the ion plasma and cyclotron frequencies Π_{i} and Ω_{i}, and the electron plasma and cyclotron frequencies Π and Ω. Electromagnetic resonances of interest here occur at the positive frequency roots of

$$\omega^2 \mp \omega\Omega - \Pi^2 = 0\,,$$

that is, in the vicinity of the electron plasma frequency, for weak magnetic fields, and also at the Doppler-shifted cyclotron frequencies

$$\omega = s\gamma\Omega/(1-\beta_{\parallel}\,\eta\cos\theta), \qquad \omega = s\gamma\Omega_{\mathrm{i}}/(1-\beta_{\parallel}\,\eta\cos\theta),$$

where $\gamma = (1-\beta^2)^{\frac{1}{2}}$, s is the harmonic number, η is the refractive index, θ is the wave-normal angle, $\beta = v/c$, and $\beta_{\parallel}$ is the component of β in the direction of the field.

Electrostatic resonances exist at the electron plasma frequency Π, and at the hybrid resonance frequencies

$$(\Pi^2+\Omega^2)^{\frac{1}{2}} \qquad \text{and} \qquad \Pi\Omega(\Pi^2+\Omega^2)^{-\frac{1}{2}}M^{-\frac{1}{2}},$$

where M is the ratio of ion to electron mass. Transformation of plasma waves with these frequencies into electromagnetic waves may occur in the solar corona by Rayleigh scattering on irregularities or by combination scattering between the plasma waves. In the latter case, electromagnetic waves may be produced with intensity maxima at these frequencies, at the combination frequency

$$(\Pi^2+\Omega^2)^{\frac{1}{2}}+\Pi\Omega(\Pi^2+\Omega^2)^{-\frac{1}{2}}M^{-\frac{1}{2}},$$

and at the harmonic frequencies $2(\Pi^2+\Omega^2)^{\frac{1}{2}}$ and 2Π. A full discussion of the possible combination frequencies is given by Tidman, Birmingham, and Stainier (1966).

(i) *Electromagnetic Resonances*

Although the observations of triple frequency splitting in some bursts would appear to point to radiation at the electromagnetic resonances $\omega = \Pi$ and $\omega \simeq \Pi \mp \frac{1}{2}\Omega$, only the two higher frequency components would be able to escape unless some radiation were emitted also at the harmonic frequencies $\omega = 2\Pi$ and $2\Pi \mp \Omega$; that is, it would be expected that a triple burst would be associated with a double burst near the plasma frequency. The two elements near the plasma frequency would with this mechanism be expected to have opposite polarization.

No triple bursts were observed in chains that showed harmonic structure. In addition, some triple bursts were recorded together with double bursts in chains that did not show harmonic structure. That is, the triple bursts occurred in circumstances that did not suggest the presence of harmonic radiation.

Doppler cyclotron radiation.—Fung (1966) has shown that a helical electron stream moving through the coronal plasma can radiate coherent cyclotron radiation that appears likely to be most easily observable when emitted in the ordinary mode at frequencies near the second harmonic of the local cyclotron frequency. If the stream is moving radially with respect to the Sun and at a large angle to the direction of the observer, then it is possible for the radiation to travel along two ray paths to the observer, one direct and one that is reflected at a level in the corona lower than the point of emission. Through the Doppler effect, the radiation travelling along the former ray path will be at a higher wave frequency than that travelling along the latter path; i.e. a double burst would be observed with the lower frequency element delayed slightly by the reflection compared with the higher frequency element. The two elements would have the same polarization.

The Doppler equation shows that when the frequency interval between the elements is small ($\Delta f \ll f$) it should increase almost linearly with the longitudinal particle speed, which, in the present observations, might reasonably be taken to be indicated by the frequency–time slope of the elements. However, examination of the data shows that, although the f–t slope increases with frequency interval over a range of wave frequencies, it appears to be independent of the frequency interval for bursts occurring near the same wave frequency (Fig. 13).

(ii) *Electrostatic Resonances* (*Plasma Radiation*)

Types II and III solar bursts have long been believed to originate in plasma radiation excited by moving sources in the corona. The theory of this process was generalized to include the effects of a local magnetic field by Sturrock (1961), who showed that radiation would be emitted near the plasma frequency Π and near the hybrid resonance frequency $\omega = (\Pi^2+\Omega^2)^{\frac{1}{2}}$. It was further developed by Tidman, Birmingham, and Stainier (1966), who investigated the expected intensities in the different spectral lines.

An important feature of the theory of plasma radiation is its prediction of second harmonic emission, and the observation of bursts with similar spectral features at two frequencies nearly harmonically related is usually taken as evidence of plasma radiation. Type II and type III bursts, and type II bursts with frequency splitting, all have this property.

The observation of double bursts associated with, and sometimes within, type III bursts hence implies that the frequency of the double bursts is close to that of the type III at the same instant, i.e. near the plasma frequency. In addition, the existence of bursts showing frequency splitting both in the fundamental and harmonic chains may be taken as circumstantial evidence for the plasma radiation process in the absence of the identification of harmonics of the individual bursts, while the distribution of the frequency interval with frequency in the range 38–48 MHz (Fig. 5) also suggests the occurrence of fundamental and harmonic bursts.

With this mechanism, the two elements of the bursts may be identified with radiation near the plasma frequency Π and the upper hybrid frequency $(\Pi^2+\Omega^2)^{\frac{1}{2}}$. Self-absorption in the plasma for wave frequencies near Π would account for the generally smaller intensity of the lower frequency element and its narrower bandwidth. It should be noted that the actual plasma frequency in the vicinity of the source would then be expected to be somewhat less than the centre frequency of the lower element.

The three elements of the occasional triple bursts may be identified with the resonance and combination frequencies

$$\Pi, \qquad (\Pi^2+\Omega^2)^{\frac{1}{2}} \qquad \text{and} \quad \Pi\Omega(\Pi^2+\Omega^2)^{-\frac{1}{2}}M^{-\frac{1}{2}}+(\Pi^2+\Omega^2)^{\frac{1}{2}}.$$

For weak magnetic fields, these become

$$\omega_1 = \Pi, \qquad \omega_2 = \Pi+\tfrac{1}{2}\Omega^2/\Pi \qquad \text{and} \qquad \omega_3 = \Pi+\tfrac{1}{2}\Omega^2/\Pi+\Omega M^{-\frac{1}{2}}.$$

If the plasma frequency is taken to be approximately given by the wave frequency of the bursts, then either of the upper or lower frequency intervals of triple bursts or the frequency interval of double bursts is a measure of the cyclotron frequency in the region of emission. In addition, the two frequency intervals of the triple bursts shall be functionally related according to

$$\omega_2-\omega_1 = \tfrac{1}{2}M(\omega_3-\omega_2)^2/\Pi.$$

With a plasma frequency of 26 MHz, for example, and an upper frequency interval of $0\cdot1$ MHz, the lower frequency interval is $0\cdot35$ MHz.

Although the actual mean frequency intervals for bursts near 26 MHz observed on March 17, 1966, were 0·13 and 0·133 MHz respectively, it is likely that an unknown part of the lowest frequency element is suppressed through self-absorption at and immediately below the plasma frequency. The relative magnitudes of the two frequency intervals as measured between the centres of the triple-burst elements do not therefore provide a direct test of the plasma radiation theory, although the existence of double and triple bursts is consistent with the theory. The coronal magnetic field intensities required to account for the splitting vary from 2 gauss at the 25 MHz plasma level to 10 gauss at the 60 MHz level.

IV. Acknowledgments

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V. References

Elgaroy, O. (1961).—*Astrophys. norv.* **7**, 123.
Ellis, G. R. A. (1967).—*Nature, Lond.* **213**, 790.
Ellis, G. R. A., and McCulloch, P. M. (1966).—*Nature, Lond.* **211**, 1070.
Fung, P. C. W. (1966).—*Aust. J. Phys.* **19**, 489.
Roberts, J. A. (1959).—*Aust. J. Phys.* **12**, 327.
Sturrock, P. A. (1961).—*Nature, Lond.* **192**, 58.
Tidman, D. A., Birmingham, T. J., and Stainier, H. M. (1966).—*Astrophys. J.* **146**, 207.
Wild, J. P. (1950).—*Aust. J. scient. Res.* A **3**, 399.
Wild, J. P., Murray, J. D., and Rowen, W. C. (1954).—*Aust. J. Phys.* **7**, 439.