SOLAR RADIO BURSTS OF SPECTRAL TYPE II

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Contents

Summary

The characteristics of bursts of spectral type II are studied in a sample of 65 bursts. Approximately half the bursts show harmonic structure and about half are compound type III–type II events. Band splitting, the doubling of both the fundamental and second harmonic bands, is also relatively common. A rather less common feature is the appearance of herring-bone structure in which the slowly drifting band of the type II burst appears to be a source from which rapidly drifting elements diverge towards lower and higher frequencies.

Statistics are given of the rate of occurrence of the bursts, their frequency range, the rate of frequency drift, and the harmonic ratio.

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Many of the type II bursts occurred near or after the maximum of a chromospheric flare. However, only about 3 per cent. of flares (of Class 1 or greater) are accompanied by type II bursts, although the figure rises to 30 per cent. for Class 3 flares.

There is a greater tendency for the geomagnetic field to be disturbed in the few days following a type II burst than there is after large flares which are not accompanied by type II bursts, or after large radio bursts of spectral type III. Statistically the greatest disturbance occurs after about two days, implying a mean speed of travel of about 1000 km/sec.

I. Introduction

One of the challenging discoveries made by the early investigators of solar radio emission was the existence of a class of intense metre-wavelength " burst " in which the emission appeared first at the higher frequencies (several hundred megacycles per second) and in the following minutes drifted slowly downward in frequency to perhaps 10 Mc/s. These bursts were first recognized from records made simultaneously at a number of discrete frequencies (Payne-Scott, Yabsley, and Bolton 1947), and were later studied with a dynamic spectrum analyser (Wild and McCready 1950; Wild 1950). Wild and McCready introduced the designation *spectral type II* for the bursts. They gave as the defining characteristic the drift of spectral features, with time, from high to low frequencies at a rate of the order of $\frac{1}{4}$ Mc/s per sec.

The observations made over the past five years with the Dapto radio-spectrograph have fully confirmed the existence of a distinct class of solar burst conforming with this definition. A total of 65 such bursts were recorded in the period from September 1952 to March 1958, and the present paper presents an analysis of these events. While many of the properties of the bursts have already been described in the literature, there is at present no comprehensive review of a large sample of bursts. This paper is an attempt to meet this need.

The main features of the bursts are described in Section II and are illustrated by a selection of records reproduced in the plates. The frequency range and the rate of frequency drift are discussed in Sections III and IV, while the following four sections deal with features which appear prominently in many of the bursts but are not universal characteristics of the type. The majority of these features have already been described in publications by Wild and his collaborators, but the " herring-bone structure " (Section VII) has not been described previously.* In this variation of the type II burst the characteristic slowly drifting band appears to be a source from which rapidly drifting, short-duration bursts emerge. In some cases the rapidly drifting elements have both positive and negative slopes, so that in the frequency-time plane the burst has the appearance of a herring-bone.

In two further sections of the paper statistics are given of the association of type II bursts with solar flares (Section IX) and with geomagnetic storms (Section X).

Although the paper is primarily intended as a summary of the observational material, some discussion of the results is given. In this, the plasma hypothesis

* A brief account of the " herring-bone structure " was presented by the author at the I.A.U.-U.R.S.I. Radio Astronomy Symposium at Paris in August 1958.

is adopted, i.e. it is assumed that the bursts represent radiation from oscillations induced in the coronal plasma by the outward passage of a disturbance. This theory suffers from severe difficulties as regards the coupling of the oscillations to the radiation field, but it appears to be the most hopeful of the theories proposed to date. (See e.g. Wild, Murray, and Rowe 1954; Ginzburg and Zheleznyakov 1958, 1959; Wild, Sheridan, and Trent 1959.)

II. Bursts of Spectral Type II

(a) *Equipment*

The observations reported in this paper were made with the Dapto radio-spectrograph, which has been briefly described by Wild, Murray, and Rowe (1954). In this instrument the receiver sweeps through the frequency range of 40–240 Mc/s every half second,* and the output is used to intensity modulate the spot of a cathode-ray tube. The spot is deflected in synchronism with the sweeping of the receiver frequency so that when it is photographed on film moving slowly and continuously at right angles to the deflection, a complete dynamic spectrum is built up on the film in a manner similar to the formation of a television image. Examples of records of type II bursts made with this equipment will be found in Plates 1–5.

At the lower frequencies the weakest signals that can be clearly detected with the equipment have flux densities of about† 5×10^{-21} W m^{-2} (c/s)$^{-1}$, and with the normal adjustment of the equipment flux densities up to about 5×10^{-19} W m^{-2} (c/s)$^{-1}$ can be comfortably accommodated on the film. At higher intensities saturation in both the receiver and the film can lead to loss of detail. At the higher frequencies the sensitivity decreases by a factor of up to 5 times.

Arrangements are also available for determining the polarization of the incoming radiation over the whole range of frequencies (Komesaroff 1958).

(b) *Spectral Characteristics of Type II Bursts*

The records reproduced in Plates 1–5 have been chosen to illustrate the chief characteristics of the 65 bursts which have been classified as spectral type II. The common feature in these bursts is the drift of some of the main spectral features from high to low frequencies at rates of up to 1 Mc/s per sec. The total duration of the bursts is of the order of minutes. This definition of the type is sufficiently wide to embrace all the 65 bursts and at the same time is sufficiently narrow to exclude the majority of other bursts on the records.

Although all the bursts have these features in common, it is seen that they differ widely amongst themselves and that some exhibit other outstanding characteristics. We may list seven notable features which are present in some, but not all, bursts of this class.

(i) *Narrow Bandwidth.*—In the majority of the bursts the drifting bands are remarkably narrow, the bandwidths being as low as a few megacycles per second. The theoretical implications of this observation have been emphasized

* Since September 1957 the upper limit of the range has been 200 Mc/s.

† Flux densities are specified for one plane of polarization.

by Wild, Murray, and Rowe (1954). While narrow bandwidths are common, they do not occur invariably, as is illustrated by the burst of February 14, 1956 (Plate 2).

(ii) *Harmonic Structure*.—In approximately 60 per cent. of the bursts the drifting bands appear in harmonic pairs. This feature, described by Wild, Murray, and Rowe (1954), is evident in all the examples in Plates 1, 3, and 4. It is discussed in detail in Section V.

(iii) *Band Splitting*.—Many of the bursts show a secondary doubling of the bands, which is illustrated by the examples in Plate 4. In these events both the fundamental and the second harmonic bands are split into a pair of ridges with a separation which is usually small compared with that between the two harmonics. This phenomenon was described in the original paper by Wild (1950). Some statistics and a theoretical discussion are given in Section VI.

(iv) *Multiple Bands*.—In some of the bursts there are several " independent " drifting bands which are neither harmonically related nor caused by band splitting. They are presumably generated by separate disturbances travelling through the corona. Although these bands are not harmonically related, each may be accompanied by a second harmonic, as in the events of January 19, 1956 (Plate 3) and January 15, 1958 (Plate 2). Furthermore, each of the fundamental and second harmonic bands may themselves be split as in the event of August 6, 1957 shown in Plates 1 and 4. The resulting band structure is quite complex. Other bursts with large numbers of drifting bands have been observed, but it has not been possible to analyse them in this way. Some of these bursts begin suddenly over a wide range of frequencies.

(v) *Compound Type III–Type II Bursts*.—Another characteristic common to approximately half the bursts is the appearance of a group of type III bursts preceding the type II burst by some minutes (Plate 1). Section VIII contains a more detailed description of this phenomenon, which was first described by Wild, Roberts, and Murray (1954).

(vi) *Herring-bone Structure*.—A somewhat less common feature is the appearance of the herring-bone structure mentioned in the introduction. Plate 5 contains examples of this structure, which is discussed in Section VII.

(vii) *Other Fine Structure*.—Besides the herring-bone structure various other forms of fine structure are seen in the bursts. The drifting bands are rarely smooth and continuous but fluctuate in intensity over periods of seconds. In some cases the bands consist of a series of short-duration, narrow-band bursts which themselves show the type II frequency drift. Examples are seen in Plate 3 in the events of November 15, 1955 and January 19, 1956. On other occasions some or all of the " sub-bursts " forming the bands are much more amorphous and resemble the narrow-band type I bursts.

For examples see the events of November 13, 1957 and August 6, 1957 illustrated in Plate 4. Fine structure of the type described by Haddock (1958), in which the sub-bursts resemble type III bursts of short duration, is of course present in the bursts with herring-bone structure, but otherwise was not a noticeable feature in the bursts.

(*c*) *Occurrence*

Type II bursts are rare by comparison with types I and III. Figure 1 shows that even near sunspot maximum such bursts occur only about once in 50 hr on the average, whereas at this time the average rate of occurrence of type I and type III bursts is probably one every few minutes. The figure indicates a marked increase in occurrence towards sunspot maximum, but many more observations are needed to delineate the details of the solar cycle variation.

On a shorter time scale the bursts are not randomly distributed in time either. On three occasions two type II bursts have been recorded within a few hours of one another, and many of the other bursts occur on days grouped closely together. Furthermore, there are several examples of events which

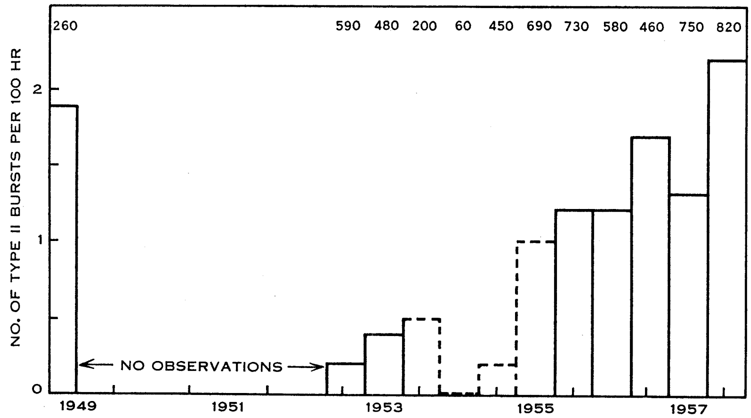

Fig. 1.—Showing the frequency of occurrence of type II bursts. The numbers at the top of the figure show the number of hours of observation in each 6-monthly period. The observations in 1949 are those made by Wild and McCready (1950) with the original solar radio-spectrograph (70–130 Mc/s). During the period near sunspot minimum (1954), where the histogram is shown dashed, the observing time was confined entirely to occasions when sunspots were visible on the disk.

really consist of two type II bursts separated by only a few minutes in time. Some of these are compound bursts in which the double type II burst is preceded by two groups of type III bursts with a similar time separation. In Plate 1 the earlier event on August 6 is of this nature.

From this clustering of type II bursts it is inferred that some active regions on the Sun produce many type II bursts, while others do not produce any. The correlations with solar flares discussed in Section IX are fully in accord with this deduction.

(*d*) *Intensity and Polarization*

The peak intensities of type II bursts range from the limit of detection up to several times 10^{-18} W m^{-2} (c/s)$^{-1}$. Intensities in excess of 10^{-19} W m^{-2} (c/s)$^{-1}$ are not uncommon. These high intensities, together with the durations of minutes or tens of minutes, led Wild (1950) to identify type II bursts as the "outbursts" recorded on single-frequency equipments. However, it is now recognized that many of these outbursts are large groups of intense type III bursts. Such events are more common than strong type II bursts and often have very great intensities. In some compound type III–type II events the energy in the type III part outweighs that in the type II burst (e.g. the events of August 6, 1957 illustrated in Plate 1).

Evidence on the polarization of type II bursts is very incomplete. However, there are sufficient measurements available to show that these bursts are usually not strongly polarized (Komesaroff 1958). More recent measurements have confirmed Komesaroff's finding and have further shown that even split-band type II bursts are not strongly polarized.

III. The Frequency Range of Type II Bursts

In the course of a type II burst the frequency of emission may drift over hundreds of megacycles per second, but in no recorded case does the *fundamental* band extend over the whole frequency range of the equipment. Typically, the burst begins suddenly with the fundamental and second harmonic beginning nearly simultaneously (Plates 1, 3, and 4). At this onset the frequency of the fundamental is commonly below 80 Mc/s and no case is known in which the fundamental band extends above 120 Mc/s (Fig. 2). In a number of the more intense bursts the fundamental band continues to the lower limit of the observed

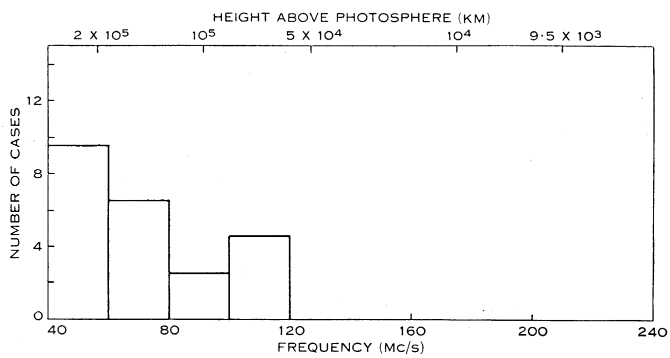

Fig. 2.—Histogram showing the distribution of the starting frequency of the fundamental band of 23 harmonic type II bursts. The height scale is derived on the assumption of emission at the plasma frequency in a Baumbach-Allen model corona.

range at 40 Mc/s and occasionally the second harmonic also extends to this limit. In other cases, however, both the fundamental and second harmonic bands stop suddenly and almost simultaneously before reaching 40 Mc/s (Plates 3 and 4). In a few such cases the emission begins again at a later time, and in the frequency-time plane the later emission lies along an extension of the earlier ridge-line (Plate 2, event of December 6, 1957). It is as if the burst consisted of a pair of continuous harmonic ridges, but for part of the time the emission ceased.

In seeking an explanation of these sudden changes, one first notices that, because the effects occur nearly simultaneously in the fundamental and second harmonic bands, they cannot be caused by changes in the propagation conditions in the Sun or in the ionosphere. The refractive index of an ionized medium is so strongly dependent on the frequency (f^{-2}) that the fundamental and second harmonic bands would be affected quite differently. To explain the phenomenon on the plasma theory it seems necessary to suppose that some critical condition must be satisfied before the travelling disturbances will excite the corona to radiate. With such an assumption it is possible to account for the sudden onset of the type II bursts and also for the occurrence of several sections of a ridge with the intervening parts missing.

Whatever this unknown condition for emission may be, it is evidently rarely satisfied in the lower corona (below the 100 Mc/s plasma level). This is inferred from the observation that the fundamental band rarely extends into this range, although the evidence of the compound bursts (Section VIII) strongly suggests that the exciting disturbances travel outward through this region.

IV. The Rates of Frequency Drift and the Inferred Speeds

Figure 3 (a) shows the rate of frequency drift in type II bursts as a function of the frequency. These measurements relate to 24 bursts with clear harmonic structure and apply to the fundamental band. Where the rate of drift was measured at a number of frequencies in the one burst the measured values are joined by a line : where the drift was measured at only one frequency the value is shown by a cross. The mean drift rate is seen to increase from 0·04 Mc/s per sec at 30 Mc/s to 0·35 Mc/s per sec at 90 Mc/s. The spread of the observed values also increases with the frequency, but the spread of values expressed as a percentage of the mean is fairly constant.

According to the plasma hypothesis, when the height distribution of electron density in the corona is known the observed drift rates can be converted to equivalent radial components of speed. The actual distribution of electron density at the time and place of a burst is not known, and it is customary to use the densities given by one of the coronal models based on averaged eclipse observations. Such a procedure will not yield reliable results, since the coronal density varies with time, particularly above sunspots. Indeed, Wild, Sheridan, and Trent (1959) have recently measured the direction of arrival of the different frequencies in type II bursts and have shown that, while the results qualitatively support the plasma hypothesis, they require the scale of the corona to be several times greater than in the conventional models. However, in the absence of detailed knowledge of the electron densities in the corona, it appears worth while to discuss the drift rates in terms of an averaged model, whilst bearing in mind that the results may be correct to order of magnitude only. The speeds so obtained are likely to be low, perhaps by a factor of three.

With these considerations in mind, we proceed to a discussion of the drift rates in Figure 3 (a), adopting the Baumbach-Allen model corona (Allen 1947). The broken curves in Figure 3 (a) show the drift rates expected in such a corona for disturbances with radial speeds of 300, 500, 700, and 1000 km/sec. It is seen that these curves embrace the observed values fairly well ; below 60 Mc/s the curve for 500 km/sec is almost the line of medians. For five of these bursts actual height-time plots based on the same model are given in Figure 4. As was

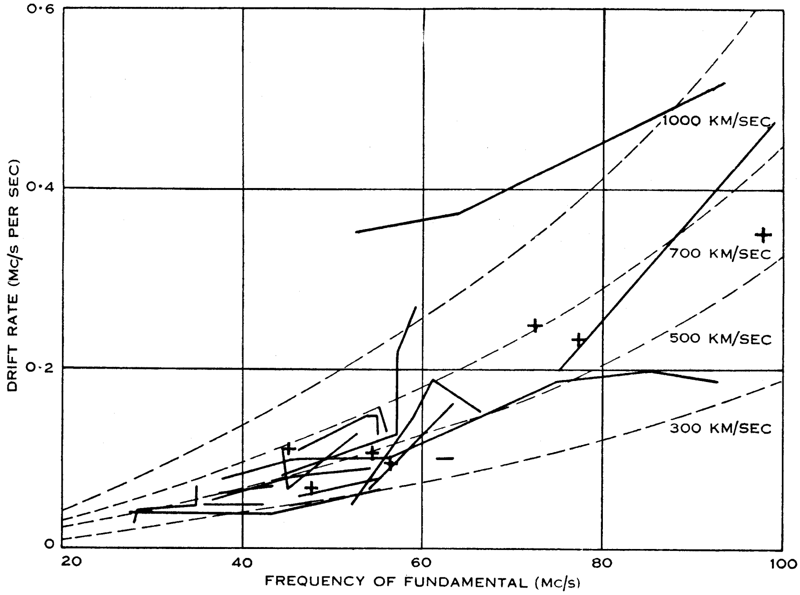

Fig. 3 (*a*).—Showing the frequency dependence of the drift rate in the fundamental band of 24 harmonic type II bursts. Where the frequency drift was measured at a number of frequencies in the one burst the measured values are joined by a line: where the drift was measured at only one frequency the value is shown by a cross. The dashed curves show the drift rates expected for disturbances moving through a Baumbach-Allen model corona at constant radial speeds of 300, 500, 700, and 1000 km/sec.

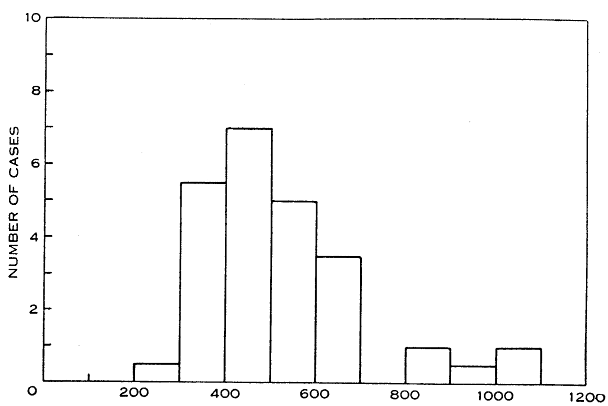

Fig. 3 (*b*).—Histogram of the derived mean radial speeds of the 24 harmonic type II bursts included in Figure 3 (*a*). Baumbach-Allen model corona.

suggested by the comparisons in Figure 3 (*a*), many of these graphs are essentially straight lines. This somewhat surprising result perhaps indicates that the actual density distribution along the trajectory of the disturbance differs from the model mainly by a change in the height scale.

In passing, it may be noted that a gravitational deceleration would not be expected to be detectable except when the true radial speed was below about 350 km/sec.

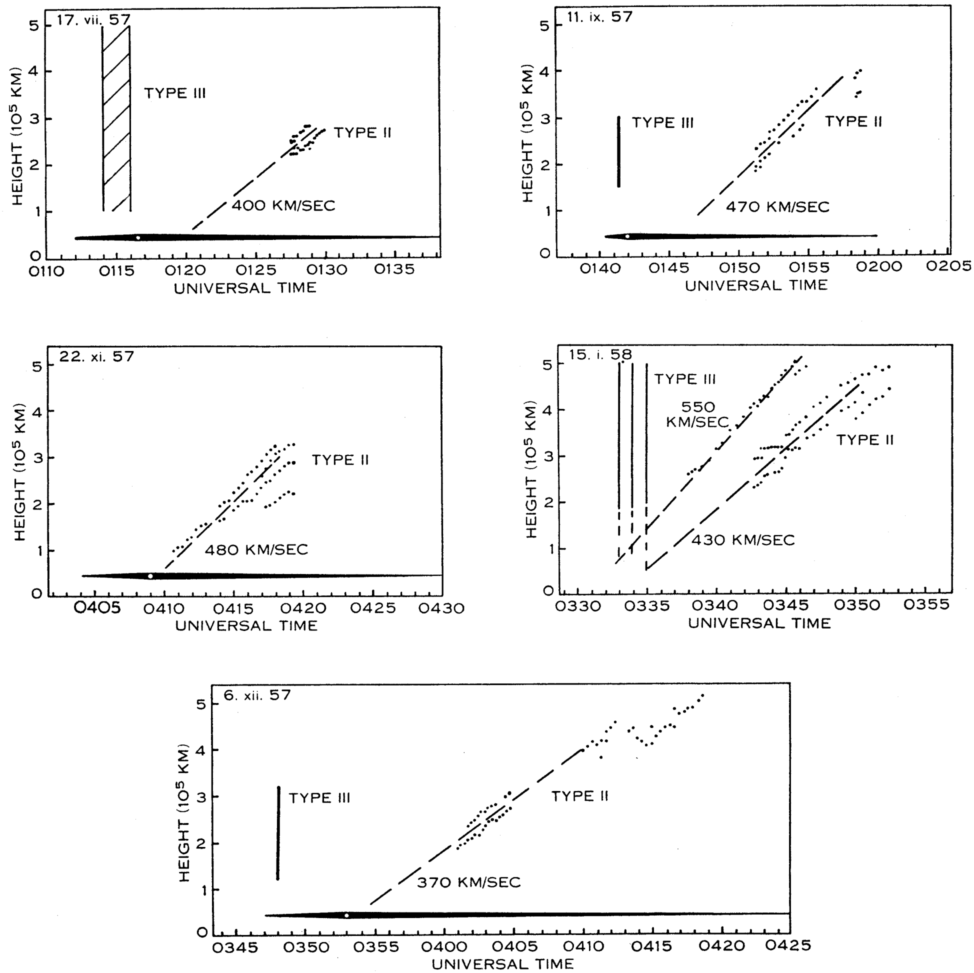

Fig. 4.—Derived height-time plots for five harmonic type II bursts. Reproduction of the spectral records of three of these bursts will be found in Plates 1 and 2. The graphs assume that emission occurs at the fundamental and second harmonic of the local plasma frequency in a Baumbach-Allen model corona. For the events of July 17, 1957 measurements were made on the fundamental band: in all other cases on the second harmonic. Where two nearly parallel series of points appear in these graphs they refer to a split band (Section VI). Preceding type III bursts are shown on the figures and known flares (beginning, maximum, and end) are indicated by the heavy tapered lines at the bottom of the graphs.

Because the height-time plots are essentially straight lines, a single speed can be assigned to each burst ; a histogram of these " radial velocities " is given in Figure 3 (*b*). The mean and median are both close to 500 km/sec, there are few values below 300 km/sec, but there appears to be a long tail on the high velocity side extending beyond 1000 km/sec. Of course, at this stage it is not clear whether the histogram really shows the distribution of radial speeds of the type II disturbances or whether it merely reflects changes in the electron density distribution in the corona. However, since the true velocities are almost certainly greater than those given in this figure, it is apparent that the disturbances travel at speeds well in excess of the speed of sound in the corona, which is $\sim$170 km/sec. Whatever the nature of the disturbances, therefore, it is probable that the shock fronts accompanying them are the agencies which excite the oscillations in the corona.

Before concluding this section, mention should be made of one case (April 5, 1957, 0004–0013 U.T.) in which the frequency drift was at first in the usual sense of decreasing frequency but then reversed and continued for some minutes in the positive sense, with an *absolute* value quite typical of type II bursts. This event is thus analogous with the type III U bursts (Haddock 1958 ; Maxwell and Swarup 1958), and is most simply explained by supposing that the type II disturbance reached a maximum height and then fell back towards the Sun. Suggestions of a similar behaviour can be seen in one or two other events.

V. Harmonic Structure

An outstanding feature of the stronger type II bursts is the appearance of fundamental and second harmonic bands. This harmonic structure is clearly visible in 60 per cent. of the bursts recorded and in an even higher percentage of those bursts which are of at least moderate intensity and consist of well-defined ridges. All the examples of type II bursts in Plates 1, 3, and 4 have harmonic bands, and the structure can also be seen in many of the examples in the other plates. The correspondence in detail between the two bands is quite remarkable and leaves no doubt that both are generated in the same process. As the measured ratio of the frequencies of the two maxima always lies close to 2 (Fig. 5), it is clear that the two bands are harmonics radiated from a common oscillating source.

(*a*) *Relative Intensities*

The intensities of the two harmonic bands are usually quite similar. However, there are cases in which one or the other harmonic is the more intense. If the harmonics were generated by a non-linear oscillation one would expect the relative intensities of the harmonics to depend on the intensity of the event, the second harmonic being relatively stronger in the stronger events. The evidence does not support this prediction ; there are a number of examples of quite weak bursts in which the second harmonic is somewhat stronger than the fundamental.

(*b*) *Harmonics Higher than the Second*

No examples of first, second, and third harmonics are known. For 11 of the 35 harmonic bursts in this analysis a third harmonic would have been detected if its intensity had been as great as that of the second harmonic, and for 4 of these cases it would still have been detected at $\frac{1}{5}$ of the second harmonic intensity. Since in 9 of the 11 cases, including all of the 4 cases mentioned, the intensity of the second harmonic was similar to that of the fundamental, we conclude that the intensities of the first two harmonics are often similar, but that the third harmonic is considerably less intense.

For most non-linear oscillations, including plasma oscillations (Smerd 1955), the ratio of the energy in the third harmonic to that in the second is similar to the ratio of the energy in the second harmonic to that in the fundamental. It would seem, therefore, that the observed intensity ratios could be explained most directly by supposing that the oscillations are not sufficiently

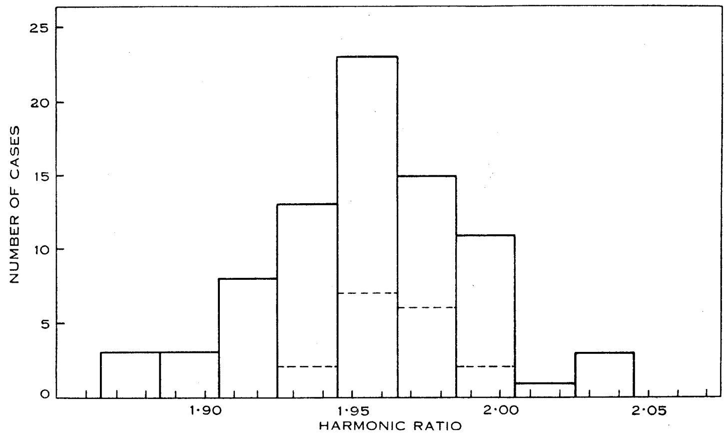

Fig. 5.—Histogram of the harmonic ratio measured as the ratio of the frequencies of maximum intensity in discrete narrow-band features. Data for 19 bursts. The histogram shown in full lines includes all measurements with equal weight: for the dashed curve the mean ratio in each burst has been used, and each burst has been given unit weight.

non-linear to radiate appreciable third harmonic, and that the radiation efficiency in the fundamental mode is considerably less than that in the second harmonic. It is interesting to note that the model suggested by Wild, Murray, and Rowe (1954) achieved this effect by inhibiting the escape of much of the fundamental band. While the evidence presented below (Section V (*d*)) suggests that this model is not correct in detail, some similar phenomenon may explain the observed intensity ratios.

Although no examples of first, second, and third harmonics are known, there is one case in which it is possible that the second, third, and fourth harmonics have been observed: the corresponding fundamental band would have been below the frequency limit of the equipment. Part of the record of the dynamic spectrum of this burst is reproduced in Plate 3 (event of April 25, 1956) and graphs of the ridge-lines in the intensity-time plane are given in Figure 6. The graphs are designed to test the idea that the three bands are in the frequency ratio 2 : 3 : 4. The bands are shown at the observed frequencies by full lines, and the high frequency band is replotted at half the frequency (dashed lines) and at three-quarters of the frequency (dash-dot lines). There is seen to be a close correspondence between the observed and replotted bands, indicating that the frequencies of the bands are closely in the ratio of 2 : 3 : 4 throughout their duration.

On the basis of this evidence it would seem likely that these bands are the second, third, and fourth harmonics of a fundamental band lying below 40 Mc/s. It is only the absence of a third harmonic in many other bursts of similar or greater intensity that suggests that there may be another explanation of this structure. One possibility is that the upper two bands are the two parts of a split second-harmonic band (Section VI) and that the 3 : 4 ratio is fortuitous. However, the frequency separation of these bands ($\sim$25 Mc/s) is greater than usual in split bands.

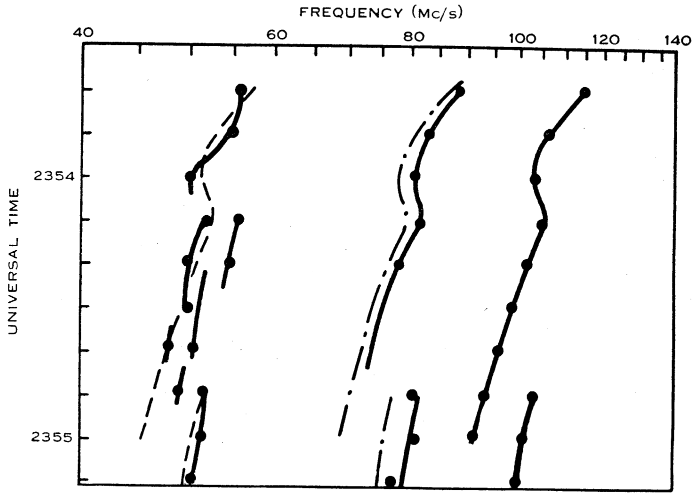

Fig. 6.—The full curves show the ridge-lines in the frequency-time plane for the type II burst of April 25, 1956 (Plate 3). The dashed lines show the highest frequency band replotted at half the frequency, and the dash-dot lines show the same band replotted at three-quarters of the frequency.

(c) *Group Delay between Harmonics*

Sharply defined features in harmonic bursts occur in the fundamental band about 1 sec after they occur in the second harmonic band. This delay is thought to be the result of a lower velocity of propagation for the fundamental mode. For frequencies near the local plasma frequency the group velocity in the corona is very low. Following the methods of Jaeger and Westfold (1950), it may be shown that, for central rays in a Baumbach-Allen model corona, the travel time for radiation at the fundamental frequency to come from the plasma frequency level is greater by approximately $\frac{3}{4}$ sec than the time for radiation at the second harmonic frequency to come from the same point. The general agreement between these predicted and observed delays may be taken as further evidence for the plasma hypothesis.

(*d*) *The Harmonic Ratio and the Position on the Disk*

In their discussion of the first recorded harmonic type II bursts, Wild, Murray, and Rowe (1954) showed that the ratio of the peak frequencies in the two bands was usually somewhat less than 2. This is a general effect and is clearly evident in Figure 5. For the two bursts which they studied, these authors compared the frequency profiles of the harmonic bands by replotting the second harmonic profile at half the frequency. This comparison showed that the lower frequencies in the fundamental band appeared to have been removed, an effect which accounted for the frequency ratio being less than 2. It was suggested that these lower frequencies had been unable to escape from the Sun in the direction of the Earth, and it was shown that this could be explained on a standard model of ray propagation in a spherically symmetric corona. For a source in the centre of the disk it was predicted that the lower half of the fundamental band would be removed but the ratio of the peak frequencies would be 2 : 1 ; for a source away from the centre of the disk a greater part of the fundamental band would be removed and the ratio would be less than 2 : 1.

Although further observations have confirmed that the ratio of the peak frequencies is usually less than 2, they do not support this theory in detail. Figure 7 gives the results of a study of the variation of the harmonic structure with the distance of the burst from the centre of the disk. Direct measurements of the positions of the type II bursts are not available but a rough measure of the position may be obtained from the association with optical events (Section IX). Figure 7 (*a*) shows that two harmonics can be received from almost any position on the disk, whereas the theory referred to above predicts that no significant part of the fundamental band should escape in bursts beyond $\sim 0 \cdot 5 R_{\odot}$. Furthermore, the harmonic ratio shows no significant variation with the position of the burst on the disk (Fig. 7 (*b*)), and it certainly does not decrease with radial distance in the way predicted by the theory and shown by the dashed curve in this figure.

Properly calibrated frequency profiles are not available for many of the bursts included in the present study but in the five cases which were examined the frequency ratio was close to 2 and the profiles of the two harmonics were similar in shape. If any of the lower frequencies had been removed from the fundamental band it was quite a minor effect. The prediction of the theory, that the entire low frequency half of the fundamental band should be absent, was not fulfilled.

It seems possible that a modification of the theory along the following lines may provide an explanation of these results. Firstly, it is supposed that small-scale irregularities in the corona near the plasma frequency level cause radiation in the fundamental band to be scattered through large angles and so to escape from the Sun in a wide beam. This modification ensures that both harmonics can be received from most parts of the disk and that the harmonic ratio is not a critical function of the position of the burst on the disk. It seems necessary to invoke small-scale irregularities for this purpose (small compared with the size of the source). Large-scale structures would modify the ray paths, and in favourable circumstances it might be possible for both the fundamental and second harmonic of the plasma frequency to be received from a source well away from the centre of the disk. However, large-scale structures will not destroy the strong beaming of the fundamental frequency, so that in most cases only the second harmonic could be received. We may note that the observations of occultations of the radio source in Taurus have already provided evidence for the existence of small-scale irregularities in the corona.

The second modification needed in the theory is to suppose that the bandwidth of the emission at any one time is determined primarily by the range of densities in the excited region of the corona and not by the natural bandwidth of emission of a homogeneous region of the plasma. In radiation from a region of the plasma which is small enough to be considered homogeneous, the lower

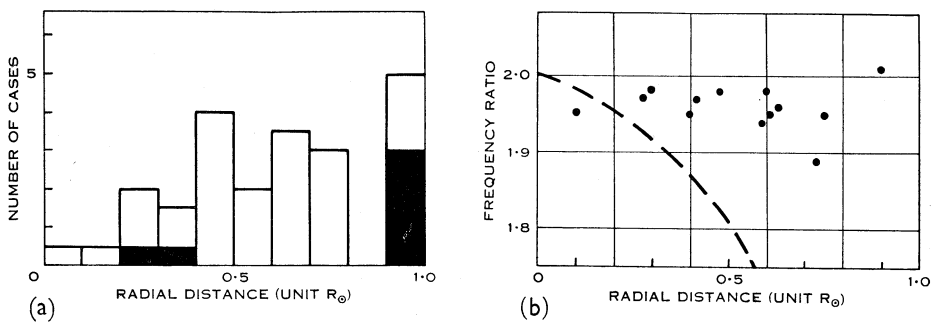

Fig. 7 (*a*).—Distribution of type II bursts with radial distance from the centre of the solar disk. Unshaded regions refer to bursts with fundamental and second harmonic bands : shaded regions to bursts with a single band at such frequencies that harmonic structure could have been detected if it had been present. Indefinite cases in which harmonic structure may or may not have been present are omitted. The radial distances are those of the associated optical events, which in 19 cases were flares of Class 1 or greater and in the remaining 3 cases were prominences ejected beyond the limb (Giovanelli and Roberts 1958).

The trend seen in this figure for more bursts to occur at larger radial distances presumably arises from the increase with distance of the area of the (flare-producing) solar surface associated with a fixed interval of radial distance.

Fig. 7 (*b*).—The dependence on radial distance of the ratio of the frequencies of corresponding features in harmonic bursts. The points show the mean values in each of 13 bursts : the curve shows the predicted ratio for a spherically symmetric corona (Wild, Murray, and Rowe 1954).

half of the fundamental band will still be removed, i.e. for such regions the results will be somewhat like those for the centre of the disk in the absence of irregularities. However, the observed frequency profile is now supposed to be an integration of many such " filtered " profiles centred on neighbouring frequencies. The shape of the resulting profile will be determined by the distribution of the excitation. The profile of the fundamental will resemble that of the second harmonic but its peak frequency will exceed half the peak frequency of the second harmonic by a frequency of the order of the natural bandwidth of the oscillations of a homogeneous element of plasma. On this basis the observed mean harmonic ratio of $\sim 1 \cdot 95$ (Fig. 5) is taken to imply that the natural bandwidth of the plasma oscillations is only a few per cent. This agrees very well with the theoretical predictions made from considerations of Landau damping (Berz 1956).

VI. Band Splitting

(a) Observations

Wild (1950) and Wild, Murray, and Rowe (1954) pointed out that in many type II bursts the individual harmonic bands are themselves double. Several examples of this phenomenon are shown in Plate 4. Each harmonic band is split into two ridges, which are separated by the order of 10 Mc/s in the fundamental band. The details of the split-band structure are duplicated in the second harmonic, where the splitting is twice as great. In many cases the two

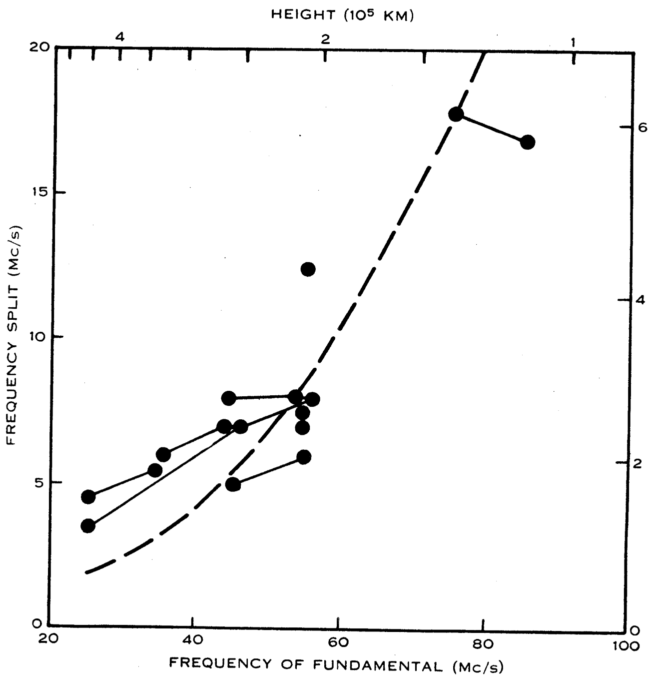

Fig. 8.—The frequency separation in split bands as a function of the mean frequency of the band. The points show the measured values, those which are joined referring to the same burst. The dashed curve shows the variation of the gyro frequency (ordinate) with the coronal plasma frequency (abscissa) for a Chapman model sunspot of surface field 3000 G and with the Baumbach-Allen model of coronal electron densities. For this curve the scales may be relabelled to show magnetic field as a function of height, the change from frequency to magnetic field being according to the relation $f_H = 2 \cdot 9$ Mc/s per gauss, and that from frequency to height following the Baumbach-Allen model (data from Smerd 1950).

parts of the split band are similar, but this is not always so. For example, in the event of December 6, 1957, illustrated in Plate 4, the lower frequency ridge is considerably narrower than the higher frequency one. In a few cases a trebling of the band has been observed.

The measured values of the frequency splitting are shown in Figure 8 as a function of the mean frequency of the two parts of the band. All the points for any one burst are joined by a fine line. Although in individual bursts there is little evidence for a consistent variation of the splitting with frequency, the overall result is a variation from approximately 5 Mc/s separation at 30 Mc/s, to 18 Mc/s separation at 80 Mc/s. All these results are referred to the fundamental, although, where possible, the measurements were made on the second harmonic, which is less likely to be distorted by propagation effects.

The dashed curve in this figure shows the gyro frequency above a model sunspot as a function of the plasma frequency. It is discussed below in connexion with the explanation of the band splitting.

(b) *Interpretation*

The close correspondence between the two parts of a split band, including the appearance of features in the two parts at similar times, suggests that the radiation is produced in a common source emitting at two different frequencies. It appears unlikely that the two parts are produced by two different disturbances which travel out through the corona. Further evidence for this view is found in the narrow range of frequency separations observed at any one frequency (Fig. 8). Wild and co-workers suggested that the double band structure might be the result of magnetic splitting, analogous to the Zeeman effect. Unfortunately, the theory of the oscillation of a plasma in the presence of a magnetic field is at present somewhat confused. Westfold (1949) suggested that such a plasma has three proper frequencies of vibration which are the three frequencies for which the refractive index is zero. On the other hand Gross (1951), Sen (1952), and Bayet (1954) have taken the frequencies of plasma oscillations in a magnetic field to be the two frequencies for which the refractive index is very great. As we shall see, neither of these theories appears to predict all the observed properties of the split bands.

The three frequencies for which the refractive index vanishes are the plasma frequency f_p, and the frequencies $\sqrt{(f_p^2+\frac{1}{4}f_H^2)}\pm\frac{1}{2}f_H$, where f_H is the gyro (cyclotron) frequency of the electrons.* For small magnetic fields ($f_H^2 \ll f_p^2$) the latter two frequencies are approximately $f_p\pm\frac{1}{2}f_H$. It is believed that the lower of these two frequencies cannot escape from the Sun but is reflected by an overlying stop region (see e.g. Pawsey and Bracewell 1955). Hence, in the fundamental band two peaks should be observed at the frequencies f_p and $f_p+\frac{1}{2}f_H$. To this extent the theory fits the observations, since the observed splitting could be explained by the presence of fields $\sim$5 G in the corona. Indeed, Figure 8 shows that the observed variation of the magnitude of the split with the frequency of the burst agrees well with that predicted on a current model of the variation of the magnetic field of a sunspot with height. However, it is necessary to add that our knowledge of the magnetic fields at these heights is extremely limited.

The difficulty with this theory is that, when the values of f_p and f_H are chosen to fit the observations, it is found that the second harmonics of *all three* frequencies should escape from the Sun. Since in most cases only two peaks are seen in the second harmonic band, it seems that this theory cannot be correct, at least in its present form.

* $f_p=(Ne^2/\pi m)^{\frac{1}{2}}=0\cdot 9\times 10^4 N^{\frac{1}{2}}$ Mc/s, where N is the electron density in cm^{-3}; $f_H=eH/2\pi mc=2\cdot 9H$ Mc/s, where H is the magnetic field in gauss.

The alternative theory predicts only two frequencies of oscillation, but only one of these is close to the plasma frequency. The frequencies near which the refractive index becomes very great are

$$[\tfrac{1}{2}\{f_p^2+f_H^2\pm\sqrt{(f_p^4-2f^2f_H^2\cos 2\theta+f_H^2)}\}]^{\frac{1}{2}},$$

where θ is the angle between the magnetic field and the direction of propagation. When $f_H^2 \ll f_p^2$ the upper sign yields a frequency $\sim f_p$ while the lower sign leads to a value $\sim f_H$ or less. Thus this theory of the oscillation of a plasma in a magnetic field does not predict a splitting of the plasma level into two frequencies close to the plasma frequency. It predicts one oscillation at a frequency near the plasma frequency and one at a frequency below the gyro frequency.

To decide whether the observed doubling of the bands could be the result of magnetic splitting evidently requires the development of a more complete theory, e.g. the extension of the work of Akhiezer and Sitenko (1952) and Pines and Bohm (1952) to cover the case of a charged particle projected through a plasma which is pervaded by a steady magnetic field. If such a theory should show that oscillations occur at two frequencies separated by $\sim f_H$, then the data of Figure 8 would support the identification of the observed splitting as magnetic splitting. Such an identification would provide a very valuable tool for the measurement of magnetic fields high in the corona, in a region not at present accessible to optical observations.

The observed lack of polarization of the split bands is a further difficulty for this type of theory. If the two parts of a split band represent radiation in two different modes, then they would be expected to have distinctive polarizations. Furthermore, provided the properties of the corona change sufficiently slowly with height, the radiation would remain in the same mode throughout its passage through the corona and would emerge with a distinctive polarization. This conclusion is in conflict with the observation that the split bands are substantially randomly polarized.

Randomization could be achieved by combining the emission from regions in which the magnetic field directions were different. However, to be consistent with the observed narrow bandwidths, the magnetic field would have to reverse in a distance $\sim 10^4$ km.

VII. The Herring-bone Structure

(a) *Observations*

On April 26, 1956 from 0154 to 0205 U.T. a unique burst was recorded. Two sections of the record of this event are reproduced at the top of Plate 5. The dominant feature is a rapid succession of short-lived, broad-band elements. These have fast frequency drifts of both positive and negative signs and appear to diverge from a narrow-band feature which drifts from high to low frequencies at a rate typical of a type II burst. The resulting appearance in the frequency-time plane resembles a herring-bone. In the later stages of the burst the rapidly drifting elements extend over a much smaller range of frequencies, and at times the " backbone " is missing, i.e. the narrow-band, slowly drifting feature exists only as a gap between the rapidly drifting elements diverging in the two directions.

From this part of the burst it is clear that the structure is by no means as regular as the term herring-bone may suggest. In particular, the elements which drift in the positive and negative sense do not occur in pairs.

No other event closely resembling this has been recorded, but quite a number of type II bursts contain structure which is similar to the later stages of this event (section from 0201·5 to 0202·5 U.T.). For example, the section of the type II burst on April 8, 1958 which is reproduced in this plate contains similar structure. In such bursts the herring-bone form is much less clearly developed. The rapidly drifting elements extend over only 5 or 10 Mc/s, and often the drift rates are lower, and the elements are of rather longer duration, than those in the event of April 26, 1956.

There are rather more examples of events in which only half the herring-bone is present, i.e. rapidly drifting elements extend from the type II band towards the lower frequencies but not towards the higher frequencies. Again, there is one outstanding event of this nature in the records. This occurred on July 6, 1956 from 0245 to 0300 U.T. Part of the record is reproduced in Plate 5. The burst began as a fairly typical harmonic type II, but after the burst had been in progress for approximately 3 min, rapidly drifting elements suddenly appeared extending from the low frequency side of each of the harmonic bands (see Plate 5). These elements have higher drift rates and are of even shorter duration than those in the event of April 26. The drift rates are greater than those commonly seen in type III bursts and the durations (at one frequency) are very short, often less than 1 sec.

Plate 1 contains an example of a somewhat similar event which occurred on January 24, 1957. In this case the rapidly drifting elements are much weaker and more diffuse but they resemble type III bursts more closely. In still other cases the rapidly drifting elements would undoubtedly be classified as type III bursts : the event of January 19, 1956 shown in Plate 3 is in this class, but the type III elements are difficult to see in the reproduction.

There are very few type II bursts in which the herring-bone structure is a dominant feature, but vestiges of it can be seen in perhaps 20 per cent. of all type II events. It is possible that the structure reported by Haddock (1958) is of a similar nature. This author describes the type II bursts which he has observed as being composed of elements in which the dominant drift rate is typical of the type III bursts.

(b) *Interpretation*

On the plasma hypothesis the herring-bone structure implies that the outward-travelling disturbance responsible for the type II band is a source which ejects rapidly travelling disturbances producing the type III elements. In cases where both positively and negatively drifting elements are present the fast ejections must travel both into and out from the Sun : in the other cases either only outward ejections occur, or radiation from the inward-travelling ejections cannot reach the Earth. To explain the similarity between successive elements (and their short duration at one frequency) it is necessary to suppose that the ejections all occur within the same narrow range of directions and have closely similar speeds. The very sudden onset of the ejections in the burst of July 6, 1956 (Plate 5) suggests that the coronal properties changed in some critical way in a distance certainly less than 1000 km.

As discussed in Section IV, it seems likely that the disturbances producing the regular bands in type II bursts are shock fronts accompanying supersonic ejections. We do not know of a mechanism whereby such a shock front could produce fast, beamed ejections with speeds several hundred times as great as the shock front. However, if, as Westfold (1957) and others have suggested, the corona is able to support other shock waves of a different nature and having speeds appropriate to type III bursts, then it is perhaps possible that such shock waves are generated by the sonic shock when it encounters sudden changes in the corona. Shock waves so generated might be beamed in the direction of the original shock motion (and the reverse) and this could account for the nature of the type III elements. It may also be worth considering whether a sonic shock, on reaching a region of lower temperature in the corona, might not " break " in the manner of a water wave approaching a beach and throw off high speed particles.

It is perhaps significant that the frequency drift rate in the type II section of the event on July 6, 1956 is considerably greater than the usual. The inferred speed of the disturbance is over 1000 km/sec (Fig. 3 (*a*)). However, the drift rate in the event of April 26, 1956 is not unusually great.

VIII. Compound Type III–Type II Bursts

(*a*) *Observations*

Wild, Roberts, and Murray (1954) drew attention to the tendency for a type II burst to be preceded by a group of type III bursts, which apparently formed part of the same event. The present more extensive observations have shown that this is a common occurrence : 36, or 60 per cent., of the bursts were preceded by a type III event which appeared to be unambiguously associated with the type II burst. Some examples are given in Plate 1. Often the type III events are outstanding : they may consist of groups of 10 or more bursts and may contain considerably more energy than the type II burst. Such is the case in the events of August 6, 1957, illustrated in Plate 1, and December 19, 1957, illustrated in Plate 2. In other cases, however, the type III event may be weak and perhaps consist of only one or two bursts. Examples of this type are seen in Plate 2 (events of December 6, 1957 and January 15, 1958) and in Plate 3 (event of November 15, 1955).

Occasionally type III bursts occur at the time of a type II burst, but not in a preceding group (Plate 2, event of January 15, 1958). Also in rare cases a preceding group is of very great duration, containing many tens of bursts and some of these may overlap the type II burst (see Plate 4, event of November 13, 1957).

For the apparently associated events the time delay between the type III group and the onset of the type II burst ranges from 1 to 18 min. The median value is $5\frac{1}{2}$ min, and 50 per cent. of the values lie between 4 and $9\frac{1}{2}$ min.

(b) *Interpretation*

The explanation of the compound type III–type II burst, proposed by Wild, Roberts, and Murray (1954), involved the ejection of two sets of disturbances from a single explosion, supposed to occur low in the solar atmosphere at the time of the type III event. The first set of disturbances, travelling with speeds of $0 \cdot 1$–$0 \cdot 3c$, were supposed to produce the type III bursts ; the other disturbance, with a speed $\sim$500 km/sec, was responsible for the type II burst. In support of this explanation it was shown that for the three events studied the velocity lines of the two parts of the burst diverged from an origin in the lower corona within 10^5 km of the photosphere.

TABLE 1

COMPILATION OF DATA ON HARMONIC COMPOUND BURSTS

(The heights of intersection are for a Baumbach-Allen model corona)

Date	Frequency (Mc/s)	Time Delay of Type II Burst after Type III Event (min)	Drift Rate in Type III Burst Fundamental (Mc/s per sec)	Height of Intersection of Trajectories (10^5 km)
9. vi.55	45	$8\frac{1}{2}$	0·11	—0·8
5. vii.55		6 to 13	0·13	—3·5 to —0·2
24. i.57		11	0·08	—0·6
17. vii.57		$12\frac{1}{2}$ to 14	0·06	—0·4 to —0·2
6.viii.57		$5\frac{1}{2}$ to 7	0·11	—0·2 to +0·4
2. ix.57		2 to 13	0·05	+0·3 to +2·2
11. ix.57		10 to $11\frac{1}{2}$	0·08	—0·7 to —0·3
6. xii.57		16	0·06	—0·8
15. i.58		$5\frac{1}{2}$	0·08	+1·1
		10	0·06	+0·4
19. i.56	50	7	0·05	+1·2
6.viii.57		4 to $5\frac{1}{2}$	0·12	+0·6 to +0·8
15. xi.55	60	3	0·1	+1·2
18. xi.55		6	0·13	—0·4

The height-time plots given in Figure 4 include four examples of compound bursts. For one of these events (January 15, 1958) the velocity lines similarly diverge from a common point in the corona within 10^5 km of the photosphere. For the other events, however, the point of intersection lies somewhat below the photosphere. The results of a study of all the harmonic compound bursts are shown in Table 1. It is seen that the apparent origin from which the disturbances diverge usually lies within 10^5 km of the photosphere, but is quite often below it. In view of the uncertainties in the electron density distribution, it thus seems that the hypothesis of a common origin is reasonable, but it is not possible to determine the height of origin by extrapolating the velocity lines in this way.

IX. Type II Bursts and Chromospheric Flares

The relationship of type II bursts to solar flares can be studied most satisfactorily when continuous optical observations of the Sun are available for the periods of the radio spectral observations. A combined study of this nature, covering 18 type II bursts, has been reported recently by Giovanelli and Roberts (1958). These authors found definite optical associations for 70 per cent. of the bursts and ambiguous associations for another 10 per cent. Most of the optical events were bright flares showing particle ejections.

Unfortunately optical observations of the Sun were not made at Sydney at the times of many of the type II bursts reported in this study. In the analysis of this section, therefore, the reports of flares seen at Sydney, which were kindly supplied by Dr. R. Giovanelli of the Division of Physics, C.S.I.R.O., have been supplemented by the reports of flares appearing in the " Quarterly Bulletin of Solar Activity " (to December 1956), in the " Daily Maps of the Sun " issued by the Fraunhofer Institute, and in " Solar-Geophysical Data " issued by the National Bureau of Standards. For the times of each of the 65 type II bursts the above-mentioned flare reports were examined. For 28 of the bursts, flares of Class I or greater were reported at times which suggested that they were related to the bursts. This relationship is indicated in Figure 9. Figure 9 (*a*) refers to the 15 bursts for which the beginning of the flare was observed. For each event it shows all the bursts of type II or type III and all the flares of Class I or greater which were reported in the period from 10 min before to 2 hr after the beginning of the relevant flare. Figure 9 (*b*) gives similar data for the remaining 13 bursts. In this case the period covered is from 20 min before to 2 hr after the beginning of the type II burst.

It is obvious from these diagrams that the flares and type II bursts are associated. A clear pattern is evident, with the type II burst beginning near the maximum of the flare and continuing after it, while in the case of a compound burst the type III event usually occurs before the flare maximum. This diagram is similar to those given by Dodson and co-workers (Dodson, Hedeman, and Owren 1953 ; Dodson 1958) showing the relationship of flares to bursts observed on single-frequency recorders. However, as already discussed in Section VIII, it does not seem to be possible at present to identify unambiguously the spectral types in Miss Dodson's analysis. The diagram also agrees with that given by Dodson (1958) for 13 of the bursts in the present study.

Since not all flares are observed, the associations listed in Figure 9 give only a lower limit for the percentage of the type II bursts which are accompanied by flares. Indeed, the last two years have seen a remarkable increase in the percentage of the bursts which are accompanied by reported flares, an effect which presumably may be attributed to the improved coverage of the flare patrols. Flares of Class I or greater were reported at the times of 64 per cent. of the 25 type II bursts recorded since July 1, 1957 ; for the 10 bursts since December 1, 1957, the figure is 80 per cent. It is clear, therefore, that the majority of type II bursts are accompanied by flares, not including sub-flares.

Although most type II bursts are associated with flares, it is actually rare for a flare to be accompanied by a type II burst. This is made clear in Table 2

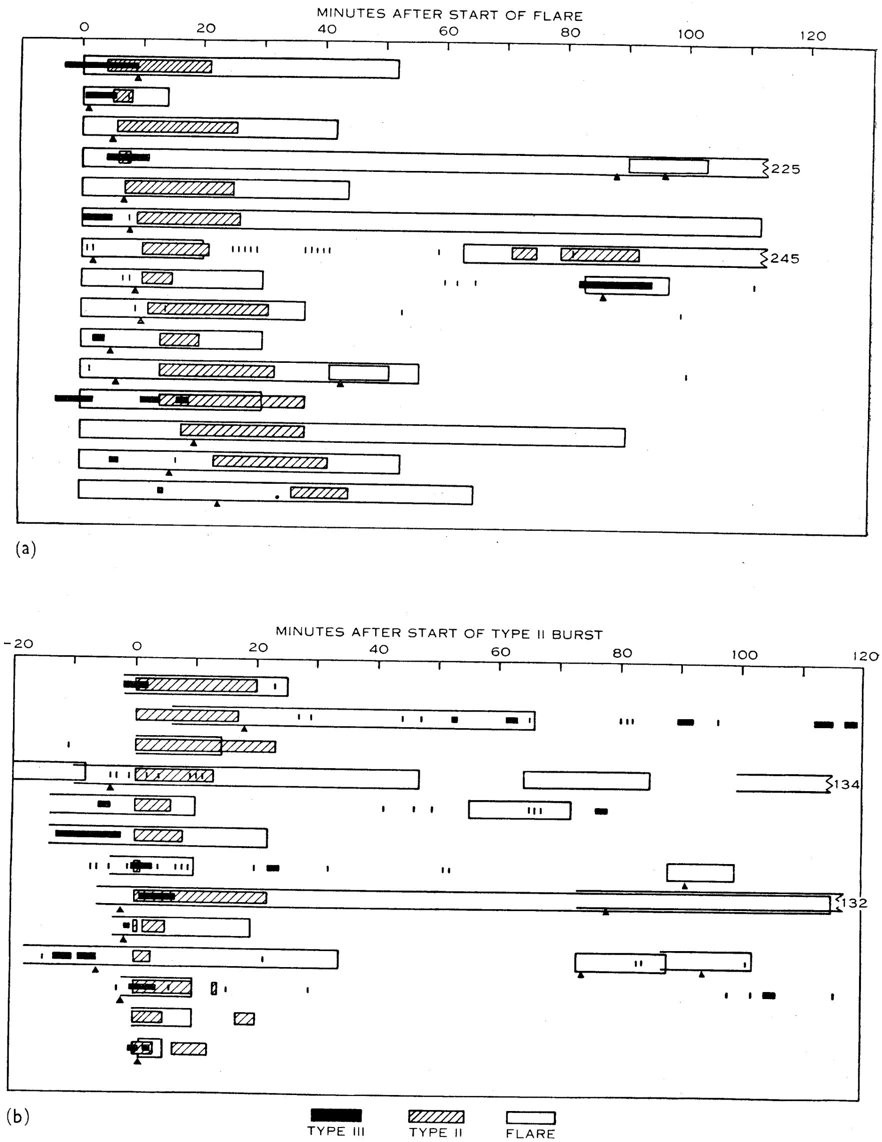

Fig. 9.—Showing the temporal relationship of flares and associated type II bursts.

(*a*) Data for 15 cases in which the beginning of the associated flare was observed. The figure shows all the bursts of spectral types II and III and all the flares of Class I or greater which occurred within the period from 10 min before to 2 hr after the beginning of the associated flare. Type III bursts are shown by heavy lines, type II bursts by shaded rectangles, and flares by open rectangles. The maxima of flares are indicated by solid triangles.

(*b*) Similar data for another 13 cases in which the beginning of the associated flare was not observed. In this case the period covered is from 20 min before to 2 hr after the start of the type II burst.

which gives the distribution by importance class of the 702 flares reported during the observing hours of the radio-spectrograph from January 1955 to March 1958 and also gives the number (and percentage) of these flares which were accompanied by type II bursts. It is seen that only about 3 per cent. of flares of Class I or greater are associated with type II events. However, the percentage increases

TABLE 2

ANALYSIS OF FLARES AND TYPE II BURSTS BY IMPORTANCE CLASS

Flare importance	1	2	3	1, 2, or 3
Number of flares during radio observations	566	120	16	702
Number of flares accompanied by type II bursts	11	8	5	24
Percentage of flares accompanied by type II bursts	2	7	31	3

rapidly with the importance of the flare, and approximately 30 per cent. of Class 3 flares are accompanied by bursts. Evidently some rare condition must be satisfied before a flare is accompanied by a type II burst. Since many flares are accompanied by visible ejections, we may conclude that the presence of an ejected stream is not a sufficient criterion for the occurrence of a type II burst. If only those ejections with supersonic speeds are effective (see Section IV and

TABLE 3

ANALYSIS OF FLARES AND TYPE II BURSTS BY DISK LONGITUDE

Disk longitude of flare . .	0–30°	31–60°	61–90°
Number of flares accompanied by type II bursts	14	9	5
Percentage of all flares observed (from Goldberg, Dodson, and Müller 1954)	41	36	23
Relative probability of a flare being accompanied by a type II burst	1	0·7	0·6

Giovanelli and Roberts (1958)), the numerical agreement would probably be better. Data on the frequency of occurrence of supersonic ejections from flares would be of interest in this connexion.

Table 3 gives the distribution with disk longitude of the flares accompanied by type II bursts. Rather more such flares are seen near the centre of the disk than at the limb. However, a similar comment applies to all the flares observed

(Goldberg, Dodson, and Müller 1954) so that the probability of a flare being accompanied by a type II burst is relatively independent of the longitude of the flare. This implies that the type II radiation is emitted in a broad cone, in contrast to the type I radiation which is thought to be beamed radially outwards.

It is clear from a study of these flare associations that some active regions on the Sun are very prolific in producing type II bursts, while others produce none at all. In an attempt to determine what parameters are responsible for this behaviour, a statistical investigation was made of the effect of the type of spot group. Groups were classified according to their Zurich class (as given in the Fraunhofer Institute " Daily Maps of the Sun ") and also according to their Mt. Wilson magnetic class. No significant dependence on either of these parameters was found.

X. Type II Bursts and Geomagnetic Storms

When particle streams with speeds $\sim 10^3$ km/sec were suggested as the source of type II bursts it was natural to try to identify these streams with those causing magnetic storms and aurorae on the Earth. However, it was not possible to identify particular magnetic storms unambiguously with individual type II bursts, and, as Wild, Murray, and Rowe (1953) emphasized, the inferred speeds of about 500 km/sec for type II bursts were smaller by a factor of 2 or 3 than those implied by the delay of magnetic storms after important flares. The present sample of type II bursts is large enough for statistical methods to be used in searching for possible effects of these bursts on the geomagnetic field, and in this section the results of a superposed epoch analysis are given.

Figure 10 shows the mean value of the magnetic index A_p for the period from 8 days before to 13 days after a type II burst. The A_p values appear to be high from $1\frac{1}{2}$ to $2\frac{1}{2}$ days after a type II burst, the maximum value being about $1\frac{1}{2}$ times the quiet value. The significance of this increase has been tested by dividing the data into two halves. The dashed curves in Figure 10 show the corresponding results for the first 30 and the second 30 bursts separately. Both of these curves contain the peak on the second day, while, by contrast, the other (lower) peaks in the full curve appear in only one or the other of the dashed curves. This provides considerable grounds for believing the peak on the second day to be real. The significance may also be tested by computing a standard deviation from all the points and in this way it is found that the probability of the peak value occurring by chance in a normal distribution is about 1 in 10^3.

The form of this curve is similar to that found by Dodson (1958) for the geomagnetic variability after " major early bursts " at frequencies $\leqslant 200$ Mc/s. However, in her analysis Miss Dodson found a longer period of high magnetic variability extending from approximately 2 to 7 days after the burst. The maximum variability occurred on the 3rd and 4th days after the burst and not on the second as found here. We have already referred in Section VIII to the difficulty of correlating the spectral and single-frequency classifications of bursts : the tests reported later in this section may be taken as suggesting that the bursts used by Miss Dodson contained a high proportion of type II events, but this is no more than a suggestion.

We may also mention that a curve similar to that in Figure 10 was prepared for the 37 type II bursts observed with the Harvard radio-spectrograph from October 1956 to December 1957 (Maxwell, Stone, and Swarup 1957). This curve did not show any pronounced peak but did show a period of enhanced geomagnetic variability for approximately 10 days after the bursts. This

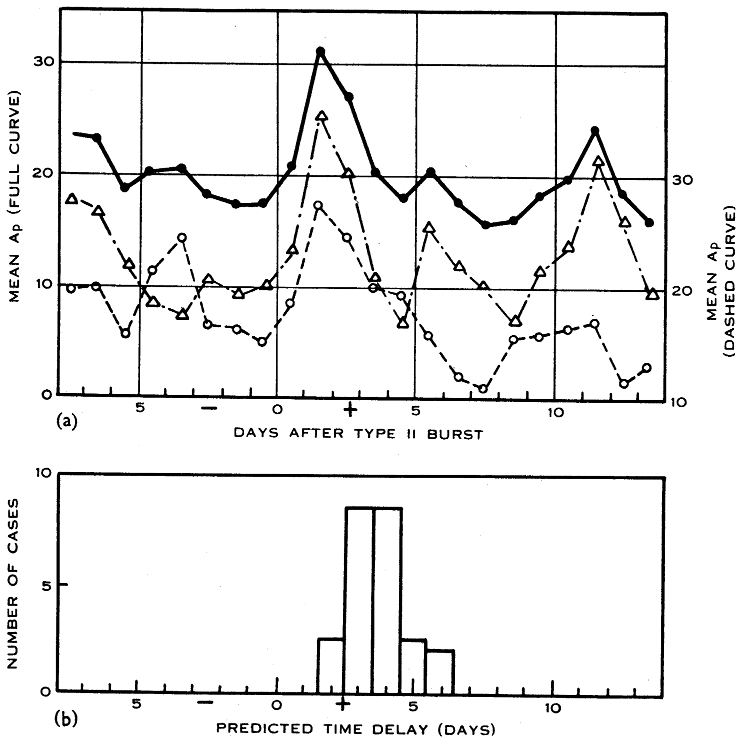

Fig. 10 (*a*).—Superposed epoch diagram showing the mean value of the geomagnetic index A_p on days before and after 60 type II bursts recorded in the period January 1955 to March 1958. The dashed lines give the corresponding diagrams for the first 30 and the second 30 bursts separately. Note that these latter curves are plotted on a displaced scale of A_p.

Fig. 10 (*b*).—The predicted time delays inferred from the frequency drift rates in 24 of the type II bursts in which harmonic structure could be clearly recognized. It is assumed that the type II disturbances move radially outwards through a Baumbach-Allen model corona and cause emission at the local coronal plasma frequency.

suggests that there may be some difference between the events classified as type II by the two groups of workers. However, the statistics are limited and more data are needed.*

Figure 10 indicates a tendency for the geomagnetic field to be considerably disturbed on the first, second, and third days after a type II burst. With the

* A similar analysis for Harvard and Sydney type II bursts was reported by A. R. Thompson at the I.A.U.-U.R.S.I. Paris Symposium on Radio Astronomy in August 1958.

purpose of determining whether the type II bursts were the significant events, similar superposed epoch diagrams were prepared showing

(i) the mean value of A_p before and after 70 flares, of importance 2 or greater, known not to be accompanied by type II bursts and occurring on days for which neither Sydney nor Harvard reported type II bursts (Fig. 11 (*a*)), and

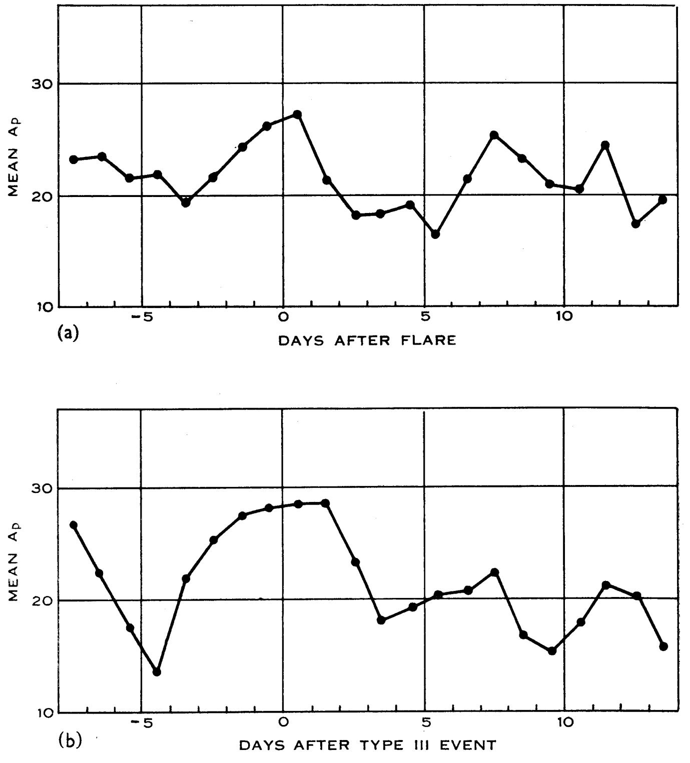

Fig. 11 (*a*).—Superposed epoch diagram showing the mean magnetic variability (mean A_p) on days following 70 flares of importance 2 or 3, which were *not* accompanied by type II bursts and which occurred on days when neither Sydney nor Harvard reported a type II burst. (The flares included are those satisfying the above conditions which were reported during the observing periods of the Dapto radio-spectrograph from June 1955 to November 1957.)

Fig. 11 (*b*).—A similar superposed epoch diagram for days following 53 outstanding type III radio events reported by Sydney in the period from July to December, 1957, on days when neither Sydney nor Harvard reported a type II burst. The type III events chosen are those groups of bursts of intensity class 2 or 3 and with durations $\geqslant 1$ min.

(ii) the mean value of A_p before and after 53 days on which at least one group of strong type III bursts was reported by Sydney, and no type II burst was reported by Sydney or Harvard (Fig. 11 (*b*)). Neither of these diagrams indicates an increase in storminess beginning a day or more after the events in question. Indeed, neither contains a peak of such apparent significance as that found after the type II events. This evidence therefore suggests that the occurrence of a type II burst gives a more positive indication of the ejection of magnetic storm particles from the Sun than is given either by the occurrence of an important flare or of a radio " outburst " of spectral type III.

Both the plasma hypothesis and the suggested association with geomagnetic storms can be tested by comparing the travel time of $1\frac{1}{2}$ to 2 days indicated by Figure 10 (*a*) with the travel times inferred from the frequency drift rates of the bursts. Figure 10 (*b*) shows to the same scale as Figure 10 (*a*) a histogram of the inferred travel times to the Earth for 24 of the bursts with clear harmonic structure. This figure contains the same data as Figure 3 (*b*), presented in a different way. The figure is based on the assumption of radial motion of the type II disturbances through a Baumbach-Allen model corona.

The mean time delay inferred in this way is seen to be about $3\frac{1}{2}$ days, or twice the mean delay of the geomagnetic disturbance after the burst. However, as already indicated, the velocities inferred from the Baumbach-Allen model are almost certainly low by a factor $\sim$2, so that the agreement is considerably better than is suggested by these figures. Indeed, it may not be too optimistic to hope that the direct measurements of the motion of the sources of type II bursts now being made by Wild, Sheridan, and Trent (1959) may make it possible to associate a particular magnetic storm with a particular type II burst.

XI. Conclusion

In concluding this review it is appropriate to consider the definition of the bursts of spectral type II. The 65 bursts included in this study all appear to belong to a fairly well-defined class having the common characteristics of a drift of some of the main spectral features from high to low frequencies at rates of up to 1 Mc/s per sec, and a duration of the order of minutes (Section II (*b*)). They are clearly of the class which Wild and McCready (1950) designated as spectral type II, and indeed the definition given by these authors (Section I) appears to have been very well chosen.

The definition outlined above differs from Wild and McCready's definition in two points. Firstly, their specification of the drift rate as " of the order of $\frac{1}{4}$ Mc/s per sec " is replaced by " up to 1 Mc/s per sec ". It is clear from Figure 3 (*a*) that the observed drift rates are frequency dependent, and while $\frac{1}{4}$ Mc/s per sec is fairly representative in the frequency range in which Wild and McCready made their observations (70–130 Mc/s), it is not appropriate at the lower frequencies. The suggested new phrasing is purposely somewhat loose, but appears at present to be fairly adequate to define the class. However, further observations may make it necessary to specify the drift rate more closely, e.g. by stating it to be of the order of $0\cdot05$ Mc/s per sec at 30 Mc/s and $0\cdot3$ Mc/s per sec at 100 Mc/s, or perhaps by some simple functional dependence such as $0\cdot1(f/50)^{1\cdot5}$ Mc/s per sec, where the frequency f is in megacycles per second.

It will be noticed that the wording is chosen so as to include type II " U " bursts and bursts with pronounced herring-bone structure provided only that *some* of the main features show the typical type II drift.

The second departure from Wild and McCready's definition is to specify that the duration is of the order of minutes. This restriction was made to exclude from the class some bursts which have drift rates similar to type II bursts, but durations of only a few seconds. Such bursts are sometimes seen in the "tails" of type III bursts, and, as indicated in Section II (*b*) (vii), type II bursts are themselves sometimes composed of many such sub-bursts. Further observations may show that these bursts are in fact of the same nature as the type II bursts, but they have not been included in the present discussion except when they formed a drifting band having a duration of the order of minutes.

As worded, the suggested definition would properly include some of the drifting bands of type I bursts described by Wild (1957). In part, this reflects the lack of certainty that these events are fundamentally different from type II bursts. Most of the drifting bands of type I bursts can be excluded by requiring that the events be distinct and not part of a storm, or by using one of the more restrictive definitions of the frequency drift rate suggested above, which would exclude all but the most rapidly drifting of the bands of type I bursts. However, the bands of type I bursts occur with a wide variety of drift rates and in varying degrees of isolation, so that in a few cases it appears to be impossible to determine from the dynamic spectrum alone whether the event is of type I or of type II. Further observations of other parameters (polarization, position, and movement) may provide a means of distinguishing these events or may provide additional evidence of a continuous transition between events which are at present classified as type I and type II.

The present sample of bursts does not include events which by virtue of their slow rate of drift or association with a type I storm can be clearly classed as drifting bands of type I bursts. There are less than five events included which may perhaps be of type I.

XII. Acknowledgments

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EXPLANATION OF PLATES 1–5

PLATE 1

Reproductions of the dynamic spectra records of four compound type III–type II bursts. Time increases from left to right, wavelength from bottom to top, and the intensity is indicated by the degree of whiteness. Sharp features at constant frequency are interfering signals due to mobile communications, etc. Diffuse features at constant frequency arise from variations in receiver gain.

All four type II bursts contain two harmonic bands. The event on July 17 and the earlier event on August 6 have " split bands " ; that on January 24 appears to be the source of diffuse type III bursts (" herring-bone structure "). The earlier event on August 6 is double—there are two intense clusters of type III bursts and each is followed after a delay of 5 or 6 min by a harmonic split-band type II burst.

PLATE 2

Examples of dynamic spectral records of type II bursts on a more compressed time scale. These records were prepared by photomechanically compressing the original records made on 35 mm film at $\frac{1}{2}$ in. per minute (see Wild 1957). Interfering signals appear as sharp features at constant frequencies : many are visible in the record of December 6, 1957. The dark lines parallel to the time axis are caused by the change from one range to the next, while the narrow dark lines parallel to the frequency axis seen in some of the records are simply short gaps in the observations.

The event of December 6, 1957 is a simple harmonic burst with band splitting; that of January 15, 1958 is a compound type III–type II event in which the type II burst contains two separate sets of harmonic bands, the second of which are split bands; the burst of February 14, 1956 contains broad diffuse bands; and the event of December 19, 1957 is a compound type III–type II event, with a large cluster of type III bursts and complex structure in the type II burst.

Plate 3

Spectral records of type II bursts with outstanding harmonic structure. The first two examples have fundamental and second harmonic bands, the third event (April 25, 1956) may be an example of a second, third, and fourth harmonic (see text).

The curved, diagonal lines in these records are due to mains frequency interference.

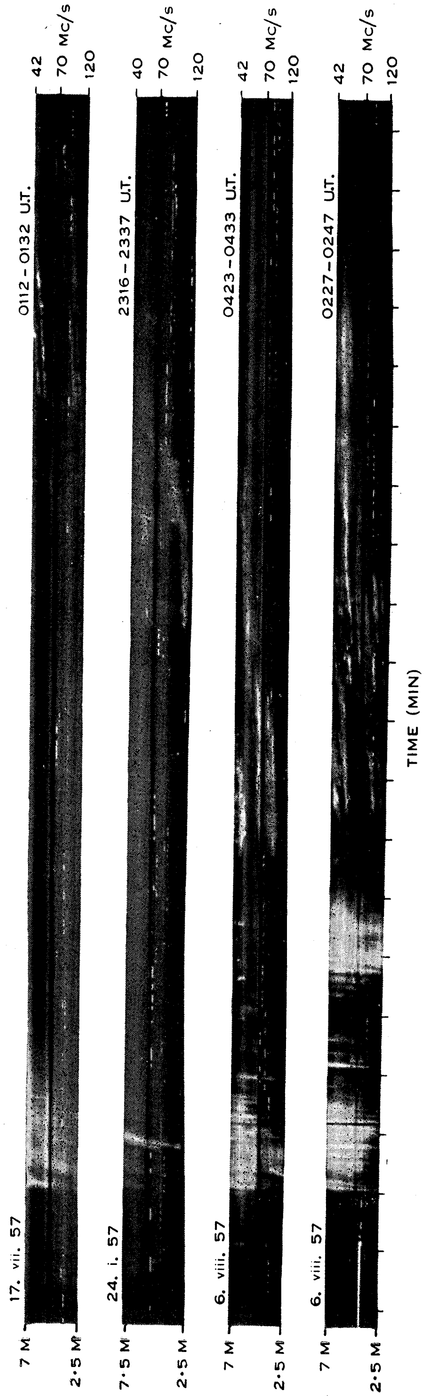
Plate 4

Sample records of the dynamic spectra of type II bursts containing two harmonic bands, each of which is split into a pair of closely spaced ridges. In each case only part of the whole event is reproduced; for three of the cases the full event is shown in Plate 1 or 2.

Plate 5

Illustrating the herring-bone structure in type II bursts. Only a small part of the burst is shown in each case: two sections of the burst on April 26, 1956 are included.

SOLAR RADIO BURSTS OF SPECTRAL TYPE II



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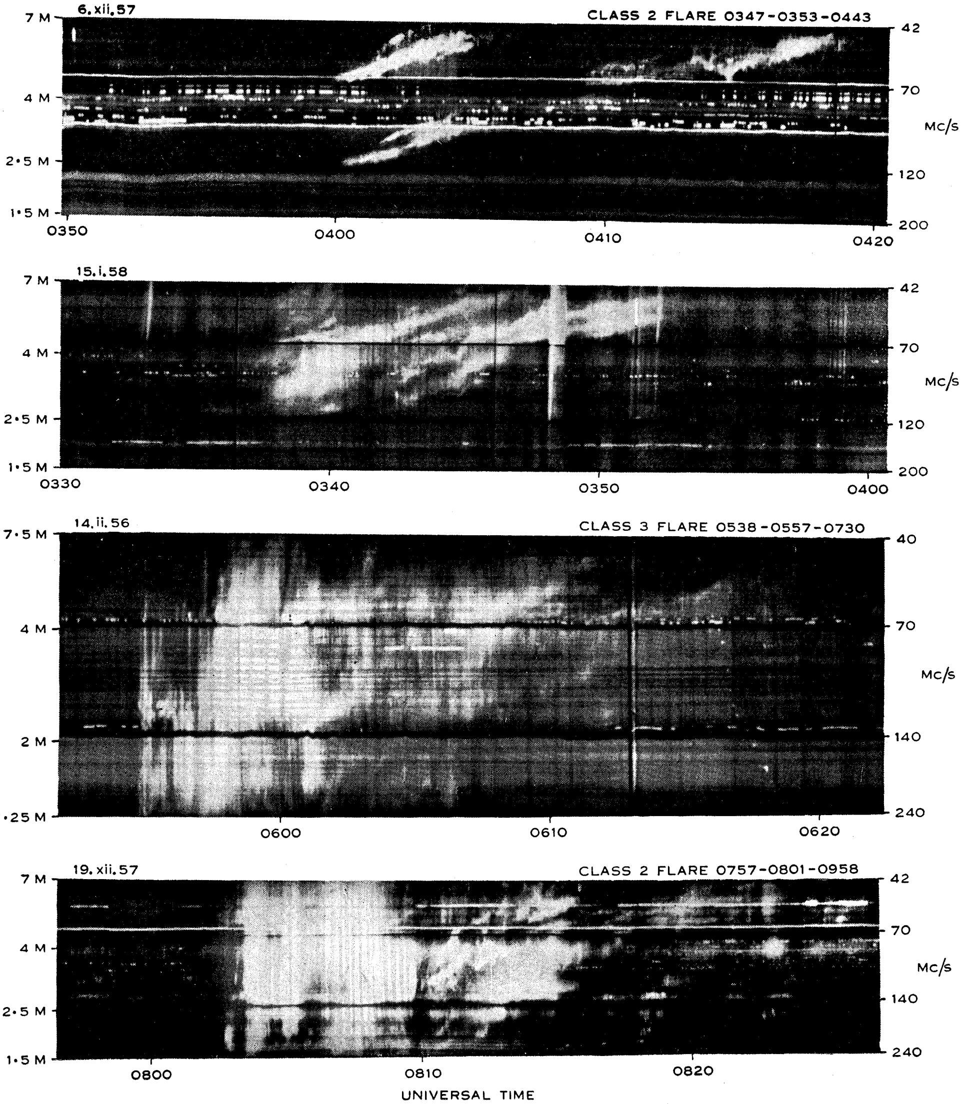

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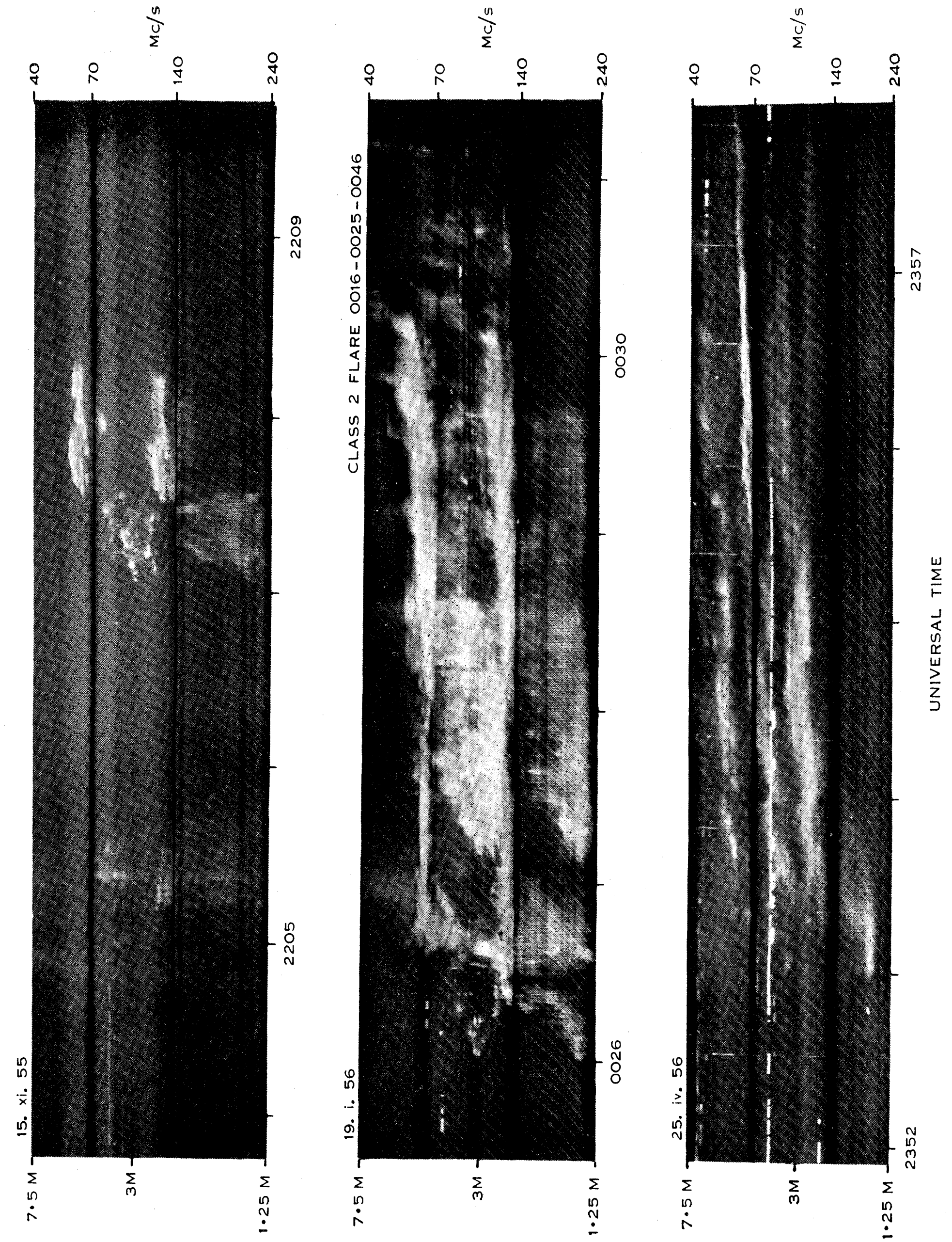

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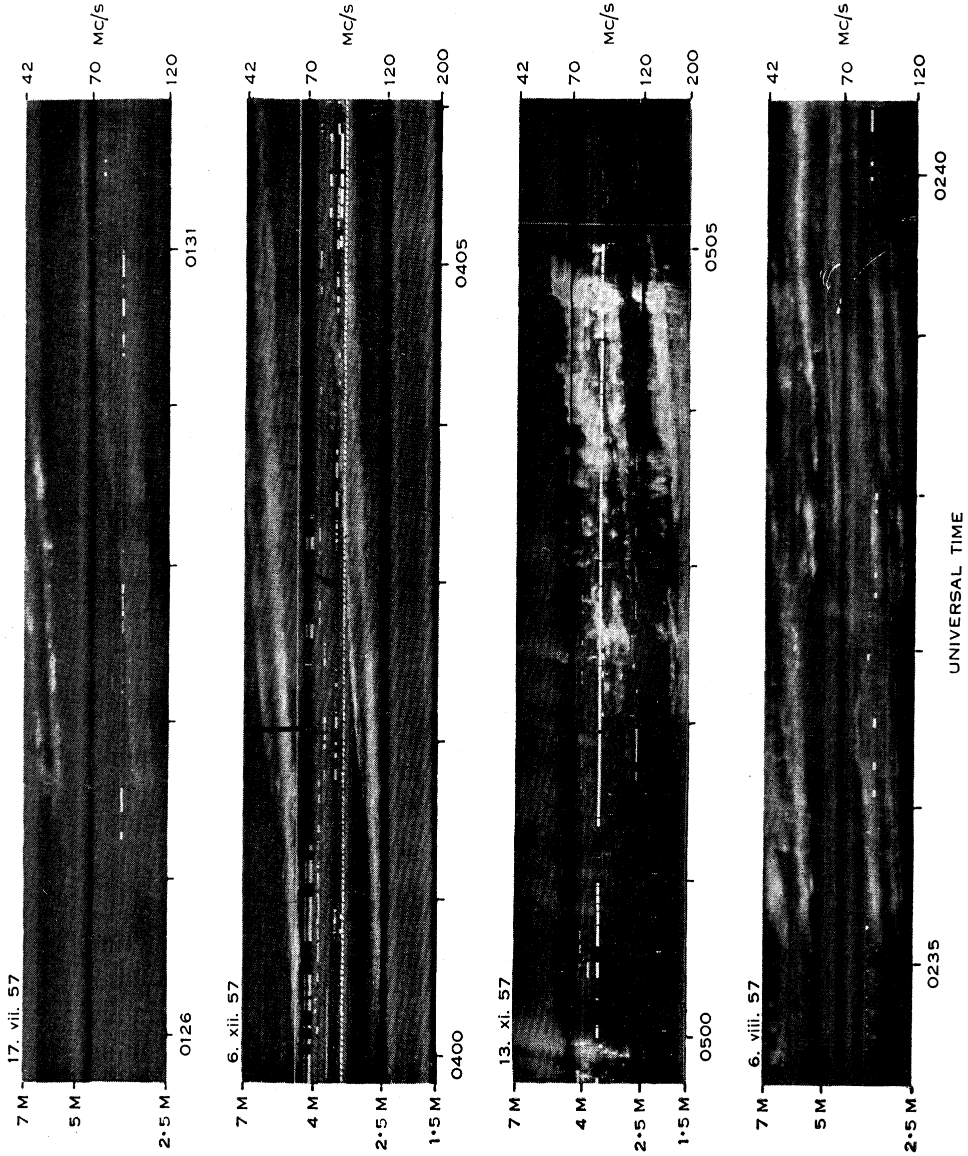

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