EVIDENCE OF ECHOES IN THE SOLAR CORONA FROM A NEW TYPE OF RADIO BURST

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Summary

A new spectral type of solar radio burst is described. The bursts contain two elements, the second being a repetition of the first after a delay of $1\frac{1}{2}$–2 sec. In each element the frequency *increases* with time at a rate of 2–8 Mc/s per sec. The bursts are of very short duration and are confined to the longer metre wavelengths. Occasionally they occur within, and evidently form part of the structure of, a burst of spectral type III.

It is suggested that the second elements of the bursts are echoes of the first, reflected from lower levels of the solar corona. If the burst radiation is assumed to occur at the second harmonic of the coronal plasma frequency, the delay between the elements can be quantitatively explained providing the coronal density gradient is $1 \cdot 5$ times steeper than in the Baumbach-Allen model.

Two alternative explanations of the rising frequency characteristic are considered. Either the exciting disturbances travel in through the corona at speeds between 2 and 5×10^4 km sec^{-1}, or the outward travelling disturbances responsible for type III bursts encounter " hills " of electron density in the corona.

I. Introduction

It is known from the work of Wild and McCready (1950) that the dynamic frequency spectrum provides a natural means of classifying solar radio bursts. Furthermore, observations over the past 5 years with a spectrograph covering the range 40–240 Mc/s (Wild, Murray, and Rowe 1954) have shown that the great majority of solar bursts fall naturally into the three spectral classes defined by the former authors. Of the rarer events which do not fit this classification there are some which form a distinct class characterized by a double structure in which two short-lived features drift rapidly from lower to higher frequencies. This positive frequency drift is in contrast to the negative drift in spectral types II and III. These bursts are therefore termed *reverse drift pairs*, or more briefly, *reverse pairs*.

In the following section a detailed description of the reverse pairs is given under a number of headings, and in Section IV a possible theory of the origin of the bursts is considered. Section III contains a brief description of certain other bursts which have some features in common with the reverse pairs, but which, on present evidence, appear to form separate classes of phenomena.

A preliminary account of this work was presented by Dr. J. L. Pawsey at the U.R.S.I. Assembly in Boulder, Colorado, in August 1957.

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II. A Class of Double Burst with Positive Frequency Drift

The reverse drift pairs were first recognized in records taken on December 1 and 2, 1955. More than 20 of these quite characteristic bursts were observed at that time, and many hundreds of such bursts have been recorded since. There are therefore sufficient data available to delineate the basic characteristics of the type.

Spectral records showing examples of the bursts are reproduced in Plates 1 and 2, and in Figure 1 the appearance of the bursts on a single-frequency (40 Mc/s) record is compared with that of bursts of spectral types I and III.

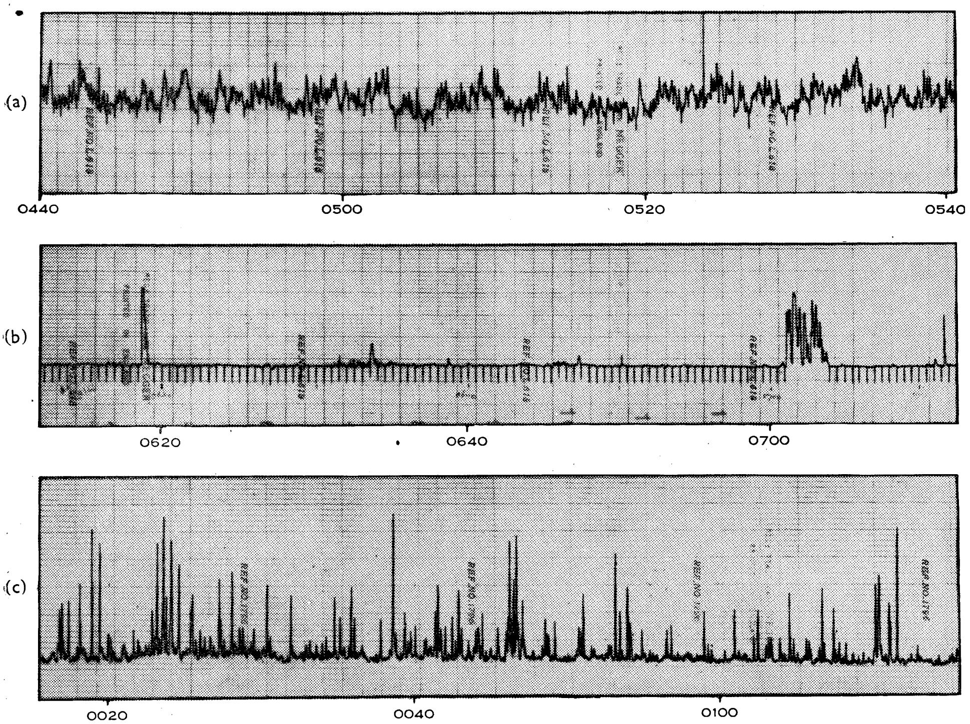

Fig. 1.—Single-frequency (40 Mc/s) records of (*a*) bursts of spectral type I (April 30, 1957), (*b*) bursts of spectral type III (April 4, 1957), (*c*) reverse drift pairs (March 13, 1957). In (*b*) time marks at intervals of $\frac{1}{2}$ min are shown by negative deflections (Universal times).

It is seen that in the frequency-time plane the reverse pairs have the appearance of two parallel ridges drifting rapidly from lower to higher frequencies at rates typically between 2 and 8 Mc/s per sec. The two elements of the bursts are usually very similar in form, although the intensities are sometimes markedly different. Many of the bursts begin at frequencies below 40 Mc/s, but from examples in which the full form of the burst is visible it is clear that both ridges commonly begin at the same frequency, the second ridge being delayed by approximately 2 sec after the first. In many cases the two ridges also terminate near the same frequency.

Each ridge is quite sharp—the duration at a single frequency is usually less than 1 sec, while the instantaneous bandwidth lies between 1 and 10 Mc/s. These durations and bandwidths are considerably less than those of type III bursts, which are the previously defined spectral type bearing most resemblance to the reverse pairs. A complete reverse pair may extend over a range of a few megacycles per second to a few tens of megacycles per second, with the corresponding total duration ranging from a few seconds to about 10 sec.

(*a*) *Occurrence*

Bursts of this type are rare. In the period from November 1955 to July 1957 observations were made on about 250 days and on only 38 of these days were reverse drift pairs observed. The bursts show a strong tendency to occur in storms lasting for hours or days. For the period of this investigation all clearly defined reverse pairs have been analysed—a total of 172 bursts in all. Of these, 59 (or 34 per cent.) occurred on March 12 and 13, 1957, a further 23 (13 per cent.) on June 5, 1957, 17 (10 per cent.) on December 1 and 2, 1955, and 10 (6 per cent.) on November 11, 1956. These four storms between them thus account for 63 per cent. of the bursts analysed.*

(*b*) *Frequency Range*

The frequency range of all the bursts studied is summarized in Figure 2. In this figure each burst is represented by a pair of contiguous lines which show the extent in frequency of the two elements of the burst. Figure 2(*b*) is a histogram showing the total number of bursts observed in each frequency interval.

It is immediately evident that the reverse pairs occur predominantly at the lower frequencies of the observed range, many extending below the frequency limit of the equipment at 40 Mc/s. The histogram shows an apparent decrease in the rate of occurrence for frequencies below 45 Mc/s, but this may be the result of overlooking inconspicuous events in which the reverse pairs barely extend into the frequency range of the observations.

(*c*) *Spacing between the Elements*

The double nature of the bursts and the constancy of the time separation of the two elements are distinctive characteristics of the reverse drift pairs. The histograms of Figure 3 show that for 80 per cent. of those analysed the time separation was from $1\frac{1}{2}$ to 2 sec. While reading errors certainly contribute to the spread of values in these figures, there are genuine variations between bursts, and between different frequencies in the same burst. Such variations with frequency are not always in one sense. The histograms show no significant consistent trend with frequency.

While the time separation of the elements lies between such close limits, the frequency separation varies considerably. This is evident from the wide variation in the rate of frequency drift (see Section II (*f*) below). Frequency separations range from a few megacycles per second to 10 Mc/s or more. The majority of values lie between 4 and 10 Mc/s.

* Since the preparation of this paper an outstanding storm of these bursts was recorded on September 2 and 3, 1957.

(*d*) *A Time Delay, not a Frequency Separation*

Double structure in the frequency-time plane could arise either from the simultaneous emission of two different bands of frequencies or from the occurrence of two similar events with a time delay between them. In the former case one

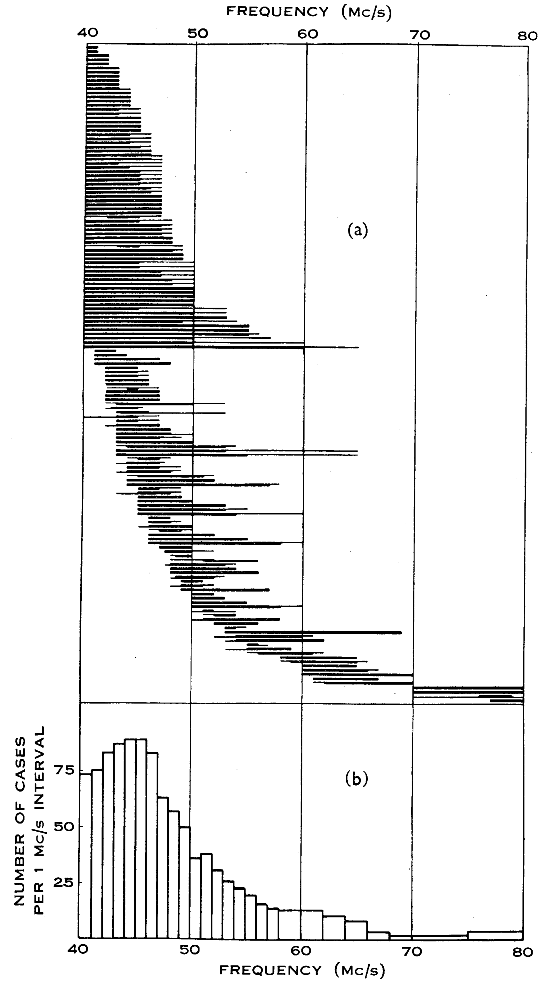

Fig. 2.—To illustrate the range of frequencies covered by the reverse pairs. (*a*) Each reverse pair is represented by a pair of contiguous lines which show the frequency extent of the two elements of the burst. (*b*) Histogram showing the prevalence of bursts at different frequencies.

would expect the burst to have the form shown in Figure 4(*a*), where the two elements begin (and end) simultaneously at different frequencies, and any structure in the burst occurs simultaneously in both elements. In the latter case the form shown in Figure 4(*b*) would be expected. Here both elements start at the same frequency (and both elements end at the same frequency), but they are separated in time. Any structure in the first element is repeated in the second element after a time delay and *at the same frequency.*

Examination of the examples given in Plates 1 and 2 and of the diagrammatic representation in Figure 2 shows that not all the reverse pairs conform to either of the idealized sketches of Figure 4. However, a large number of the examples conform approximately to the model of Figure 4(*b*)—a separation in time. In

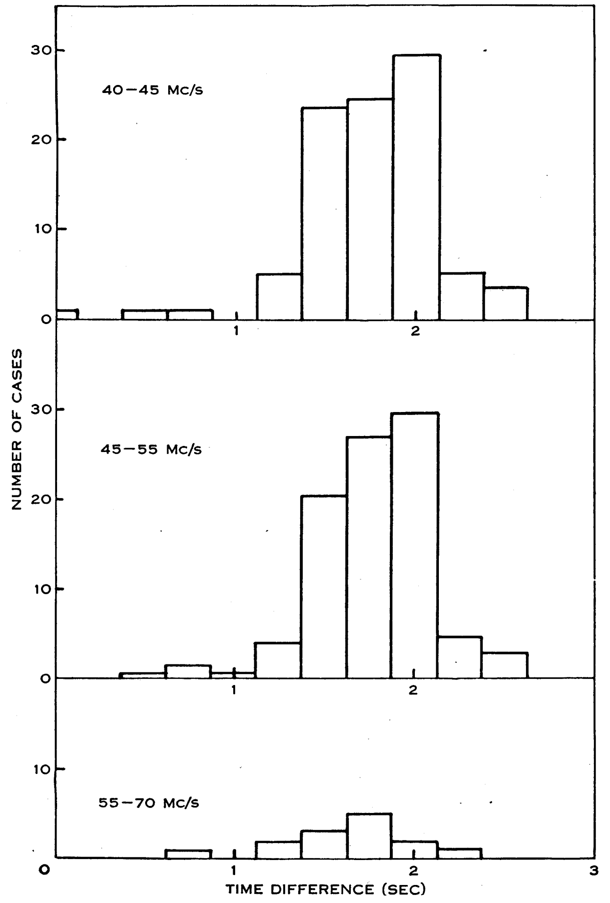

Fig. 3.—Histograms showing the separation in time of the two elements in the reverse pairs.

Plate 1 there are many cases of bursts in which both elements end at approximately the same frequency. Furthermore, in this plate, and particularly in Plate 2, there are striking examples of structure which is repeated in the second element of the burst at the same frequency (and not at the same time).

There is only one example in these figures which appears to conflict with the model of a time delay, namely the burst in Plate 1 on December 2, 1955 at 0032 U.T. In this reverse pair the curvature at the high frequencies appears to occur simultaneously in the two elements, rather than at the same frequency. As no other clear example of this nature has been observed, it seems that this should be regarded as an unusual feature. A possible explanation is suggested in Section IV(*e*).

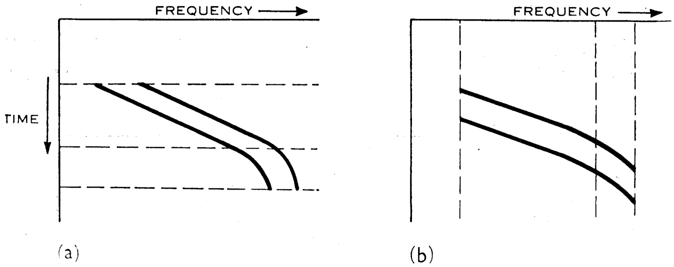

Fig. 4.—Idealized bursts. (*a*) Two bands of frequencies emitted simultaneously. (*b*) A single band of frequencies received via two channels with different propagation times.

The high degree to which the reverse pairs conform to the "time-delay" model is illustrated by Figure 5. From this it is seen that in the 83 bursts for which the beginning was observed, the difference between the frequencies at

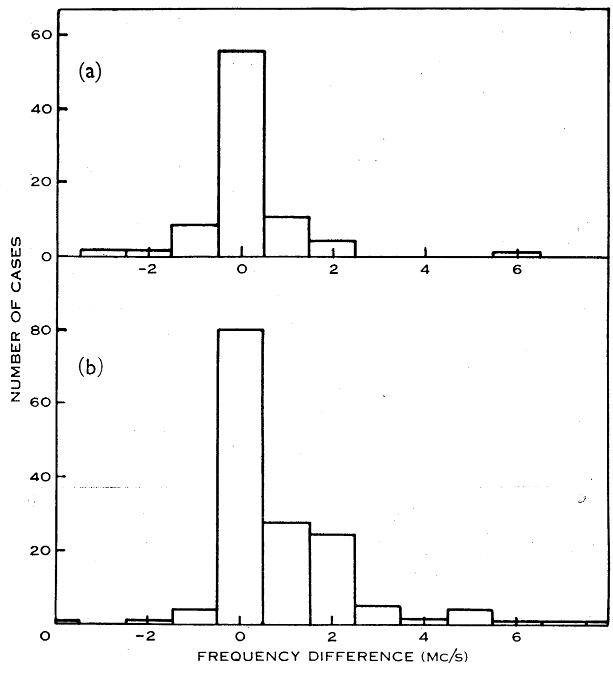

Fig. 5.—Histograms showing the difference in (*a*) the starting frequency, and (*b*) the finishing frequency of the two elements of the observed reverse pairs.

which the two parts began was distributed symmetrically about zero. Some 89 per cent. of the values lay between $\pm 1 \cdot 5$ Mc/s. If the bursts had in fact conformed to the double-frequency model (Fig. 4 (*a*)), these values would have been negative and equal to the frequency separation of the bursts. Thus according to Section II(c) the values would have been mainly between −4 and −10 Mc/s.

Similar remarks apply to the distribution of the difference between the frequencies at which the two parts ended (Fig. 5 (b)). However, here there is a small, but definite, asymmetry in the distribution.

Finally, it may be mentioned that another feature favouring the time delay model is the small range of values of the time separation of the elements as compared with the frequency separation (Section II (c)).

(e) *Duration at a Single Frequency*

The reverse drift pairs appear on the records as very sharp features owing to their short duration at a single frequency. This duration is substantially independent of frequency. A histogram of durations given in Figure 6 shows that values greater than 1 sec are rare. By contrast, type III bursts at these frequencies usually last several seconds.

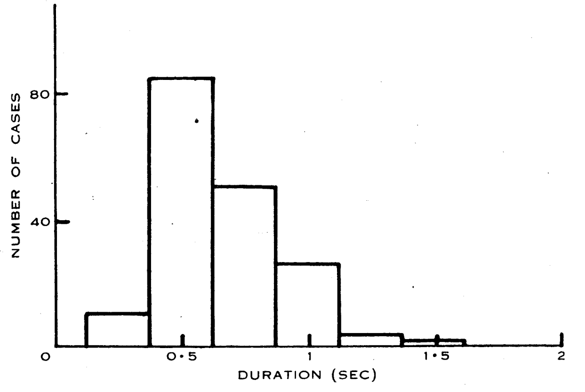

Fig. 6.—The duration of a single element of the reverse pairs at any one frequency.

Successive spectra are separated by $\frac{1}{2}$ sec in time, so that durations of less than $\frac{1}{2}$ sec are difficult to assess. For bursts with *total* durations of some seconds, however, the single-frequency duration may still be determined. It is likely that some of the values appearing in the histogram in the column centred on $\frac{1}{2}$ sec properly belong in the column centred on $\frac{1}{4}$ sec. Nevertheless, the commonest duration is probably close to $\frac{1}{2}$ sec.

(f) *Rate of Frequency Drift*

The distribution of the rate of change of frequency in the reverse pairs is shown in Figure 7. For 80 per cent. of the bursts the frequency increases at a rate between 2 and 8 Mc/s per sec. The frequency drift, besides being in the opposite sense to that in type III bursts, is also somewhat smaller in magnitude. For most type III bursts, at frequencies near 40 Mc/s the rate of decrease of the frequency of the fundamental band lies between 3 and 12 Mc/s per sec.

Not shown in Figure 7 are 13 cases in which the frequency drift was immeasurably great. In most of these cases the condition existed only at frequencies near 40 Mc/s and the rate decreased at higher frequencies. In two cases, however, all frequencies in the burst occurred simultaneously within the

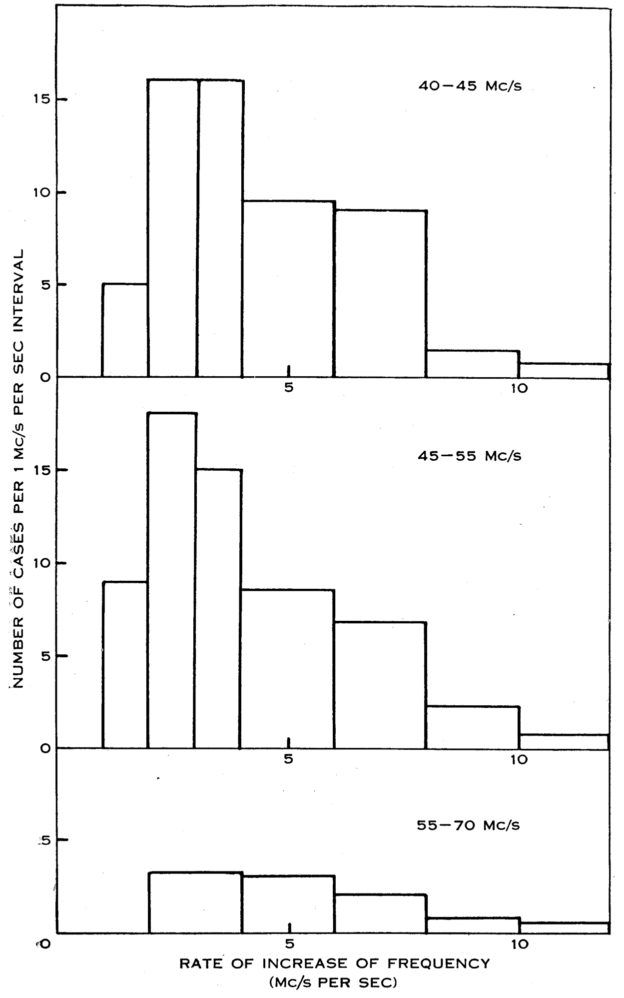

Fig. 7.—The rate of frequency drift in the reverse pairs.

limits of measurement. In addition, one case was noted in which the frequency drift was negative near 40 Mc/s but became positive at higher frequencies, so that frequencies near 42 Mc/s occurred first.

According to the histograms of Figure 7, the frequency drift, when averaged over many reverse pairs, is very similar at all frequencies. Most of the bursts in Plate 1 will be seen to agree individually with this statistical result, when allowance is made for the slight curvature produced by the compression of the frequency scale at the upper end. However, in some of the examples in this plate the rate of change of frequency decreases markedly at the higher frequencies (later times). In the examples in Plate 2 (*a*) there are sudden changes in the rate of frequency drift, several changes occurring in the same burst.

(*g*) *Intensity and Polarization*

Compared with other bursts occurring at these frequencies, the reverse pairs are relatively weak. Measured flux densities in one plane of polarization range from the limit of detection ($\sim 5\times10^{-21}$W m^{-2} (c/s)$^{-1}$) up to about 5×10^{-20}W m^{-2} (c/s)$^{-1}$. Often the two elements of the bursts are of similar intensity, but there is a tendency for the second element to be weaker. This is illustrated by the histogram of intensity ratios in Figure 8, which summarizes the data for 26

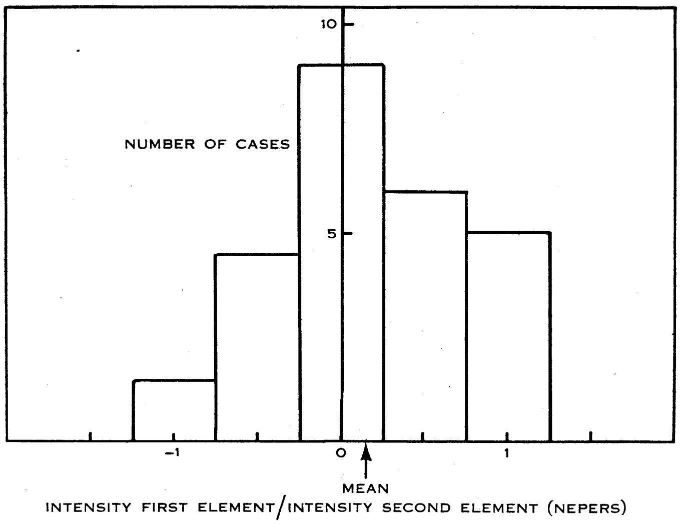

Fig. 8.—Histogram showing the ratio of the intensities of the two elements of the reverse pairs. Data for the 26 strongest bursts in three periods of approximately 15 min each on March 12 and 13, 1957. Results derived by microphotometering the film records, scanning along a line of constant frequency, which was 40 Mc/s for two of the periods and 45 Mc/s for the third period.

reverse pairs on March 12 and 13, 1957. This histogram is thought to be reasonably representative of this storm. On other occasions the relative weakness of the second elements has been more marked ; numerous cases of single elements bursts have been noticed.

As yet no observations have been made of the polarization of these bursts.*

(*h*) *Positional Observations*

On March 12 and 13, 1957 some reverse pairs were observed with a swept-frequency interferometer similar to that described by Wild and Roberts (1956). When the approximate declination of a source is known, this instrument is capable of determining the Right Ascension of the source to within a few minutes

* Reverse drift pairs observed on September 19, 1957, were found to be not strongly polarized.

of arc. Unfortunately the reverse pairs observed with the interferometer did not extend over a sufficiently wide range of frequencies to enable all ambiguities to be resolved. There are therefore a number of possible values of Right Ascension for the bursts. If the declination of the source is assumed to be close to that of the Sun, all these position in Right Ascension lie within a solar diameter of the centre of the disk, and the most probable position is 5 min of arc E. These observations therefore strongly suggest that the reverse pairs are indeed of solar origin, and this conclusion is completely supported by the association with type III bursts, which is discussed in the next subsection.

On June 4 and 5, 1956, Kraus (1956*a*) observed short duration " double-humped " bursts at 27 Mc/s. He gave an indirect argument suggesting that the bursts originated on Venus. As the spectrograph recorded a small storm of reverse drift pairs on June 5, it seems possible that the bursts reported by Kraus may be of the same nature.* The interferometer records referred to above were therefore re-examined to see if it were possible that the reverse pairs came from Venus. Although, on the day in question, Venus was within 10° of the Sun, the interferometer records make it quite impossible that these bursts could have come from Venus. For a source on Venus the frequency separation of the interferometer lobes would have been 32 Mc/s while the observed value was 2·73 Mc/s. Similar considerations apply in the case of Mercury, the only other planet close to the Sun at this period.

(*i*) *Relationship to Bursts of Other Spectral Types*

About 10 per cent. of the reverse pairs appear to occur in, and evidently form part of, a burst of spectral type III. Some examples of such events are shown in Plate 2(*b*), and the last example in Plate 1 may also be of this type. These reverse pairs occurring within type III bursts appear to be otherwise indistinguishable from those occurring separately. However, as yet no reverse pair extending over a wide range of frequencies (>15 Mc/s) has been observed in a type III burst.

In all of these events the reverse pair is of greater intensity than the type III burst, and in most cases the type III event is very weak and diffuse. A reverse pair has never been observed in a very intense type III burst.

The number of clear examples of these events so far recorded is insufficient to define properly the relationship between the two bursts. As is seen from Plate 2(*b*) there seems to be a tendency for the extent of the first element of the reverse pair to be limited to the extent of the type III burst. However, in other less clearly defined cases, the reverse pair appears to extend beyond the type III burst. In some cases the rate of frequency drift in the type III burst is apparently smaller on the low frequency side of the reverse pair.

No definite relationship has been found with any other type of activity, and indeed on a number of occasions (e.g. March 12, 1957) reverse pairs have been

* It is not yet possible to say whether the reverse drift pairs are modulated at audio frequencies as described by Kraus. In a later publication Kraus (1956*b*) found that double-humped bursts on June 29, 1956 had a *negative* frequency drift. No spectrograph records are available for this date, but see Section III (*a*) of the present paper.

the only activity recorded. However, in the case of all the four storms mentioned in Section II (*a*), a type I storm was also in progress at the higher frequencies for at least part of the time.

(*j*) *Repetition of Features at Several Frequencies*

Another feature of the reverse pairs which may be of some significance is the occasional occurrence of an event in which two or more reverse pairs occur simultaneously, or nearly simultaneously, at different frequencies. Some examples are seen in Plate 2. The ratio of the frequencies of the two bursts is considerably less than 2 and in fact varies widely from case to case. In the examples in Plate 2(*b*) the two related reverse pairs are evidently superimposed on the same type III burst. Other examples of this behaviour are known. In Plate 2(*a*) there is a quite extraordinary example of this repetition. The burst appears to consist of four separate reverse pairs, together with a superimposed pair with negative frequency drift which extends from below 40 Mc/s to 44 Mc/s. These bursts are so combined that over the greater part of the frequency range the event appears to consist of two ridges parallel to the frequency axis.

III. Other Multiple Bursts

In this section a brief description is given of two other types of multiple burst which are similar in some respects to the reverse drift pairs described above.

(*a*) *Bursts with Negative Frequency Drift*

A small number of bursts have now been recorded which are very similar to the reverse pairs except that the sense of frequency drift is opposite, i.e. the frequency decreases with the passage of time. Some examples of these bursts may be seen in Plate 3, Figure 1. These bursts are even more rare than the reverse pairs. Only 12 bursts have been examined in detail, so that the description given here is necessarily tentative.

The bursts all occurred on days when reverse pairs were also recorded. The spacing of the elements again appeared to be mainly a separation in time; the mean separation measured was $1\frac{1}{2}$ sec and the range of values $1\frac{1}{4}$–2 sec. In the sample available the duration of each element of the burst (at a single frequency) was noticeably less than in the reverse pairs. In most of the examples in Figure 1 of Plate 3 the durations are less than $\frac{1}{2}$ sec so that at any one frequency the bursts appear on only one scan.

Frequency drift rates range from $-1\cdot5$ to -3 Mc/s per sec, with a mean value of $-2\cdot4$ Mc/s per sec. These values are very similar in *magnitude* to those for the reverse pairs (Fig. 7): the rates are noticeably lower than those for type III bursts. The contrast between these bursts and type III bursts is well illustrated by the last example in Figure 1 of Plate 3 where two of these double bursts with negative frequency drift appear superimposed on a type III burst.

All the bursts of this nature so far recorded have occurred at frequencies below 80 Mc/s, but the concentration to the lower frequencies does not appear to be as marked as in the case of the reverse pairs. None of the bursts recorded has been of very great intensity. If the sample at present available is typical, these bursts do not form such a homogeneous class as the reverse pairs. The sample contains a high proportion of single bursts and some triple bursts.

(b) *Unusual Bursts with Positive Drift*

On June 5, 1957, five unusual double bursts were recorded. All were remarkably similar in form. Four are reproduced in Figure 2 of Plate 3. These bursts may be described as double bursts with positive frequency drift, but they do not appear to belong to the class referred to as reverse drift pairs. In the bursts of Plate 3, Figure 2, the two elements begin at the same time and end at the same time, i.e. the splitting is in frequency and not in time. Furthermore, the rate of frequency drift is very much less than in the reverse pairs—the values range from 0·33 to 0·42 Mc/s per sec.

All five bursts occurred between 43 and 46 Mc/s and each lasted between 3 and 4 sec. The frequency separation of the two elements ranged from $\frac{1}{2}$ to 1 Mc/s. The two parts of the bursts are not simple ridges, but contain remarkable fine structure, some of which is visible in the figure. In several of the bursts the lower frequency element is double, with a separation of a few tenths of a megacycle per second between the " fine-structure " ridges. This separation varies between bursts and throughout the course of any one burst. In some cases the high-frequency element also appears to be split, the separation in this case being very much less ($\sim$0·03 Mc/s).

It is necessary to add that there is no proof that these bursts are of solar origin. Many reverse drift pairs were also observed on this day, but, as the positions of these unusual bursts were not measured, it is possible that they did not come from the Sun.

IV. A Theory involving Echoes in the Regular Corona

(a) *Introduction*

This section outlines a possible theory of the origin of the double bursts with positive frequency drift, described in Section II. The discussion is confined to these reverse drift pairs as the present observations appear to be inadequate to define the basic characteristics of the other bursts described in Section III.

(i) *Echoes in the Regular Corona.*—It was shown in Section II(*d*) that the second elements of the reverse pairs are approximate repetitions of the first elements after a time delay of $1\frac{1}{2}$–2 sec. This suggests that a single band of frequencies is generated but that it is received via two paths with different propagation times. Many possibilities of this nature suggest themselves—echoes could occur from coronal irregularities, propagation could be via the two magneto-ionic modes, etc. However, echoes from the *regular* corona would seem to be the first possibility to investigate, since it has been shown (Jaeger and Westfold 1950) that such echoes should occur and should have time delays of several seconds.*

* Jaeger and Westfold in fact proposed that the " double-humped " forms of " unpolarized bursts " were due to echoes from the regular corona. However, it is now known that in these bursts (of spectral type III) the second part is the second harmonic and not a delayed repetition of the first part (Wild, Murray, and Rowe 1954).

Jaeger and Westfold showed that there are, in general, two rays to the Earth from any accessible point in the solar corona. These may be described as the direct and reflected rays (Fig. 9). The time delay between receiving a disturbance via the direct and reflected paths—the echo delay—depends on the height of the source, its position on the disk, and the frequency. When the source lies on the escape level for the frequency in question the two paths are identical and the delay is zero. As the height of the source is increased above the escape level the echo delay increases, reaching 5–10 sec at a height of 1 solar radius. Thus, to explain the observed delays in terms of echoes, we seek a natural reason for locating the source at such a height as to produce delays of the order of 2 sec.

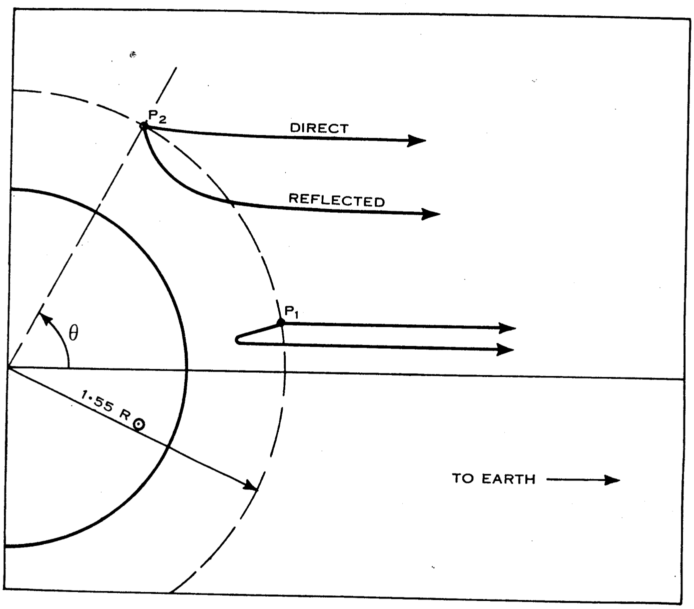

Fig. 9.—Showing the paths of direct and reflected rays in the corona for a source located at the 30 Mc/s plasma level and radiating at 60 Mc/s.

(ii) *Radiation at the Second Harmonic of the Coronal Plasma Frequency.*—The theory considered here supposes that the height of origin is determined by the condition that the radiation occurs at frequencies close to the second harmonic of the local coronal plasma frequency. This hypothesis is a simple extension of the theory which has found support as an explanation of the features of bursts of spectral types II and III (Wild, Murray, and Rowe 1954). It accounts naturally for the constancy of the time delay over periods of years and it will be shown that it can give reasonable quantitative agreement with the observations.

For a source near the centre of the disk radiation at frequencies near the *fundamental* plasma frequency would also be expected to escape (Wild, Murray, and Rowe 1954). For these frequencies the echo delay would be only a fraction of a second, so that such a burst would appear single. This leads to one of the tests of the present hypothesis discussed in Section IV (*c*) (iv).

(iii) *The Positive Frequency Drift.*—Two explanations of the positive frequency drift are considered. In the first it is supposed that a disturbance travels inward through the corona exciting successively higher frequencies of oscillation as it penetrates to regions of higher electron density. On this theory observed frequency drift rates imply speeds of $2\text{–}5\times10^4$ km sec^{-1}, which are far greater than the speed resulting from falling under gravity from infinity.

In the other theory, suggested to the author by Mr. J. P. Wild of this laboratory, the radiation is supposed to be produced by outward travelling disturbances when they encounter " hills " of electron density in the corona. This second explanation is suggested by the occurrence of these bursts within type III bursts (Section II (*i*)), the type III bursts being attributed to the interaction of the outward moving disturbances with the regular corona. The common occurrence of the reverse pairs without an accompanying type III burst requires one to assume that in these cases the type III part is too weak to be detected. On this theory the frequency drift rates imply that the gradients of electron density in the " hills " are about two-thirds of the gradient in the regular corona.

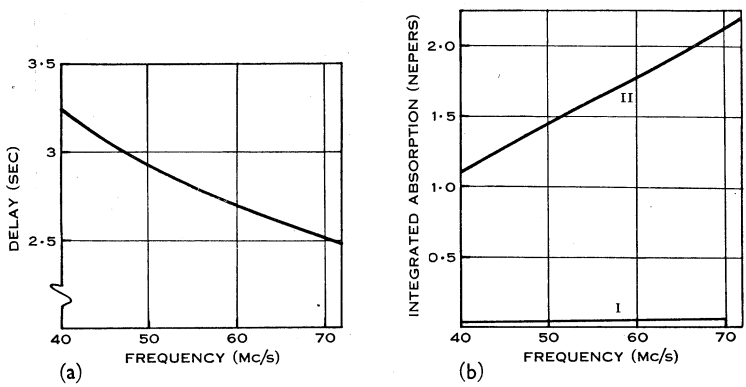

Fig. 10.—Frequency dependence of the properties of rays from a source in the centre of the disk radiating at twice the local coronal plasma frequency. Baumbach-Allen model. (*a*) Time delay of the reflected ray after the direct ray. (*b*) Integrated absorption in the direct ray (curve I) and excess integrated absorption in the reflected ray (curve II).

(*b*) *Predicted Properties of the Echoes*

Many of the characteristics of the echoes from a source in the corona radiating at the second harmonic of the local plasma frequency can be deduced from the curves given by Jaeger and Westfold (1950). Some further properties are derived in Appendix I, and the results are summarized in Figures 10 and 11. In the derivation of these results it has been assumed that the corona is spherically symmetrical and that the electron density distribution is that given by Allen (1947).

Figure 10 shows the frequency dependence of the delay between the direct and reflected waves for a source in the centre of the disk. The absorption in the direct ray and the excess absorption in the reflected ray are also given in this figure. If the source is not in the centre of the disk the predicted delay is less (Fig. 11 (*a*)). As the source is displaced from the centre of the disk (but kept at the same height) the paths of the two rays become more alike, and when the source lies on the escape level the paths are identical and the time delay is zero. No radiation can be received from sources beyond this point.

The absorption in the direct ray increases as the source is displaced from the centre of the disk, but is never appreciable (Fig. 11 (*b*)). The excess absorption in the reflected ray decreases to zero as the two paths approach identity.

Refraction modifies the emission polar diagram of the source (Fig. 11 (*c*)). When the source is near the centre of the disk the atmosphere acts as a converging lens for the direct rays but the reflected rays diverge so that the reflected image is of lower apparent intensity. As the source is displaced from the centre of the disk both direct and reflected rays become converging, so that if rays leave the source isotropically the apparent intensity of the source increases. As the source approaches the escape level this focusing effect becomes very pronounced.

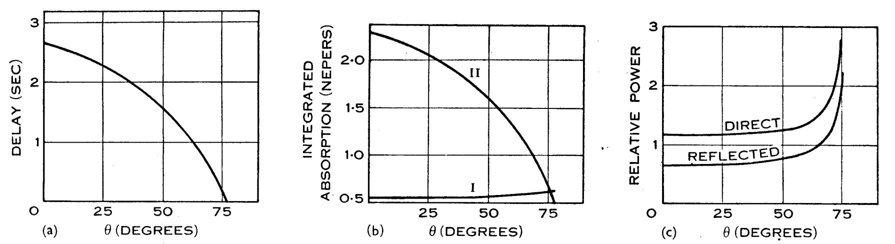

Fig. 11.—Centre to limb variation for a source at the 30 Mc/s plasma level radiating at a frequency of 60 Mc/s. The source position angle θ is defined in Figure 9. (*a*) Time delay of the reflected ray after the direct ray. (*b*) Integrated absorption in the direct ray (curve I) and excess integrated absorption in the reflected ray (curve II). (*c*) Effective emission polar diagram (unnormalized). The results in this figure are derived from the curves given by Jaeger and Westfold (1950). The effective emission polar diagram in (*c*) is just $d\theta'/d\theta$ where θ', θ are the initial and final directions of the ray measured from a radial line through the source.

(*c*) *Comparison with Observations*

(i) *Time Delays.*—A comparison of the observed time delays (Fig. 3) with those predicted for central rays (Fig. 10(*a*)) shows that the predicted values are certainly of the right order. However, if the sources were observed at all (accessible) distances from the centre of the disk, the predicted delays would range over all values from zero up to that for central rays (Fig. 11(*a*)). This conflicts with the narrow range of values observed. If this theory is correct, therefore, it seems that the sources are observed only over a narrow range of distances from the disk centre. Neither absorption (Fig. 11 (*b*)) nor refraction (Fig. 11 (*c*)) can account for this, so that it is necessary to suppose that the rays leave the source preferentially in certain directions.

If the sources are observed only near the centre of the disk, i.e. if the preferential directions are radial (inwards and outwards) and the sources lie at low latitudes, then the predicted delays are too great by approximately 1 sec (Fig. 10(*a*)). To secure agreement it is then necessary to suppose that the density gradient in the corona is greater, by a factor of about 1·5, than that given by the Baumbach-Allen model (r^{-6} approximation).

Alternatively the observed delays would agree with those predicted for the Baumbach-Allen model if the sources were observed only between about 40 and 60° from the centre of the disk. Such a restriction to a non-central range of angles would arise if the sources occurred at high latitudes ($\sim$40°), and had radially directed polar diagrams of appropriate width.

It is of course necessary to consider whether the deficit of low values in the measured delays (Fig. 3) is not due to the coalescence of the two elements when the delay becomes small. Although this effect should become appreciable for time separations $\sim$1 sec, it is not thought that many bursts are overlooked through this process as relatively few single bursts of long duration are observed.

(ii) *Differential Absorption.*—The relative intensities of the two elements of the bursts should provide another parameter for testing the theory. However, there are insufficient measurements available for an exhaustive test. Furthermore, the measurements on March 12 and 13, 1957 (Fig. 8) show a very wide scatter, including cases in which the second element is the stronger. This suggests that some other process, perhaps scattering by irregularities, produces relative intensity differences between the two rays, which can be of either sign.

Figure 8 shows that the *mean* intensity ratio on March 12 and 13, 1957 was only about one-sixth of the predicted ratio for central rays (Fig. 10(*b*)).

(iii) *The Two Explanations of the Positive Frequency Drift.*—It is not possible at present to decide between the two suggested explanations of the positive frequency drift, namely, inward-travelling disturbances exciting the regular corona or outward-travelling disturbances encountering " hills " of electron density in the corona. However, the former explanation is slightly favoured, as the short duration and narrow bandwidth are then readily explained merely by supposing that the distubances are of sufficiently small extent ($\lesssim 10^4$ km). With the alternative theory it is difficult to account for the narrow bandwidth. The appearance of the reverse pairs superimposed on the type III bursts, without evident distortion of the type III event, implies that the lateral extent of the travelling disturbance is very much greater than that of the coronal " hill ". One would therefore expect the disturbance to excite a continuous range of plasma frequencies corresponding to the range of densities in the hill up to the highest point reached by the disturbance.

Further study of the relationship between the reverse pairs and type III bursts might well decide between the two theories. While the occurrence of reverse pairs within type III bursts is inherent in the alternative theory, with the first theory such an event must imply a " collision " of an inward and an outward moving disturbance. There are thus differences between the predictions of the two theories regarding the details of such an event. While the form of the event observed in a number of cases (Plate 2(*b*)) favours the collision model, there are considerable variations between events. Many more examples will be needed to define the properties of this association adequately.

(iv) *The Second Harmonic Nature of the Bursts*.—As was pointed out in Section IV(*a*) (ii) the theory discussed here implies that reverse pairs originating near the centre of the disk will be accompanied by *single* bursts—the fundamental band—at half the frequency. This prediction should provide a test of the theory, provided the bursts sometimes originate near the centre of the disk (cf. Section IV (*c*) (i)). So far only one double burst has been observed at a sufficiently high frequency for the predicted fundamental band to lie within the frequency range of the equipment. In this case no fundamental was detected. However, this burst was by no means typical of the class ; the time separation was $4\frac{1}{2}$ sec and the duration at a single frequency was 2 sec.

This test may be made in another way if a plasma origin is assumed for the type III bursts also. For then it follows that the type III band in which the double bursts occur should be the second harmonic band. Unfortunately, in no event of this kind so far recorded has it been possible to assign a harmonic number to the type III component involved.

It appears that further observations, preferably extending to lower frequencies, are needed to check these predictions.

(*d*) *Echoes of Other Solar Bursts*

It remains to consider whether echoes of other solar bursts should not be observed if this theory were correct. Evidently the second harmonic components of type III bursts are all that need be considered. At frequencies near 40 Mc/s the durations of these bursts are many seconds, so that any echo would be masked. At higher frequencies, the situation is more confused. Above about 100 Mc/s the durations are often 1 sec or less, so that on the model of Figure 10 separate echoes should be recorded. A number of examples of possible echoes are found in the records, but the tendency for type III bursts to occur together in groups makes it impossible to be sure that the suspected echoes are not, in fact, separate bursts.

(*e*) *Structure Simultaneous in Time*

In Section II(*d*) attention was drawn to an exceptional case in Plate 1 in which the curvature in the two elements appears to occur more nearly at the same time than at the same frequency. As there seems to be ample evidence to show that the second element of a reverse pair is usually a delayed repetition of the first, it is suggested that in this case both elements were simultaneously subjected to some extra delay. Such a delay could perhaps arise from the source (and the image) passing behind a coronal streamer.

(*f*) *The Decay Time of Coronal Plasma Oscillations*

Attention may be drawn to a general conclusion which follows from the assumption that the reverse pairs and type III bursts both originate in coronal plasma oscillations. Westfold (1949) (see also Payne-Scott 1949) suggested that the duration of type III bursts (at one frequency) was determined by the decay of the oscillations of the coronal plasma after the excitation was removed. As the duration of the present bursts is very much less than that of type III bursts (at the same frequency), it follows that the duration of type III bursts is not determined by the decay time; it is presumably determined by the extent of the exciting disturbance.

In proposing the decay-time theory of the duration of type III bursts, Westfold showed that the durations were close to the values predicted on the assumption that the oscillations were damped by collisions. However, it has been suggested by Dr. R. Q. Twiss (personal communication) that coronal plasma oscillations would be much more rapidly damped by the diffusing effect of thermal velocities—a process known as Landau damping (Landau 1946; Berz 1956).

V. Conclusion

The main characteristics which distinguish the reverse drift pairs from other known types of solar radio bursts may be summarized as follows:

(i) The bursts are double, the second part apparently being a repetition of the first part after a delay of $1\frac{1}{2}$–2 sec (Section II(*c*) and (*d*)).

(ii) The frequency drift is positive, the frequency increasing with time at a rate of 2–8 Mc/s per sec (Section II(*f*)).

(iii) The duration of the bursts at a single frequency is very short, usually less than 1 sec (Section II(*e*)).

(iv) The bursts are confined to the lower frequencies, the rate of occurrence of the bursts increasing steadily with decreasing frequency, at least to $\sim$40 Mc/s (Section II(*b*)).

(v) Occasionally the bursts appear in close association with type III bursts and may be a feature of those bursts.

All of these characteristics distinguish the bursts as a separate type of activity—they are not, for example, a variety of type III burst with positive frequency drift. However, there is a type of burst with negative frequency drift, which resembles the reverse pairs fairly closely (Section III(*a*)).

The theory discussed in Section IV appears to be capable of explaining the main features of these bursts, but to achieve quantitative agreement some additional assumption or modification is required (Section IV(*c*) (i) and (ii)). With certain assumptions as to the emission polar diagram of the source, reasonable agreement could be secured if the gradient of electron density in the corona were steeper (by a factor $\sim 1\cdot 5$) than that given by Allen (1947). Alternatively agreement may be possible if the bursts occurred at fairly high latitudes ($\sim 40°$).

This theory predicts that the reverse pairs will sometimes be accompanied by *single* bursts at half their frequency, and that they will not occur in the fundamental band of type III bursts. Further observations, particularly if extended to lower frequencies, should allow these predictions to be tested. Such observations will also define more clearly the relationship of the reverse pairs to the type III bursts in which they occur. It is felt that a study of this relationship will throw considerable light on the origin of the bursts. Accurate position measurements would provide a further check of the theory, and, if both coordinates of the burst position were measured, a decision between some of the alternative forms of the theory would be possible.

Whether or not the suggested theory is correct, it can be concluded from propagation conditions alone that the reverse pairs are generated in the high corona. This itself is suggestive of incoming material. No optical counterpart to the bursts has been discovered; these considerations suggest that correlation should be sought with optical phenomena in the upper corona, and perhaps at high latitudes.

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Appendix I

The frequency dependence of the echo delay for central rays is derived under the following assumptions:

(i) The radiation occurs at the second harmonic of the local coronal plasma frequency,

(ii) The coronal electron density is given by the r^{-6} approximation to the Baumbach-Allen distribution, and

(iii) Coronal magnetic fields do not produce appreciable effects.

The refractive index μ is then given by (Jaeger and Westfold 1950, equation (**10**))

$$\mu^2 = 1 - 1\cdot 41 \times 10^9 f^{-2} r^{-6},$$

where f is the wave frequency in megacycles per second and r is the distance from the centre of the Sun in units of 10^5 km. It will be convenient to introduce $x = 1\cdot 41 \times 10^9 f^{-2} r^{-6}$, so that $\mu^2 = 1 - x$.

When the wave frequency is equal to the local plasma frequency $x=1$ and $\mu=0$. This is the turning point for a central ray. At the generation level, where the frequency is twice the local plasma frequency, $x=\frac{1}{4}$. The time delay between the direct and reflected rays is thus given by

$$2\int_{x=1}^{x=\frac{1}{4}} \frac{\mathrm{d}r}{\mu c},$$

where c is the free-space velocity of light.

The integral is evaluated by first changing the variable to give

$$3\cdot 72 f^{-1/3}\int_{\frac{1}{4}}^{1} x^{-7/6}(1-x)^{-\frac{1}{2}}\mathrm{d}x.$$

Then expanding $(1-x)^{-\frac{1}{2}}$ and integrating term by term gives

$$3\cdot 72 f^{-1/3}\left[\sum_{n=0}^{\infty} \frac{(2n)!x^{n-1/6}}{n!n!2^{2n}(n-1/6)}\right]_{\frac{1}{4}}^{1}.$$

The series converges for $x\leqslant 1$. At the upper limit ($x=1$) the sum is known to be

$$\frac{\Gamma(-1/6)\Gamma(\frac{1}{2})}{\Gamma(\frac{1}{2}-1/6)}=-4\cdot 23.$$

At the lower limit the convergence is reasonably rapid and the sum is found to be approximately $-7\cdot 35$.

Thus one finds for the time delay between the direct and reflected rays

$$11\cdot 6 f^{-1/3} \text{ sec},$$

where f is the wave frequency in Mc/s. These values are plotted in Figure 10 (*a*).

The integrated absorption for central rays is computed in a similar fashion. The integrated absorption is

$$2\int \varkappa \mathrm{d}r,$$

where $\varkappa$ is the *field* attenuation coefficient. Using Jaeger and Westfold's value for the collision frequency (but dropping the r^{-10} terms), the integral can again be expressed in terms of x to give

$$2\int \varkappa \mathrm{d}r=4\cdot 61\times 10^{-3} f^{7/6}\int x^{7/12}(1-x)^{-\frac{1}{2}}\mathrm{d}x.$$

The integral is evaluated by expanding $(1-x)^{-\frac{1}{2}}$ and one finds ultimately for the integrated absorption in the direct ray

$$3\cdot 5\times 10^{-4} f^{7/6} \text{ nepers},$$

and for the excess integrated absorption in the reflected ray

$$1\cdot 34\times 10^{-2} f^{7/6} \text{ nepers}.$$

As before f is measured in megacycles per second. These values are plotted in Figure 10 (*b*).