THE PREVALENCE OF SECOND HARMONIC RADIATION IN TYPE III BURSTS OBSERVED AT KILOMETRIC WAVELENGTHS

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Abstract. We present the analysis of 64 type III solar bursts that drifted from 3.5 MHz down to the range 350–50 kHz between March 1968 and February 1970. Bursts arrival times were predicted by a simple model and then compared with observations. The results show that, as the bursts drift, the fundamental often disappears below a certain frequency range while the second harmonic remains. Below about 1 MHz the second harmonic occurrence predominates. Recognizing this fact we deduce a mean velocity of $0.32c \pm 0.02c$ for the exciter particles, where the uncertainty is the standard error and c the velocity of light in vacuum; the electron density model used is comparable to a solar wind model.

1. Introduction

This is the second paper of a series in which we present the analysis of observations of type III solar bursts at kilometric wavelengths. The data were obtained with the radiometer that the University of Michigan has aboard the OGO-5 satellite. The description of the instrument and of the observations has been given in a previous paper that will be referred to as Paper I (Alvarez and Haddock, 1973). Briefly, the instrument consists of a 9.15-m long antenna and of a receiver that steps in 9.2 s through the following frequencies: 3.5, 1.8 MHz, 900, 600, 350, 200, 100, and 50 kHz. This study is based on 64 of the 79 events that were observed at a frequency of 350 kHz or lower, that is, in the kilometric wavelength range between March 1968 and February 1970. The data for the other 15 events were not available at the time of this analysis.

Following the local plasma hypothesis (Wild, 1950) we have assumed that the bursts are produced by a group of fast particles traversing the solar corona with a constant velocity and exciting the local plasma frequency, its second harmonic or both modes. In this paper we will denote a velocity by its fraction, β, of the velocity of light in vacuum.

Most of the velocity determinations depend on a model of electron density distribution of the solar corona. The exceptions are the works of Wild *et al.* (1959), Slysh (1967) and Fainberg and Stone (1970). Wild *et al.* made direct measurements of source position with a sweep frequency interferometer and found velocities between 0.2 and 0.8 with an average of 0.45. Slysh used the angular distance of the source from the Sun to analyze two radio events and found velocities between 0.4 and 0.5. Fainberg and Stone studied active sources on the disc as they followed the Sun's rotation and determined an average value of 0.38; their results are only weakly dependent on a

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model. An average velocity of 0.33 has been generally used in theoretical work.

We have predicted the times of arrival of the burst radiation, fundamental and second harmonic, at the frequencies of observation based on the assumptions used in Paper I. Comparing with observations we found that, as the bursts drift down in frequency, the fundamental often disappears from our records below certain frequency and only the second harmonic remains. The occurrence of the second harmonic becomes more frequent as the frequency decreases; below about 1 MHz the occurrence rate of the second harmonic predominates over the fundamental.

Early workers found that they needed electron densities as high as those in dense solar streamers to obtain velocities of the order of 0.33. The implication was that the bursts originate in solar streamers, at least at distances from the Sun corresponding to frequencies of ground-base observations. The recognition of the prevalence of the second harmonic mode has allowed us to obtain the velocity of the exciter particles for 32 events. The deduced velocities are in agreement with model-independent determinations and also do not require dense streamers. The velocity distribution has a mean value of 0.32 ± 0.02, where the uncertainty is the standard error. The disappearance of the fundamental mode may give a simple alternative explanation for the deceleration reported by some observers.

In Section 3 we start the discussion by describing the first method used in the analysis. This method led to spurious results exhibiting some systematic characteristics. These characteristics were fully explained by the second method that showed them to be artifacts arising from the omission of the second harmonic emission. The purpose in presenting the first method here is to lend greater credence to the validity of the conclusions from the second method.

2. The Observations

We will follow the definitions established in Paper I. A 'component' is a rise and fall in signal at a given time in a given frequency channel. A 'burst' is a frequency and time sequence of properly related components; a burst may be related to the fundamental mode or to the second harmonic mode of oscillation of the local plasma frequency. An 'event' is a group of bursts closely associated in time.

The observations are the same used in Paper I. As was explained there the time profiles of our events were usually the result of the blend of many bursts. Most of them were strong and often drove the receiver to saturation. In general, the bursts within an event drifted down to different frequencies.

The onset times of the components were plotted in graphs displaying frequency vs time. We plotted not only the time of start of well identifiable components but also those times at which a discontinuity in either the rising or decaying part of a blended profile suggested a hidden burst. Because of radio interference in the four low-frequency channels we often lost accuracy in the measurement of arrival times, however the problem did not affect seriously our analysis because the delays observed between these low frequencies are long.

3. Discussion of the Results

3.1. The prevalence of the second harmonic

The first method used to study the bursts arrival times was explained in Paper I. It consisted in drawing a smooth curve through the components onset plotted in a frequency-vs-time graph, and then in measuring the slope of this curve at different frequencies. Following this method we analyzed the frequency drift rates (FDR) defined by the onset of the leading burst. Plots of the logarithm of FDR vs the logarithm of frequency for individual events gave curves that could be piecewise fitted by a few straight segments. Because of the shapes of the curves so obtained the bursts could be grouped into six sub-types (Haddock and Alvarez, 1970a). Five of these are

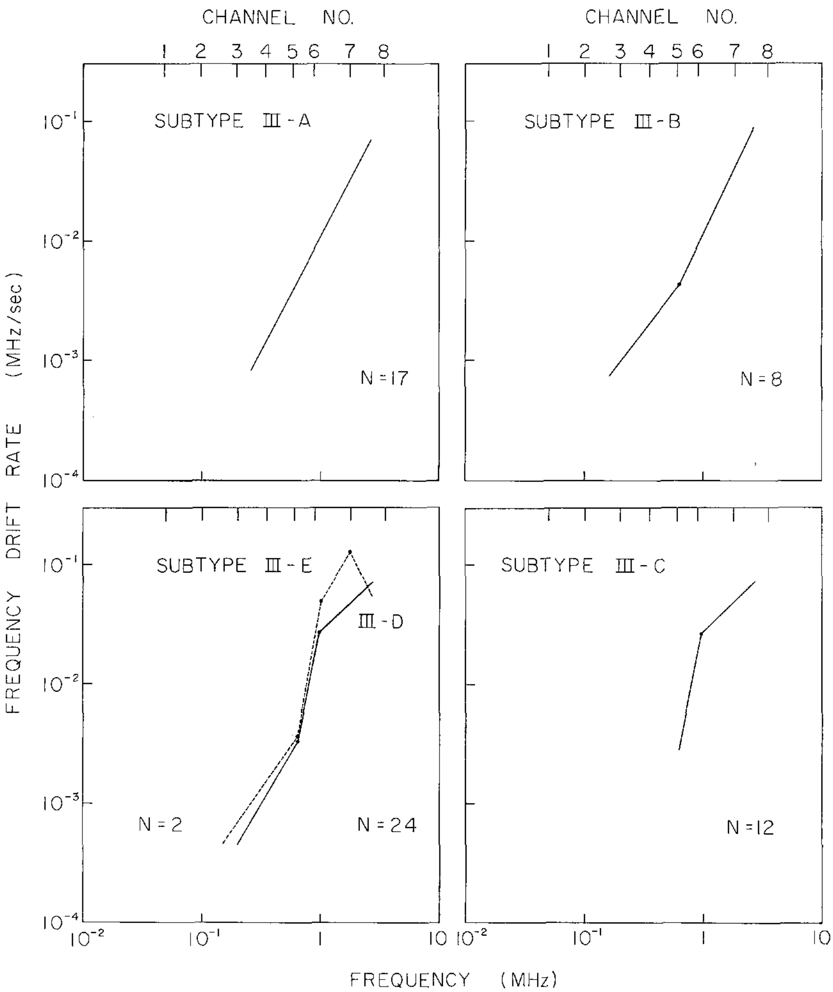

Fig. 1. Average frequency drift rate curves of five sub-types of type III bursts determined by the first method. As explained in the text these sub-types turned out to be spurious and reduce to sub-type III-A when the second harmonic emission is taken into consideration. *N* indicates the number of cases.

shown in Figure 1. The events in the sixth sub-type could not be fitted to a simple pattern. The FDR curves of sub-types III-B, -C, and -D have discontinuities primarily at about 600 or 950 kHz, or at both frequencies.

In Paper I we defined the FDR index as the slope of a straight line in a plot displaying the logarithm of FDR, in MHz s^{-1}, vs the logarithm of frequency, in MHz. To study the shapes of the curves shown in Figure 1 we plotted the FDR index of each of the different segments vs the central meridian distance of the flares associated with the bursts. We found that the index of the mid-frequency section of the sub-type III-D curves was strongly correlated with the flare position. (See Figure 2.) The indices of

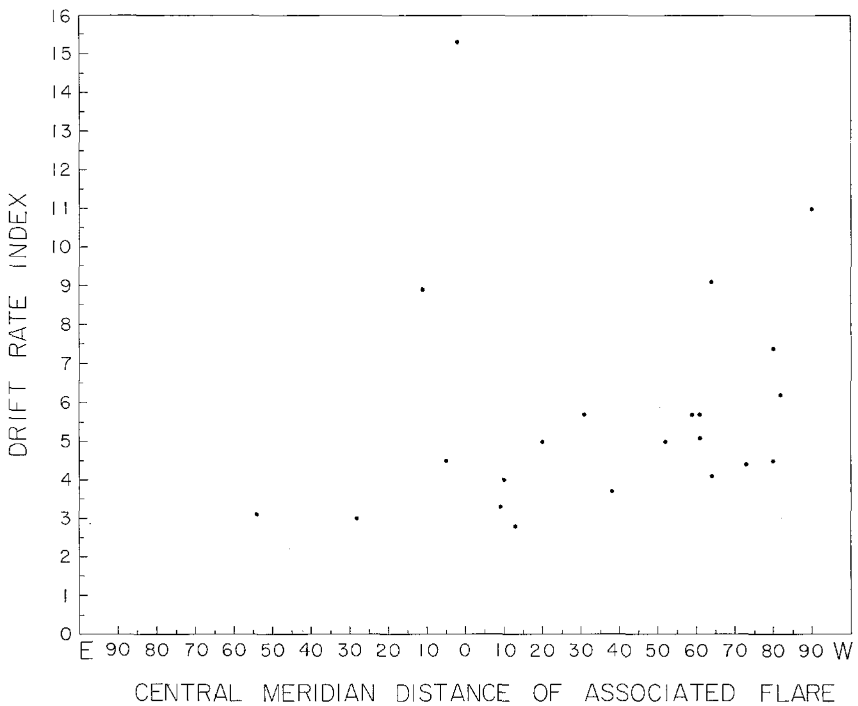

Fig. 2. Fictitious correlation between the central meridian distance of the bursts associated flares and the frequency drift rate index of the midfrequency segment in sub-type III-D bursts. Our interpretation of the observations gives satisfactory explanations for this correlation and for the spurious sub-types.

the high- and low-frequency segments did not show such correlation. A correlation was also found in the mid-frequency section of sub-types III-E and -C (Haddock and Alvarez, 1970a). In search for an explanation of these peculiar shapes we devised a method based on a model for the prediction of the times of arrival of the bursts fundamental and second harmonic radiation at the observing frequencies of the OGO-5 radiometer. The final analysis indicated that these shapes and this correlation are spurious because the second harmonic radiation was overlooked. In the model we adopted the same assumptions used in Paper I:

(a) The local plasma hypothesis. We allow for the second harmonic emission by writing

$$f = 9 \times 10^{-6} j N_e^{1/2} \text{ MHz}, \quad (1)$$

where f is the radiated frequency, N_e is electron density in cm^{-3}, $j=1$ for the fundamental mode of the plasma frequency and $j=2$ for its second harmonic mode. We assumed that both modes are emitted simultaneously and from the same general small region.

(b) The velocity of the exciter particles is constant throughout their motion.

(c) The trajectory of the exciter particles is an Archimedes spiral contained in the plane of the ecliptic. Its shape is such that when it originates on the western limb of the Sun it passes through the Earth. The origin of trajectory in each case was determined by the position of the optical flare associated with the radio event. This position was expressed by the angle θ_F from the central meridian of the Sun. Flare data were obtained from the *Solar-Geophysical Data*, National Oceanic and Atomospheric Administration (NOAA). We assumed also that the exciter particles follow the solar wind magnetic field lines with zero pitch angle.

(d) The electromagnetic waves propagate from the burst source to the Earth as in vacuum.

For the electron density distribution we used an early numerical model of ours. To describe it we will refer to the curves in Figure 4 of Paper I: Between 1 and 100 $R_\odot$ the used model is practically equal to curve 3, between 100 and 215 $R_\odot$ it is a few percent lower than curve 2.

To predict the arrival times we assume that at a given frequency f two emissions modes can be observed: one emitted at the fundamental of the local plasma frequency f and the other at the second harmonic of the local plasma frequency $f/2$ at a level further from the Sun where the density has dropped by a factor of 4. The latter will be called the half-frequency harmonic of the former. Thus, the fundamental radiation at a particular frequency and that of its half-frequency harmonic are emitted at the *same frequency* but from *different levels* of the solar corona. On the other hand radiations at the plasma frequency f and that of its second harmonic at $2f$ are produced at the *same level* and, for our purposes, at the *same time*.

We used the arrival time of the 3.5 MHz fundamental as reference. We varied the orientation θ_F between $\pm 90°$, in steps of $10°$ and the velocity β between 0.10 and 0.50, in steps of 0.01. For each θ_F we obtained plots of frequency vs time of arrival for different velocities.

A direct overlay of the plot of the observed times of arrival with the plots computed for the angle closest to that of the associated flare permitted us in each case to select the velocity β that gave the best fit. We applied this technique to the onset of the radio events. It soon became apparent that often the components observed at the higher frequencies would fit the arrival time of the fundamental mode while the lower frequencies would fit best the arrival time of the half-frequency harmonic (Haddock and Alvarez, 1970b). Examples are shown in Figures 3a, b and c where we have drawn

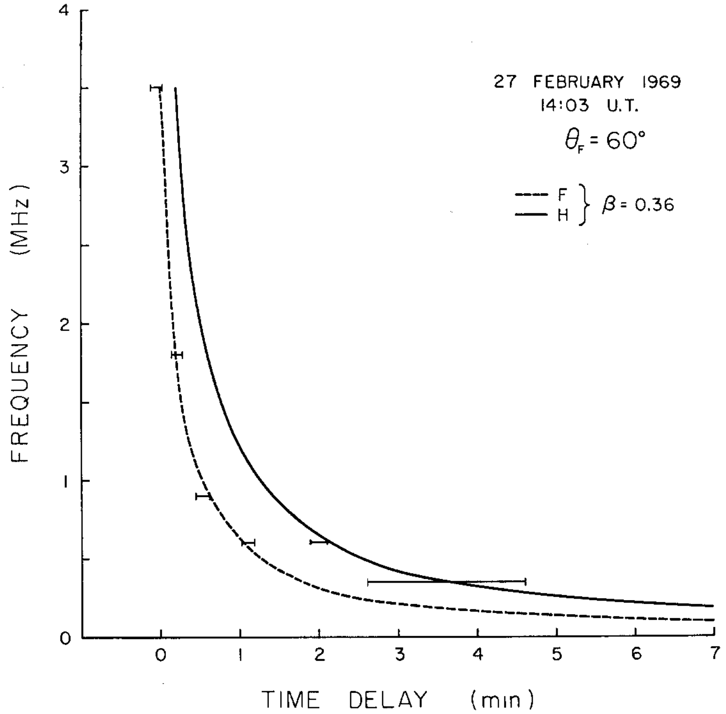
27 FEBRUARY 1969
14:03 U.T.
θ_F = 60°
F
H
β = 0.36
FREQUENCY (MHz)
TIME DELAY (min)
0
1
2
3
4
0
1
2
3
4
5
6
7

Fig. 3a.

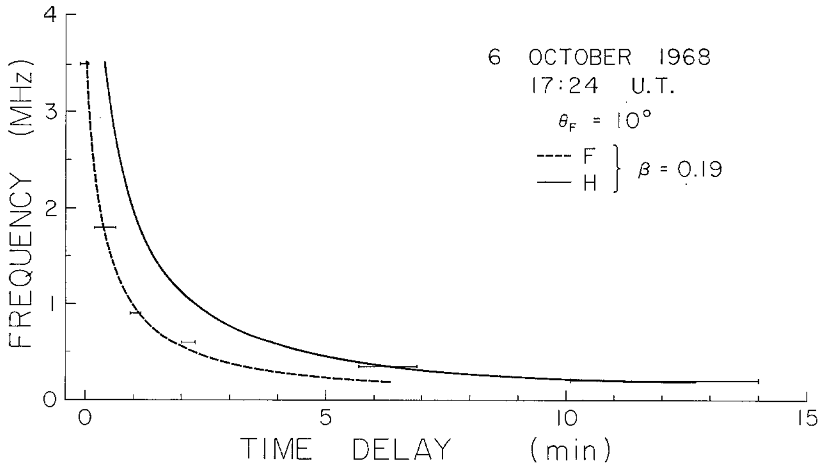
6 OCTOBER 1968
17:24 U.T.
θ_F = 10°
F
H
β = 0.19
FREQUENCY (MHz)
TIME DELAY (min)
0
1
2
3
4
0
5
10
15

Fig. 3b.

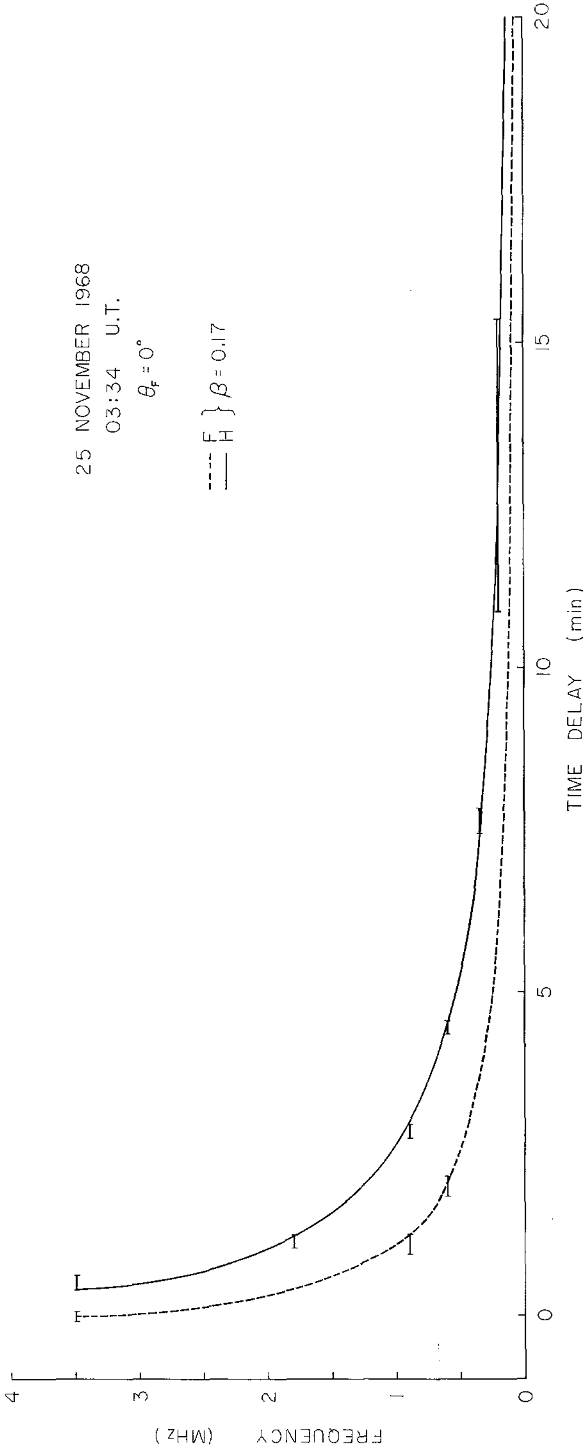
25 NOVEMBER 1968
03:34 U.T.
$\theta_F = 0°$
F
H
β = 0.17
FREQUENCY (MHz)
0
1
2
3
4
TIME DELAY (min)
0
5
10
15
20

Fig. 3c.

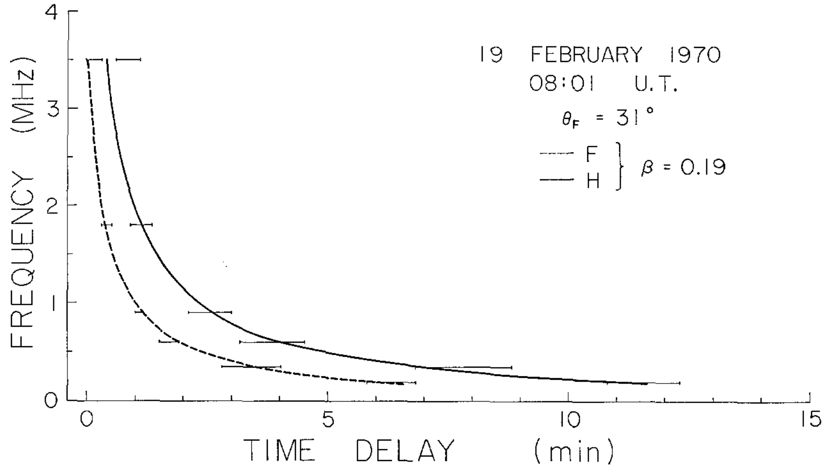

Fig. 3d.

Figs. 3a–d. Comparison of theoretical and observational arrival times of a type III burst. *F* and *H* stand for fundamental and second harmonic, respectively. Notice the disappearance of the fundamental below 600 kHz in Figures a, b and c.

curves through the computed times of arrival. *F* and *H* stand for fundamental and second harmonic, respectively. Figure 3c shows an event where the second harmonic is observed in the six upper channels. We notice that the lowest frequency at which the fundamental is observed is 600 kHz, below which the radiation is all second harmonic. In other cases, as in Figure 3d, the fundamental does not disappear. The degree of overlap of fundamental and half-frequency harmonic radiation varies from burst to burst, but in most cases the overlap occurred between the channels at 1.8 and 0.35 MHz. We have no explanation of why the second harmonic seems to set in at different frequencies. Measurements more precise on more bursts may reveal a pattern. In cases like those shown in Figure 3 we were able to determine unambiguously a velocity; however the method gives ambiguous results when the observed components fitted only one mode. In fact, the predicted arrival times for second harmonic emission associated with a velocity β are very close to those for fundamental emission associated with a velocity of approximately $\beta/2$. The computed curves shown in Figure 4 illustrate this situation of ambiguity. In practice we cannot identify modes because the arrival time delays in the upper channels are smaller than the read-out time resolution of our instrument; the delays in the lower channels are larger but cannot always be detected because of radio interference problems.

After applying this method to the leading burst of an event we proceeded successively with the rest of the bursts. Here we assumed that an event consists of a succession of bursts generated by bunches of exciters streaming from the same flare region, all bunches having average velocities within a narrow range. To assign a velocity to an event we estimated the average of the bursts velocity within the event giving more weight to the bursts that drifted to the lower frequencies; in gereral, the range of velocities averaged was small compared to the overall standard deviation. We obtained

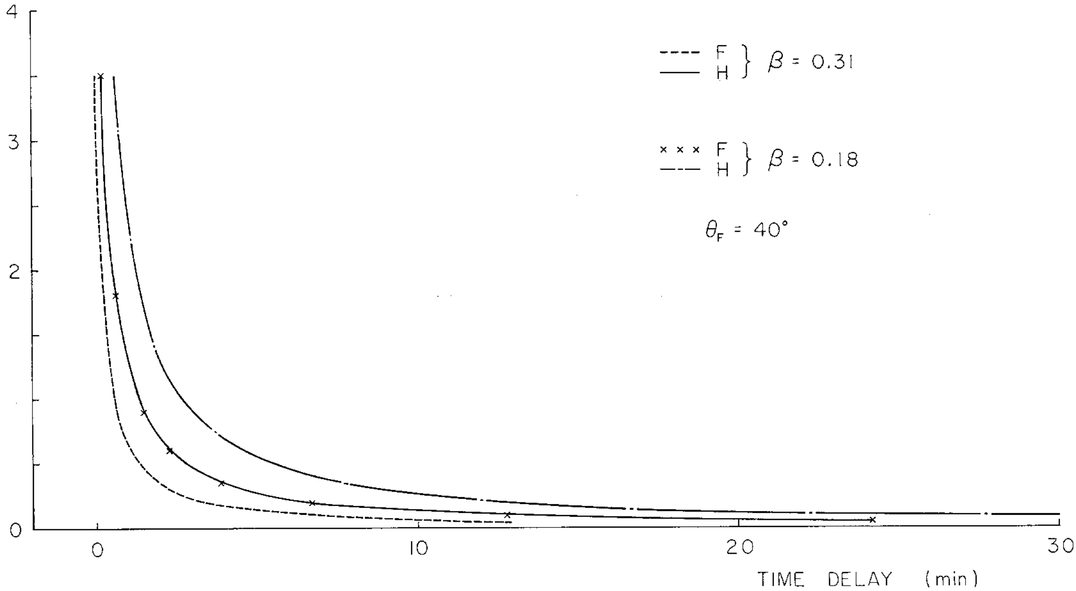

Fig. 4. Theoretical arrival times of a type III bursts. Case of ambiguity between the arrival of the second harmonic radiation associated with a velocity β and the arrival of the fundamental radiation associated with a velocity $\sim \beta/2$.

an unambiguous velocity value for 32 bursts while the velocity determination was ambiguous in 31 cases.

We analyzed the 32 bursts with unambiguous velocity values in order to study the fraction of second harmonic occurrence. The procedure consisted of counting, at each frequency of observation and for all the bursts, the number of observed components that were fitted either as fundamental or as second harmonic; we counted only the components that presented less uncertainties in their identification. Besides a component, to be counted, should belong to a burst with at least four components or, in other words, the burst should be observed at least in four channels.

Denoting by n_F and n_H the total number of components fitted as fundamental and second harmonic, respectively, we defined the harmonic content ϱ as:

$$\varrho = \frac{n_H}{n_H + n_F} \times 100. \qquad (2)$$

Figure 5 shows the results. Numerals in parentheses indicate the number of components counted. The appropriate data obtained from ground-base observations are very limited. They show that the definite recognition of harmonics is possible in only a small fraction of the observed bursts. This could indicate that the harmonic occurrence is a rather rare phenomenon however many doubtful cases there are (Wild *et al.*, 1954; Smerd *et al.*, 1962). Figure 5 reveals a clear tendency of increase in the harmonic content of the received radiation as the frequency decreases. Below about 1 MHz

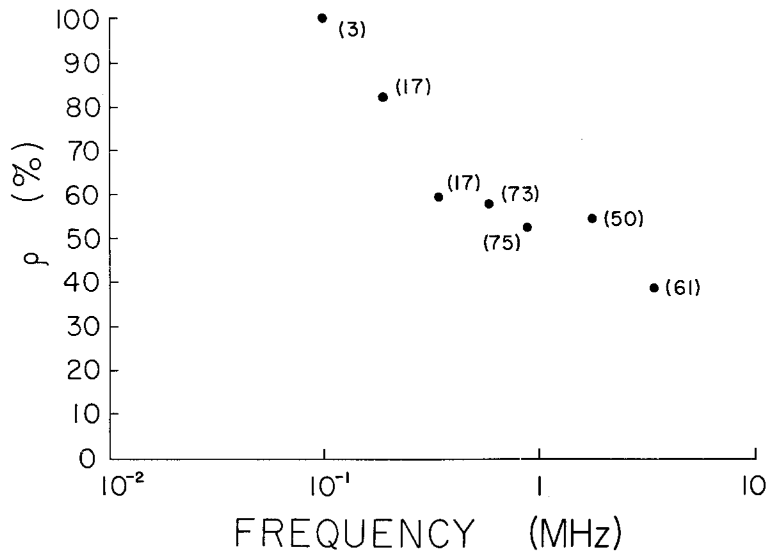

Fig. 5. Content of second harmonic components in unambiguous type III bursts that have four or more components out of eight. Numerals in parenthesis indicate the number of cases used.

more radiation is observed at the second harmonic than at the fundamental. For this reason we have referred to this finding as the prevalence of the second harmonic below 1 MHz (Haddock and Alvarez, 1971). It should be kept in mind that our results were derived from intense and complex type III events.

Our interpretation of the findings answers more questions than it poses.

(1) The disappearance of the fundamental below 1 MHz provides a good explanation to the peculiar shapes of the FDR curves obtained by the early method where mode identification was overlooked (see Figure 1); in fact, we generated curves by passing indiscriminately through the onset times of fundamental and second harmonic mode components. The position of the discontinuities is influenced somewhat by the selection of the observing frequencies however the prevalence of the second harmonic cannot be explained by an instrumental effect.

(2) The disappearance of the fundamental explains in a natural way the spurious correlation discussed in connection with Figure 2. Thus the difference in time arrival for the fundamental at 1.8 MHz and the second harmonic at 900 kHz, for example, increases as the associated flare moves to the west because of propagation geometry. When we use this time difference to compute a drift rate, as we inadvertently did, we find that this drift rate depends on the central meridian distance. Other explanations for the early spurious results such as combinations of accelerations and decelerations of the exciter particles, or discontinuities in the electron density distribution are complicated and unrealistic, besides it is not obvious how could they explain the dependency on θ_F.

(3) The disappearance of the fundamental below 1 MHz could give the appearance of deceleration of the exciter particles. Consider for example a burst that in the high-

frequency range is observed in both the fundamental and the second harmonic modes and let us assume that the fundamental disappears below a critical frequency. The delays observed between the onsets at two frequencies, one above and the other below the critical frequency, will then be longer than expected for either mode; if we are not aware of the phenomenon we can attribute it to a deceleration of the burst exciters. The initial and final velocities would differ approximately by a factor of 2. Evidently our findings are valid within the limitation of the measurements, but they do not preclude the possibility of some real deceleration.

(4) The implications of our findings in the determination of constant velocities is discussed in Section 3.2.

(5) The recognition of the prevalence of the second harmonic is relevant in the analysis of the bursts time profiles. For example, it is important to know whether to associate the decay time and flux density of a burst at a given frequency with the distance corresponding to the fundamental or with the distance corresponding to the half-frequency harmonic. These two distances differ by a factor approximately equal to 2.

Finally, the emission at the second harmonic helps to explain the problem of escape of the radiation in the Earth's direction, especially at low frequencies where the angles Sun–Earth-source can be large (Slysh, 1967; Haddock, 1971).

The main question raised by our findings is why the second harmonic is prevalent at very low frequencies. To answer this question we have not attempted to use current theories of the emission mechanism of type-III bursts because they have been derived for the metric range of wavelengths, that is, 10^2 and 10^3 times shorter than OGO-5's (Smith, 1970; Melrose, 1970; Zheleznyakov and Zaitsev, 1970; Yip, 1970). Several simple hypotheses could be considered:

(a) Directionality in the radiation pattern of the source, or focusing by the ambient plasma, or both. In either case we could expect a dependence of the phenomenon on the position of the associated flare, θ_F. To investigate this we plotted the distribution of θ_F for ambiguous and unambiguous cases. Since the latter were, in general, those in which the fundamental mode disappear within the frequency range of our radiometer we could expect them to have a different distribution than the ambiguous events. However we found no evidence that the two groups differ with respect to the positions of the associated flares.

(b) The fundamental radiation from a level at a distance $r(f)$ may be actually much weaker than the half-frequency harmonic at distance $r(f/2)$.

(c) The fundamental and the half-frequency harmonic intensities may be of the same order of magnitude but scattering and refraction effects of the intervening medium would tend to affect the fundamental more than the half-frequency harmonic because the first is emitted at a point further from the Earth and also because the ambient conditions at the two levels are different.

3.2. The velocity distribution

A direct consequence of the recognition of the prevalence of the second harmonic is the determination of the exciter particles velocity. The distribution of unambiguous velocities is shown in Figure 6. The mean veloity, $\bar{\beta}$, is 0.32 ± 0.02, where the standard error is given. Individual values range between 0.17 and 0.49. We observe that there is a narrow concentration of velocities around approximately 0.19 that make the distribution look bimodal. This could be attributed to the real existence of two preferred ranges of velocities centering at about 0.19 and 0.36; however, we have no observational evidence or theoretical prediction to support this hypothesis. It is probably due to chance fluctuations.

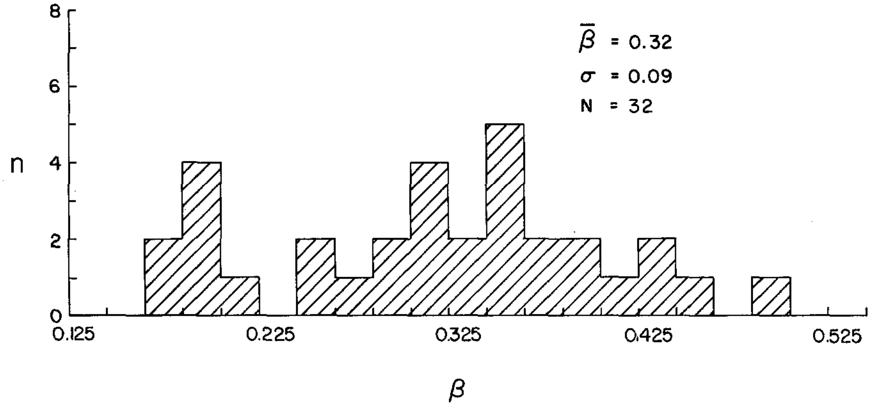

Fig. 6. Distribution of velocities for unambiguous cases.

The obtained mean value is somewhat smaller than the determinations made independently of an electron density model (0.45, Wild *et al.*, 1959; 0.45, Slysh, 1967) or almost independently (0.38, Fainberg and Stone, 1970). Model-dependent velocities as low as 0.05 (Malville, 1962; Alexander *et al.*, 1969) and averages of the order of 0.10 (Boischot, 1967) have been deduced using streamer models. We have estimated qualitatively that our velocities could be increased by the consideration of trajectories out of the ecliptic plane for the exciter particles. Propagation effects on the electromagnetic waves would increase the velocities also. Wild *et al.* (1959), corrected their data for group retardation effect. From Figure 15 of that reference we have roughly estimated that an observed velocity of 0.35 should be increased about 12%. This number may be different in the hectometric and kilometric wavelength ranges. Scattering would also lengthen the particles' path leading to an increase in the deduced velocity. The velocities shown in Figure 6 are sensitive to the electron density model used. By making it eight times denser we found that the lower and upper limits of the velocity distribution were shifted to 0.38 and 0.80, respectively.

An advantage of our method of velocity determination is that the fitting was done for individual bursts in a frequency coverage corresponding to an approximate range of distances of 10–200 $R_\odot$.

For each of the 31 ambiguous cases we have two choices of velocity and therefore we cannot obtain the velocity distribution. However we can determine an upper bound to the average by assuming that all the events were associated with the highest of the two velocities, similarly we can obtain a lower bound by selecting the lowest velocity in all cases. The parameters obtained under both conditions are presented in Table I, where σ is the standard deviation.

TABLE I

Parameters of the velocity distributions

Case	$\bar{\beta}$	σ	Number of events
Unambiguous events	0.32	0.09	32
Ambiguous events			
High-velocity choice	0.33	0.05	31
Ambiguous choice			
Low-velocity choice	0.18	0.03	31

The ambiguous velocities range between 0.10 and 0.42. The fact that the average value, 0.18, of the low-velocity choice is so close to the center, 0.19, of the low-velocity concentration of the unambiguous cases (Figure 6) may indicate the possibility of mode misidentification in a few cases. Based on different considerations we made attempts to resolve the ambiguity in the 31 cases but without success.

4. Conclusion

We have devised a method to study the arrival times of type III solar bursts. This consisted of predicting the times of arrival at the Earth of the fundamental emission and of the half-frequency harmonic for the frequencies of observation. The predictions were based on a simple model and the results were compared with observations. This method revealed that in most of the bursts the fundamental emission disappeared below approximatley 1 MHz and that the bursts observed below this frequency were mainly emitted at the second harmonic of the local plasma frequency. The prevalence of the second harmonic is such that the likelihood of observing second harmonic rather than fundamental emission increases as the frequency decreases.

This finding allowed us to determine unambiguously the velocity of the exciter particles in 32 cases. We obtained a distribution with a mean velocity of 0.32 ± 0.02, where the uncertainty is the standard error. These velocities were derived by using a model of coronal electron density distribution within solar wind values, therefore we have relaxed the requirement of having dense streamer beyond about $10 R_{\odot}$ extending to the Earth's orbit in order to increase the deduced velocities.

In view of our results we assume that type III bursts are excited by particles ejected from the Sun and traveling through dense streamers which gradually merge into the solar wind beyond about $10 R_{\odot}$. The metric and decametric wavelength emission originate in the streamers while the hectometric and kilometric wavelengths emission originate in the solar wind. The exciter particles travel with a constant velocity that has a mean value between 0.30 and 0.40.

The disappearance of the fundamental could give the appearance of deceleration of the exciter particles. A correct analysis of the bursts time profiles should be based on previous identification of the radiation mode.

Our interpretation answers more questions than it poses. The raised question is why the second harmonic predominates at the very low frequencies.

Acknowledgements

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