ON THE RELATIVE POSITION AND ORIGIN OF HARMONICS IN THE SPECTRA OF SOLAR RADIO BURSTS OF SPECTRAL TYPES II AND III

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Summary

Observational results are given concerning the relative positions on the Sun's disk of the fundamental and second-harmonic emissions of solar radio bursts of spectral types II and III. Contrary to simple theory, the results indicate that it is common for the harmonic emission in type II bursts to arrive from directions corresponding to much lower heights in the solar atmosphere than the fundamental. The results for type III bursts are inconclusive but suggest the same trend.

Possible interpretations are considered, and one theory is developed in some detail. The theory supposes that harmonic emission can be generated preferentially in backward directions (i.e. towards the photosphere), so causing the image of the harmonic source reflected in the corona to dominate the source directly observed. Such preferential backward emission is shown to be a natural consequence of a theory of burst generation, proposed by Ginzburg and Zhelezniakov, in which the harmonic emission is supposed to arise from combination scattering of longitudinal plasma waves at charge fluctuations in a thermal plasma.

I. Introduction

Harmonically related features in the spectra of solar radio bursts were first observed in the case of slow-drift bursts of spectral type II and shortly after in fast-drift bursts of spectral type III (Wild, Murray, and Rowe 1954). Characteristically, the fundamental spectrum is duplicated by a spectrum at twice the frequency ; the relative intensity of harmonic varies widely but in typical cases the intensities appear to be of the same order of magnitude. Occasionally there is a suggestion of higher harmonics (Haddock 1958 ; Roberts 1959) but their existence has not been established ; if higher harmonics do exist they must be much rarer or weaker than the fundamental and second harmonic. For the remainder of the present paper the second harmonic will simply be referred to as the harmonic.

At least half the type II bursts (Roberts 1959) and an unspecified but certainly much smaller fraction of type III bursts show recognizable harmonic structure. The recognition of harmonic structure in type III bursts is more difficult than in type II bursts because the harmonic tends to merge with the fundamental.

The discovery of harmonics was taken as evidence that the emissions find their origin in oscillations at the plasma frequency

$$f_0 = e\frac{\sqrt{n}}{\pi m},$$

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excited in a localized region in the solar corona characterized by a given electron density, n; and that the frequency drift was due to the passage of the exciting agency along an outward path of decreasing electron density. This *plasma hypothesis* was further substantiated by simultaneous position observations at different frequencies in the metre wavelength band (Wild, Sheridan, and Neylan 1959; Wild, Sheridan, and Trent 1959). Combination of spectral and position measurements suggested average source velocities of about 1000 km/sec for type II bursts and up to $0 \cdot 5$ c (150,000 km/sec) for type III bursts.

The plasma hypothesis did not commit itself on mechanisms either for generating plasma oscillations in the Sun's atmosphere or for converting these electron oscillations into electromagnetic radiation. A number of theories have been advanced to explain these processes, and it has become clear that further observational evidence is needed to decide between them or at least to restrict their number. The present investigation is aimed at exploring a particular new line of evidence, namely the relative position on the Sun's disk of fundamental and harmonic emissions in types II and III bursts, and discussing its theoretical implications.

Clearly, if (as implied by the plasma hypothesis) the harmonic is generated at the same point as the fundamental, and if the emission in both fundamental and harmonic bands were propagated towards us directly along approximately rectilinear paths, then we should expect the fundamental (frequency f) and harmonic (frequency $\sim 2f$) generated simultaneously to arrive from about the same direction. This behaviour could in principle be tested by simultaneous observations at a pair of frequencies, f and $2f$. However, this system of observation is rather unsound owing to the effects of ionospheric refraction which in general would displace the position of different frequencies by different amounts. Instead we have preferred to observe the relative positions of fundamental and harmonic *as they drift through a given frequency*, necessarily at different times. We should then expect the harmonic emission to arrive from the point at which the $\frac{1}{2}f$ plasma level is crossed, that is, in the case of a non-central burst, from a position on the Sun's disk well outside the position of the fundamental.

The evidence given in Section II is that the observed positions often do not comply with this prediction and, in a number of striking cases, especially of type II bursts, positively contradict it. In Section III it is shown that the contradictory cases can be interpreted by supposing that the harmonic emission is generated within a cone of emission directed *inward* towards the Sun and reflected. Thence we examine an existing theory of the generation of plasma waves and their conversion to electromagnetic radiation and show that under certain conditions the inward direction of propagation is indeed preferred for the second harmonic.

II. The Observations

The observations used here are the dynamic spectra of solar bursts in a frequency range of 25 to 210 Mc/s and the one-dimensional burst positions in a frequency range of 40 to 70 Mc/s recorded at Dapto, near Sydney. The instruments and techniques employed in the observations have been described elsewhere (Wild, Sheridan, and Neylan 1959). Positions are obtained by a swept-frequency interferometer with two aerials 1 km apart on an east-west line (some 100 to 200 wavelengths over the frequency range). A " short " base of $\frac{1}{4}$ km is used to resolve ambiguities in position. The positional accuracy is about 1′ arc, although, in practice, refraction at ionospheric irregularities usually limits the accuracy. The interferometer is operated four hours a day around local noon.

TABLE 1

DETAILS OF EVENTS USED IN THE PRESENT ANALYSIS

Date	Time U.T.	Burst Position*		Associated Flare	
		Fund.	Harm.	Imp.	Position
Type II Bursts					
7. vii.58	0033–0048	7·5 W.	3·2 W.	1^+	N. 25, E. 07
20.viii.58	0046–0105	18·4 E.	8·7 E.	2^+	N. 16, E. 18
9. ii.59	0208–0245	20·6 E.	13·4 E.	2	N. 13, E. 90
28. iv.60	0120–0146	20·2 E.	10·5 E.	3	S. 5, E. 34
Type III Bursts					
12. i.59	0400^{20}	8·0 W.	8·0 W.		
11.viii.59	0016^{06}	12·5 W.	7·5 W.	1^-	N. 18, W. 14
5. iv.60	0018^{18}	22·2 W.	17·3 W.	1^- to 1^+	N. 11, W. 65
16. v.60	0156^{00}	11·1 E.	11·2 E.		
26. vii.60	0318^{20}	14·7 E.	22·4 E.		
	0347^{56}	14·0 E.	19·8 E.		
	0348^{04}	13·8 E.	19·2 E.		
12.viii.60	0045^{52}	22·9 W.	22·8 W.		

* Positions are given in minutes of arc E. or W. of the centre of the Sun's disk measured along the scanning direction (terrestrial E.-W.). They refer to frequencies of 55 Mc/s (type II bursts), and 60 Mc/s (type III bursts), the frequencies being chosen to allow the maximum number of events to be listed.

The records were examined for harmonic bursts in the period May 1958 to November 1960. The earlier date marks the beginning of regular position measurements. During this period we found in the records a total of four type II bursts and six independent groups of type III bursts in which both fundamental and harmonic bands crossed some frequency in the 40–70 Mc/s range. These are the events used in the present analysis, and general details of them are given in Table 1.

(*a*) *Type II Results*

Observations of spectrum and position for a typical type II burst are illustrated in Figure 1. The positions of fundamental and harmonic are given at the four frequencies 45, 50, 55, and 60 Mc/s ; each full line denotes the mean of many independent readings of position. In Figure 2 are given positions

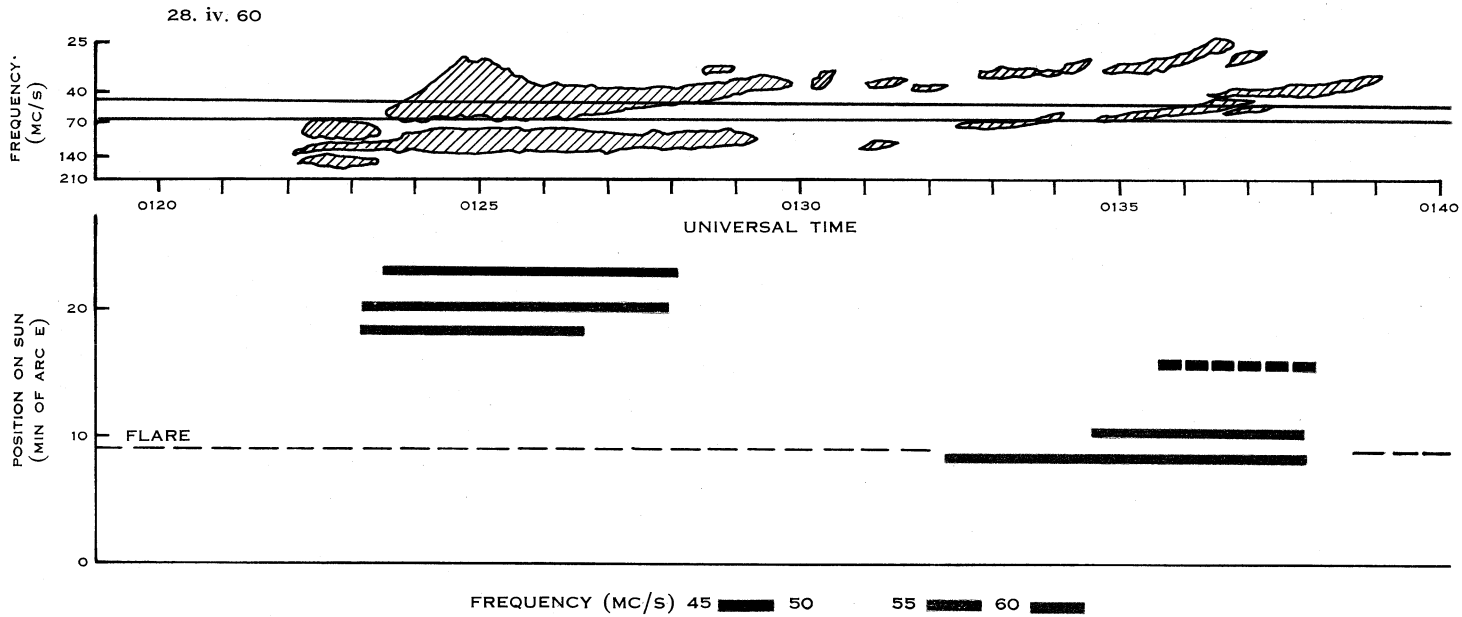

Fig. 1.—Dynamic spectrum and E.-W. position observations of the type II burst recorded on April 28, 1960.

on the solar disk of fundamental and harmonic bands of the four type II events* together with those of their associated flare. In all four cases the harmonic radiation is seen to arrive from a position *inside* that of the fundamental. The 55 Mc/s data of the same events are presented in another form in Figure 3 (open circles), which is a plot of the relative displacement of fundamental and harmonic *versus* the position of the fundamental. This graph will be referred to later for comparison with theory.

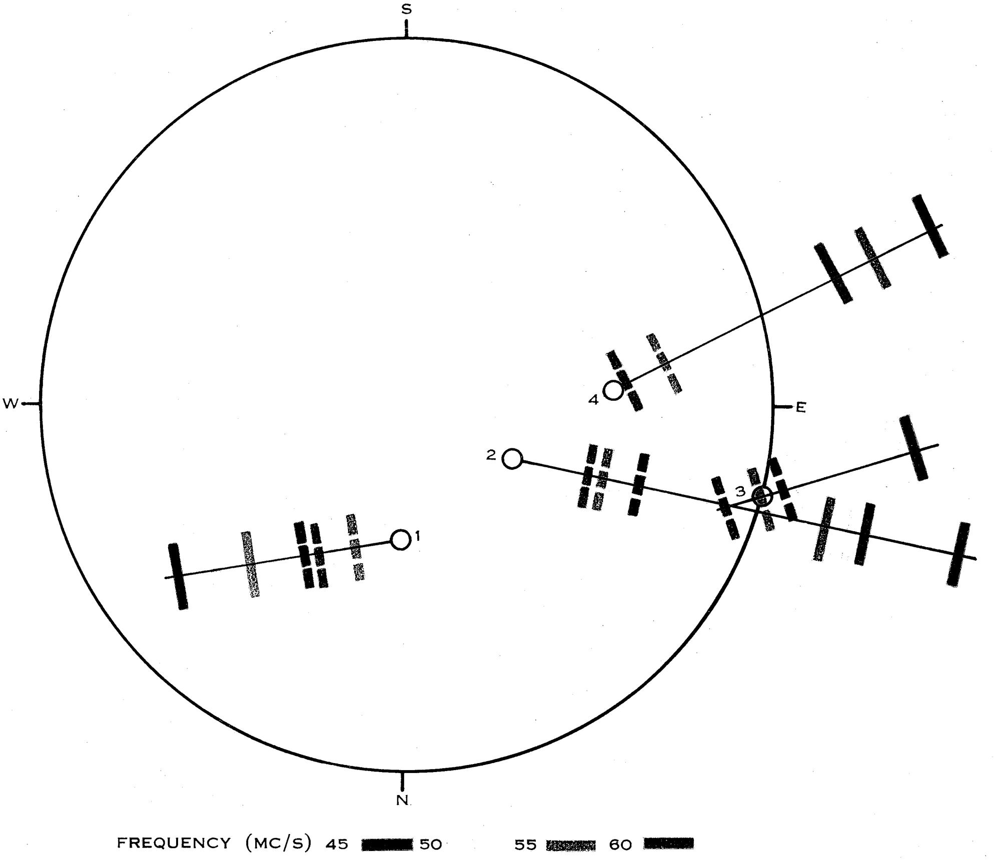

Fig. 2.—Mean positions of fundamental and harmonic bands for the four type II bursts discussed in the text. The positions are shown as short lines perpendicular to lines drawn through the associated flare position (open circles) parallel to the scanning direction.

* One of the four type II events (7.vii.58) was described by Wild, Sheridan, and Trent (1959) at the Paris Symposium on Radio Astronomy, 1958, and it is recorded that Dr. J. F. Denisse commented on the peculiar position of the harmonic relative to the fundamental. In reply, one of the authors (J.P.W.) suggested that, despite their apparent 2 : 1 ratio, the two bands may not necessarily be harmonically related, especially since the spectrum showed no fine structure in the two bands suitable for establishing a certain harmonic relationship. However, the evidence now at hand of three further cases showing the same general behaviour has seemed to us sufficient for accepting the original event as one with true harmonics.

(b) *Type III Results*

As previously intimated, the proportion of type III bursts with clearly recognizable harmonics is much smaller than that of type II bursts. It is for this reason that of the vast number of type III bursts recorded in the $2\frac{1}{2}$ year period of observations, only six independent bursts were considered to show clear enough harmonics for inclusion in the present analysis. In two cases the

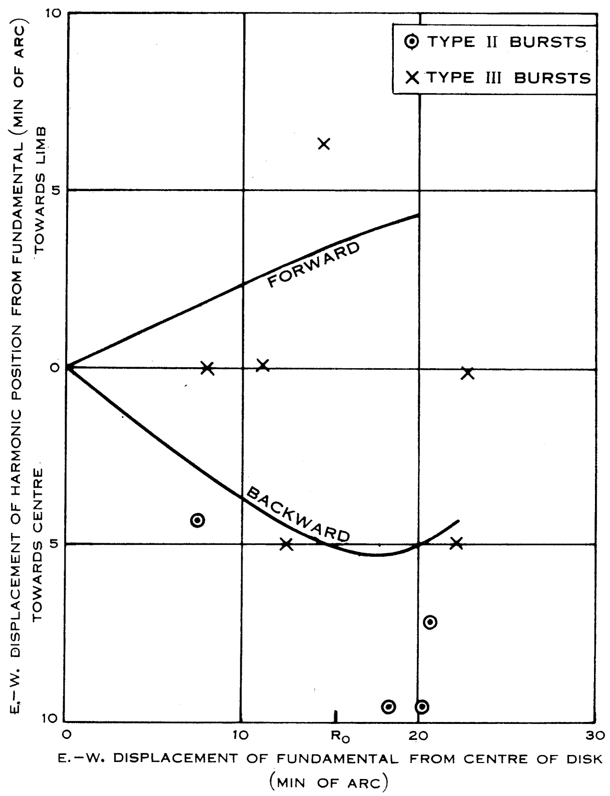

Fig. 3.—The observational points, taken from Table 1, plotted to show the relative displacement between harmonic and fundamental positions as a function of the distances of the fundamental from the centre of the disk. The full lines show theoretical curves on which the points would lie according to a simple model discussed in Section III (*a*), with propagation of the harmonic along forward and backward rays respectively.

harmonic position was inside that of the fundamental, in one it was outside, and in three no appreciable shift was found. These results, which are indicated by crosses in Figure 3, are inconclusive and indicate the need for further observation, preferably with higher time resolution. They seem, however, to provide evidence that the pronounced outward shift of the harmonic relative to the fundamental predicted by the simple theory is not observed in the majority of cases.

III. Interpretation

(a) *Possible Explanations*

These observations invite us to explain the rather puzzling result that for type II bursts (perhaps in the majority of cases) and type III bursts (in some cases at least), radiation in the second harmonic arrives from a direction closer to the centre of the disk than that in the fundamental band. (The observations refer to the situation in which fundamental and harmonic are both observed at the same frequency, a lapse of time separating the two measurements while the frequency drift of the bursts brings first the fundamental and then the second harmonic band into observation.) As discussed in Section I, a simple application of the plasma hypothesis to the case of an outward-moving stream ejected from a non-central part of the Sun would lead to a prediction in quite the opposite sense, that is, that the harmonic source should appear outside the fundamental.

Several possible explanations may be suggested. One is that the outward-moving disturbance is a broad-fronted phenomenon and that some geometrical or physical factor favours emission of harmonic radiation from a more central part of the front than the fundamental. No clear reason for the existence of such a factor has however occurred to us.

Another possibility, suggested by Denisse's (1960) discussion, is that the harmonics arise from non-linear components of plasma waves, and that the coupling between plasma and electromagnetic waves at the second-harmonic plasma frequency ($2f_0$) occurs, not in the immediate vicinity of the initiating disturbance, but rather much deeper in the Sun's atmosphere near the level where the plasma wave encounters a region in which the fundamental plasma frequency is $2f_0$. But this explanation requires that inward-propagating plasma waves be set up by a presumably outward-moving disturbance. This difficulty seems especially pronounced in the case of type III bursts which are believed to be initiated by a simple stream of electrons directed outwards.

A third possibility is that the anomalously central position of the harmonic results from an effect of reflection or refraction in the solar atmosphere. This possibility seems to us to offer the best prospects for an explanation of the phenomenon as known at the present time; it will be considered in some detail in the following Subsections (*b*) and (*c*).

(b) *Direct and Reflected Sources of Harmonic Emission*

It is well known that radiation originating within a spherical atmosphere can escape towards a distant observer along two paths, so long as the frequency exceeds a critical escape frequency (see Fig. 4). One of the rays follows an almost direct path, while the other starts in a backward direction and is then reflected from a region near or higher than the layer of zero refractive index. In general the second harmonic of the plasma frequency (unlike the fundamental) would reach us from the Sun by two distinct paths, so that it is possible that harmonic radiation from a solar burst could appear on a radio image of the Sun as a double source.

The calculation of the apparent positions on the Sun's disk of the direct and reflected sources has been undertaken by several workers, including Jaeger and Westfold (1950) who applied their results to the Baumbach–Allen model of the corona. We have made similar calculations assuming a spherically symmetrical atmosphere with radial distributions of electron density given by Newkirk's curve for a typical active region of the corona; this model has previously been found to be generally consistent with the radio observations (see Wild, Sheridan, and Neylan 1959). The relative apparent positions of harmonic and fundamental emissions from a point source were then calculated as a function of position on the disk, and the results are shown by the lines in Figure 3; one line assumes the harmonic to appear in the position of the direct source, the other the reflected source. In each case it has been assumed that the fundamental is propagated from its plasma level along a rectilinear path, for reasons discussed by Shain and Higgins (1959) and Wild, Sheridan, and Neylan (1959).

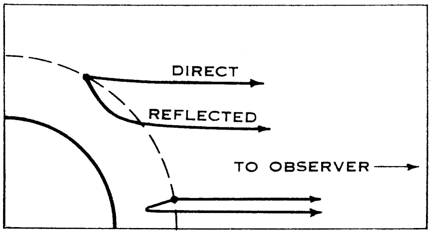

Fig. 4.—Showing direct and reflected rays along which radiation of frequency greater than the plasma frequency can escape from a spherically symmetrical atmosphere.

Inspection of the figure strongly favours the reflected source for the harmonics of the four observed type II bursts. The type III results are less conclusive and more mixed. One event appears qualitatively consistent with forward propagation, two with backward, while the remainder fall midway between. The latter category could be explained by supposing that direct and reflected sources were present simultaneously with comparable intensity—a circumstance incapable of detection by the present interferometer but directly capable of test by more refined directional techniques. Meanwhile the present observations, crude though they may be, seem to give a firm indication that propagation of the harmonic along the direct ray alone is untenable in a number of cases, especially of type II bursts, while introduction of the notion of propagation along the reflected ray offers a satisfactory explanation. The question then remains as to why the role of the reflected source should be so dominant.

(c) *Theory of Backward Emission of the Harmonic*

Ginzburg and Zhelezniakov (1958) suggested that the second harmonic of certain solar bursts arises from the interaction of pairs of plasma waves of frequency ω_0, yielding an electromagnetic wave of frequency near $2\omega_0$. We now explore this process, called *combination scattering*, with a view to calculating the direction of electromagnetic emission.*

We suppose the primary out-going disturbance to be a low-density, high-energy stream of electrons with velocity much greater than the mean velocity of thermal electrons, v_t. On passing through a region at which the local plasma frequency is ω_0, the stream is assumed to set up, by means of the Cerenkov effect, a longitudinal plasma wave which propagates in the direction of the stream.† The Cerenkov condition then demands that the phase and stream velocities are equal. Thus, to the first order, we represent the wave by the linear equation

$$E(\mathbf{r},t) = E_0 e^{i(\omega t - \mathbf{k}.\mathbf{r})}, \tag{1}$$

where the direction of $\mathbf{k}$ is aligned with the direction of motion, and the magnitude of $\mathbf{k}$ is related to the angular frequencies ω, the angular plasma frequency ω_0, and the phase velocity v, by the well-known dispersion relation

$$\omega = (\omega_0^2 + k^2 v_t^2)^{\frac{1}{2}} = \omega_0(1 - v_t^2/v^2)^{-\frac{1}{2}} \approx \omega_0, \tag{2}$$

whence

$$k \approx \omega_0/v. \tag{3}$$

The dispersion relation (2) is shown in Figure 5, where the determination of ω and k is exemplified by the point P for a wave set up by a stream with velocity $\frac{1}{3}c$.

As the plasma wave propagates through the medium, it generates electromagnetic radiation of frequency ω_0 by Rayleigh scattering from quasi-neutral fluctuations of the density of the medium (e.g. those of thermal origin). The propagation of this radiation is restricted by refraction effects to within a finite cone centred on the outward direction normal to the surface of constant refractive index (i.e. constant density). This process is to account for the fundamental frequency band of the burst.

The travelling plasma wave encounters not only quasi-neutral density fluctuations in the medium, but also electrical charge fluctuations caused by Cerenkov excitation of the plasma by the thermal electrons. It is these fluctuations which are considered to produce the combination scattering responsible for the second harmonic. The fluctuating electron density may be written as the Fourier sum of plane waves

$$n'(\mathbf{r},t) = \Sigma^{k'} n_{k'} e^{i(\omega' t - \mathbf{k}'.\mathbf{r})}. \tag{4}$$

* In a more recent discussion, Ginzburg and Zhelezniakov (1961) tend to discount combination scattering as the cause of harmonics in type II bursts owing to some evidence of Jennison (1959) that the fundamental and harmonics of these bursts may be partially mutually coherent. Whatever the mechanism of generation, this result seems most surprising in view of the gross difference in phase path suffered by the waves of frequency f_0 and $2f_0$ during their passage through the dispersive medium of the corona. Jennison himself remarks that independent confirmation of the result would be very desirable.

† This assumption seems appropriate to the geometry of a wide-fronted stream in which the electrons behave as a single medium. This case contrasts with that of a low density stream in which the electrons behave as individual particles and the angular spectrum of plasma waves is beamed predominately normal to the direction of motion (Cohen 1961).

Each component obeys the dispersion relation (2), but all except the longer waves (appreciably in excess of the Debye length) are heavily damped by Landau damping. The undamped long waves possess frequencies, ω', only slightly greater than ω_0, that is,

$$\omega' \approx \omega_0,$$

while their wavenumbers are given in terms of their phase velocities, V', by

$$k' \approx \frac{\omega_0}{V'}.$$

Owing to the non-linearity of plasma oscillations, interaction takes place between the main disturbance (1) and the fluctuations (4) resulting in the appearance of waves with the form

$$\exp\,[\mathrm{i}\{(\omega+\omega')t-(\mathbf{k}+\mathbf{k}').\mathbf{r}\}] \approx \exp\,[\mathrm{i}\{2\omega_0 t-(\mathbf{k}+\mathbf{k}').\mathbf{r}\}],$$

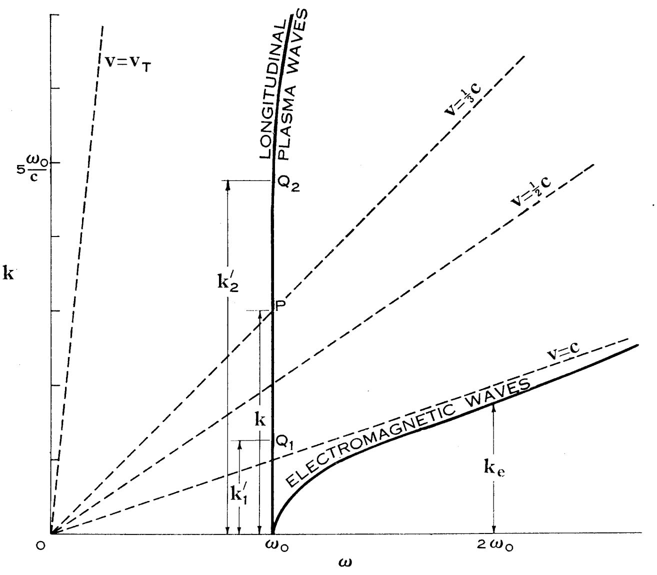

Fig. 5.—Dispersion relation for longitudinal plasma waves and electromagnetic waves in a thermal plasma in the absence of a magnetic field.

that is, waves of double the frequency. Whatever the values of $\mathbf{k}$ and $\mathbf{k}'$, this high-frequency disturbance is unable to propagate in the form of longitudinal waves owing to Landau damping. Certain components, however, may propagate as transverse electromagnetic waves in those directions in which the transverse oscillatory field is appreciable, and for which

$$\mathbf{k}+\mathbf{k}'=\mathbf{k}_e, \tag{5}$$

where $\mathbf{k}_e$ is the wave number of the electromagnetic wave, $\exp\,\{\mathrm{i}(2\omega_0 t-\mathbf{k}.\mathbf{r})\}$, and must satisfy the dispersion relation for electromagnetic waves (Fig. 5)

$$\omega^2=\omega_0^2+k_e^2c^2,$$

where c is the velocity of light. Since $\omega \approx 2\omega_0$

$$k_e \approx \frac{\sqrt{3}\omega_0}{c}. \tag{6}$$

Figure 5 illustrates two special solutions of equation (5), the point Q_1 giving the value of k' necessary for the electromagnetic radiation to propagate in the same direction as the stream, and Q_2 in the opposite (backward) direction.*

In the absence of self absorption, Ginzburg and Zhelezniakov give the intensity of the radiation in the direction making an angle θ with that of the progressive plasma wave as proportional to

$$F(\theta) = (n_{k'})^2 \sin^3 \theta. \tag{7}$$

They conclude that the electromagnetic radiation emitted in this process of combination scattering can be sufficient to account for observed intensities of burst radiation.

Let us now explore the implications of this theory as it relates to the question of forward or backward emission of the harmonic, or more generally to the angular distribution. The latter can be obtained from equation (7) if $\overline{(n_{k'})^2}$ is known. We here adopt a result of Kahn (1959) and Salpeter (1960) and write, for the appropriate long-wave approximation,

$$\overline{(n_{k'})^2} \propto k'^2. \tag{8}$$

k' is given in terms of the angle, θ, between the $\mathbf{k}$ and $\mathbf{k}_e$ directions by solving the vector triangle (5), namely,

$$k'^2 = k^2 + k_e^2 - 2kk_e \cos \theta. \tag{9}$$

Equations (3), (6), (7), (8), and (9) then give the required angular distribution, namely,

$$F(\theta) \propto \sin^3 \theta [1 + 3(v/c)^2 - 2\sqrt{3}(v/c) \cos \theta].$$

This distribution is plotted in Figure 6 (a) for velocities of $\frac{1}{2}c$ and $\frac{1}{8}c$. In both cases the emission is seen to be beamed strongly in directions normal to that of the progressive plasma wave ; such is to be expected since the electronic oscillations in the plasma wave are longitudinal. However, in directions making small inclinations to the stream direction there is a marked preference for backward emission, especially in the case of the faster velocity. This result is emphasized in Figure 6 (b) which gives the backward-forward ratio, $F(\pi - \theta)/F(\theta)$, for different inclinations, θ.

(d) *Comparison of Theory with Observations*

Let us now consider the extent to which the results of Figure 6 offer a possible explanation of the observations described in Section II. We assume a burst

* These two cases have been chosen as the simplest illustration of the relation between $\mathbf{k}$, $\mathbf{k}'$, and $\mathbf{k}_e$ as given in equation (5) ; they are, however, hypothetical since no power is radiated either in or opposite to the stream direction as is clear from equation (7).

to be initiated by a progressive plasma wave (eqn. (1)) travelling radially outwards through a spherically symmetrical corona for which the ray trajectories depicted in Figures 3 and 4 apply. Figure 6 then implies that the harmonic radiation will be emitted most strongly in a direction rather backwards of the transverse direction. The higher the velocity, v, of the plasma wave, the more backward the beaming becomes, and when $v \gtrsim \frac{1}{2}c$ the backward emission exceeds the forward by an order of magnitude at least. Hence under these conditions much more radiation will escape along the reflected ray than the direct.

In the case of a type III burst we take the initiating disturbance to be an electron stream with velocity $\sim\frac{1}{2}c$ (Wild, Sheridan, and Neylan 1959), and assume this to be accompanied by a travelling wave of the same velocity. Under the assumed conditions, therefore, the theory predicts that the reflected source

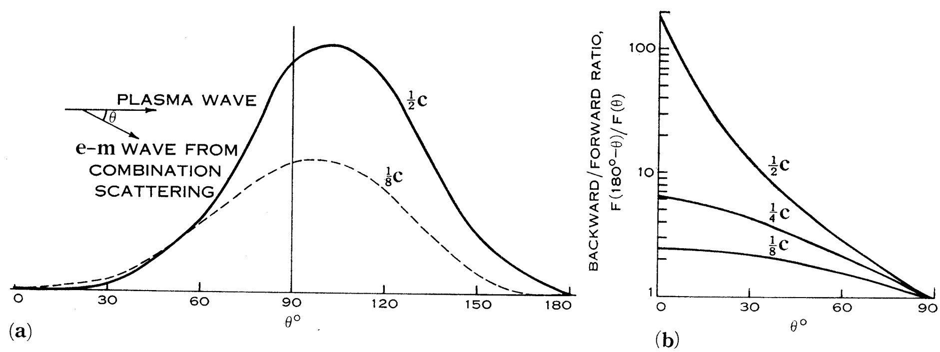

Fig. 6.—(a) Calculated angular power spectrum for radiation at the second harmonic of the plasma frequency, when the radiation is assumed to arise from combination scattering. (b) The backward/forward ratio of intensities derived from (a).

of harmonic radiation should dominate the direct source and hence that the centroid of the combined source distribution should appear much closer to the centre of the Sun's disk than the position of the direct source. The observed positions (Fig. 3) give inconclusive results, some being consistent with backward propagation, some forward, and some intermediate. More observations are obviously needed, but in the meantime it is worth noting that several factors, for example, departures from spherical symmetry in the actual corona, non-radial propagation of the plasma wave, and confusion between direct and reflected sources—will all combine to vary the observed effect.

In the case of a type II burst the basic outgoing disturbance is believed to have velocity $\sim$1000 km/sec. Were this velocity to be attributed to the progressive plasma wave, the theory would predict beaming of the harmonic radiation in the transverse directions, with no significant preference for backward over forward emission. This would lead to a result in conflict with the observations which, in terms of the present reflection theory, strongly favour backward radiation. This difficulty is removed, however, if we suppose the slow disturbance to be the seat of continuous ejections of high-energy electrons and hence fast plasma waves. Support for this idea is to be found in the observation that, in many type II bursts, the principal drifting bands appear to emit a continuous succession of type III bursts; this phenomenon culminates in the "herring-bone" effect (Roberts 1959) in which fast-drifting bursts of both positive and negative drift appear on the spectral records to diverge from a central backbone. the idea is also supported by the general association of type II bursts with high-energy phenomena on the Sun and Earth, and by the widely held view that the bursts originate at shock fronts, themselves the harbour of a turbulent collection of high-energy particles.

Explicitly, therefore, the reflection theory can account for the present observations of anomalous positions of type II harmonics if in all four reported cases the travelling disturbance emitted a continuous succession of fast electrons predominantly in the forward direction.

The theory is manifestly unproven both for type II and type III bursts but represents the only explanation we have to offer at the present time. Fortunately the theory is open to a number of predictions capable of direct observational test as more refined techniques come into use. We conclude by listing four of these predictions:

(i) That the harmonics of type II and possibly type III bursts may sometimes appear on the Sun's disk as double sources.

(ii) That if sometimes reflected and sometimes direct sources dominate the harmonics of type III bursts, the direct sources should be associated with the slower disturbances and with the more limbward events.

(iii) That harmonics of type III bursts which show a complete reversal in direction of travel from outgoing to ingoing (the "U" bursts of Maxwell and Swarup 1958) should, in favourable circumstances, show a sudden change of position towards that of the fundamental at the reversal point.

(iv) That if the herring-bone effect occasionally observed in type II bursts is due to a disturbance issuing high velocity electrons both inwards and outwards, then harmonic emission from the two components should appear to arrive from different positions: one from the direct source, the other from the reflected source.

IV. Acknowledgments

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V. References

Cohen, M. H. (1961).—*Phys. Rev.* **123**: 711.

Denisse, J. F. (1960).—Les phenomenes radio electriques solaires et leur interpretation physique. Presented to Commission V of URSI at the XIIIth General Assembly (London).

Ginzburg, V. L., and Zhelezniakov, V. V. (1958).—*Astr. Zh.* **35**: 694. (English trans.: *Soviet Astronomy A.J.* **2**: 653.)

Ginzburg, V. L., and Zhelezniakov, V. V. (1961).—*Astr. Zh.* **38**: 3. (English trans.: *Soviet Astronomy A.J.* **5**: 1.)

Haddock, F. T. (1958).—*Proc. Inst. Radio Engrs., N.Y.* **46**: 3.

Jaeger, J. C., and Westfold, K. C. (1950).—*Aust. J. Sci. Res.* A **3**: 376.

Jennison, R. C. (1959).—*Observatory* **79**: 111.

Kahn, F. D. (1959).—*Astrophys. J.* **129**: 205.
Maxwell, A., and Swarup, G. (1958).—*Nature* **181**: 36.
Roberts, J. A. (1959).—*Aust. J. Phys.* **12**: 327.
Salpeter, E. E. (1960).—*Phys. Rev.* **120**: 1528.
Shain, C. A., and Higgins, C. S. (1959).—*Aust. J. Phys.* **12**: 357.
Wild, J. P., Murray, J. D., and Rowe, W. C. (1954).—*Aust. J. Phys.* **7**: 439.
Wild, J. P., Sheridan, K. V., and Neylan, A. A. (1959).—*Aust. J. Phys.* **12**: 369.
Wild, J. P., Sheridan, K. V., and Trent, G. H. (1959).—"Paris Symposium on Radio Astronomy." p. 176. (Stanford Univ. Press.)