HARMONIC STRUCTURE AND BAND SPLITTING OF TYPE II SOLAR RADIO BURSTS

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Summary

An analysis of single-frequency records of type II solar radio bursts at 29 Mc/s has been made. Such characteristic features as harmonic structure and band splitting due to coronal magnetic fields have been identified. Calculations indicate that the shock fronts generating the type II bursts experience a deceleration as they move outwards. Existing theories have been used to estimate the magnetic field strengths, which come out to be of the order of 3–8 G at a height of 0·7 solar radius above the photosphere at the time of occurrence of these bursts.

I. Introduction

Correlation of optical solar flare data with the solar radio emission at metre wavelengths obtained from single-frequency records and swept-frequency methods has been established by Shain and Mitra (1954), Dodson (1958), Roberts (1959), and others. The authors have reported (Krishnamurthi, Sivarama Sastry, and Seshagiri Rao 1962*a*) a close correlation between flares of importance 3 or 3$\pm$ which occurred during the IGY period for the year 1958 and the related effects in the 29 Mc/s cosmic noise observations at Hyderabad, India (lat. 17°26′ N.; long. 78°27′ E.). In another paper the authors (Krishnamurthi, Sivarama Sastry, and Seshagiri Rao 1962*b*) have indicated a new method of obtaining the velocities of the shock fronts generating type II bursts, from an analysis of the single-frequency records. On a re-examination of these records for the year 1958, the authors have observed that information regarding the other features of type II bursts, such as harmonic structure and band splitting, can also be derived from the single-frequency data. Data obtained from such an analysis are presented in the present paper.

II. Experimental Results and Discussion

(*a*) *Velocities of Shock Fronts*

The equipment used for obtaining the single-frequency records employs a radio telescope, operating at 29 Mc/s, consisting of a broadside array of 30 full-wave dipoles giving a half-power beamwidth of 8·8° in the east–west direction and 18° in the north–south direction. The other details of the equipment have been described in an earlier paper (Krishnamurthi, Sivarama Sastry, and Seshagiri Rao 1958). For the period January–December 1958, nine sudden cosmic noise absorptions (SCNA's) have been recorded in these single-frequency records, and they have been correlated with the optical flares of importance 3 or 3$\pm$ occurring at the same time.

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In each of these SCNA's, an intense outburst of solar radio noise has been observed at about the maximum phase of the flare. These outbursts have been identified as type II bursts by virtue of their high intensity and their duration (a few minutes). Since the start of the SCNA has been closely identified with the start of an optical flare, the time elapsed for the appearance of the type II burst is used to estimate the velocity of the shock fronts generating these bursts. The method of calculation is described in an earlier paper (Krishnamurthi, Sivarama Sastry, and Seshagiri Rao 1962*b*). By this procedure it has become possible to obtain the velocities of shock fronts in the solar corona without the aid of elaborate swept-frequency methods.

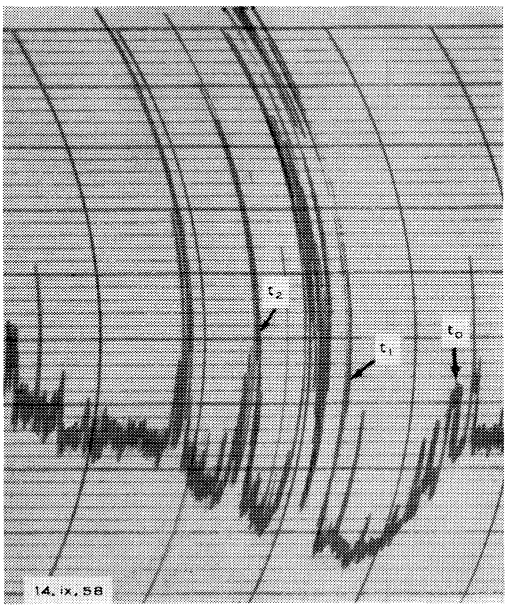

Fig. 1.—Sudden Cosmic Noise Absorption, September 14, 1958. t_0, beginning of SCNA; t_1, start of the first type II event; t_2, start of the second-harmonic burst.

(*b*) *Harmonic Structure*

Ordinarily, it is not possible to describe the harmonic structure of the type II bursts from single-frequency records. In fact, only since the advent of swept-frequency methods has the occurrence of harmonic bands for the type II events been established, together with such other characteristic features as band splitting and herring-bone structure in some cases (Roberts 1959).

Roberts has reported the presence of fundamental and second-harmonic bands in 60% of the type II bursts observed by him and in a larger proportion in the case of moderate and high-intensity bursts. The type II bursts recorded at 29 Mc/s by the authors occur at about the maximum phase of an intense SCNA, and are therefore of very high intensity. A closer examination of these records has shown that in all these events there is another distinct outburst occurring a few minutes after the first intense outburst. The intensity of this second outburst is comparable with that of the first. Since the receiver is tuned to the single frequency of 29 Mc/s all the time, it cannot receive the second-harmonic frequency of 58 Mc/s. Therefore, the burst occurring at the time t_2 shown in Figure 1 can be due to the second harmonic of a burst whose fundamental frequency is half that of the receiver frequency. In other words, if the shock front in its travel outwards in the solar corona reaches a level where the electron density is appropriate to excitation of 14·5 Mc/s radiation, then at the same instant the second harmonic of this fundamental radio wave will also be excited, and may be recorded by the radio telescope which is kept tuned to this second-harmonic frequency.

Table 1

VELOCITIES OF SHOCK FRONTS IN THE SOLAR CORONA, DERIVED FROM SECOND-HARMONIC BURSTS

Serial No.	Date	Start of SCNA (U.T.) h m	t_1-t_0 (s)	t_2-t_0 (s)	$V_{\text{fund.}}$ (km/s)	$V_{\text{2nd harm.}}$ (km/s)	Deceleration (km/s²)
1.	3. iii.58	10 10	710	1279	567	556	0·043
2.	23. iii.58	09 51	568	1042	709	682	0·119
3.	5. v.58	04 10	474	853	851	834	0·093
4.	6. vi.58	04 36	521	947	774	751	0·112
5.	29. vii.58	03 00	616	947	655	751	—
6.	16.viii.58	04 45	379	758	1063	938	0·668
7.	14. ix.58	08 53	900	1658	448	429	0·052
8.	19. x.58	07 27	379	710	1063	1001	0·383
9.	3. xii.58	07 02	805	—	501	—	—

On this assumption, since shock fronts are generating 14·5 Mc/s radiation at the appropriate level in the corona at a time t_2 after the start of the flare, their velocities may be estimated. On the basis of the Baumbach–Allen model, the height of the layer in the solar corona where the 14·5 Mc/s radiation is excited is estimated to be $1\cdot022\ R_\odot$, where $R_\odot$ is the radius of the Sun's visible disk ($0\cdot6957\times10^6$ km). The velocities thus obtained are given in Table 1, and are compared with the velocities calculated earlier for the same events from the fundamental outburst occurring at time t_1 after the start of the flare (Fig. 1). The times given in this table are determined to within ± 10 s.

It can be seen that the two values for the velocities agree closely, justifying the above procedure. In the last event occurring on December 3, 1958, the second burst is not recorded. For the event occurring on July 29, 1958, the value for $V_{\text{2nd harm.}}$ is much higher than $V_{\text{fund.}}$. In this case, therefore, it is not clear whether or not the second burst at t_2 is the second-harmonic burst. For all the other cases the value for $V_{\text{2nd harm.}}$ comes out to be smaller than $V_{\text{fund.}}$. Since it is likely that the shock wave experiences a deceleration in its travel outwards in the corona, $V_{\text{2nd harm.}}$ will always be less than $V_{\text{fund.}}$. Assuming uniform deceleration for the shock wave, values of deceleration may be calculated from the distances travelled during the time intervals (t_1-t_0) and (t_2-t_0), and are given in Table 1.

A different type of calculation has also been made in the following manner. Assuming that the shock front continues to travel with a uniform velocity as obtained from the time interval (t_1-t_0) corresponding to the fundamental outburst, the height at which the harmonic outburst is generated is calculated using the time interval (t_2-t_0). The plasma frequency f_p corresponding to this level is calculated in the usual way. The ratio of this frequency to the receiver frequency gives the harmonic ratio. Table 2 gives these values for the different events.

TABLE 2

CALCULATED VALUES OF HARMONIC RATIO

Date	$V_{\text{fund.}}$ (km/s)	t_2-t_0 (s)	Height h ($R_\odot$)	f_p for Height h (Mc/s)	Harmonic Ratio
3. iii.58	567	1279	1·042	14·16	2·05
23. iii.58	709	1042	1·062	13·83	2·10
5. v.58	851	853	1·043	14·14	2·05
6. vi.58	774	947	1·053	13·97	2·08
29. vii.58	655	947	0·892	17·17	1·69
16.viii.58	1063	758	1·158	12·43	2·33
14. ix.58	448	1658	1·068	13·72	2·11
19. x.58	1063	710	1·085	13·45	2·16
3. xii.58	501	..	No harmonic observed		..

Wild, Murray, and Rowe (1954) were the first to record the harmonic type II bursts, and they showed that the ratio of peak frequencies in the two bands was usually somewhat less than 2. This was explained by assuming that the lower frequencies in the fundamental band were unable to escape from the Sun in the direction of the Earth, and because of this the harmonic ratio varies with the position of the burst on the Sun's disk. Later observations by Roberts (1959) have shown that the harmonics could be received from any position on the disk and that the harmonic ratio does not vary significantly with the position of the burst.

It can be seen from Table 2 that the harmonic ratio is slightly greater than 2 in all cases except for the event of July 29, 1958. This clearly establishes that the burst occurring at time t_2 must be the second harmonic of the plasma frequency appropriate to that level. It is noteworthy that the harmonic ratio is always greater than 2. This higher value is obtained because it is assumed that the shock wave is travelling with uniform velocity, namely $V_{\text{fund.}}$.

(c) *Band Splitting*

For all the events listed in Table 1, except for the one on May 5, 1958, a doubling of the fundamental burst has been observed. A typical record is reproduced in Figure 2. This feature, observed in the structure of all the type II bursts, is considered to be analogous to the band splitting noticed in the swept-frequency records. In swept-frequency records a splitting of the fundamental and harmonic bursts into two components, separated in frequency by a few percent, has been observed by Roberts. Since the plasma region where the flare occurs is permeated by a general magnetic field of the sunspot group, a magnetic splitting analogous to the Zeeman effect may be responsible for the observed band splitting. Westfold (1949) has suggested that such a plasma region has three frequencies for which the refractive index is zero. These are given by the plasma frequency f_{p} and the frequencies

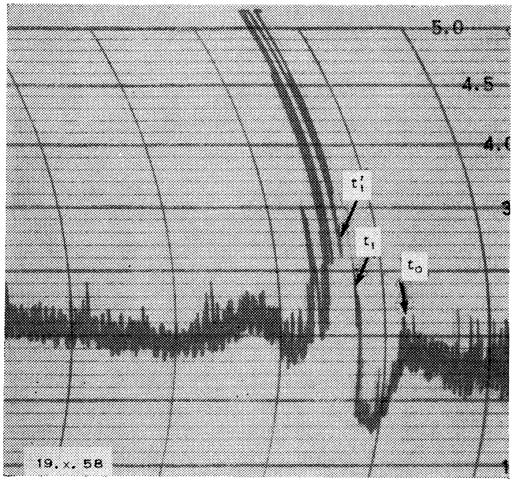

Fig. 2.—Sudden Cosmic Noise Absorption, October 19, 1958. t_0, beginning of SCNA; t_1, start of the first type II event; t_1', start of the burst due to band splitting.

$(f_{\mathrm{p}}^2+\frac{1}{4}f_H^2)^{\frac{1}{2}}\pm\frac{1}{2}f_H$, where f_H is the gyro frequency $(eH/2\pi mc)$. The lower of these cannot escape from the plasma region. On the other hand, from the dispersion relation

$$\omega^2 = \tfrac{1}{2}[\omega_{\mathrm{p}}^2+\omega_H^2\pm(\omega_{\mathrm{p}}^4+\omega_H^4-2\,\omega_{\mathrm{p}}^2\,\omega_H^2\cos 2\theta)^{\frac{1}{2}}],$$

Sturrock (1961) has recently obtained the frequencies that can be observed in band splitting. By imposing the condition $\mathrm{d}\omega/\mathrm{d}\theta = 0$, the frequencies of the lowest group velocity modes that are preferentially excited are obtained as ω_{p} and $(\omega_{\mathrm{p}}^2+\omega_H^2)^{\frac{1}{2}}$, and their separation is nearly equal to $\frac{1}{2}(\omega_H^2/\omega_{\mathrm{p}})$, $(\omega_{\mathrm{p}} \gg \omega_H)$.

In the present calculation, the procedure followed is to determine the frequency corresponding to the level where the burst at t_1' (Fig. 2) has occurred. The difference between this frequency and the receiver frequency of 29 Mc/s gives the band separation appropriate to the level where the burst at t_1' is excited. For these calculations the velocities $V_{\mathrm{fund.}}$ given in Table 1 are used. The height h' of these levels, their appropriate frequencies f_{p}', the band separation $(29-f_{\mathrm{p}}')$, and the associated magnetic field strengths H are presented in Table 3. The magnetic field strengths are calculated using both the theories mentioned above.

The values of magnetic field strength calculated using the expressions given by Westfold and by Sturrock compare favourably with the values indicated by Roberts earlier. Sturrock has estimated a magnetic field of 20 G at a height corresponding to 80 Mc/s radiation. The lower field strengths arrived at in the present analysis give an indication of how the associated magnetic field decreases in intensity with increasing height in the solar corona. However, the values obtained in this investigation are much higher than the average magnetic fields at these heights for a Baumbach–Allen corona over a Chapman model sunspot field of 3000 G. This might perhaps be expected for the coronal streamer regions over highly intense sunspot fields that give rise to flares of importance 3 or 3$\pm$.

TABLE 3

OBSERVED BAND SPLITTING AND ASSOCIATED MAGNETIC FIELDS CORRESPONDING TO TYPE II BURSTS

Date	$V_{\text{fund.}}$ (km/s)	$t_1'-t_0$ (s)	Height h' ($R_\odot$)	f_p' (Mc/s)	Band Separation (Mc/s)	f_H* (Mc/s)	f_H† (Mc/s)	H* (G)	H† (G)
3. iii.58	567	899·5	0·735	21·79	7·21	12·62	19·14	4·5	6·8
23. iii.58	709	662·8	0·677	24·06	4·94	9·04	16·19	3·2	5·8
5. v.58	851	..	..	No band splitting observed			..	..	..
6. vi.58	774	663·1	0·738	21·69	7·31	12·77	19·25	4·6	6·9
29. vii.58	655	758·1	0·714	22·58	6·42	11·41	18·20	4·1	6·5
16.viii.58	1063	592·1	0·906	16·86	12·14	19·20	23·60	6·9	8·4
14. ix.58	448	1113·1	0·717	22·46	6·54	11·61	18·35	4·2	6·6
19. x.58	1063	473·7	0·725	22·15	6·85	12·09	18·72	4·3	6·7
3. xii.58	501	947·1	0·682	23·84	5·16	9·40	16·51	3·4	5·9

* Values calculated using the formula given by Westfold (1949).

† Values calculated using the formula given by Sturrock (1961).

While the swept-frequency techniques have established the various features of type II bursts such as harmonic structure and band splitting, the foregoing analysis of single-frequency records seems to give more accurate data, once these features are seen to be characteristic of type II bursts.

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