LOCATION OF THE SOURCES OF 19 Mc/s SOLAR BURSTS

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Summary

By using large aerials in a new way, it has been possible to locate, with considerable accuracy, the sources of 19 Mc/s solar bursts. The positions of these sources have been correlated with the positions of optically active regions associated with them, and the radial distances of the radio sources from the centre of the Sun have been deduced. In 1950–1951, 18·3 Mc/s bursts came from sources at a radial distance estimated as $3 \cdot 4R_0$; more reliable data in 1957 indicated that the sources of 19·7 Mc/s bursts were at a radial distance of $2 \cdot 9R_0$. It is thought that these measurements give the distances of the fundamental plasma levels in coronal streamers.

I. Introduction

The progress of radio astronomy has been closely linked with the development of equipment and novel techniques for obtaining high angular resolving power. In the application of new direction-finding techniques it is often simpler to study solar radio emission than cosmic sources, because in some circumstances the Sun, or at least some part of it, is the outstandingly bright object in the sky. In particular, at about 20 Mc/s, the undisturbed Sun is very faint, but solar bursts commonly have intensities many times the intensity of the galactic background. Observations of solar radio spectra (Wild, Murray, and Rowe 1954) have shown that these bursts most probably originate at a level in the corona where the plasma frequency is equal to the frequency on which the bursts are observed; they are often associated with solar flares.

Since the sources of metre-wavelength radio emission must be well above the chromosphere, bursts from sources away from the centre of the solar disk will appear substantially displaced from the position of the associated optical phenomenon (Payne-Scott and Little 1951) and, conversely, if these displacements can be measured, we can obtain information about the actual height in the corona of the appropriate plasma level.

Some years ago, in 1950, an aerial system constructed near Sydney for cosmic noise observations (Shain and Higgins 1954) was used in a novel way to measure with useful accuracy the positions, in one coordinate only, of the sources of 18·3 Mc/s bursts from the Sun. Although these observations gave a clear indication that the sources of emission were rather higher in the corona than might have been expected on the basis of the Baumbach-Allen model of the corona, they could not be correlated in detail with optical data, simply because adequate optical data were not available. More recently we have again made

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solar position measurements, this time using the east-west array of the 19·7 Mc/s cross-type aerial (Shain 1958) and, as these measurements were made during the International Geophysical Year, optical information is much more complete.

The aim of the present paper is to present the results of these observations and to deduce from them the apparent heights of origin of the bursts, and hence of the plasma levels in the corona. This information could then be combined with similar results obtained from observations at other frequencies (see, for example, Wild, Sheridan, and Neylan 1959) to construct a model of the coronal electron density distribution, but no attempt will be made to do this here.

II. Observational Technique

Since most solar noise bursts last for times of the order of 10 sec, any direction-finding equipment designed to observe these bursts must be able to operate very rapidly. In the metre-wavelength range the usual method involves interferometers employing widely spaced aerials and rapid variation of the phase paths to the receiver. Little and Payne-Scott (1951) operated at a single frequency and used a fast, mechanical phase changer ; Wild and Sheridan (1958) use fixed lines but sweep in frequency.

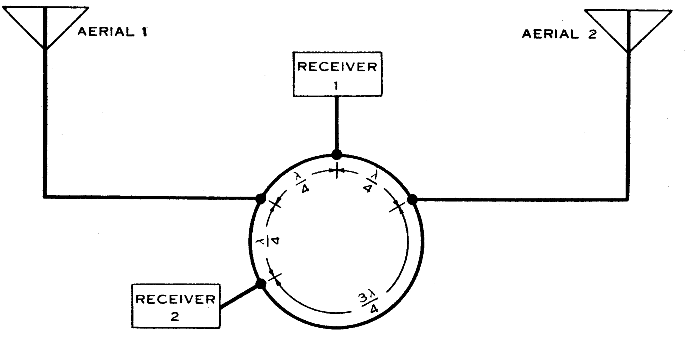

Fig. 1.—The arrangement of aerials and receivers.

For the present work, no attempt was made to sweep in phase. Two similar aerials were connected by equal feeders to a bridge, and two separate receivers to the other corners of the bridge (see Fig. 1). The feature of such a bridge (Westcott 1948) is that the two receivers are quite independent of one another in operation, and the aerials are connected to Receiver 1 in-phase, but to Receiver 2 out-of-phase. Now, if the Sun is in the primary beams of the aerials and a burst occurs, in general the burst amplitude as recorded by the two receivers will be different, and the ratio of the amplitudes is a function only of the angle between the source direction and the line joining the two arrays. If r is the ratio of the in-phase (power) amplitude to the out-of-phase amplitude, and φ the angle between the source and the line joining the aerials,

$$r=\cot^2\left(\frac{\pi d}{\lambda}\cos\varphi\right),$$

where d is the separation between the aerials and λ the wavelength. If the aerials are on an east-west line,

$$\cos \varphi = \cos \delta \sin h,$$

where δ and h are the declination and hour angle respectively of the source.

In practice, Aerials 1 and 2 (Fig. 1) were actually two halves of one large array. The earlier series of observations (in 1950–1951) used the 30-dipole array which has been described previously (Shain and Higgins 1954). For the later series (in 1957) an exactly similar arrangement was used. Although, for galactic work, it is normally operated as a complete array 3500 ft long, the east-west array of the 19·7 Mc/s Cross may be divided into two, with separate feeders for the eastern and western arms, and these separate arms formed Aerials 1 and 2 of Figure 1.

As in all interferometer observations there are ambiguities in position at intervals corresponding to the various values of φ which give the same value of r. In one way these ambiguities are more serious than with the conventional interferometer technique, because amplitudes are measured without regard to phase and near a maximum or minimum of the interferometer pattern the same ratio is measured at two fairly close positions. It is therefore desirable to compute positions for only those bursts for which the ratio is in the range, say, $0 \cdot 2 < r < 5$. On the other hand, by using the two halves of the one array there is virtually no gap between the "interferometer" aerials and, apart from the centre lobe and the two neighbouring lobes, all the lobes are of very small amplitude.

The two receivers were either two communications receivers or two sections of the receiver used with the 19·7 Mc/s Cross. The important requirements of the receivers are that they should be tuned to exactly the same frequency and that the overall time constants, including the recorders, should be the same. Intensity calibrations for each receiver were included on all the records. The accuracy with which the two receivers must be set to the same frequency depends on the spectral characteristics of the bursts. In this connexion it is of interest to note that on several occasions, not included in the present study, certain short-duration bursts have been recorded with very different intensities (allowing for aerial and receiver instrumental effects) at frequencies only 40 kc/s apart at about 19·7 Mc/s. For the present work the frequencies to which the receivers were tuned differed by no more than 1 kc/s.

A typical pair of records is shown in Figure 2; the apparent positions deduced from the ratios of burst amplitudes are shown in the lowest section of the figure.

Although the observations were all made near solar transit, so that "spherical" refraction in the ionosphere would have had only a negligible effect on measurements of hour angle, the diurnal variation of electron density produces horizontal gradients which give rise to appreciable "wedge" refraction in the east-west direction. Corrections to the observed source positions were made using the data of Komesaroff and Shain (1959), derived from observations of discrete sources of cosmic noise. In that paper it was shown that the applications of the corrections described there greatly reduced the scatter of the observed positions (to about $\pm 0^\circ \cdot 1$) but there remained a systematic displacement in Right Ascension. It is now known that this effect arose out of the assumption that the time variation of the critical frequency of the ionosphere could be interpreted as a spatial variation along a line of constant latitude. Further study of the data from the ionospheric sounding stations in eastern Australia and at Watheroo, Western Australia, has shown that this assumption was not fully justified, and a more complete correction for ionospheric refraction is now possible (Komesaroff and Shain, in preparation).

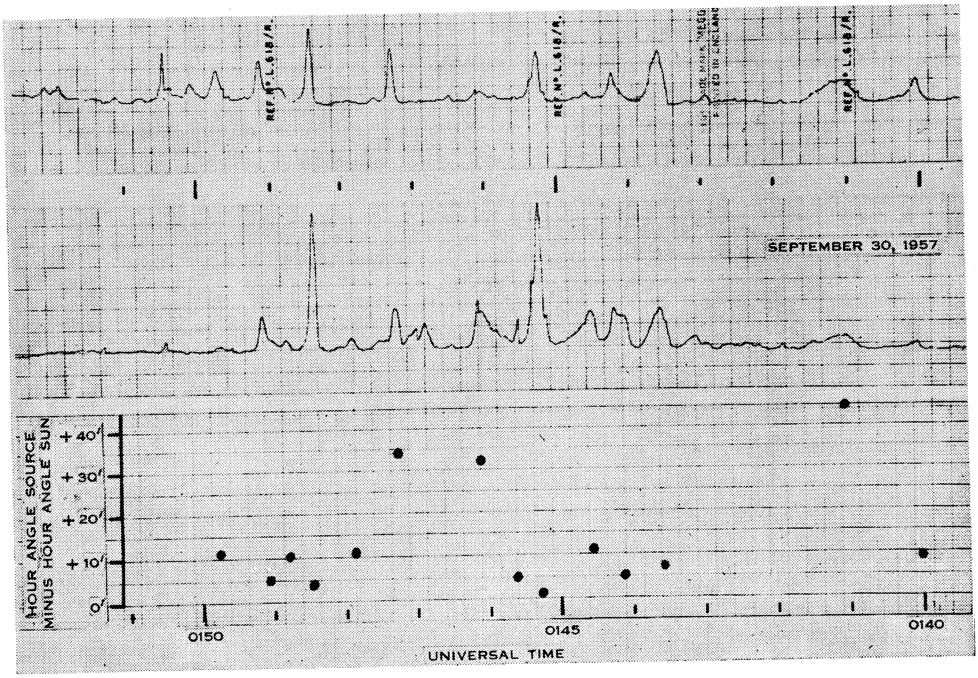

Fig. 2.—The two records for September 30, 1957. The " out-of-phase " record is on top and the " in-phase " record underneath. The lowest section of the figure shows the positions derived from the ratios of burst intensities, after making a small and constant correction for ionospheric refraction. It is clear that most of the bursts come from one source, but three bursts probably arose in another source further to the west. Only the main source has been listed in Table 2.

Because of the high intensity of solar bursts, the accuracy obtainable in reading the source positions from the records is very high, the uncertainty being only a small fraction of the beamwidth of the whole aerial array (17° to half-power at 18·3 Mc/s in 1950–1951 and 1°·5 at 19·7 Mc/s in 1957). The main source of uncertainty for the 19·7 Mc/s observations, and a contributing source for the 18·3 Mc/s observations, arises in the estimation of the ionospheric refraction, especially as interpolation from hourly data is necessary in order to estimate the ionospheric parameters. Therefore, although we have listed the positions of the radio sources to the nearest 5 min of arc, estimates of the probable uncertainties of the positions for any one day are $\pm 0^\circ \cdot 1$ and $\pm 0^\circ \cdot 3$ for the 1957 and 1950–1951 observations respectively.

It should be noted that, since there is no phase-switching involved, the rate at which direction-finding observations can be made is limited only by the overall time constant of the system. By using suitably rapid recorders, it should be possible to detect any changes in apparent position which might occur even during bursts lasting only 1 sec. Position changes have been observed during some bursts, or series of bursts, lasting several minutes, but these will not be considered in the present paper.

III. Observational Data

(a) *18·3 Mc/s Observations in 1950–1951*

The dates and times of the 1950–1951 observations are listed in Table 1, together with the positions of some optical regions with which the radio emission on the various days might reasonably be associated. As mentioned above, there were many long gaps in the optical observations during the periods of interest so that some of these associations are doubtful, and also some radio data

Table 1

1950–1951 observations

Date	Hour Angle Radio Source minus Hour Angle Sun (min. of arc)		Optical Active Region	Hour Angle Optical Source minus Hour Angle Sun (min of arc)
	18·3 Mc/s	97 Mc/s		
1950				
Nov. 16 ..	0	+2·5	(8) Flare	0
17 ..	+20	+5·5	—	—
1951				
Jan. 30 ..	+10	+7·5	(7)	+ 4
Feb. 1 ..	+40	+15	(7) Flare	+ 9
2 ..	+20		(5) Flare	+ 6
24 ..	— 5		(13)	— 1
Mar. 16 ..	—40		(18)	—13
17 ..	—25		(18)	—12·5
18 ..	—35		(18)	—12
19 ..	+10		(18)	— 9·5
20 ..	—10		(18)	— 7
22 ..	—10		(18)	— 0·5
24 ..	+ 5		(18)	+ 5·5
25 ..	+50		(18)	+ 8·5
26 ..	+80		(18)	+11

had to be omitted because there was no clear identification with any particular optically active region. In Table 1 the regions are identified by the numbers given in the appropriate issue of the *Quarterly Bulletin on Solar Activity*; the word " Flare " is added if a solar flare was observed during the time of observation on any day. Since the aerial was practically on an east-west line and the observations were limited to times near transit of the Sun, the position measured was the difference between the hour angles of the source and of the centre of the Sun. On four days for which 18·3 Mc/s data are available the Potts Hill 97 Mc/s swept-phase interferometer (Little and Payne-Scott 1951) was operating, although not necessarily at the same times, and Mr. A. G. Little has kindly supplied the positions deduced from these observations ; these, too, are included in Table 1.

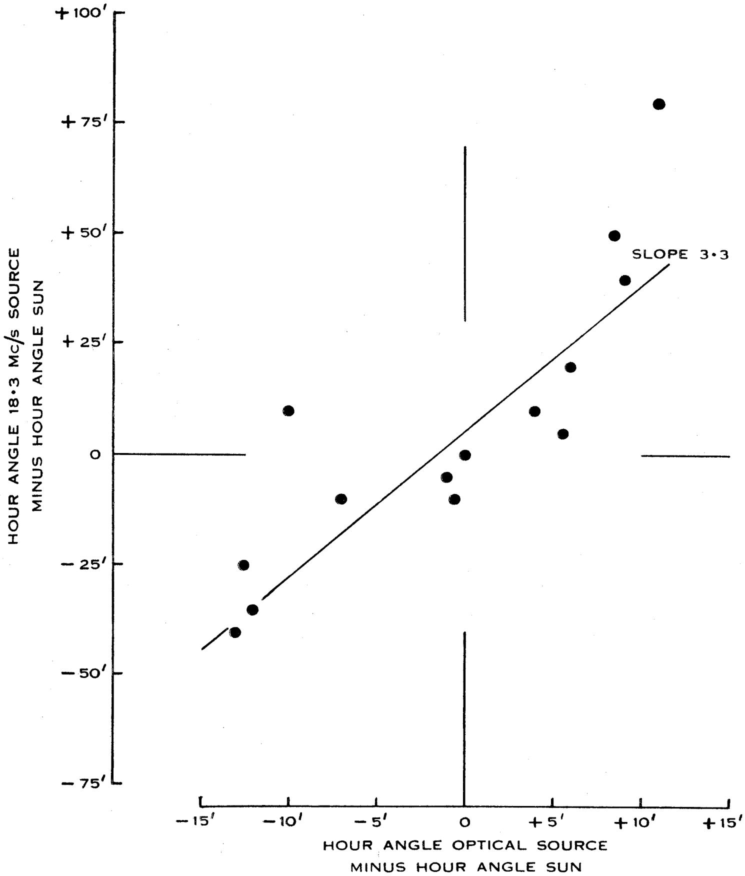

Fig. 3 (*a*).—The observed east-west displacements from the centre of the Sun of the 18·3 Mc/s sources plotted against the positions of the associated optically active regions ; data from Table 1.

In Figure 3 (*a*) the east-west displacement between the radio source and the Sun's centre is plotted against the corresponding optical displacements. There is clearly a strong correlation between the two quantities, but this must be partly due to observational selection—to a certain extent the few optical data were chosen to fit the radio data. In view of all the uncertainties, no significance is attached to the fact that the line in Figure 3 (*a*) does not pass exactly through the origin. Figure 3 (*b*) shows the 18·3 Mc/s positions plotted against the corresponding 97 Mc/s positions for the few occasions on which both measurements were available.

In spite of the uncertain optical identifications, one thing is clear from Table 1 and Figure 3 (*a*), namely, that the radio sources lie far out in the corona : the east-west displacements of the radio sources range up to 50 min of arc, whereas the diameter of the optical disk is only 16 min of arc. Further, Figure 3 (*b*) shows that the 18·3 Mc/s bursts must come from a region much further out even than the region of origin of 97 Mc/s bursts.

(*b*) *19·7 Mc/s Observations in 1957*

Table 2 gives the circumstances of the position measurements made with the large 19·7 Mc/s array in 1957 ; the rather narrow primary beam of the aerial restricted the observations to times within about 15 min of solar transit. On the majority of days listed in the table the bursts were observed at times when

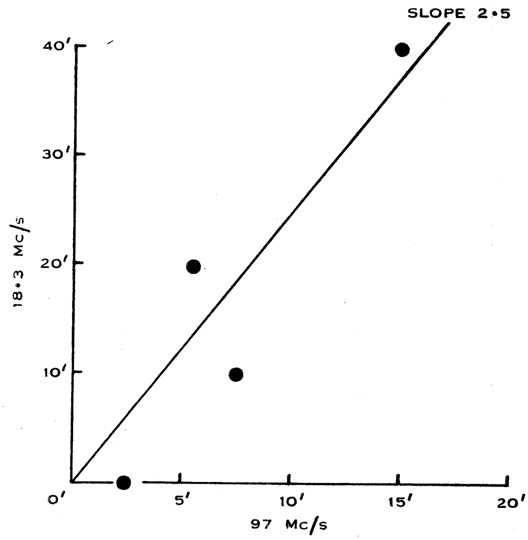

Fig. 3 (*b*).—The east-west displacements of 18·3 and 97 Mc/s sources on four days.

solar flares were visible on the Sun and it appears reasonable to associate the radio bursts and the flares. On other days there were no flare observations just at the time of the radio observations. For these days the " adopted optical source " has been taken as the McMath Plage Region (MPR) which produced most flares and sub-flares during the 6 hr on either side of the time of observation. The plage regions are identified by the numbers published in the Central Radio Propagation Laboratory's monthly " Solar-Geophysical Data "* from which also some of the flare information was taken. Other flare information came from the patrol observations of the C.S.I.R.O. Division of Physics, Sydney.

It is impossible to decide with certainty, from the single-frequency observations, the spectral type of the radiation being studied, but comparison with the

* U.S. National Bureau of Standards, Central Radio Propagation Laboratory, Series CRPL–F Part B, Issued Monthly.

TABLE 2
1957 OBSERVATIONS

Date	Times of Bursts Analysed (U.T.)		Hour Angle 19·7 Mc/s Source minus Hour Angle Sun (min of arc)	Adopted Heliographic Position of Optical Source		Hour Angle Optical Source minus Hour Angle Sun (min of arc)	Optical Source	Concurrent Radio Spectral Observations
	First	Last		Lat.	Long.			
1957								
Aug. 26 ..	0153·0	0206·4	—40	N 28	E 82	—15·5	MPR 4124	U, III before and after
			—15	S 30	E 64	— 9	MPR 4125	
28 ..	0151·2	0203·7	—15	S 28	E 38	— 2·5	Flare Mitaka 0122–0135–0154	III 0146, 0200
30 ..	0148·5	0152·8	+30	S 25	W 33	+11	Flare Sydney 0133–0216–	Weak I all day
								IIIg 0159, 0200 ; IIIb 0201
Sept. 23 ..	0145·4	0153·8	—30	N 18	E 62	—14	MPR 4159	
24 ..	0141·0	0142·2	+80	N 13	W 62	+11	Flare Sydney 0142–0143–0148	Weak I all day
								III 0141, 0142
25 ..	0141·4	0149·0	+35	N 24	W 85	+11	Flare Hawaii <0132– –>0138	U, III before and after
27 ..	0140·4	0153·3	—35	N 16	E 50	—12	MPR 4162	Strong I all day
			0	N 18	E 3	— 2	MPR 4159	III storm all day
28 ..	0142·2	0151·2	+ 5	N 18	W 11	+ 1	MPR 4159	No observations
			+30	S 15	W 45	+12	MPR 4157	
30 ..	0140·1	0149·8	+ 5	N 18	W 37	+ 5·5	MPR 4159	U, III before and after
Oct. 1 ..	0145·0	0202·4	—10	N 29	E 23	— 7	Flare Sydney 0131–0139–0148	No observations
							Flare Sydney 0158–0200–0204	
2 ..	0149·5	0153·3	—30	S 20	E 40	— 6	MPR 4167	III after
4 ..	0151·0	0153·4	—60	N 20	E 94	—15·5	Flare Sydney 0149–0152–0200	III before and after
17 ..	0136·4	0145·6	+30	S 13	W 28	+ 9	Flare Sydney 0143–0154–0205	IIIg 0138, 0139 ; IIIb 0141
25 ..	0136·0	0142·0	+15	N 13	W 7	+ 1	Flare Sydney 0131–0145–0159	III before
Nov. 15 ..	0133·0	0152·0	+30	N 15	W 37	+ 5	Flare Sydney 0136–0138–0144	III before
18 ..	0138·0	0206·0	+20	N 5	W 50	+11	Flare Sydney 0120– –0230	U 0204–0205
							Flare Hawaii 0126–0132–0138	
Dec. 9 ..	0201·0	0204·0	—15	S 20	E 8	— 1	Flare Sydney 0157–0201–0226	IIIG 0200–0203

Dapto radio-spectrograph data for the days concerned suggests that in almost all cases the radiation was type III. The doubtful cases are those when type I storms were observed at Dapto, in particular on September 27, 1957 ; one of the two positions observed on this day probably refers to type I emission, the other to type III. There may have been a few cases of type V bursts, but types

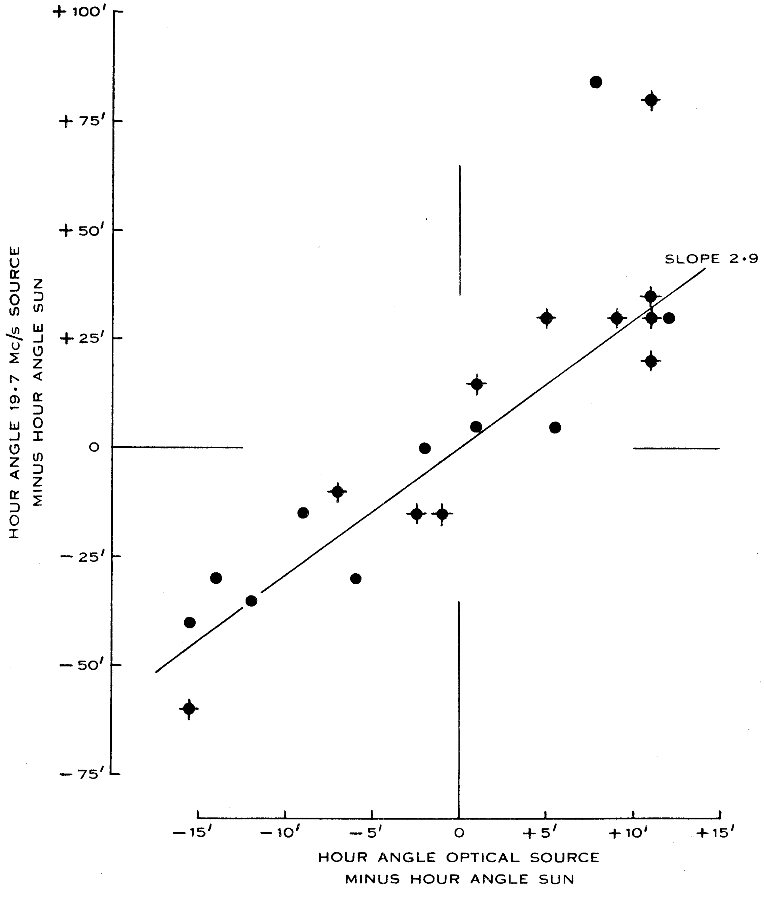

Fig. 4.—The observed east-west displacements from the centre of the Sun of the 19·7 Mc/s sources plotted against the positions of the associated " adopted optical source " ; data from Table 2. The points marked with a cross correspond to radio sources directly associated with solar flares.

II and IV can be excluded as they occur together and the spectra of type II bursts are such that any reaching to 20 Mc/s would have been identifiable on the spectrograph records.

The east-west displacements of the radio and optical sources from the centre of the Sun are compared in Figure 4. As with the earlier observations, again there is good correlation and it can be inferred that the radio sources must be well out in the corona. This point is discussed in more detail below.

IV. Height of the Sources of Emission

From their study of the radio-spectrograph data, Wild, Murray, and Rowe (1954) concluded that there was strong evidence that " fundamental " type III bursts at any frequency were generated at the corresponding plasma level in the corona. In interpreting our observations, we may consider two greatly different coronal models.

Firstly, if the corona were smooth and spherically symmetrical, the critical " escape surface ", from below which radiation cannot reach the Earth, is everywhere higher than the plasma level, so, for radiation to reach the Earth from a source at the plasma level, it is necessary to modify the simple model by introducing scattering near the escape surface. We then have the kind of situation illustrated in Figure 5 (*a*) : the source of bursts in the plasma level radially above the optical source, but the observable position probably referring to the intersection of the escape surface and the radius through the source. With the

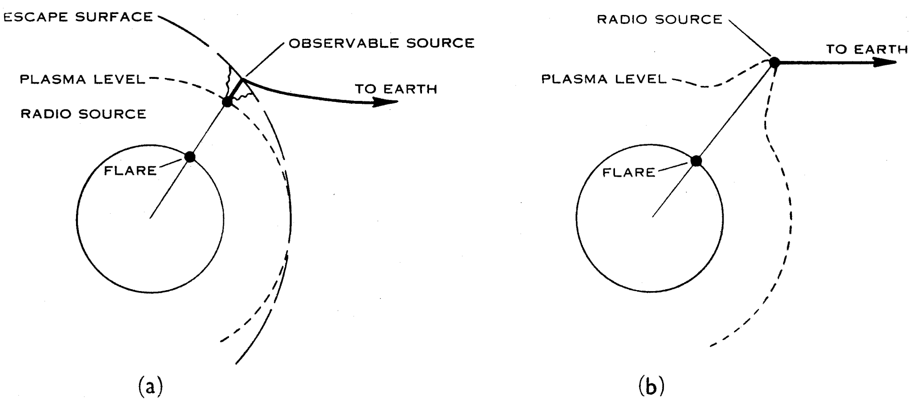

Fig. 5.—Illustrating two possible coronal models considered in the interpretation of the radio position observations.

comparatively smooth, regular model of the corona, the ray path suffers appreciable refraction in the outermost regions of the corona and the apparent position as measured at the Earth is moved back towards the centre of the Sun. We have considered in detail the apparent movement of a radio source across the Sun's disk on the basis of this model and, surprisingly, it appears that the refraction almost counterbalances the effect of the increased height of the escape surface as the source nears the limb. It follows that, to within the accuracy involved in the assumption that the radio source is radially above the optical source, the observations can be interpreted as if the source moves around the plasma level surface with no refraction after leaving the source. The slope of the line through the points on diagrams such as Figures 3 (*a*) and 4 then gives directly the distance of the plasma level from the Sun's centre in units of the radius of the optical Sun.

On the other hand, there are, in fact, generally large irregularities in the corona, the coronal streamers (van de Hulst 1953), and as these are specially prominent over active regions it is probable that the radio sources are actually in coronal streamers. The disturbance exciting the source will probably travel along the streamer and the source might be expected to be at the highest point of the surface of equal electron density corresponding to the plasma frequency, as in Figure 5 (*b*). Provided the streamer is fairly narrow there will be little refraction in the " normal " outer corona, because the electron density there will be much lower than in the streamer. In this case also, then, we can deduce the height of the source directly from the observations, but this would be the height of the plasma " level " in a coronal streamer and not in the normal corona.

In either case it appears reasonable to assume that on the average the initiating disturbances travel radially outwards from the optical active region, although for any particular disturbance there may be considerable departures from radial motion.

Turning to the observational results, from Figure 3 (*a*) we deduce that in 1950–1951 the 18·3 Mc/s sources were at a radial distance of $3 \cdot 5R_0$ from the centre of the Sun (R_0 being the Sun's optical radius), although this value is rather uncertain because of the scatter of the points and the basic uncertainties in identifying the optical sources. Again, from Figure 3 (*b*) we find that the 18·3 Mc/s sources were at a distance about 2·5 times the distance of the 97 Mc/s sources. Taking the Baumbach-Allen model of the corona (Smerd 1950), the distance of the 97 Mc/s plasma level is $1 \cdot 15R_0$, but Payne-Scott and Little (1951) estimated that the sources of 97 Mc/s noise storms were not less than $0 \cdot 3R_0$ above the visible surface. In conjunction with Figure 3 (*b*) this would lead to a radial distance of $3 \cdot 2R_0$ for the 18·3 Mc/s sources, in good agreement with the value from Figure 3 (*a*); the average gives $3 \cdot 4R_0$.

For the later and more reliable 19·7 Mc/s observations, the slope of the line in Figure 4 indicates a radial distance of $2 \cdot 9R_0$ for 19·7 Mc/s sources in 1957.

V. Discussion

The immediate inference that might be drawn from the results of the previous section is that the sources of 19 Mc/s bursts are much higher than the " normal " 19 Mc/s plasma level (radial distance about $1 \cdot 8R_0$ (Smerd 1950; van de Hulst 1953)), but this simple interpretation requires further consideration, for the following reason. It was pointed out above that the spectral type of the bursts cannot be decided with certainty from the single-frequency records and there is a possibility that the derivation of a large height for the 19 Mc/s plasma level is due to the fact that the bursts studied were actually harmonics of 10 Mc/s bursts; the 10 Mc/s plasma level is certainly higher than the 19 Mc/s level. Before considering this question more closely, it may be remarked that even the 10 Mc/s level in the normal corona is only at a radial distance of about $2 \cdot 25R_0$, and it would appear to be established that the bursts originated in coronal streamers where electron densities are rather higher at any height than in the normal corona.

If some of the bursts observed were fundamental bursts and some harmonics, the scatter of the points in an idealized diagram like Figures 3 (*a*) and 4 would increase for sources near the limb. There are, of course, other factors contributing to the scatter in these figures : observational errors, departures from radial motion of the initiating disturbances, and differences in the electron density distribution for different streamers. In Figure 4, particularly, the scatter appears to be much the same all the way along the line and, in fact, a very large part of this must be due to observational errors. It follows that any component of the scatter due to a mixture of fundamental and harmonic bursts is small, and one or other must predominate.

Wild, Murray, and Rowe (1954) have shown that the disturbances which initiate the bursts travel outwards through the corona, but are often brought to rest before escaping from the Sun. The height at which this occurs varies from

TABLE 3

DERIVED HEIGHTS OF PLASMA LEVELS

Year	Frequency (Mc/s)	Electron Density (cm^{-3})	Radial Distance from Centre of the Sun
1950–51 ..	18·3	$4\cdot1\times10^{6}$	$3\cdot4R_0$
1957	19·7	$4\cdot8\times10^{6}$	$2\cdot9R_0$

burst to burst, but one would expect that the 19 Mc/s level would be excited more often than the higher 10 Mc/s level, so that most of the bursts observed were fundamentals.

Although the evidence is not conclusive, we incline to the view that the radial distances of the plasma levels, derived in this paper, refer to the fundamental plasma frequencies. The results are brought together in Table 3. Of the two sets of observations, the 19·7 Mc/s is the more reliable, but the earlier result is in good agreement, considering all the uncertainties involved and the time interval between the observations.

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