SOME CHARACTERISTICS OF SOLAR RADIO EMISSIONS

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(Received 1948 September 9)

Summary

An analysis is given of solar radio emissions, observed mainly at a wave-length of 4·1 metres between 1946 March and 1947 September, and their relation to visual solar phenomena and their geophysical accompaniments. The associations of solar radio bursts with flares are considered in detail and it is shown that the most intense flares are the most likely to produce radio bursts. It is also shown that in general the radio emission lags by several minutes behind the visual or ultra-violet flare radiations.

The apparent tendency for coincidences between flares and bursts to be greater on the eastern than on the western half of the Sun's disk is discussed. The distribution of coincidences with respect to solar longitude from central meridian is contrasted with the sharply-beamed pattern of continuous radiation associated with sunspots.

1. *Introduction*

The observations of the intense solar radio emissions at metre wave-lengths here described form a continuation of the experimental investigations made at the Army Operational Research Group in 1942 February and 1946 February, which have been described by Appleton and Hey.* These investigations showed that intense electromagnetic radiations could emanate from the Sun during the transit of a large sunspot across the Sun's disk. It was demonstrated that the received radio intensity was particularly high in the region of 5 metres wave-length and that the average level of radiation reached its maximum value when the spot was within a few days of central meridian passage. It was also found that there were sudden increases in radio power flux of 10–100 times the mean level which occurred at approximately the same time as solar flares and radio communication fade-outs.

Observation of solar radio emissions was subsequently made at various times until 1946 July, since when recordings at a wave-length of 4·1 metres have been made almost continuously every day from sunrise to sunset. Occasionally, additional measurements have been made of the solar radiation at several wave-lengths between 1·5 metres and 12·5 metres. It became evident that the relationship between visual and radio solar emissions was very complex. It was possible to find examples of striking correlations between solar and radio phenomena, but there were also many occasions in which such association was absent. A comprehensive account can, therefore, only be given after consideration of a large number of cases. These may be analysed so as to determine the numbers of coincidences and an assessment of their significance can be made on a statistical basis. It will then be of particular value to distinguish any trends in the correlations with variations in the measurable properties of the different phenomena. The present investigation is an attempt to achieve this object. The principal phenomena with which we deal are the intensities of the solar radio

* J. S. Hey, *Nature*, **157**, 47, 1946; AORG Memo J4, 1942, and **Report 275, 1945** [Restricted Circulation]. E. V. Appleton and J. S. Hey, *Phil. Mag.*, **37**, 73, 1946.

emissions, the magnitudes and positions of sunspots and solar flares, and the geomagnetic disturbances which give indirect evidence of solar activity.

2. *The Measurement of Solar Radio Intensities*

2.1. *The Apparatus.*—A sensitive radio receiver was operated on a mean wave-length of 4·1 metres with a band-width of 3 Mc./s. The rectified output of the receiver was marked on a recording ammeter, the overall time constant of response being of the order of 1 second. The recording chart moved at the rate of 6 inches per hour. Hourly timing-marks were made on the recording chart by means of a chronometer relay. The chronometer was checked daily against G.M.T. by G.P.O. telephone. By these means any solar noise recorded on the chart could be timed to an accuracy better than ½ minute.

The recorded output was calibrated in terms of the radio noise input in absolute units by means of a noise-signal generator which presented an impedance approximately equal to that of the aerial.

The aerial system consisted of a twin yagi array using horizontal polarization. The array was normally tilted at 20° elevation which gave adequate sensitivity up to 40° elevation. For those times of day during the summer months when the Sun's elevation exceeded 40°, the tilt of the yagi array was altered to 60°. The aerial sensitivity in the vertical plane was known approximately from previous measurements on similar arrays using a small oscillator suspended on a balloon as the source of signal. A rough check of aerial sensitivity was made by comparing the solar noise received by the yagi array with that received simultaneously by a single dipole. The aerial gain in the direction of maximum sensitivity was estimated to be about 5½ times that of a half-wave dipole in free space.

The aerial array was mounted on the receiver cabin which was rotated about a vertical axis by a motor drive adjusted to keep the aerials to within a few degrees of the bearing of the Sun. A knowledge of the aerial sensitivity in the vertical plane and of the calibration characteristics of the receiver thus made it possible to calculate the power flux of radiation in the incident wave to an accuracy of about 25 per cent.

2.2. *Intensity Measurements.*—Radio emissions may be classed into two types, continuous emission of fluctuating intensity and sudden bursts of intensity which are often of the order of a few minutes in duration. Previous work * has indicated that the former type is more particularly associated with spots and reaches a maximum near central meridian passage, whilst the latter type is more particularly associated with flares.

The recordings of solar radio emissions have been converted into absolute power flux received at the Earth's surface in watts/sq.m.cyc./sec. band-width. These values can, if desired, be converted into equivalent solar black-body temperatures for the wave-length under consideration.† It must be noted,

* E. V. Appleton and J. S. Hey, *loc. cit.* L. L. McCready, J. L. Pawsey and R. Payne Scott, *Proc. Roy. Soc. A.*, **190**, 357, 1947. M. Ryle and D. D. Vonberg, *Proc. Roy. Soc. A.*, **193**, 98, 1948.

† The power flux at the Earth's surface, assuming the Sun to be a black-body radiator, is

$$F=\frac{2KT\,d\nu\,.\,d\Omega}{\lambda^2},$$

where K=Boltzmann's const.
T=absolute temperature.
$d\nu$=frequency band-width.
$d\Omega$=solid angle subtended by the Sun.
λ=wave-length.

however, that such temperatures have no significance except as alternative indications of magnitude. Not only is the source of radiation not the whole Sun, but both the spectrum and the great intensity of the radio emission suggest that it is of non-thermal origin.

For convenience of analysis the radio bursts have been classified in intensity according to an arbitrary scale of 3. This plan was adopted for simplicity in order to divide the occurrences into a few intensity groups in a similar manner to the accepted classification of solar flares. During the analysis it was found desirable to introduce a further group for minor radio bursts and this has been numbered ½. The radio scale of intensity for radio bursts was chosen as follows:—

Scale Number	Radio Intensity in units of 10^{-22} watts/sq.m.c.p.s. (horizontal polarization)
0	<20
½	20–100
1	100–500
2	500–1500
3	>1500

The unit of intensity, 10^{-22} watts/sq.m.c.p.s. band-width, is of the order of the smallest detectable signal with the present apparatus. Since the smallest measurable intensity varies with the altitude of the Sun, and because of uncertainties in distinguishing minute bursts from interference, it was considered desirable to count as category 0 all intensities below a certain small level, namely <20 units. It should be noted also that receiver noise would be equivalent to a power flux of about 10 units at the aerial when the Sun is in the direction of maximum aerial sensitivity, whilst galactic noise represents a further 20 units on the average. Hence our unit of intensity corresponds to only 3·3 per cent of receiver plus average galactic noise. In terms of equivalent temperature this unit of power flux at 4·1 metres wave-length is equivalent to approximately $1{\cdot}8\times10^6$ degrees Kelvin. Martyn* has shown that we should expect the effective black-body temperature of the quiescent Sun at this wave-length to be the electron temperature of the corona and hence about a million degrees. Thus our unit of intensity is of the same order as the expected black-body radiation for the Sun at this wave-length.

3. *Correlations of Radio Bursts with Solar Flares*

3.1. *Solar Flares Observed Visually.*—An analysis of the solar flare and radio burst data will now be made in order to determine the extent to which these phenomena are correlated. The visual solar flare data have been obtained from the I.A.U. Bulletin on Solar Activity, which at the time of writing is available up to 1947 March. The available solar data after that time have been supplied by the Observatories at Greenwich, Muswell Hill (Mr Sellers) and Sherborne (Dr Ellison).

Visual solar data are necessarily intermittent, being obtainable only in clear weather conditions. The solar flare observations have, therefore, been chosen as the primary entity and the radio burst data have been examined to find on which occasions bursts coincide with flares. To do this, some choice of time

* D. F. Martyn, *Proc. Roy. Soc.*, **193**, 44, 1948.

interval has to be made in counting a burst as coincident with a flare. Only in a proportion of the flare observations was the actual beginning and end of the flare seen. In this connection it is of interest to note the summary of flare characteristics given by Newton and Barton.* They found that the average duration of flares varied from about 20 minutes for low-intensity flares to about 40 minutes for those of high intensity. The periods of visual observations of the Sun vary considerably between a few minutes and several hours. A further complication arises if there exists a variable time difference between the occurrence of a flare and an associated radio burst. There is evidence that such time differences do exist and these are discussed more fully later (in Section 3.5). It is, therefore, possible that a radio burst associated with a flare may occur outside the period of visual watch. With these considerations taken into account it was felt that a reasonable time allowance would be made by counting bursts as coincident with flares if they occurred within the flare period ± 5 minutes when the beginning or end of the flare was observed, or within the flare observation period ± 20 minutes, if the beginning or end of the flare was not seen (if, for example, a flare was already in progress on initial viewing of the solar disk and the termination of the flare was seen, then a burst was counted if it occurred within the flare observation period extended from 20 minutes before the beginning to 5 minutes after the end of the flare). The coincidence rates graded according to flare and burst intensities are given in Table I. It must be emphasized that if several radio bursts occur in a single observation period the occurrence is reckoned as a single flare-burst coincidence. If several flares occur simultaneously the one of highest intensity is considered. Whatever arbitrary definition of a coincidence between a flare and a burst is chosen it is of course necessary to examine the probability of significance. This is revealed in one way by trends in the coincidence rate with variations in the flare characteristics. A detailed discussion of significance is given later in Section 3.4.

TABLE I

Chances of coincidences between solar flares and radio bursts

Flare Intensity	Number of Cases	Percentage of Cases with Radio Bursts of Intensity :—			
		>0	$>\frac{1}{2}$	>1	>2
1	170	32	23	12	3
2	46	48	39	30	13
3	14	57	57	43	21

The average duration of all the cases is 42 minutes.

The results in Table I indicate that there is a progressive increase in the chance of a coincident measured burst with an increase in flare intensity. The number of observations of high-intensity flares made when the solar set was in operation was small. Fortunately radio communications fade-outs provide a more complete record of high-intensity flares, and the coincidence of fade-outs and radio bursts will be discussed in the next section.

* H. W. Newton and H. J. Barton, *M.N.*, **97**, 594, 1937.

3.2. *Indirect Evidence of Solar Flares by Radio Communication Fade-outs.*— Radio communication fade-outs are caused by absorption of radio waves in the D-layer when the ionization is enhanced by ultra-violet solar radiation. The analysis of the relation between solar flares and fade-outs by Newton and Barton * shows that when a radio fade-out occurs there is a high probability of there being a solar flare. The converse is not true, since there are many solar flares which do not produce fade-outs. The highest incidence of associated fade-outs occurs for the most intense flares. We may thus consider a radio communication fade-out as a geophysical accompaniment of a solar flare very probably of high intensity. When the fade-out is complete it is almost certain that the flare is of the type class 3 or 3+. Details of fade-outs on wave-lengths of 16–25 metres have been supplied to us by Cable and Wireless Ltd., and these provide, therefore, an important indirect record of high-intensity flares free from the visibility limitations which so severely restrict the numbers observed directly. As in the case of solar flares, an arbitrary time interval must be chosen in which to count a radio burst as coincident with a fade-out. For comparative analysis of coincidences it is further required that the average time interval should be approximately the same in both cases. The onset of the fade-out is usually fairly abrupt, but the subsequent recovery of signal strength is gradual and the end of the fade-out often very indefinite. After consideration of the time differences between the occurrences of bursts and fade-outs, as discussed in Section 3.5, the rule chosen was to count as coincidences those cases in which a burst occurred not more than 10 minutes before the first reported onset time and 20 minutes after the mean onset time.† The fade-outs may be graded in intensity according to the number of communication links affected and the degree of attenuation produced. The analysis of surges coincident with fade-outs is given in Table II.

TABLE II

Coincidences between Radio Communication Fade-outs and Solar Radio Bursts

Type of Fade-out	Number of Cases	Percentage of Cases with Radio Bursts of Intensity :—			
		>0	>½	>1	>2
Weakening	69	33	27	22	10
Some Links C.F.O.	39	51	38	36	23
All Links C.F.O.	42	69	62	50	36

The average time interval of all the cases is approximately 42 minutes.
C.F.O. = Complete Fade-out.

Table II thus provides a confirmation of Table I and clearly points to a progressive increase with flare intensity in the number of coincidences with radio bursts and in the proportion of bursts of high intensity.

* H. W. Newton and H. J. Barton, *loc. cit.*

† As stated in Section 3.5, in the great majority of cases the fade-out onset precedes the burst.

3.3. *Indirect Evidence of Solar Flares from Magnetic Crochets.*—A grade of solar flares of even higher intensity is probably indicated by those accompanied by magnetic crochets. These deviations of the magnetic elements have been described in detail by Newton.* Table III lists distinct magnetic crochets observed at Abinger between 1946 March and 1947 September while the solar noise recording apparatus was in operation. This suggests a very high probability that a flare of intensity sufficient to produce a magnetic crochet will be accompanied by a radio burst of high intensity.

TABLE III

Coincidences between Magnetic Crochets and Solar Radio Bursts

Date	Magnetic Crochet		Solar Radio Burst			Time Differences Radio Burst minus Crochet	
	Onset	Maximum	Onset	Maximum	Intensity	Onset	Maxima
	h m	h m	h m	h m		m	m
1946 Mar. 5	11 28	11 29	11 31	11 31	3	3	2
1947 Apr. 6	11 52	11 55	11 59	11 59	3	7	4
1947 May 6	10 14	10 15	10 17	10 17	2	3	2
1947 June 14	10 36	10 40	10 40	10 40	3	4	0
1947 Aug. 1	15 17	15 19	...	...	0	...	...
1947 Aug. 31	14 54	14 58	14 43*, 53	14 54	3	−11*, −1	−4
1947 Sept. 2	08 57	08 59	...	...	0 †	...	...

* In this instance, the rise of intensity of the major burst commenced at $14^h 53^m$; the preceding minor burst commenced 10 minutes earlier.

† A burst occurred at wave-lengths of 1·5 and 2 metres, onset at $09^h 00^m$ and maximum at $09^h 02^m$.

3.4. *Significance of Solar Flare and Radio Burst Coincidences.*—In order to appreciate the significance of the percentage coincidences between radio bursts and flares (or fade-outs) it is necessary to know what are the chances of a burst occurring in a similar period of time when there is no flare present on the Sun's disk. This has been estimated in the following way. The average time period of flare observation, extended as described in Sections 3.1 and 3.2, is approximately 42 minutes. Now the average chance of a radio burst occurring in any 42-minute period, irrespective of the occurrence of flares, can readily be obtained from the radio-noise recordings. With a knowledge of the chances of occurrence of flares of various intensities it is then possible to derive, from the observed coincidence rates of bursts with flares, the average rate of occurrence of bursts in a 42-minute interval when no flare is present.

Let p_1, p_2, p_3 be the chances of a burst occurring in the given interval when flares of intensity 1, 2 and 3 respectively are observed, and let q_1, q_2, q_3 be the chances of occurrence of flares 1, 2 and 3 in this time interval; if more than one flare occurs in the time interval, the intensity taken is that of the greatest. Let p_0 be the average chance of occurrence of a burst when there is no flare, and p_a the average chance irrespective of the occurrence of a flare, the time interval being the same, namely 42 minutes in each case. Then we have:—

$$p_a = p_1q_1 + p_2q_2 + p_3q_3 + p_0[1 - (q_1 + q_2 + q_3)]. \tag{1}$$

* H. W. Newton, *M.N.*, *Geophys. Suppl.*, **5**, 200, 1948.

From this expression p_0 may be determined as follows. The values p_1, p_2 and p_3 for the observed chances of flare-burst coincidences are given in Table I. (Although 42 minutes is the average time interval, and the distribution of individual time intervals with respect to the average may bias the results, it is considered that any such bias would probably be small and would not affect the general conclusions.) p_a, the average rate of occurrence of bursts, determined from the 1947 radio-noise records, is given in Table IV, line a. The average chance of the occurrence of flares was derived from the I.A.U. Bulletin for the first quarter of 1947 from the data of flare occurrences when the Sun was under continuous visual observation for periods of 42 minutes or more. It was found that the chance of a flare occurring during a 42-minute interval was 11 per cent. The total number of cases is too small for a reliable determination of the intensity distribution. The proportions derived by Newton and Barton * have therefore been used; they found that of all flares observed in 1935 and 1936 the relative proportions with intensities 1, 2 and 3 were 77 : 19 : 4. Our criterion, that if more than one flare occurs only the largest is counted, affects the distribution only very slightly. The chances of occurrence, q_1, q_2, q_3 of flares of intensity 1, 2 and 3 are thus estimated to be 8·5 per cent, 2·1 per cent and 0·4 per cent respectively. Equation (1) may now be used to derive p_0, the chance of occurrence of bursts in a 42-minute period when there is no flare, and the results obtained are given in Table IV, line b.

A quantitative assessment of the significant correlations can now be made. For if P_1, P_2, and P_3 are the chances of a significantly correlated radio burst occurring when there are flares of intensity 1, 2 and 3 respectively, then we have:—

$$P_1 = \frac{p_1 - p_0}{1 - p_0} \text{ and similar expressions for } P_2 \text{ and } P_3.$$

TABLE IV

Summarized table of coincidences between solar flares and radio bursts

	Flare Phenomena during 42 minute interval		Percentage of Cases with Radio Bursts of Intensity :— >0	$>\frac{1}{2}$	>1	>2
a	Irrespective of Flares		26	17	$6\frac{1}{2}$	3
b	No Flare		25	$15\frac{1}{2}$	5	$2\frac{1}{2}$
c	Flares of Intensity	1	32 (10)	23	12	3
		2	48 (31)	39	30	13
		3	57 (43)	57	43	21
d	Type of Fade-out	Weakening	33 (11)	27	22	10
		Some links C.F.O.	51 (34)	38	36	23
		All links C.F.O.	69 (59)	62	50	36

The figures in brackets are corresponding numbers for radio bursts which are assessed as significantly correlated with the flare phenomena.

* H. W. Newton and H. J. Barton, *loc. cit.*

The results of this assessment are given in Table IV, line c, for visually observed flares, and in Table IV, line d, for the flares which produce the radio communication fade-outs.

Table IV shows that the chance of a significant burst occurring increases with increasing flare intensity. The significance of the coincidences also tends to increase with radio burst intensity. Some examples of large radio bursts and the associated flare data are shown in Figs. 1, 2 and 3.

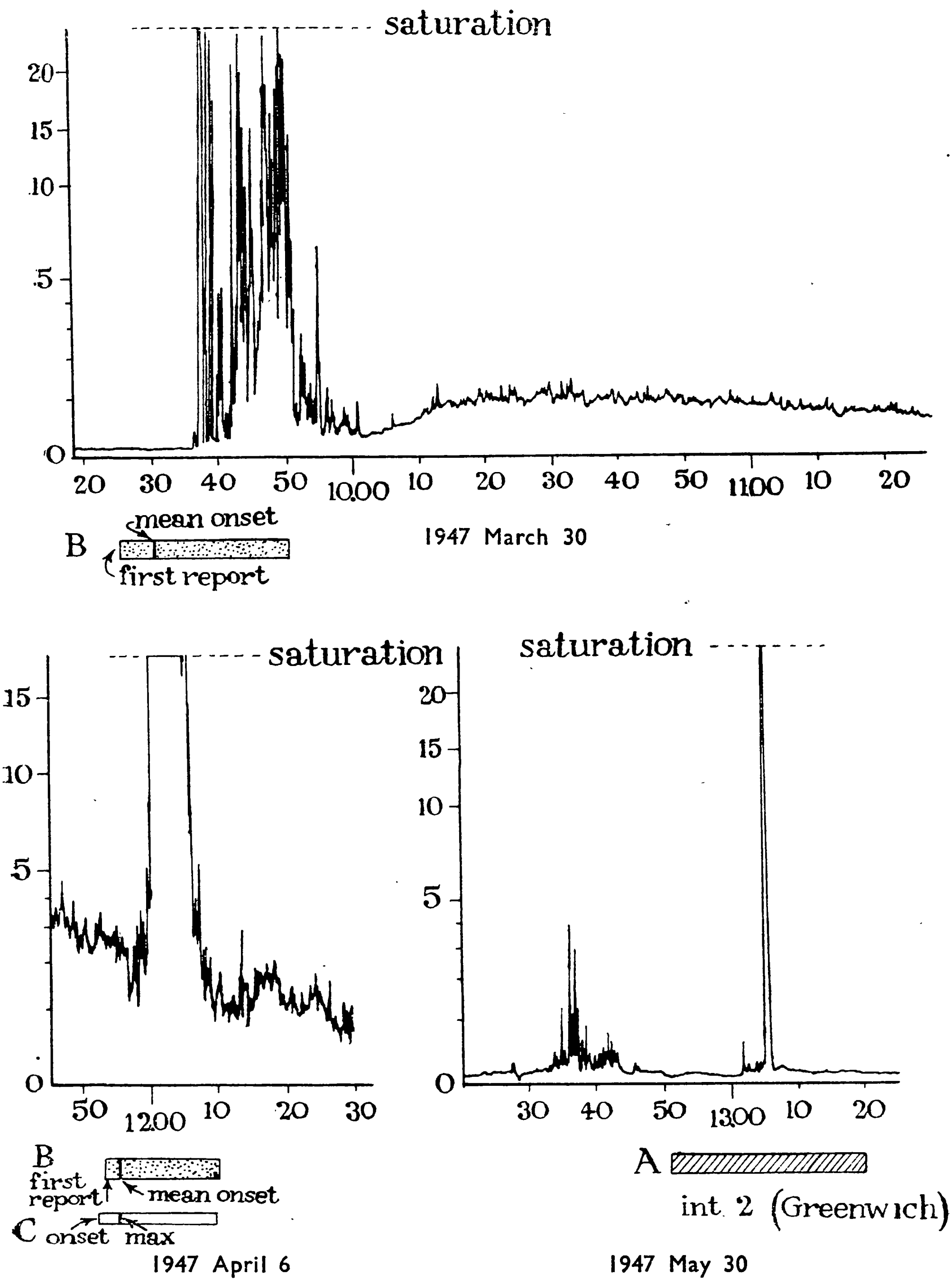

FIG. 1.—*Large radio bursts (observed at A.O.R.G. on $\lambda = 4{\cdot}1$ m.) and associated data.*
A : *Solar flare.*
B : *Radio communication fade-out (Cable and Wireless Ltd.).*
C : *Magnetic crochet (Abinger).*
Ordinates : *Power (relative units).*
Abscissae : *Time (U.T.).*

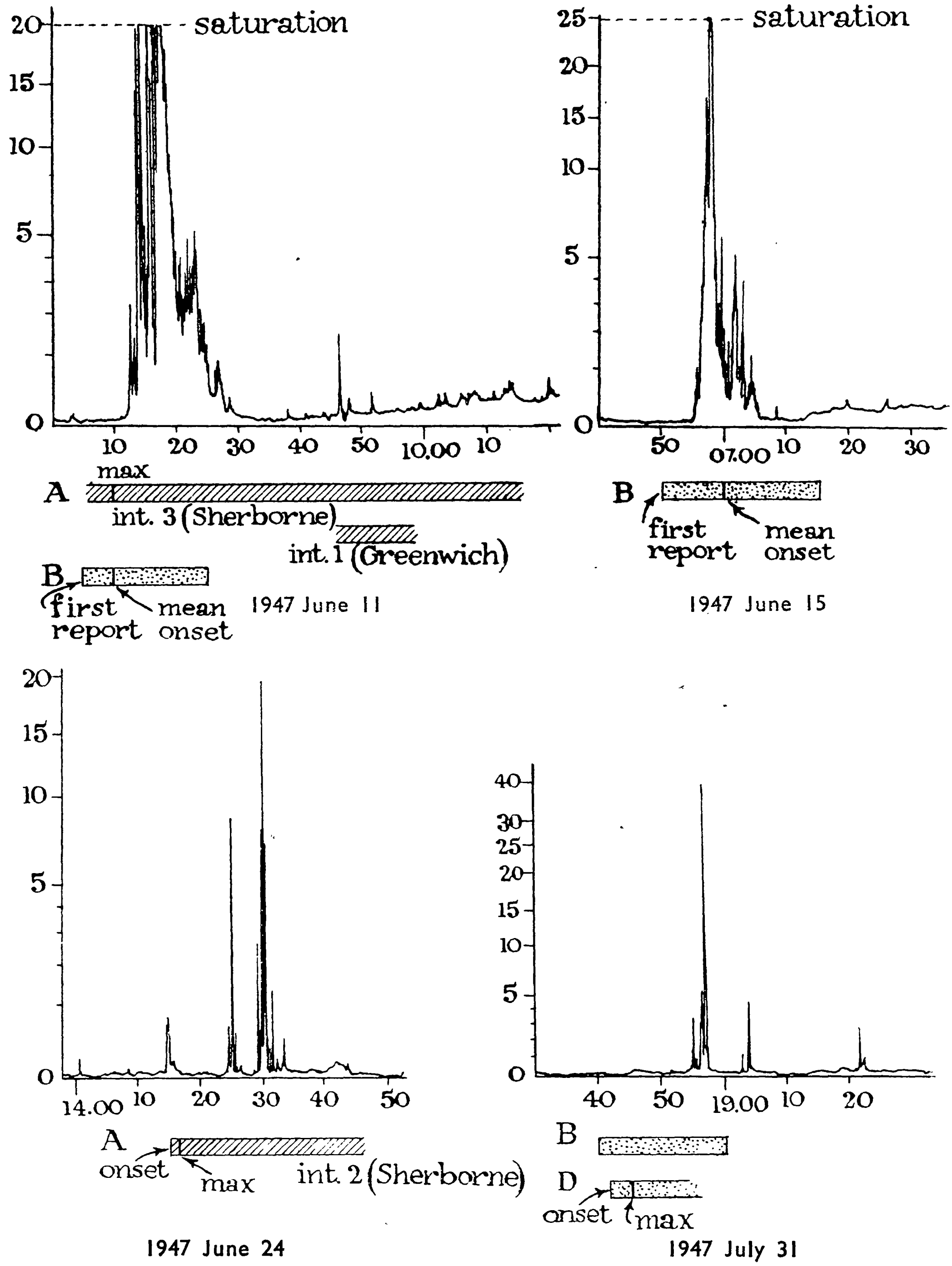

FIG. 2.—*Large radio bursts (observed at A.O.R.G. on* $\lambda = 4{\cdot}1$ *m.) and associated data.*
A : *Solar flare.*
B : *Radio communication fade-out (Cable and Wireless Ltd.).*
D : *Galactic noise fade (A.O.R.G.).*
Ordinates : *Power (relative units).*
Abscissae : *Time (U.T.).*

An alternative method of testing significance can be applied to the radio fade-out data by comparing the rate of occurrence of bursts a few hours before and after with that within the fade-out period. Such a test has been carried out for a period of $\pm 1\frac{1}{2}$ hours beyond the counted fade-out period. If the rate of occurrence of bursts within the fade-out period was greater than that in the adjacent periods, then we may regard the coincidence of bursts and fade-out as probably significant. It was found that 92 per cent of the cases satisfied this test. This suggests that the significant proportion as given in Table IV is not overestimated.

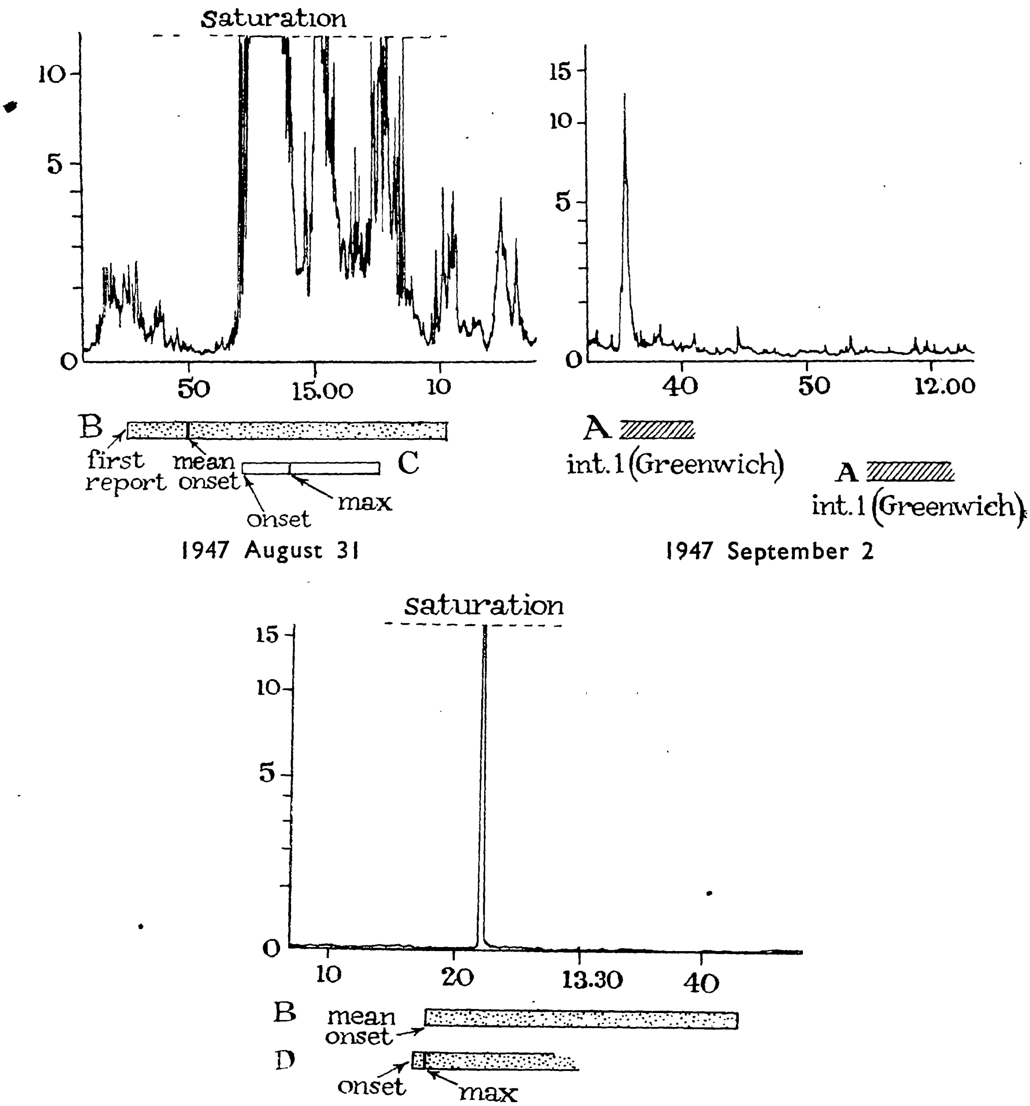

FIG. 3.—*Large radio bursts (observed at A.O.R.G. on λ=4·1 m.) and associated data.*
A : *Solar flare.*
B : *Radio communication fade-out (Cable and Wireless Ltd.).*
C : *Magnetic crochet (Abinger).*
D : *Galactic noise fade (A.O.R.G.).*
Ordinates : Power (relative units).
Abscissae : Time (U.T.).

3.5. *Time Difference between Radio Bursts and Solar Flares.*—Isolated examples of a time lag of radio bursts with respect to flares have been reported by the authors * and by Payne Scott, Yabsley and Bolton.† We know from Table IV that a coincidence between an intense flare and an intense burst has a high probability of being a significant association. Unfortunately the number of cases in which

* J. S. Hey, S. J. Parsons and J. W. Phillips, *Nature*, **160**, 371, 1947.

† J. L. Payne Scott, D. E. Yabsley and J. G. Bolton, *Nature*, **160**, 256, 1947.

such bursts have occurred when a visual flare has been seen for which the times of commencement and maximum intensity are known are too few for any general appreciation of time differences.

We must, therefore, again rely on radio communication fade-outs to provide a more comprehensive list of cases. If we take only those cases which satisfy the significance test referred to at the end of Section 3.4 and for which not less than two communication links reported complete fade-outs, we find that in 88 per cent of the cases the burst onset came later than the first reported fade-out commencement and the average time lag of the bursts was 13½ minutes. Now Newton and Barton * found that on the average the reported fade-out commencement was 4 minutes after the beginning of the solar flare. If we take this into consideration, then the average time lag of the onset of the radio burst after the onset of the flare is more than 17 minutes. Although, then, from the available information one cannot rule out the possibility of a significantly connected burst occurring before the flare onset, there is plainly a marked tendency for the bursts to occur after the beginning of the flares. This accords with the explanation offered by the authors (1947) and by Payne Scott, Yabsley and Bolton (1947), that the visible and ultra-violet emissions from a flare occur at a chromospheric level where the electron density is too great for a radio disturbance to escape; if the disturbance travels outwards from the Sun with a velocity less than that of light (for example, as a corpuscular stream) associated radio emissions will be able to escape when the disturbance reaches higher levels in the corona where the electron density is sufficiently small.

A discussion of time differences between phenomena would be incomplete without a comparison of the curves of intensity plotted as a function of time. Newton and Barton † state that, in general, flares rise rapidly to maximum intensity in 5 to 10 minutes and decline slowly. Ellison ‡ has demonstrated the type of intensity curve in detail by a series of measurements of $H\alpha$ line-width made at short intervals during the progress of a number of flares. Comparison with the intensity curves for radio bursts, as illustrated in Figs. 1, 2 and 3, indicates that the latter are far more spasmodic and irregular in form. The radio emission fluctuates tremendously in amplitude, but there is often discernible a major peak which may, in the largest radio bursts, represent an increase of intensity of the order of 1000 times occurring in a time of the order of a minute.

As the variation of intensity generally shows different forms for the radio and visual radiations associated with solar flares, it is of interest to compare not only the differences between the times of onset but also the differences between the times of maximum intensity. Unfortunately, details of the times of the maxima for high-intensity flares with associated radio bursts are available in only a few instances during the present period of analysis.

Ellison § made detailed measurements of $H\alpha$ line-width during the great flare (intensity 3+) of 1946 July 25. He describes the radiation burst in $H\alpha$ emission lasting 2–3 minutes and he estimates the peak to have occurred at $16^h\,27^m \pm 1^m$. Radio observations by the authors showed a peak reaching saturation between $16^h\,24^m$ and $16^h\,32^m$. An examination of the curves of $H\alpha$

* H. W. Newton and H. J. Barton, *loc. cit.*
† H. W. Newton and H. J. Barton, *loc. cit.*
‡ M. A. Ellison, *M.N.*, **103**, 3, 1943; *M.N.*, **106**, 500, 1946.
§ M. A. Ellison, *loc. cit.*

line-width and radio intensity indicates that in this instance the peaks were approximately simultaneous. On the other hand, the radio intensity curve shown in Fig. 2, obtained on 1947 June 24 while a flare (intensity 2) was being observed at Sherborne, may be taken as an example of a time difference between the maxima of the two phenomena. The maximum flare intensity occurred at $14^h 17^m$, but Fig. 2 shows the maximum intensity of radio emission at about $14^h 30^m$; it may be noted that the first radio burst probably associated with this flare occurred at the same time as the flare onset $14^h 15^m$. The radio burst associated with a flare (intensity 3+) on 1947 June 11, shown in Fig. 2, is an example of a time lag in the onsets and maxima of the radio burst with respect to $H\alpha$ emission. The flare was already in progress at $09^h 06^m$, the commencement of the visual observations at Sherborne, and the maximum $H\alpha$ intensity occurred at $09^h 10^m$. The radio burst commenced at $09^h 12^m$, and although the time of maximum intensity is somewhat uncertain owing to saturation of the receiver, it was not before $09^h 13^m$.

The examination of the time differences may be supplemented by the analysis of the intensity-time relations between solar radio bursts and the D-layer ionization arising from the enhanced ultra-violet radiation from solar flares. The D-layer ionization is perhaps best indicated by the attenuation of galactic radio noise at wave-lengths of about 12–15 metres, as described by Jansky * and the authors †, but, unfortunately, owing to the difficulty of making highly-directional aerials at long wave-lengths, the attenuation may be masked by solar radio emissions. Alternatively, D-layer ionization is roughly indicated by the data of radio communication fade-outs. A comparison of 15 cases where time of maximum galactic radio attenuation (at $\lambda = 12$ metres) could be compared with the mean time at which the various communication links reported the fade-outs, showed that the time difference, maximum galactic noise attenuation minus mean fade-out onset was in every case not more than a few minutes, the average value being $2^m \cdot 3$. An analysis of 31 cases of intense radio fade-outs and associated radio bursts shows that the mean time difference, maximum of solar radio burst minus mean fade-out onset is $6^m \cdot 9$. Thus, if we assume that the maximum D-layer ionization is on the average $2^m \cdot 3$ later than the mean fade-out onset, we find that the radio burst maximum occurs on the average about $4\frac{1}{2}^m$ after the maximum D-layer ionization. We thus conclude that, in general, the maximum radio burst intensity lags behind the maximum ultra-violet flare emission, but the time difference is smaller than that between the onsets of the two phenomena. It may be noted here that the absorption of radio waves by the D-layer is proportional to λ^2, and at a wave-length of 4·1 metres used for the observation of solar radio bursts it is generally negligible. We may thus disregard this as an effect making any real contribution to the time differences estimated above.

The curves shown in Figs. 1, 2 and 3 serve to illustrate the time-differences discussed above. The curve of radio intensity for 1947 September 22 in Fig. 3, for example, shows a striking single burst at $13^h 22^m$ of duration approximately $\frac{1}{2}^m$. The fade-out was very sharp for all links at $13^h 18^m$ and the maximum galactic radio-noise attenuation occurred at $13^h 18^m$ also. The radio burst phenomenon thus lags by approx. 4^m. Similarly, examples of radio burst time

* K. G. Jansky, *Proc. I.R.E.*, **25**, 1517, 1937.

† J. S. Hey, S. J. Parsons and J. W. Phillips, *loc. cit.*

lags will be seen in Figs. 1, 2 and 3; but in one case, that of 1947 June 15 in Fig. 2, although the radio burst onset at $06^h\ 55^m$ came after the first fade-out report at $06^h\ 50^m$, the maximum of the burst at $06^h\ 57^m$ occurred before both the mean fade-out onset report at $07^h\ 00^m$ and the maximum galactic noise attenuation estimated at about $07^h\ 03^m$. Cases of the radio burst phenomenon preceding the enhanced $H\alpha$ or ultra-violet radiation are exceptional.

Several cases of the time relations between magnetic crochets and radio bursts are given in Table III. With one exception, the radio burst phenomena come a few minutes later.

3.6. *Effect of Solar Longitude from Central Meridian on the Correlation of Solar Flares and Radio Bursts.*—Any influence of position on the relation between solar flares and radio bursts can, of course, only be studied for flares seen directly on the Sun's disk. This means that the number of cases for any given region of the Sun is fairly small for a period of analysis as short as eighteen months. It was noticed, however, when the coincidences between solar flares and radio bursts were plotted in coordinates of solar latitude and longitude, that both in 1946 and in 1947 there was a tendency for the proportion of coincidences to be higher for eastern than for western flares. The eastern half of the Sun's disk is the visible surface which, as the Sun rotates, is approaching central meridian passage, while the western half is the receding visible surface. This asymmetrical effect of solar longitude on flare-burst coincidences is shown in Fig. 4. The results are plotted (a) as the proportions of coincidences for groups within longitude intervals chosen so as to keep the numbers in each group approximately constant, in this case around 20, and (b) as the average radio burst intensity per flare. As we have shown, however, that the significant proportion of coincidences between flares and bursts is little more than 30 per cent for flares of intensity 1, and these form the greater part of the observations, too much reliance cannot be placed on the form of the distribution shown in Fig. 4. More data are needed before firm conclusions can be drawn.

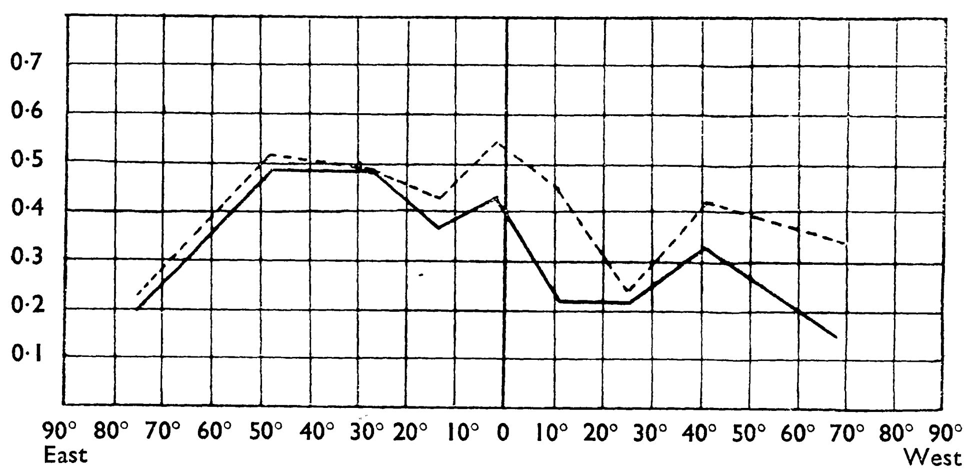

FIG. 4.—*Effect of solar longitude from central meridian on coincidences between solar flares and radio bursts.*
Continuous line: No. of bursts/No. of flares. Broken line: Burst intensities/No. of flares.

A radio burst asymmetry with respect to solar longitude from central meridian might be caused in the following manner. Solar flares occur in the vicinity of sunspots, that is in disturbed regions of the Sun. Now Milne * has shown

* E. A. Milne, *M.N.*, **86**, 457, 1926.

that from disturbed regions one might expect atoms and ions to be expelled with velocities of the order of 1600 km. per sec. As pointed out by Chapman and Ferraro *, the streams would be likely to consist of neutral and ionized atoms and electrons, the latter being carried forward with the positive ions by electrostatic attraction. If the electron density and collision rate are sufficient, radio waves which traverse a solar corpuscular stream may undergo appreciable absorption. The geometry of solar streams has been discussed by Chapman †, who considered the possibility of detecting such streams by their absorption of solar light. He showed that although we may expect the particles to move essentially in straight lines from the Sun, the effect of the Sun's rotation is such that the envelope of the stream becomes curved, as shown in Fig. 5. This diagram also illustrates how the envelope of the stream overtakes the Earth in its orbital motion. It is also seen that owing to the curvature of the stream the straight path from the disturbed region to the Earth traverses a considerable distance within the stream when the region is West of central meridian, but not when the region is East. If appreciable absorption of radio bursts occurs a lower correlation of radio bursts and solar flares West of central meridian might be expected.

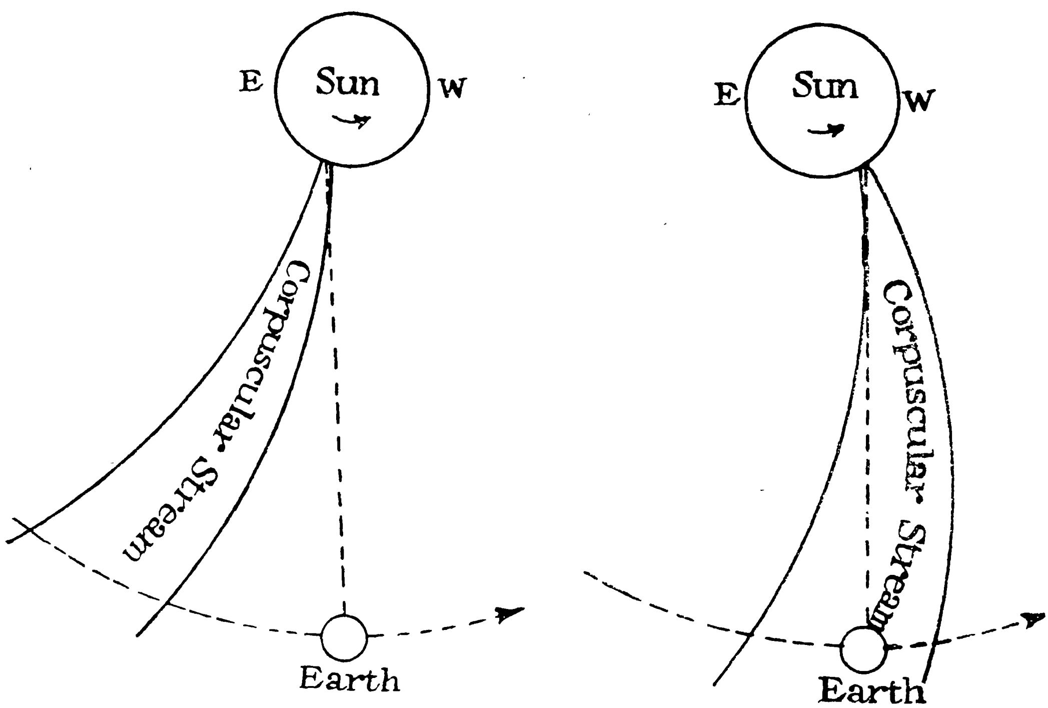

FIG. 5.—*Illustration of asymmetrical effect of solar corpuscular streams.*

Fig. 4 suggests that such absorption effects may occur over a considerable range of solar longitudes and are particularly marked from about 0° to 50° W. We would expect the extent to depend on the initial angular width of the emitted stream and on the velocity which determines the curvature of the envelope. Chapman ‡ derived an angular width of the order of 25° from a consideration of the average duration of the mature-stream type of magnetic storm. Newton § showed that for the great magnetic storms associated with intense solar flares

* S. Chapman and V. C. A. Ferraro, *M.N.*, **89**, 470, 1929.
† S. Chapman, *M.N.*, **89**, 456, 1929.
‡ S. Chapman, *M.N.*, *loc. cit.*
§ H. W. Newton, *M.N.*, **103**, 4, 1944; *M.N.*, **104**, 244, 1944.

the average stream velocities agree well with the values predicted on Milne's theory. Newton found that the equivalent cone of emission may be sometimes as great as 90°. The suggested explanation of the flare-burst asymmetry in terms of solar stream absorption seems feasible from considerations of stream-width. It would appear that a test of the correctness of the absorption theory might be made by comparing the flare-burst coincidence rates for flares which occur just prior to and during magnetic storms with those at other times. At present the total numbers of occurrences are insufficient for any conclusions to be reached. The asymmetry should also be more marked at longer radio wave-lengths, since radio absorption increases with wave-length.

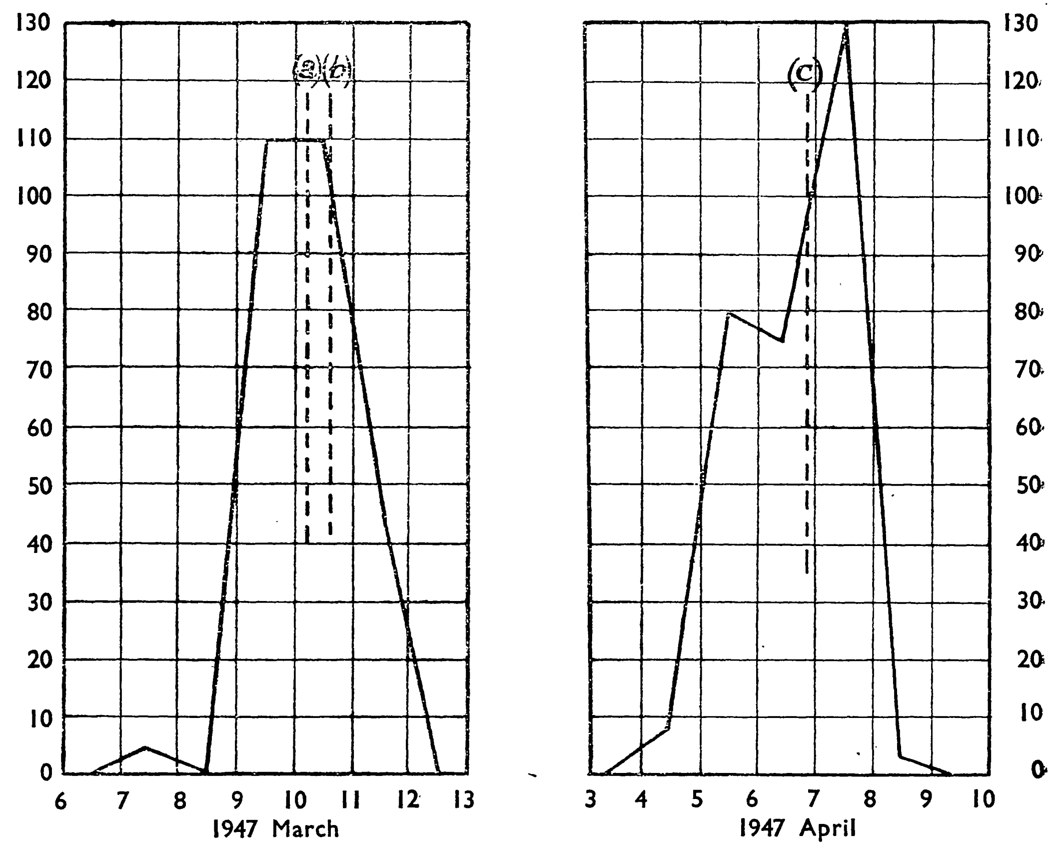

FIG. 6.—*Mean level of solar radio emission from sunspots.*

(*a*) *Central meridian passage*: *March* 10·2 *Area*: 4300. *Latitude*: −23°. *Earth's latitude*: −7°.

(*b*) *Central meridian passage*: *March* 10·6 *Area*: 1400. *Latitude*: +13°.

(*c*) *Central meridian passage*: *April* 6·8 *Area*: 5400. *Latitude*: −24°. *Earth's latitude*: −7°.

Ordinates: *Power flux in units of* 10^{-21} *watts/sq. m.c.p.s.*

4. *Radio Emission from Sunspots.*—The more continuous emission of radio noise which can be associated with sunspots will now be considered. The intensity of the sunspot radiation often fluctuates very considerably and rapidly, but it is usually possible to make rough estimates of mean level. The average levels around noon for several spots are shown in Figs. 6 and 7. An inspection of the radio and spot data* has shown that of the spots with areas greater than

* The spot data have been obtained from the Solar Notes in *The Observatory*, and from *Publications of the Astronomical Society of the Pacific.*

1000 millionths of the Sun's visible hemisphere, fewer than half produced any measurable continuous radio emission; and although there tends to be a greater chance of emission with increasing size of spots there is no simple proportionality.

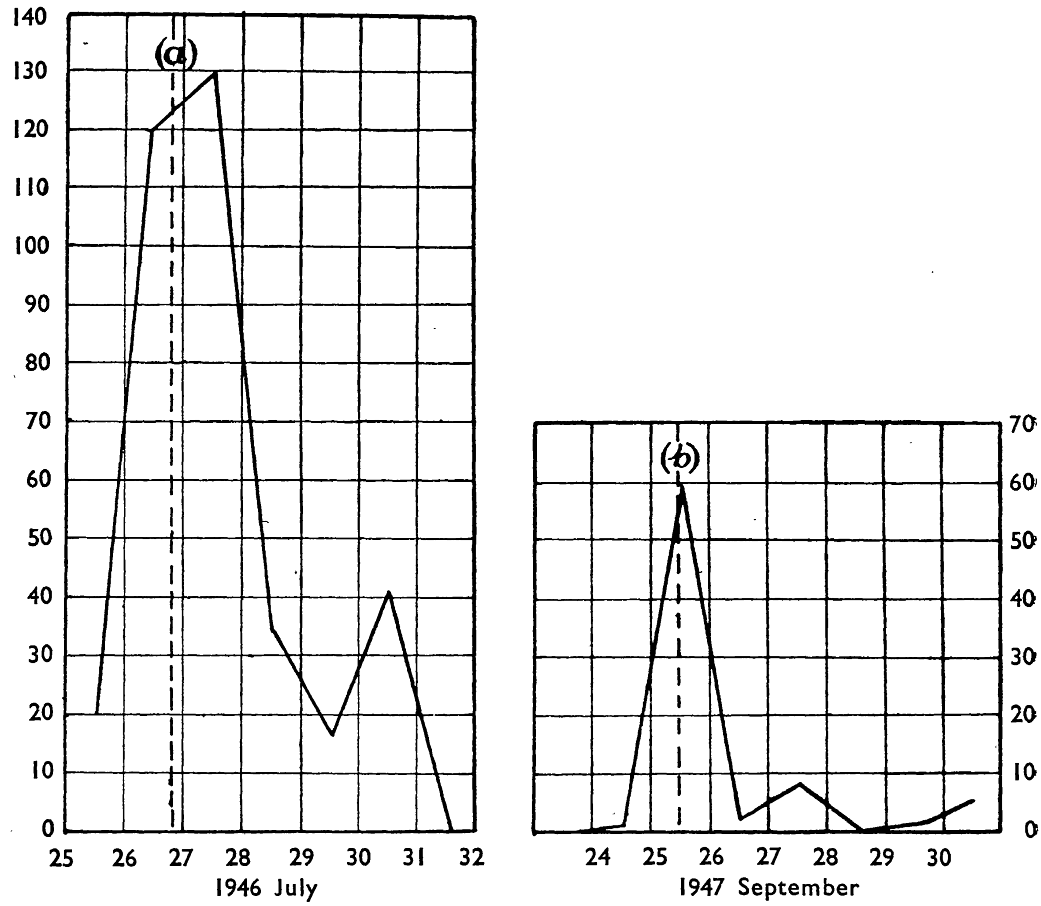

FIG. 7.—*Mean level of radio emission from sunspots.*
(*a*) *Central meridian passage: July* 26·9. *Area*: 3685. *Latitude*: +23°. *Earth's latitude*: +6°.
(*b*) *Central meridian passage: September* 25·5. *Area*: 750. *Latitude*: +17°. *Earth's latitude*: +6°.
Ordinates: *Power flux in units of* 10^{-21} *watts/sq. m.c.p.s.*

It is readily seen from Figs. 6 and 7 that the intensity of the radiation attains a sharp peak near central meridian passage of the spots. Particulars of the five most strongly radiating spots which occurred between 1946 March and 1947 September are listed below.

TABLE V

Date of Central Meridian Passage	Area of Spot (in millionths of solar hemisphere)	Max. Radio Int. Level (in units of 10^{-22} watts/sq. m.c.p.s.)	Solar Rotation between Radio Int. Levels $\frac{1}{10}$ of Max.	Heliographic Latitude of	
				Spot	Earth
1946 July 26·9	3685	1300	56°	+23°	+6°
1946 Dec. 17·0	2600	500	25	− 6	−1
1947 Mar. 10·2	4300	1100	49	−23	−7
1947 Apr. 6·8	5400	1300	48	−24	−7
1947 Sept. 25·5	750	600	24	+17	+6

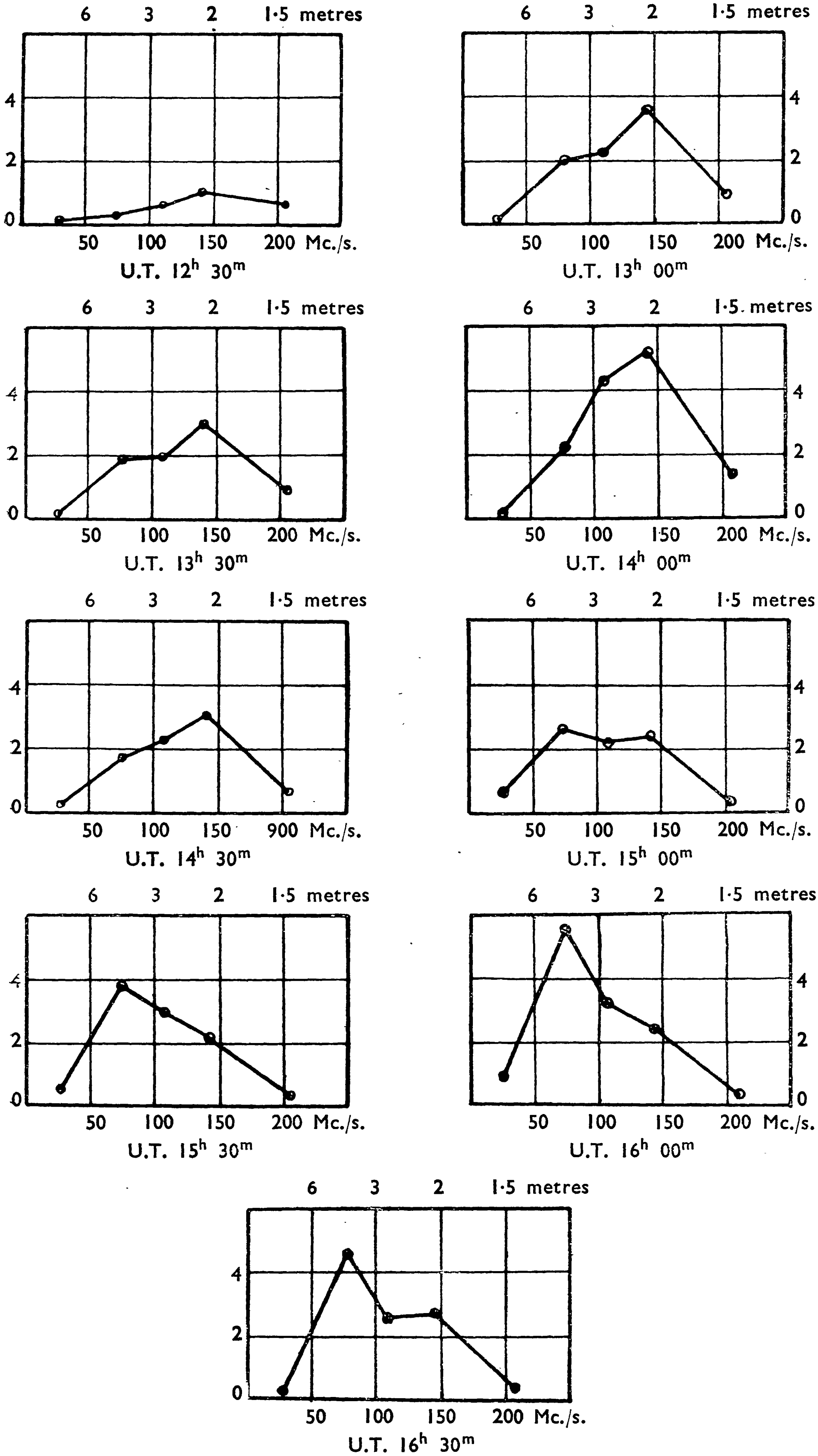

FIG. 8.—*Solar radio spectrum obtained on 1947 September 25.*
Wave characteristics shown in wave-length (metres) and frequency (Mc./s).
Ordinates: Power flux in units 10^{-20} *watts/sq.metre/c/s band-width.*

The mean angle of solar rotation between mean intensity levels of $\frac{1}{10}$ maximum for these spots is 40°. From the heliographic latitudes given in Table V (the difference between that of the spot and that of the Earth is in all cases less than half the solar rotation) it can be seen that the average beam-width across the centre of the spot will not be much greater than 40°. We thus have a fairly directional beam with its axis approximately normal to the spot. There are too few examples and the mean level is too uncertain to establish whether any bias exists with respect to central meridian passage. The narrowness of the beam would in any case make it difficult to detect the asymmetry observed in flares. It may be of interest to note here the possibility of a bias due to another cause. A. S. D. Maunder * found that on the average more spots occur on the eastern half of the Sun than on the western, and an interpretation has been suggested by Minnaert † by assuming that the spot axes are tilted westwards from the vertical by amounts of the order of 5° for long-lived spots.

In conclusion it must be emphasized that the wave-length of 4·1 metres for observation of the solar radio emissions was to some extent an arbitrary choice, and simultaneous observation over a very wide radio wave-length band is desirable. In Table III, for example, we referred to a radio burst which appeared at wave-lengths of 1·5 metres and 2 metres but not at 4·1 metres. Measurements of sunspot radio emission made at five wave-lengths between 1·5 metres and 12 metres on 1947 September 25, are illustrated in Fig. 8; these show the maximum intensity of power flux first at about 2 metres and 2 hours later at about 4 metres. Nevertheless, experience so far has indicated that both the continuous type of emission from sunspots and the bursts associated with flares can generally be detected over a wide band of wave-lengths, and that although the spectral distribution is variable the maximum intensity often appears to be in the region of 5 metres.

5. *Acknowledgments.*—We are particularly indebted to Mr H. W. Newton, of the Royal Observatory, Greenwich, with whom we have had many valuable discussions. We also wish to thank Sir Edward Appleton, Professor S. Chapman, Dr R. d'E. Atkinson and Dr A. Hunter for helpful remarks included in the revision of the text.

We are indebted to the Astronomer Royal, Dr M. A. Ellison and Mr F. Sellers for the supply of data in advance of publication from the Observatories at Greenwich, Abinger, Sherborne and Muswell Hill, and to Cable and Wireless Ltd. for data of radio communication fade-outs.

We wish to thank all our assistants at the Operational Research Group for their valuable help in the preparation and maintenance of the radio-noise apparatus, and in the subsequent analysis of the results.

Finally, we wish to thank the Scientific Adviser and Deputy Scientific Adviser, War Office, and Superintendent, Army Operational Research Group, for their interest in the work and permission to publish this paper.

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1948 *September* 7.

* A. S. D. Maunder, *M.N.*, **67**, 451, 1907.
† M. G. J. Minnaert, *M.N.*, **106**, 98, 1946.