OCCULTATIONS OF THE CRAB NEBULA BY THE SOLAR CORONA IN JUNE 1957 AND 1958

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[*Manuscript received January* 5, 1959]

Summary

A description is given of some observations of the occultations of the Crab nebula by the solar corona in June 1957 and 1958, obtained with pencil-beam, fan-beam, and interferometer-type instruments. It is shown that the distribution of 85·5 Mc/s radiation on days when the angular separation is less than 10 solar radii is not consistent with a symmetrical scattering process. Better agreement is obtained by postulating the existence of scattering and regular refraction of comparable magnitude. Certain unexplained features of the pencil-beam distributions indicate that large-scale electron irregularities may be important in the scattering and refraction process. Additional evidence is presented for very short-term changes in the transmission properties of the corona.

I. Introduction

Since Machin and Smith (1951) and Vitkevitch (1951) suggested that the observation of discrete radio sources through the solar corona could provide hitherto unavailable information on the distribution of electron density in the solar atmosphere, a number of investigations have been made by English, Russian, French, and Australian observers. In June 1952, Machin and Smith (1952) used interferometers on wavelengths of 3·7 and 7·9 m to observe the Crab nebula (I.A.U. No. 05N2A) whose angular separation from the Sun at the time was between 5 and 20 solar radii. They found significant reductions in the amplitudes of the interference patterns over this range of angular separations, a result which could only be explained by postulating the existence of a large number of electron irregularities high in the corona ; these were regarded as an assembly of randomly distributed scattering centres, which, by scattering the incident radiation from the radio source, effectively increased its angular size and reduced the visibility of the interference fringes.

The observations were repeated on a more extensive scale in June 1953 by Hewish (1955), who confirmed the earlier work and showed that his observations were consistent with multiple scattering from electron density irregularities of rather large linear dimensions. The width of the scattered cone of radiation was found to be about 20 min of arc on the days of least angular separation at a wavelength of 3·7 m, and appeared to increase as the square of the wavelength.

Extensive observations were also carried out by Vitkevitch (1955*a*, 1955*b*) at the occultations of June 1952, 1953, and 1954, using interferometers on wavelengths of 6 and 3·5 m. He also concluded that the large reductions he noted

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in the amplitudes of the interference patterns were due to a scattering mechanism, the angle of scattering increasing with wavelength. In addition, Vitkevitch found evidence for possible refraction effects and short-time changes in the scattering properties of the corona.

While it is theoretically possible to synthesize a source brightness distribution from records taken at a number of interferometer spacings, it is obvious that the method may be beset with uncertainties. In addition to the ever-present possibility of an unwanted solar contribution to the observed interferometer patterns, one is faced with the task of reconstructing a brightness distribution at a particular wavelength from a practically imposed limit of one or two interferometer spacings. Both the Russian and English results described above were obtained by using at most two interferometer spacings on a given wavelength. It is obvious that one or two Fourier components of the brightness distribution are not enough to reconstruct the distribution with any certainty, especially in the presence of possible asymmetry. With such observations one tends to adopt the simplest brightness distribution which will fit the restricted nature of the observations.

The first observations of a coronal occultation of the Crab nebula using a narrow-beam aerial were made by Slee (1956). Here the fan-shaped beam of the east-west arm of the 85·5 Mc/s cross-type aerial at Sydney was used. The apparent intensity of the radio source appeared to be significantly reduced on two days in June 1956 when the angular separation of the source and Sun was in the range 7–11 solar radii. These observations were explained by postulating that some of the radiation incident on the corona was being scattered to much larger angles ($\geqslant \pm 1°$) than those deduced from the English and Russian interferometer observations. Hewish (1957), in describing the results of his observations at the same occultation, was unable to reconcile the fan-beam and interferometer measurements.

The purpose of the present paper is to present the results of measurements made at the occultations of the Crab nebula in June 1957 and 1958. In both years the observations were made by means of the pencil beam of the 3·5 m cross aerial, supplemented by recordings at the output of the fan beam of the east-west arm of the same aerial; in addition, during the 1957 occultation a 60λ spaced east-west interferometer was used on the same wavelength. These observations support the preliminary 1956 results to the extent that very significant modifications to the Crab nebula response patterns occurred on June 13, 14, 15, and 16 in each year. In addition, some new information regarding the distribution of the scattered radiation is presented and there is also more definite evidence for the short-term changes in the scattering properties of the corona first noted by the Russian observers.

II. The Observations

During the occultation of June 1957 recordings of the Crab nebula were obtained at the outputs of three distinct aerial systems all operating at a frequency of 85·5 Mc/s. These recordings will be called respectively fan-beam, pencil-beam, and interferometer observations. The observations in June 1958 were made with the fan and pencil beams only. Each system possessed its own advantages in rejecting interference from the Sun. It was hoped that a comparison of two or more records would result in obtaining information on the distribution of the Crab nebula emission with some certainty that solar interference had been taken into account.

Before describing the operation of the three systems, it is useful to have some information on the relative positions of the radio source and Sun on the days of least angular separation. This is given in Figure 1.

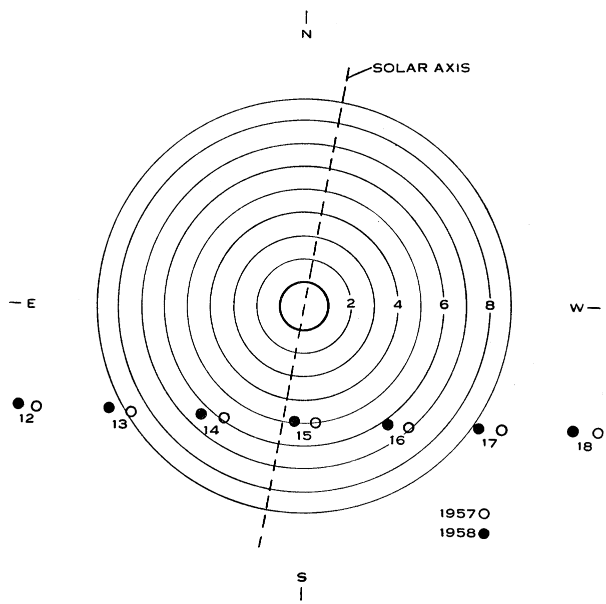

Fig. 1.—Relative positions of the Sun and the Crab nebula in the period June 12–18 in 1957 and 1958. The distance scale is marked in units of solar radii.

(a) *The Fan-beam System*

The east-west arm of the 85·5 Mc/s cross aerial has a beamwidth 0°·6 east-west and 50° north-south to half-power points. During the observations the maximum of the beam was directed 15° north of the zenith, so that the Crab nebula was well within the fan beam for a few minutes about its transit time. The output of the array was connected to the receiver used in the Mills Cross operation, but some of the signal was withdrawn and amplified in a separate i.f. unit. After detection and D.C. amplification the signal was applied to a recording milliammeter. Because of the very narrow east-west beamwidth of this array, records of the Crab nebula could be obtained on every day of the occultation except on June 15 of each year when the Right Ascensions of the Sun and radio source were almost identical. The type of record obtained with the fan beam is illustrated in Figure 2, which shows tracings of drift patterns obtained on four days in June 1958. On June 14 and 16, the resolution of the fan beam was not good enough to see the complete response curve of the Crab nebula,

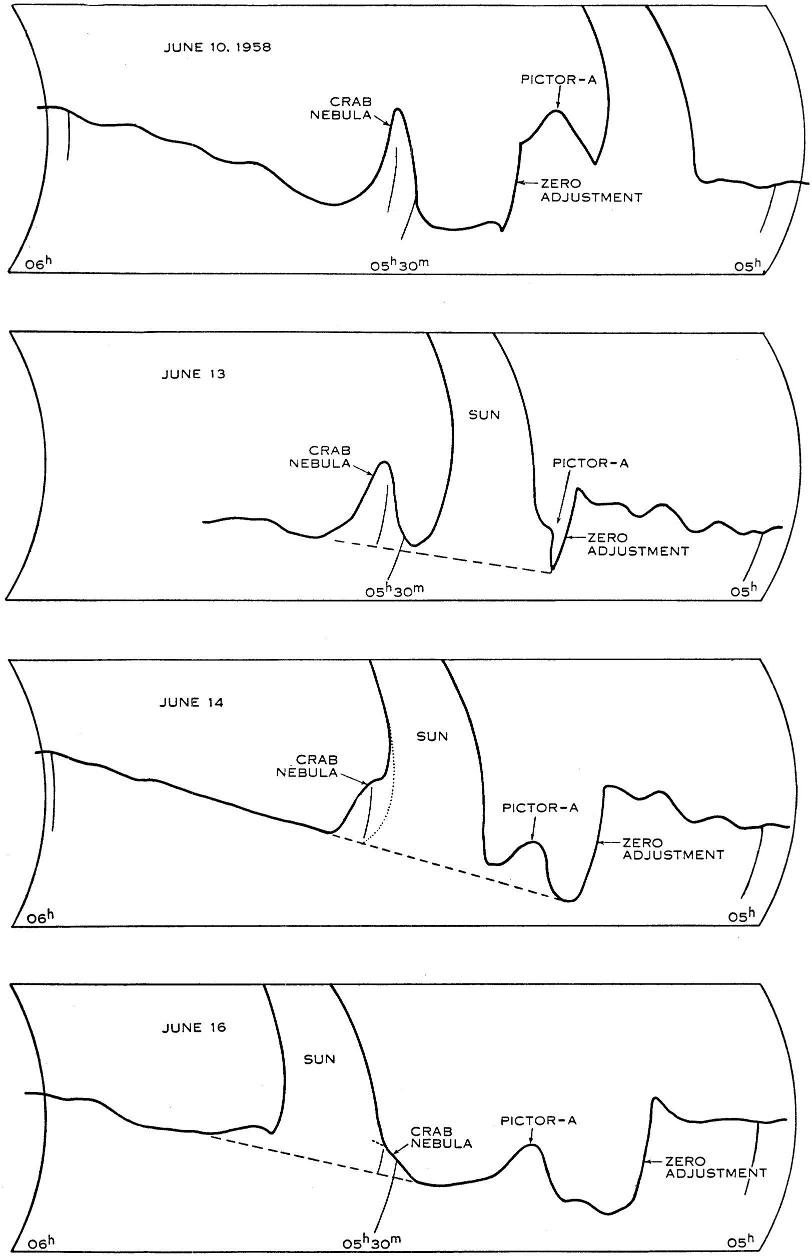

Fig. 2.—Fan-beam records taken during the occultation of June 1958. The vertical line inserted at sidereal time $05^{h}\ 31^{m}\cdot 9$ in each record corresponds with the Right Ascension of the source.

but in these cases it was possible to trace the response at least as far as its normal transit time on the side remote from the Sun. The receiver was calibrated daily by means of a noise generator, and in addition the deflections due to less intense discrete sources served to check the overall sensitivity of the aerial and receiver.

It is obvious from Figure 2 that significant changes in the drift patterns of the Crab nebula occurred on June 13, 14, and 16; for example, on June 16 the recorder deflection at the normal transit time of the radio source, shown by the vertical line, was reduced to about 0·25 of the corresponding peak deflection on June 10. The response curves derived from this type of record will be discussed in more detail in a later section.

(*b*) *The Pencil-beam System*

The 85·5 Mc/s crossed aerial system has been described in some detail by Mills *et al.* (1958) and little further explanation is needed here. Briefly, by combining the outputs of two long aerial arrays arranged in the form of a cross, cyclically in and out of phase, it is possible to produce an effective pencil-beam type of response. The beam shape of this aerial when pointed 56° from the zenith to the declination of the Crab nebula is elliptical, being 50 min of arc east-west and 85 min of arc north-south to half-power points. With a beam of these dimensions it was realized that, on the days of closest approach of the Crab nebula to the Sun, the resolution in declination would not be adequate to reject the solar radiation completely; however, it was hoped that the recorder deflection due to the latter would be reduced to such a low level that the general east-west brightness distribution of the radio source could be deduced with some certainty.

Examples of pencil-beam records obtained during the occultation of June 1958 are shown in Figure 3. The upper record is a drift pattern obtained when the angular separation of the Sun and Crab nebula was 13 solar radii; the Crab nebula response on this record is typical of those obtained when the radio source was unaffected by the solar corona. The lower recording was taken on June 16 when the angular separation was 6·25 solar radii. Before an estimate can be made of the response pattern due to the Crab nebula from records such as this, the unwanted solar deflection must be subtracted from the observed response. A likely solar response on June 16, 1958 is shown by the broken curve in Figure 3. It can be seen that the response pattern of the radio source (obtained by subtracting one curve from the other) has been modified appreciably both in amplitude and shape. In particular, the response at the usual transit time of the source is much lower than its normal value. The means by which the solar contributions were estimated, and the resulting derived pencil-beam distributions will be discussed in the next section.

(*c*) *The Interferometer System*

During the occultation observations of June 1957, records were obtained with an east-west interferometer operating at 85·5 Mc/s, in addition to the fan- and pencil-beam records described above. The interferometer was formed by using the north-south arm of the cross in conjunction with two helical aerials, spaced 63λ from the former along a base line inclined at a slight angle to the east-west line. A schematic diagram of the interferometer system is shown in Figure 4 (*a*). The resulting interference fringes projected onto the celestial sphere are depicted by the set of sloping straight lines in Figure 4 (*b*), which also shows the paths of the Crab nebula and Sun relative to the fringe system. The already considerable north-south directivity of the array, combined with the north-south interference pattern of the two helices, resulted in a maximum

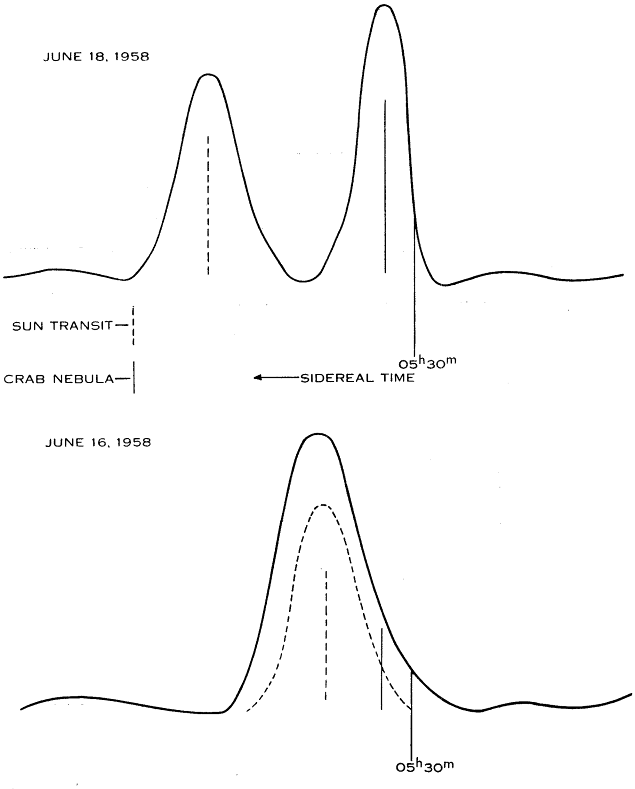

Fig. 3.—Pencil-beam recordings of the Crab nebula and the Sun for June 16 and 18, 1958. The broken line curve inserted on the record for June 16 represents the probable solar contribution to the observed response.

response from the radio source and an effectively zero response from the Sun for about 20 min around the transit time of each source. The remainder of the equipment consisted of a conventional phase-switched receiver, phase detector, and D.C. amplifier driving a recording milliammeter.

Some examples of the interferometer records obtained during the occultation of 1957 are given in Figure 5. The recording of July 5 is typical of the Crab nebula pattern obtained on days when the radio source was well separated from the Sun, while the other three patterns show the marked effects of the solar corona on the radiation from the Crab nebula. In interpreting the recordings shown in Figure 5, reference should be made to Figure 4 (*b*), which shows that, when the hour angles of the Sun and radio source are almost identical, a solar interference pattern will be produced on either side of the pattern due to the Crab nebula. For a time of the order of 10 min on either side of the transit time of the radio source, the steady solar radiation may be entirely neglected, and even solar bursts of the order of 1000 times the quiet level scarcely make any contribution to the

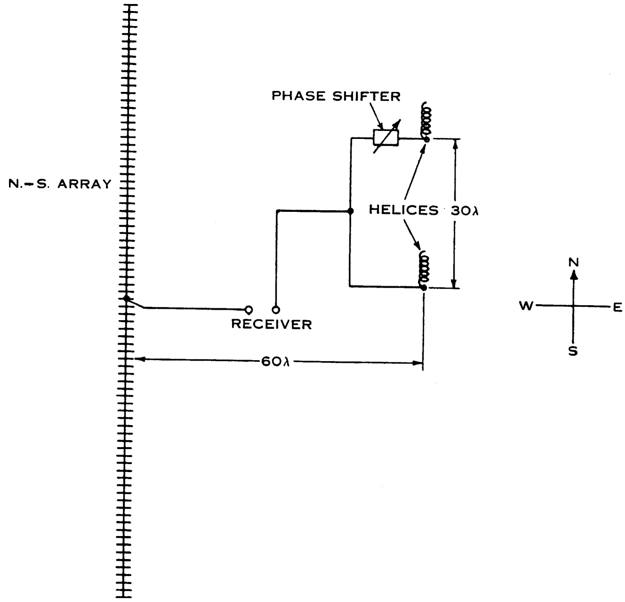

Fig. 4 (*a*).—Diagram illustrating the layout of the interferometer system used in June 1957.

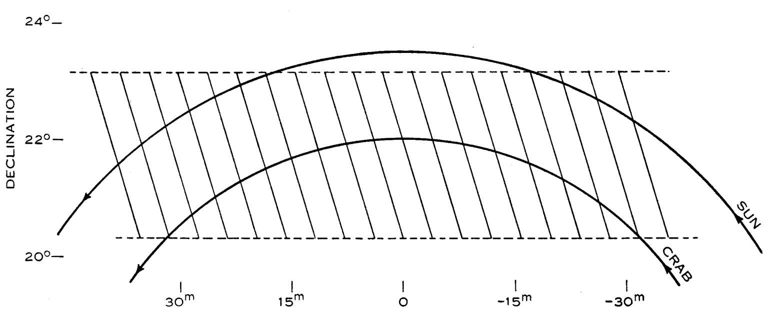

Fig. 4 (*b*).—Paths of the Sun and the Crab nebula relative to the interference fringes projected onto the celestial sphere.

observed output. The noticeable feature of the interferometer records is the great reduction in the amplitude of the interference pattern on days when the angular separation of the Crab nebula and Sun is small. An additional interesting characteristic is the sudden change in the amplitude of the Crab pattern at about $05^{h}\ 36^{m}$ on June 16 ; this is believed to be due to a genuine change in the transmission characteristics of the corona, since the possibility of solar interference at this time seems very remote. Although the intensity scale of the system was calibrated daily by means of a noise generator, it was not possible to perform an accurate calibration of the phase of the interferometer patterns ; this was mainly due to the use of a long length of coaxial cable from the receiver to the helical aerials, and it was common to find that the phase of the calibration pattern had changed by up to 30° from the beginning to the end of each day's observations, due, no doubt, to the changing ambient temperatures.

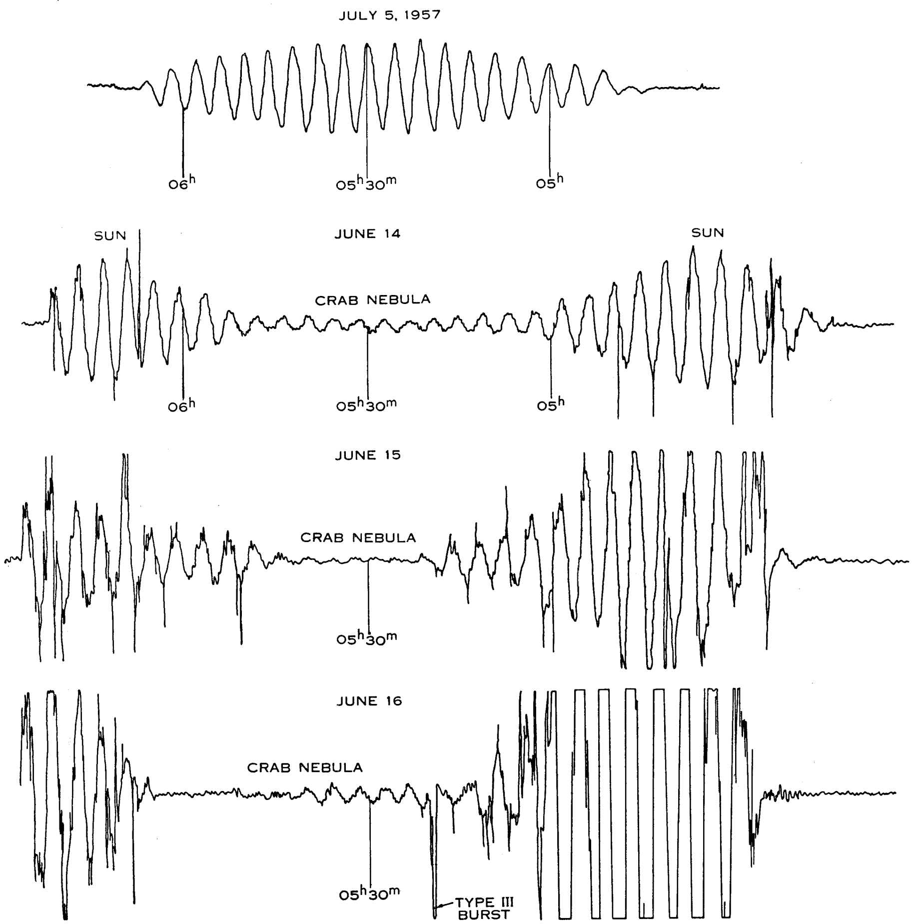

Fig. 5.—Examples of recordings obtained during the occultation of 1957 with an interferometer of east-west spacing 60λ. All times shown are sidereal.

III. Reduction of the Observations

The principal object of the analysis is to derive the main features of the east-west brightness distribution across the Crab nebula on days when the source is behind the solar corona. In this connexion the pencil-beam recordings assume the greatest importance, although the fan-beam and interferometer results can provide valuable confirmatory evidence, especially if there is doubt concerning the magnitude of the solar contribution to the former.

The information most easily obtained from the recordings is the response of the fan-beam and interferometer systems at the usual transit time of the Crab nebula. The daily observed values of this quantity for the occultations of 1957

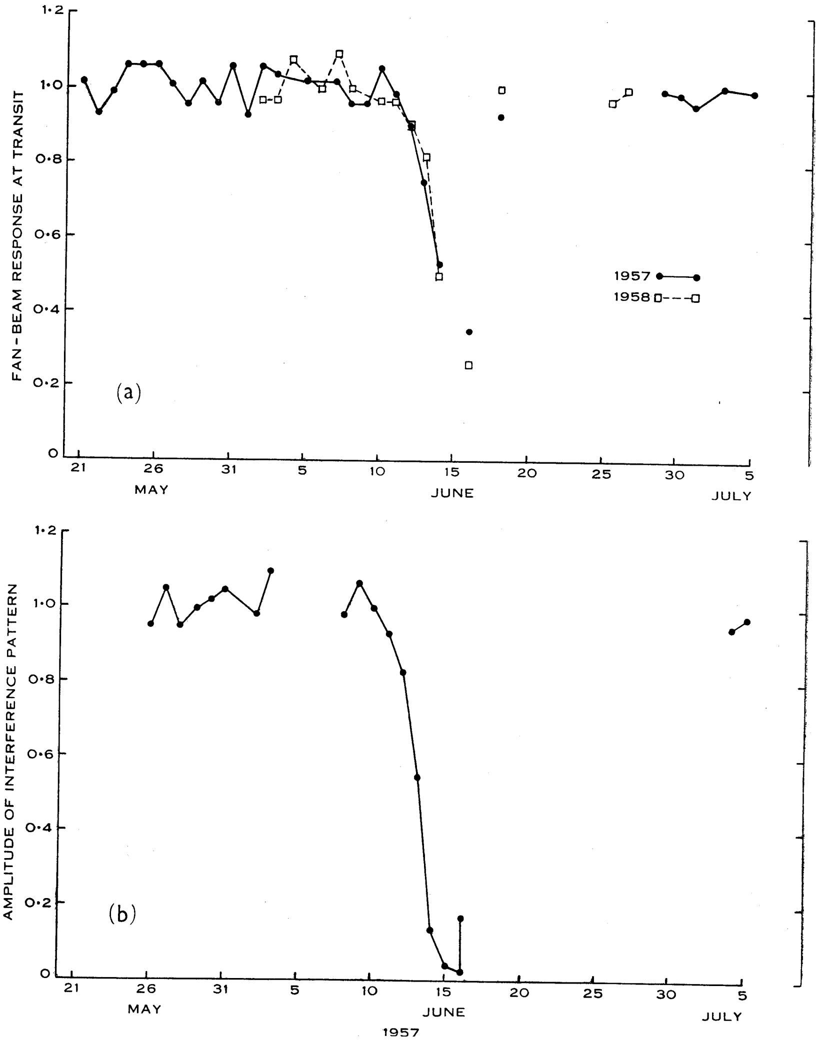

Fig. 6 (*a*).—Daily values of the fan-beam responses to the Crab nebula during June 1957 and 1958. All values are relative to the average response when the angular separation was greater than 20 solar radii.

Fig. 6 (*b*).—Amplitudes of the interferometer patterns during June 1957. Points plotted are relative to the average response when the angular separation was greater than 20 solar radii.

and 1958 are plotted in Figure 6. Data for this figure are also given in Table 1. Also included in the table are the corresponding quantities from the pencil-beam recordings ; a description of their derivation will be given later in this section. All values plotted in Figure 6 and entered in Table 1 are relative to the average responses obtained when the angular separation of the Crab nebula and Sun was greater than 20 solar radii. It will be noted that no fan-beam record was obtained on June 15 of either year because the Crab nebula was lost in the much stronger solar response ; in addition, recordings were not obtained on some other days because of interference or intense solar activity.

It is obvious from Figure 6 that the 3·5 m radiation from the Crab nebula was greatly modified by its passage through the solar corona between June 12 and 16 of each year, when the angular separation of the radio source and Sun was in the range 5–12 solar radii. Although the recordings obtained from both aerial systems showed pronounced effects over this period, the greatest reductions in the transit response occurred for the interferometer. This can only be interpreted as proving that the major part of the effect is not due to an absorption process in the corona. Since the interferometer is much more susceptible to changes in

TABLE 1

RESPONSES TO THE CRAB NEBULA AT ITS USUAL TRANSIT TIME

Date	1957			1958	
	Fan Beam	Interferometer	Pencil Beam	Fan Beam	Pencil Beam
June 10	1·06	1·00	0·98	0·97	1·04
11	0·99	0·93	1·11	0·97	1·04
12	0·90	0·83	0·82	0·90	0·98
13	0·75	0·55	0·84	0·82	0·80
14	0·53	0·14	0·79	0·50	0·80–0·86
15	—	0·05	0·43	—	0·32–0·61
16	0·35	0·17* 0·03	—	0·26	0·17–0·27
17	—	—	—	—	0·98
18	0·93	—	—	1·00	0·98

* Amplitude of interference pattern changed during observation.

the east-west brightness distribution of a radio source than the fan beam, it must be concluded that the observations are consistent with a redistribution of the Crab nebula radio flux over a relatively large range of angles in the east-west direction. Such a process can occur either by scattering or refraction in the solar corona. Figure 6 and Table 1 also indicate that the effects were of similar magnitude in 1957 and 1958, and are not symmetrical about June 15, the day of closest approach.

Any attempt which is made to define the east-west brightness distribution across the Crab nebula on the days of closest approach to the Sun must in the main be restricted to an analysis of the fan-beam and pencil-beam recordings ; it is obviously not possible to obtain an unambiguous distribution from the single 60λ Fourier component given by the interferometer record. The latter should, however, be useful in checking a likely distribution obtained, for example, from the pencil-beam response.

The drift patterns obtained with the fan beam on the interesting days of the occultations of June 1957 and 1958 are given in Figure 7. These patterns were derived from the type of recordings illustrated in Figure 2. No attempt was made to deduce the Crab nebula response while the Sun was in the fan beam, so that the patterns shown should be free of solar interference. In deciding the shape of the solar response, use was made of a supplementary low sensitivity fan-beam record. The response patterns for corresponding days in 1957 and 1958 show a pronounced similarity. It is not possible to deduce details of the Crab nebula east-west brightness distribution from the fan-beam drift patterns because only half the response pattern can be seen on the most interesting days. However, there is here ample evidence that the angular distribution of the radiation

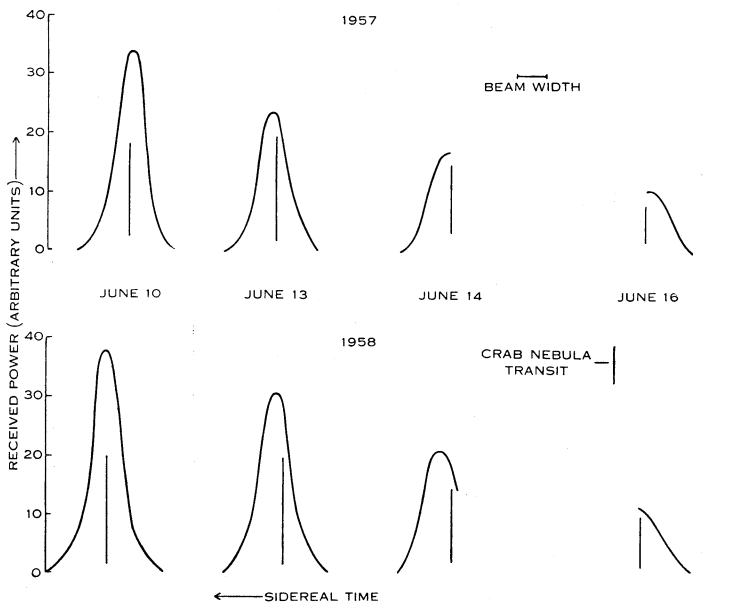

Fig. 7.—Fan-beam responses to the Crab nebula during the main phases of the occultations of 1957 and 1958.

has been changed from its normal width of a few minutes of arc to values which appreciably exceed the east-west beamwidth of the array. Assuming for the present that all the radiation from the Crab nebula was being subjected to a symmetrical scattering process in the corona, the records of June 16, for example, indicate that the width of the scattered cone was some 2° to half-power points.

Figure 8 shows some east-west drift patterns of the Crab nebula derived from pencil-beam recordings of the type shown in Figure 3. Before the Crab nebula response could be deduced from one of these records, it was necessary to extract an estimated solar contribution from the observed pattern. The solar deflection for any particular day was found as follows.

Pencil-beam records of the Sun were obtained as often as possible on the days preceding and following the main phase of the occultation. In addition, low sensitivity fan-beam records were taken each day. The solar responses on the two sets of records were compared, resulting in the establishment of a linear relationship between the two types of response; this relationship was subject to some random errors. On each of the three days when the Sun and Crab nebula could not be unambiguously separated by the pencil beam, the solar deflection on the low sensitivity fan-beam record was used to estimate a minimum and maximum solar pencil-beam response, corresponding to the standard deviation of the derived relationship.

The upper and lower series of curves in Figure 8 refer to observations in 1957 and 1958 respectively. An increase in solar activity prevented the taking of useful pencil-beam records after June 15, 1957, but it was found possible to obtain recordings on all the most interesting days in June 1958. The two curves

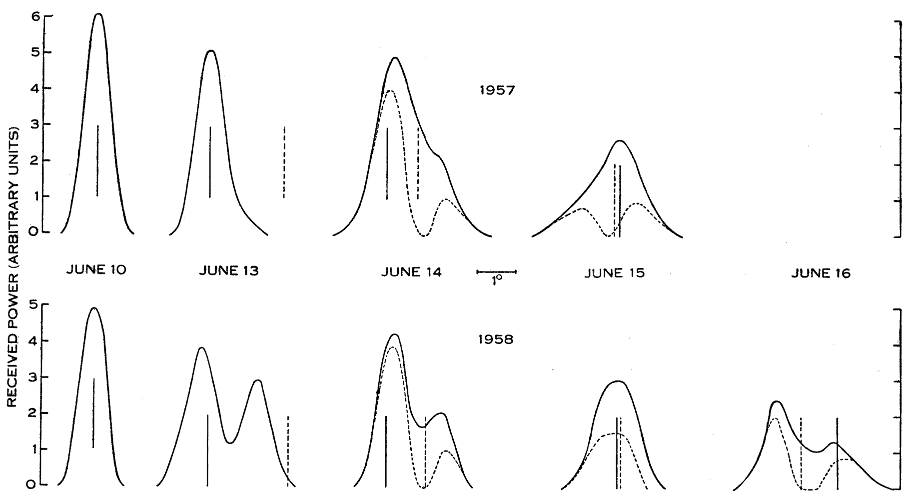

Fig. 8.—East-west pencil-beam distributions for the Crab nebula for June 1957 and 1958. The full and broken vertical lines represent the transit times of the Crab nebula and the Sun respectively. For June 14, 15, and 16 the true distribution lies somewhere between the two limiting curves shown.

outlined by the full and broken lines for each of the days, June 14, 15, and 16 correspond to the distributions obtained by subtracting the minimum and maximum solar contributions from the observed pencil-beam responses. The true distribution lies, in each case, somewhere between the two curves shown.

On June 14 and 15, 1957, it was found possible to use the interferometer records of the same dates to ascertain which of the two curves shown in Figure 8 was nearer the true distribution. This was done by extracting the Fourier component of spatial frequency 60λ from a number of possible pencil-beam distributions obtained by allowing various solar deflections between the adopted limits. The amplitude and phase of each Fourier component was then compared with the observed interference pattern. It was found that distributions close to the shapes of the full-line curves for June 14 and 15, 1957, would give rise to the observed interference patterns; distributions similar to the broken-line curves would result in an interference pattern of far greater intensity than that recorded, and hence may be disregarded.

It is of interest to note that the integrated radio flux due to the true east-west distribution of June 14, 1957, is some 30 per cent. greater than that due to the Crab nebula when well separated from the Sun. Similarly, on June 14, 1958, although there is no means of defining the distribution as accurately as for the corresponding day in 1957, it can be said with some confidence that the integrated flux is equal to or higher than that of the unocculted source. On the other hand, for June 15 in both years and June 16, 1958, it appears that the integrated flux is less than or equal to the unocculted value. The solar contribution to the observed pencil-beam response of June 13, 1958 is negligible, and in this case it is possible to say that the integrated flux is 60 per cent. higher than the unocculted value.

In addition to the question of the total radio flux reaching the Earth, there are two other features of the pencil-beam distributions worthy of comment. Firstly, attention should be directed to the marked extensions of the curves in the direction toward the Sun on June 13, 14, and 16. In some cases there is definite evidence for a secondary peak in the distribution, especially for the records of June 13, 14, and 16, 1958 ; on these days appreciable radio flux is arriving at the receiver from points in the sky separated by as much as $1\frac{1}{2}°$ from the position of the Crab nebula in the east-west direction towards the Sun. In contrast to this behaviour, the records of June 15 of each year (the day of closest approach of the radio source to the Sun) show a much greater degree of symmetry about the position of the Crab nebula, although the response is greatly broadened and reduced in peak amplitude. The existence of the secondary maxima depends on the adopted shapes of the pencil-beam solar responses on the days concerned. All curves shown in Figure 8 were derived by assuming that the solar response curve was symmetrical about the time corresponding to the transit of the centre of the Sun's disk. An examination of the corresponding low sensitivity fan-beam records on which the peak Sun deflections exceed those of the Crab nebula by a factor of 10 supported the assumption of symmetry. Hence it was concluded that the secondary peaks were real features of the Crab nebula distributions on the days they occurred.

The second point of interest concerns the noticeable reductions in the pencil-beam responses at the normal transit time of the source indicated in Figure 8 by the continuous vertical lines. These quantities are set out in Table 1 alongside the fan-beam responses for the same days. For June 14, 15, and 16, 1958, two figures are given in the table for the pencil-beam response corresponding to the uncertainty in the solar contributions to the record. In principle it should be possible to relate the pencil-beam responses at transit with the corresponding quantities of the fan-beam records in order to deduce the size of the radio source in both east-west and north-south directions. The peak deflections of the pencil-beam records should suffer less diminution than those of the fan-beam responses because of the wider east-west beamwidth of the former aerial, provided that the size of the source in the north-south direction does not approach the north-south beamwidth of the pencil beam (85 min of arc). An inspection of Table 1 shows in fact that the pencil-beam response at transit was generally higher than that of the fan beam, with one notable exception, the record of June 16, 1958. The angular size of the Crab nebula, as deduced from these records, will be quantitatively discussed in the next section.

IV. Interpretation of Results

The east-west brightness distributions of the Crab nebula when occulted by the solar corona are obviously difficult to interpret unambiguously. In the first instance, we do not know the complete drift pattern for each day because of some uncertainty in the solar contribution to the records. In addition, granted that the distributions are correct, it is apparent that the resolving power of the aerial systems is not good enough to define with precision the relative positions of possible sources of radio energy. In attempting an interpretation of the results, the following characteristics of the records should be kept in mind: (*a*) the responses of the fan-beam and pencil-beam systems at the normal transit time of the Crab nebula are reduced ; (*b*) the east-west distribution may be greatly extended in the direction toward the Sun, and in some cases a secondary peak is present ; (*c*) the integrated radio flux of the Crab nebula may be greater than or less than the unocculted value. These experimental results are not consistent with the symmetrical scattering mechanism that has been proposed by the English and Russian authors to account for their interferometer observations of the Crab nebula when occulted by the corona. If scattering were the only process occurring, then the pencil-beam distributions of Figure 8 would remain symmetrical about the normal transit time of the radio source, although they would be widened and reduced in peak amplitude. As a possible alternative mechanism it is proposed to consider the effects of both coronal scattering and regular refraction on the Crab nebula radiation.

Imagine the solar corona to have a radial gradient of average electron density upon which is superposed random density variations of dimensions much greater than the operating wavelength. The average component will give rise to a regular refraction of the plane wave incident on the corona from a cosmic radio source. The irregular fluctuations in the density will cause a scattering of the same radiation. The problem of refraction in the solar corona has been given theoretical treatment by Link (1952) and Bracewell and Preston (1956). Both analyses were made on the assumption that the Sun was surrounded by a spherically symmetrical corona having a radial gradient of electron density of the form $N=a\rho^{-n}$ in which a is a constant, ρ is the distance from the solar centre, and n is a constant which may have values between 3 and 6. Recent optical determinations of the coronal electron density by Michard (1954) and Blackwell (1956) are consistent with a value of about 3 for the exponent over the range 2–10 solar radii. Calculations of the refraction using the approximate expression developed by Link shows that, at a frequency of 85·5 Mc/s, the Sun is surrounded by an occulting sphere of radius approximately 5 solar radii. A point cosmic radio source outside this sphere will be seen both by means of the direct ray, which will undergo slight refraction away from the Sun, and also by a " reflected " ray which is formed by the radiation which in traversing the corona inside the occulting sphere has been refracted through the angle between the direction of the radio source and the direction to the centre of the Sun. Hence to the observer on the Earth, an image of the source will appear within the occulting sphere. As the angular separation between the source and Sun decreases, the image will appear to approach the source until they are both located at the limb of the occulting sphere; at this point the source is occulted, the radio flux reaching the observer dropping rapidly to zero. The behaviour just described will be modified by the existence of scattering in the corona. To an observer at the Earth, scattering will increase the angular sizes of both radio source and its image. There is good reason for believing that the radiation which forms the image will be scattered through larger angles than that of the direct ray, since the former must traverse regions of higher electron density; hence it is likely that the image will appear extremely diffuse. It is believed that the absorption

Table 2

SCATTERING SUFFERED BY CRAB NEBULA—JUNE 1957, 1958

Date	Half-power Width of Scattered Cone (min of arc)	
	1957	1958
June 12	16	16
13	32	24
14	57	63
15	—	—
16	93	133

of the radiation forming the image will be negligible until the angular separation of the source and Sun is so great that the image falls within about 2 solar radii of the Sun's centre. Certainly absorption may be neglected when the angular separation is less than 10 solar radii.

Some idealized calculations have been made of the refraction and scattering which may occur, based on the experimental results for June 1957 and 1958. The methods used are described in detail in Appendix I. For these calculations it was assumed that the corona exhibited spherical symmetry. It was also assumed that at any point in the corona the electron density was given by twice the value found by Michard and Blackwell, since their observations apply to sunspot minimum. The degree of scattering suffered by the direct ray was estimated from the reduction in the peak response of the fan beam at the normal transit time of the Crab nebula. The distribution of scattered radiation was taken to be Gaussian in all directions about the position of the source. The degree of scattering suffered by the radiation forming the image is not known, but a minimum value may be estimated from the fan-beam results. Values for the scattering angle to half-power points are set out in Table 2, and plotted as a function of the angular separation in Figure 9. It is apparent that the scattering angle increases rapidly when the angular separation of the Crab nebula and Sun is less than 10 solar radii, and continues the trend noted by Hewish (1958) from interferometer observations at larger angular separations during the same occultations. Some caution should, however, be used in interpreting the fan-beam reductions as being due solely to the increased size of the source; when the angular separation is small and the scattering angle very large it is likely that part of the reduction is caused by an eclipse of some of the scattered radio flux by the occulting sphere surrounding the Sun. Under these conditions, the scattering at the smallest angular separations will be over-estimated by this

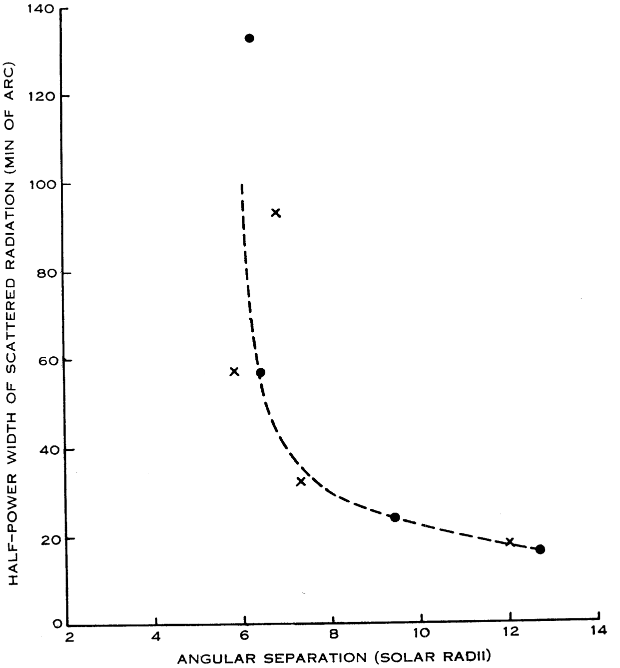

Fig. 9.—Half-power width of the scattered cone of radiation as a function of the angular separation between the Crab nebula and the Sun in June 1957, 1958. × 1957, ● 1958.

method, but it appears reasonable to assume that the radiation forming the image, which will lie mainly in the range 4–5 solar radii, will be scattered through angles of the order of 2–3° to half-power points.

Figure 10 shows idealized sketches of the effects of scattering and refraction for June 13, 14, 15, and 16, 1958, calculated by making use of the above assumptions. The sketches for June 1957 would have a similar appearance. Since the scattering angle increases rapidly with decreasing angular distance from the Sun, the cross sections of the scattered radiation patterns will depart from the circular shapes expected at greater angular separations; part of the scattered radiation will, however, be blocked from the observer by the occulting disk on June 14, 15, and 16. The diffuse image of the Crab nebula will occupy an appreciable portion of the occulting disk, being elongated around and concentrated towards its periphery.

The model outlined above will account for some of the features of the pencil-beam distributions shown in Figure 8. For example, on June 13, the idealized distribution of Figure 10 predicts a distinct and well-resolved image of the Crab nebula separated from the radio source by about 1°·5 in the westerly direction toward the Sun ; the experimental distribution of June 13, 1958 definitely agrees

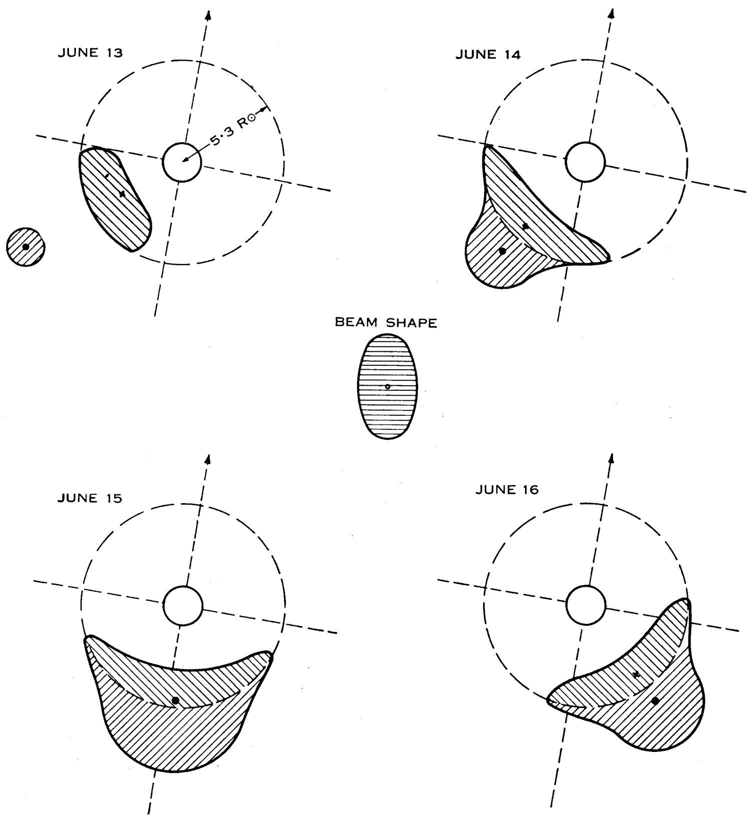

Fig. 10.—Idealized sketches showing the effects of scattering and refraction on the distribution of the Crab nebula radio flux in June 1958. The cross-hatched areas are contained within the half-power contours of the distributions. The positions of the point radio source and its image are shown by the filled-in circle and cross respectively.

with the prediction but there is no clear evidence for an image on the corresponding day in 1957, although the tail of the distribution is extended somewhat in the Sun's direction. The experimental results for June 15 of both years agree qualitatively with the calculated distribution, which, it can be seen, is symmetrical about the position of the radio source and greatly broadened. On June 14 and 16, the model indicates that the distributions should be greatly extended in the direction toward and past the solar axis, the curve dropping smoothly to zero ;

the experimental curves for these days indicate that not only are the distributions extended in the predicted directions, but also show distinct secondary peaks.

It is clear that the spherical model does not adequately represent the observational results and that the distribution of Crab nebula radiation is markedly affected by refraction and scattering in large-scale coronal irregularities. The secondary peak, which represents the main departure of the observations from the simple spherical model, was recorded in both 1957 and 1958, and suggests the existence of semipermanent regions in the corona of higher than average electron density.

The question of the integrated radio flux in the presence of scattering and refraction is of interest. The existence of an image implies that the total radio flux reaching the observer can be appreciably increased. For any particular observation, this quantity will depend upon the amount of energy occulted and the distribution of scattered and refracted radio flux with respect to the aerial beam. The half-power contour of the aerial beam has been sketched in Figure 10. These diagrams show that on June 13 and 14 most of the scattered and refracted energy will be swept through the aerial beam, so that the integrated flux may be expected to be higher than normal. On June 15 and 16, however, a reasonable proportion of the radiation is either occulted or removed by the directivity of the aerial beam, so that a decrease in the integrated flux may be observed. These conclusions are supported by the measurements of integrated flux described in Section III. Evidence for large changes in integrated flux has also been obtained by other observers. Blum and Boischot (1957), while making observations of the Crab nebula during the 1957 occultation with a diffraction grating type of east-west interferometer at 169 Mc/s, found that the integrated radio flux was some 60 per cent. greater than normal on June 13, 1956; the increase was ascribed to the effects of refraction in the corona. Hewish (1958) describes observations made in 1956 with an interferometer of spacing 8λ at 38 Mc/s, and points out that, because the large fringe separation of approximately 7° probably exceeds the scattering angles likely to be produced, any reduction in the depth of modulation must be due to a decrease in the integrated radio flux reaching the observer. His results show that the amplitude of the interference pattern had fallen virtually to zero at an angular separation of about 7 solar radii. It can only be concluded that the radius of the solar occulting disk for 38 Mc/s radiation must extend to at least 7 solar radii near sunspot maximum. This is in keeping with the value of $5 \cdot 3$ solar radii deduced from the present pencil-beam results for $85 \cdot 5$ Mc/s radiation.

It is of some interest to re-examine the preliminary observations obtained by Slee (1956). As a result of the more complete observations in 1957 and 1958, it must be concluded that the reductions noted in the fan-beam responses of June 16 and 17 were wrongly interpreted. It is now apparent that the scattering experienced by the radio source is too complete to be described by a partial scattering process. Nearly all the energy is scattered from the radiation incident on the corona and redistributed in a different angular spectrum. This is in accord with the deductions of the English and Russian observers.

V. Temporal Changes in the Transmission Properties of the Corona

Hewish (1958) has given evidence that the scattering power of the corona increases markedly from sunspot minimum to maximum. This is especially true of the polar regions, where, during sunspot maximum, the electron density, and presumably the degree of inhomogeneity, approaches that of the equatorial regions.

There has also been some evidence for very short-term changes in the transmission properties of the corona, involving times of the order of minutes or seconds. Vitkevitch (1955*b*) describes relatively sudden disturbances to the amplitudes of interference patterns obtained during the occultations of 1953 and 1954 and attributes them to the occurrence of dynamic processes in the outer corona. Evidence for a similar effect was obtained by the author during the observations on June 16, 1957. This is evident from the interferometer record shown in Figure 5, which indicates that the amplitude of the interference pattern due to the Crab nebula was reduced to the noise level of the receiver in a time of the order of 6 min shortly after the transit time of the source. The possibility of a beat between an interference pattern due to the Sun and that of the radio source seems very unlikely, since the record shows no trace of a group of solar bursts which occurred between $05^{\mathrm{h}}\ 30^{\mathrm{m}}$ and $05^{\mathrm{h}}\ 34^{\mathrm{m}}$ sidereal time, proving that the solar contribution to the record was negligible at this time.

It is natural to interpret the observed modification to the interference pattern as a change in the transmission properties of the corona. For example, the propagation of streams of charged particles outward from an active area on the Sun's disk may progressively change either the dimensions or electron densities of the scattering irregularities. Alternatively, the ejection of a sufficiently large number of electrons into the corona may result in appreciable absorption or a marked increase in refraction of the Crab nebula radiation.

Assuming that the change in the interference pattern was due to the progressive growth of one of these effects, it is possible to obtain an approximate value for the velocity of the particles responsible. In order to account for the observed change in a time of 6 min, the disturbance would need to be propagated across a zone in the corona of about 1° angular diameter (allowing for the existing degree of scattered radiation) with a velocity of approximately 7×10^3 km/sec.

It is of some interest that an intense solar burst was recorded at $05^{\mathrm{h}}\ 19^{\mathrm{m}}$ sidereal time, the peak intensity of the burst being estimated at about 1000 times the quiet-Sun level. Due to the fact that the Sun had not completely passed out of the interference fringes at this time, the burst was seen on the record. Radio-spectrometer measurements of this burst (kindly supplied by Mr. J. P. Wild of this Laboratory) showed that it was of spectral type III. Assuming that a disturbance, coincident with the radio burst, was ejected into the corona in the right direction to intercept the ray paths from the Crab nebula to the Earth, it can be shown that it would need to have travelled with a velocity of about 5×10^3 km/sec in order to have been responsible for the observed effect 17 min later.

This value for the propagation velocity is consistent with the previous figure estimated from a different argument; it is, however, lower by an order of magnitude than the ejection velocities believed to be associated with type III bursts, and somewhat higher than the average velocity of particles causing terrestrial magnetic storms and aurorae. Unfortunately, the occurrence of strong, discrete solar radio bursts during occultation observations was not frequent enough to confirm their possible relationship with changes in coronal structure.

VI. Conclusions

The observations which have been described in this paper complement and in several important respects extend the results which have been obtained by the Russian and English observers over the past 7 years. They have been particularly valuable in extending the observations well into the corona at the peak of the present sunspot cycle; under these conditions the degree of scattering and occultation of radiation traversing the corona becomes so pronounced that interferometer observations, even on the closest spacings, can give little information on the distribution of the radio energy. The following is a summary of the results obtained by means of pencil-beam, fan-beam, and interferometer measurements in June 1957 and 1958.

(1) The angular distribution of the radio flux from a discrete radio source is greatly modified by its passage through the solar corona. When the angular separation between the Crab nebula and the Sun is less than 10 solar radii, the east-west distribution at 85·5 Mc/s becomes markedly asymmetrical about the position of the discrete source. It is then extended, and sometimes shows a secondary maximum, in the direction towards the Sun. The integrated radio flux on these occasions may be greater than or less than its unocculted value.

(2) The symmetrical scattering theory developed by the Russian and English workers to account for their interferometer observations is not consistent with the present results.

(3) A simple spherical coronal model, in which electron irregularities cause a scattering of up to 3° and the average electron content a regular refraction of the same order, is in better agreement with the pencil-beam observations. However, the lack of detailed agreement suggests that the effects of large semi-permanent regions of higher than average electron density may be important.

(4) There appears to be definite evidence for short-term changes in the transmission properties of the corona, possibly coupled with the ejection of disturbances from active areas on the Sun's disk.

The results of these observations demonstrate the feasibility and desirability of conducting occultation observations with fan-beam and pencil-beam type instruments. There is little doubt that, in the presence of the complex brightness distributions obtained at the smallest angular separations, the interpretation of interferometer results could be very misleading. Even during sunspot minimum there is a strong possibility that refraction effects would not be negligible. It would be of great interest to continue occultation observations by means of fan and pencil beams, if possible of higher resolution than those used here, in an attempt to obtain a detailed picture of the coronal electron density throughout the sunspot cycle.

VII. Acknowledgments

The author wishes to express his gratitude to all those who helped in various ways with the observations. In particular, great assistance was rendered by Mr. A. Watkinson in the construction of equipment and with the observations during the 1957 occultation. In addition, the author is indebted to Mr. E. R. Hill for valuable advice on some of the computational problems encountered, and to Dr. J. L. Pawsey for his continued stimulating interest throughout.

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Appendix I

Refraction of Radiation from a Discrete Source in the Corona

Referring to Figure 11, (*a*) is a view in the line of sight of the observer; (*b*) is a diagram of the ray paths in a plane containing the Earth at E, the centre of the Sun at S, and the radio source. When the terrestrial observer looks towards the point A separated from the Sun by the angle θ and at position angle P, his line of sight intersects a point B on the celestial sphere which has the same position angle but is separated from the Sun by the angle φ. Obviously $\varphi=\theta+\omega$, where ω is the refraction suffered by the ray. A convenient method of finding the image, given the source position φ, consists of constructing a graph of $\theta+\omega$ as a function of θ, the values of refraction being calculated by an approximate expression due to Link (1952) or by ray tracing. Such a graph constructed for a frequency of 85·5 Mc/s and incorporating angles of refraction based on the electron density distribution described in the text is shown in Figure 12. To find the apparent positions of the source and its image, the graph is entered at the ordinate corresponding to the known source position and a horizontal line drawn to intersect the curve at points a and b. The abscissae of these points then define the image and apparent source positions respectively. The horizontal line $\varphi=\varphi_0$, which is tangent to the minimum point on the curve, corresponds to the radius of the circular zone on the celestial sphere occulted by the corona.

If the radio source is an extended object, the graph may again be used to find the apparent brightness distribution. Every value of φ over the extended source will give rise to two values of θ as before. The radial magnification of the image $d\theta/d\varphi$ will be negative and appreciably less than unity; the lateral magnification $\sin\theta/\sin\varphi$ will also be less than unity.

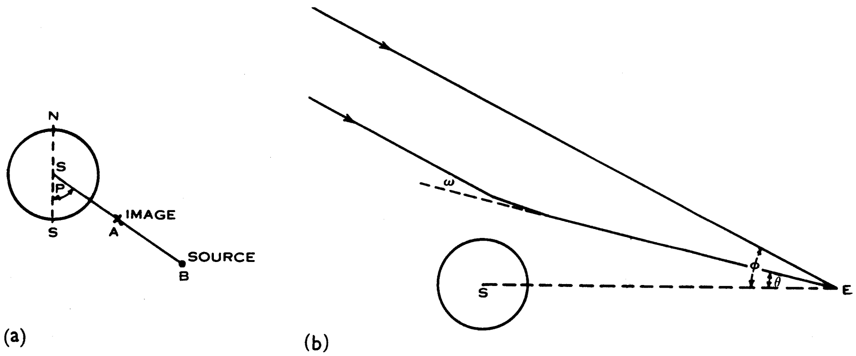

Fig. 11 (*a*).—View looking along the line of sight of the terrestrial observer towards a radio source and its image in the corona.

Fig. 11 (*b*).—View of the ray paths in the plane containing the radio source, the centre of the Sun, and the Earth.

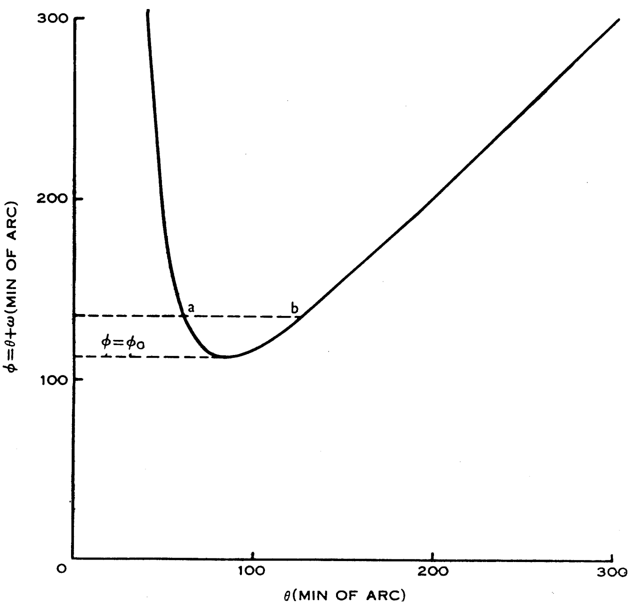

Fig. 12.—Relation between the true angular separation of the radio source and the Sun, φ, and the apparent separation θ, due to refraction in the corona.

For the case of a radio source which is both scattered and refracted in the corona, an approximate brightness distribution may be obtained provided the scattering angle is known as a function of the angular separation from the Sun.

In this case we may calculate the image brightness distribution on the assumption that it is due to an extended source of dimensions comparable with the scattering suffered by radiation traversing the inner parts of the corona. The approximate distributions of Figure 9 were derived on the assumption that the radiation forming the image had been scattered through an angle of 3° to half-power points. These diagrams are, however, highly idealized, since it is most likely that the scattering function will vary considerably over the region of the corona in which the image is formed, leading to departures from the distributions shown.