INVESTIGATION OF THE RADIO SOURCE 3C 273 BY THE METHOD OF LUNAR OCCULTATIONS

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THE observation of lunar occultations provides the most accurate method of determining the positions of the localized radio sources, being capable of yielding a positional accuracy of the order of 1 sec of arc. It has been shown by Hazard[1] that the observations also provide diameter information down to a limit of the same order. For the sources of small angular size the diameter information is obtained from the observed diffraction effects at the Moon's limb which may be considered to act as a straight diffracting edge.

The method has so far been applied only to a study of the radio source *3C* 212 the position of which was determined to an accuracy of about 3 sec of arc[1,2]. However, *3C* 212 is a source of comparatively small flux density and although the diffraction effects at the Moon's limb were clearly visible the signal-to-noise ratio was inadequate to study the pattern in detail and hence to realize the full potentialities of the method. Here we describe the observation of a series of occultations of the intense radio source *3C* 273 in which detailed diffraction effects have been recorded for the first time permitting the position to be determined to an accuracy of better than 1″ and enabling a detailed examination to be made of the brightness distribution across the source.

The observations were carried out using the 210-ft. steerable telescope at Parkes, the method of observation being to direct the telescope to the position of the source and then to record the received power with the telescope in automatic motion following the source. Three occultations of the source have been observed, on April 15, at 410 Mc/s, on August 5 at 136 Mc/s and 410 Mc/s, and on October 26 at 410 Mc/s and 1,420 Mc/s, although in October and April only the immersion and emersion respectively were visible using the Parkes instrument. The 410 Mc/s receiver was a double-sided band receiver, the two channels, each of width 10 Mc/s, being centred on 400 Mc/s and 420 Mc/s, while the 136 Mc/s and 1,420 Mc/s receivers each had a single pass band 1·5 Mc/s and 10 Mc/s wide respectively.

The record of April 15, although of interest as it represents the first observation of detailed diffraction fringes during a lunar occultation, is disturbed by a gradient in the received power and is not suitable for accurate position and diameter measurements. Therefore, attention will be confined to the occultation curves recorded in August and October and which are reproduced in Fig. 1. It is immediately obvious from these records that *3C* 273 is a double source orientated in such a way that whereas the two components passed successively behind the Moon at both immersions, they reappeared almost simultaneously. The prominent diffraction fringes show that the angular sizes of these components must be considerably smaller than 10″, which is the order of size of a Fresnel zone at the Moon's limb.

The most interesting feature of Figs. 1(*e*) and 1(*f*) is the change in the ratio of the flux densities of the two components with frequency. The ratio of the flux density of the south preceding source (component *A*) to that of the north following source (component *B*) is 1 : 0·45 at 410 Mc/s and 1 : 1·4 at 1,420 Mc/s, indicating a striking difference in the spectra of the two components. If it be assumed that the flux densities[3] of *3C* 273 at 410 Mc/s and 1,420 Mc/s are 60 and 35 Wm^{-2} $(c/s)^{-1}$ and that over this frequency-range the spectrum of each component may be represented by $S \propto f^n$, then the above ratios correspond to spectral indices for components *A* and *B* of −0·9 and 0·0 respectively. The spectral index of *A* is a representative value for a Class II radio source; but the flat spectrum of *B* is most unusual, no measurements of a comparable spectrum having yet been published. If the spectral indices were assumed constant down to 136 Mc/s then at this frequency component *A* must contribute almost 90 per cent of the total emission, a conclusion which is confirmed by a comparison of the times of immersion at 136 Mc/s and 410 Mc/s on August 5.

It has been shown by Scheuer[4] that it is possible to recover the true brightness distribution across the source from the observed diffraction pattern, the resolution being subject only to limitations imposed by the receiver bandwidth and the finite signal to noise ratio and being independent of the angular scale of the diffraction pattern. However, in this preliminary investigation we have not attempted such a detailed investigation but based the analysis on the calculated curves for uniform strip sources of different widths as published by Hazard[1]. As a first step in the investigation approximate diameters were estimated from the intensity of the first diffraction lobe and the results corresponding to the three position angles defined by the occultations and indicated in Fig. 2 are given in Table 1.

As already indicated here, the 136-Mc/s measurements refer only to component *A* and hence no diameter measurements are available for *B* at this frequency. The 410-Mc/s observations of the August occultation are the most difficult to interpret owing to the components having both comparable flux density and small separation relative to the angular size of the first Fresnel zone. At immersion the widths were estimated by using a process of curve fitting to reproduce Fig. 1(*d*); at emersion (position angle 313°) the diameter of component *B* was assumed to be 3″ as indicated by the estimates at position angles 105° and 83°. The individual measurements at each frequency are reasonably consistent but there is a striking variation of the angular size of component *A* with frequency and evidence of a similar variation for component *B*. As at the time of the August occultation the angular separation of the Sun and the source was about 50° and hence coronal scattering of the type observed by Slee[5] at 85 Mc/s is not likely to be significant, this variation in size suggests that the model of two uniform strip sources is inadequate.

Therefore, a more detailed analysis was made of the intensity distributions of the lobe patterns given in Figs. 1(*c*) and 1(*f*), and it was found that in neither case can the pattern be fitted to that for a uniform strip source or a source with a gaussian brightness distribution. The 1,420-Mc/s observations of component *B* can be explained, however, by assuming that this source consists of a central bright core about 0·5″ wide contributing about 80 per cent of the total flux embedded in a halo of equivalent width of about 7″. Fig. 1(*b*), where component *A* predominates, suggests that this source has a similar structure

Table 1. EFFECTIVE WIDTH OF EQUIVALENT STRIP SOURCE (Sec. of arc)

Frequency Mc/s	Component *A* Position angle 106°	Component *A* 313°	Component *A* 84°	Component *B* Position angle 105°	Component *B* 314°	Component *B* 83°
136	6·4	6·4	—	—	—	—
410	3·1	4·2† 2 (6)*	4·2	3·1	3·0†	2·7
1,420	—	—	2·9	—	—	2·1 0·5 (7)*

* Estimated from an analysis of the whole diffraction pattern.
† Component *B* assumed to have width of 3″.

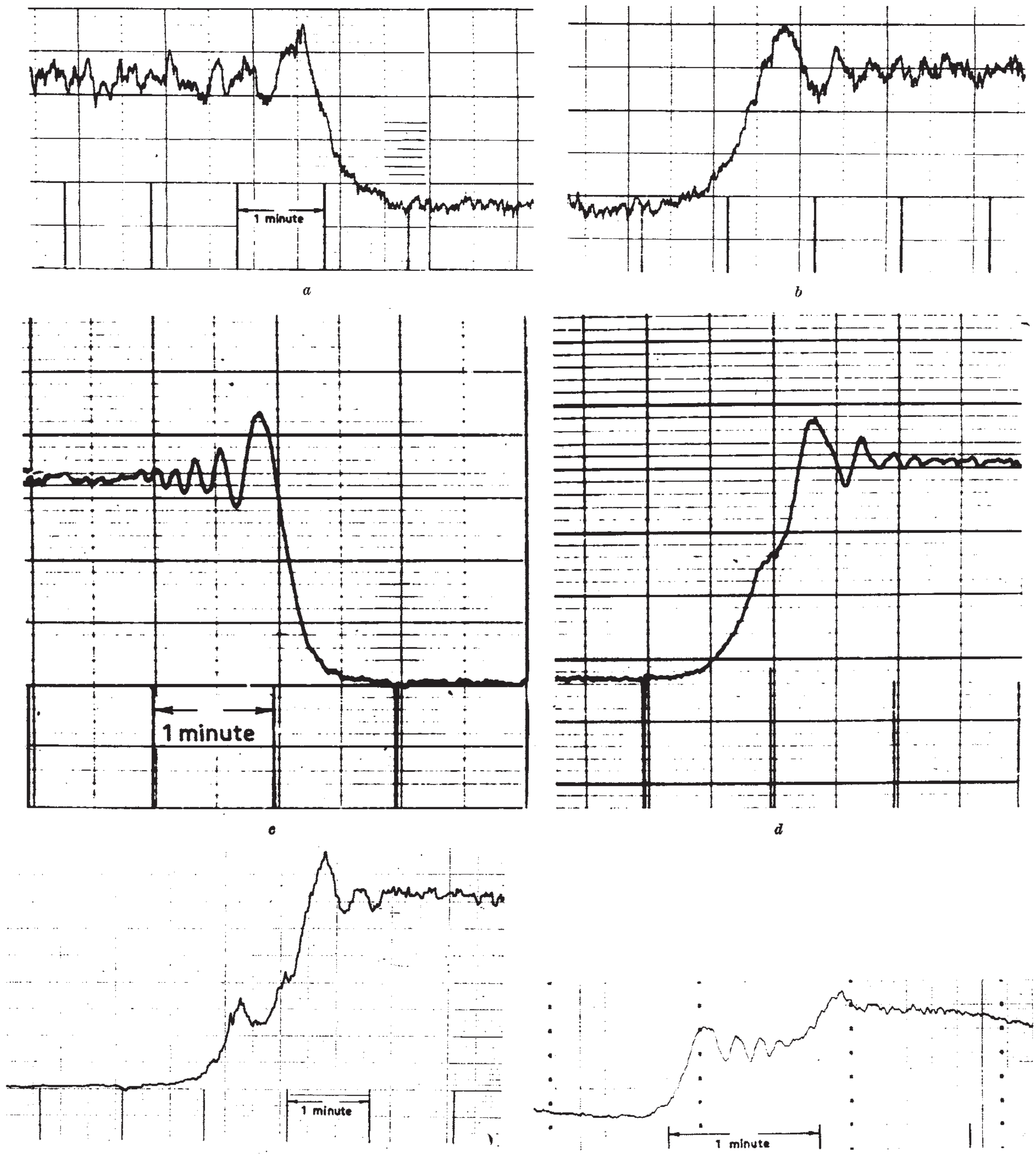

Fig. 1. Facsimiles of records showing occultations on August 5 and October 26, 1962, at different frequencies. (*a*) Emersion of August 5, 1962, at 136 Mc/s; (*b*) immersion of August 5, 1962, at 136 Mc/s; (*c*) emersion of August 5, 1962, at 410 Mc/s; (*d*) immersion of August 5, 1962, at 410 Mc/s; (*e*) immersion of October 26, 1962, at 410 Mc/s; (*f*) immersion of October 26, 1962, at 1,420 Mc/s. Abscissæ, U.T.; ordinates, flux density

but with a core of effective width about 2″ at 410 Mc/s and a halo of width 6″. It therefore seems that the overall extent of both components are comparable but that the emission is more highly concentrated to the nucleus in *B* than in *A*. The close agreement between the halo size of *A* and its effective diameter at 136 Mc/s suggests that the observed variation of effective size with frequency may be due to a difference in the spectra of the halo and central regions. This would imply that the spectrum becomes steeper in the outer regions of the sources, that is, in the regions of lower emissivity. It is of interest that the integrated spectral indices of the two components show an analogous effect. Thus the spectrum of *B*, where most of the emission arises in a source about 0·5″ wide, is markedly flatter than that of *A*, where it arises in a source about 2″ wide.

The analysis is not sufficiently accurate to reach any reliable conclusions on the ellipticity of the individual components of 3*C* 273, but allowing for the uncertainty in the estimated widths and position angle 314°, the 410-Mc/s observations indicate that both components may be elliptical with *A* elongated approximately along the axis joining the two components and *B* elongated perpendicular to this axis.

The position of each source was calculated from the observed times of disappearance and reappearance, which were estimated from the calculated flux density at the edge of the geometrical shadow and, where possible, from the positions of the diffraction lobes; these times are given in Table 2. In estimating the values of $T_D{}^A$ and $T_R{}^A$ from the 136-Mc/s records a small correction was applied for the effects of component *B*, this correction being estimated by comparison with the 410-Mc/s records. The corresponding times for *B* were estimated from the 410-Mc/s observations using the estimated position of component *A* and the known flux density ratio of the two components. For each component the times and associated errors given in Table 2 define three strips in each of which the source should lie ; the centre lines of these strips represent the limb of the Moon at the time of observation and define in each case a triangular-shaped area. In principle, the position of the source lies in the area common to the three associated strips but it was found that for each component, and in particular for component *A*, that the size of the triangles defined by the Moon's limb was larger than would be expected from the estimated timing errors. This suggests that errors in the positions of the Moon's limb are more important than the estimated timing errors, and possibly that the effective position of the source varies slightly with frequency. The position of each source was therefore assumed to be given by the centre of the circle inscribed in the triangle defined by the Moon's limb at the relevant times. Dr. W. Nicholson of H.M. Nautical Almanac Office has kindly carried out these calculations and the estimated positions are as follows:

Component *A* (Epoch 1950)	R.A.	12h 26m 32·38s ± 0·03s
	Decl.	02° 19′ 27·8″ ± 1·5″
Component *B* (Epoch 1950)	R.A.	12h 26m 33·29s ± 0·02s
	Decl.	02° 19′ 42·0″ ± 0·5″

The average positions of the two sources given here represent the most accurate determination yet made of the position of a radio source. The quoted errors were estimated from the size of the triangles defined by the Moon's limb at the times of disappearance and reappearance, for the method is not subject to uncertainties introduced by refraction in the Earth's ionosphere or troposphere and is also free from the effects of confusion. A comparison of the times of disappearance and reappearance at different frequencies indicates that there is also no significant source of error due to refraction in either the solar corona or a possible lunar ionosphere; any refraction appears to be less than 0·3″ even at 136 Mc/s. This may be compared with the upper limit of 2″ at 237 Mc/s and 13″ at 81 Mc/s as estimated by Hazard[1] and Elsmore[6] respectively, and allows a new limit to be set to the density of the lunar ionosphere. Thus, from his observations at 81·5 Mc/s, Elsmore has set an upper limit to the electron density of 10^3 cm^{-3}; and it follows that the present measurements set a limit of about 10^2 cm^{-3}. Similarly, Buckingham[7] has estimated that at 50 Mc/s a ray passing at 50° to the Sun would be deviated by 1″ if the electron density in the solar corona at the Earth's distance from the Sun is 100 cm^{-3}. The present observations at 136 Mc/s and 410 Mc/s on August 5 indicate that at 50 Mc/s the deviation is less than 2″ at this angle, setting an upper limit to the electron density of about 200 cm^{-3}, which may be compared with an upper limit of 120 cm^{-3}, set by Blackwell and Ingham[8] from observations of the zodiacal light.

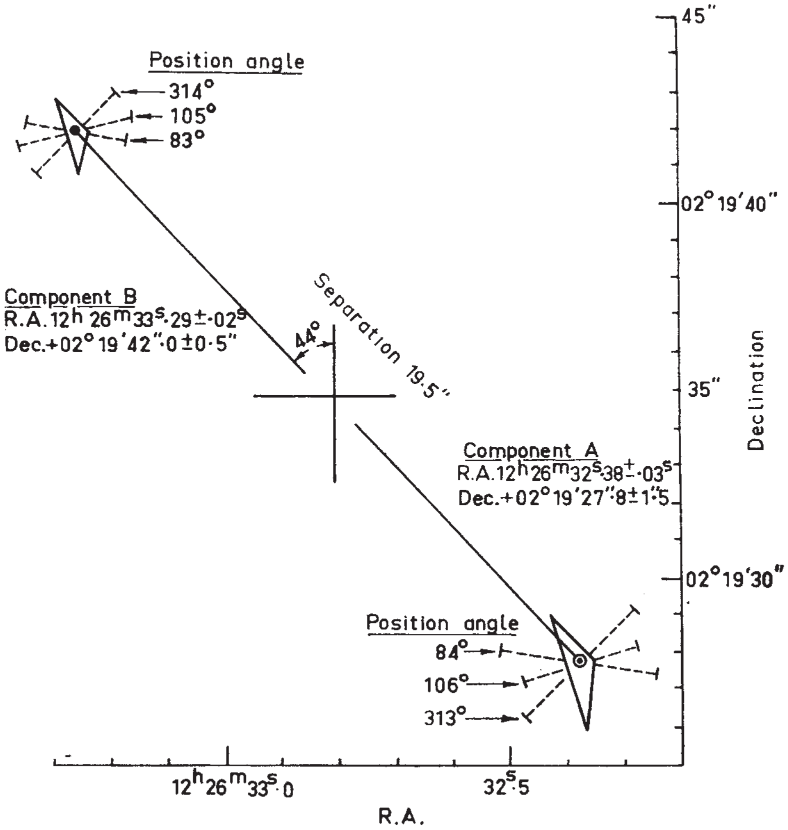

Fig. 2. Diagram of the radio source 3C 273. The sides of the full line triangles represent the positions of the limb of the Moon at the times of occultation. The broken lines represent the widths of the equivalent strip source as measured at 410 Mc/s for each of three position angles indicated

In a preliminary examination of a print from a 200″ plate it was noted that the position of component *B* agreed closely with that of a thirteenth magnitude star. We understand that the investigations by Drs. A. Sandage and M. Schmidt of the Mount Wilson and Palomar Observatories have revealed that this star and an associated nebulosity is very probably the source of the radio emission.

We thank Mr. J. G. Bolton for his interest in this work, and his assistance, with that of the staff at Parkes, in ensuring the success of these observations. We also thank Dr. W. Nicholson, who calculated the positions of the sources, for his valuable co-operation and interest in the occultation programme. One of us (C. H.) thanks Dr. E. G. Bowen for his invitation to continue occultation work at Parkes as a guest observer from the Narrabri Observatory of the School of Physics of the University of Sydney.

Table 2. Observed Occultation Times of the Two Components of 3C 273

	Component *A* (U.T.)	Component *B* (U.T.)
Time of disappearance August 5, 1962	07h 46m 00s ± 1s	07h 46m 27·2s ± 0·5s
Time of reappearance August 5, 1962	09h 05m 45·5s ± 1s	09h 05m 45·7s ± 1·5s
Time of disappearance October 26, 1962	02h 55m 09·0s ± 1s	02h 56m 01·5s ± 0·4s

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