LUNAR OCCULTATION OBSERVATIONS OF 24 RADIO SOURCES

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Abstract

Some details of the structure of 24 radio sources have been deduced from measurements of the occultation of radio sources by the Moon. The measurements were made at Parkes between July 1964 and December 1966. Most of the sources have been resolved and shown to have structure greater than 2″ arc in extent. A brief description is given of the observing technique and of the method of analysis.

I. Introduction

Hazard (1962) seems to have given the first systematic discussion of the observation of lunar occultations as a method for investigating the structure of radio sources. He showed that it would be possible to measure radio source positions at metre wavelengths to an accuracy of a few seconds of arc and that it would also be possible to measure some details of the structure at this scale. He went on to demonstrate the value of the method by measuring the position of the radio source 3C 212 to an accuracy of 3″ arc. At that time the positions of few radio sources were known to better than 1′ arc.

One important consequence of the introduction of this observational technique for making very accurate radio position measurements was that it became possible to make more reliable identifications of radio sources with optical objects. Until then most radio source positions were known too imprecisely to allow many identifications to be made. The measurement of the position of the radio source 3C 273 from a series of occultation observations (Hazard, Mackey, and Shimmins 1963) and the undoubted association of the two components of the radio source with two optical features led directly to the recognition of the quasi-stellar radio sources. Precise radio positions and details of the structure of several other radio sources were also found from other occultations which were observed with the 64 m telescope at Parkes (Hazard, Mackey, and Nicholson 1964).

The extensive series of occultation observations which is described in the present paper was undertaken to make precise measurements of the position and structure of as many sources as possible. The positions were to be used to make optical identifications wherever possible and also to provide a network of precise radio positions for the calibration of position measurements made by other techniques. In practice, however, conventional radio position measurements have rapidly improved to the point at which reliable optical identifications can be made from them (e.g. Shimmins, Clarke, and Ekers 1966) and also to the point at which measurements of positions of simple radio sources are as accurate as those measured from occultations (e.g. Adgie and Gent 1966). The principal interest in occultation observations has therefore been in the details of source structure that have been discovered. Although

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much of the information obtained is fragmentary there is still no other direct method of measuring details of the metre wavelength structure of sources a few seconds of arc in extent. Measurements of similar resolution made with long baseline interferometers do not give the structures of the sources without model fitting.

II. Observations

(a) *Zodiacal Catalogue*

For a number of years H.M. Nautical Almanac Office have made regular predictions of the occultation of radio sources by the Moon. In 1962, when occultation observations were started at Parkes, the list of occultable sources which was used for these predictions was drawn largely from the 3C and MSH source catalogues. However, C. Hazard and M. B. Mackey soon started a survey of the zodiacal region to find more sources which might be occulted, since it was clear that it would be possible to use the Parkes telescope to make good observations of the occultations of sources which were too weak to be included in the standard catalogues. The observing techniques which Hazard and Mackey adopted were similar to those used in the preparation of the Parkes catalogue of radio sources (Ekers 1969). I continued these observations when Hazard and Mackey stopped observing at Parkes.

The zodiacal catalogue took the form of a working list of the approximate positions and flux densities of radio sources within 6° of the plane of the ecliptic. Most of the sources were observed later during the surveys for the Parkes catalogue and the positions and flux densities were then measured more precisely. The remaining sources were ones which were excluded from the main catalogues either because they lay at low galactic latitudes or because they were too weak. The zodiacal catalogue contained approximately 370 sources.

Each source in the list was examined for a possible occultation each month and detailed computations were made of the circumstances of the occultations which were predicted. The observing program was compiled from this list of likely occultations. Observations were not attempted within two days of a new Moon or when only a single occultation scan through the source (i.e. only a disappearance or a reappearance) would be observable at Parkes during the following few months. Under normal conditions the telescope can be used only for observations at altitudes greater than 30° and this restriction meant that frequently only one of the two parts of the occultation could be observed.

(b) *Techniques*

It is desirable to make occultation observations over as wide a range of frequencies as possible to discover whether the structure of sources is frequency dependent. Multifrequency observations are simple to arrange with a fully steerable reflector, and three frequencies were used for most of the observations discussed here. The usual feeds were three pairs of dipoles with the dipoles for the highest and lowest frequencies mounted orthogonally to those for the third frequency. The frequencies used for most of the observations were 154, 410, and 1410 MHz, though 640 MHz replaced 410 MHz for some of the later observations and 136 MHz was used instead of 154 MHz for some early observations; 2650 MHz was used instead of 1410

MHz on a few occasions. The 136, 154, 640, 1410, and 2650 MHz receivers were all single sideband receivers with bandwidths of 1·5, 4, 8, 10, and 100 MHz respectively. The 410 MHz receiver was a double sideband receiver with two 10 MHz passbands separated by 10 MHz. It rarely happened that all three receivers were working perfectly at the time of an observation but measurements were usually obtained at two of the three frequencies.

The method of observing followed closely the technique used at Parkes by Hazard. The telescope tracked the point on the limb of the Moon at which the source was expected to disappear or reappear. Good telescope following is essential for occultation observations at high frequencies if the change in level of signal received from the Moon during an observation is not to obscure the change in level due to the occultation of the radio source. The record obtained at 2650 MHz during the occultation of 0316+16 (CTA 21) on 1965 February 9 is shown in Figure 1. A tracking error of 17″ arc would have produced a step in the baseline level of the same size as the step introduced by the occultation itself. It will be seen that on this occasion, as on most other occasions, the tracking was much better than this.

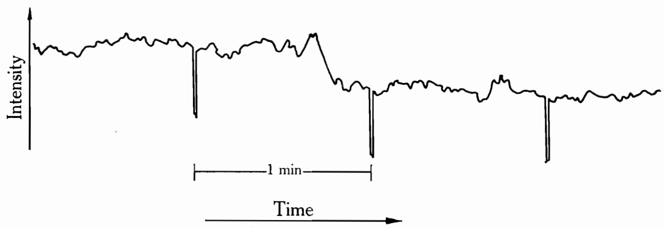

Fig. 1.—Record of immersion of 0316+16 on 1965 February 9 as observed at 2650 MHz. The flux density from this source at this frequency is 4·8 f.u. ($4 \cdot 8 \times 10^{-26}$ W m^{-2} Hz^{-1}; Shimmins, Clarke, and Ekers 1966).

The data were recorded digitally at the time of observation. Because the digital equipment was unsuitable for sampling more frequently than three times a second, the output of each of the three receivers was only sampled once each second. For this reason the receiver time constant was set to be 1 s, although a shorter time would have been preferable for several of the observations.

A total of 44 observations out of a possible 70 was made during the period from July 1964 to December 1966. Bad weather prevented a few observations and some more were omitted to simplify the telescope observing program. Useful information was obtained on 24 sources, although the amount of detail available varied from seven scans through 2113−21 to single scans through several sources. Further details of the observations are given in Section IV.

Several authors (e.g. Scheuer 1962, 1965; von Hoerner 1964; Hazard, Gulkis, and Bray 1967; Lang 1969) have considered the optimum observing technique for lunar occultation observations. Few of the limitations they discuss are significant in the work described here. One or two measurements have suffered because of the relatively wide bandwidth used at 154 and 410 MHz, but in most cases the limitation was set by the signal-to-noise ratio in the observations rather than by parameters more directly under the observer's control.

III. Analysis

The reduction of the observations fell into two parts: the computation of the source position and the restoration of the occultation curves.

The source position was found from a calculation of the points of intersection of the apparent limb of the Moon as seen from Parkes at the times of disappearance and reappearance. These times were first estimated from the unconvolved chart records and were then revised from the restored records. For simplicity a smooth spherical Moon was assumed in the position calculation and any corrections for limb irregularities (Watts 1963) were added afterwards. The position angles of the

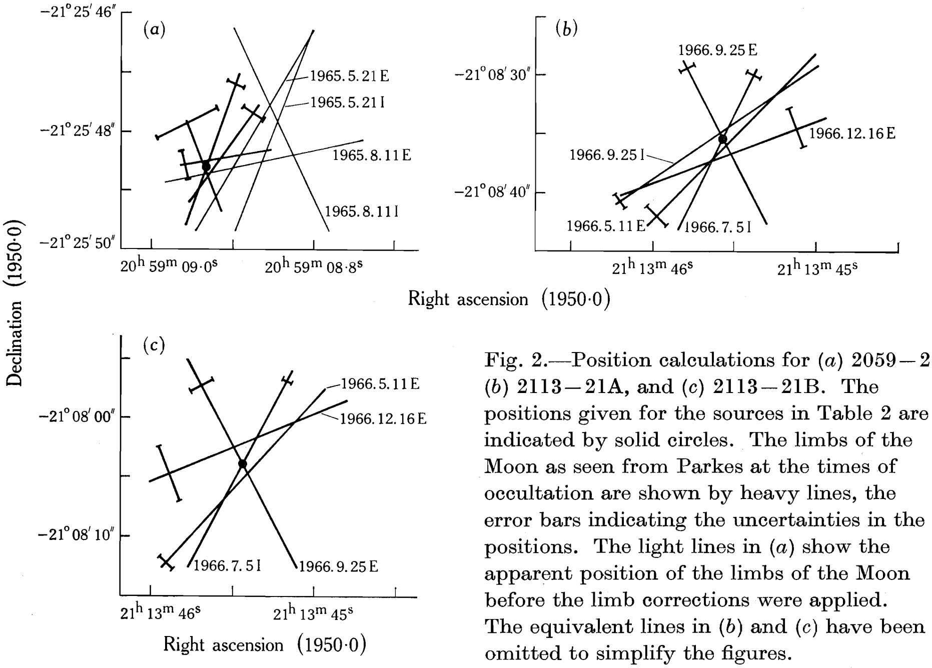

Fig. 2.—Position calculations for (*a*) 2059−21, (*b*) 2113−21A, and (*c*) 2113−21B. The positions given for the sources in Table 2 are indicated by solid circles. The limbs of the Moon as seen from Parkes at the times of occultation are shown by heavy lines, the error bars indicating the uncertainties in the positions. The light lines in (*a*) show the apparent position of the limbs of the Moon before the limb corrections were applied. The equivalent lines in (*b*) and (*c*) have been omitted to simplify the figures.

limbs of the Moon and the rate of eclipse of the source were found from the changes in the point of intersection of the limbs when the adopted times for disappearance and reappearance were each offset in turn from their nominal values. The approximate values for the rate of eclipse and the position angles derived from the occultation prediction calculations were not sufficiently accurate for the interpretation of the most precise observations. Some typical position calculations are shown in Figure 2. The first, for 2059−21, is for a single component source and the other two are for the components of the double source 2113−21.

The restoration of occultation records has been discussed by a number of authors since the procedure was first described by Scheuer (1962). The restoration functions used in the present work were computed from the formulae given by Scheuer in a later paper (Scheuer 1965). These formulae seemed to be the most suitable for restoring observations which are sampled, of necessity, at a uniform rate in time and not at a uniform rate in angular separation from the Moon. No corrections were applied for a nonuniform rate of occultation when the occultation was near grazing. There did not appear to be any sources of extremely small diameter in which the signal-to-noise ratio was sufficiently good to justify such corrections, which, in any case, would have been difficult to apply to the data in the form in which they were recorded.

All the observations which were of sufficiently good quality were restored with a range of different effective beams. Two examples of an observed record and the restored distribution are shown in Figure 3. The precise times of occultations and the structural details of complex sources were deduced from the restored profiles. Corrections for beam broadening introduced by the finite receiver passband were applied where necessary.

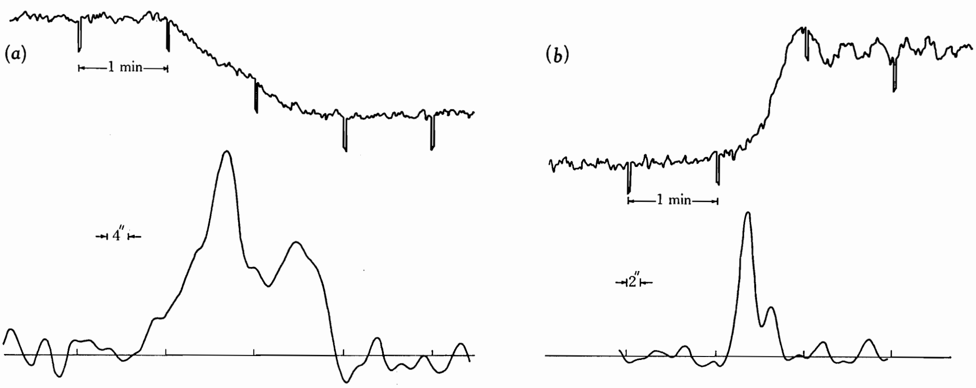

Fig. 3.—Occultation observations and restored distributions for (*a*) the immersion of 0307+16 on 1965 September 15 and (*b*) the emersion of 1859−23 on 1964 August 19. The flux densities from the sources at the frequencies of observation are approximately 30 f.u. for 0307+16 at 154 MHz and 10 f.u. for 1859−23 at 410 MHz. The effective restored beamwidths are 4″ arc for (*a*) and 2″ arc for (*b*).

The restored distributions showed that most of the sources consisted of one or two discrete components and sometimes an additional ridge of emission joining the components. The models of sources which are described in the next section were deduced by recognizing the same component in different scans across the same source and solving for the position of each component independently. Any other structural or positional data which were available were used to resolve ambiguities and to supplement the occultation observations when they were insufficient to define a model by themselves.

No use was made in the analysis of the more sophisticated methods proposed by Bracewell (1956) or Bracewell and Riddle (1967) for finding brightness distributions from a series of strip distributions. These methods offer little advantage when one has to place a few isolated components or to understand a linear source which is unresolved in a direction normal to its long axis. Bracewell's techniques are more useful in deducing the distribution across a source which is extended in two dimensions, and Taylor (1967) has used them successfully to interpret his occultation observations of the radio source 3C 192.

IV. Results

The most striking feature of the results is that all the sources, with the exception of 0316+16 and perhaps also the weak sources 1946−23, 2059−21, and 2144−17, are resolved by these observations and have some angular structure greater than 2″ arc. There are probably a few components in some of the other sources which are unresolved but in each case the object is part of a complex, usually two-component,

Table 1

SUMMARY OF OBSERVATIONS

(1) Source number	(2) Other designation	(3) Date of occultation (U.T.)	(4) 2650	(5) 1410	(6) 640	(7) 410	(8) 154	(9) 136	(10) Posn. angle (deg)* I	(11) E
			Frequency of observations (MHz)*							
0034−01	3C 15	1964 July 29		IE		IE			110	2
0118+03	(3C 39)	1964 July 30				IE			21	90
0128+06	3C 44	1965 Sept. 13		I		I	I		97	
0218+11		1965 June 24		(E)		I	I		58	53
0229+13		1965 Nov. 8		I		I	I		63	
		1966 Jan. 2		E		IE	I		64	51
0307+16	3C 79	1965 Sept. 15					I		26	
0316+16	CTA 21	1965 Feb. 9	I			I	IE		78	58
0319+17		1965 Aug. 19				E	E			112
1217+02		1966 Oct. 13			I				165	
1226+02	3C 273	1965 Nov. 19				I			107	
1335−06	13−011	1965 Aug. 30		I		I	I		163	
		1966 Jan. 13					I		90	
		1966 Mar. 9		IE		IE	IE		67	10
1514−16		1966 Jan. 15				I	I(E)		78	158
1623−22		1966 July 27			I		(E)		105	92
1710−24		1966 July 28			IE		E		131	91
1711−25		1966 July 28		E	E		IE		144	75
1859−23	19−21	1964 Aug. 19		IE		E		I	42	131
1946−23		1964 Nov. 10				IE			66	80
		1965 Jan. 31				I			66	
2030−23	20−28	1965 June 17				E				64
		1965 Sept. 7		E		E				80
2059−21		1965 May 21		E		IE			68	59
		1965 Aug. 11				IE	E		115	12
2113−21	21−23	1966 May 11			E		E			46
		1966 July 5				IE	IE		63	91
		1966 Sept. 25		I	IE		IE		33	117
		1966 Dec. 16		I	IE		IE		99	21
2135−18	21−116	1965 Jan. 6		E		E				54
		1965 Mar. 28		I		IE	IE		62	77
2144−17		1964 Oct. 16				IE			53	94
		1965 Jan. 6		I		E			35	86
2154−18	21−123	1966 May 12			E					15
2308−10		1964 Nov. 14		E		IE			105	5
		1966 June 10		E		E				28

* I, immersion; E, emersion; (E), poor emersion observation.

source. There were few examples of the high-order Fresnel fringes which were noted by Hazard, Mackey, and Shimmins (1963) during the occultation observations of 3C 273.

The observations from which useful data have been obtained are summarized in Table 1, which shows the date of the occultation, the frequencies at which the observations were made, and the position angle of the scan across the source.

Because many of the observations are incomplete, in the sense that there are insufficient measurements to define the positions of the components precisely or unambiguously, it is difficult to present the results in a simple table. Positions and angular sizes of components which are well determined are given in Table 2, together with references to published optical identifications. Most of the identifications were well established from earlier observations; those which followed or were confirmed from these measurements have already been published (Kinman *et al.* 1967).

Although measurements of flux density were included as a routine part of the observing program, it was clear from the internal self-consistency of the measurements of the same sources at different times that the measurements were not as good as those made as part of a series of routine flux density observations. Values of flux density are only given below for sources which have not appeared in other catalogues. Estimates are also given of the ratio of the flux density of components of multiple-component sources.

More detailed notes on the structures of the individual sources are given below. These notes are to be read in conjunction with the details given in Table 2.

0034—01

The source consists of a ridge of emission and two compact features. The ridge, which extends $46'' \pm 10''$ arc in position angle $160° \pm 10°$, has its midpoint at $00^{h}\,34^{m}\,30^{s}\cdot 6 \pm 0^{s}\cdot 3$, $-01°\,25'\,40'' \pm 5''$. The width of the ridge (in position angle 70°) is not defined by the occultation observations, but interferometer observations by Bash (1968a, 1968b) suggest that it is probably about 10″ arc. The two compact features apparent in the 410 MHz observations correspond closely to the components A and C noted by Hazard, Mackey, and Nicholson (1964) after an earlier occultation measurement of this source at the same frequency. There is no small-diameter object which corresponds with the component B reported by Hazard, Mackey, and Nicholson.

At 1410 MHz the position of component C appeared to be significantly different from that given by the 410 MHz measurements. The 1410 MHz position is given as C′ in Table 2. Although this position shift was apparent at both immersion and emersion there is some doubt about the interpretation because there were marked gain fluctuations in the 1410 MHz receiver during the observations.

The approximate distribution of flux density between the components, expressed as a fraction of the total flux density for the source, is 0·15 (A), 0·25 (C′), and 0·60 (ridge) at 1410 MHz, and 0·25 (A), 0·25 (C), and 0·50 (ridge) at 410 MHz.

Véron (1966, 1968) has published two positions for the galaxy with which Hazard, Mackey, and Nicholson (1964) had identified the source. The revised position (Véron 1968) puts the galaxy close to component A; the earlier position had put it approximately midway between A and C. Either position would be consistent with the identification of the radio source with the galaxy.

0118+03

The two components of this source appear to lie on a weak ridge of emission which runs along the line joining the components and extends about 10″ arc beyond each.

Table 2

MEASURED POSITIONS AND STRUCTURES OF SOURCES

(1)	(2)		(3)		(4)	(5)		(6)		(7)	(8)
Source number	Radio position (1950·0) R.A. h m s	s	Dec. ° ′ ″	″	Component size	Optical position (1950·0) R.A. h m s	s	Dec. ° ′ ″	″	Identi-fication	Ref.*
0034−01 (3C 15) A	00 34 30·2	±0·2	−01 25 34	±3	~5″						
C†	00 34 30·8	±0·3	−01 25 52	±5	9″ p.a. 110°, 4″ p.a. 2°	00 34 30·62	±0·07	−01 25 35·8	±1	18^m E gal.	2, 10
C′†	00 34 30·0	±0·3	−01 25 48	±5	<5″ p.a. 110°, <2″ p.a. 2°						
0118+03 (3C 39) A	01 18 25·1	±0·2	03 28 37	±3	14″±5″ p.a. 85°, <7″ p.a. 175°	01 18 26·15	±0·03	03 28 29·3	±0·5	18^m QSO?	1
B	01 18 27·5	±0·3	03 28 40	±5	12″±4″ p.a. 85°, <7″ p.a. 175°						
0128+06 (3C 44) A	01 28 45·2	±0·3	06 08 55	±3	B probably <3″ in	See notes in text and Figure 4					
B	01 28 44·5	±0·3	06 07 50	±5	p.a. 97° at 410 MHz						
0218+11 A	02 18 05·9‡		11 07 46‡		~3″·5 p.a. 58°	Blank field on 48 in. Sky Survey prints					
B	02 18 06·3‡		11 08 14‡		~4″ p.a. 58°						
0229+13	02 29 02·55	±0·13	13 09 38·8	±2	1410 and 410 MHz: ~4″ p.a. 64°, <2″ p.a. 51°; 154 MHz: ~6″ p.a. 64°	02 29 02·35	±0·06	13 09 41·0	±0·3	18^m QSO	1
0307+16 (3C 79)	See notes in text					03 07 11·31	±0·07	16 54 37·4	±1	19^m N gal.	7, 9
0316+16 (CTA 21)	03 16 09·11‡		16 17 40·3‡		<1″ p.a. 78°	Blank field on 200 in. plate					
0319+17	03 19 31·5	±0·7	17 37 30	±10	Probably <5″ in p.a. 112°	Blank field on 48 in. Sky Survey prints					
	Position of centroid†										
1217+02	See notes in text					12 17 38·1	±0·20	02 20 22	±2·5	16^m QSO	3
1226+02 (3C 273)	See notes in text					12 26 33·31	±0·01	02 19 43·7	±0·1	13^m QSO	5, 6
1335−06 (13−0*11*) A	13 35 31·44	±0·07	−06 11 59·2	±1	~2″	13 35 31·34	±0·07	−06 11 57·4	±1	18^m QSO	8
B	13 35 30·89	±0·07	−06 11 51·6	±1	~4″						

1514−16	See notes in text					No radio position available					
1623−22	16 23 18·1	±0·3	−22 49 02	±4	~6″ p.a. 105°, probably double	Obscured region					
1710−24 A	17 10 07·8	±1·5	−24 58 02	±20	120″±20″ p.a. 139°±10°, <50″ p.a. 49°	Crowded star field					
B	17 10 14·6	±1·5	−24 59 21	±20							
1711−25 A	17 11 43·19	±0·07	−25 11 13·4	±1	<2″ at 1410 and 154 MHz	Crowded star field					
B	17 11 43·29	±0·07	−25 11 03·0	±1							
1859−23 (19−21) A	18 59 47·30	±0·03	−23 34 16·5	±0·5	<1″	Obscured region					
(B)	(18 59 47·54	±0·15	−23 34 18	±2)							
1946−23	19 46 24·44‡		−23 34 41‡		Probably <4″ in p.a. 66°	Obscured region					
2030−23 (20−28)†	20 30 19·05	±0·3	−23 03 35	±5	~10″	20 30 19·85	±0·03	−23 03 27·5	±0·3	$19^m \cdot 5$ D gal.	1
2059−21	20 59 08·93	±0·02	−21 25 48·6	±0·3	Probably <1″	See notes in text					
2113−21 (21−23) A	21 13 45·57	±0·14	−21 08 35·5	±2	13″ p.a. 160°±10°, <3″ p.a. 70°	See notes in text					
B	21 13 45·43	±0·14	−21 08 04	±2	18″ p.a. 176°±10°, <3″ p.a. 86°						
2135−18 (21−116)	21 35 17·85	±0·3	−18 57 01	±4	21″±4″ p.a. 135°±10°, <4″ p.a. 45°	21 35 19·14	±0·15†	−18 57 09·7	±0·8	19^m D gal.	1
2144−17	21 44 17·65	±0·07	−17 54 06·6	±1	<2″	21 44 17·62	±0·11	−17 54 05·6	±1·5	$19^m \cdot 5$ QSO	1, 4
2154−18·4 (21−123) A	21 54 14·0	±0·4	−18 28 22	±5	~6″ p.a. 195°	See notes in text					
B	21 54 13·3	±0·7	−18 28 02	±10	Probably <3″						
C	21 54 10·15	±0·14	−18 27 43	±2	<2″						
2308−10	23 08 40·49	±0·07	−10 55 08·3	±1	4″·5±1″ p.a. 147°±10°	23 08 40·40	±0·15	−10 55 07·8	±1·0	19^m QSO?	1

* References: 1, Bolton (1968); 2, Bolton and Ekers (1966); 3, Bolton *et al.* (1966); 4, Burbidge (1970); 5, Greenstein and Schmidt (1964); 6, Jeffreys (1964); 7, Sandage (1967); 8, Sandage, Véron, and Wyndham (1965); 9, Véron (1966); 10, Véron (1968).

† See notes in text for further details.

‡ See notes in text for error limits.

The angular sizes determined for the components differ from the 4″ arc (A) and 10″ arc (B) determined by Hazard, Mackey, and Nicholson (1964) from an earlier occultation observation of the source at the same frequency. There is evidence, however, from the present observations that A may contain a small-diameter component contributing about one-third of its total flux density.

The ratio of the flux densities, B/A, found here is about $0 \cdot 33 \pm 0 \cdot 05$, while Hazard, Mackey, and Nicholson estimated the ratio to be $0 \cdot 8$.

The object which Clarke, Bolton, and Shimmins (1966) suggested as an optical identification for the source lies about 9″ arc off the line joining the two components. The present observations would seem to support this identification.

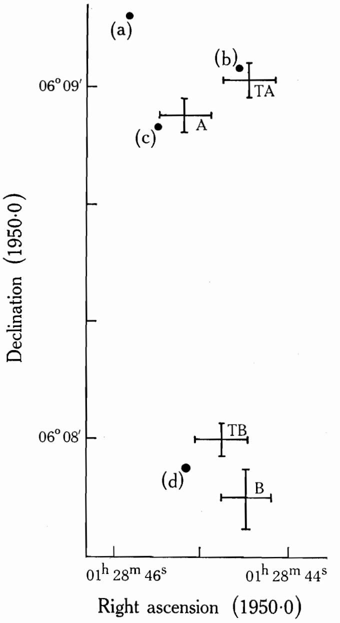

Fig. 4.—Field of the source 0128+06. A and B are the positions given in Table 2 for the two components of the source, while TA and TB are the positions for A and B found by Taylor and De Jong (1968). (a) is the object proposed as an identification by Clarke, Bolton, and Shimmins (1966) and it is clearly marked on a finding chart in their paper. (b) and (c) are two other stars. (d) is the faint blue object noted by Mackay (1969). The remote component found by Mackay lies about 15′ arc to the north of the main source and close to a line drawn through (a), A, and B.

0128+06

The single scan obtained from the present observations shows that this source comprises two components with a projected separation of 7″ arc in position angle 97° but it does not define the positions of the objects. Other occultation observations by Taylor and De Jong (1968) have confirmed that the source consists of two components, which they have designated A and B. Their component A is probably misplaced, since it does not satisfy the present observations. Further evidence for the structure comes from interferometer observations by Bash (1968a, 1968b), which show that the source probably consists of two components with a projected separation of 38″ arc in position angle 68°.

All the evidence available suggests a double source with components in the positions given in Table 2. There is some evidence that component B is extended along the line of separation of the components.

The position angle of the line joining the components is about 10°. This angle is close to the position angle, 4°, of the line joining the main source to the isolated component found by Mackay (1969) from his observations at 408 MHz.

The new positions for components A and B and those proposed by Taylor and De Jong (1968) are shown in Figure 4. Component A is close to a star (c) about 17″ arc south-east of the star (b) noted by Taylor and De Jong as close to their position for component A. It is also about 20″ arc south of the object (a) first suggested as an identification by Clarke, Bolton, and Shimmins (1966). The faint blue object (d) noted by Mackay (1969) lies about 12″ arc east of component B.

0218+11

The observations of this source are incomplete. Two components were seen to disappear but the reappearance of one component was lost because of an observing error. It has been assumed, in placing the components, that the best estimate of the mean source position is obtained by combining the right ascension given by Gower, Scott, and Wills (1967) with the declination measured by Shimmins, Clarke, and Ekers (1966). Both immersion and emersion occurred at nearly the same position angle and the positions are poorly determined in one direction. The estimated errors in the position of A are $\pm 2''$ arc in position angle 55° and $\pm 20''$ arc in position angle 145°, and, in the position of B, $\pm 2''$ arc in position angle 55° and $\pm 10''$ arc in position angle 145°.

The ratio B/A of the flux densities from the components is $1 \cdot 1 \pm 0 \cdot 1$ at 410 MHz.

0229+13

Scintillation observations of this source (Harris and Hardebeck 1969) indicate an angular size less than $0'' \cdot 13$ arc in position angle 64° while the size inferred from the occultation observations is about 4″ arc. This suggests that the source consists of at least two well-separated small-diameter components.

The radio position is quoted more precisely here than in the preliminary position reported by Kinman *et al.* (1967).

0307+16 (3C 79)

The present observations of this source consist of a single scan at 154 MHz. This shows the two components which also appear in the occultation observations by Gulkis, Hazard, and Bray (1968) and in the aperture synthesis map by Macdonald, Kenderdine, and Neville (1968). The projected spacing of the components is 14″ arc in position angle 26°, though there is some emission from a region extending over about 30″ arc along the line of the scan. There is a bright spot of about 4″ arc extent superposed on the earlier component. The record obtained during the occultation of this source is shown in Figure 3(*a*).

The positions of the components found by Macdonald, Kenderdine, and Neville (1968) lie on the lines defined by the occultation to within the limits set by their quoted errors. The position calculated by Gulkis, Hazard, and Bray (1968) for their component B is almost certainly incorrect. They derived the correct position for A, but their assumption that A and B reappeared together must be in error.

The ratio A/B of the flux densities from the two components is variously given as $1 \cdot 67$ at 1407 MHz (Macdonald, Kenderdine, and Neville 1968); $1 \cdot 8$ at 430 MHz (Gulkis, Hazard, and Bray 1968); $1 \cdot 31 \pm 0 \cdot 15$ at 154 MHz (present observations), and $1 \cdot 6$ at $41 \cdot 7$ MHz (Gulkis, Hazard, and Bray). The identification with a 19^m galaxy is well known.

0316+16 (CTA 21)

An account of the observation of this occultation has already appeared (Clarke and Batchelor 1965). Because of the considerable uncertainty in the time of emersion the error rectangle is $0'' \cdot 7$ arc by $10''$ arc with the long axis in position angle 168°. A more precise position ($03^h 16^m 09^s \cdot 11 \pm 0^s \cdot 09$, $16° 17' 41'' \cdot 2 \pm 0'' \cdot 8$) has subsequently been measured from another occultation by Taylor (1966).

Observations made with a long baseline interferometer (Clarke *et al.* 1969) have shown that the radio source consists of two components with angular size less than $0'' \cdot 01$ arc separated by $0'' \cdot 11$ arc.

0319+17

Only one occultation scan through this source has been observed, although the failure to observe a possible occultation on another occasion allows some further restrictions to be placed on the position. The scan shows the source to be double with the two components lying on a connecting ridge. The projected separation of the components is $34''$ arc in position angle 112° while the angular size of the components themselves is probably less than $5''$ arc. Position measurements by Pauliny-Toth, Wade, and Heeschen (1966), Gower, Scott, and Wills (1967), and Merkelijn (1969) have been used in conjunction with the occultation scan to derive the best estimate of the position of the source centroid.

The galaxy which Merkelijn noted as lying about $0' \cdot 5$ arc to the south-west of the radio source is probably not related to it.

1217+02

This source is double with a projected spacing between the components of $28''$ arc in position angle 165°. Each component extends about $15''$ arc in the same position angle. One component of the double source probably lies within $5''$ arc of the quasi-stellar object with which the source has been identified by Bolton *et al.* (1965).

1226+02 (3C 273)

The position angle of the scan is within 2° of the position angle of immersion observed from Parkes during the occultation of 1962 August 5. The ratio of the flux densities of components B and A, as determined from the restored scan, is $0 \cdot 38 \pm 0 \cdot 01$. The ratio determined from the restored scan of the 1962 occultation which was published by Scheuer (1965) is $0 \cdot 37 \pm 0 \cdot 01$. This value is similar to the ratio of $0 \cdot 36$ which Hazard, Gulkis, and Bray (1966*b*) found from their own analysis of the 1962 observation. There is thus no evidence for any change ($> 8\%$) in the ratio for the three-year period from August 1962 to November 1965. This conclusion confirms the observation by Hazard, Gulkis, and Bray (1966*a*) that the ratio changed by less than 7% from 1962 to June 1965.

The times of the immersion measured from the 1965 occultation are 3 s earlier than the times which would be expected if the two components were in the positions found by Hazard, Mackey, and Shimmins (1963). This discrepancy is much larger than the estimated uncertainty of $\pm 0^{s}\cdot 3$ in the measured times. The lines on which the components appear to lie each pass $1''\cdot 5$ arc to the early side of the usual positions. Values quoted by Hazard, Mackey, and Shimmins suggest that the refraction due to a lunar ionosphere and the solar corona should not exceed $0''\cdot 1$ arc at 410 MHz, and it would appear that this effect is insufficient to account for the discrepancy.

1335—06

The two components of this source are separated by 11″ arc in position angle 133°. There is some evidence which suggests that the sizes of the individual components decrease with increasing frequency. The ratio B/A of the flux densities from the components is $0\cdot 80 \pm 0\cdot 08$ at 1410 MHz and $0\cdot 84 \pm 0\cdot 08$ at 410 MHz.

The quasi-stellar object with which the source has been identified lies on the line joining the components A and B and is nearer A than B.

1514—16

The measurements at immersion suggest that this source consists of two components with a projected separation of about 20″ arc in position angle 78°, but the record at emersion suggests a more complex structure. It is difficult to reconcile the occultation measurement with the position measured by Shimmins, Clarke, and Ekers (1966).

1623—22

The emersion observation for this source is poor and it introduces most of the error into the position determination. The position calculated from the occultation observation is consistent with the position measured by Shimmins (1968).

1710—24

The flux densities from the two components of this source are equal to within 10% at each of the observing frequencies, 640 and 154 MHz. The total flux density at 640 MHz is 14 ± 2 f.u.* The two components are separated by $2'\cdot 4$ arc in position angle 139°, and this, together with the low galactic latitude of the source, suggests that the object may be galactic rather than extragalactic. The star field is too crowded for any significant association with an optical object to be made.

1711—25

The immersion of this source occurred a few minutes before the emersion of the source 1710—24. There was not enough time available to make good observations of both these events and only the emersion of 1710—24 was observed at all frequencies. Observations of the immersion of 1711—25 were obtained, however, at 154 MHz, as the two sources are separated by only 20′ arc, much less than the telescope beam-width at this frequency.

* 1 flux unit (f.u.) = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

The two components are found at 154 MHz but only one, A, is present at 1410 MHz. Component A shows an extension towards B at 640 MHz but no separate component B can be recognized. The discrete components found at 1410 and 154 MHz all have angular size less than 2″ arc. The separation of the components is $10''\cdot4$ arc in position angle 7°.

Estimated values of the flux density from the source are $3\cdot6\pm0\cdot4$ f.u. at 1410 MHz, $6\cdot1\pm0\cdot6$ f.u. at 640 MHz, and 21 ± 3 f.u. at 154 MHz. Component A contributes $0\cdot7\pm0\cdot1$ of the total flux density at 154 MHz. The source lies in a crowded star field at low galactic latitude and no identification can be reliably suggested.

1859–23

The observations at emersion of this source show that the separation between the components differs at 1410 and 410 MHz. The projected separation in position angle 131° is $2''\cdot8$ arc at 1410 MHz and $4''\cdot2$ arc at 410 MHz. The observations at immersion, at 1410 and 136 MHz only, show no clear separation into two components and it is difficult to estimate the time of disappearance of B, the weaker component. The position of component A is well determined from the observations but the position of B is very uncertain and the coordinates quoted for it are estimated mean values from the measurements at both frequencies. One of the records obtained during the occultation of this source is shown in Figure 3(*b*).

The measured values of flux density are $4\cdot4\pm0\cdot4$ f.u. at 1410 MHz and $10\cdot4\pm1\cdot0$ f.u. at 410 MHz. Shimmins (1968) gives a value of $1\cdot7$ f.u. at 2650 MHz. The ratio B/A of the flux densities from the components is $0\cdot32\pm0\cdot02$ at 410 MHz.

1946–23

Although there were three independent observations of this source very little can be deduced from them, since the measurements made at the emersion from the first occultation are very poor and both immersions occurred at the same position angle.

The declination measured by Shimmins, Clarke, and Ekers (1966) has been used in conjunction with the good occultation observations to derive the position quoted. The emersion record appears to confirm this position. The errors in the position are $\pm1''$ arc in position angle 66° and $\pm6''$ arc in position angle 156°.

2030–23

The observations of this source are close in position angle and interpretation is difficult. The source appears to consist of a small-diameter component and an extended region. The position given in Table 2 is that of the compact component. The extended region extends 72″ arc in position angle 39° from $20^{\mathrm{h}}30^{\mathrm{m}}18^{\mathrm{s}}\cdot4$, $-23°03'24''$ to $20^{\mathrm{h}}30^{\mathrm{m}}21^{\mathrm{s}}\cdot7$, $-23°02'28''$ with an uncertainty of $\pm10''$ arc in both positions. The compact component does not lie in the extended region. The D galaxy with which the source has been identified is about 15″ arc away from both radio features and it would appear to be outside the region of radio emission.

The compact region contributes $0\cdot29\pm0\cdot05$ of the total flux density from the source at 410 MHz.

2059−21

This source is too weak to have been included in the Parkes catalogue. Approximate values of the flux density are $1\cdot5 \pm 0\cdot4$ f.u. at 1410 MHz and $1\cdot6 \pm 0\cdot4$ f.u. at 410 MHz.

There is no object on the Sky Survey prints within 15″ arc of the radio source position.

2113−21

Most of the useful data for this source are at 640 MHz but there is no evidence of markedly different structures at the other frequencies. The separation of the components is 31″ arc in position angle 176°. The ratio A/B of the flux densities from the components is $1\cdot24 \pm 0\cdot06$ at 640 MHz and $1\cdot16 \pm 0\cdot08$ at 154 MHz.

There is no object visible on the Sky Survey prints in the position of the radio source apart from a very faint image just noticeable on the red print. This object, which is probably a star, lies about 15″ arc to the south-east of B and well off the line joining the components; the position of the object is approximately $21^{h}\,13^{m}\,46^{s}\cdot1$, $-21°\,08'\,11''$.

The position and possible identification for the source which were reported by Brown (1966) after an occultation observation appear to be in error. The present measurements are mutually self-consistent (see Fig. 2) and are inconsistent with Brown's position at $21^{h}\,13^{m}\,50^{s}\cdot20$, $-21°\,11'\,15''\cdot4$.

2135−18

The range of position angles covered by the occultation observations for this source is small and its structure is not well defined.

There is a faint object on the red Sky Survey print closer to the radio position than the galaxy with which the source has been identified by Bolton and Ekers (1966). The faint object, which is about 4″ arc in position angle 135° from the radio centroid, is within the region of radio emission. The galaxy is 21″ arc away from the radio source in position angle 105°.

2144−17

The radio and optical positions for this source agree to within $1''\cdot5$ arc. The radio position given here differs slightly from the preliminary position given by Kinman *et al.* (1967).

2154−18·4

Taylor and De Jong (1968) have also observed an occultation of this source and their measurements have been used in the interpretation of the Parkes observation. The occultation measurements reported here were not consistent with the position of 2154−18 given by Shimmins, Clarke, and Ekers (1966) and subsequent observations have shown the existence of two separate sources 2154−18·3 and 2154−18·4 (Shimmins 1968). There is always some ambiguity in the choice of the positions of two nearly equal components when only two scans are available. In the light of the additional data now available it seems better to choose the alternative pair of positions from those chosen by Taylor and De Jong.

The fractions of the total flux density at 640 MHz coming from each of the three components are approximately 0·5 (A), 0·2 (B), and 0·3 (C).

Bolton and Ekers (1966) proposed an identification for this source with a $16^m\cdot5$ quasi-stellar object on the basis of the radio position measured by Shimmins, Clarke, and Ekers. This proposal was later withdrawn because it was inconsistent with the revised radio position for the source 2154−18·4 and because the optical object was probably a foreground star (Burbidge and Burbidge 1967).

2308−10

The angular structure which is given for the source in Table 2 is based on projected sizes of $3''\cdot5$ arc in position angle 5° and $2''\cdot3$ in 28°.

V. Conclusions

The picture of radio sources which is revealed by these occultation observations is very similar to the picture which has been obtained from other radio astronomy measurements. Most sources appear to be complex, with two-component sources as the typical pattern. Some sources have two similar components (e.g. 1335−06) while others have two dissimilar components (e.g. 3C 273). Several sources appear to have a ridge of emission joining the main components. There is little evidence for marked variation of structure with frequency, although the spectra of individual components within the source may differ.

Several of the sources studied have been identified with quasi-stellar objects or with galaxies (Table 2) but only one identification, that of 0229+13, followed from the occultation measurements (Kinman *et al.* 1967); the others were known from earlier work. The remaining sources consist of objects at high galactic latitudes which do not appear to be associated with any object visible on the 48 in. Sky Survey prints, and objects which lie in directions close to the galactic plane. Source fields at low galactic latitudes tend either to be obscured by dust or to be too crowded with stars for any reliable identification to be possible.

There is no obvious radio difference between the identified sources and the unidentified sources, and the radio positions of most of the high galactic latitude sources which remain unidentified are good enough to allow an identification to be made if a suitable object exists above the print limit. This suggests that the making of identifications may depend on coincidence between a recent outburst in the source, giving a bright optical image, and an old outburst giving the radio emission. If this coincidence is absent one finds either a blue stellar object or an unidentifiable radio source.

The observations described in this paper were made between July 1964 and December 1966 as part of a program to use lunar occultations to study radio sources. Earlier measurements, particularly the occultations of 3C 273 observed from Parkes, had demonstrated that the technique was potentially a very powerful one for the study of radio sources. The more extended series of measurements in which observations of most of the observable occultations were attempted has confirmed some of the advantages and disadvantages of the method.

Occultation observations suffer even more acutely than most other astronomical observations from the fact that the observer has no control over the objects he is studying. He cannot choose which sources to observe nor can he select the times at which observations are to be made. Poor or unsuccessful observations cannot be repeated. Many of the observations reported here are incomplete in the sense that more occultation data are needed to allow an unambiguous picture of the source structure to be deduced, but no more data will be available for several years.

Observations of lunar occultations have been most useful in determining the position and low-frequency structure of sources with two well-separated unresolved components. The positions of these sources are difficult to measure with radio interferometers, which tend to measure a weighted mean position for the components. The high-frequency structure of the sources may sometimes be determined from measurements with synthesis telescopes but no existing telescope has a beam at 400 MHz less than 1′ arc. In addition, most synthesis telescopes are unsuitable for observations at the declinations near the celestial equator at which many occultations occur.

The least satisfactory occultation observations are those of sources with more than two components or with resolved components, and these measurements are often uninterpretable without considerable additional structural data from other observations. In many cases there are no comparable alternative data available. It appears that there is no satisfactory substitute for a full synthesis map in the interpretation of the structure of a complex radio source.

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