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Lunar Occultation Observations of 25 Radio Sources Made with the Ooty Radio Telescope: List I

G. SWARUP, V. K. KAPAHI, N. V. G. SARMA, GOPAL KRISHNA, M. N. JOSHI, and A. P. RAO
Tata Institute of Fundamental Research, Bombay 5, India

A survey of radio sources by the method of lunar occultation is being carried out at Ootacamund in India with a large steerable radio telescope whose collecting area is 8700 m². Results for 25 weak radio sources with flux densities lying in the range 0.4 to 4 fu at 327 MHz are presented here. Seven sources have clear double components with separations ranging from 2.5 to 20 arc sec. Optical identifications have been suggested for 8 of the 25 sources, 5 of which are possibly QSOs. The unidentified radio sources seem to be galaxies with high redshifts.

INTRODUCTION

It is now well known that the method of lunar occultation can provide information about the position and structure of a radio source with a resolution up to 1 arc sec or better. Since the first occultation observation of an extragalactic radio source made by Hazard (1961), about 70 sources have been studied so far by this technique by various observers. Occultations of weak radio sources, down to about 0.7 fu (1 fu $= 10^{-26}$ W m^{-2} Hz^{-1}) at 430 MHz, have been observed mainly at the Arecibo Observatory (Hazard *et al.* 1967, Hazard *et al.* 1968, Gulkis *et al.* 1969, Lang *et al.* 1970). Extension of high resolution observations to a larger number of weak radio sources is of considerable importance for cosmological studies. A large cylindrical radio telescope (Swarup *et al.* 1971) has been in operation at Ootacamund since February 1970 and is specially designed to study a large number of radio sources by the occultation technique. To date, occultations of over 300 sources, a majority of them previously uncatalogued, down to 0.2 fu at 327 MHz have been recorded. In this paper we give the results for 25 sources for which the analysis is complete.

THE OOTY RADIO TELESCOPE

The Ooty radio telescope consists of a parabolic cylinder 530 m long and 30 m wide with an effective collecting area of about 8700 m². It operates at a frequency of 326.5 MHz. The long axis of the radio telescope has been made parallel to the earth's axis of rotation by locating it on a north–south hill slope of about 11°, the same as the latitude of the station. Thus, a mechanical rotation around this axis enables a source to be tracked for about 9.5 hr per day. The telescope can be steered in declination electrically by $\pm 36°$ by means of phase shifters incorporated between the 968 dipoles located along the focal line (Kapahi *et al.* 1968). The receiver system produces 12 simultaneous beams separated by 3 sec δ arc min, in declination. The radio telescope is operated simultaneously both in the total power and in the phase-switched modes by adding and by multiplying the outputs of the north and south halves of the antenna respectively. In hour angle each beam has a half-power width of 2°. In declination, the beamwidth is 5.6 sec δ arc min for the total power mode and 3.9 sec δ arc min for the phase-switched mode. With a typical system temperature of about 400 K (including the sky and moon background), a bandwidth of 4 MHz and time constant of 1 sec, the minimum detectable signal at 5 to 1 signal-to-noise ratio for the phase-switched mode is about 0.5 fu (corresponding to an antenna temperature of about 1.5 K).

OBSERVATIONS AND ANALYSIS

Since occultations of sources much weaker than those in the existing catalogues can be observed by the Ooty radio telescope, we generally track the moon continuously and wait for occultations to occur. While the moon is tracked continuously in hour angle for 9.5 hr, it is followed in declination by flipping the beams in discrete steps by 36 sec δ arc min at suitable intervals of time (Swarup *et al.* 1971). The 12 simultaneous beams separated in

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declination by 3 sec δ arc min cover the moon fully in declination at all times.

The phase-switched system is used for the occultation observations in order to minimize contributions due to the moon and the varying galactic background. Thus the baseline change caused by a drift in the declination of the moon is reduced to less than 0.5 K antenna temperature per min most of the time. Total power observations provide additional sensitivity but are useful only when the variations due to the moon and the background are small. Outputs of the 12 beams are recorded on 12 chart recorders as well as digitally on a magnetic tape unit by use of an on-line computer (Varian 620-i). A bandwidth of 4 MHz is used normally but a provision is made for using a bandwidth of 0.8 or 0.3 MHz whenever occultation of a strong source is predicted. A time constant of 1 sec is used for the chart recorders and 0.5 or 0.25 sec for digital recording. For many of the 25 sources presented here, digital data were not available and the analysis (restoration) has been done by manually digitizing the chart recorder outputs.

One-dimensional brightness distributions were obtained for the observed sources by convolving the data with restoring functions as described by Scheuer (1962). Source positions were obtained by an iteration process; occultation times were first estimated from a visual examination of the occultation records and the derived brightness distributions were used to give more accurate values for the occultation times and thus determine the accurate positions. For a number of sources repeated occultations are observed and the error in position is reduced further. Since the observations are made simultaneously with 12 beams which are narrow in declination, the position of a source can be determined unambiguously in declination from a single disappearance or reappearance record.

OPTICAL IDENTIFICATION

A search for optical identification of the 25 sources has been made using the 48-in Palomar sky survey prints. The method often used is to generate a transparent overlay on which accurate positions of some reference stars are marked around the radio position and then to examine the field for possible optical identification. Although the method is comparatively fast, the accuracy of derived optical position is not better than about 5 arc sec. Since our radio positions are accurate to 1 arc sec, it is desirable to obtain a similar accuracy for the optical positions as well. Therefore, a different procedure has been followed here. A contact plate is taken from the sky survey print for the region around the radio source. This plate is then used to measure x, y coordinates of reference stars and all interesting objects within 1 arc min of the radio source, by use of a Zeiss coordinate measuring machine (the prints cannot be directly used with this machine). Optical positions are then calculated by the method of dependences. The error in measuring x, y coordinates of a star is found to be of the order of 5 microns, which amounts to 0.35 arc sec. Two triangles, that is 6 stars, are used in calculations for each object. To determine the accuracy of the method, optical positions of 40 reference stars taken from 14 prints were calculated and compared with the positions given in the Smithsonian Astrophysical Observatory star catalogue. The maximum error was ± 1.2 arc sec and the rms error was ± 0.6 arc sec.

For one of the sources, namely PKS 1148 − 00, an accurate optical position has been measured independently by Kristian and Sandage (1970) and is in agreement with our measurements within the quoted errors.

RESULTS

The results are given in Tables 1 and 2. In Table 1 the source number appears in column 1 and an alternate number is given in column 2 if the source has been catalogued earlier. The rms error in flux-density given in column 3 is about 20 per cent. Column 5 gives the optimum resolution achieved for a Gaussian beamwidth of β_r for a signal-to-noise ratio of 5:1 (Von Hoerner 1964). Each source has been scanned in 2 or more position angles (column 4) but the data given in columns 5 to 7 are only for the 2 most illustrative scans. Column 7 gives the angular size of the components along the position angles of the scan given in column 6. Additional information about the structure of double sources is given in columns 8 to 10. Errors in component sizes are of the order of $0.5\,\beta_r$ in most cases. Errors in component separa-

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TABLE 1

Structural data at 327 MHz for 25 radio sources

1	2	3	4	5	6	7		8	9	10	11
				Observed data				Derived structure			
Source OTL	Other cat. number	Flux at 327 MHz fu	No. of scans	β_r	PA of scan	Angular size of components A	B	PA A to B	Comp. sep.	Flux ratio A/B	Remarks
0018 + 05	4C05.04	2.0	3	1.0″	12°	≦1.3″	~4″	25°	8″	1.0	
				1.0	198	≦1.4	~4				
0133 + 14		0.8	4	2.6	35	≦2.0					
				2.6	269	~2.5					
0139 + 15		0.8	2	1.9	352	≦1.8					
				4.1	310	≦3.5					
0142 + 15		0.6	4	2.0	126	~4.0					
				2.0	187	~12.0					Possibly double.
0150 + 16	4C16.04	1.9	4	2.0	42	~4.0	~3	90	8	1.5	
				1.0	239	~4.0	~2				
0248 + 21	4C21.10	1.5	2	1.0	65	< 1.2					
				1.0	225	≦0.8					
0410 + 26	4C26.15	2.1	4	1.0	17	~2.0	~1	108	3	0.6	
				1.0	290	~1.5	~1.5				
0556 + 28		1.2	2	1.0	82	< 1					Possibly double.
				1.0	307	< 1					
0746 + 24	OI277	1.0	2	1.0	111	~1					Possibly double.
				1.0	306	~1					
0815 + 23	4C23.19	1.5	2	2.5	55	< 2					
				2.5	357	< 2					
0820 + 22	4C22.21	3.5	4	2.0	172	< 2.5					
	PKS			2.0	253	< 2.5					
1003 + 13		1.0	2	2.5	150	< 2					
				4.1	300	< 3.5					
1108 + 03	4C03.21	4.2	6	2.3	176	< 2	~2.6	59	8	0.5	
	PKS			2.3	256	~2.2	< 2				
1148 − 00	4C − 00.47	2.5	2	10	122	< 7					Resolution limited due to
	PKS			5	323	< 6					ionospheric scintillation.
1159 − 02	4C − 02.50	2.4	2	2.0	113	< 1.5					
				1.0	338	< 1.5					
1350 − 15		1.0	2	2.5	75	~3					
				2.5	359	~3					
1411 − 19		0.9	4	2.5	149	< 2					
				2.5	253	< 2					
1527 − 24		0.8	2	4.3	52	~4					
				4.3	326	< 4	< 4	141	21	1.3	
1556 − 26		0.6	4	5.0	71	~14					
				5.0	293	~8					
1557 − 26		0.9	4	8.2	132	~10					
				8.2	227	~20					
1559 − 26		0.4	2	8.6	150	~5					
				4.3	217	~5					
1627 − 27		0.8	2	2.2	59	≦1.5					
				2.2	306	≦1.7					
2109 − 18		0.6	2	4.3	103	≦4	~6	46	11	1.0	
				4.3	189	≦3.5	~6				
2111 − 18		3.0	2	2.0	94	~6.8		4	16	1.0	
				2.0	203	~5	~7				
2150 − 14		0.6	4	2.1	23	≦2.2					
				2.1	273	≦1.4					

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TABLE 2

Positions of radio sources, optical positions and notes on optical identifications

1	2		3		4	5	6	7	8	9	10
	Position (1950.0)						Radio-optical				
	Radio				Optical						
Source OTL	RA		Dec		RA	Dec	OA	OB	Angle AOB	m_p	Notes on optical objects
0018+05	A $00^h\ 18^m\ 22.09^s$	$\pm 0.07^s$	$+05°\ 16'\ 40.7''$	$\pm 1''$							No object within 1 arc min of radio source.
	B 00 18 22.33	0.07	+05 16 48.5	1							
0133+14	01 33 01.39	0.07	+14 40 37.7	1	00.50^s	41′ 15.9″	40″			19	BSO, visible only in blue.
0139+15	01 39 00.27	0.07	+15 32 11.3	1	00.53	32 16.8	6			19	*BSO.
0142+15	01 42 15.16	0.07	+15 22 30.7	1	15.11	22 32.2	1			18	*Red galaxy with compact nucleus
0150+16	A 01 50 17.40	0.07	+16 26 33.9	1							No object within 1 arc min of radio source.
	B 01 50 17.93	0.07	+16 26 33.9	1							
0248+21	02 48 05.51	0.1	+21 08 58.2	1	04.27	08 59.4	18			19	Visible only in red.
0410+26	A 04 10 19.83	0.05	+26 41 42.2	1	19.40	41 57.6	17	19″	6°	18	Stellar object with faint wisp towards radio source.
	B 04 10 20.01	0.05	+26 41 41.4	1							
0556+28	05 56 31.13	0.07	+28 18 13.8	1	31.44	18 11.8	5			17	Stellar, crowded field, galactic plane.
0746+24	07 46 29.99	0.07	+24 47 11.5	1	27.65	47 00.5	34			18	Red stellar object.
0815+23	08 15 06.42	0.1	+23 49 37.2	1.5	06.23	49 36.5	3			18	*BSO with diffuse envelope (Jauncey and Hazard 1970).
0820+22	08 20 28.59	0.07	+22 32 45.0	1	28.57	32 44.9	0			19	*QSO (Merkelijn *et al.* 1968).
1003+13	10 03 41.92	0.1	+13 00 03.0	1.5	40.57	00 14.3	23			18	BSO.
1108+03	A 11 08 47.76	0.07	+03 25 24.2	1							Empty field in region of small cluster.
	B 11 08 48.28	0.07	+03 25 28.8	1							
1148−00	11 48 10.19	0.07	−00 07 11.7	1	10.11	07 13.0	2			18	*QSO (Bolton and Kinman 1966).
1159−02	11 59 58.51	0.07	−02 23 21.0	1	56.46	23 29.5	32			20	Visible only in red.
					58.69	22 24.4	57			18	BSO.
1350−15	13 50 39.13	0.07	−15 24 31.0	1	39.81	24 25.4	11			19	Brighter in red.
1411−19	14 11 59.69	0.07	−19 08 54.0	1	59.58	08 40.5	14			17	Stellar object.
1527−24	A 15 27 35.22	0.2	−24 17 34.2	3	35.4	17 43.7	9	13	138	20	*Galaxy visible only in red.
	B 15 27 36.18	0.2	−24 17 50.7	3	37.6	17 40.3	35	23	35	18	BSO.
1556−26	15 56 23.23	0.1	−26 05 21.0	1.5	24.23	05 18.3	14			19	BSO, Crowded field.
1557−26	15 57 22.50	0.2	−26 21 31.2	3	22.18	21 30.4	3			20	*Much brighter in red.

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TABLE 2 (*Continued*)

Positions of radio sources, optical positions and notes on optical identifications

1	2		3		4	5	6	7	8	9	10
	Position (1950.0)						Radio-optical				
	Radio				Optical						
Source OTL	RA		Dec		RA	Dec	OA	OB	Angle AOB	m_p	Notes on optical objects
1559−26	15 59 35.33	0.1	−26 31 12.7	1.5	34.04	31 16.8	18			19	Brighter in red. Compact nucleus with envelope in blue.
1627−27	16 27 55.76	0.07	−27 16 43.1	1	55.37	16 49.6	9			18	Red galaxy, crowded field.
					53.62	16 26.1	34			16	BSO.
2109−18	A 21 09 28.88 B 21 09 29.43	0.1 0.2	−18 52 45.6 −18 52 37.8	1 3							No object within 1 arc min of radio source.
2111−18	A 21 11 29.11 B 21 11 29.19	0.1 0.1	−18 31 34.1 −18 31 18.1	1 1	29.17	31 22.9	12	5	165	21	*Visible only in blue.
2150−14	21 50 47.95	0.1	−14 16 16.2	1							No object within 1 arc min of radio source.

* Suggested identification.

tion are generally about 10 per cent but may be higher when the position angles of the two scans are not very different. Errors in position angle of the axis of a double source as given in column 8 are likely to be about 15° but may be as large as 40° when component separation is small.

Table 2 gives the radio positions and details of the associated optical fields. The radio positions are referred to Newcomb's equinox. Corrections have been made for the irregularities of the moon's limb, from Watts' maps (1963). The errors quoted are standard errors and arise mainly from signal-to-noise ratio, uncertainties in timing, and limb irregularities. Observations in certain cases have been affected by ionospheric scintillation, which limits the resolution. For the sources shown as 'possibly double' in Table 1, the given radio positions refer to the centroid of emission. In columns 4 and 5 are given the optical positions of the interesting or the nearest objects within 1 arc min of the mean radio position. For right ascension, only seconds of time values and for declination, only arc min and arc sec values are given, the rest being the same as for the radio position. Angular separations of the optical objects from the radio source, and from each component if the source is double, are given in columns 6 and 7. Column 8 gives angle AOB between the two lines that join the optical object O to the two components A and B of a double radio source. Photographic magnitudes of the optical objects, given in column 9, were estimated by measuring their diameters and may be in error by 1 magnitude.

Suggested identifications with optical objects have been marked with an asterisk just before the remarks column in Table 2. Finding charts for 5 new identifications suggested here are given in Figure 1.

CONCLUSIONS

Accurate radio positions and structures have been obtained for 25 radio sources with flux densities lying in the range 0.4 to 4 fu. Optical identification based on positional agreement can be suggested only for about 30 per cent of the sample, which figure is much lower than that of about 75 per cent suggested by Hazard and his collaborators

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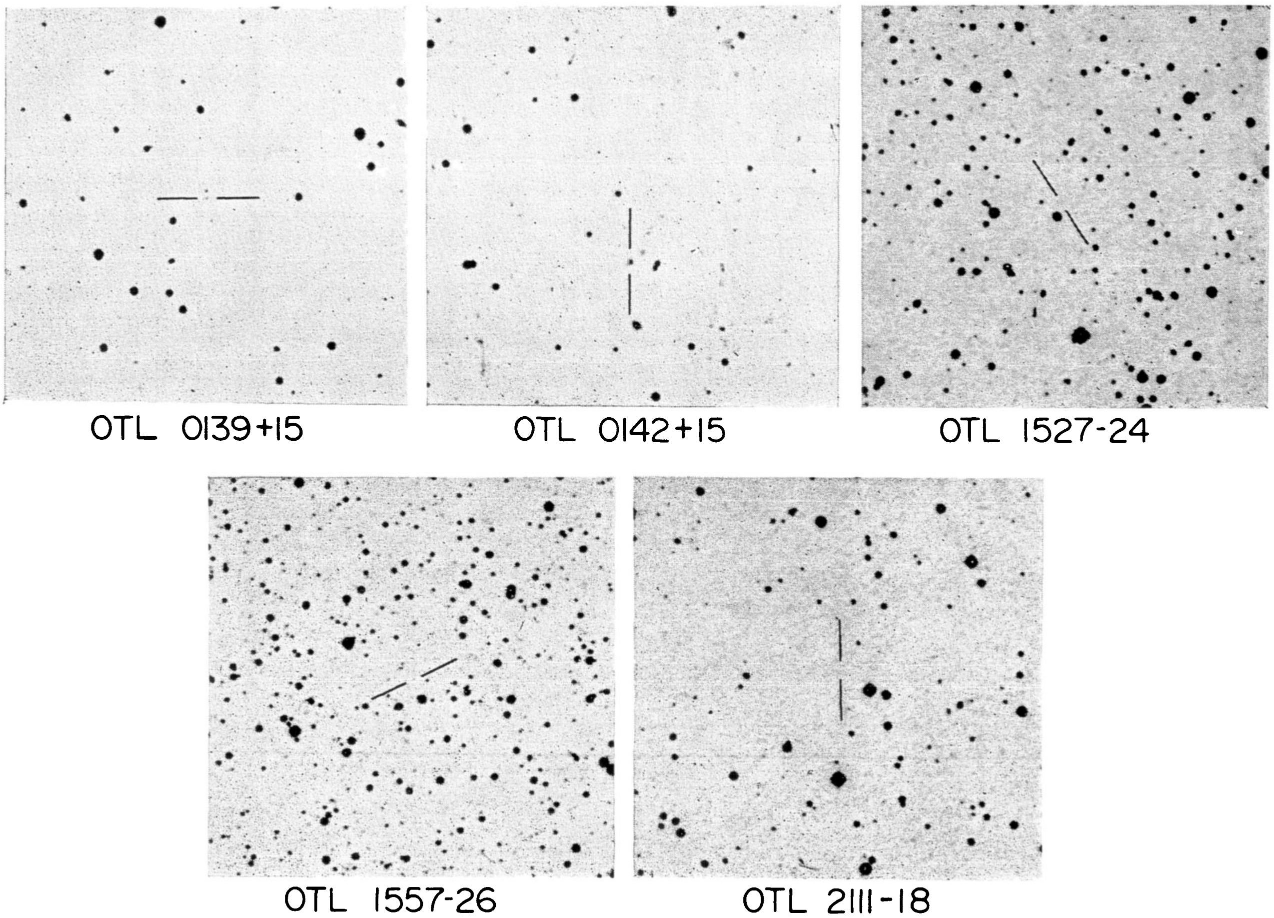

FIG. 1. Finding charts for the 5 new optical identifications. North-east is at the top left hand corner and the scale is approximately 5 mm = 1 arc min. The prefix OTL is used to designate sources observed in the Ooty Lunar occultation survey.

for the 35 sources in the Arecibo lists. But many of the Arecibo sources had high positional accuracy only in one position angle, which might have given rise to a higher chance coincidence.

The component-separation of double radio sources with flux densities less than about 3 fu at 327 MHz is mostly $\lesssim 20$ arc sec, indicating that they are located at redshift $z \gtrsim 0.5$ (Legg 1970). Further, as shown by Wills and Bolton (1969) and Braccesi *et al.* (1970), unidentified radio sources with flux density of about 1 or 2 fu at 408 MHz are most likely to be redshifted galaxies below the plate limits of the Sky Survey Prints rather than QSOs.

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