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OCCULTATION STUDIES OF WEAK RADIO SOURCES: LIST 2

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ABSTRACT

The positions and structures of ten radio sources are derived from occultation observations. Optical identifications are suggested for all ten sources.

I. DESCRIPTION OF LIST

In a previous paper (List 1) we described the methods of observation and analysis used in an occultation study of radio sources that is now in progress using the 1000-foot radio telescope at Arecibo, Puerto Rico (Hazard, Gulkis, and Bray 1967). The method of analysis was illustrated by a detailed account of its application to the observations of five weak sources.[1] The results of this analysis and a preliminary analysis of the more extensive observations now available confirm that the radio sources, in general, are complex, with the majority having a basic two-component structure with a component separation $\leq 10''$ for sources with a flux density less than or equal to a few flux units (1 flux unit = 10^{-26} W m^{-2} (c/s)$^{-1}$). To assist in an understanding of the emission processes involved in these complex sources, it is important to know not only the general features of the radio structures but also the relationship of these features to the position of the associated optical objects. This type of information is particularly required for the quasi-stellar radio sources, since, up to the present, it has been possible to compare the optical and radio structures of only five of these objects (Hazard 1967). It is in this context that occultation observations are of particular importance, for it is only the occultation technique that provides component positions for these complex sources to the accuracy (of the order of $\pm 1''$) required to position them relative to the optical identifications (the accurate radio positions insure that for most occulted sources a reliable identification is available). It follows that detailed optical studies of those sources studied by the occultation technique are of particular importance. Therefore, in order for the occultation observations to be available to the optical workers as soon as possible, we have decided to publish short lists giving the radio positions and structures and finding charts for the associated optical objects as soon as a reasonable number (about ten) have been studied, rather than wait until we have observed and analyzed about one hundred sources, when a statistical study of the radio data would be significant. It is not intended, in these communications, to give the observed occultation curves or the derived brightness distributions except in a few cases of special interest. This information will be given in the Cornell-Sydney University Astronomy Center (CSUAC) reports and will be available on request to those interested.

Although some of the sources studied appear in recent source lists, it has been decided to retain the numbering system adopted in a previous publication (Hazard *et al.* 1967) when only one of the sources then under consideration appeared in existing catalogues;

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[1] Due to a copying error, the right ascension of one of these sources, AO 0952, was given in this paper as $09^h52^m10\overset{s}{.}81$ instead of $09^h52^m11\overset{s}{.}81$. This latter figure corresponds to the preliminary value quoted by Burbidge and Burbidge (1967) after applying a small correction for limb errors.

that is, each source is identified by the prefix "AO" (Arecibo Occultation) followed by the hours and minutes of right ascension and the degrees of declination. Apart from the prefix, this is the same system as that used in the Parkes catalogues. Alternative source numbers will be given for sources appearing in other catalogues.

Table 1 gives the positions of the ten sources and the number of occultation curves on which the position is based. In the case of double sources, the positions of the components are given whenever possible. For complex sources, possible doubles, or doubles where the positions of the components cannot be determined separately, the position refers to the centroid of the emission unless otherwise indicated in the last column. When more than one occultation curve was obtained, the estimated errors in right ascension and declination are given; these errors represent maximum errors and include the errors introduced because of uncertainties in timing the occultation, in the shape of the Moon's limb, and in the value of ΔT (the correction to universal time to obtain ephemeris time where $\Delta T = \text{E.T.} - \text{U.T.}$). For cases in which only one occultation curve was obtained, the errors are quoted in the notes to Table 1 for axes perpendicular to and along the Moon's limb. In these cases, the section of the limb along which the source must lie was usually estimated using the method of analysis described in our earlier paper (Hazard *et al.* 1967). When this method was unsuitable due to the circumstances of the occultation or to the finite size of the source, the relevant section of the limb was determined using positions from the 4C or Parkes catalogues or was measured using the Arecibo telescope as a pencil-beam instrument.

Table 2 gives the details of the source structures, the approximate flux, and, where sufficient measurements are available, the spectral index of each source. The spectral indices are based on measurements at Arecibo at 195, 430, and 610 Mc sec^{-1}, and at NRAO, Green Bank, at 750 and 1420 Mc sec^{-1}. The angular sizes given in the fifth column refer to the over-all source size and not necessarily to the smallest scale structure visible, except when the source components are listed separately when the angular sizes of each component are given. Further information on the structure of multiple or extended sources is given in the sixth column. It will be noted that of the ten sources listed, three are definite doubles, one is probably double, one is certainly complex and possibly double, one has a core halo or double structure, and two are possibly double. Only two show no evidence of structure, and, for one of these, only one occultation curve was available. The results in Table 2, therefore, support the conclusions drawn from previous occultation studies that the majority of radio sources are complex with angular structure of the order of seconds of arc at a flux-density level around 1 flux unit.

Scintillation observations at 430 Mc sec^{-1} have been carried out on all occulted sources as they pass close to the Sun, and the presence or absence of scintillation is noted in the last column of Table 2, together with an estimate of the size of any small-scale structure. For these weak sources, the term non-scintillator indicates a percentage scintillation <20 per cent.

II. IDENTIFICATIONS

A search has been made of the *Sky Survey* plates in the positions of the ten sources. The results of this investigation are summarized in Table 3, which gives the positions of the optical identifications together with their approximate photographic magnitudes and the suggested type of object. The quoted positions should be accurate to about $\pm 5''$. Finding charts for each region are given in Figure 1 (Plate 1). For those sources where only one occultation curve is available, the positions of the limb along which the sources are estimated to lie are shown in Figures 2–5. Some comments on the source structures and identifications are given below.

a) AO 0526+24

For this source there was a noticeable difference in the lobe structure of the occultation curves at immersion and emersion, showing immediately the presence of structure

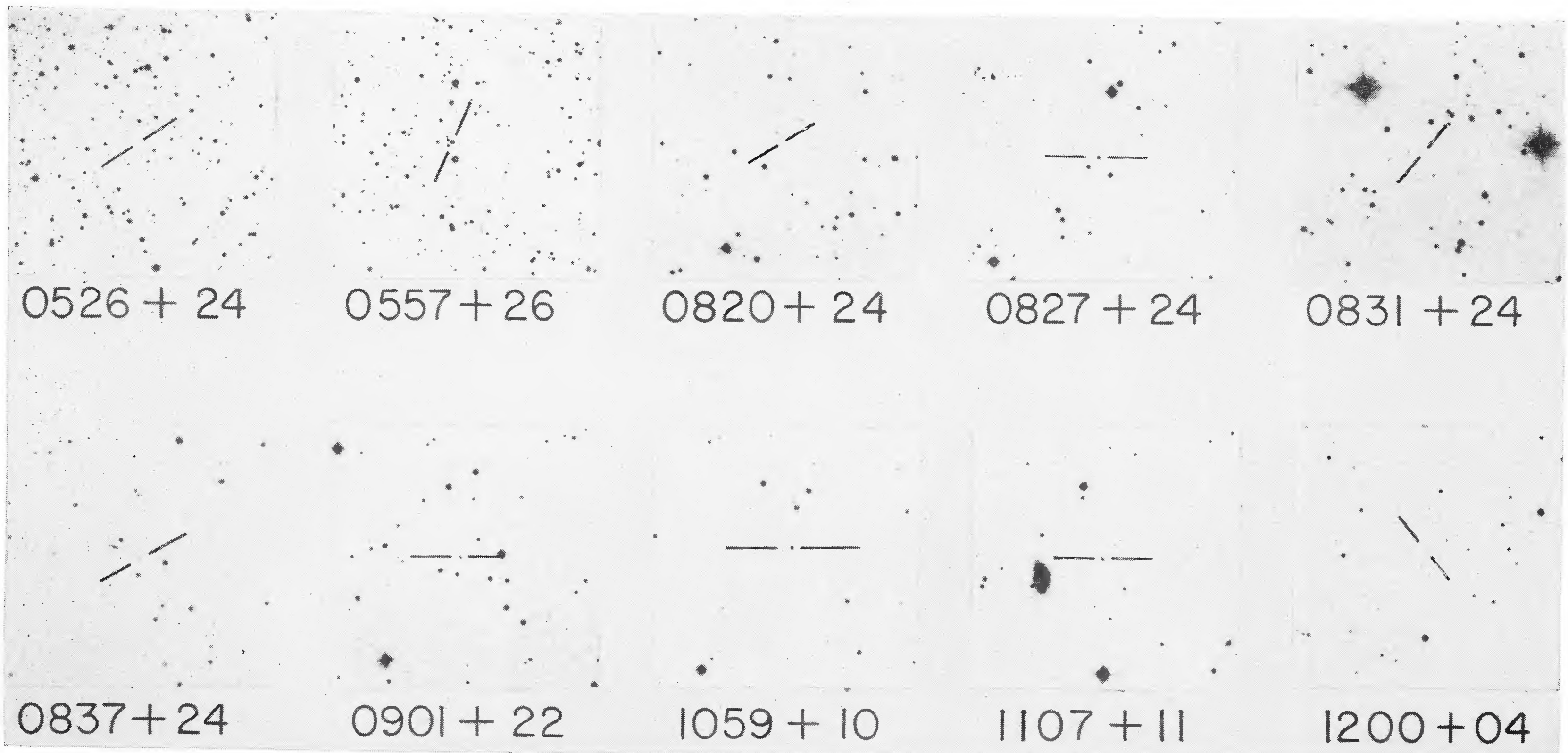

FIG. 1.—Regions of sky around the ten occulted sources. The plates are enlargements from the *Palomar Sky Survey*. When an accurate radio position is available, its position is indicated by the solid lines. For cases in which only one occultation curve was available, an object close to the Moon's limb at the time of occultation is indicated; for these sources see Figs. 2–5 and the text. The regions of sky shown are approximately 9′ square.

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TABLE 1

POSITIONS OF TEN WEAK RADIO SOURCES DERIVED FROM OCCULTATION OBSERVATIONS

Source	No. of Occultation Curves	Radio Position (1950.0) Right Ascension h	m	s	Error ±s	Declination °	′	″	Error ±″	Notes
AO 0526+24	2	05	26	05.71	0.05	24	58	29.0	2	
AO 0557+26	1	05	57	28.83	—	26	02	23.2	—	Positional accuracy: ±1″ in P.A. 143°, ±40″ in P.A. 53°. Position quoted is most probable position along limb obtained using scaling technique.
AO 0820+24	2	08	20	09.0	0.3	24	40	16	5	Position given is that of the centroid of emission.
AO 0827+24	4	08	27	54.40	0.03	24	21	06.5	0.5	Double source; position quoted is that of the centroid of emission.
AO 0831+24	5	08	31	40.23	0.04	24	08	51.3	0.5	
AO 0837+24 (4C 24.18)	1	08	37	00.67	—	24	13	47.4	—	Positional accuracy: ±0″.5 in P.A. 142°, ±20″ in P.A. 52°. Position derived using scaling technique.
AO 0901+22A	2	09	01	56.49	0.1	22	31	30.7	2	
0902+22B (4C 22.22)		09	01	56.81	0.1	22	31	39.1	2	
AO 1059+10A	4	10	59	40.46	0.07	10	45	13.2	0.7	
1059+10B (4C 10.31)		10	59	40.51	0.07	10	45	19.4	0.7	
AO 1107+11 (Pks 1107+10)	1	11	07	09.6	—	11	00	09.5	—	Positional accuracy: ±1″ in P.A. 115°, ±1′ in P.A. 25°. R.A. taken from Parkes and declination is that of the point on limb corresponding to this R.A. (see text). Position given is that of main component.
AO 1200+04	1	12	00	48.2	—	04	31	03	—	Positional accuracy: ±1″ in P.A. 118°, ±70″ in P.A. 28°. Position obtained using scaling technique.

TABLE 2

STRUCTURAL DATA ON TEN RADIO SOURCES DERIVED FROM OCCULTATION OBSERVATIONS

Source	Frequency of Observation (Mc sec^{-1})	Approximate Flux Density at 430 Mc sec^{-1} ($\times 10^{-26}$ W m^{-2} (c/s)$^{-1}$)	Spectral Index n ($S \propto f^{-n}$)	Angular Size*	Notes on Structure
AO 0526+24	430	1 8	. .	<0″.8 in P.A. 112° ≈1″ in P.A. 48°	In P.A. 48° source is definitely resolved, possibly double with component separation 1″–2″. Strong scintillator
AO 0557+26.	430	0.8	. . . .	≤1″.8	No evidence of structure down to a resolution of 2″. Scintillator
AO 0820+24 .	430	0 8	1 0	3″.5±1″ in P.A. 153° ≈10″ in P.A. 71°	Source is complex, possibly a double with component separation 5″ along P.A. ≈70°. Weak or non-scintillator
AO 0827+24(A+B)	430	0.8	0 4	≤1″.5 in P.A. 141° ≤2″ in P.A. 89° In P.A. 47°, A≤0″.8, B≤2″	Double source; flux A/flux B≈3/1. Component separation 4″.5 in P.A. 47°; distribution in P.A.'s 141° and 89° shows evidence of structure at resolution of 1″. Strong scintillator
AO 0831+24 . .	430	1 0	1 0	≤0″.7 in P.A.'s 85° and 139° ≤0″.5 in P.A.'s 98° and 133°	No evidence of structure, strong scintillator
AO 0837+24 .	430	1 7	0 6	≈2″ in P.A. 142°	Derived brightness distributions depend on assumed source position. Probably double with projected component separation 11″ in P.A. 142°; components equal flux, with size ≤0″.7. Strong scintillator
AO 0901+22A . .	195	3 5	0 9	≈2″.5 in P.A. 100° ≈4″ in P.A. 61°	Definite double with components of approximately equal flux. Components oriented along P.A. 58°, separation 9″.6. Weak or non-scintillator
AO 0901+22B	195	3 5	0 9	≈2″.5 in P.A. 100° ≈4″.5 in P.A. 61°	
AO 1059+10A .	195 430	. 3 9	. 1 3	≤2″ in P.A. 187° ≈3″.5 in P.A. 167° ≤1″.5 in P.A. 276°	Measurements in P.A. 187° at 195 Mc sec^{-1}; others at 430 Mc sec^{-1}. Flux A/flux B=1 5 at 430 Mc sec^{-1} and 2 4 at 195 Mc sec^{-1}. Component separation 6″.2 along P.A. 7°. Component A elongated along axis but possibly complex or double, with component separation 2″.5 in P A. 167°. Majority of flux from A arises in structure ≤0″.3. Scintillator
AO 1059+10B .	195 430			≤2″ in P.A. 187° ≤1″.0 in P.A. 167° ≤1″.5 in P.A. 276°	
AO 1107+11.	430	2 0	0 5	≤1″ in P.A 115°	Possibly a weak source (or extension) with approximately 30 per cent of flux of main component at a projected distance (or extending to) 10″ from this component in P.A. 295°. Strong scintillator
AO 1200+04	430	1 3	0 2	≈50 per cent of flux is component ≤0″.8 in P.A. 118°. Remainder in region with extent ≈4″	Brightness distribution depends on assumed source position. Appears to have a core-halo structure but is possibly double with component separation ≈2″ in P.A. 118°. Strong scintillator

* Minimum restoring beam used in analysis was 0″.8 No attempt was made to achieve the full resolution (≈0″.3) of which the occultation system is capable, since the presence of scintillations is evidence of structure ≤0″.5.

TABLE 3

POSITIONS OF OPTICAL IDENTIFICATIONS

Source		Optical position: Right Ascension h	m	s	Declination °	'	"	Approximate mpg	Type of object	Notes
AO 0526+24		05	26	05.7	24	58	34	+20	Galaxy, red	Probably member of faint cluster. Not visible on blue plate.
AO 0557+26	(a)	05	57	28.8	26	02	16	17.5	Stellar	Object "b" is the more probable identification.
	(b)	05	57	29.4	26	02	17.8	18.5	Stellar, blue	
AO 0820+24	(a)	08	20	09.0	24	40	29	20	Galaxy, red	Closest objects to radio source but both appear to lie north of the radio positions.
	(b)	08	20	09.5	24	40	43	18.5	Stellar, blue	
AO 0827+24		08	27	54.2	24	21	08	17.5	Stellar	No other object within 20" of radio position.
AO 0831+24	(a)	08	31	39.4	24	08	41	21	Stellar? blue	Object "b" is closer to the radio position.
	(b)	08	31	40.0	24	08	51	20.5	Galaxy, red	
AO 0837+24		08	37	01.5	24	13	59	19	Stellar, blue	Lies close to an unusual blue galaxy.
AO 0901+22		09	01	56.5	22	31	33	18.5	Stellar, blue	No other object close to radio position.
AO 1059+10		10	59	40.8	10	45	16	17.5	Stellar	No other object within 1'
AO 1107+11	(a_1)	11	07	09.9	11	00	14	18	Stellar, red	Object "a_2" is suggested as the possible identification.
	(a_2)	11	07	09.7	11	00	11	19	Stellar, blue?	
	(b)	11	07	07.9	10	59	38	21	Galaxy? red	
AO 1200+04		12	00	48.0	04	31	00	19.5	Galaxy? blue	Possibly member of a faint cluster.

$\geq 1''$. As the scintillation observations show that at least 70 per cent of the total emission arises in structure $\leq 0\rlap{.}''03$, the interpretation of the occultation data as representing a close double is probably correct.

Only the faint red object shown in Figure 1 lies near the radio position.

b) AO 0557+26

Because only one occultation curve was obtained, we are able to define only a section of the Moon's limb along which the source must lie. Figure 2 shows the estimated position of this section of the limb at the time of occultation after correction for limb errors, and it can be seen that it runs through a group of five optical objects. The stellar object *a*, which is the brightest member of this group and lies closest to the limb, is the object marked on the finding chart in Figure 1. Three other objects lie at a distance from the limb within the errors of measurement of the optical position. Of these, *b* is a blue stellar object and is suggested as the most probable identification.

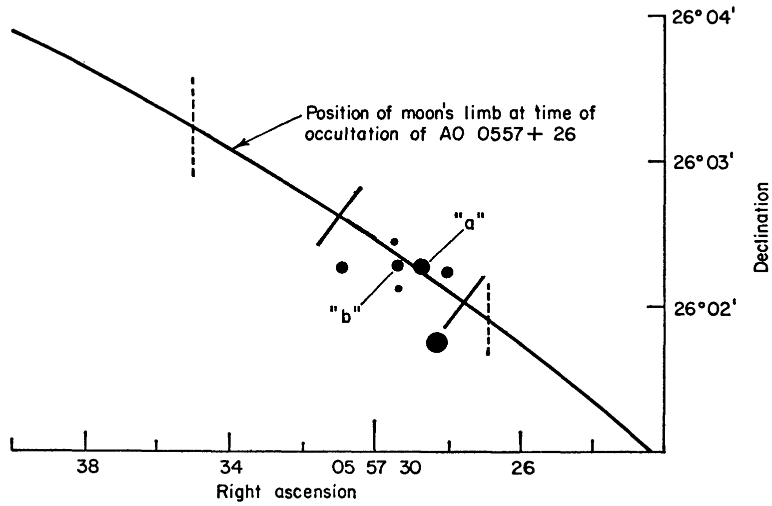

FIG. 2.—Section of the limb of the Moon near the point of occultation of AO 0557+26 It is estimated that the source must lie along that section defined by the solid lines, whose position was determined using a scaling technique described by Hazard, Gulkis, and Bray (1967). Broken lines represent limits to the position determined, using a pencil-beam measurement of the source position. Solid circles represent positions of optical objects in the region.

c) AO 0820+24

There is no optical object above the plate limits coincident with the radio position indicated in Figure 1, and there are only two objects close to it. The brighter of these is a blue stellar object (designated *b* in Table 3), easily visible on the finding chart some 30″ north of the radio position, while the fainter (*a*) is a faint galaxy that lies some 13″ north. This galaxy, therefore, lies just outside the combined estimated errors in the optical and radio positions ($\pm 5''$ in each case), but, in view of the extended nature of the radio source and the absence of other objects in the region, it may be considered the probable identification.

d) AO 0827+24

This is a certain identification. No other object lies close to the radio position.

e) AO 0831+24

There appear to be two possible identifications, which are designated *a* and *b* in Table 3. The estimated position of *b*, which is probably a faint galaxy, is closer to the radio position and lies between the two lines on the finding chart in Figure 1. Object *a* is very faint and appears to be blue and possibly stellar, but its estimated position lies about 15″ from the radio position, south preceding. On the basis of the agreement of the optical and radio positions, *b* must be considered the more probable identification. However, since the small radio size suggests that this may be a quasi-stellar source, and since it is known that the optical and radio positions do not always coincide, it is suggested that, if possible, optical studies also be made of *a*. It my be noted that about 1′ north of the radio position, there is a brighter blue stellar object (m_{pg} +19), which would possibly have been chosen as the identification but for the very accurate radio position available.

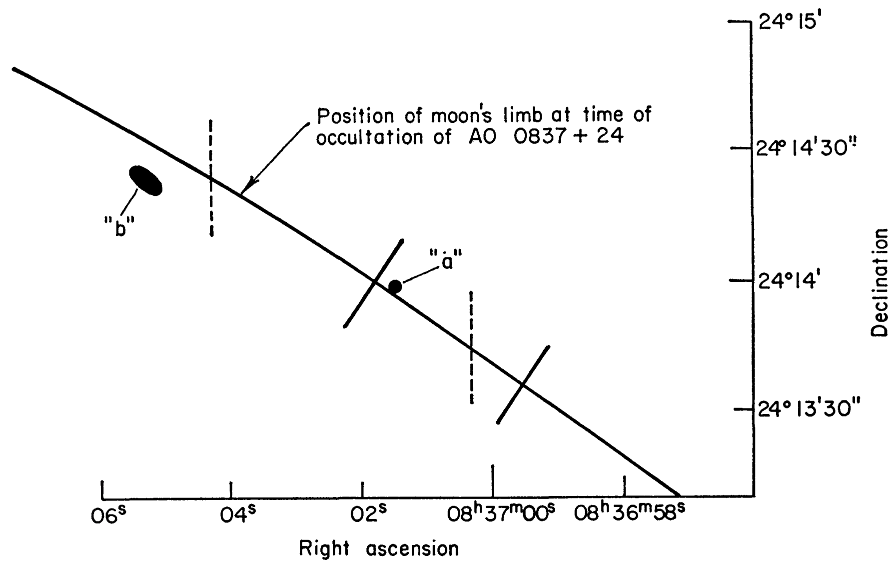

FIG. 3 —Section of the Moon's limb near the point of occultation of AO 0837+24 Solid lines represent the section along which the source must lie, determined by using the scaling technique, while the broken lines represent the limits set by the 4C position. The objects *a* and *b* represent optical objects close to the limb.

f) AO 0837+24

The identification is the most interesting of those discussed in the present communication. The position of the limb of the Moon, defined by the single occultation curve, is shown in Figure 3; the section of the limb along which the source must lie, as defined by the scaling technique, is indicated by the solid lines, while the section defined by the 4C position is indicated by the broken lines. Two interesting objects lie close to the limb but, of these, only *a* lies in that section defined by solid and also by broken lines. Object *b*, however, appears to be the more interesting. It is a very blue galaxy with an unusual structure, probably consisting of a bright nucleus from which protrudes a prominent jet. It is such an unusual object that it must be considered the probable identification although possibly displaced from the radio position. It may be noted that the blue stellar object *a* lies along a line defined by the direction of the jetlike feature.

g) AO 0901+22

This is a certain identification with a blue stellar object.

h) AO 1059+10

This source appears to have a structure similar to 3C 273. Thus the B component, which contributes 40 per cent of the total emission at 430 Mc sec^{-1}, is unresolved at the three position angles observed, while the A component is noticeably elongated along the source axis. Furthermore, as in 3C 273, the extended A component has a markedly steeper spectral index than the more compact B component. As the scintillation observations show that about 40 per cent of the total flux arises in a region $\leq 0\rlap{.}''3$, they are

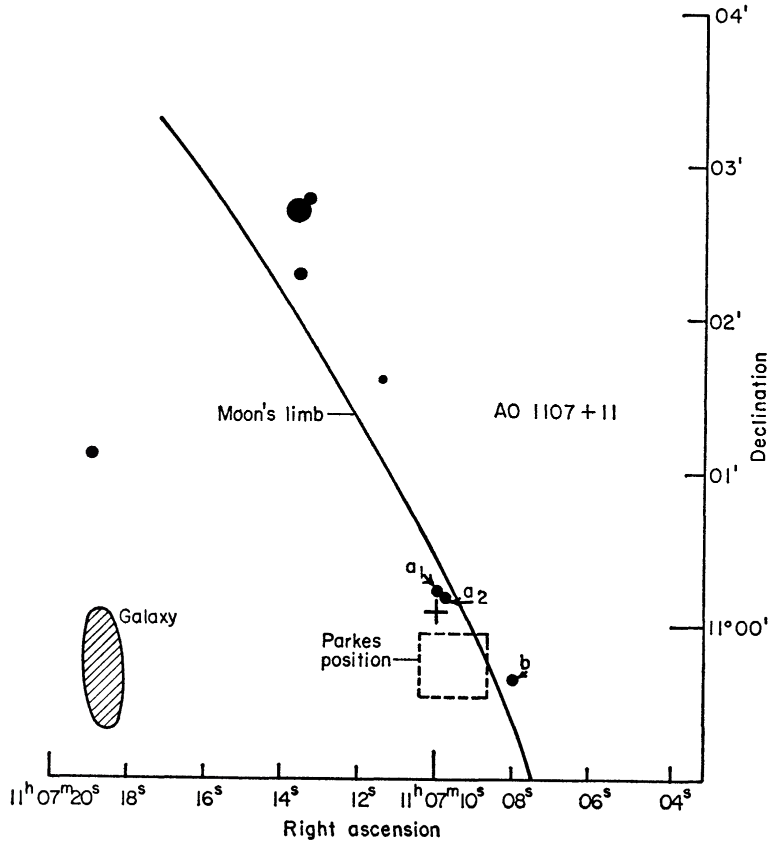

FIG. 4.—Section of the limb of the Moon near the point of occultation of AO 1107+11. The broken square shows the rms error of the Parkes position, and *a* and *b* represent the two optical objects closest to the limb near this position; *a* is apparently double and a_1 and a_2 represent the positions of its components. The cross represents the position of *a* given by Clarke, Bolton, and Shimmins (1966).

consistent with the scintillations being due entirely to the small-size B component. Other than the suggested identification, no other object lies within 1′ of the radio position.

i) AO 1107+11

This was almost a central occultation, and, consequently, the scaling technique could not be used to locate the source on the Moon's limb. However, an accurate Parkes position is available (Shimmins, Clarke, and Ekers 1966), and this position has been used to locate the region of the limb of interest. Figure 4 shows the position of the limb at the occultation time, the estimated rms error rectangle of the Parkes position, and the positions of the optical objects close to the limb. Two objects lie close to the limb in the region of the Parkes position: *a*, which appears double on the blue plate (and whose components are indicated by a_1 and a_2), and the faint red object b. Object a has already been suggested as the identification by Clarke, Bolton, and Shimmins (1966), and their quoted position for the object, which is indicated by the cross, is in good agreement with the positions given in Table 3 and indicated by the solid circles a_1 and a_2 in Figure 4. On the basis of the position measurements alone, a_1, a_2, and b can all be considered possible identifications. However, as the radio source is a very strong scintillator with the majority of the radiation arising in a region $\leq 0''.06$, it appears likely that it is associated with a quasi-stellar object. As both a_1 and b are markedly red objects while a_2 is neutral

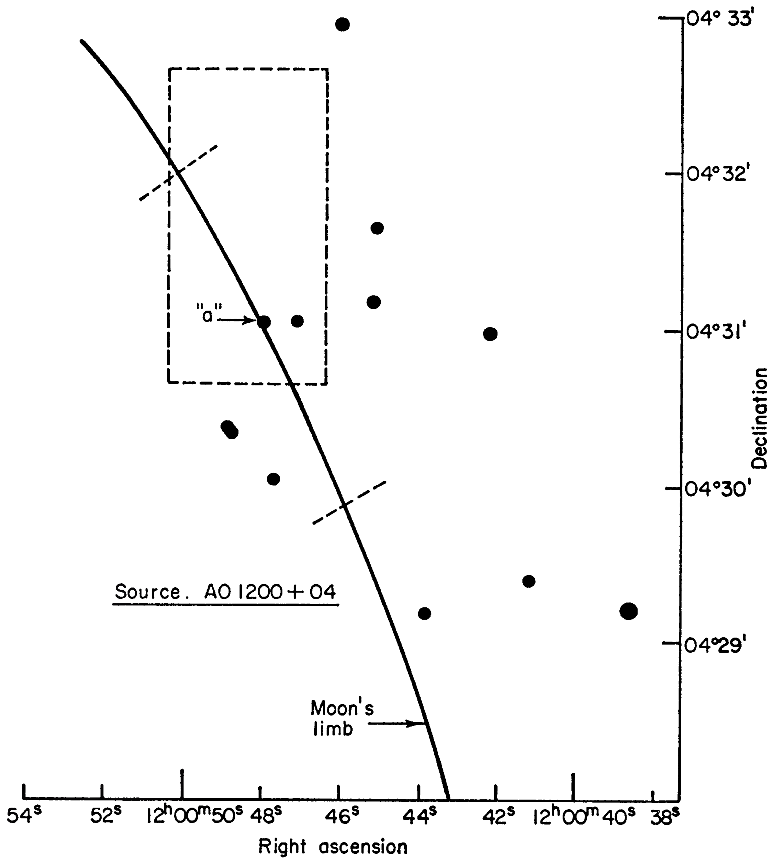

FIG. 5.—Limb of the Moon near the point of occultation of AO 1200+04 The broken rectangle represents limits of error of a pencil-beam determination of the source position, while broken lines perpendicular to the limb represent limits to the position along the limb, determined by using the scaling technique. Solid circles represent optical objects in the region.

or blue, the object a_2 is suggested as the most probable identification. It cannot be excluded, however, that a_1 and a_2 are physically associated.

j) AO 1200+04

The faint object a, which is possibly a member of a faint cluster of galaxies, is the only object that lies along that section of the limb defined, using the scaling technique, and within the error rectangle of the position measured, using the Arecibo telescope as a pencil-beam instrument. Adopting this position, the brightness distribution across the source can be uniquely determined and corresponds to the distribution of the core-halo type described in Table 2.

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