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LUNAR OCCULTATION STUDIES OF FIVE WEAK RADIO SOURCES OF SMALL ANGULAR SIZE

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ABSTRACT

This paper describes the investigation of five small-angular-size sources based on occultation observations made with the 1000-foot steerable telescope at Arecibo All the sources contain structure $\leq 1''$, and at least three appear to possess a double structure similar to that of 3C 273 Only one source reveals no evidence of resolution or of complex structure, and for this source only one occultation curve was observed. Identifications are proposed for four of the five sources investigated, but for the remaining source there is no object within the plate limits near the source position All objects are faint, three being close to the plate limits with a magnitude ≥ 20. It is suggested that all are probably quasi-stellar radio sources, a suggestion which is supported by the recent measurement of the redshift ($z = 1\ 47$) of the brightest of the new identifications. It appears probable that the remaining sources are at even greater distances. The extension of the observations to fainter sources, which will soon be possible using a new telescope feed now under construction, should permit an investigation of the structure of objects with redshifts in excess of 2, when a test of certain classes of cosmology should then become feasible.

I. INTRODUCTION

The lunar occultation technique has proved to be one of the most powerful methods for the investigation of the radio sources of small angular size. Not only does it provide positions for these sources to an accuracy of 1″, but it also provides detailed information on the source structure down to a resolution limit of the order 0″.1 (Hazard, Gulkis, and Bray 1966). Until recently, the two most powerful instruments available for observing occultations have been the 250- and 210-foot steerable paraboloids at Jodrell Bank and Parkes, respectively. With these instruments a number of occultations have been observed (Hazard 1962, 1965; Hazard, Mackey, and Shimmins 1963; Conway, Haslam, Kronberg, and Slater 1964; Clarke and Batchelor 1965) down to a flux limit of about 7 flux units at 400 Mc/s (1 flux unit = 10^{-26} W m^{-2} [c/s]$^{-1}$). However, in the past year the 1000-foot steerable radio telescope at Arecibo in Puerto Rico has come into operation, and it provides a much more powerful tool for occultation studies. Although its field of view is limited at present to $\pm 23°$, this is more than compensated for by its large collecting area, which is twenty-five times greater than that of the Parkes telescope with which most of the occultation observations have been made. This increase in collecting area brings into view in a given area of sky more than one hundred times as many sources, and it enables high-resolution studies to be made of sources which are much weaker, and therefore of more cosmological significance, than have yet been observed using long-base-line interferometers. Although the main feed is not yet working at full efficiency, it already has been used to observe occultations as weak as 0.5 f.u., and since the beginning of 1965 about sixty occultations have been observed. The results obtained so far confirm the conclusions drawn from previous Parkes observations (Hazard 1965) that the stronger sources are in general complex; the majority have a basic two-component structure, but two have been observed with as many as five components. The results are now being analyzed. In this communication we present the observations on five sources of small angular size to show the potential of the Arecibo instrument for occultation studies.

II. METHOD OF OBSERVATION

The telescope, which has been described in detail by Gordon (1964), consists basically of a fixed spherical reflecting surface, 1000 feet in diameter, and a movable feed which permits the beam to be directed to any point within $\pm 20°$ of the zenith (18°21′ N.) with an accuracy of better than $\pm 1'$. For occultation studies two feed systems are used. For weak sources the main feed, 96 feet long and designed to correct the spherical aberration of the reflecting surface and so feed the full 1000-foot aperture, is employed. For stronger sources a smaller feed system mounted on a separate movable support and offset to increase the field of view to $+23°$ is used. This system operates on at least three of the frequencies 41.7, 195, 430, and 610 Mc/s. It is at present being redesigned to allow simultaneous observations at five frequencies, each frequency utilizing at least 600 feet of the total reflector surface. The observations presented here were all made at 430 Mc/s using the large line feed and a receiver with a parametric amplifier first stage with a maximum input band width of 8 Mc/s.

Because of the demand on the telescope time and the small size of the beam (10′ at 430 Mc/s) it is not possible to carry out extensive tracking observations while waiting for occultations to occur, and in general only predicted occultations are observed. As there are at present no published data or sources as weak as 0.5 f.u., a survey of the Moon's path is made before each period when the Moon is visible with the telescope. The Moon is visible about ten days per month and on the average about five occultations are observed in that period. The observations are made by directing the aerial beam to that point on the Moon's limb at which the occultation is predicted to occur and recording the received power on magnetic tape with the telescope automatically tracking this point on the limb across the sky. This method of observation is used when observing weak sources with a narrow-beam antenna, and has the advantage over the tracking of the source position in that it removes the severe gradient in the received power which would then be produced by the motion of the Moon through the aerial beam. The receiver power is sampled at intervals of $0\overset{s}{.}1$ and later smoothed with a suitable Gaussian "time constant" for analysis and presentation purposes. For all the sources described here the observations were made using predetector band widths of 1 and 3 Mc/s (defined by I.F. filters) and an output time constant of $0\overset{s}{.}1$.

III. OBSERVATIONS

Figure 1 shows the occultation curves observed for five sources with flux densities between 1 and 3 f.u.; the half-power width of the assumed Gaussian beam used in smoothing the observed data is indicated in each case. Because of the limited field of view of the telescope in only one case, that of September 22 was a complete occultation (consisting of immersion and emersion) observed, but in two cases (October 20/January 10 and November 13/March 3) two separate occultations of the source were observed. In each of these three cases there is a marked difference between the two occultation curves, showing either that the source has an asymmetrical brightness distribution or that it is complex and consists of two or more separate components. As the occultation curve of October 18 also shows evidence of beating in the lobe pattern, which suggests that it may be double or complex, it appears that only the source observed on October 15 (Fig. 1, *c*) can possibly be considered unresolved or be represented by a simple Gaussian-type

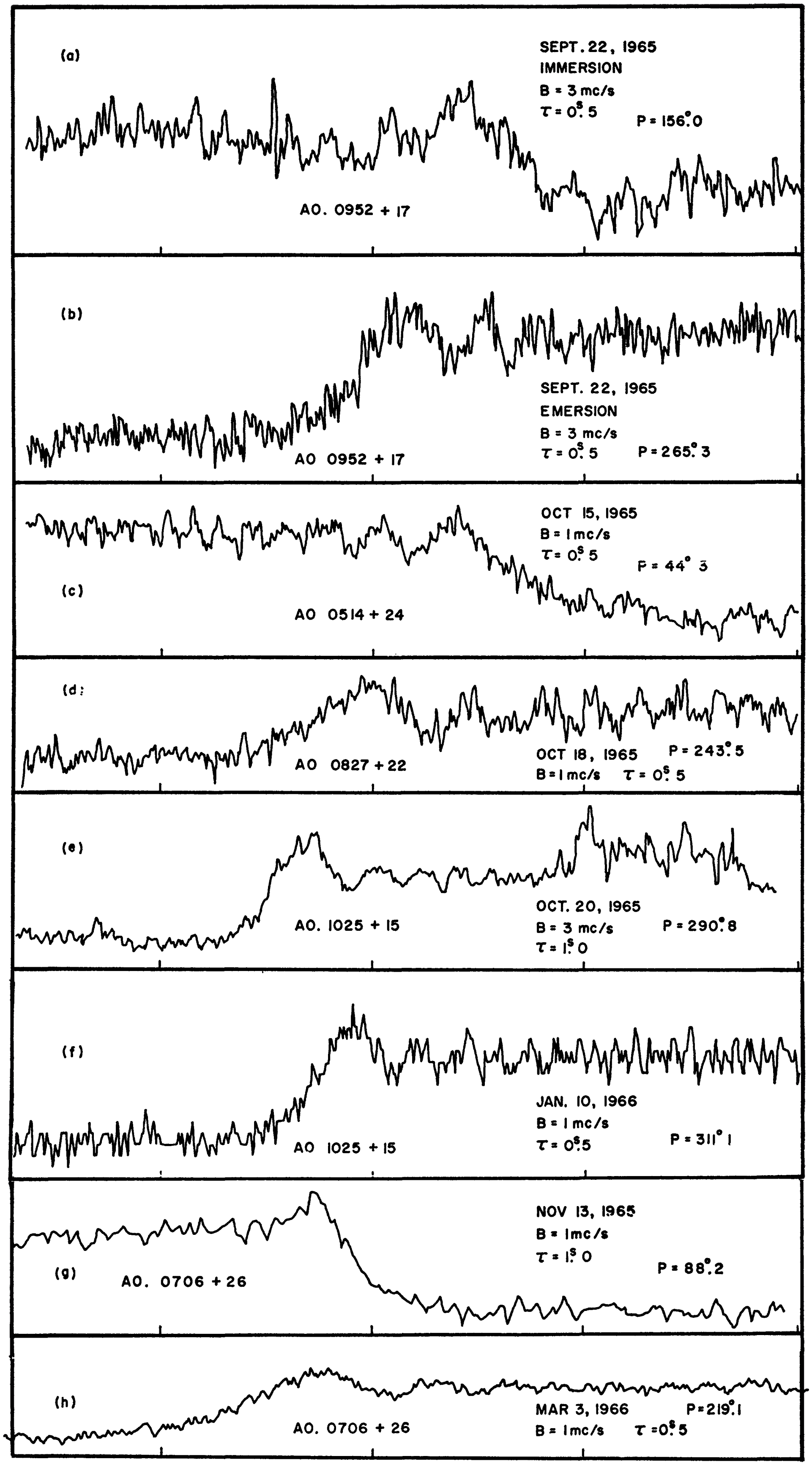

FIG. 1.—Observed occultation curves for five radio sources. B is the band width used in making the observations, τ the half width of the Gaussian used to smooth the observations, and P the position angle of the strip integral of the brightness distribution across the source. *Horizontal scale:* one division represents 1 min U.T.

brightness distribution. The most extensive diffraction patterns are exhibited by curves *c*, *d*, and *f* of Figure 1, showing that although two of these three sources are probably complex, each has an effective width at the indicated position angle of much less than 1″.

The clearest examples of complex structure are provided by the sources represented by Figure 1, *e* and *f* and *g* and *h*. Thus the diffraction pattern shown in *f* and which corresponds to a cut across the source in position angle 311° is a typical pattern for a single source with an angular size $\leq 1''$; Figure 1, *e*, however, which corresponds to position angle 291°, exhibits a diffraction pattern which not only cannot be represented by a single Gaussian brightness distribution but in addition shows the presence of source structure some 4″ in extent. Similarly, the single diffraction lobe visible in *g* indicates an angular size for this source of 3″ in position angle 88°, while the more extensive and complex pattern in *h* reveals the presence of much narrower structure in position angle 219° and in addition suggests that the source is double with a component separation of about 3″.

IV. METHOD OF ANALYSIS

In order to investigate the source structures in more detail Scheuer's (1962) convolution procedure has been used to derive their equivalent strip-brightness distributions. The principle of this method of analysis, which gives the true strip-brightness distribution as seen by an assumed Gaussian beam of arbitrary width, is now well known. Attention will therefore be confined to a brief discussion of some refinements which become necessary when attempting a resolution of $<0''.5$ (a resolution so far not attempted by other observers using the convolution technique) and also to a discussion of the use of the method to determine an accurate source position from a single occultation curve.

To calculate the required restoring function, it is first necessary to derive the relationship between the time scale of the occultation curve and the angular scale across the source in a direction perpendicular to the limb of the Moon at the time of occultation. If the Moon is assumed to be a straight edge, this relationship is given by

$$t = 1/(s \cos \theta) , \tag{1}$$

where t is the time taken to move 1″ in a direction perpendicular to the limb, s''/sec is the rate of motion of the Moon, and θ, which will be called the occultation angle, is the angle subtended at the center of the Moon by the Moon's path and the source at the time of occultation.

Because of the curvature of the Moon's limb, the occultation angle varies throughout the period of the occultation, and it has been pointed out (Hazard, Mackey, and Sutton 1967) that if this curvature is neglected it will set a limit to the maximum resolution which can be achieved. In practice, before carrying out any restorations at high resolution the observed occultation curve is rescaled to remove the effects of the variation of θ, and in the following discussion it will therefore be considered to be constant.

The value of θ is in general calculated from the source position and the known position of the Moon at the time of occultation. It will be shown later that to achieve a resolution of $<0''.5$ it is then necessary to know the source position to an accuracy of a few seconds of arc which for most sources (particularly weak sources) requires that the position be obtained from the occultation observations themselves, as indicated in § IV*a*. However, with the Arecibo instrument, with its limited field of view, in many cases only one occultation curve is obtained and the alternative method of analysis described in § IV*b* must be adopted.

a) *Analysis When Two Occultation Curves Are Observed*

When two occultation curves are available, the approximate occultation times are read from the record and the preliminary source position calculated from these times is used to calculate the occultation angle (θ) and hence the value of t to be used in performing the convolution; this value of t is sufficiently accurate for resolutions coarser than about 1″ provided θ is small ($\lesssim 30°$). The derived brightness distributions using this value of t are now used to estimate new occultation times and to derive a new, more accurate, source position. For large values of θ, where $\cos\theta$ varies appreciably with a small change in the assumed source position, and even for small values of θ if resolutions higher than 1″ are required, this accurate source position is used to calculate a more accurate value of t and the convolution procedure repeated. As indicated above, in the final derivation of the brightness distributions account is also taken of the curvature of the Moon's limb, which otherwise limits the resolution attainable (Hazard 1965).

b) Case Where Only One Occultation Curve Is Observed

When only one occultation curve is observed, the position of the source cannot be determined by the method discussed above, as the single occultation time defines only an arc of a circle on which the source must lie. However, an accurate position and at the same time an accurate brightness distribution can still be determined, provided the source is of small angular size and a diffraction pattern is visible.

The principle of the method is as follows. The angular scale of the diffraction pattern is first calculated in terms of v, where

$$v = (\lambda/2d)^{1/2} ,$$

λ being the wavelength of observation and d the Moon's distance.

The lobe separation is known in terms of v from the theory of diffraction at a straight edge and the time scale of one unit of v may be derived from the observed occultation curve. If one unit of v corresponds to t_1 sec, then from equation (1),

$$t = t_1(\lambda/2d)^{-1/2} = 1/(s \cos\theta) . \tag{2}$$

The value of s is now calculated from the Moon ephemeris at the time of occultation and substitution into equation (2) gives the corresponding value of θ. The source position is defined by the intersection of a line from the center of the Moon at an angle θ to its direction of motion with the arc of a circle defined by the Moon's limb at the time of occultation.

In practice, use is made of the fact that, if the wrong value of θ, and hence the wrong time scale, is adopted in deriving the brightness distribution for a source of small angular size, then the higher-order lobes in the convolving function and observed occultation curve are out of phase, which results in an asymmetry in the restored distribution accompanied by a series of overshoots. An approximate source position is therefore adopted and used to calculate the time scale of the restoring function, t. The brightness distribution is then derived using this value of t for a resolution of about 2″ and this distribution will in general show the asymmetry and overshoots discussed above. The value of t is now adjusted until the overshoots disappear and the whole process repeated at successively higher resolutions until the signal-to-noise ratio finally becomes too low to recognize the presence of overshoots. The value of the time scale and hence the occultation angle used in deriving the restored curve with the minimum of overshoots at the highest resolution is then used to derive the source position and the final brightness distributions at a number of selected resolutions. The permissible range of θ in which the source must lie depends not only on the angular size of the source but also on the value of θ itself, being smaller at large angles where $\cos\theta$ varies more rapidly with θ; for sources of angular size less than 1″ and for values of θ greater than about 20° it is found possible to define the source position to within about $\pm 10''$ along the limb of the Moon.

In the above discussion it has been assumed that the Moon is a perfect circle, whereas the actual limb has an irregular outline which can deviate from the ideal limb by as much as 3″ and whose effective slope over regions comparable in size to a Fresnel zone can differ from that of the ideal limb by several degrees. As a deviation of 1° in the slope of the limb produces an error in the estimated position of the source along the limb of 15″, the assumption of an ideal circular Moon can result in an error in the source position of up to ±3″ perpendicular to the limb and perhaps up to ±1′ along the limb. However, using the data given by Watts (1963) it is possible not only to estimate the displacement of the true limb from the ideal limb (the "limb error") to an accuracy of about ±0″.1 but also to estimate the effective slope of the true limb to an accuracy better than ±1°, the accuracy depending on the detailed shape of the limb near the point of occultation. The errors introduced into the position due to an uncertainty in the shape of the Moon can therefore be reduced to about ±0″.1 perpendicular to the limb and less than ±15″ along the limb.

It should be noted that the irregular nature of the Moon's limb is the main source of error in deriving the brightness distributions at high resolution for even when as in § IV*a* the source position is known from two occultation curves to an accuracy of ±1″ in both coordinates, the derived value of the occultation angle is subject to the uncertainties introduced by the irregular outline of the Moon. In arriving at a limit to the angular size of an unresolved source the problem is not serious, for it is adequate to adjust the scaling factor experimentally to remove all evidence of overshoots and to produce the narrowest possible brightness distribution, a procedure which corresponds to deriving the best mean slope of the limb at the point of occultation. For a resolved or complex source, however, a variation of the scaling factor merely results in an apparent change in the brightness distribution across the source or in a change in the relative fluxes of the separate source components. It follows that to investigate weak fine structure in a complex or resolved source it is necessary to know the true shape of the limb near the point of occultation in considerable detail. Along many sections of the limb the shape is such that it is not possible to estimate the mean slope of the limb to an accuracy much better than about 1°, whereas at high resolution it is found that the apparent source structure can change as a result of a variation in the adopted value of the occultation angle of less than 0°.25 (see § V*c*). Great care must therefore be exercised in the interpretation of the fine details in the source structure as determined by the occultation technique.

V. RESULTS

The results of the analysis of the five sources by the methods described in the previous section are summarized in Table 1. For reference purposes the sources have been identified by the prefix "AO" (Arecibo Occultation) followed by the hours and minutes of right ascension and the degrees of declination. The data relating to each source will now be considered in more detail. The brightness distributions given in this section represent the true brightness distributions convolved with (*a*) the assumed beam and (*b*) a Gaussian beam of half-power width equal to 0″.26 for a band width of 1 Mc/s and 0″.35 for a band width of 3 Mc/s. The total effective width of the restoring beam (β) is indicated on each curve. The curves are normalized so that for a given set of brightness distributions and in the absence of instrumental limitations on the beam width an unresolved source would have a constant height at all resolutions.

a) Source AO.0514+24

For this source only one occultation curve is available, and the method of analysis described in § V*b* was used. The method is illustrated in Figure 2, which shows the observed brightness distributions derived from the 1 Mc/s band-width observations for a resolution of 0″.9 using values of θ of 21°33′, 22°56′, and 24°36′. The brightness distributions derived using $\theta = 21°33′$ and 24°36′ show clearly the overshoots referred to earlier, but these overshoots are not visible using $\theta = 22°56'$, indicating that it is close to the true distribution. The brightness distributions at different resolutions calculated using this optimum value of θ are given in Figure 3. These curves reveal no evidence of complex structure and show no significant change in height or any significant broadening even at a resolution of 0″.36, indicating that the total emission arises in a region with an effective half-power width of $\lesssim$ 0″.2 in position angle 44°.3.

Figure 4 shows the position of the limb of the Moon at the time of occultation after correction for the limb errors. The sections of the ideal limb defined by the values of θ at which overshoots become apparent in the restored brightness distributions are indicated by the broken lines. The data given by Watts (1963) indicate that the Moon's limb is particularly smooth over this region with no deviations greater than 0″.1 within 15″ of the point of occultation and none greater than 0″.2 within 30″. This accounts for the high resolution achieved and suggests that any error due to the uncertainty in the slope of the limb is probably <10″. Adopting a value of ±0″.1 for the uncertainty in the limb correction and ±0″.1 for the errors in timing the occultation, the source must lie within 0″.2 of the limb and along that section between the broken lines.

TABLE 1

RADIO AND OPTICAL DATA ON FIVE OCCULTED SOURCES OF SMALL ANGULAR SIZE

RADIO DATA

Source AO	Radio Position (1950)		Approximate Flux 430 Mc/s (×10⁻²⁶ W m⁻² (c/s)⁻¹)	Angular Size	Component Separation	Position Angle of Axis of Source
	R A	Decl				
0514+24	05h 14m 41s.0	24° 32′ 42″.1	1	≤0″.2	...	...
0706+26A	07 06 01 71±0s.07	26 09 28 1±1″.5	1	1″.6×1″.9	3″2	84°
0706+26B	07 06 01 51± 07	26 09 27 9±1 5	1	≤0″.9×2″	...	
0827+23	08 27 24 4	23 33 46 6	2	≤0″.8	(0″.5)	
0952+17	09 52 10 81± 02	17 57 45 9±0 4	1 5	≤0″.5	≈2″.5	...
1025+15	10 25 39 33±0 25	15 26 56 7±1 5	3	≤0″.3×7″	(1″.5)	311

OPTICAL DATA

Source AO	Optical Position (1950)		Approximate M_{pg}	Notes
	R A.	Decl.		
0514+24	05h 14m 41s.4	24° 32′ 38″	21	Position error of radio source is ±0″.2 perpendicular to limb of Moon and ±10″ along limb
0706+26A	07 06 01 6	25 09 31	..	
0706+26B	.. .. ..	.. . ..	20	
0827+23	08 27 23 6	23 34 02	20	Optical object is central member of a group of four faint objects of approximately equal magnitude. Position error of radio source is ±0″.2 perpendicular to limb of Moon and ±25″ along limb. Probably a double radio source
0952+17	09 52 11 4	17 57 46 1	18	Double radio source. Position given is for center of two components
1025+15		.	.	No optical object in radio position. Could be double

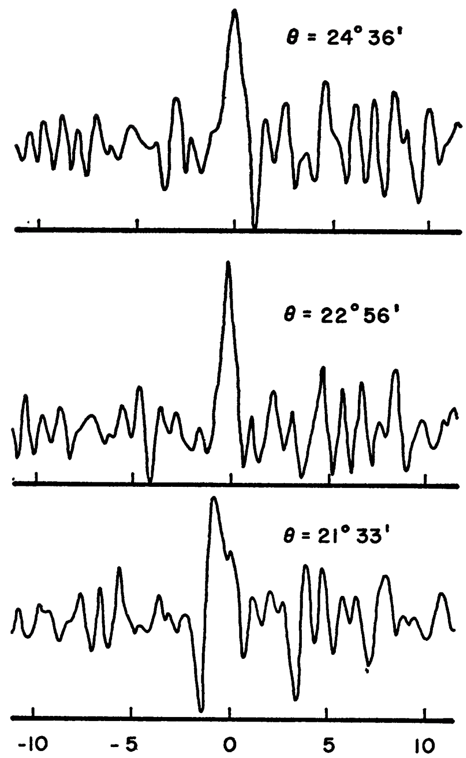

FIG. 2.—Diagram illustrating the effect of an error in the occultation angle (θ) used to derive the brightness distribution across a source of small angular size. The records are for source AO.0514 + 24. *Horizontal scale:* angular distance from center of source. One division represents 5″.

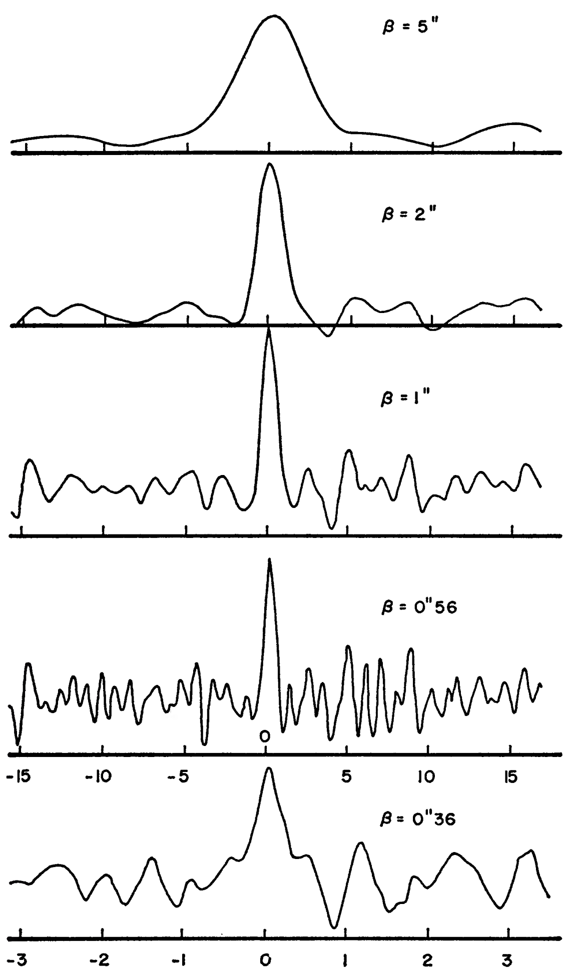

FIG. 3.—Brightness distributions across AO.0514 + 24 at different resolutions (β). *Horizontal scale:* angular distance from center of source; for β = 5″–0″56, one division represents 5″; for β = 0″36, one division represents 1″.

b) *Source AO.0706+26*

As two occultation curves were available for this source, namely, those of November 13, 1965, and March 3, 1966, the method of analysis outlined in § IV*a* was adopted.

The estimated brightness distributions are given in Figures 5 and 6, the distributions in Figure 5 referring to a position angle of 88°.2 and those in Figure 6 to a position angle of 219°.1. There is not only a decrease in height with increasing resolution showing that the source is extended, as already inferred from an inspection of the occultation curve of November 13, but at the highest resolutions there is in both cases a clear separation

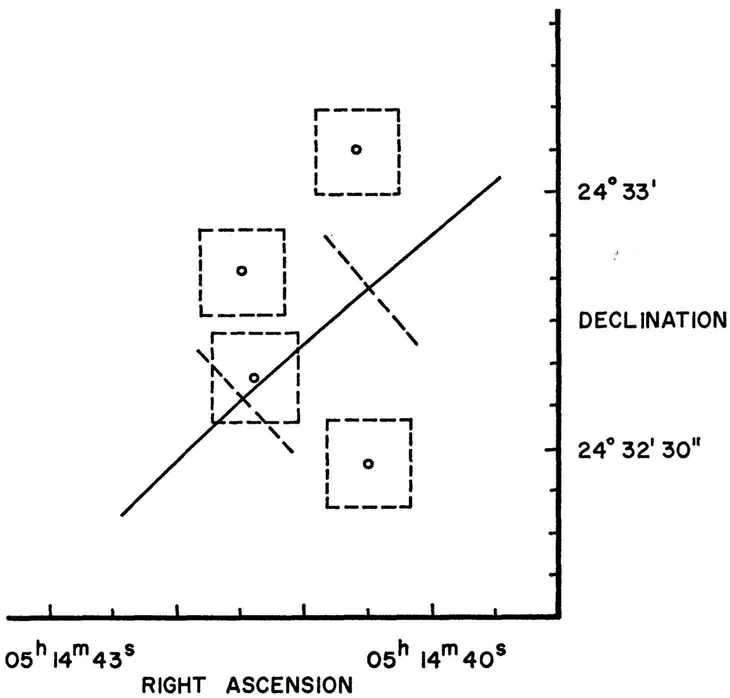

FIG. 4—The section of the limb of the Moon near the point of occultation of AO.0514 + 24. It is estimated that the source must lie along that section of the limb between the broken lines. The open circles represent four optical objects in the region, and the squares defined by the broken lines the estimated errors in the optical positions It is estimated that the limb is positioned to an accuracy of about ±0″.2. *Horizontal scale:* right ascension. One division represents 0s.5 R.A. *Vertical scale:* declination. One division represents 5″.

into two components. The apparent separation of these components is about 3″ at position angle 88°.2 and 2″ at position angle 219°.1, and on the assumption that both are of comparable angular size, the ratio of their fluxes is about 1.5:1.

The angular sizes of the individual components are more difficult to estimate, but it is clear that the distribution at a resolution of 1″.6 in Figure 5 is not consistent with a double source consisting of two unresolved components. The simplest separation of the components is indicated by the broken line in Figure 5, *b*, which suggested that each component has an angular size of about 1″.9 in position angle 88°.2. In Figure 6, *c*, the sources are barely resolved, and the separation into two components is consequently even more arbitrary than in Figure 5, *b*. However, that at least one of the sources is extended is shown by the sum of the peak amplitudes at a resolution of 0″.9 being significantly less than the total height of the source at a resolution of 3″.6, for if both were unresolved these two values should be equal. The broken lines in Figure 6, *c*, represent the only reasonable separation of the two sources which gives a flux ratio of

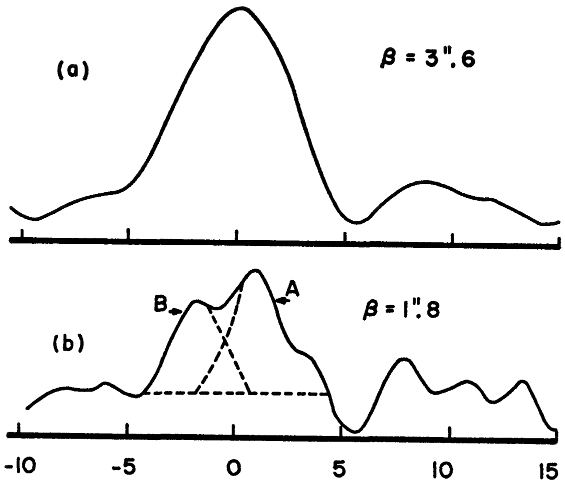

FIG. 5.—Brightness distributions across AO.0706 + 26 at different resolutions (β) in position angle 8°82. The broken lines represent a possible separation into two components. *Horizontal scale:* angular distance from center of source. One division represents 5″.

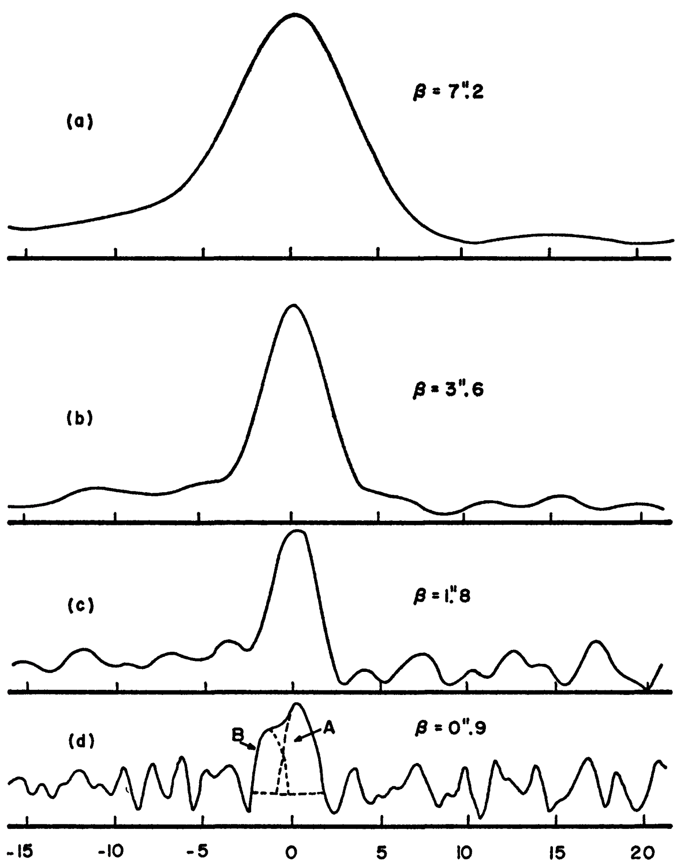

FIG. 6.—Brightness distributions across AO.0706 + 26 in position angle 219°1 for different resolutions (β). The broken lines represent a possible separation into two components. *Horizontal scale:* angular distance from center of source. One division represents 5″.

the two components equal to that in Figure 5, *b*. Adopting this division of the flux, component A is extended with angular size of about 1".6 while B is barely resolved and therefore ≤0".9. It was noted that, when deriving the brightness distributions at emersion, the shape of the B component was more sensitive to a variation of θ than that of A, which confirms the suggestion that B has significantly smaller angular size. Further evidence for the small angular size of at least one of the components is provided by the presence of several diffraction lobes in the observed occultation curve at emersion.

It therefore appears that AO.0706+26 is a double source with the weaker B component showing a significant elongation in the direction of the maximum source separation, that is, along the axis of the source; the estimates of the angular size of A suggest that it may also be elongated along this axis, but in view of the difficulty in separating the sources the small difference between the two estimates cannot be considered significant. The positions given in Table 1 show that the separation of the two components is 3".2 and that they are oriented along position angle 83°.7. If we adopt these values and assume that the brightness distribution across B is elliptical with the major axis directed along the source axis, it follows that the size of B is 2" × ≤0".9. The elongated nature of this component suggests that it may represent a jet extending outward from A, especially as this type of feature appears to be fairly common among the small angular size sources (Hazard *et al.* 1967).

A comparison of the areas under the two components at emersion in Figure 6, *d*, with the area under the curve in Figure 6, *a*, shows no evidence of any other extended feature in the brightness distribution. These areas are equal within the limits of experimental error and allowing for these errors shows that at least 80 per cent of the emission must arise in the components visible in Figure 6, *d*.

The errors in the positions of A and B given in Table 1 are due almost entirely to the difficulty in separating the two source components. It should be noted, however, that these positions depend on a correct pairing of the components in Figures 5, *b*, and 6, *c*. It seems unlikely that this can be in error, but if an incorrect choice has been made, the position angle of the axis will be rotated but the centroid of the emission remains unaltered. For identification purposes this is irrelevant, as the source separation is so small that it will result in displacement of each position of only about 2".

It is of interest to note that when the brightness distributions were derived from the records of March 3 with the assumption of an ideal circular Moon, they showed the overshoots and asymmetry characteristic of an error in the scaling function. As the occultation angle (θ) in this case was 53° and hence the scaling function very sensitive to a change of θ, this suggested that the slope of the true limb must deviate significantly from that of the slope for an ideal Moon. It was found that the overshoots and asymmetry could be removed by assuming that the true limb was inclined to the ideal limb by 1°36′ in such a sense as to increase the occultation angle. An analysis of the shape of the limb over this region using the data given by Watts (1963) showed that it was indeed inclined to the true limb in just this way. The angle of inclination was estimated to be 1°50′ ± 30′. The excellent agreement between this value and that estimated experimentally confirms the validity of the method described in § IV*b* for the analysis of a source for which only a single occultation curve is available.

c) Source AO.0827+23

The brightness distributions derived for this occultation using the method of § IV*b* are given in Figure 7. The decrease in the height of the restored distribution and the associated beam broadening which is apparent using an effective restoring beam of 0".56 show that the emission from this source arises in a region about 1" in diameter. Records shown in Figure 7, *d–f*, are of particular interest in that they show the difficulty of using the occultation technique to derive details of the brightness distribution for a source of less than about 1" in size. These distributions correspond to changes in the

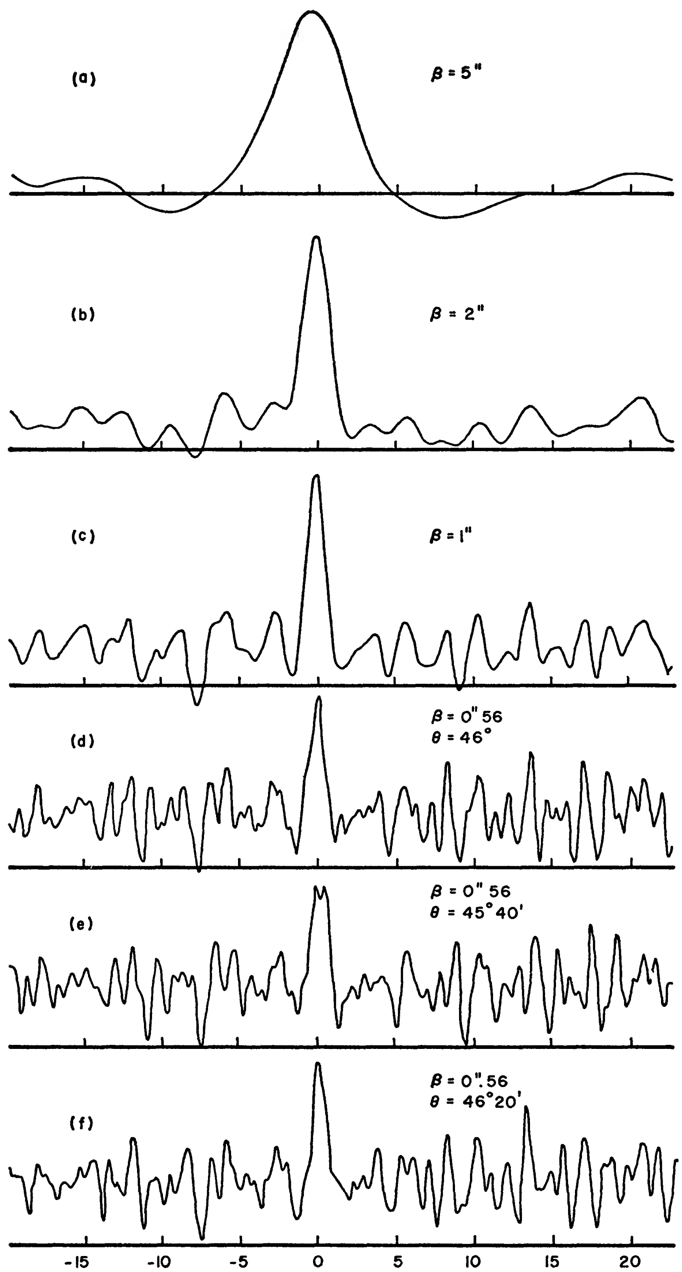

FIG. 7 —Brightness distributions across AO 0827 + 23 at different resolutions (β) in position angle 243°.4 Parts *d–f* show the effect on the estimated brightness distributions due to a change in the adopted occultation angle θ *Horizontal scale:* angular distance from center of source One division represents 5″.

value of θ and, hence, the value of the slope of the limb of the Moon at the point of occultation, of 20′. As for larger changes in the value of θ, the side-lobe structure referred to in § IV*b* becomes apparent; Figure 7, *d–f*, represents the range over which the structure of the source may vary. When the distribution given in Figure 7, *f*, is adopted, the source has a simple structure with an angular size of 0″.8, as indicated by the half-power width of the restored distribution of 1″. Figure 7, *e* and *f*, however, suggests that the source is more complex and possibly double, with a component separation of about 0″.5 with each component having an angular size of $\leq$0″.5. The ratio of the fluxes of the two components is indeterminate, depending on the value of θ adopted. In the present case the uncertainty in the value of θ represented by these possible brightness distributions produces an uncertainty of $\pm$5″ in the position at which the source passed behind the limb of the Moon. However, even if the position were known to an accuracy, say, of $\pm$1″, from two occultation curves, the uncertainty concerning the same structure would remain unless the slope of the Moon's limb at the point of occultation could be determined to an accuracy much better than $\pm$20′. It is probable that this accuracy could be achieved in this case; over the whole section of interest, apart from a slight hillock about 6″ in extent and 0″.3 high near the point of occultation, the limb deviates from a true circle by less than 0″.1. It is considered that the true distribution probably lies between those given in Figure 7, *d* and *e*, and hence that the source is possibly a close double. If this is indeed the case, then, as the source moves closer to the Sun, the presence of structure $\leq$0″.5 should be revealed by the presence of coronal scintillations. It is hoped that such observations will be carried out as they will prove a powerful tool in elucidating the true source structure.

Although as pointed out above the limb of the Moon deviates from a true circle by less than 0″.1 over most of the range of interest, the radius is less than that of the ideal Moon by 0″.9 $\pm$ 0″.1; the main source of error in this estimate is due to the presence of the small rise in the Moon's profile near the point of occultation and the uncertainty as to the point along the limb at which the occultation occurred. The estimated position of the source after correcting for the limb error is indicated in Figure 8. It is estimated that the error in the position along the limb of the Moon due to limb irregularities does not exceed $\pm$20″. This uncertainty, which is mainly due to the irregularity in the limb near the point of occultation, is considerably greater than the error of $\pm$5″ arising from the uncertainty of $\pm$20′ in the value of θ. It may be noted that this latter error is considerably less than that estimated for AO.0514+24, for although the finite angular size of the source tends to reduce the sensitivity of the restored brightness distributions to a variation of θ relative to that for AO.0514+24, this is compensated for by the increase in θ and the consequent more rapid variation of $\cos\theta$ which determines the scaling factor.

d) Source AO.0952+17

The brightness distributions for this source are given in Figures 9 and 10. The distribution derived from the immersion curve is too noisy to reveal much detail concerning the source structure but shows that the majority of the emission arises in a region with an angular size less than or equal to about 1″, although there is a faint suggestion that the source may be complex. The emersion curves corresponding to a position angle of 265°.3 are of better quality. The source is definitely resolved at a resolution of 1″ and apparently consists of two components with a separation of 1″.6 in position angle 265°.3. The brightness distributions at even higher resolution suggest that the angular size of each of these components is $\leq$0″.5. An investigation of the shape of the Moon's limb near the point of occultation shows that, although it is inclined to the true limb, there are no discontinuities in the profile and no features which could cause a spurious resolution into two components.

A comparison of the brightness distributions in Figures 9 and 10 shows that the peak amplitudes are equal at the coarsest resolutions. At a resolution of 1″.0, however, it is

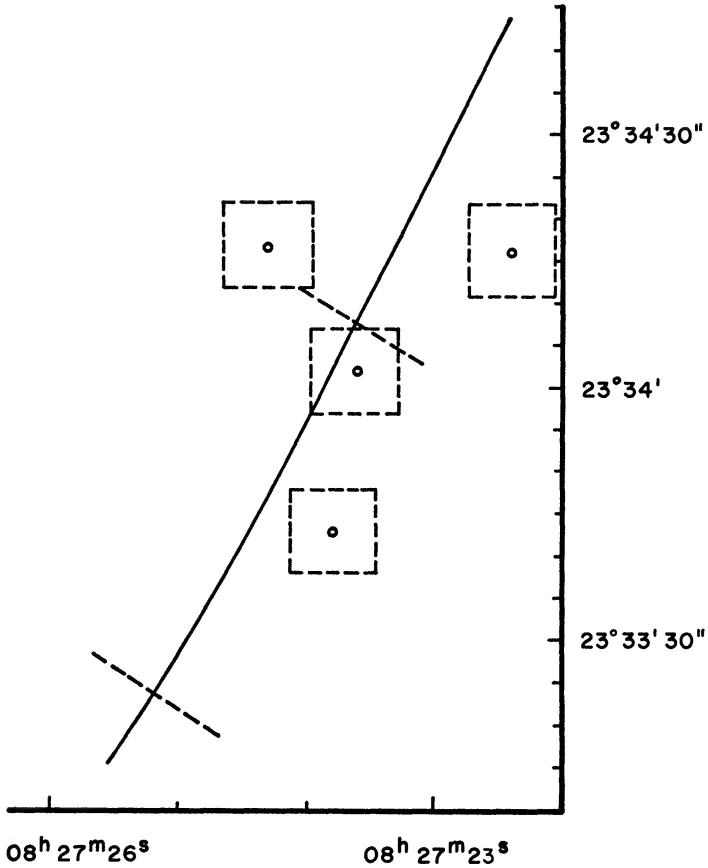

FIG. 8.—The section of the limb of the Moon near the point of occultation of AO.0827 + 23. It is estimated that the source lies within 0″.2 of that section of the limb between the broken lines. The open circles represent the positions of four faint objects in the region. The broken squares represent the size of the errors in the optical positions. *Horizontal scale:* right ascension. One division represents 1 second. *Vertical scale:* declination. One division represents 5″.

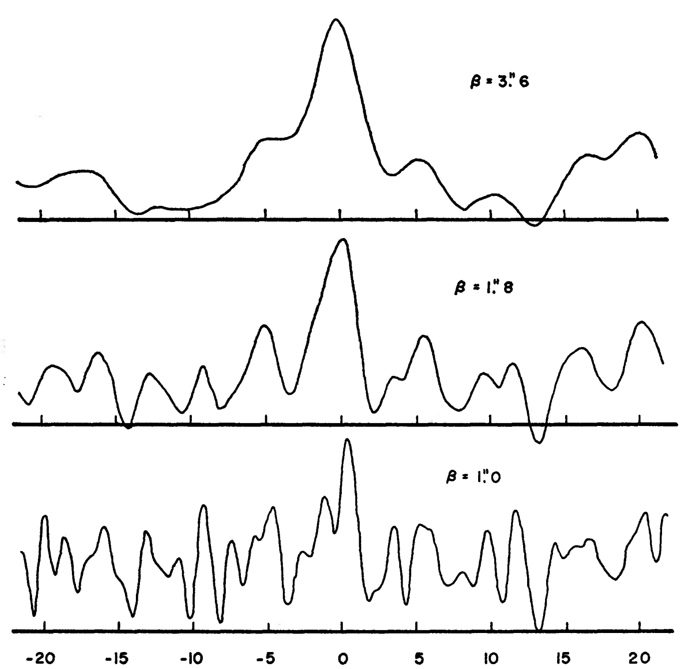

FIG. 9.—Brightness distributions derived from the immersion curve of AO.0952 + 17 on September 22, 1965. The curves represent the strip integrals of the brightness distributions in position angle 156° at different resolutions (β). *Horizontal scale:* angular distance from center of source. One division represents 5″.

clear that the main peak in the brightness distribution at immersion can represent only one of the two components seen at emersion. This suggests that in position angle 156° one component is resolved at a resolution of 1″.0, whereas in position angle 265°.3 its angular size is less than 0″.5. It would appear, therefore, that AO.0952+17 is similar to 3C 273 (Hazard *et al.* 1966) and 3C 245 (Hazard *et al.* 1967) and represents another example of a small angular source with a jetlike feature extending from it.

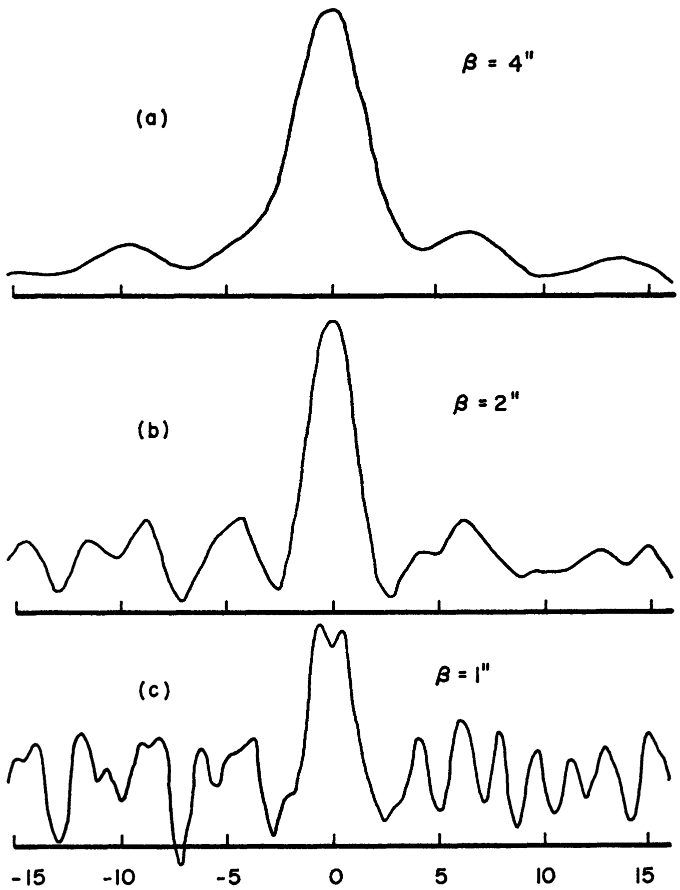

FIG. 10 —Brightness distributions derived from the emersion curve of AO 0952 + 17 on September 22, 1965. The curves represent the strip integrals of the brightness distributions at different resolutions (β) in position angle 265°.3. *Horizontal scale:* angular distance from center of source. One division represents 5″.

As the quality of the restored brightness distributions at immersion is not adequate to allow a measurement of the immersion times of each individual source component, the position given in Table 1 represents the position of the centroid of emission. It is possible that the asymmetry which can be seen in Figure 9, *b*, is a result of the presence of the extended component in which case it is separated from the narrow component visible at the higher resolutions by about 1″.5. This is comparable to that observed at immersion and suggests that the maximum component separation does not exceed 2″.5.

e) Source AO.1025+15

The brightness distributions corresponding to position angles 290°.8 and 311°.1 are given in Figures 11 and 12. The distributions in Figure 12 derived from the January 10, 1966, observations are particularly simple. As had already been inferred from a simple inspection of the corresponding occultation curve, there is no evidence of complex structure and no evidence of resolution using a restoring beam as narrow as 0″.4. The apparent width of the source in position angle 311°.1 is therefore ≤0″.3.

It is clear, however, from an inspection of the occultation curve of October 20 (Fig. 1, *g*) that the structure in position angle 290°.8 is much more complex. This occultation curve is certainly not compatible with a single unresolved source but shows evidence of beating in the diffraction pattern which suggests that the source may be double. Unfortunately, the latter part of this emersion curve is disturbed by external interference

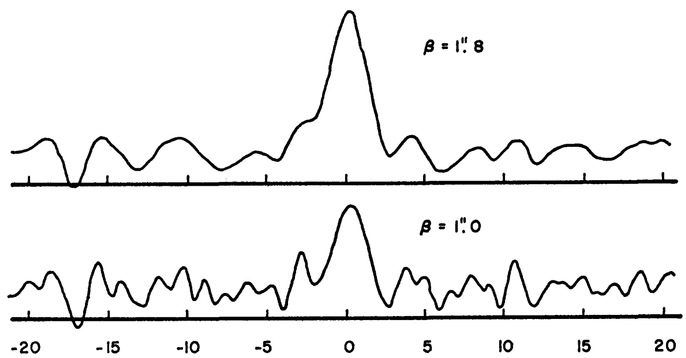

FIG. 11.—Brightness distributions across AO.1025 + 15 in position angle 29°.08 at resolutions (β) of 1″.8 and 1″.0. *Horizontal scale:* angular distance from center of source. One division represents 5″.

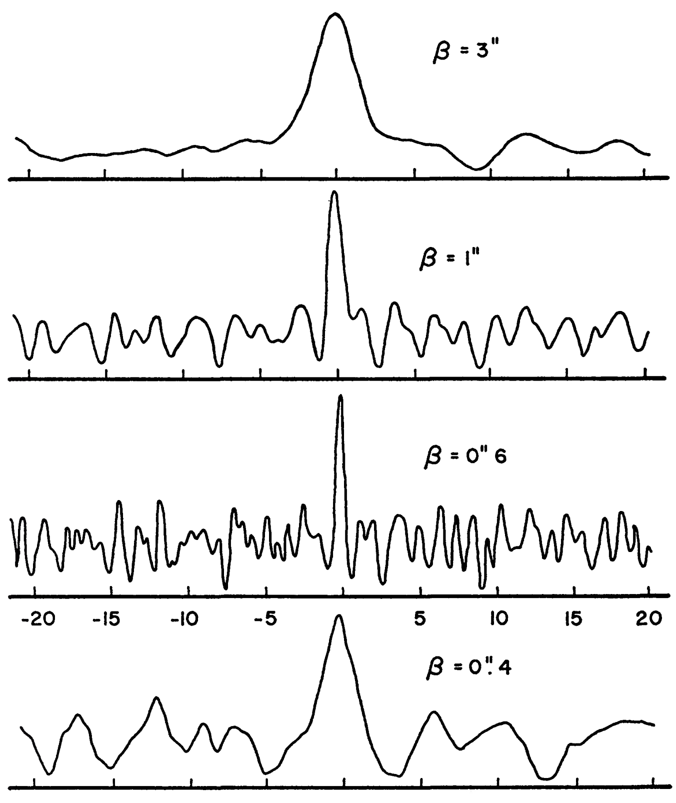

FIG. 12.—Brightness distributions across AO.1025 + 15 in position angle 311°.1 at different resolutions (β). *Horizontal scale:* angular distance from center of source. For resolutions β = 3″–0″.6, one division represents 5″. For β = 0″.4, one division represents 1″.

which destroyed the higher lobes in the diffraction pattern and consequently precludes an investigation of source structure finer than about 2″. This limitation must be kept in mind when considering the distributions shown in Figure 11 which were derived using assumed restoring beams of 1″.8 and 1″.0. These distributions show that the majority of the emission apparently arises in a source which is resolved at a resolution of 1″.0 and has a width between half-brightness points of about 2″.5. The small peak in the distribution about 3″.6 from the peak associated with AO.1025+15 cannot represent a genuine source, as its width is considerably narrower than the resolution limit imposed by the presence of the interference over the later part of the occultation curve.

If the resolution suggested by the distributions in Figure 11 is real, then the source is highly elongated, for the January 10 observations show that in position angle 311° its width is $\leq 0''.3$. This suggests that it represents the emission from a jetlike feature similar to those already observed in 3C 273 and 3C 245 and for which there is also some evidence in two of the sources described earlier in this paper. However, no source of small angular size is apparent similar to 3C 273B or 3C 245A. This could indicate that the structure is similar to that of 3C 273 at frequencies below 200 Mc/s where the emission from the jet is the dominant feature of the source and the emission from the B component negligible. It may be noted that the marked change in source size indicated by Figures 11 and 12 occurs for a change in position angle of only 20°. To explain this change over such a small angle, the length of the jet would have to be about 7″, which may be compared with its width of $\leq 0''.3$.

A close inspection of the lobe pattern in the observed occultation curve (Fig. 1, *e*) suggests that the structure along the jet may be more complex than indicated by the brightness distributions given in Figure 11. The observed decrease in the amplitude of the lobes confirms that the over-all angular size must be of the order of 2″.5. However, in addition to the decrease in lobe amplitude, there appears to be a beating in the lobe pattern between the second and third lobes. A beating pattern of this type can arise from a uniform strip source of total length about 3″ to 4″ (corresponding to the restored distribution) or from a double source with a component separation of about 1″.5. As the presence of the interference limits the possible resolution to about 2″, it is not possible to distinguish between these two possibilities. If the source is double, however, then to explain the variation in lobe amplitude, at least one of the components must be highly elongated and the suggestion that the source contains a jetlike feature still holds.

The possibility has been considered that the extension of the source indicated by the October 20 observations could be due to irregularities in the Moon's limb. This section of the limb is indeed irregular, but as the irregularities do not exceed $\pm 0''.5$, the irregularity cannot account for an apparent width as great as 2″.5. It is therefore concluded that AO.1025+15 is a highly asymmetrical source resembling the jetlike features seen in 3C 273 and 3C 245 but that no reliable deductions can be made about the structure along its major axis. There is a possibility that it is a double source in which case at least one of the components must possess an elongated structure.

VI. SOURCE IDENTIFICATIONS

A search has been made of the *Sky Survey* plates in the regions of the five sources and has resulted in a probable identification in all but one case. The results of this investigation are summarized in Table 1, which gives the radio data and the positions of the suggested identifications. The quoted optical positions should be accurate to better than $\pm 5''$. Finding charts for each region are given in Figure 13 (Plate 1).

a) AO.0514+24

Only one occultation curve was observed of this source, and consequently the observations define only a section of the limb along which the source must lie. However, because of the smooth nature of the limb profile, the errors along the limb do not exceed

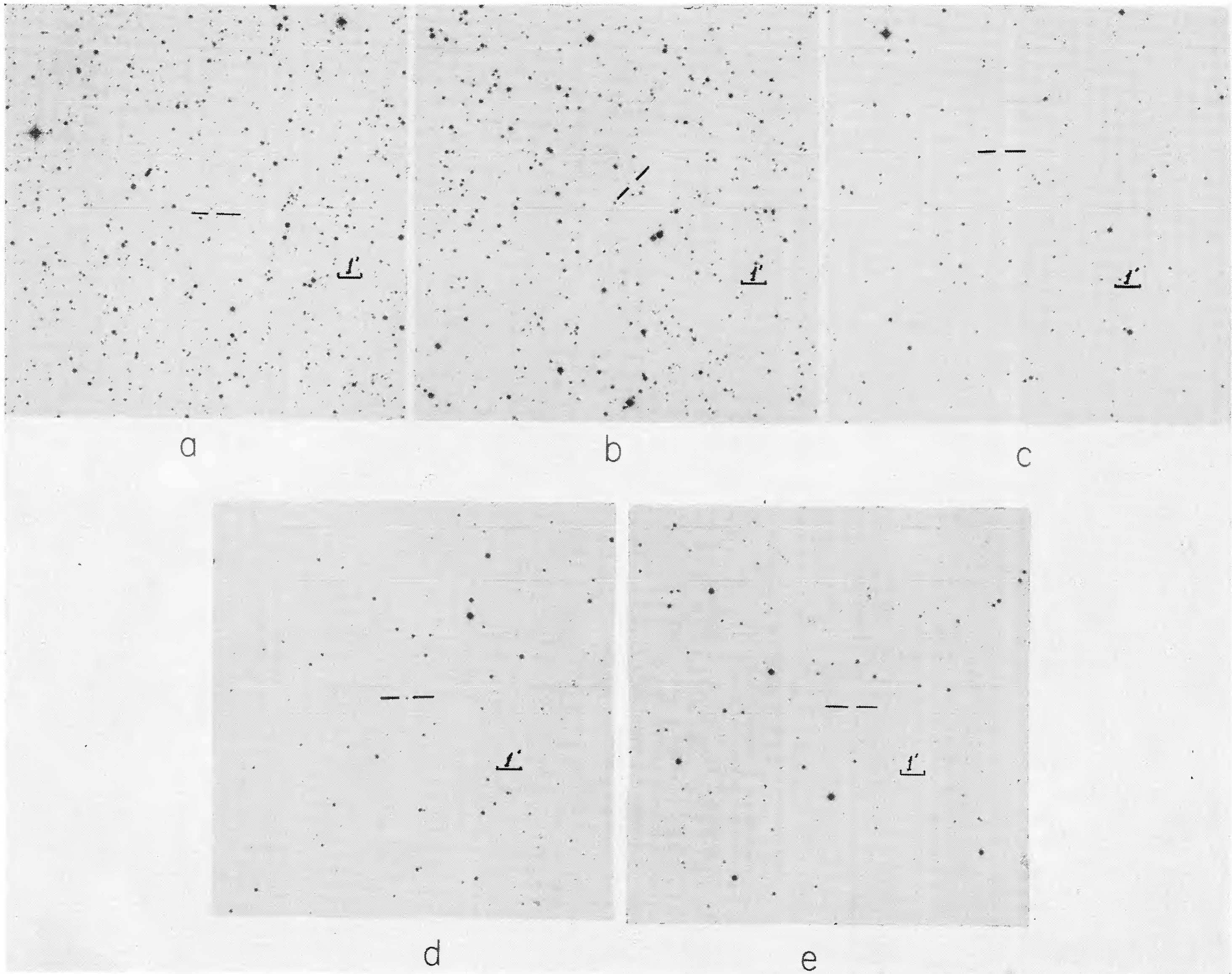

FIG. 13.—Regions around the five sources discussed in the present paper. The plates are enlargements from the *Palomar Sky Survey*. The position of the radio source is indicated by the solid lines.

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±10″ and only one object in the region lies on the limb within the estimated errors of measurement. It is a very faint red object ($m \approx 20$) and stellar in appearance. For finding purposes its position is indicated in Figure 4 together with the positions of three brighter objects in this region. It should be noted that the faint red object indicated on the finding chart is considered as a probable identification solely on the basis of its agreement in position with the limb of the moon at the time of occultation. However, it is known that the optical and radio positions of identified radio sources do not always coincide. It follows that the nearby optical objects in the field must also be considered as possible identifications. A definite identification must await an optical study of all these objects.

b) AO.0706+26

The object which lies closest to the radio position and is indicated on the finding chart is very faint ($m \approx 19$–20) but easily visible on the *Sky Survey* plates. Its estimated position appears to lie between that of the two radio components. However, in view of the large uncertainty in the optical position and the size of the optical image, which is appreciably greater than the total extent of the radio source, this cannot be considered significant. There are two other objects in the field whose positions differ from the radio position by less than 10″ and which must also be considered possible identifications. The brighter of these appears to be bluer than the nearby objects in the field, which suggests that it may be a quasi-stellar object and hence the more probable identification.

c) AO.0827+23

This is an interesting identification. The plate of the region (Fig. 13, Pl. 1, *a*) shows an apparently empty field between two stars of 17th or 18th magnitude. The original *Sky Survey* plates, however, show that in this region there are four faint stellar objects which are almost at the plate limits ($m \approx 21$). The positions of these objects are indicated in Figure 8. It can be seen that the limb of the Moon passes almost through the center of the group but that only the central object lies within the combined errors of the radio and optical positions. As it appears from the small angular size of the source that it cannot be associated with the group as a whole, this object therefore represents the most probable identification. However, the objects are so nearly equal in brightness that there is a strong possibility that the four are associated.

d) AO.0952+17

Other than the suggested identification, no other object lies above the plate limits within 1′ of the radio position. This identification has been confirmed by Burbidge and by Schmidt (1966) who have shown that it is a quasi-stellar radio source with a redshift of 1.47.

e) AO.1025+15

No object above the plate limits lies within 1′ of the radio position.

VII. DISCUSSION

The observations presented in this paper show that, by using the Arecibo radio telescope, it is possible to determine the positions of sources as weak as 1 flux unit to an accuracy better than 1″ of arc, and also to investigate the details of the structure of these weak sources to a limit of the order of 0″.2. They also demonstrate that a positional accuracy adequate for identification purposes can be obtained from a single occultation curve.

Of the five sources described, all contain angular structure ≤1″ and at least three appear to possess a double structure similar to the well-known quasi-stellar sources 3C 273, 3C 245, and MSH 14-1*21*. For two of these three sources, one of the components appears to be elongated, thus resembling the jetlike features of 3C 273 and 3C 245; AO.1025+15 may also possess a similar structure. This suggests that all are probably quasi-stellar sources but, because of their smaller flux and smaller component size, at even greater distances. Their identification with optical objects which are 2–3 mag fainter than the optical counterpart of 3C 245 also suggests that they are more distant objects. This suggestion appears to be confirmed by the measurement of the redshift of the brightest of the new identifications AO.0952+17 which is 1.47 (Burbidge and Schmidt 1966) compared with the value of 1.029 (Schmidt 1965) measured for 3C 245. This indicates that these sources are beyond the distance for which certain cosmologies predict a minimum in the angular size of a standard source as it is moved to successively greater and greater distances. If the observations are extended to fainter sources, it follows that for these models the component separation of the double sources should remain stationary or even increase. It is hoped that an improvement in the feed of the Arecibo telescope will increase the sensitivity by at least a factor of 3 and so extend the observations to sources of the order of 0.25 flux units. As present indications are that the majority of the weak sources are doubles and that for a redshift of around unity (where the effects of the minimum in the angular size distribution are becoming apparent) the component separation is a few seconds of arc, a test of certain classes of cosmology should then become feasible. An analysis of the observations of all the sources of small angular size so far observed with the Arecibo telescope is now in progress, and the results will be presented shortly.

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