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THE OCCULTATION OF AG+29°398 BY 93 MINERVA

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ABSTRACT

The occultation of AG+29°398 by 93 Minerva on 22 November 1982 was successfully observed at ten sites. The data are best fitted by a circular limb profile having a diameter of 170.8 ± 1.4 km, a value that agrees well with the published radiometric diameter for this asteroid. However, evidence of significant departure from a spherical shape is found in the occultation observations and in photometric measurements of Minerva made at Lowell Observatory over several months. Additional observations are needed to specify definitively the three-dimensional figure of Minerva.

INTRODUCTION

On 22 November 1982, the asteroid 93 Minerva occulted AG+29°398 (= SAO 76017A), a 7th-magnitude star of A0 spectral type. The occultation was originally predicted by Taylor (1981) and was independently discovered by Wasserman, Bowell, and Millis (1981). The latter authors gave a nominal predicted ground track stretching from Egypt through Spain, and then diagonally across the United States from New England to southern Arizona.

In an effort to refine the location of the ground track, a multiple-exposure plate containing both Minerva and AG+29°398 was taken with the 0.5-meter Carnegie double astrograph at Lick Observatory on

16 November 1982. This plate yielded consistent results for the coordinates of the target star, but the coordinates of Minerva showed larger scatter than is typical, particularly in declination. At the 1σ level, the predicted centerline of the occultation ground track based on this plate lay somewhere between northern Arizona and central Texas. Poor sky conditions prevented exposure of additional plates.

Because of the relatively large uncertainty in the location of the ground track, observers from Lowell Observatory and the University of Arizona coordinated the deployment of portable equipment in such a way that at least three telescopes would be in the track, should it pass across the southern third of Arizona. Independent visual observations in the Phoenix (Arizona) area were undertaken by members of the Saguaro Astronomy Club. Three teams from the Massachusetts Institute of Technology traveled to the Midwest to observe the occultation. The event was also observed at Central Michigan University in Mount Pleasant, and a very close appulse was recorded by a team from the University of Wisconsin - Eau Claire observing near Fort Atkinson, Wisconsin. In this paper we discuss the results of these efforts, together with additional observations from Europe that have subsequently come to our attention.

OBSERVATIONS AND ANALYSIS

The observations included in this analysis are summarized in Table I. The name of the observing site is given in the first column. An asterisk in this column indicates that the measurements were made photoelectrically. At Pic du Midi the occultation was recorded with video equipment (Laques et al., 1982). All other observations were visual. The coordinates and altitude of each site are given in columns 2, 3, and 4. The observed UTC times of immersion and emersion are listed in columns 5 and 6, respectively. If the observer reported that no occultation occurred, it is so indicated in these columns. Column 7 contains estimates of the uncertainty in the absolute timing, when available. The names of the various observers and brief descriptions of their telescopes are included in the footnotes to Table I. Most of the instrumentation used in this effort is portable and has been specially designed for occultation work.

Two sets of visual timings have been excluded from our analysis. These observations by J. F. Leborgne, 15 km north of Pic du Midi (see IAU Circular No. 3746), and R. Musach at Mollet, Spain (Dunham, 1982) are uncertain by 20% or more in the duration of the occultation. Consequently, we believe that these data cannot usefully contribute to a solution for the size and shape of Minerva.

The data in Table I have been analyzed by standard techniques which have been fully described in a series of earlier papers (e.g., Millis and Elliot, 1979; Wasserman et al., 1979). Each observed time of immersion or emersion specifies the position of one point on the limb of the asteroid. A circular or--if warranted--elliptical limb profile is fitted by least squares to the data to obtain (1) a measure of the diameter of that face of the minor planet seen at the time of the occultation and (2) corrections to the right ascension and declination of the asteroid, assuming arbitrarily that all positional error is in the asteroid's ephemeris. The ephemeris used in this analysis is given in Table II. The adopted 1950 coordinates of AG+29°398, based on the Lick astrometry for epoch of observation 1982.87, are $\alpha = 3^h33^m6\overset{s}{.}645$, $\delta = +29°49'6\overset{''}{.}37$. As in past studies where we have combined visual and photoelectric data (e.g., Millis et al., 1984), the response time of each visual observer has been treated as a free parameter in the least-squares solution while holding the observed durations fixed. Because of the relatively large uncertainty in the absolute timing at Mount Pleasant, those photoelectric data were treated in the same way.

The results of the least-squares fit of a circular limb profile to the data are shown in Figure 1 and are summarized in Table III. The pairs of fitted points from each observing site have been connected in Figure 1 by straight lines indicating the corresponding chords across Minerva. From north to south, the chords are from sites 1 through 10 in Table I. Photoelectric data, denoted by arrows in Figure 1, have been given full weight in the solution, while visual observations have been assigned half weight. The dashed lines represent the most closely constraining negative observations, consistent with the solution, on the northern and southern sides of the ground track. These observations were obtained at Fort Atkinson and Argyle Lake, respectively. A map of the occultation ground track computed on the basis of the circular solution is shown in Figure 2.

The adjustments in time required to bring the visual observations and the photoelectric data from Mount Pleasant into agreement with the rest of the photoelectric data are given in column 8 of Table I. Note that the shifts for all of the visual observers are negative, strongly suggesting that reaction time corrections, where applied, have been underestimated. The data indicate that actual reaction times are typically 0.5 to 1 second, as found in earlier studies (e.g., Millis et al., 1983). Likewise, the radial residuals are comparable in size to those found for other well-observed asteroid occultations (e.g., Millis et al., 1981).

We have not attempted to fit the entire data set with an elliptical limb profile because, in our opinion, the extent of coverage of the ground track and the typical timing accuracy are not sufficient to justify the additional free parameters in the least-squares solution. An elliptical solution was attempted based on the three highly accurate data sets from Palmcroft, Florence, and Picacho. The resulting profile was seriously inconsistent with the negative photoelectric results from Fort Atkinson, but gave an effective diameter which agreed within its formal uncertainty with the result of the circular solution. The formal uncertainty from the elliptical solution was, however, about four times larger than that from the circular solution. Consequently, we have adopted the circular solution as best representing the apparent profile of Minerva at the time of occultation.

Two visual observers reported negative results which are inconsistent with the limb profile shown in Figure 1. One was near the center of the ground track, and his report accordingly must be discounted. The other, observing north of Phoenix, Arizona (site 14 in Table I), was also located well within the expected ground track. However, he was closer to the northern edge of the track than all of the observers who did detect the occultation and, as a consequence, his report cannot be dismissed on the basis of independent evidence. Had this observer detected an occultation, the corresponding chord in Figure 1 would be about six-tenths of the way from the northernmost observed chord to the northern edge of the fitted limb probile. The circular solution predicts that a 6.2-second occultation would have occurred at the north Phoenix site.

No secondary occultations were reported, although at some sites variable cloudiness caused large excursions in the photometric records.

DISCUSSION

The least-squares solution described above gives a value of 170.8 ± 1.4 km for the effective diameter of Minerva as seen from Earth at the time of occultation. This value agrees very well with the radiometric diameter of 168 km quoted by Morrison and Chapman (1976). However, the true uncertainty in the occultation diameter is greater than the formal value quoted. First of all, the limb profile is not truly circular, particularly on the eastern side, as is evident from a comparison of the accurately timed chords obtained at Palmcroft, Pic du Midi, Florence, and Picacho (see Figure 1). Secondly, a significant portion of the northern limb of the asteroid was not sampled by the photoelectric data. Indeed, the existence of the negative report by a visual observer in this portion of the ground track gives one reason to suspect that Minerva may be more abruptly truncated on the northern side than is shown in Figure 1. If so, the actual effective diameter may be a few percent less than the occultation result.

A single set of occultation observations provides a measure of the occulting body's apparent profile at the time of the occultation, i.e., its cross-section on the plane of the sky. In order to estimate the asteroid's three-dimensional size and shape, it is necessary to refer to independent data. Results from a different occultation by that object could be used, but only for one asteroid, Pallas, have two occultations been well observed (Wasserman et al., 1979; Dunham et al., 1983). More commonly, the photometric behavior of the object as a function of rotational phase and aspect is considered. In favorable cases where the orientation of the axis of rotation is known, a unique three-dimensional figure can be derived on the basis of photometry and the results of a single occultation (e.g., Wasserman et al., 1979). Even when the pole direction is not known, but extensive photometry of the asteroid is available, one can estimate the range of variation in cross-sectional area as a function of aspect and thereby gauge how representative the occultation results are of the average dimensions of the occulting body (e.g., Millis et al., 1981).

Because a literature search failed to reveal any information about the rotational lightcurve of 93 Minerva, UBV observations were undertaken on seven nights between October 1982 and March 1983 with the 72-inch Perkins reflector at Lowell Observatory. The numerical results are given in Table IV, and lightcurves from four nights are plotted in Figure 3. The peak-to-peak amplitude of brightness variation on these nights is on the order of 0.1 mag. Similar results were obtained by Harris and Young (1983), who, on the basis of data from two nights in December 1982 and one night in January 1983, derived a provisional rotational period of $5^{h}.979 \pm 0^{h}.001$. If one adopts this value for the period, the rotational phase at which the occultation occurred is that indicated by an arrow in Figure 3. Harris and Young also observed Minerva for nearly seven hours on 11 April 1980 and found a peak-to-peak amplitude of 0.05 mag.

While the available lightcurves are all of low amplitude, there do appear to be relatively large changes in the mean absolute brightness of Minerva, even with rather small changes in viewing aspect. In Figure 4, the mean magnitude of Minerva reduced to unit distance from the Sun and Earth from the seven nights of observations in Table IV is plotted as a function of solar phase angle. The observations from December, January, and February, taken when Minerva was located within the same one-degree-radius patch of the sky, fall closely along a straight line. In October and March, the asteroid was located 6 to 12 degrees further east, and the corresponding magnitudes fall well below the line in Figure 4. Since the photometric uncertainty associated with the October and March observations is believed to be small compared with the deviations and since the deviations of the single observations on 9 and 10 March are much greater than the expected rotational variation, we conclude that the departures from the line are most likely caused by variation in the mean apparent cross-sectional area of the asteroid with changing aspect and/or by changes in large-scale shadowing. An oblate spheroid and a disk are examples of asteroidal shapes that would be expected to give consistently low-amplitude rotational lightcurves but large changes in mean brightness. Additional photometry of Minerva is needed before its overall shape can be estimated reliably.

The phase coefficient corresponding to the line in Figure 4 is 0.05 mag/degree. Extrapolating linearly to zero degrees phase angle gives V(1,0) = $7\overset{m}{.}84$. The corresponding visual geometric albedo is 0.043, a value typical of C-type asteroids.

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TABLE I.

Location	Longitude#	Latitude	Altitude (m)	UTC Immersion	UTC Emersion	Uncertainty in absolute timing (sec)	Shift (sec)	Residuals (km) Immersion	Residuals (km) Emersion
[1]Palmcroft*	$7^h28^m20^s$	+33°28'05"	331	$3^h41^m16^s.64$	$3^h41^m26^s.74$	±0.03 immersion ±0.02 emersion		−1.8	+4.2
[2]Mt. Pleasant*	5 39 05.89	+43 35 15.3	258	3 38 33.7	3 38 44.3	±1.0	0.64±0.12	+2.8	+2.8
[3]Tempe 1	7 27 55.8	+33 23 23	360	3 41 17.0	3 41 27.5	–	−0.87±0.17	−2.0	−2.0
[4]Tempe 2	7 27 43.7	+33 23 20	360	3 41 17.0	3 41 28.0	–	−2.30±0.16	+0.3	+0.3
[5]Pic du Midi†	−0 00 34.13	+42 56 12.0	2862	3 31 31.8	3 31 43.1	+0.2	–	−0.1	−2.1
[6]Magma 1	7 25 58.00	+33 09 43.13	470	3 41 15.0	3 41 26.5	–	−0.41±0.16	−3.1	−3.1
[7]Magma 2	7 25 58.02	+33 10 34.6	471	3 41 14.9	3 41 26.6	–	−0.35±0.15	−1.6	−1.6
[8]Florence*	7 24 58.87	+33 04 03.0	488	3 41 14.13	3 41 25.03	±0.01 immersion +0.01 −0.04 emersion	–	+1.1	−7.7
[9]Picacho*	7 25 18.62	+32 36 00.5	500	3 41 18.32	3 41 26.55	±0.01	–	+0.2	+5.3
[10]Barcelona	−0 08 32.47	+41 24 28	140	3 31 23.1	3 31 30.2	±0.1	−0.65±0.26	+0.8	+0.8
[11]Flagstaff*	7 26 08.5	+35 05 48	2198	No occultation.					
[12]Mayer*	7 28 57.3	+34 23 44	1381	No occultation.					
[13]Fort Atkinson*	5 55 26	+42 55 43	241	No occultation.					
[14]North Phoenix	7 28 28.41	+33 49 56.2	533	No occultation.					
[15]Argyle Lake*	6 03 11.28	+40 27 36.2	213	No occultation.					
[16]Mt. Lemmon*	7 23 09.13	+32 26 33.9	2790	No occultation.					
[17]Rail X Ranch*	7 22 49.6	+31 37 39	1400	No occultation.					
[18]Amado*	7 24 15.0	+31 42 25	950	No occultation.					

[1]R. Nye, 0.4-m reflector.
[2]W. Osborn, 0.35-m reflector. Estimated uncertainty in duration is ±0.3 sec.
[3]S. Stiers, 0.25-m reflector. No reaction time correction has been applied.
[4]G. Fillingham, 0.2-m reflector. No reaction time correction has been applied.
[5]P. Laques, J. Lecacheux, J. Vedere. See I.A.U. Circular No. 3746.
[6]G. Rattley, 0.25-m reflector. The times listed include a reaction time correction of 0.3 second.
[7]P. Manly, 0.2-m reflector. Reaction time corrections of 0.3 sec on immersion and 0.2 sec on emersion have been applied.
[8]E. Bowell, L. Wasserman, 0.35-m reflector.
[9]R. Millis, T. Kreidl, 0.35-m reflector.
[10]C. Schnabel, 0.2-m reflector. Reaction time corrections of 0.2 sec on immersion and 0.4 sec on emersion have been applied.
[11]N. White, 1.0-m reflector.
[12]R. Lines, H. Lines, 0.2-m reflector.
[13]R. Elliott, W. Smethells, 0.2-m reflector.
[14]G. Balazs, 0.25-m reflector.
[15]D. Mink, G. Aldering, 0.35-m reflector.
[16]W. Wisniewski, 1.5-m reflector.
[17]O. Franz, R. Oliver, 0.35-m reflector.
[18]W. Hubbard, L. Gilliland, 0.35-m reflector.
*Photoelectric.
†Video.
#A negative sign denotes east longitude.

TABLE II

Geocentric Astrometric Ephemeris of Minerva

Ephemeris day at 0^h ET (1982)	R.A. (1950)	Declination	Δ (AU)
15 Nov	$3^h40^m32^s.905$	30°01'44".47	2.048448
16 Nov	3 39 30.633	30 00 21.77	2.047856
17 Nov	3 38 28.198	29 58 51.32	2.047560
18 Nov	3 37 25.671	29 57 13.28	2.047563
19 Nov	3 36 23.125	29 55 27.80	2.047864
20 Nov	3 35 20.631	29 53 35.05	2.048464
21 Nov	3 34 18.260	29 51 35.23	2.049363
22 Nov	3 33 16.080	29 49 28.55	2.050561
23 Nov	3 32 14.163	29 47 15.21	2.052058
24 Nov	3 31 12.575	29 44 55.44	2.053853
25 Nov	3 30 11.383	29 42 29.50	2.055946
26 Nov	3 29 10.654	29 39 57.62	2.058336
27 Nov	3 28 10.451	29 37 20.07	2.061022
28 Nov	3 27 10.835	29 34 37.10	2.064002
29 Nov	3 26 11.868	29 31 49.00	2.067275

TABLE III

Results of the Circular Solution

Diameter	170 ± 1.4 km
Correction to right ascension	$-0^{s}.0709 \pm 0^{s}.0001$
Correction to declination	$-1''.181 \pm 0''.001$
UTC of minimum geocentric separation	$3^{h}36^{m}50^{s}.9$
Minimum geocentric separation	$1''.27$

TABLE IV

UBV Photometry of Minerva

UTC	V	B-V	U-B
18 October 1982			$\alpha = -12^{\circ}.8$
$6^{h}.233$	$12^{m}.65$		
6.373	12.70		
6.436	12.72		
6.549	12.67		
6.716	12.65		
6.970	12.65		
7.059	12.64		
7.162	12.60		
7.305	12.59		
7.645	12.61		
7.750	12.59		
8.123	12.59		
8.278	12.59		
8.751	12.65		
8.881	12.63		
9.362	12.59		
9.559	12.57		
14 December 1982			$\alpha = 9^{\circ}.1$
$6^{h}.343$	$12^{m}.42$		
6.590	12.34	$0^{m}.69$	
6.756	12.33	0.70	
6.974	12.32	0.70	
7.251	12.36	0.67	
7.504	12.35	0.68	
7.823	12.36	0.68	
8.027	12.37	0.67	
8.295	12.37	0.67	
8.496	12.37	0.67	
8.795	12.36	0.65	
9.019	12.35	0.66	
15 December 1982			$\alpha = 9^{\circ}.4$
$2^{h}.224$	$12^{m}.41$		
2.421	12.40		
2.935	12.41		
3.092	12.40		
3.495	12.40		
4.023	12.41		
4.181	12.41		
4.561	12.43		
4.733	12.43		
5.059	12.41		
5.255	12.40		
5.695	12.39		
5.866	12.37		
6.264	12.37		
16 January 1983			$\alpha = 16^{\circ}.7$
$2^{h}.231$	$13^{m}.130$	$0^{m}.69$	$0^{m}.31$
3.491	13.062	0.69	
4.604	13.078	0.70	
5.688	13.105	0.69	
6.966	13.109	0.69	
11 February 1983			$\alpha = 18^{\circ}.6$
$3^{h}.582$	$13^{m}.51$	$0^{m}.70$	$0^{m}.37$
9 March 1983			$\alpha = 17^{\circ}.7$
$3^{h}.225$	$13^{m}.85$	$0^{m}.67$	$0^{m}.34$
10 March 1983			$\alpha = 17^{\circ}.6$
$3^{h}.428$	$13^{m}.84$	$0^{m}.65$	

FIGURE CAPTIONS

Figure 1. A least-squares fit of a circular limb profile to the observed chords across Minerva. Arrows indicate chords derived from photoelectric or video observations. The dashed lines represent constraints placed on the solution by the closest negative photoelectric observations.

Figure 2. The ground track of the 22 November 1982 occultation by Minerva determined on the basis of the solution shown in Figure 1.

Figure 3. Rotational lightcurves of Minerva observed at the 72-inch Perkins reflector. Examination of comparison star observations indicates that the plotted points are usually accurate to within their diameter. The curves have been drawn freehand through the points.

Figure 4. The brightness of Minerva as a function of solar phase angle. Mean brightness has been plotted for nights when more than one measurement was made.

OCCULTATION OF AGK+29 398
BY (93) MINERVA

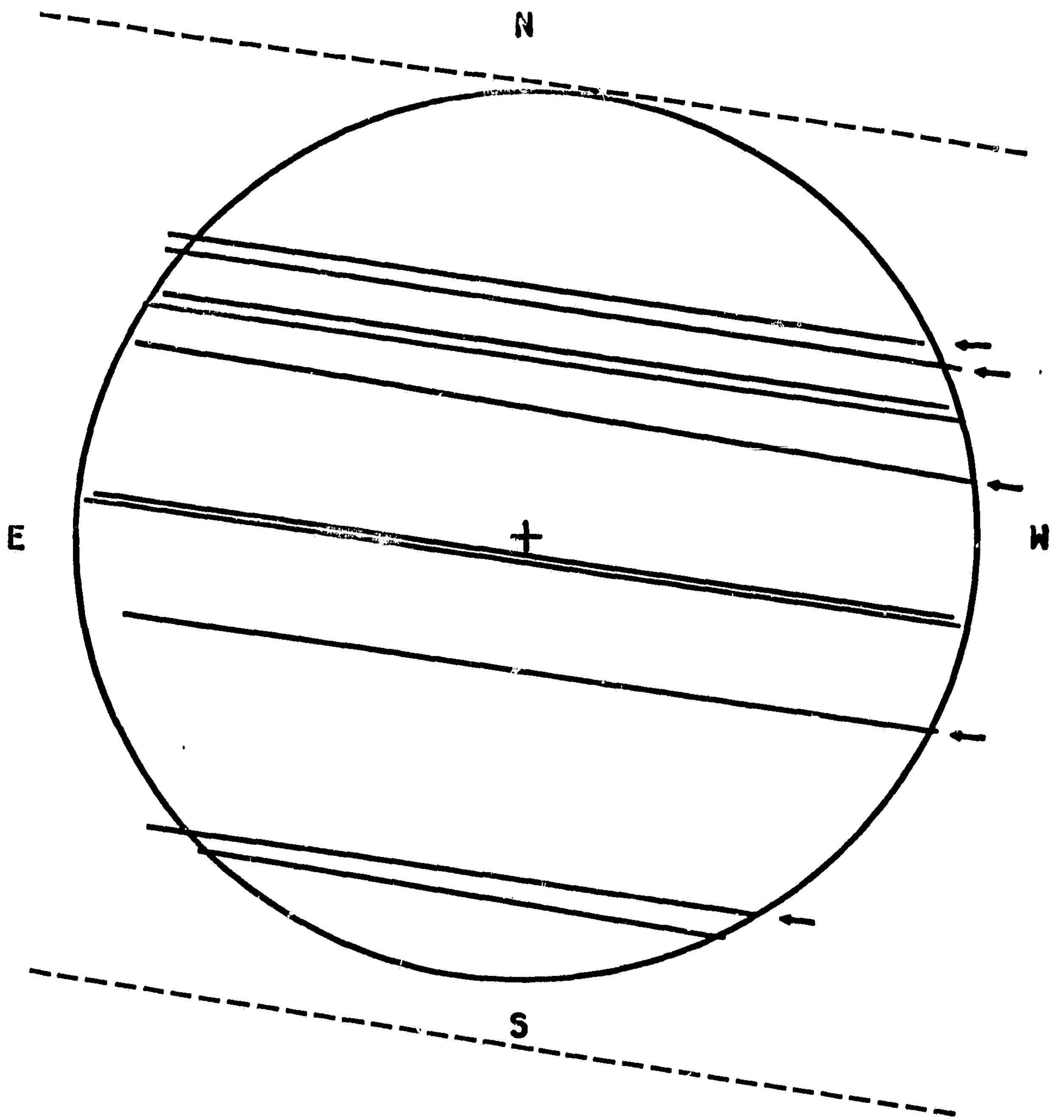

FIGURE 1.

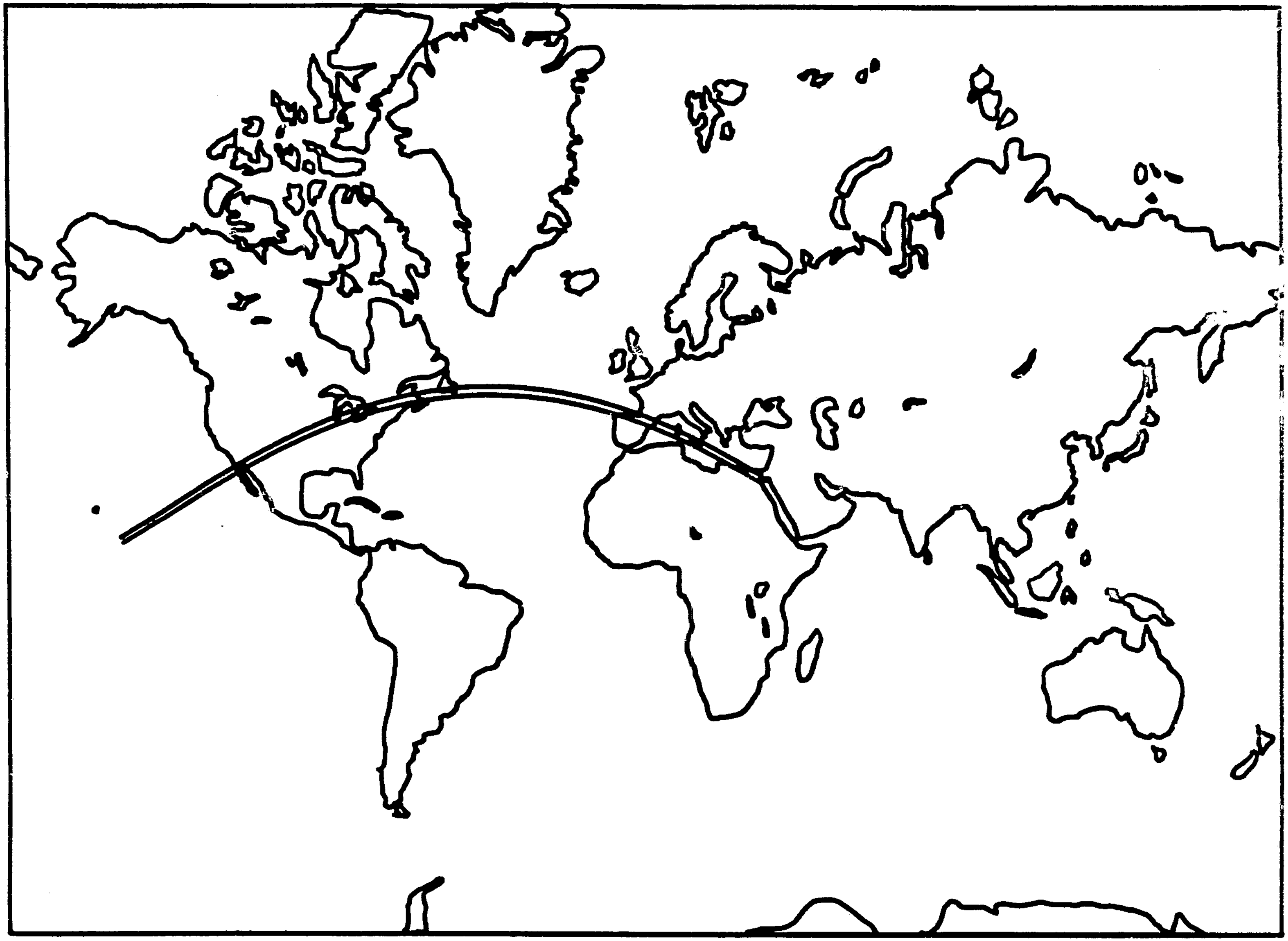

FIGURE 2.

OF POOR QUALITY

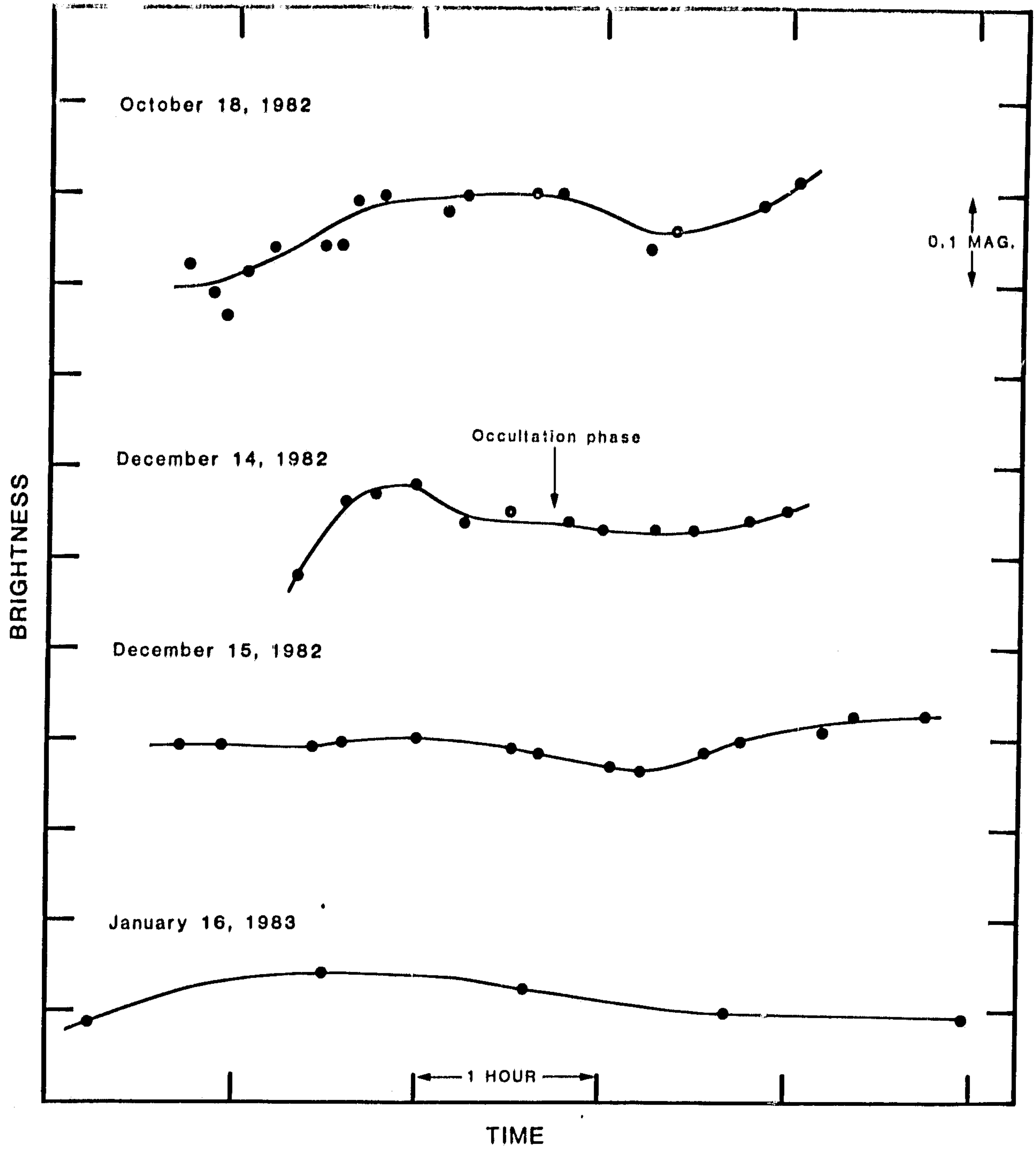

FIGURE 3.

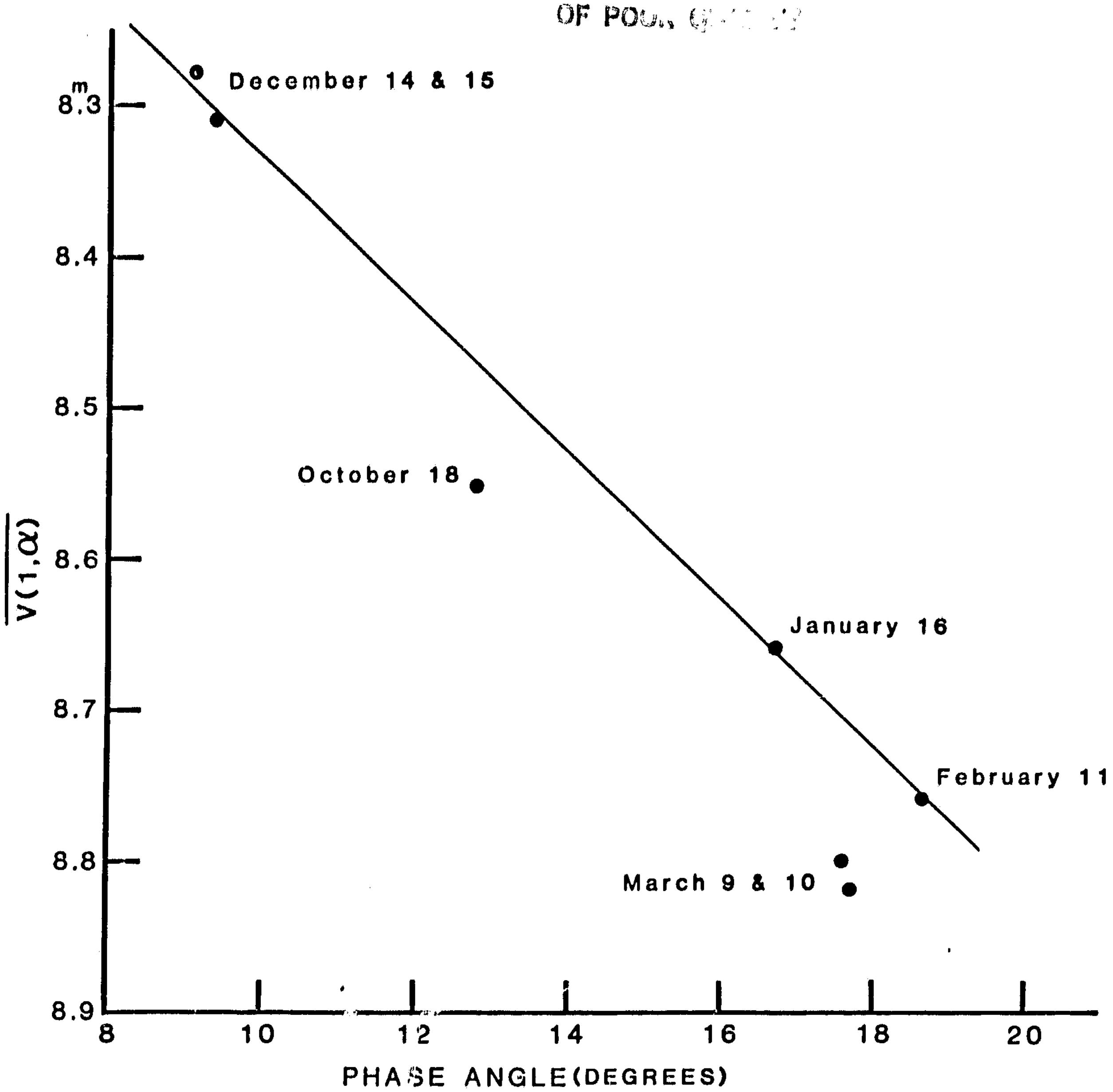
December 14 & 15
October 18
January 16
February 11
March 9 & 10
8.3
8.4
8.5
8.6
8.7
8.8
8.9
V(1,α)
8
10
12
14
16
18
20
PHASE ANGLE(DEGREES)

FIGURE 4.