OBSERVATIONS OF THE 8 DECEMBER 1987 OCCULTATION OF AG +40°0783 BY 324 BAMBERGA

R. L. MILLIS, L. H. WASSERMAN, O. G. FRANZ, E. BOWELL, R. A. NYE, D. T. THOMPSON, AND N. M. WHITE
Lowell Observatory, Flagstaff, Arizona 86001

W. B. HUBBARD, R. E. EPLEE, JR., L. A. LEBOFSKY, R. L. MARCIALIS, R. J. GREENBERG, AND D. M. HUNTEN
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

H. J. REITSEMA
Ball Aerospace Systems Division, Boulder, Colorado 80306

QIAN BOCHEN
Shanghai Observatory, Shanghai, China

D. W. DUNHAM
International Occultation Timing Association (IOTA) and Computer Sciences Corporation, Lanham–Seabrook, Maryland 20706

P. D. MALEY
International Occultation Timing Association (IOTA), Houston, Texas 77059

A. R. KLEMOLA
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

D. K. YEOMANS
Jet Propulsion Laboratory, Pasadena, California 91109
Received 6 March 1989; revised 15 May 1989

ABSTRACT

The occultation of AG + 40°0783 by 324 Bamberga on 8 December 1987 was observed at 13 sites in the United States, Japan, and China. At four sites the event was observed photoelectrically; the other observations were visual. A least-squares fit of a circular limb profile to the data gives a diameter of 227.6 ± 1.8 km. However, this solution is inconsistent with a negative visual observation near the northern edge of the ground track. The inconsistency cannot be removed by assuming an elliptical profile. The data suggest that Bamberga, despite its low-amplitude light curve, may depart significantly from a spherical or ellipsoidal shape. The asteroid also appears to be at least 10% smaller than indicated by infrared radiometry.

I. INTRODUCTION

On 8 December 1987, the asteroid 324 Bamberga occulted AG + 40°0783, a ninth magnitude star in Auriga. This occultation, first predicted by Wasserman *et al.* (1985), had several favorable characteristics. In particular, it was expected to be visible in the telescope-rich areas of the western United States and eastern Asia. The predicted duration of the occultation, 29.5 s, was comparatively long and the angular diameter of Bamberga was sufficiently large so that the location of the occultation ground track could be accurately predicted. Accordingly, a cooperative effort to observe this occultation, involving both professional and amateur astronomers, was organized. In this paper, we report the results of that effort.

The initial predicted location of the ground track for the occultation was refined on the basis of plates taken with the 20 in. Carnegie Double Astrograph at Lick Observatory on 19 November 1987 and with the 18 in. Lowell Astrograph on 2 and 6 December 1987. Three exposures were made each night. The positions of AG + 40°0783 and of Bamberga relative to its ephemeris were measured with the Gaertner automatic measuring machine at Lick and the PDS microdensitometer at Lowell. All exposures were weighted equally and averaged to give the final predicted track shown in Figs. 1(a) and 1(b). An updated orbit incorporating the Lick and Lowell observations was computed at the Jet Propulsion Laboratory and used for the final prediction. The formal 1σ cross-track uncertainty in the predicted ground track location was just under half the width of the track. The track shown in Figs. 1(a) and 1(b) is displaced to the south about three track widths relative to the nominal track published by Wasserman *et al.* (1985).

According to Tholen (1989), Bamberga is a CP-type asteroid. Bowell *et al.* (1979) quote its diameter as 256 km, a value determined from ground-based infrared radiometry. This asteroid was observed twice by *IRAS* and a diameter of 242 ± 7 km was derived by Matson *et al.* (1986) from those data. Bamberga's light curve has been studied by Gehrels and Owings (1962) and Scaltriti *et al.* (1980). The latter authors determined the rotational period to be 29.42 ± 0.01 hr, which is unusually long compared with the periods of other large asteroids. Both Gehrels and Owings and Scaltriti *et al.* found the peak-to-peak amplitude of the light curve to be near 0.07 mag, but the asteroid's longitude when observed by these investigators differed substantially from that at the time of the occultation.

II. OBSERVATIONS AND ANALYSIS

Six portable telescopes equipped with photoelectric photometers were deployed for this occultation by astronomers

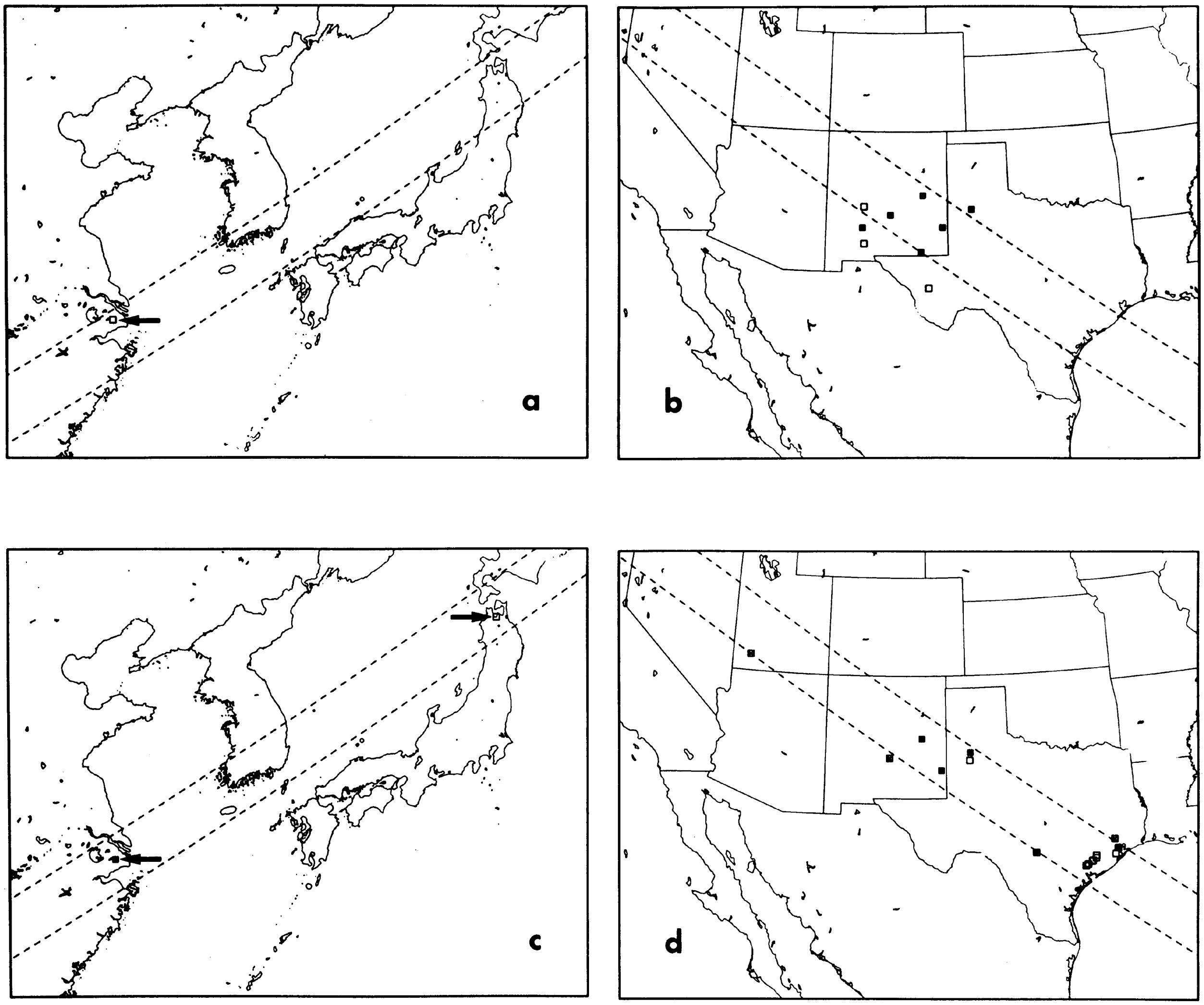

FIG. 1. (a) and (b) Maps showing the final predicted ground track of the 8 December 1987 occultation of AG +40°0783 by 324 Bamberga as it crossed eastern Asia (China, Korea, and Japan) and the southwestern United States, respectively. Filled squares indicate the positions of photoelectrically equipped portable telescopes deployed for this event by the Lowell Observatory and the University of Arizona. Open squares mark the locations of permanent observatories where photoelectric observations were attempted. (c) and (d) The "observed" location of the ground track based on observations from 13 sites. Filled squares are locations where the occultation was observed photoelectrically, while the open squares denote sites where it was detected visually. The squares containing crosses mark sites near the edges of the path where observers reported that an occultation did not occur.

from the University of Arizona and the Lowell Observatory. Photoelectric monitoring of the event also was undertaken with permanently mounted telescopes at Shanghai Observatory, New Mexico State University, McDonald Observatory, and the Joint Observatory for Cometary Research. The locations of the portable telescopes are indicated by filled squares in Fig. 1(b), while the permanent observatories are shown as open squares in that figure and in Fig. 1(a). Additionally, visual observations of the occultation were attempted at many places. This effort was particularly intensive in Texas, where 45 visual observers coordinated by the International Occultation Timing Association (IOTA) turned out.

The occultation was actually observed at the 13 sites marked by filled or open squares in Figs. 1(c) and 1(d). At four of these (indicated by filled squares) the observations were made photoelectrically; the others were manned by visual observers (open squares). The coordinates and altitudes of the 13 successful sites are listed in Table I along with the names of the corresponding observers and the size of their telescopes. The same information is given for five other sites relatively near the edges of the track [marked by squares containing crosses in Fig. 1(d)] where negative results were reported. As will be discussed, some of the negative observations are useful in constraining the least-squares solution for the diameter of the asteroid and provide additional clues to Bamberga's shape.

The observed times of immersion and emersion at the 13 successful sites are listed in Table II. (Emersion was not observed at site 8 because high winds deflected the telescope.) No correction for reaction time has been applied to the times reported by visual observers. The observed times of immersion and emersion, the site coordinates and altitudes given in Table I, Bamberga's ephemeris listed in Table III [based on an orbit by Yeomans (1987)], and the coordinates of AG +40°0783 (R.A. $6^{h}37^{m}18^{s}.500$, Dec. $+40°9'21''.21$) determined from the Lick and Lowell plates

TABLE I. Observing sites.

Site No.	Site Name	Longitude	Latitude	Altitude (m)	Telescope Aperture (m)	Observers
1	Humble, Texas	$6^h20^m39\overset{s}{.}01$W	+30°00′29″.9	21	0.20	K. Kaufman
2	La Porte, Texas	6 20 08.6 W	+29 37 51.2	3	0.20	R. Harper
3*	Abernathy, Texas	6 47 27.40W	+33 50 53.10	1000	0.36	R. Millis D. Thompson
4	Algoa, Texas	6 20 41.87W	+29 24 06.07	11	0.20	A. Kelly
5	Lubbock, Texas	6 47 34.50W	+33 32 13.00	30	0.32	P. Bell
6*	Shanghai, China	8 04 44.23E	+31 05 46.1	97	1.56	Qian Bochen
7	Hungerford, Texas	6 24 19.63W	+29 24 13.19	32	0.20	B. Wilson
8*	Fort Sumner, New Mexico	6 57 02.00W	+34 26 05.00	1230	0.36	L. Lebofsky R. Marcialis
9	Wharton, Texas	6 24 23.08W	+29 18 17.55	30	0.25	L. Mitchell
10	Pierce, Texas	6 25 03.20W	+29 12 06.84	32	0.20	B. Bourgeois
11	El Campo, Texas	6 25 10.75W	+29 11 19.34	32	0.25	K. Drake
12	Aomori City, Japan	9 23 12.07E	+40 49 31.00	3	0.07	Odagiri
13	Ganado, Texas	6 25 58.08W	+29 04 35.41	21	0.20	D. Pearce
14	Jackson County, Texas	6 26 25.03W	+29 00 48.50	21	0.20	M. Delavoryas
15*	Tatum, New Mexico	6 53 12.71W	+33 08 30.00	1204	0.36	L. Wasserman R. Nye
16	Cedar City, Utah	7 32 29.66W	+37 39 52.62	1740	0.36 0.20 0.20 0.20	B. Sorensen C. Howard K. Starmer V. Denniston
17	Pipe Creek, Texas	6 35 33.1 W	+29 40 25.7	549	0.40	D. McDavid
18*	Carrizozo, New Mexico	7 03 28.93W	+33 38 48.5	1654	0.36	W. Hubbard E. Eplee

*Photoelectric observation; all others are visual.

TABLE II. Observations and residuals.

Site No.	Universal Time Immersion	Universal Time Emersion	Weight	Radial Residual Immersion (km)	Radial Residual Emersion (km)	Time Shift (sec)
3	$12^h36^m06\overset{s}{.}26$	$12^h36^m23\overset{s}{.}90$	1.0	5.8	2.4	...
4	12 35 12.26	12 35 32.30	0.2	−1.2	−1.2	−1.6
5	12 36 06.0	12 36 26.2	0.2	−6.7	−6.7	−2.4
6	12 54 54.7	12 55 19.5	0.5	−3.2	−3.2	+2.0
7	12 35 13.2	12 35 37.4	0.2	−5.6	−5.6	−1.0
8	12 36 18.5	...	1.0	−5.6	...	...
9	12 35 12.26	12 35 37.85	0.2	−0.6	−0.6	−1.3
10	12 35 13.0	12 35 38.0	0.2	−2.9	−2.9	−1.6
11	12 35 12.9	12 35 39.1	0.2	2.7	2.7	−2.1
12	12 52 25.0	12 52 49.0	0.2	−2.0	−2.0	−10.6
13	12 35 13.40	12 35 37.76	0.2	−0.7	−0.7	−1.5
14	12 35 12.4	12 35 38.2	0.2	9.4	9.4	−1.1
15	12 36 06.14	12 36 29.58	1.0	3.5	0.1	...

TABLE III. Ephemeris of 324 Bamberga.

Ephemeris Date at 0^h (ET)	(1950.0) RA	Dec	Δ (AU)
5 Dec 87	$6^h41^m19\overset{s}{.}650$	$+40°07'52\overset{''}{.}71$	1.268079
6 Dec 87	6 40 13.696	+40 08 34.72	1.266691
7 Dec 87	6 39 05.850	+40 09 03.97	1.265523
8 Dec 87	6 37 56.209	+40 09 20.06	1.264577
9 Dec 87	6 36 44.875	+40 09 22.62	1.263858
10 Dec 87	6 35 31.954	+40 09 11.29	1.263368
11 Dec 87	6 34 17.556	+40 08 45.75	1.263112
12 Dec 87	6 33 01.798	+40 08 05.68	1.263092

and referred to equator and equinox 1950 provide the basis for determining the size and shape of the asteroid's apparent limb profile. The steps to be followed in the analysis are well established, and have been described in detail by several investigators (e.g., Millis and Dunham 1989). Here we simply note that each observed time of immersion or emersion establishes a point on the apparent limb profile. Conventionally, a circle or ellipse is fitted by least squares through all observed points on the limb to establish the best representation of the size and shape of the asteroid. Corrections in right ascension and declination to the asteroid's ephemeris are also derived from the least-squares solution, although it is understood that all or part of these errors could be in the star's position.

The results of a least-squares fit of a circular limb profile to the observations of the occultation are given in Table IV and shown graphically in Fig. 2. In the solution, weights were assigned to the data from the individual sites as indicated in column 4 of Table II. The photoelectric data from sites 3, 8, and 15 (indicated by arrows in Fig. 2) have been given the greatest weight. At sites 3 and 15 the occultation light curves were simultaneously recorded electronically with WWV time signals. Consequently, their reported times of immersion and emersion are believed to be accurate to within ± 0.01 s. WWV reception failed at site 8, but a secondary calibration provided absolute timing accuracy of ± 0.2 s or better. At Shanghai Observatory (also marked by an arrow in Fig. 2), the relative times of the star's disappearance and reappearance are known to within approximately ± 0.1 s, but the absolute timing is less certain. Visual observations, which depend on subjective matters of perception and reaction time, generally have relative errors in the times of immersion and emersion of a few tenths of a second and an uncertainty on the order of a second or more in the absolute times of these events. Accordingly, they have been given lower weight in the solution. While this scheme of weighting the observations is, in our opinion, appropriate, it should be noted that one derives the same diameter as that quoted in Table IV, to within the errors, if all the data are weighted equally.

Because we believe that real limb irregularities, rather than timing errors, are the dominant cause of departures of the data from the fitted circular profile, radial residuals as opposed to timing residuals were minimized in the least-squares solution (see Dunham *et al.* 1984). Additionally, we have included the response times of the visual observers as adjustable parameters in the solution for the asteroid's diameter as discussed by Millis *et al.* (1989). A "response time" at Shanghai was also included because the absolute timing accuracy of those photoelectric measurements was relatively uncertain. The radial residuals at each site relative to the fitted limb are given in columns 5 and 6 of Table II, and the time shifts for each visual observer and for Shanghai are in the final column. All the shifts for the visual observers are negative, and thus are in the sense expected if reaction times were underestimated or not applied. Except in the case of the data from Aomori City, the time shifts are similar in magnitude to those derived from previous occultation analyses, when one allows for the absence of estimated reaction time corrections in the reported times of immersion and emersion. At Aomori City, a clock error of several seconds must be present in addition to the observer's reaction time. It is true that approximately 16 to 19 min elapsed between the observations of the occultation in the United States and those in Japan and China. However, if the rotational period of Bamberga is 29.42 hr as measured by Scaltriti *et al.* (1980), then the asteroid would have rotated only about $3\overset{\circ}{.}5$ as its shadow crossed the Pacific Ocean, causing only minor changes in the apparent limb profile.

Figures 1(c) and 1(d) show the location of the "actual" occultation ground track as derived from the results given in Table IV. Note that the path is shifted northward relative to the predicted path [shown in Figs. 1(a) and 1(b)] by approximately three tenths of the predicted track width.

III. DISCUSSION

The diameter of 227.6 ± 1.8 km derived from the occultation observations is approximately 10% smaller than published radiometric estimates of Bamberga's size quoted earlier in this paper. Furthermore, there is evidence in the occultation dataset that the diameter we have derived may be an overestimate of Bamberga's size. The dashed lines in Fig. 2 trace regions in the fundamental plane covered from five of the sites at which observers reported that no occultation occurred. Two of the lines intersect the fitted circle: the

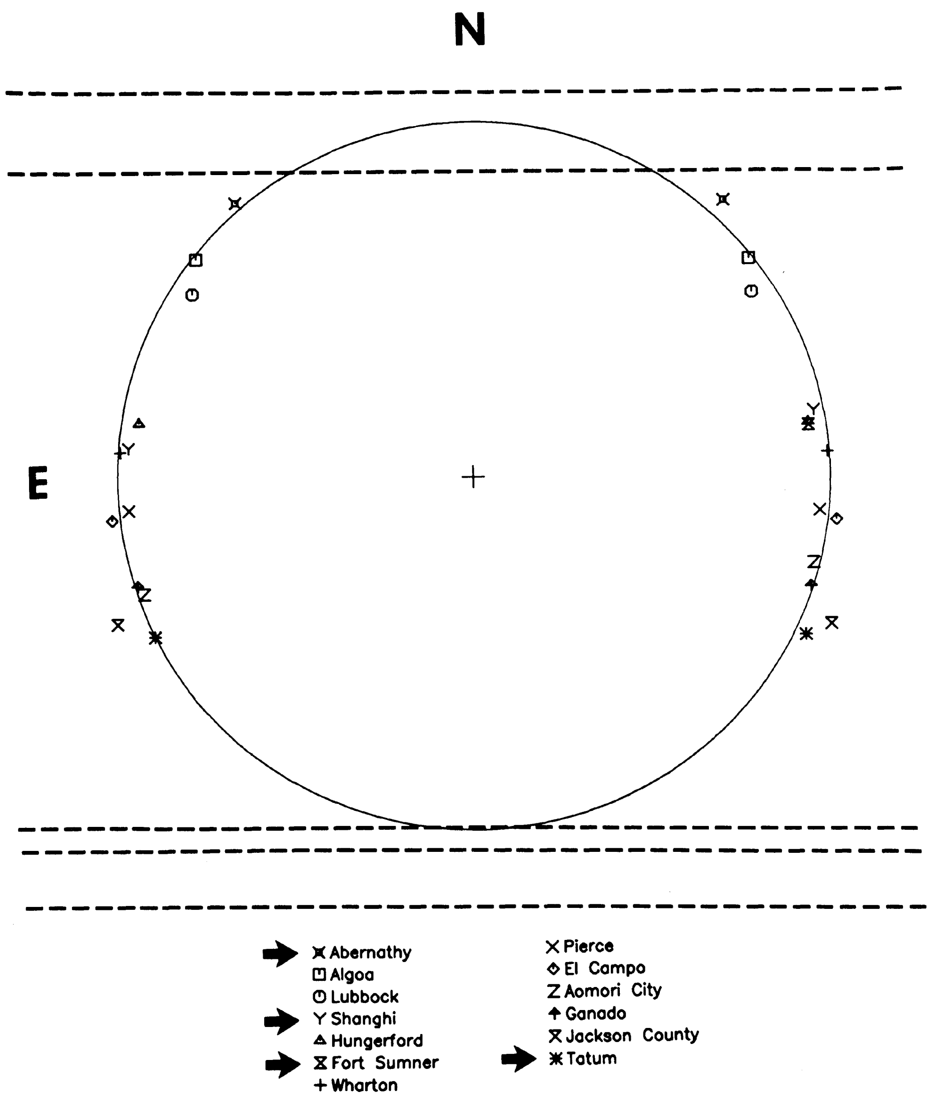

FIG. 2. Circular limb profile fitted by least squares to the occultation data. The sites marked by arrows are those where the observations were recorded photoelectrically; elsewhere the timings are based on visual observations. Constraints placed on the solution by negative reports from sites near the edges of the ground track (from north to south, sites 1, 2, 16, 17, and 18 in Table I) are indicated by dashed lines.

one on the north corresponds to La Porte, TX, where R. Harper observed the occultation visually; the one on the south corresponds to Southern Utah State College in Cedar City, where four visual observers independently reported no occultation. The negative observations at Cedar City imply that the actual limb is inside the fitted profile by at least 1.5 km on the south, while the report from La Porte indicates that the corresponding deviation on the north is 16 km or more. One cannot escape this dilemma by fitting an elliptical limb profile to the data; such an approach results in a much more severe violation of the constraints imposed by the negative observations. Given that there were four observers at Cedar City, the negative report from that site seems firmly established. The corresponding residual, however, is comparable to those seen along the eastern and western limbs and would not imply an unusual departure from an overall circular profile. The observation from La Porte, on the other hand, implies a much more dramatic irregularity. Because only one observer was present at this site, the reality of the indicated large irregularity in Bamberga's limb must be re-

TABLE IV. Results of least-squares solution.

Diameter	227.6 ± 1.8 km
Correction to Right Ascension	$+0^{\rm s}.04932 \pm 0^{\rm s}.00010$
Correction to Declination	$-0''.6688 \pm 0''.0022$

garded as less firmly established. It is possible that the wrong star was monitored or the observer's attention was diverted. We do emphasize, however, that the occultation was easily detectable visually. A similar situation occurred in connection with the 1982 occultation by 93 Minerva (Millis *et al.* 1985). Both incidents serve to emphasize the need for more occultation observers.

Given the large gap in observational coverage between the southernmost observed chord at Tatum, NM, and the negative observations at Cedar City, Utah, and recognizing the observational evidence that the northern end of the asteroid may be lopped off, one must admit that the actual cross-sectional area of the face of Bamberga seen at the time of the occultation could be significantly smaller than that corresponding to the fitted circular profile. However, if such were the case, an even larger error in the ground-based and *IRAS* radiometric diameters would be indicated and the occultation observations would require that Bamberga have a rather elongated, blocklike shape. Of course, there is ample evidence that many asteroids are quite irregular in shape, but such a state of affairs for Bamberga would appear to contradict the low-amplitude brightness variations observed by Gehrels and Owings (1962) and Scaltriti *et al.* (1980). These investigators observed when the asteroid was near ecliptic longitudes 161° and 50°, respectively, whereas the occultation occurred at longitude 277°. While light-curve observations taken near the time of the occultation have not been published, it seems unlikely that Bamberga's apparent cross section could have varied by only 7% due to rotation when at 161° and 50°, but still present a highly noncircular profile when at 277°. Perhaps an extremely oblate object having its rotational pole perpendicular to its orbital plane could produce this type of photometric behavior, but the limb profile plotted in Fig. 2 lends little support to this interpretation.

Obviously, the existing information is not sufficient to permit an exact specification of Bamberga's figure. Additional photometry at a variety of different aspects would help resolve the matter, as would observations of future occultations by this body. However, in spite of the remaining questions about the shape of Bamberga, we do believe that the diameter given in Table IV is a firm upper limit. A realistic estimate of the downside uncertainty in the diameter is difficult to specify. For the reasons discussed above, we doubt that the effective diameter can be as small as 210 km (which corresponds to an actual cross-sectional area 15% smaller than that of the fitted circle). A reasonable guess at the downside uncertainty can probably be had by quadrupling the formal 1σ error bar. Hence, in our opinion, the best estimate of the effective diameter of Bamberga from the occultation observations is $227 \; +2/-8$ km.

Three hours prior to the occultation, the V magnitude of Bamberga was measured to be 0.64 ± 0.01 mag fainter than that of AG $+40°0783$ and was constant within the quoted limits for $2\frac{1}{2}$ hr. In view of this steady behavior and Bamberga's known long rotational period, it is safe to assume that the magnitude difference quoted above also pertains, within a percent or so, to the time of occultation. Some weeks earlier, we had measured the V magnitude of AG $+40°0783$ to be 9.16 ± 0.02. Consequently, the apparent V magnitude of the asteroid at the time of occultation was $9.80 + 0.03$. Assuming that $G = 0.10$ (Tedesco 1986), it follows that $H = 6.81 \pm 0.06$ mag, whence the visual geometric albedo on the H,G magnitude system (Bowell *et al.* 1989) is $P_H = 0.066^{+0.009}_{-0.005}$.

This research was supported at Lowell Observatory by NASA Grant No. NSG-7603, at the University of Arizona by NASA Grant Nos. NSG-7045 and NSG-7114, and at Lick Observatory by NSF Grant No. AST 84-14142. We thank our colleagues at McDonald Observatory, New Mexico State University, and the Joint Observatory for Cometary Research, and the large cadre of visual observers who attempted successfully and otherwise to observe the 8 December occultation. Their reports contributed significantly to this research. Dr. Wayne Warren arranged for rapid transmission of the final predictions for this occultation to observers in China.

REFERENCES

Bowell, E., Gehrels, T., and Zellner, B. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 1108.

Bowell, E., Harris, A. W., and Lumme, K. (1989). In preparation.

Dunham, E. W., Baron, R. L., Connar, S., Dunham, D. W., Dunham, J. B., Schneider, G., Cohen, H. L., Helms, V. T., Croom, M., and Safko, J. (1984). Astron. J. **89**, 1755.

Gehrels, T., and Owings, D. (1962). Astrophys. J. **135**, 906.

Matson, D. L., Veeder, G. J., Walker, R. G., Fowler, J. W., Chillemi, J. R., Lebofsky, L. A., and Tedesco, E. F. (1986). In *IRAS Asteroid and Comet Survey: Preprint Version No. 1, Part III*, edited by D. L. Matson (Jet Propulsion Laboratory, Pasadena), p. 14.

Millis, R. L., and Dunham, D. W. (1989). In *Asteroids II*, edited by R. P. Binzel and T. Gehrels (University of Arizona, Tucson) (in press).

Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Nye, R., Osborn, W., and Klemola, A. (1985). Icarus **61**, 124.

Millis, R. L., Wasserman, L. H., Bowell, E., Harris, A. W., Young, J. W., Barucci, M. A., Williamon, R. M., Manly, P. L., Dunham, D. W., Olson, R. W., Baggett, W. E., and Zeigler, K. W. (1989). Icarus (in press).

Scaltriti, F., Zappalà, V., Stanzel, R., Blanco, C., Catalano, S., and Young, J. W. (1980). Icarus **43**, 391.

Tedesco, E. F. (1986). In *IRAS Asteroid and Comet Survey: Preprint Version No. 1, Part II*, edited by D. L. Matson (Jet Propulsion Laboratory, Pasadena), p. 9:1.

Tholen, D. J. (1989). Private communication.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1985). Astron. J. **90**, 2124.

Yeomans, D. K. (1987). Unpublished.