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THE DIAMETER OF JUNO FROM ITS OCCULTATION OF AG+0°1022

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ABSTRACT

The 11 December 1979 occultation of AG+0°1022 by Juno was observed photoelectrically from 15 sites distributed across the occultation track. The observations are well represented by a mean elliptical limb profile having semimajor and semiminor axes of 145.2 ± 0.8 and 122.8 ± 1.9 km, respectively. The corresponding effective diameter of Juno is 267 ± 5 km, where the uncertainty has been conservatively increased to reflect the presence of limb irregularities clearly seen in the observations. Published radiometric and polarimetric diameters for Juno are 6% to 7% smaller than the occultation result. No secondary occultations attributable to possible satellites of Juno were recorded at any of 23 photoelectrically equipped observing sites.

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I. INTRODUCTION

On 11 December 1979 the asteroid 3 Juno occulted AG+0° 1022, a ninth-magnitude star in the constellation Canis Minor. The initial prediction by Taylor (1979a) indicated that the occultation would be visible along a narrow path crossing portions of Canada and the United States. Because of the opportunity this event provided for directly determining the size and shape of Juno (see Millis and Elliot 1979 for a discussion of the technique), and perhaps because of interest generated by recent reports of minor-planet satellites (e.g., Van Flandern, Tedesco, and Binzel 1979), astronomers from several institutions made plans for observing the 11 December occultation. This paper summarizes the results of those efforts.

II. PREPARATIONS

a) *Astrometry*

The first task in an occultation campaign of this type is refinement of the predictions. Taylor's initial predictions were based solely on Juno's ephemeris and the catalog position of AG+0° 1022. Experience has shown that such predictions may be in error by as much as one arcsecond in the predicted geocentric separation of the star and asteroid at closest approach. For an object at the distance of Juno on 11 December, an error of one arcsecond translates to a cross-track uncertainty in the position of the occultation track of approximately 1000 km, or about four times the expected width of the track.

To reduce the uncertainty in the predictions, 11 plates were taken with the 0.51-m Carnegie Double Astrograph on Mount Hamilton. Both Juno and AG+0° 1022 were present on each plate. The plates were measured with Lick Observatory's Gaertner automatic measuring system relative to a reference frame defined by stars chosen from the Perth 70 catalog. Table I lists the coordinates of AG+0° 1022 and the residuals of Juno relative to its ephemeris derived from the 0.51-m telescope plates. The average values of these parameters were used to derive the "final" predicted track shown in Fig. 1. In addition to crossing much of the continental United States as illustrated in Fig. 1, the track was predicted to traverse the Hawaiian Islands as well. Less extensive astrometric measurements performed at the Royal Greenwich Observatory (Taylor 1979b) and the U.S. Naval Observatory (Harrington 1979) generally supported the Lick results.

b) *Photometry*

Photoelectric photometry of Juno has been published by Groeneveld and Kuiper (1954), Gehrels and Owings (1962), and Chang and Chang (1962). These authors found rotational brightness variation with an amplitude near 0.15 mag and a period of $7\overset{h}{.}210 \pm 0\overset{h}{.}002$. While little change has been reported in the amplitude of Juno's light curve, significant variation in the shape of the light curve has occurred. Figure 2 shows the light curve of Juno observed shortly before the December occultation. Note that the occultation occurred at a rotational phase about halfway down a steeply descending portion of the light curve.

Photometry of AG+0° 1022 on two nights with Lowell Observatory's 1.1-m reflector gave the following *UBV* magnitudes and color indices: $V = 8\overset{m}{.}76 \pm 0\overset{m}{.}01$, $B - V = 0\overset{m}{.}90 \pm 0\overset{m}{.}01$, $U - B = 0\overset{m}{.}55 \pm 0\overset{m}{.}01$. Juno is quite similar in color, with $B - V = 0\overset{m}{.}82$ and $U - B = 0\overset{m}{.}42$ (Bowell *et al.* 1979), values not untypical of an S-type asteroid. At the time of the occultation, the apparent visual magnitude of Juno was expected to be near $8\overset{m}{.}2$. Consequently, the brightness change at immersion and emersion would be about 0.5 mag, regardless of passband.

III. OBSERVATIONS

Circumstances surrounding the occultation of AG+0° 1022 were unusually favorable. The track passed across telescope-rich regions of southern California and Hawaii. The objects involved were relatively bright, permitting the use of small, portable telescopes. (It will be seen later that the portable equipment was crucial to the success of this effort.) The apparent motion of Juno across the sky was comparatively slow, thereby easing timing requirements. For example, a one-second uncertainty in the measured duration of the occultation would cause an uncertainty of less than 4 km in the length of the corresponding chord across Juno.

Table II lists coordinates and other information for sites where the occultation was successfully observed or where clearly negative results were recorded. A wide variety of telescopes was used, ranging from the 3.8-m United Kingdom Infrared Telescope on Mauna Kea, Hawaii to small portable instruments. Equal diversity was present in the data-recording equipment. A few keen-eyed individuals detected the occultation visually. Others used simple photoelectric equipment with output via a strip chart recorder. Several observers had access to high-speed recording devices capable of resolving the Fresnel diffraction pattern, though that aspect of the observations will not be discussed in this paper (see Reitsema *et al.* 1981). Because of the large number of observing sites, details of individual sets of equipment, except for telescope aperture and passband, are omitted.

The observed times of immersion and emersion are given in columns 2 and 3 of Table III for the 15 sites where the occultation was observed photoelectrically and the three sites where visual observations were made. Quoted timing uncertainties were estimated by the individual observers. At Wrightwood, California; Eau

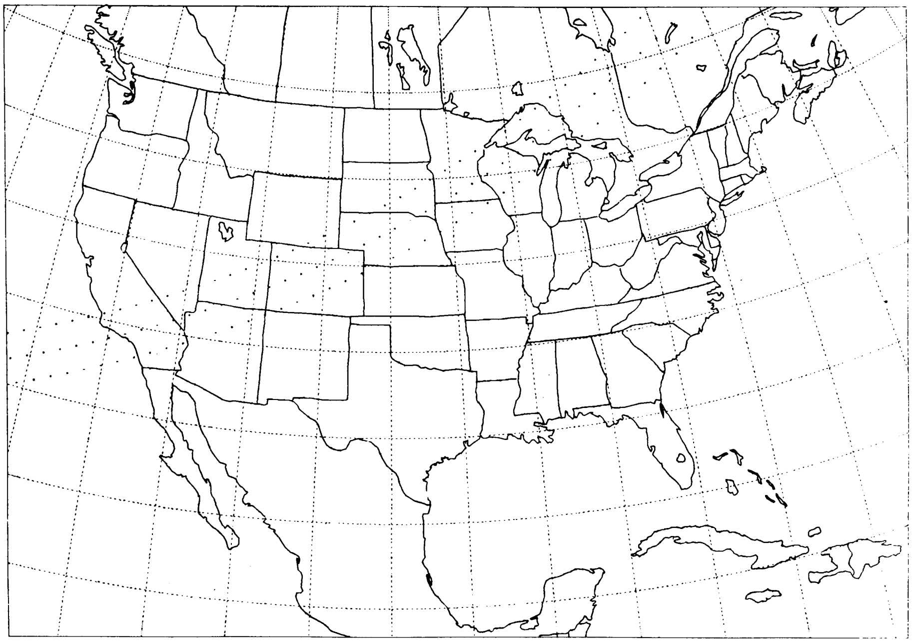

FIG. 1. The predicted track of the 11 December 1979 occultation of AG+0°1022 by Juno based on 11 plates taken with the 0.51-m Carnegie Double Astrograph at Lick Observatory.

Claire, Wisconsin; and Mauna Kea, relative timing was significantly more accurate than absolute timing, so the duration of the occultation was determined more precisely at these sites than the listed uncertainties would suggest.

IV. ANALYSIS

A detailed description of the method of analysis used in this paper has been given by Wasserman *et al.* (1979). Briefly stated, one projects the positions of observers at the corresponding times of immersion and emersion onto a plane known as the Besselian plane which passes through the Earth's center and is instantaneously perpendicular to the axis of the asteroid's shadow. The coordinates of the points in this plane relative to x,y axes moving with the shadow directly map out the asteroid's limb profile. In principle, with unlimited observational coverage, the limb profile of any asteroid, no matter how irregular, can be precisely mapped. In practice, the observed points of stellar immersion and emersion are usually rather widely spaced around the limb, and the true profile must be approximated, usually by a circle or ellipse fitted to the data by least squares.

Early in our analysis it was apparent that the limb profile of Juno seen at the time of the occultation could not be represented adequately by a circle. The best-fitting elliptical solution based on the 15 pairs of photoelectric timings is shown in Fig. 3. Constraints placed on the solution by the negative results obtained at Palomar Mountain and near Lone Pine, California are illustrated by the solid diagonal lines. The observers near Lone Pine were about 10 km outside the track to the north; Palomar Mountain missed by nearly 20 km. The visual observa-

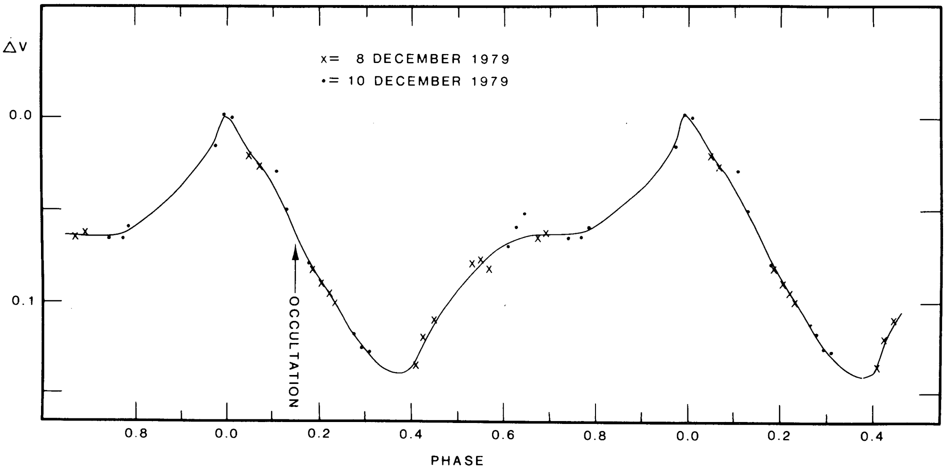

FIG 2. The rotational light curve of Juno derived from observations on 8 and 10 December 1979 with the Lowell Observatory 1.1-m reflector. The arrow indicates Juno's rotational phase at the time of the 11 December 1979 occultation.

TABLE I. Astrometry.

Epoch (UT 1979)	Juno (1950) α	Juno (1950) δ	Residuals ($O-C$) α	Residuals ($O-C$) δ	AG+0°1022 (1950) α	AG+0°1022 (1950) δ
Nov. 21.54167	$7^{h}46^{m}11^{s}.687$	2°06′26″.98	$0^{s}.033$	0″.02	$7^{h}45^{m}23^{s}.777$	0°35′40″.42
Nov. 25.43091	7 47 4.498	1 42 43.13	0.033	0.18	23.774	40.39
Nov. 25.43299	4.520	42.23	0.039	0.01	23.778	40.54
Nov. 25.44479	4.618	38.29	0.047	0.16	23.772	40.47
Nov. 25.44618	4.624	37.75	0.043	0.11	23.772	40.41
Dec. 1.45243	7 47 25.997	1 11 6.03	0.034	0.19	23.781	40.54
Dec. 1.45382	25.994	5.60	0.038	0.15	23.780	40.42
Dec. 1.45521	25.990	5.48	0.040	0.42	23.788	40.48
Dec. 1.46285	25.962	3.04	0.048	0.12	23.764	40.45
Dec. 1.46424	25.925	2.55	0.017	0.02	23.782	40.28
Dec. 1.46563	25.935	2.34	0.034	0.20	23.778	40.57
Mean	—	—	0.037 ±0.003 s.e.	0.14 ±0.04 s.e.	23.778 ±0.002 s.e.	40.45 ±0.03

Predicted time of geocentric conjunction in R.A.: $9^{h}3^{m}12^{s}.5$ UT.
Predicted separation in declination at conjunction: 4″.56.
Predicted time of minimum geocentric separation: $9^{h}10^{m}25^{s}.1$ UT.
Predicted minimum separation: 4″.19.

tions were not included in this solution but will be discussed in Sec. V c.

The elliptical solution illustrated in Fig. 3 had five free parameters: lengths of the semimajor and semiminor axes of the apparent ellipse, position angle of the minor axis, and corrections to the right ascension and declination of Juno. We have arbitrarily assumed that all positional error is in Juno's ephemeris. Table IV contains the resulting values for these five parameters along with the time of conjunction and the difference in declination of the star and asteroid at that time. The ephemeris used in the solution is given in Table V, while the radial re-

TABLE II. Observing sites.

Location	Observer(s)	Telescope aperture (m)	Longitude (west)	Latitude (north)	Altitude (m)	Passband Central λ	Passband FWHM
		Photoelectric detections					
Little Lake, Calif.	White, Bertram	0.36[a]	$7^{h}51^{m}39^{s}.53$	35°53′23″.06	1146	4400 Å	1000 Å
Ridgecrest, Calif.	Zellner, Lebofsky	0.36[a]	7 50 35.36	35 39 36.13	679	4300 8000	1200 2000
Mojave, Calif.	Tucker	0.20[a]	7 52 13.47	35 7 35.0	792	unfiltered PMT	
Edwards AFB, Calif.	Franz, A'Hearn	0.36[a]	7 51 26.17	34 59 5.80	691	4400	1000
Haleakala, Hawaii	Cruikshank, Macknik	0.4	10 25 2.09	20 42 37.43	3049	unfiltered PMT	
Barstow, Calif.	Dunham, Wasserman	0.36[a]	7 48 8.72	34 49 4.80	791	4700 7100	1500 1400
Eau Claire, Wis.	Elliott, Bicay, Donnell	0.36	6 5 59.84	44 47 44.42	268		
Stoney Ridge, Calif.	Faulkner	0.76	7 51 59.00	34 17 55.0	1729	5550	850
Wrightwood, Calif.	Harris, Sandmann	0.6	7 50 43.4	34 22 54.0	2286	5550	850
Mt. Wilson, Calif.	Horne	1.5	7 52 13.6	34 13 28.7	1740	unfiltered S-20 PMT	
Los Angeles, Calif. (UCLA)	Ford, McKenna, Etzel, Wood	0.4	7 53 46.05	34 4 10.3	155	unfiltered PMT	
Ludlow, Calif.	Reitsema, Hubbard	0.36[a]	7 44 39.13	34 43 23.7	530	4300 8000	1200 2000
29 Palms, Calif.	Lockwood, DuPuy	0.36[a]	7 44 36.0	34 17 42.0	609	4400	1000
Joshua Tree, Calif.	Stanton	0.4	7 45 33.67	34 6 1.0	1066	4400	1000
Mauna Kea, Hawaii	Becklin, Gatley, Morrison, Kunkle, Lee, Lonsdale	3.8 (UKIRT)	10 21 53.33	19 49 34.0	4200	2.2 μm	0.42 μm
		Visual detections					
Little Lake, Calif.	Young	0.25[a]	7 51 45.5	36 2 56	1000		
China Lake, Calif.	McMahon	0.25	7 50 38.46	35 41 23.8	667		
Oak Flats, Calif.	Nolthenius, Anderson, Hawkins, Lee	0.15[a]	7 54 47.13	34 34 24.0	783		
		Negative observations					
Big Pine, Calif.	Millis, Nye	0.25[a]	7 52 54.3	37 3 13	1180		
Lone Pine, Calif.	Baron, Bowell	0.36[a]	7 51 26.2	36 30 0.9	1155		
Palomar Mtn., Calif.	Gomer, Bus	0.5	7 47 27.36	33 21 22.4	1706		
Flagstaff, Ariz.	Hoag, Martin, Thompson, Lutz	1.1 0.5	7 26 39.2	35 12.1	2210		
Ames, Iowa	Beavers	0.6	6 15 45.8	42 0 20.0	332		
Mt. Lemmon, Ariz.	Wisniewski	1.5	7 23 9.8	32 26 29	2776		
Catalina Stn., Ariz.	Tedesco	1.5	7 22 55.67	32 25 0.7	2510		
Ft. Davis, Texas	Barnes	0.9	6 56 5.34	30 40 17.7	2081		

[a] Portable telescope.

TABLE III. Observations.

Location	Immersion (UTC)	Emersion (UTC)	Residuals (km) Immersion	Residuals (km) Emersion
Little Lake, Calif.	$9^{h}\ 9^{m}58\overset{s}{.}0 \pm 0\overset{s}{.}2$	$9^{h}10^{m}41\overset{s}{.}6 \pm 0\overset{s}{.}2$	5.8	−4.7
Ridgecrest, Calif.	9 9 51.81 ± 0.01	9 10 49.57 ± 0.01	−0.3	3.4
Mojave, Calif.	9 10 3.2 ±0.2	9 11 7.0 ±0.2	−2.1	−1.3
Edwards AFB, Calif.	9 10 0.26 ± 0.02	9 11 7.19 ± 0.02	−2.6	1.2
Haleakala, Hawaii	9 24 48.84 ± 0.1	9 25 $55.96^{+0.1}_{-0.4}$	−5.9	−4.4
Barstow, Calif.	9 9 46.73 ± 0.005	9 10 54.16 ± 0.005	−2.3	0.5
Eau Claire, Wis.[a]	9 0 20.5 ± 0.5	9 1 27.5 ± 0.5	−4.0	1.4
Stoney Ridge, Calif.	9 10 11.3 ± 0.2	9 11 18.6 ± 0.2	1.7	−0.3
Wrightwood, Calif.	9 10 4.20 ± 0.2	9 11 11.73 ± 0.2	2.6	1.4
Mt. Wilson, Calif.	9 10 13.535 ± 0.005	9 11 20.645 ± 0.005	2.3	0.3
Los Angeles, Calif.	9 10 22.92 ± 0.01	9 11 29.89 ± 0.03	2.6	0.0
Ludlow, Calif.	9 9 32.77 ± 0.01	9 10 35.79 ± 0.01	3.8	−0.9
29 Palms, Calif.	9 9 44.07 ± 0.05	9 10 36.67 ± 0.05	4.6	5.1
Joshua Tree, Calif.	9 9 53.80 ± 0.2	9 10 36.82 ± 0.2	0.5	1.5
Mauna Kea, Hawaii	9 25 10.85 ± 2	9 25 41.15 ± 2	−3.7	−7.8
Little Lake, Calif.	9 10 12 ±5	9 10 43 ±5	visual observations	
China Lake, Calif.	—	9 10 50.3		
Oak Flats, Calif.	9 10 24.06 ± 0.2	9 11 29.52 ± 0.2		

[a] The times listed for Eau Claire differ from those published in IAU Circular No. 3431, which had not been corrected for a $0\overset{s}{.}5$ delay introduced by the data-recording scheme.

siduals between the observed and fitted limb are listed in columns 4 and 5 of Table III. It is perhaps worth noting that previous single-chord occultation observations of Juno are consistent with the dimensions derived here (Taylor 1962; Dunham and Sheffer 1979).

V. DISCUSSION

a) *The Size, Shape, and Albedo of Juno*

Observations of the type reported in this paper are primarily motivated by the desire to measure directly, and to high accuracy, the sizes of a representative sample of asteroids. Given this data set, it will be possible to assess objectively the reliability of the radiometric and polarimetric methods of size determination. If necessary, these widely applied, model-dependent techniques can then be recalibrated on the basis of the occultation results.

While occultation observations can precisely gauge an asteroid's dimensions projected onto the plane of the sky, they give no information about its extent along the line of sight. Hence, a diameter determined from a single occultation refers to a particular aspect of the asteroid, while published radiometric and polarimetric diameters are usually in some sense averages over several aspects. A comparison of the occultation and indirect results requires that attention first be given to the asteroid's overall shape. In favorable cases where (1) the orientation of the minor planet's rotational axis is known and (2) the object is large enough that gravity can be expected to ensure a reasonably regular shape, a meaningful estimate of its three-dimensional figure can be made on the basis of occultation results and photometry (e.g., Wasserman *et al.* 1979). However, Juno satisfies neither of the above conditions; and furthermore, its light curve (see Fig. 2) provides ample evidence that significant irregularities and/or albedo variations are present.

Although we cannot derive the overall figure of Juno with confidence, we can argue on the basis of the amplitude of the brightness variation that the apparent cross sectional area of this asteroid does not vary by more than ±7%. Its effective diameter therefore varies with rotational aspect by less than ±3%. Since the occultation occurred near Juno's median brightness (see Fig. 2), the diameter derived from the occultation observations should agree well with an average over all rotational phases and should differ by no more than 3% from the value observed at any phase. Consequently, we have adopted the effective diameter of 267 km from the elliptical solution (with the associated uncertainty conservatively increased to ±5 km) as the occultation diameter of Juno.

The published radiometric and polarimetric diameters (Morrison and Zellner 1979) are respectively 7% and 6% smaller than the occultation result. Considering that an accuracy better than ±5% has never been claimed for the indirect methods, the agreement is about as good as can be expected. It is significantly better than that for Pallas, the only other asteroid whose diameter has been well determined by the occultation method. In that case the radiometric result is about 9% larger, and the polarimetric diameter 18% larger than the occultation value (Wasserman *et al.* 1979). Broadband radiometric measurements of Juno in the 10- and 20-μm bands were obtained by Dr. Charles Telesco with the NASA 3-m Infrared Telescope Facility on Mauna Kea on the night of the occultation. These data will be presented separately in a discussion of the absolute calibration of the radiometric method of the determination of albedos and dimensions of asteroids.

One question remains to be considered: Does the elliptical solution give the best possible picture of Juno's

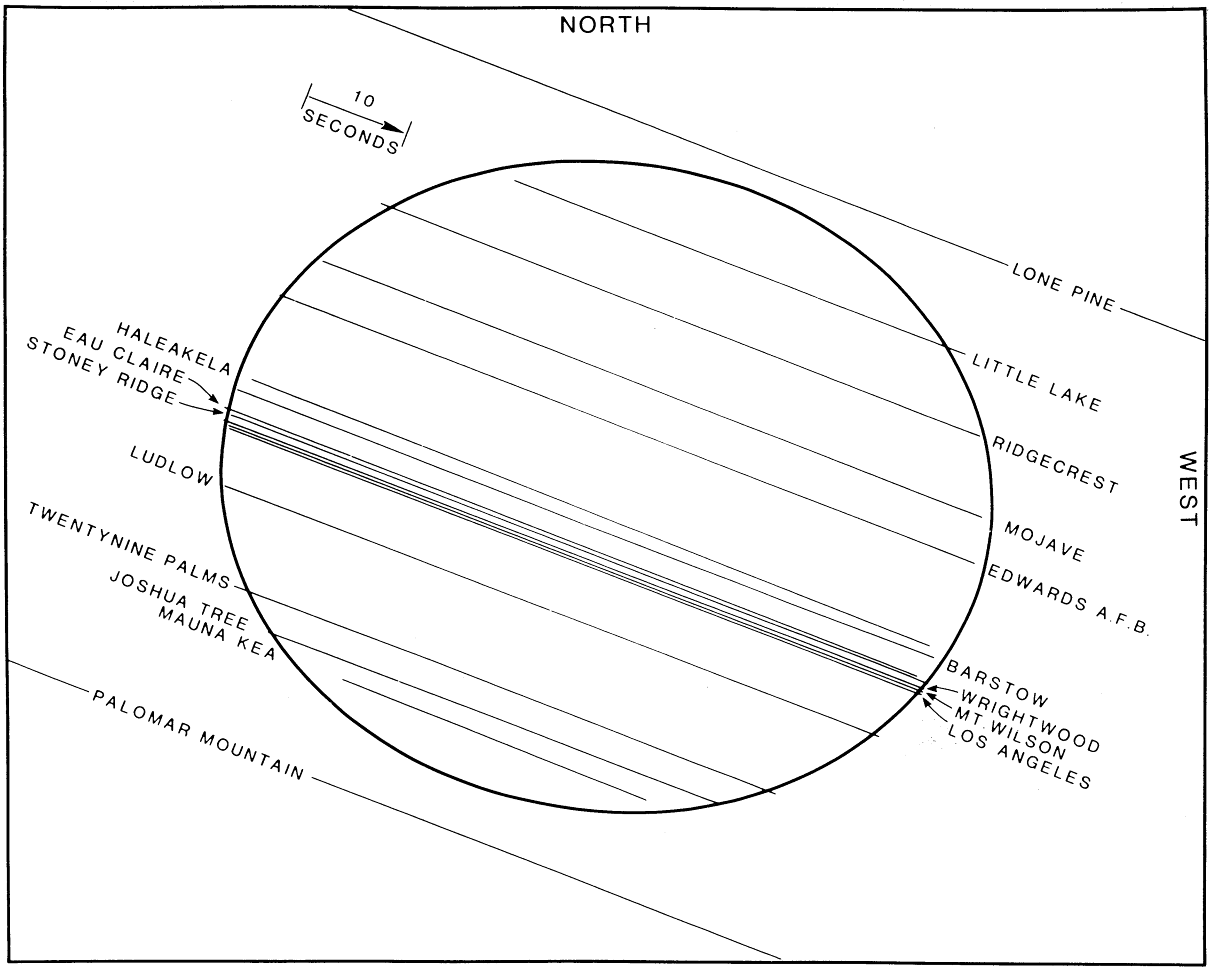

FIG. 3. The elliptical solution. Parallel lines represent chords across Juno as determined from the 15 sets of photoelectric observations. An elliptical limb profile has been fitted by least squares to the end points of the chords. The solid lines labeled "Lone Pine" and "Palomar Mountain" indicate constraints placed on the asteroid's profile by the closest negative observations.

limb at the time of occultation? Certainly, real departures from the fitted elliptical profile are seen. Recall that, except for data from three sites, the photoelectric observations listed in Table III have associated timing uncertainties of 0.2 s or less, corresponding to a spatial uncertainty along the track of no more than 0.8 km. The positions of individual observers are known to significantly better accuracy. Consequently, of the 15 chords in Fig. 3, the end points of 12 are accurate to within the width of the line. The residuals given in Table III show that the measured limb departs from the elliptical solution by as much as ±6 km at some points.

TABLE IV. Results of elliptical solution.

Semimajor axis *a* (km)	145.2 ± 0.8
Semiminor axis *b* (km)	122.8 ± 1.9
Effective radius $(ab)^{1/2}$ (km)	133.5 ± 1.3
Position angle of semiminor axis	$351\overset{\circ}{.}2 \pm 2\overset{\circ}{.}5$
Declination correction[a]	$-0\overset{''}{.}224 \pm 0\overset{''}{.}001$
Right ascension correction[a]	$-0\overset{s}{.}0126 \pm 0\overset{s}{.}0001$
Time of geocentric conjunction in R.A.	$9^h03^m14\overset{s}{.}3$ UTC
Difference in declination (Juno-star) at conjunction	$4\overset{''}{.}55$
Time of minimum geocentric separation	$9^h10^m25\overset{s}{.}7$ UTC
Minimum separation	$4\overset{''}{.}19$

[a] The correction is added to the ephemeris of Juno given in Table V.

TABLE V. Apparent ephemeris of Juno.

Ephemeris day at 0^h ET (1979)	R.A.	Decl.	Δ (AU)
4 Dec	$7^h48^m46\overset{s}{.}146$	$0°55'19\overset{''}{.}90$	1.32512
5 Dec	7 48 37.582	0 51 18.43	1.31902
6 Dec	7 48 27.033	0 47 30.51	1.31306
7 Dec	7 48 14.505	0 43 56.48	1.30724
8 Dec	7 48 00.010	0 40 36.72	1.30156
9 Dec	7 47 43.558	0 37 31.56	1.29602
10 Dec	7 47 25.166	0 34 41.35	1.29063
11 Dec	7 47 04.853	0 32 06.42	1.28540
12 Dec	7 46 42.643	0 29 47.10	1.28033
13 Dec	7 46 18.561	0 27 43.70	1.27541
14 Dec	7 45 52.634	0 25 56.55	1.27066
15 Dec	7 45 24.898	0 24 25.94	1.26609
16 Dec	7 44 55.385	0 23 12.15	1.26169
17 Dec	7 44 24.137	0 22 15.46	1.25746
18 Dec	7 43 51.196	0 21 36.11	1.25342

TABLE VI. Data for Juno at time of occultation.

Mean time of occultation observations	11 Dec 1979 $9^h10^m.5$ UT
Juno-Sun distance r	2.104 AU
Juno-Earth distance Δ	1.284 AU
Phase angle α	$18^\circ.91$
Linear phase coefficient[a] β_V	0.033 ± 0.004 mag/deg
Effective diameter D	267 ± 5 km
Apparent magnitude V	$8^m.22 \pm 0^m.02$
Visual geometric albedo p_V	0.164 ± 0.003

[a] Lumme and Bowell (1981).

A small part of the apparent irregularity may be due to rotation. The Hawaii observations were made approximately 15 min after the occultation occurred in California. During this interval, Juno rotated 12.5 deg. Since the asteroid's brightness was decreasing (see Fig. 2), one might expect the Hawaii chords to be shorter than nearby California observations. That is in fact the case, but the size of the difference, at least for Mauna Kea, is far greater than can be accounted for by the rotation of a smooth triaxial ellipsoid. Furthermore, the Wisconsin observation, which was made about 10 min before those in California, gives a chord which is, if anything, shorter than the nearly coincident chord from Wrightwood. Finally, one need only compare in Fig. 3 the adjacent chords from Little Lake and Ridgecrest, California to be convinced that real, kilometer-sized irregularities are present on Juno.

Probably the most realistic representation of Juno's limb at the time of the 11 December occultation can be produced by fitting a smooth curve through the end points of the chords in Fig. 3. It is then evident that Juno is flatter at its southern end than the fitted ellipse and shows clear signs of collisional processes elsewhere. Certainly, the profile produced in this way brings to mind spacecraft images of Phobos, Deimos, and Amalthea.

The visual geometric albedo of Juno, p_V, can be determined from the usual relation

$$\log p_V = 0.4(V_\odot - V + 5\log r\Delta + \beta\alpha) - 2\log D/2, \tag{1}$$

where $V_\odot = -26.77$ mag is the apparent visual magnitude of the Sun (Gehrels, Coffeen, and Owings 1964); V is the apparent visual magnitude of Juno at the time of the occultation; r and Δ are the distances in astronomical units of Juno from the Sun and Earth, respectively; β is the phase coefficient; α is the asteroid's phase angle; and D is the occultation diameter expressed in astronomical units. Values for the various parameters and the resulting visual geometric albedo are given in Table VI. The apparent magnitude of Juno was computed from the observed depth of the occultation light curve and the V magnitude of AG+0°1022 quoted in Sec. II b.

b) Satellites

None of the observers listed in Table II reported fluctuations in his photometric records which could be attributed to satellites. This fact does not rule out the existence of satellites orbiting Juno, but it casts doubt on the suggestion that such satellites are "numerous and commonplace" (Binzel and Van Flandern 1979), at least in the case of Juno.

c) The Visual Observations

The three sets of visual observations in Table III were not used in the analysis presented in Sec. IV primarily because experiments have indicated that brightness changes as small as half a magnitude are difficult to detect reliably by visual observation (Millis and Elliot 1979). This conclusion is borne out by the failure of the observer at China Lake, California to detect immediately the disappearance of the star and by the fact that two other experienced lunar occultation observers nearby failed to detect the occultation at all (McMahon 1980). Nevertheless, it is of interest to compare the visual observations that were reported with the photoelectric results. Figure 4 shows the visual observations superimposed on the photoelectric solution. It appears that reaction-time corrections have been uniformly underestimated, causing all of the visual observations to be systematically late relative to adjacent photoelectric measurements. However, at Oak Flats, California and China Lake the timing errors for emersion were not more than about one second and may have been less, depending on the local topography of Juno. Considering the difficulty of this occultation, the visual observers have done very well and presumably can be expected to achieve even better accuracy for events displaying a large brightness change. While we chose not to include the visual observations in our solution for the size and shape of Juno, the semimajor and semiminor axes of the best-fitting ellipse would each differ by only 1 km from the values given in Table IV, had we done so.

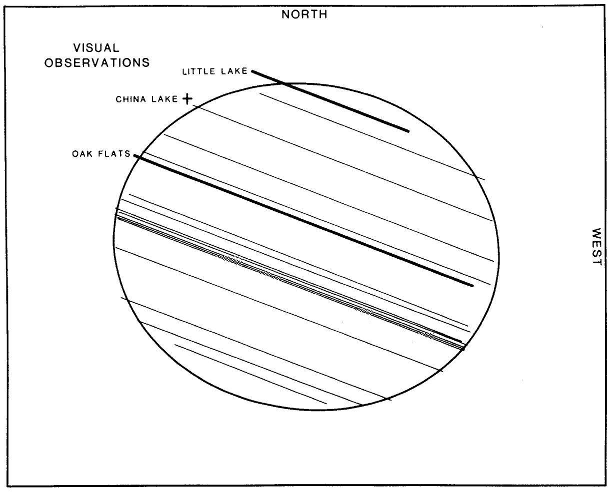

FIG. 4. Same as Fig. 3, but with visual observations from Little Lake, China Lake, and Oak Flats added.

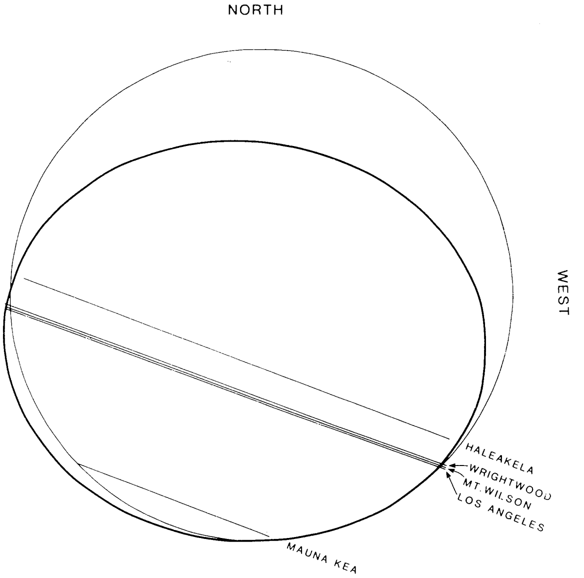

FIG. 5. A circular limb profile fitted by least squares to observations from the five permanent observatories compared with the preferred elliptical profile based on all of the photoelectric data.

d) *The Need for Portable Equipment and Good Predictions*

The high precision of the results reported in this paper is due in large part to the availability of several sets of portable equipment, much of which has been expressly designed for occultation work. All of the photoelectric observations north of the asteroid's center were made with portable equipment, as were many of the other observations (see Table II). The occultation was observed at five permanent observatories, but the cross-track distribution of these sites is poor. The best-fitting circular solution based only on the observations made at permanent observatories is compared in Fig. 5 with the elliptical solution based on all of the photoelectric observations. (An attempt to fit an ellipse to the five chords shown in Fig. 5 failed to converge.) The formal error in the radius of the fitted circle is ±3.2 km. However, Fig. 5 forcefully illustrates the difference between formal uncertainty and actual uncertainty in the sizes and shapes of asteroids determined from occultations with inadequate observational coverage.

Another factor which contributed significantly to the good coverage of the 11 December occultation was the high quality of the predictions. The ground track of the occultation derived from the elliptical solution is virtually indistinguishable from the predicted track shown in Fig. 1. (See also the last four lines of Tables I and IV.) The level of agreement achieved for this event was in part fortuitous, but examination of the standard error of the Lick astrometry suggests that the minimum geocentric separation can often be predicted to within a few hundredths of an arcsecond. With this degree of prediction accuracy, observation of occultations involving even rather small asteroids becomes practical (see Millis and Elliot 1979).

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