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RESULTS FROM THE OCCULTATION OF 14 PISCIUM BY (51) NEMAUSA

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ABSTRACT

The 11 September 1983 occultation of 14 Psc by (51) Nemausa was observed photoelectrically at six sites across the occultation track. The observations are well represented by an elliptical limb profile having a semimajor axis of 84.9 ± 2.0 km and oblateness $(1 - b'/a')$ 0.20 ± 0.05. The geocentric position of the asteroid was $0^{\mathrm{s}}18843 \pm 0^{\mathrm{s}}00022$ E and $3''5696 \pm 0''0030$ N of 14 Psc at 7:45:00 UTC on 11 September 1983. The quoted uncertainties are all formal errors from the elliptical least-squares fit. No secondary occultations were observed.

I. INTRODUCTION

The asteroid (51) Nemausa occulted the star 14 Piscium ($V = 6.0$, $A\,3$) on 11 September 1983. This occultation provided an opportunity to measure directly the shape and size of Nemausa. In addition, Nemausa's orbit is useful for correcting the positions of stars in the FK4 catalog (Dunham and Kristensen 1983; Gammelgaard and Kristensen 1983), so the normally uninteresting "by-product" of occultations, the precise offset of the asteroid from the star, was of considerable interest in this case. The occultation ground track was originally predicted by Wasserman, Bowell, and Millis (1981), and independently by Taylor (1981), to pass through Florida and Mexico. Photographic astrometric observations for refinement of the prediction were obtained at the Lick Observatory with the 0.5-m double astrograph (Klemola and Harlan 1984) and at the McCormick Observatory by B. McNamara; both sets of plates were measured at Lick Observatory. Transit-circle observations obtained at Bordeaux were reported to us by L. Kristensen. The final prediction called for a path crossing the southeast United States from southern Virginia to Louisiana and across the Gulf of Mexico. This prediction was in error by only about $0''05$ (Dunham 1983).

Owing to the brightness of the occulted star and the favorable placement of the occultation track, the occultation was observed by many visual observers. These observations will be analyzed in a future publication and will be discussed only briefly here.

II. OBSERVATIONS

The circumstances of this occultation were exceptionally favorable. The occulted star was bright and well placed, and the moon was absent. The weather was generally clear along the occultation track except in Alabama and Louisiana. Finally, the prediction was reasonably accurate and well publicized. The observations reported here were obtained at six sites distributed across the northern two-thirds of the track. The site positions and instrument characteristics are given in Table I, while the immersion and emersion times are given in Table II. No secondary occultations were observed.

III. ANALYSIS

The analysis of the occultation observations was carried out in the usual fashion (Wasserman *et al.* 1979). The points in the Besselian plane were fitted with an ellipse using a least-squares routine which minimized residuals in time rather than in radius. This method is superior in cases where the uncertainty in the limb profile is dominated by timing errors. In the present case, the major source of uncertainty is the roughness of the limb, so the two methods should be equally good. The elliptical model was characterized by five parameters: semimajor axis length (a') oblateness $(1 - b'/a')$, position angle of the minor axis, and ephemeris offsets in right ascension and declination. The results of the fit are shown in Fig. 1 and in Tables III and IV. The points for the Columbia station were not included in the fit because of difficulty in determining accurate times due to the long time constant ($\sim 1^{\mathrm{s}}3$) and slow speed (2.54 mm/s) of the chart recorder. The penalty incurred by deleting these points is fortuitously minimized by the proximity of the Contoe chord.

The placement of the Hampton chord is based on a visually determined time, but the chord length is from a photoelectric photometer recording on a fast (25.4 mm/s, $0^{\mathrm{s}}03$-s time constant) chart recorder. To explore the possibility of a significant error in the chord placement, fits were performed for various different chord offsets. The best-fit parameters differed from those with no offset by less than $1/20\sigma$, the best time offset for the chord being only $0^{\mathrm{s}}05$. Therefore, the fit in Table III uses this chord with no time offset.

TABLE I. Observing sites.

Location	Observers	Latitude (N)	Longitude (W)	Altitude (m)	Telescope aperture	Data recording system
Yorktown, VA	Croom	$37^\circ 14' 25''.7$	$76^\circ 31' 15''.1$	5	20 cm	f
Emporia, VA	Baron	$36^\circ 39' 53''.2$	$77^\circ 33' 06''.5$	38	36 cm	a
Hampton, VA	Helms	$37^\circ 05' 14''.0$	$76^\circ 22' 35''.0$	6	41 cm	b
Essex Meadows, VA	D. Dunham J. Dunham	$36^\circ 44' 59''.6$	$76^\circ 13' 59''.8$	15	20 cm	c
Macon, GA	Schneider Cohen	$32^\circ 51' 53''.0$	$83^\circ 41' 44''.5$	168	20 cm	d
Contoe, NC	E. Dunham Conner	$35^\circ 52' 19''.0$	$77^\circ 23' 49''.0$	19	36 cm	a
Columbia, SC	Safko	$33^\circ 59' 50''.7$	$81^\circ 01' 35''.8$	98	41 cm	e
Greenville, NC	Seykora	$35^\circ 36' 18''.8$	$77^\circ 21' 48''.7$	24	20 cm	f

Notes to TABLE I

[a] Data recording is on digital magnetic tape synchronized to WWV within 10 ms (Baron, Dunham, and Elliot 1983).

[b] Photoelectric record on chart recorder. 25.4 mm/s chart speed, 30 ms time constant.

[c] Videotape system, WWV recorded on audio track.

[d] Circulating buffer digital system, 25 ms sample interval, 50 ms time constant, 100 s buffer length. Synchronized to WWVB.

[e] Photoelectric record on chart recorder, WWV on event pen., 2.54 mm/s chart speed, 1.3 s time constant.

[f] Visual observation.

The true uncertainty in the fit is probably larger than the formal uncertainty quoted. An estimate of the true uncertainty can be obtained by examining the extreme observed chords, which were from visual observations of this occultation. The northernmost chord is the correct length, but is apparently offset. The southernmost chord is more troublesome, being too short and showing an apparent gap in the asteroid. Unfortunately, no observers were stationed farther south, so the gap remains unconfirmed. The fact that this chord is too short implies that Nemausa's true limb profile does not extend as far south as the fit indicates, leading us to expect the true profile to be more oblate and centered farther north and west. This expectation is borne out if the Greenville chord is included in the fit, but the change is only at the 1σ level. We conclude that the true uncertainty is not more than 50% larger than the formal error.

The ephemeris used in the analysis was provided by L. Kristensen and is given in Table V; four-point interpolation in the ephemeris table was used. The star position used was the improved position derived by Bien and Schwan (1983); $\alpha = 23^{\rm h}31^{\rm m}34^{\rm s}.939$ and $\delta = -1^\circ 31' 26''.00$ (1950.0 coordinates).

IV. DISCUSSION

A single set of occultation observations can, in principle, precisely define the shape of an asteroid as projected on the plane of the sky, but such observations provide no information in the third dimension. If the asteroid's rotational pole orientation is known and another occultation is observed at a significantly different aspect, the triaxial figure of the asteroid can be determined. Another occultation by Nemausa was in fact observed in the USSR in 1979 (Kristensen 1981). Unfortunately, only two chords were obtained, so an elliptical solution was not possible without assuming an oblateness for the asteroid. Also, the pole orientation and rotation period are not yet known well enough to establish the relative orientations of the asteroid for the two occultations. At this time, therefore, the mean radius of Nemausa can only be estimated based on this occultation and the asteroid's light curve.

A preliminary light curve of Nemausa kindly provided to us prior to publication by A. Harris (1983) shows the three-lobed appearance reported by Chang and Chang (1963), Wamsteker and Sather (1974), and Gammelgaard and Kristensen (1983). Harris' light curve was obtained during July, August, and September of 1983, but no observations were made on the night of the occultation. The occultation occurred very close to maximum light, while the peak-to-peak amplitude of the light curve was about 15%. Wamsteker and Sather (1974) found a peak-to-peak amplitude of about 20% at a different aspect.

If one determines the projected outline of a triaxial ellipsoid (with axes a, b, and c, where $a \geqslant b \geqslant c$) from a position not

TABLE II. Observations.

Location	Immersion time (UTC)	Emersion time (UTC)
Yorktown, VA[d]	7:45:06.1 $\pm 0^{\rm s}.5$	7:45:08.4 $\pm 0^{\rm s}.5$
Emporia, VA	7:45:08.665 $\pm$ 0.01	7:45:15.113 $\pm$ 0.01
Hampton, VA[a]	7:45:01.4 $\pm$ 0.2	7:45:10.8 $\pm$ 0.2
Essex Meadows, VA[b]	7:45:00.2 $\pm$ 0.1	7:45:13.4 $\pm$ 0.1
Macon, GA	7:45:45.244 $\pm$ 0.01	7:45:58.544 $\pm$ 0.01
Contoe, NC	7:45:07.406 $\pm$ 0.01	7:45:20.096 $\pm$ 0.01
Columbia, SC[c]	7:45:29.0 $\pm$ 0.4	7:45:41.3 $\pm$ 0.4
Greenville, NC[d]	7:45:11.1 $\pm$ 0.5	7:45:19.3 $\pm$ 0.5

Notes to TABLE II

[a] Duration reliable to perhaps 50 ms. The uncertainty is an estimate of the overall chord placement uncertainty. The time listed includes a reaction time correction of $0^{\rm s}.35$.

[b] Video system; WWV recorded on audio channel. Times determined by playing back video tape. The uncertainty is estimated.

[c] Timing is uncertain due to slow chart speed and long time constant.

[d] Visual observations with reaction time correction included. The uncertainties are estimated.

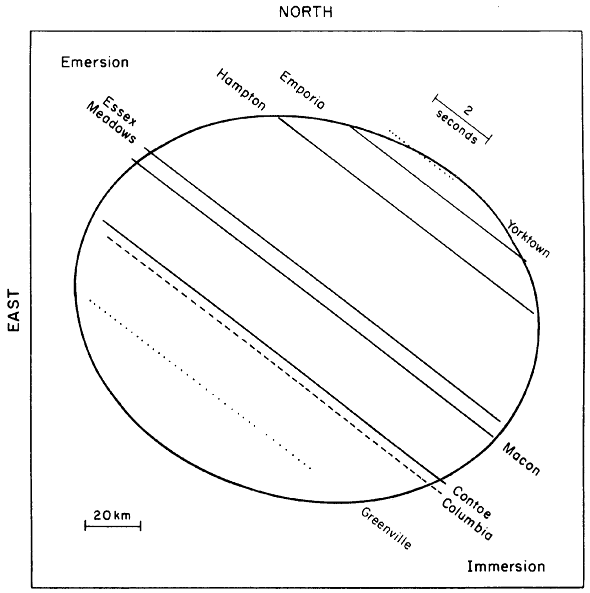

FIG. 1. Elliptical solution. The parallel lines represent observed chords, each marked with the location of the observer. The Columbia chord was not used in the fit due to timing problems. The Yorktown and Greenville visual chords were the northernmost and southernmost chords observed. They were not included in the fit, but indicate the difference between the true uncertainty in the fitted limb profile and its formal uncertainty.

along the rotational axis, and if, in addition, the rotational phase, the angle between the rotational axis and the line of sight, and the light curve amplitude for this pole orientation are known, one may then determine the lengths of the three axes.

TABLE III. Elliptical solution.

A.	Fitted parameters[a]	
	Semimajor axis, a'	84.9 ± 2.0 km
	Oblateness, $\frac{a'-b'}{a'}$	0.20 ± 0.05
	P.A. of semiminor axis	345° ± 9°
	R.A. ephemeris offset	155.7 ± 3.7 km
	Dec. ephemeris offset	64.4 ± 3.4 km
B.	Derived parameters	
	Semiminor axis, b'[b]	67.6 ± 4.5 km
	Effective radius,[b] $(a'b')^{1/2}$	75.8 ± 3.1 km
	R.A. and Dec. offset of asteroid from star at 7:45:00 UTC[a]	$\Delta\alpha = +0^{\mathrm{s}}.18843 \pm 0^{\mathrm{s}}.00022$ $\Delta\delta = +3''.5696 \pm 0''.0030$
C.	Triaxial figure[c]	
	Estimated mean radius, $(abc)^{1/3}$	74 ± 4 km
	Estimated triaxial shape: a	84.9 ± 3 km
	b	70 ± 7 km
	c	67.5 ± 6 km

Notes to TABLE III

[a] The uncertainties of these parameters are formal errors from the least-squares fit.

[b] The uncertainties of these parameters were derived by propagation of errors from the least-squares fit formal errors.

[c] See the text for discussion of the uncertainties of these parameters.

TABLE IV. Fit residuals.

Station	Residuals (s) Immersion	Residuals (s) Emersion
Emporia, VA	−0.21	−0.12
Hampton, VA	0.14	−0.07
Essex Meadows, VA	0.20	0.28
Macon, GA	0.10	0.20
Contoe, NC	−0.23	−0.30
Columbia, SC[a]	−0.43	−0.65

[a] Not included in fit.

The light curve amplitude, under the assumption that the light variation is due only to a change in the projected area of the object, allows us to write the following equation for the ratio of the maximum to the minimum projected area:

$$\frac{A_{\max}}{A_{\min}} = \frac{\{\sin^2 B + (c/b)^2 \cos B\}^{1/2}}{\{\sin^2 B + (c/a)^2 \cos B\}^{1/2}}, \qquad (1)$$

where B is the declination of the Earth as seen from the object, and it is assumed for dynamical reasons that the rotational axis is along c.

For an arbitrary rotational phase ϕ, the major (a') and minor (b') axes of the projected ellipse will be functions of a, b, c, B, and ϕ. If we know B and ϕ, these two equations combined with Eq. (1) above should be generally sufficient to determine the three principal axes. In the present case, the equations for a' and b' are simplified since the occultation occurred very close to maximum light. In fact, the major axis of the projected ellipse is within 2% of the actual major axis. If we approximate:

$$a' = a, \qquad (2)$$

then to the same approximation

$$b' = b\{\sin^2 B + (c/b)^2 \cos^2 B\}^{1/2}. \qquad (3)$$

Our problem is now reduced to solving Eqs. (1) and (3) for b and c. There is a problem, however: the pole orientation of Nemausa is unknown, so B is unknown. We can, however, limit B by requiring that the rotational axis be the smallest one, i.e., $c < b$. A numerical experiment where values of B ranging from zero to 45° were assumed showed that the condition $c < b$ was satisfied only for $|B| \lesssim 30°$. Happily, the implied values for b and c were not strongly dependent on B in this range, with b varying from 72.1 to 67.2 km and c from 67.7 to 67.4 km. The uncertainties in the triaxial shape given in Table III take this variation into account, in addition to uncertainties in the three observed parameters a', b', and $A_{\max}/A_{\min}$.

The procedure outlined above is, at best, crude in the case where the pole orientation is unknown, and for asteroids like Nemausa with unusual light curves which call into question the validity of the assumptions of triaxial shape and lack of albedo features. However, for asteroids with photometrically determined pole orientations and more reasonable light curves, the method has considerable promise.

The mean radius of 74 ± 4 km (or the effective radius, 75.8 ± 3 km if you prefer) agrees with the 1979 occultation effective radius of 76.5 ± 4 km and the published radiometric radius of 75.5 km (Morrison and Zellner 1979). The corresponding albedo of 0.062 is therefore not significantly altered. Similar agreement between the occultation radius and

TABLE V. Astrometric ephemeris of Nemausa.

Ephemeris date at 0^h ET	R.A.	(1950.0)	Dec.	Geocentric distance (AU)
10 September 1983	$23^h32^m40^s.717$		$-1°18'32''.15$	1.5200
11 September 1983	23 31 51.199		− 1 28 13.68	1.5189
12 September 1983	23 31 01.420		− 1 37 58.16	1.5181
13 September 1983	23 30 11.445		− 1 47 44.98	1.5175

the radiometric radius was found in the case of Juno (Millis *et al.* 1981), in contrast with Pallas (Wasserman *et al.* 1979), where the occultation radius was smaller than the radiometric radius by 9% and smaller than the polarimetric radius by 18%.

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