

Size and Shape of Trojan Asteroid Diomedes from Its Occultation and Photometry

Isao Satō

Watanabe Technological Laboratory, Sunrize Akimoto Building, 401, 2-8-17 Kyōnanchō, Musashino, Tokyo 180-0023, Japan
E-mail: isao@wtl.co.jp

Lenka Šarounová

Astronomical Institute, Academy of Sciences of the Czech Republic, CZ-25165 Ondřejov, Czech Republic

and

Hideo Fukushima

National Astronomical Observatory of Japan, 2-21-2 Ōsawa, Mitaka, Tokyo 181-8588, Japan

Received July 6, 1998; revised September 20, 1999

The first Trojan asteroid occultation, the occultation of HIP 014402A by (1437) Diomedes, was successfully observed from Japan on November 7, 1997. From its occultation timings at six sites including two video observations, an elongated occultation silhouette of $(180 \pm 28 \text{ km}) \times (96 \pm 5 \text{ km})$, at position angle $PA = 150 \pm 4^\circ$ was revealed.

Follow-up photometry of Diomedes obtained at Ondřejov on November 10 and 11 and at Mitaka on November 18, 19, and 24 revealed that its rotation period is 1.019 ± 0.004 days, its amplitude of light variation is 0.70 ± 0.15 mag, and its rotational phase at the occultation was almost at a minimum of the lightcurve.

From these observations, a probability distribution ellipsoidal model for Diomedes is derived. It shows that two families of ellipsoidal models are possible. One is a triaxial ellipsoid of $b/a \approx 0.55$; the other is a rather prolate ellipsoid of $b/a \approx 0.4$, $c/b \approx 1$. Possible orientation of the rotation axis is very restricted to two great circles on the celestial sphere. Mean lengths of the three principal axes of the model ellipsoid are $(284 \pm 61 \text{ km}) \times (126 \pm 35 \text{ km}) \times (65 \pm 24 \text{ km})$, i.e., approximately $a : b : c \approx 4 : 2 : 1$. © 2000 Academic Press

1. INTRODUCTION

The observation of stellar occultations by asteroids can reveal absolute size, shape, and possible satellites of the occulting asteroid, as well the angular diameter and possible duplicity of the occulted star. The potential of such events had been noticed by G. E. Taylor by 1952 (Taylor 1952). The first successful observations of such events, the occultation of BD +6° 808 by (3) Juno, was obtained from Malmö of Sweden on February 19, 1958 (Taylor 1962).

The occultation of κ Geminorum by (433) Eros on January 24, 1975, was successfully timed at eight sites in the United States thanks to last-minute astrometry, and its irregular shape was revealed (O'Leary *et al.* 1976).

Since the success of Eros event, much effort was expended to better predict asteroid occultations. Consequently, successful observations were obtained of the (6) Hebe occultation of γ Ceti on March 5, 1977 (Taylor and Dunham 1978), the (2) Pallas occultation on May 29, 1978 (Wasserman *et al.* 1979), the (18) Melpomene occultation on December 11, 1978 (Williamson 1980), the (3) Juno occultation on December 11, 1979 (Millis *et al.* 1981), the (51) Nemausa occultation on September 11, 1983 (Dunham *et al.* 1984), and the (1) Ceres occultation on November 13, 1984 (Millis *et al.* 1987), to name a few. Other successful observations were obtained mainly from the United States in the following decade. Some events suggested possible existences of satellites of asteroids.

The most remarkable success among observed events was the occultation of 1 Vulpeculae by (2) Pallas on May 29, 1983 (Dunham *et al.* 1990); this great success (130 chords) is still the record holder for asteroid occultations.

The next dozen years, 1985–1996, was a period when occultation products from countries outside the United States were increasingly obtained. Understanding the importance of asteroid occultations spread around the world, and several successful observations were obtained from Europe, South Africa, Australia, New Zealand, and Japan. Distribution of personal computers, CCDs, and video cameras facilitated the accurate prediction, measurement, and reduction of asteroid occultations by amateur astronomers as well as professionals. As a result, over 200 events have been observed to date.

The following decade, 1997–present, is the Hipparcos decade. The first astrometry satellite, ESA’s Hipparcos, brings a revolution to asteroid occultation prediction. Errors in positions, proper motions, and parallaxes of stars have been greatly reduced by catalogs derived from the Hipparcos dataset. Occultations of Hipparcos stars by some large asteroids will occur almost in accordance with the initial prediction, the main source of uncertainty now being in the ephemerides of the particular asteroids and not the stellar positions. Asteroid occultation expeditions now can be planned long before the event, much as for solar eclipses and grazing lunar occultations. Some important events visible from remote regions no doubt can be profitably observed.

Almost all successful events to date have been occultations by mainbelt asteroids. The only confirmed occultation chord by a distant asteroid (beyond Jupiter) was obtained during the occultation of Ch02 by Chiron (Bus *et al.* 1996). Some incom-

plete extinctions (probably by Chiron’s purported jets) were also detected during the occultation of Ch08 by Chiron (Elliot *et al.* 1995). Chiron has duplicate entries as a numbered asteroid (2060) and a periodic Comet 95P. These observations yielded an lower limit of Chiron’s diameter, assuming a circular model (Bus *et al.* 1996).

No stellar occultation by a Trojan had been observed. Known Trojan (and farther) asteroids are fewer in number, fainter, and slower in their motion on the sky, yielding fewer opportunities for stellar occultations. The difficulty of accurately predicting these events is also much greater, roughly increasing in proportion to the geocentric distance.

Several workers have reported that, in general, Hildas and Trojans may be systematically more elongated compared to asteroids of the same size in the inner region of the asteroid belt. Alternatively, it has been proposed that their poles may be preferentially oriented nearly perpendicular to the ecliptic. These

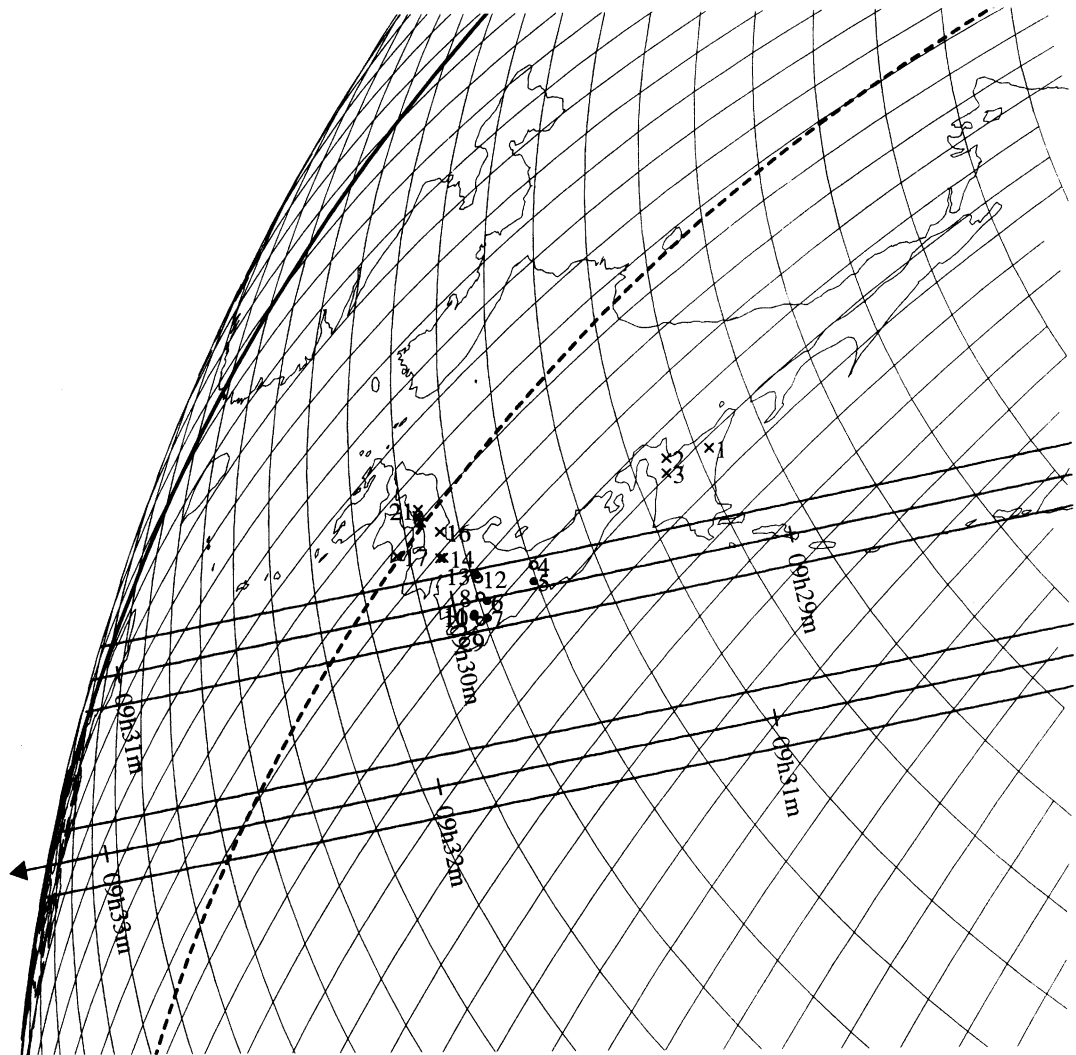


FIG. 1. Occultation tracks and observers of the occultation of HIP 014402A (top) and HIP 014402B (bottom) by (1437) Diomedes on November 7, 1997. The site numbers are listed in Table I. ●, ○, and × indicate “timed” site, “untimed” site, and “no occultation” site, respectively.

conjectures result from reports of relatively larger average light-curve amplitudes for these objects (Dunlap and Gehrels 1969, French 1987, Hartmann *et al.* 1988, Zappalà *et al.* 1989, Binzel and Sauter 1992). While neither hypothesis is proven, each is at least plausible. Collision rates should be lower compared to those in the main belt, due to longer Keplerian time scale and lower column density of planetesimals. Inner asteroids should have experienced more (and higher relative velocity) collisions, resulting in asteroids more rounded than their more remote counterparts and/or more randomized spin axes.

In this paper, we report observations of the first stellar occultation by a Trojan asteroid, the occultation of HIP 014402A by (1437) Diomedes. From the view point of the collisional evolution of the asteroid belt, this result of an absolute size and shape for a Trojan presents the first example with which to test the elongation and orientation hypotheses.

2. OCCULTATION OF HIP 014402A BY (1437) DIOMEDES ON NOVEMBER 7, 1997

The event was predicted by Satō in 1996 (the prediction was distributed to the observers in Japan in private) and updated by the Hipparcos catalog (Perryman *et al.* 1997, Kovalevsky

1997) published just 5 months before the event. The occulted star is $m_V = 6.90$ and a close double of $\rho = 0''.630 \pm 0''.004$, $PA = 274^\circ.4$, $\Delta m_V = 1.16 \pm 0.01$ according to the Hipparcos catalog. The position of the occulted star is accurate to ~ 10 mas. Diomedes was observed with a liquid N₂ cooled CCD camera attached to the 50-cm reflector at Mitaka on November 1. The observation was reduced with the GSC 1.1 (Lasker *et al.* 1990, Russell *et al.* 1990, Jenkner *et al.* 1990) and a correction for systematic error of the field was added by catalog comparison with the ACT reference catalog (Urban *et al.* 1998). This updated prediction showed that the occultation path would shift by $\Delta\sigma = 0''.000 \pm 0''.069$, $\Delta T = +0.67 \pm 0.11$ min with respect to the prediction by the Hipparcos catalog. This meant that the occultation track of the primary star would go through Japan (50% probability) with expected dimming of 1.5 mag. Occultation by the secondary (<10% probability) would result in an expected dimming of 0.3 mag.

Fortunately, skies were clear all over Japan on the day of the event. The event occurred at 18h30m JST on a Friday evening. During the event some observers were still at work and some observatories were open to the public and hence unable to observe. Nevertheless, the event was monitored at nine sites and successfully timed at six sites, including two video observations

TABLE I
Observers and Times of the Occultation of HIP 014402A by (1437) Diomedes on November 7, 1997

No.	Observer name	Tōkyō Datum (? assumed)			Location	Telescope		Method	Time keep	Phen.	Time (UTC) × rejected
		Longitude (E)	Latitude (N)	Height (m)		D (m)	f.l. (m)				
1	Kihara A. O.	142°28'13"	44°21'35"		Nayoro, Hokkaidō	0.25 L		Video			No occ.
2	Sakari Ikuta	141°17'55"	43°04'27"	18	Sapporo, Hokkaidō	0.355 SC	3.90	I.I. video			No occ.
3	Yoshihiro Tsukada	141°51'05"	42°55'28"	74	Yuni, Hokkaidō	0.20 SC		Rec. vis.	JJY		No occ.
4	Nan'yō A. O.	140°08'34"	38°04'37"		Nan'yō, Yamagata	0.31 L		Visual			Miss
5	Isao Ohtsuki	140°40'59"	37°53'47"	190	Marumori, Miyagi	0.20 L		Rec. vis. & p.g.	Tel	D	09h29m42.2s ± 0.2s
6	Tatebayashi S. C.	139°32'53"	36°14'26"	35	Tatebayashi, Gunma	0.20 R	1.80	I.I. video	Tel	R	09h29m48.2s ± 0.3s
7	Sadaharu Uehara	140°07'16".0	36°04'59".7	30	Tsukuba, Ibaraki	0.20 L	0.80	Rec. vis.	Tel	D	09h29m51.4s ± 0.1s
8	Ken Matsuya	139°09'	36°05'	600	Chichibu, Saitama	Binocular		Unrec. vis.			09h29m57.6s ± 0.1s
9	Sigeo Uchiyama	139°57'37"	35°50'01"	25	Kashiwa, Chiba	0.25 SC		Unrec. vis.	—		09h29m53.1s ± 0.3s
10	Isao Satō	139°32'52"	35°39'58"	52	Chōfu, Tōkyō	0.20 SC	2.00	Rec. vis.	JJY	D	09h29m58.7s ± 0.2s
11	Yōko Matsubasa	139°29'43"?	35°43'27"?		Kodaira, Tōkyō	0.08 B		Unrec. vis.	—		Occulted
12	Usuda Star Dome	138°25'57"	36°11'24"	935	Usuda, Nagano	0.20 R		Unrec. vis.	Clock	D	Occulted
13	Yūji Kitahara	138°17'03"	36°15'02"	700	Nagato, Nagano	0.10 R	0.80	I.I. video	JJY	D	×09h29m55.1s ± 0.2s
14	Dynic Tenkyūkan	136°18'28"	35°12'29"	215	Taga, Shiga	0.20 R		Video	Tel	R	09h30m00.6s ± 0.2s
15	Miyoshi Ida	136°11'21"	35°09'00"		Gokashō, Shiga	0.20 N		Video			5 sec.
16	Ayabe PAO	135°16'03"	35°18'31"	80	Ayabe, Kyōto	0.95 C		I.I. video	Tel	D	×09h29m56.7s ± 0.5s
17	Hiromu Maeno	134°19'08"	33°33'05"	70	Shishikui, Tokushima	0.15 R	1.05	Visual	JJY	R	×09h29m57.7s ± 0.3s
18	Yōichirō Nakajima	134°06'16".8	34°39'58".2	10	Oku, Okayama	0.25 S		Video			09h29m52.2s ± 0.1s
19	Nobuo Ohkura	133°52'36".1	34°36'24".8	3	Okayama City	0.355 SC	3.90	p.e. & video	JJY	D	09h29m56.3s ± 0.1s
20	Hidehiko Akazawa	133°42'43".3	34°34'42".6	8	Funao, Okayama	0.28 SC		p.e. & video	JJY		No occ.
21	Bisei A. O.	133°32'52".1	34°40'06".9		Bisei, Okayama	1.01 C		Video	Tel		No occ.
22	Ogawa A. O.	137°59'24"	36°39'22"	1009	Ogawa, Nagano						No occ. cloudy

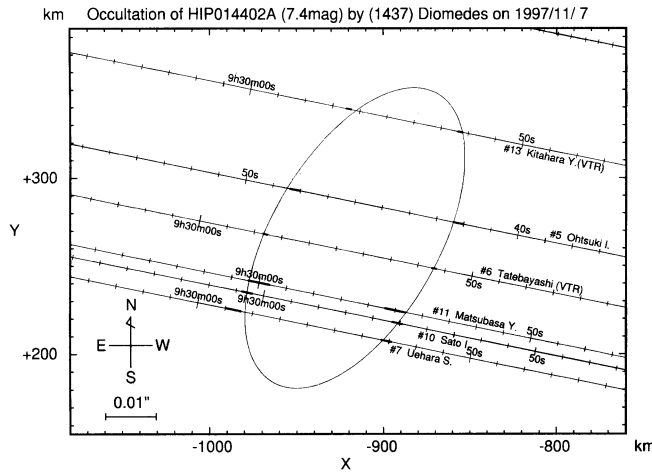


FIG. 2. Reduction map of the occultation of HIP 014402A by (1437) Diomedes on November 7, 1997. An ellipse of $(180 \pm 28 \text{ km}) \times (96 \pm 5 \text{ km})$, $PA = 150 \pm 4^\circ$ is fitted to the two video and four visual observations. The indicated time is UTC. Numbers before the observers correspond to those of Table I. The observation by Y. Matsubasa is duration only and hence the midtime is adjusted properly. Thick parts of lines indicate the $\pm 1\sigma$ level uncertainties of the observations. Some apparent deviations from the fitted ellipse are seen.

from the eastern part of Japan (Fig. 1). All reported drops were $\Delta m = 1\text{--}2$ mag, consistent with the $\Delta m = 1.5$ mag for the occultation of the primary component in the initial prediction.

Observational data of the occultation are listed in Table I. A result of reduction is shown in Fig. 2. As one occultation chord obtained at the Usuda Star Dome, Nagano, is apparently discordant with the others, this observation is rejected. The observation is an unrecorded visual observation by an aged, unskilled observer. The observer reported that he was watching the star with a 20-cm refractor, unready to time. He looked at the clock on the control panel only after he recognized an extinction. So the timing seems to be unreliable.

Two video observations were obtained by Yūji Kitahara at Nagato, Nagano, and by the Tatebayashi Science Center at Tatebayashi, Gunma. Both videos were recorded with an AVIS

image intensified camera, manufactured by Hamamatsu Photonics. Three visual observations by Isao Ohtsuki at Marumori, Miyagi, Sadaharu Uehara at Tsukuba, Ibaraki, and Isao Satō at Chōfu, Tōkyō were recorded with a time signal. One visual observation by Yōko Matsubasa at Kodaira, Tōkyō was not recorded with a time signal, just verbally counted. There were three more sites where the occultation was observed but no timing information was recorded. No occultation was reported from 11 sites.

An ellipse of $(189 \pm 28 \text{ km}) \times (96 \pm 5 \text{ km})$ illustrated in Fig. 2 is fitted to the two video observations and the four visual observations. The error bars show $\pm 1\sigma$ level uncertainties of the observations. Some apparent deviations from the fitted ellipse profile can be seen. Diomedes does not seem to be a smooth ellipsoid.

3. PHOTOMETRY OF DIOMEDES

The news of successful observations of the Diomedes occultation was distributed. Follow-up relative photometry in the R Cousins band was obtained at Ondřejov on November 10 and 11, and absolute photometry in the V Johnson band was also obtained at Mitaka on November 18, 19, and 24.

Table II shows the astrometric position of HIP 014402A and an ephemeris for Diomedes around the date of the occultation observation.

Table III shows observational circumstances of on the nights of the follow-up photometry at Ondřejov Mitaka.

A simple model lightcurve is fitted to the observed photometric data. The fitted model lightcurve is

$$m = m_0 - 2.5 \log_{10} \left(1 + \sum_{k=1}^n \left(A_k \cos \frac{4\pi kt}{P} + B_k \sin \frac{4\pi kt}{P} \right) \right), \quad (1)$$

where m_0 is a mean magnitude (of Ondřejov and Mitaka, respectively), P is a rotation period, and $\{A_k\}$, $\{B_k\}$ are coefficients.

TABLE II
Astrometric Position of HIP 014402A and Ephemeris of (1437) Diomedes

Object	Date (TDT)		R.A. (J2000.0)	Dec. (J2000.0)	Δ (AU)	r (AU)	Elong. ($^\circ$)	Mag.	Sp. type
HIP 014402A	1997 11	7.40000	3h05m46s3939 $\pm 0''.010$	+43°42'08''.906 $\pm 0''.008$				6.90v	F5
Diomedes	1997 11	4.00000	3 08 09.6567	+43 47 05.497	4.0421087	4.9314367	150.8	15.25v	
	1997 11	5.00000	3 07 27.6316	+43 45 48.197	4.0384941	4.9312680	151.3	15.24v	
	1997 11	6.00000	3 06 45.4141	+43 44 22.654	4.0351528	4.9310998	151.8	15.24v	
	1997 11	7.00000	3 06 03.0415	+43 42 48.913	4.0320864	4.9309321	152.3	15.23v	
	1997 11	8.00000	3 05 20.5513	+43 41 07.029	4.0292960	4.9307648	152.7	15.23v	
	1997 11	9.00000	3 04 37.9805	+43 39 17.066	4.0267829	4.9305980	153.1	15.22v	
	1997 11	10.00000	3 03 55.3660	+43 37 19.097	4.0245480	4.9304317	153.5	15.22v	
	1997 11	11.00000	3 03 12.7440	+43 35 13.201	4.0225920	4.9302658	153.8	15.21v	

TABLE III
Observational Circumstances of Photometries

Date (UT)	λ (°)	β (°)	Δ (AU)	r (AU)	Phase (°)	Error of photometry	Obs. Band	code
1997 Nov. 10.1	56.2	25.2	4.025	4.930	5.1	0.015–0.025	<i>r</i>	557
Nov. 10.9	56.1	25.2	4.023	4.930	5.1	0.015–0.025	<i>r</i>	557
Nov. 18.6	55.0	25.2	4.017	4.929	4.9	0.014–0.039	<i>V</i>	388
Nov. 19.6	54.8	25.2	4.017	4.929	4.9	0.016–0.035	<i>V</i>	388
Nov. 24.7	54.1	25.1	4.024	4.928	5.1	0.021–0.061	<i>V</i>	388

Change of daily apparent brightness is converted to the standard magnitude H according to Bowell's formula (Bowell *et al.* 1989). Light travel time corrections from the asteroid to Earth have been applied. The photometry at Mitaka is absolute V band compared with the occulted star HIP 014402 as a standard, while that of Ondřejov is relative R band. The mean magnitude level of Ondřejov has been adjusted to align the data with the Mitaka observations.

Changes in the lightcurve during the period we observed Diomedes (Nov. 10–25) should be negligible, due to only small changes in geometry (l , b , phase angle) over that interval. Nor would we expect the lightcurves to be strongly affected by different photometric passbands used. For these reasons, we can composite our observations.

Combined photometry and a fitted lightcurve is shown in Fig. 3. The V -mag of the ordinate is H . To facilitate discussion in the next section, we have assumed a triaxial ellipsoid model, with a symmetric, double-peak lightcurve of the first-order harmonic $n = 1$ in Fig. 3.

If we assume that the lightcurve has two maxima and two minima (other possibilities are very unlikely; the lightcurve

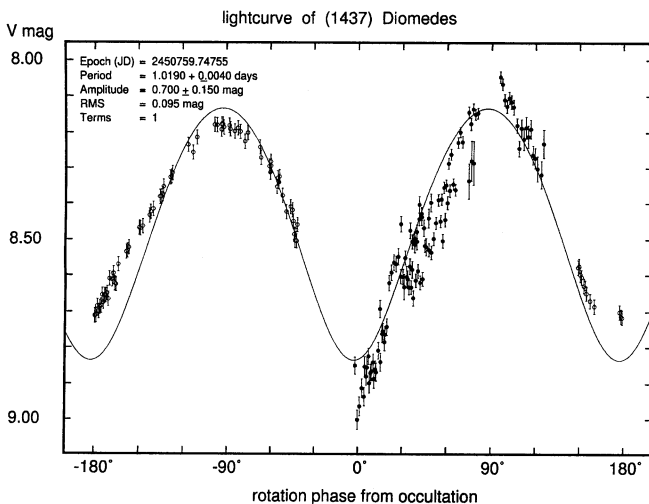


FIG. 3. Lightcurve of Diomedes from the observations at Mitaka (black circles) and Ondřejov (empty circles). The observations at the two sites are quite complementary. The fitted model lightcurve is the first-order harmonic. The rotational data show that the occultation occurred near lightcurve minimum. Thus the occultation silhouette shows a minimum cross section.

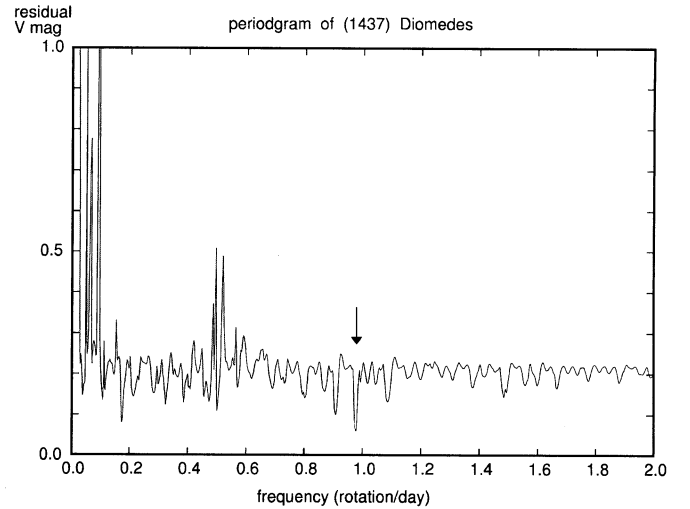


FIG. 4. Periodogram of Diomedes' lightcurve. The arrow indicates the minimum of residual, namely our solution. Residuals to fit are least at $f = 0.981 \pm 0.004$ rotation/day, and other possible solutions may be ruled out.

shape would be very complicated), the period is unambiguously 1.019 ± 0.004 days, and the rotation phase at the occultation was almost minimum: $175 \pm 5^\circ$. Previously published values for the period, 16 ± 0.5 h (Binzel and Sauter 1992) and 18 h (Lagerkvist 1989), can be ruled out thanks in the observations on two following nights (Nov. 10 and 11) and the long time span of observation on some of these nights. The amplitudes of the older lightcurves are not inconsistent with some kind of ellipsoid model derived in the later section in this paper.

Figure 4 shows a periodogram of the lightcurve. It confirms that our solution of $f = 0.981 \pm 0.004$ rotation/day yields are the smallest residuals, and other possible periods much less plausible.

The deviation of the Mitaka data from the fit is larger than that expected from the individual error estimates of the data. One likely cause of this deviation is that the actual lightcurve of Diomedes is double-peaked, but asymmetric.

Observations from the Czech Republic and Japan are at complementary portions of the rotational phase of the asteroid. However, the observations from the two sites unfortunately do not overlap. Combining the two datasets may have introduced an unexpected, systematic error in the vertical offset between the two branches of the lightcurve. However, it is more likely that the depth of two minima are not the same.

4. 3-D SHAPE OF DIOMEDES

Estimates of the spatial shape of an asteroid can be obtained from its occultation silhouette and the rotational lightcurve. As was done for (381) Myrrha, a probability distribution ellipsoidal model of Diomedes can be obtained from its occultation silhouette (Satō *et al.* 1993).

If we define the RMS (root mean square) diameter of an ellipsoid as

$$d_{\text{RMS}} \equiv \sqrt{\frac{a^2 + b^2 + c^2}{3}}, \quad (2)$$

then

$$E \left[\frac{A^2 + B^2}{2} \right] = d_{\text{RMS}}^2, \quad (3)$$

where $E[x]$ is the operator for the expected value of x , and A and B are the principal axes of the projected ellipse, respectively.

We note that this definition is different from that of the usual geometrical mean diameter ($d_{\text{GM}} \equiv \sqrt[3]{abc}$). Why we choose to adopt d_{RMS} is that we see only the *projected* principal axes, A and B , in an occultation silhouette and therefore the statistical property of Eq. (3) is more significant and convenient to use.

The occultation occurred near opposition on November 17, and therefore we assume the asteroid's brightness to be proportional to the cross section of the projected ellipsoid. Under this assumption, a probability distribution ellipsoidal model is obtained by an integral over all orientations of $(4\pi \text{ str}) \times (2\pi \text{ rad})$. Uncertainties in the observed parameters are taken into account by Gaussian weighting.

Figure 5 shows the probability distribution in ecliptic coordinates for the orientation of the rotation axis, which is assumed to be coincident with the c axis. \times indicates the position of the occulted star, and the sine curve is the orbital plane of Diomedes projected onto the sky. Most probable regions for the pole position are limited to selected regions on two great circles. The map suggests the rotation axis of Diomedes may be highly inclined to its orbital plane, much like the planet Uranus.

Figure 6 shows the probability distribution for the lengths of the principal axes. Constraints of $a > 170 \text{ km}$, $96 \text{ km} < b <$

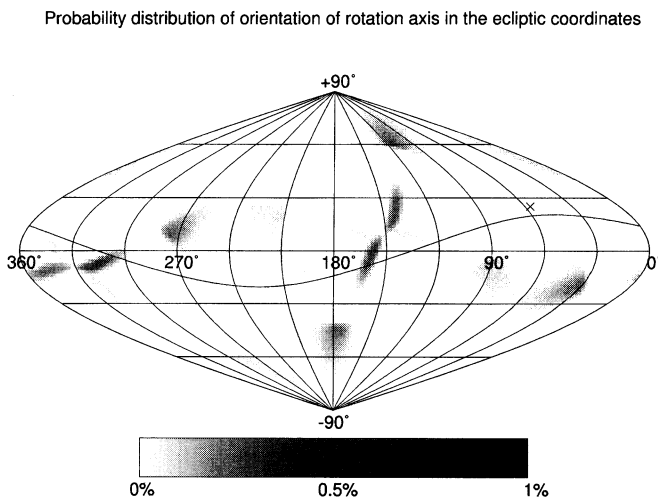


FIG. 5. Probability distributions for orientation of the rotation axis, presumed to be identical to the c axis. \times indicates the position of occulted star, and the sine curve is Diomedes' orbital plane. It is apparent that the orientation of the rotation axis is restricted to some parts of two great circles.

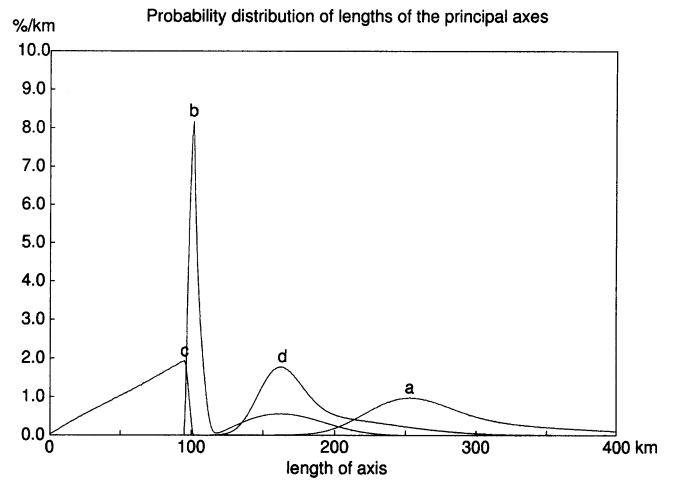


FIG. 6. Probability distribution for length of the three principal axes a , b , and c and mean diameter d .

240 km , $c < 100 \text{ km}$, and $d > 120 \text{ km}$ are apparent. Peaks of the distributions are at 255 km for the a axis, 95 km for the c axis, and 163 km for d_{RMS} . Note that there are two peaks around 100 and 160 km for the b axis, which corresponds to the two families of solutions shown in Fig. 7. The shorter b axis solution corresponds to a prolate ellipsoidal model, while the longer one corresponds to a triaxial one. However, as the occultation silhouette is almost at minimum cross section (when the a axis is most closely aligned with the line-of-sight), the length of the a axis is not well-constrained. Hence the resulting diffuse probability distribution.

Mean lengths of the axes are $a = 284 \pm 61 \text{ km}$, $b = 126 \pm 35 \text{ km}$, $c = 65 \pm 24 \text{ km}$, and $d_{\text{RMS}} = 184 \pm 38 \text{ km}$. The result suggests approximate ratio $a : b : c \approx 4 : 2 : 1$.

Figure 7 shows probability distributions for ratios of the principal axes. Two types of solution are seen. One is a triaxial

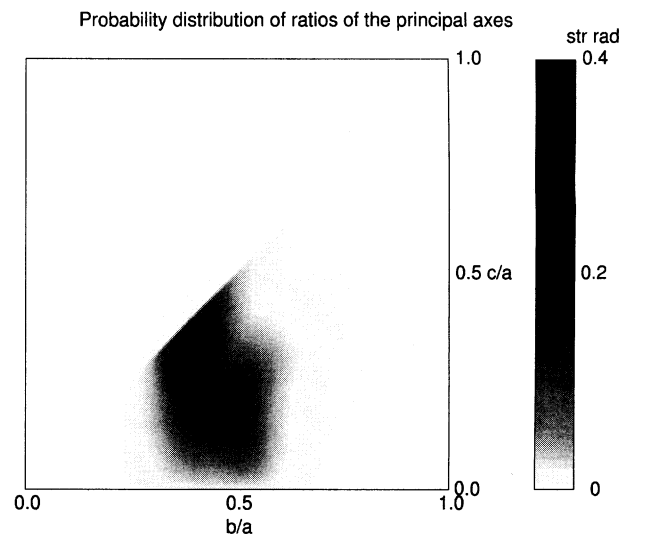


FIG. 7. Probability distribution for ratios of the principal axes b/a and c/a . Two families of solutions are seen.

ellipsoid of $b/a \approx 0.55$; the other is a rather prolate ellipsoid of $b/a \approx 0.4$ and $b/c \sim 1$.

5. CONCLUSION

The occultation of HIP 014402A by (1437) Diomedes, the first Trojan asteroid occultation to be observed, was successfully monitored from Japan on November 7, 1997, thanks to last-minute astrometry obtained at Mitaka 6 days before the event. An occultation silhouette of Diomedes was obtained from 6 chords. Follow-up photometry of Diomedes was obtained at Ondřejov and Mitaka on 5 nights. Diomedes' rotation period (1.019 ± 0.004 days) is nearly commensurate with the sidereal day, and photometry at the two sites show quite complimentary phases in the lightcurve, owing to the longitude difference between the two observatories. The lightcurve shows an amplitude of 0.70 ± 0.15 mag and the rotational phase at the time of the occultation was nearly at minimum.

The 3-D shape of Diomedes is modeled from combined observations of the stellar occultation and follow-up photometry. This is the first time that this has been possible for a Trojan asteroid. A probability distribution for the orientation of its rotation axis shows that it is limited to two great circles on the celestial sphere. Probability distributions of derived axial ratios show that two types of ellipsoidal models, one triaxial and one rather prolate, are possible. Probability distributions for lengths of the principal axes indicate two families of models according to where the peak of the b axis lies. The c axis is no longer than 100 km, and the a axis is no shorter than 170 km. Mean lengths of principal axes are $(284 \pm 61 \text{ km}) \times (126 \pm 35 \text{ km}) \times (65 \pm 24 \text{ km})$ and suggest that the most probable 3-D shape of Diomedes is approximately $a : b : c \approx 4 : 2 : 1$.

ACKNOWLEDGMENTS

We gratefully acknowledge the observers of occultation listed in Table I. This paper is written thanks to the Astronomical Data Center of the National Astronomical Observatory of Japan.

REFERENCES

- Binzel, R. P., and L. M. Sauter 1992. Trojan, Hilda, and Cybele asteroids: New lightcurves observations and analysis. *Icarus* **95**, 222–238.
- Bowell, E., B. Hapke, D. Domingue, K. Lumme, J. Peltoniemi, and A. Harris 1989. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 549–554. Univ. of Arizona, Tucson.
- Bus, S. J., M. W. Buie, D. G. Schleicher, W. B. Hubbard, R. L. Marcialis, R. Hill, L. H. Wasserman, J. R. Spencer, R. L. Millis, O. G. Franz, A. S. Bosh, E. W. Dunham, C. H. Ford, J. W. Young, J. L. Elliot, R. Meserole, C. B. Olkin, S. W. McDonald, J. A. Foust, L. M. Sopata, and R. M. Bandyopadhyay 1996. Stellar occultation on by 2060 Chiron. *Icarus* **123**, 478–490.
- Dunham, E. W., R. L. Baron, S. Conner, D. W. Dunham, J. B. Dunham, G. Schneider, H. L. Cohen, V. T. Helms III, M. Croom, and J. Safko 1984. Results from the occultation of 14 Piscium by (51) Nemausa. *Astron. J.* **89**, 1755–1758.
- Dunham, D. W., J. B. Dunham, R. P. Binzel, D. S. Evans, M. Freuh, G. W. Henry, M. F. A'Hearn, R. G. Schnurr, R. Betts, H. Haynes, R. Orcutt, E. Bowell, L. H. Wasserman, R. A. Nye, H. L. Giclas, C. R. Chapman, R. D. Dietz, C. Moncivais, W. T. Douglass, D. C. Parker, J. D. Beish, J. O. Martin, D. R. Monger, W. B. Hubbard, H. J. Reitsema, A. R. Klemola, P. D. Lee, B. R. McNamara, P. D. Maley, P. Maanly, N. L. Markworth, R. Nolthenius, T. D. Oswalt, J. A. Smith, E. F. Strother, H. R. Povenmire, R. D. Purrington, C. Trenary, G. H. Schneider, W. J. Schuster, M. A. Moreno, J. Guichard, G. R. Sánchez, G. E. Taylor, A. R. Upgren, and T. C. Van Flandern 1990. The size and shape of (2) Pallas from the 1983 occultation of 1 Vulpeculae. *Astron. J.* **99**, 1636–1662.
- Dunlap, J. L., and T. Gehrels 1969. Minor Planet. III. Lightcurves of a Trojan Asteroid. *Astron. J.* **74**, 796–803.
- Elliot, J. L., C. B. Olkin, E. W. Dunham, C. H. Ford, D. K. Gilmore, D. Kurtz, D. Lazzaro, D. M. Rank, P. Temi, R. M. Bandyopadhyay, J. Barroso, A. Barucci, A. S. Bosh, M. W. Buie, S. J. Bus, C. C. Dahn, D. W. Forysta, W. B. Hubbard, D. F. Lopes, R. L. Marcialis, S. W. McDonald, R. L. Millis, H. Reitsema, D. G. Schleicher, B. Sicardy, R. P. S. Stone, and L. H. Wasserman 1995. Jet-like features near the nucleus of Chiron. *Nature* **373**, 46–49.
- French, L. M. 1987. Rotation properties of four L5 Trojan asteroids from CCD photometry. *Icarus* **72**, 325–341.
- Hartmann, W. K., D. J. Tholen, J. Goguen, R. P. Binzel, and D. P. Griukshank 1988. *Icarus* **73**, 487–498.
- Jenkner, H., B. M. Lasker, C. R. Sturch, B. J. McLean, M. M. Shara, and J. L. Russel 1990. *Astron. J.* **99**, 2082–2154.
- Kovalevsky, J. 1997. HIPPARCOS astrometry results. The first Results of Hipparcos and Tycho. In *Abstract book of the 23rd Meeting of the IAU, Joint Discussion 14, 25 August 1997, Kyoto, Japan*, p. 61.
- Lagerkvist, C.-I., A. W. Harris, and V. Zappalà 1989. Asteroid lightcurve parameters. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 1162–1179. Univ. of Arizona, Tucson.
- Lasker, B. M., C. R. Sturch, B. J. McLean, J. L. Russel, H. Jenker, and M. M. Shara 1990. The Guide Star Catalog. I. Astronomical foundations and image processing. *Astron. J.* **99**, 2019–2058.
- Millis, R. L., L. H. Wasserman, E. Bowell, O. G. Franz, N. M. White, G. W. Lockwood, R. Nye, R. Bertram, A. R. Klemola, E. Dunham, R. L. Baron, J. L. Elliot, A. Harris, J. W. Young, J. Faulkner, R. Stanton, H. J. Reitsema, W. B. Hubbard, B. Zellner, L. Lebofsky, D. P. Cruikshank, L. S. Macknik, E. E. Becklin, D. Morrison, C. J. Lonsdale, T. D. Kunkle, T. Lee, I. Gatley, M. F. A'Hearn, D. L. DuPuy, R. Nolthenius, H. Ford, D. McKenna, Z. Placova, K. Horne, W. H. Sandman, G. E. Taylor, and R. H. Tucker 1981. The diameter of Juno from its occultation of AG+0° 1022. *Astron. J.* **86**, 306–313.
- Millis, R. L., L. H. Wasserman, O. G. Franz, R. A. Nye, R. C. Oliver, T. J. Kreidl, S. E. Jones, W. Hubbard, L. Lebofsky, R. Goff, R. Marcialis, M. Sykes, J. Frecker, D. Hunten, B. Zellner, H. Reitsema, G. Schneider, E. Dunham, J. Klavetter, K. Meech, T. Oswalt, J. Rafert, E. Strother, J. Smith, H. Povenmire, B. Jones, D. Kornbluh, L. Reed, K. Izor, M. F. A'Hearn, R. Schnurr, W. Osborn, D. Parker, W. T. Douglas, J. D. Beish, A. Klemola, M. Ríos, A. Sánchez, J. Piironen, M. Mooney, R. S. Ireland, and D. Laibow 1987. The size, shape, density, and albedo of Ceres from its occultation of BD+8° 471. *Icarus* **72**, 507–518.
- O'Leary, B., B. G. Marsden, R. Dragon, E. Hauter, M. McGrath, P. Backus, and H. Robkoff 1976. The size of κ Geminorum by Eros. *Icarus* **28**, 133–146.
- Perryman, M. A. C., and 18 colleagues 1997. The Hipparcos Catalog. *Astron. Astrophys.* **323**, L49–L52.
- Russell, J. L., B. M. Lasker, B. J. McLean, C. R. Sturch, and H. Jenker 1990. The Guide Star Catalog. II. Photometric and astrometric models and solutions. *Astron. J.* **99**, 2059–2081.
- Satō, I., M. Sōma, and T. Hirose 1993. The occultation of gamma Geminorum by the asteroid 381 Myrrha. *Astron. J.* **105**, 1553–1561.
- Taylor, G. E. 1952. Occultations of stars by asteroids 1953. In *Handbook of the British Astronomical Association, 1953*, p. 17.

- Taylor, G. E. 1962. Diameter of minor planets. *Observatory* **82**, 17–20.
- Taylor, G. E., and D. W. Dunham 1978. The size of minor planet 6 Hebe. *Icarus* **34**, 89–92.
- Urban, S. E., T. E. Corbin, and G. L. Wycoff 1998. The ACT reference catalog. *Astron. J.* **115**, 2161–2166.
- Wasserman, L. H., R. L. Millis, O. G. Franz, E. Bowell, N. M. White, H. L. Giclas, L. J. Martin, J. L. Elliot, E. Dunham, D. Mink, R. Baron, R. L. Honeycutt, A. A. Henden, J. E. Kephart, M. F. A'Hearn, H. J. Reitsema, R. Radick, and G. E. Taylor 1979. The diameter of Pallas from its occultation of SAO 85009. *Astron. J.* **84**, 259–268.
- Williamon, R. M. 1980. Observation of a secondary extinction during the occultation of SAO 114159 by (18) Melpomene. *Astron. J.* **85**, 174–175.
- Zappalà, V., M. DiMartino, A. Cellino, P. Farinella, G. De Sanctis, and W. Ferreri 1989. Rotational properties of outer belt asteroids. *Icarus* **82**, 354–368.