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The Lightcurve of 4179 Toutatis: Evidence for Complex Rotation

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The Apollo asteroid 4179 Toutatis passed within 0.0242 AU of Earth in December 1992, and photometry was obtained by observers from at least 25 sites around the world, at solar phase angles between 121° and 0.2°. The phase curve is well described in the *H*, *G* system with a mean *H* of 15.3 and a slope parameter *G* of 0.10 ± 0.10. However, the rotational lightcurve is very unusual. The amplitude is large (1.2 magnitudes) and the rotation period is extremely long (several days). Most remarkably, the lightcurve does not appear to be periodic: it is unlikely that a single rotation period can account for the lightcurve even when the rapidly changing viewing and illumination geometry during the close Earth approach is taken into account, though strong lightcurve minima recurred approximately every 7.3 days. The likely explanation is that Toutatis has complex, tumbling, rotation with a characteristic period between 3 and 7 days. As noted by A. W. Harris (1994 *Icarus* 107, 209–211), the damping time scale from complex to simple rotation for a small, slowly rotating asteroid like Toutatis is so long that complex rotation is expected, but Toutatis is the first asteroid to show such strong observational evidence for complex rotation.

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INTRODUCTION

The December 1992 close approach to Earth of the Apollo asteroid 4179 Toutatis provided an unprecedented opportunity to study the photometric behavior of a near-Earth object, because of its well-determined orbit, unusual brightness (maximum V magnitude ≈ 10.5), small geocentric distance (minimum 0.0242 AU), wide range of phase angles visible from Earth (0.24° − 169°), and the potential for "ground truth" from radar imaging (Ostro 1993). The geometry of the close Earth approach is illustrated in Fig. 1.

Toutatis' slow rotation (discussed below) and rapidly changing viewing geometry during the flyby meant that a global network of observers was necessary to properly characterize its rotational and phase behavior during the close approach period. Fortunately, the apparition aroused worldwide interest, and photometric observations were obtained at at least 25 telescopes in 14 countries (and one in space) during December 1992 and January 1993 (Table I). This paper summarizes the results of the global photometric campaign and the very unusual

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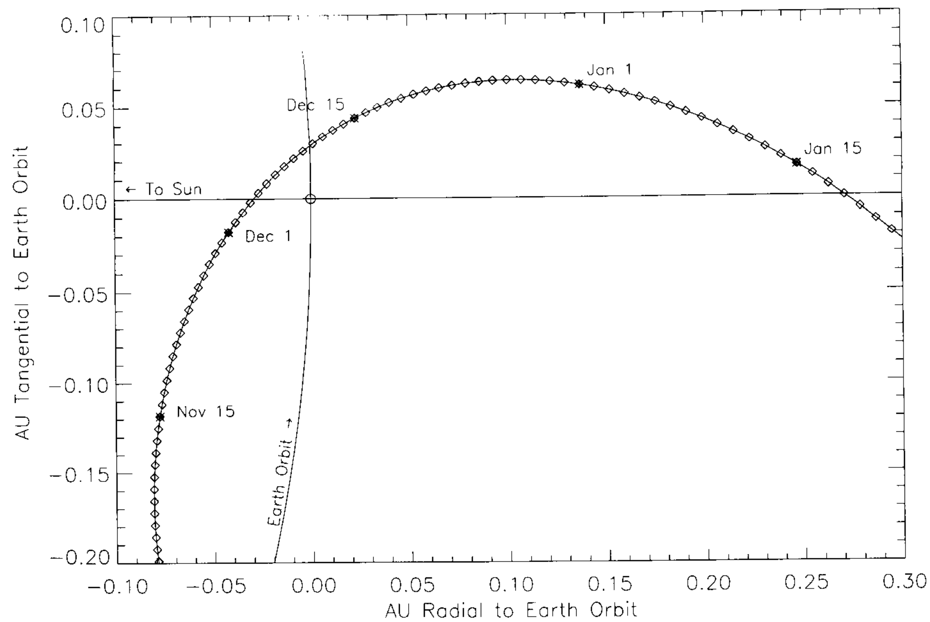

FIG. 1. The December 1992 Earth flyby of Toutatis, viewed from the North ecliptic pole in a rotating frame centered on Earth and with the direction to the Sun fixed. The small circle centered on Earth shows the size of the Moon's orbit. The position of Toutatis is shown at 1-day intervals, with some dates labeled for reference.

rotational properties that are suggested by the observations.

OBSERVATIONS

Even before the close approach, there were indications that Toutatis was an unusual object. Photometry by Wieslaw Wisniewski on 2 days in January 1989 suggested an unusually long rotation period, between 10 hr and several days. Photometry by Dotto *et al,* Tholen, and Howell and Nolan in July and August 1992, when Toutatis was still 0.6 AU from Earth (Table II and Fig. 2), showed only monotonic variations in brightness during each night of observations, with a total brightness range of 1 magnitude. This suggested an elongated object with a rotation period of more than 1 day, though it was not possible to determine the actual period from this data set.

During the close approach period, Toutatis was observed photometrically from many sites with a wide variety of telescopes, using both aperture photometers and CCDs (Table I). The bulk of the observations were obtained in the *V* filter and were reduced to standard Johnson V magnitudes, though *U*, *B*, and *R* observations were also recorded at some sites. The large number of different observers precluded uniform reduction techniques, but in most cases extinction was measured and corrected for, and color corrections were applied to transform the magnitudes to Johnson V. More detail on the standard stars used for absolute calibration, when available, is given in Table I. Extensive use of electronic mail allowed global observations to be coordinated and results distributed in near real-time. Table III lists all *V* photometry obtained during the close approach period, except for a few observations which had very low signal-to-noise or were obviously inconsistent with other near-simultaneous data. Because the slow rotation produced little brightness variation in 1 hr, observations by a single observer have been binned to 1-hr time resolution in Tables II and III and the figures. The quoted error represents either the formal photometric error of the points or the standard deviation of the magnitudes included in that point, whichever was larger. The time associated with each bin is the mean time of the individual measurements, rather than the bin center. In deriving error bars for the binned magnitudes we did not subtract any systematic trend within the bin before obtaining a standard deviation, in the interests of simplicity: this will result in overestimation of the errors in a few cases but will not affect our conclusions significantly. The data from the Ukrainian group have been published previously (Krugly *et al.* 1993), and the HST observations are described in more detail in Noll *et al.* (1995).

SOLAR PHASE ANGLE DEPENDENCE

Toutatis was observed in reflected sunlight at phase angles from 121° (a probable record for an asteroid) to 0.2°. Figure 3 plots the reduced *V* magnitude of Toutatis

TABLE I
Observation Sites

Observers	Observatory	Aperture (m)	Instrument	Calibration Notes
Angeli	Haute Provence, France	1.2	CCD	3
Barucci, Lazzaro	Pic du Midi, France	2.0	CCD	3
Birch	Perth, Australia	0.61	Photometer	2
Blanco, Riccioli	Catania, Italy	0.91	Photometer	
Dentchev	Belogradchik, Bulgaria	0.6	Photometer	
De Sanctis, Angelini	Asiago, Italy	1.8	CCD	3
Dotto, C. Venditti, R. Venditti	ESO, La Silla, Chile	1.0	Photometer	3
Green	Roque de los Muchachos, Canary Is.	1.0	Photometer	
Howell, Nolan	Catalina Observatory, Tucson, AZ, USA	1.5	CCD	3
Hudecek	Brno Observatory, Czech Republic	0.4	Photometer	
Koshkin, Dorokov	Mt. Dushak, Turkmenistan	0.8	Photometer	
Kozhevnikov	Urals University, Ekaterinburg, Russia	0.45	Photometer	
Krugly, Chiornij, Kobelev	Mt. Koshka, Simeiz, Crimea, Ukraine	0.6,1.0	Photometer	2
Lecacheux, Colas, Caruso	Pic du Midi, France	1.0	CCD	3
MacConnell	Llano del Hato, Merida, Venezuela	1.0	Photometer	3
Mueller	Kitt Peak, Tucson, Arizona, USA	2.1	CCD	3
Nakamura	Kiso, Japan	1.05	CCD	4
Neese	Lowell Obs., Flagstaff, AZ, USA	1.2	CCD	1
Noll, Zellner	Hubble Space Telescope	2.4	CCD	5
Pravec	Ondrejov, Czech Republic	0.18	CCD	3
V.S. Shevchenko, Ezhkova Korobova Mel'nikov	Mt. Majdanak, Uzbekistan	0.6	Photometer	
Spencer, Tholen	IRTF, Mauna Kea, HI, USA	3.2	Photometer	3
Tholen	Mauna Kea, HI, USA	0.6	Photometer	1
Velichko, Kalashnikov, Akimov, V.G. Shevchenko	Chuguevskaya, Kharkov, Ukraine	0.7	Photometer	2
Wisniewski	Mt. Lemmon, Tucson, AZ, USA	1.5	Photometer	
Young	Table Mountain, CA, USA	0.61	Photometer	3

Note. Absolute calibration was done using a large number of different standard stars from the following sources: (1) Tedesco *et al.* (1982), (2) Blanco *et al.* (1968), (3) Landolt (1983), (4) Lasker *et al.* (1988), (5) Hubble Space Telescope absolute calibration. A blank entry indicates that the information is not available. In most cases extinction was measured and extinction and color corrections were applied to the data, but full information on reduction is not always available.

TABLE II
V Photometry: July and August 1992

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecl-iptic Lon.	N	V	$H(\alpha)$	H	First Observer
92/07/23	12:25	23.5171	1.6985	0.6827	0.5	301.8	4	15.65 ± 0.01	15.33	15.23	Tholen
92/07/23	13:53	23.5786	1.6980	0.6822	0.4	301.7	2	15.62 ± 0.01	15.30	15.20	Tholen
92/07/24	13:17	24.5534	1.6893	0.6736	0.4	301.4	4	15.89 ± 0.02	15.61	15.52	Tholen
92/07/27	01:33	27.0649	1.6670	0.6524	2.5	300.4	5	15.59 ± 0.10	15.41	15.12	Dotto
92/07/27	02:34	27.1067	1.6666	0.6521	2.5	300.3	3	15.57 ± 0.08	15.39	15.11	Dotto
92/07/27	03:06	27.1295	1.6664	0.6519	2.5	300.3	1	15.67 ± 0.00	15.49	15.20	Dotto
92/07/30	01:39	30.0689	1.6401	0.6289	5.1	299.1	1	15.43 ± 0.00	15.36	14.91	Dotto
92/07/30	02:35	30.1076	1.6398	0.6286	5.1	299.1	2	15.44 ± 0.02	15.38	14.93	Dotto
92/07/30	03:30	30.1457	1.6395	0.6283	5.1	299.0	3	15.51 ± 0.02	15.45	14.99	Dotto
92/07/30	04:34	30.1902	1.6391	0.6280	5.2	299.0	3	15.48 ± 0.05	15.42	14.96	Dotto
92/07/30	06:27	30.2685	1.6384	0.6274	5.2	299.0	2	15.49 ± 0.01	15.43	14.97	Dotto
92/07/30	07:33	30.3147	1.6379	0.6271	5.3	299.0	3	15.55 ± 0.04	15.49	15.02	Dotto
92/07/30	08:48	30.3670	1.6375	0.6267	5.3	298.9	1	15.59 ± 0.00	15.53	15.07	Dotto
92/07/30	09:02	30.3767	1.6374	0.6266	5.3	298.9	1	15.60 ± 0.00	15.54	15.08	Dotto
92/07/31	04:42	31.1961	1.6300	0.6206	6.1	298.6	2	16.00 ± 0.01	15.98	15.48	Dotto
92/07/31	05:36	31.2335	1.6297	0.6203	6.1	298.5	1	15.99 ± 0.00	15.97	15.46	Dotto
92/07/31	06:37	31.2756	1.6293	0.6200	6.1	298.5	5	15.95 ± 0.06	15.93	15.42	Dotto
92/07/31	07:35	31.3162	1.6290	0.6197	6.2	298.5	3	15.95 ± 0.06	15.93	15.42	Dotto
92/07/31	08:40	31.3608	1.6286	0.6194	6.2	298.5	2	15.94 ± 0.04	15.92	15.41	Dotto
92/07/31	09:04	31.3780	1.6284	0.6193	6.2	298.5	1	15.94 ± 0.00	15.92	15.41	Dotto
92/08/01	01:31	32.0634	1.6223	0.6143	6.8	298.2	5	16.06 ± 0.05	16.07	15.52	Dotto
92/08/01	02:22	32.0989	1.6219	0.6141	6.9	298.2	4	15.94 ± 0.05	15.95	15.40	Dotto
92/08/01	03:23	32.1409	1.6216	0.6138	6.9	298.1	5	16.07 ± 0.07	16.08	15.54	Dotto
92/08/01	04:39	32.1939	1.6211	0.6134	7.0	298.1	7	16.26 ± 0.06	16.27	15.72	Dotto
92/08/01	05:32	32.2306	1.6208	0.6132	7.0	298.1	6	16.35 ± 0.04	16.36	15.81	Dotto
92/08/01	06:25	32.2676	1.6204	0.6129	7.0	298.1	8	16.34 ± 0.10	16.35	15.80	Dotto
92/08/01	07:32	32.3139	1.6200	0.6126	7.1	298.1	10	16.42 ± 0.10	16.44	15.88	Dotto
92/08/01	08:16	32.3445	1.6197	0.6124	7.1	298.0	2	16.38 ± 0.08	16.40	15.85	Dotto
92/08/04	01:38	35.0678	1.5953	0.5940	9.6	296.8	3	15.62 ± 0.01	15.73	15.06	Dotto
92/08/04	02:36	35.1086	1.5949	0.5937	9.7	296.8	7	15.67 ± 0.04	15.79	15.11	Dotto
92/08/04	03:35	35.1496	1.5945	0.5935	9.7	296.7	4	15.67 ± 0.07	15.79	15.12	Dotto
92/08/04	04:36	35.1917	1.5942	0.5932	9.8	296.7	3	15.76 ± 0.05	15.88	15.20	Dotto
92/08/04	05:31	35.2299	1.5938	0.5930	9.8	296.7	2	15.73 ± 0.03	15.85	15.17	Dotto
92/08/04	06:19	35.2632	1.5935	0.5927	9.8	296.7	2	15.80 ± 0.03	15.92	15.24	Dotto
92/08/04	07:18	35.3042	1.5931	0.5925	9.9	296.7	2	15.85 ± 0.07	15.98	15.30	Dotto
92/08/04	08:32	35.3555	1.5927	0.5921	9.9	296.6	3	15.94 ± 0.07	16.07	15.38	Dotto
92/08/27	05:23	58.2246	1.3860	0.4906	33.0	286.0	1	15.42 ± 0.02	16.26	14.78	Howell
92/08/28	03:23	59.1413	1.3778	0.4880	33.9	285.7	3	15.52 ± 0.08	16.38	14.88	Howell
92/08/28	04:23	59.1825	1.3774	0.4879	33.9	285.6	3	15.44 ± 0.04	16.31	14.80	Howell
92/08/28	05:21	59.2227	1.3770	0.4877	34.0	285.6	3	15.41 ± 0.07	16.27	14.77	Howell

Note. Observations within a single hour have been binned together. The stated error represents the standard deviation of the points within each bin. Number of points in each bin is given by N. "Decimal Day" is the time in fractional days since July 0.0, 1992. To convert to Julian date, add 2448803.5. Ecliptic longitude is shown to indicate the viewing geometry; due to Toutatis' small orbital inclination of 0.5° its ecliptic latitude is always small. $H(\alpha)$ is the V magnitude corrected to unit heliocentric and geocentric distance. H is the magnitude additionally corrected to zero phase angle using the H, G, photometric system and a G value of 0.10. The final column identifies the observing team by the name of the first observer (Table I).

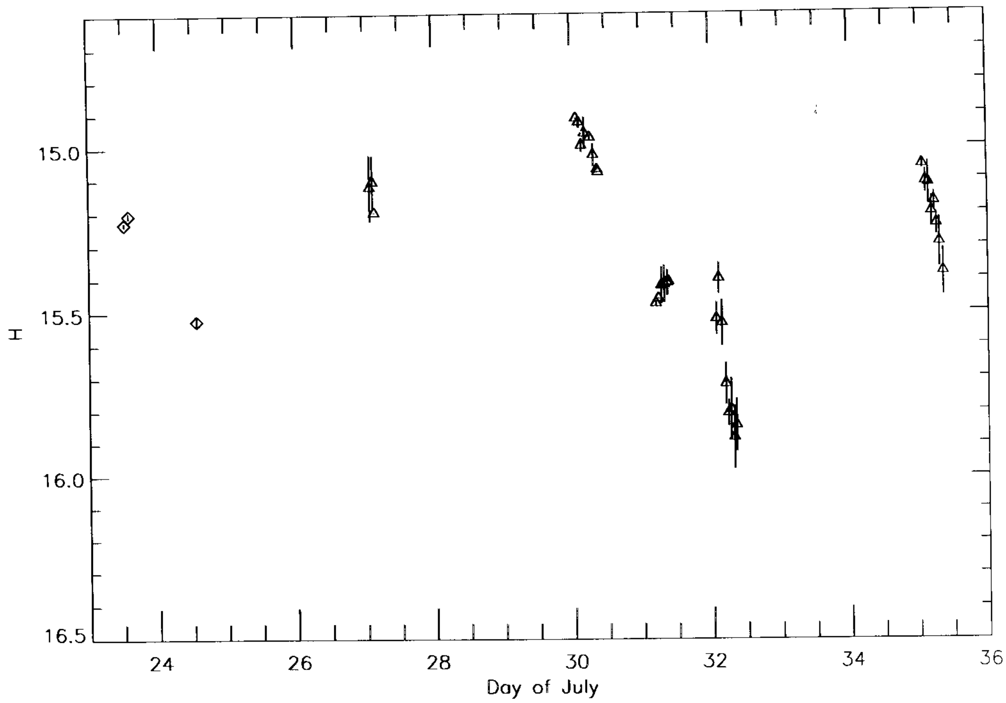

FIG. 2. Photometry of Toutatis in July and August 1992, obtained by Dotto *et al.* (triangles) and Tholen (diamonds). See Table II. Late-August photometry by Howell and Nolan is not shown. Data are binned to 1-hr time increments, and a slope parameter G of 0.10 is assumed in determining H. These observations suggest an unusually slow rotation, but are insufficient to determine a period.

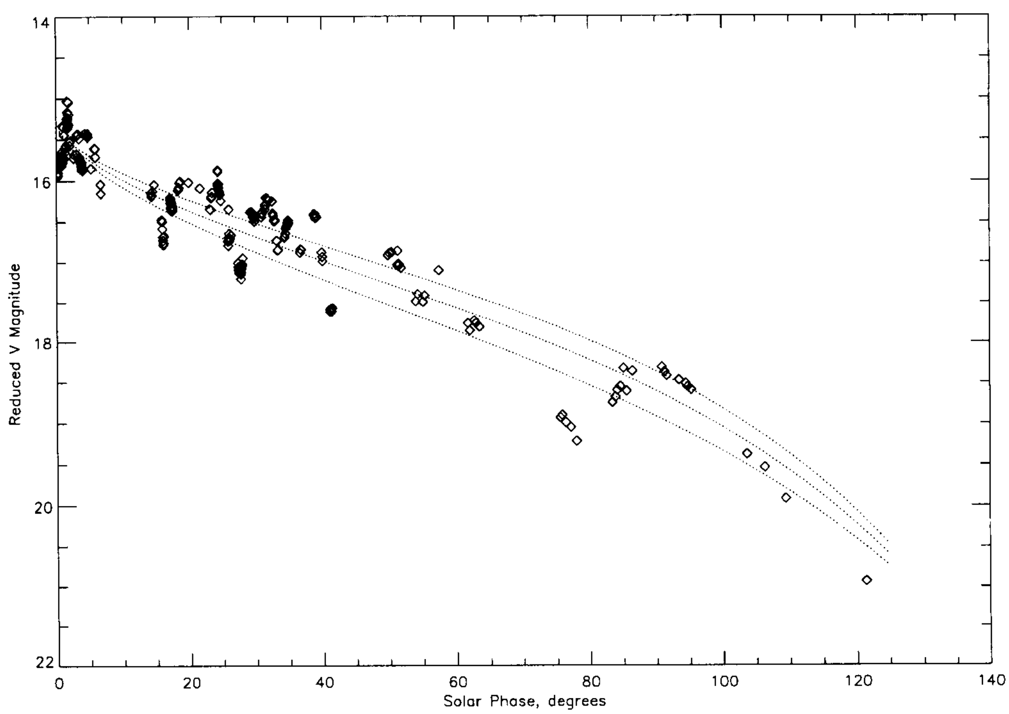

FIG. 3. Reduced V magnitude (corrected to unit geocentric and heliocentric distance) vs solar phase angle for the December 1992/January 1993 observations. The three model phase curves are calculated using the IAU H, G system (Bowell *et al.* 1989), with H = 15.30 and G = 0.0, 0.1, and 0.2 (from steepest to shallowest).

(corrected to 1 AU geocentric and heliocentric distance) as a function of solar phase angle. Also shown are model phase curves in the H, G system (Bowell *et al.* 1989) for an H value of 15.30 and a G value of 0.10 ± 0.10. Toutatis' color and spectrum indicates that it is an S type asteroid (Howell *et al.* 1994), for which a G value of 0.23 ± 0.11 is expected (Harris and Young 1988), but Fig. 1 suggests that a lower value might be more appropriate for Toutatis: we adopt $G = 0.10 \pm 0.10$. The value is not well constrained due to the large amplitude of the lightcurve (see below) and the incomplete lightcurve coverage. The large lightcurve amplitude and the radar images (Ostro *et al.* 1993) indicate that Toutatis has an elongated and irregular shape which could introduce brightness variations due to changing viewing aspect relative to its spin axis (if any: see below), as well as due to changing solar phase angle, so the low G value may not indicate unusual surface properties.

ROTATIONAL VARIATIONS

Tables II and III also list the H magnitude of Toutatis for each observation, corrected to 1 AU geocentric and heliocentric distance and to zero phase angle, assuming $G = 0.10$. Figure 4 shows H as a function of time for all observations during the close approach period. With some exceptions, near-simultaneous observations at different sites generally show excellent agreement, providing confidence that data reduction was done consistently by different observers. Where the time coverage is dense enough, a fairly coherent lightcurve can be constructed from the combined observations, though there are many gaps in the coverage. As noted by Argentini *et al.* (1985), Harris *et al.* (1987), and Zappalá *et al.* (1990), lightcurve amplitude tends to increase with increasing phase angle. Excluding the very deep minimum of December 12, which is probably influenced by the high (78°) solar phase angle at that time, the H magnitude varies between 14.67 and 15.91, a factor of 3.1 variation in brightness. Toutatis is thus highly elongated, as also suggested by the large variation in its radar depth and its two-lobed appearance in the radar images (Ostro *et al.* 1993).

In the July/August 1992 data the brightness range is similar: H magnitude varies between 14.77 and 15.90, though the lightcurve is less thoroughly sampled than during the close approach. Note that in July and August 1992 the ecliptic longitude of Toutatis was 302°–286°, while ecliptic longitude varied between 145° and 115° during the close approach, excluding the period of rapidly changing geometry before December 14, 1992. Toutatis was thus seen from almost exactly opposite directions in the two observing periods, and similar lightcurve amplitude is to be expected regardless of pole orientation.

Determination of the rotational period has proved very difficult. A lower limit can be set by looking at sections of the January/December lightcurve where coverage is particularly dense. Between 19:29 on 1993/01/20 and 09:47 on 1993/01/22 there was a period of 38 hr with no gap in coverage longer than 6.5 hr (Fig. 5). During this time H remained between 15.49 and 15.09, and the peak brightness (recorded by Nakamura) may actually have been fainter than 15.09, because the sudden brightness drop between the Nakamura and following De Sanctis observations suggests that the Nakamura brightnesses may be overestimated (Nakamura used stars P424-C, P424-D, and P424-E from the Hubble Guide Star Photometric Catalog as his standards, while De Sanctis used Landolt standards, and possibly this accounts for the discrepancy). The 38-hr time period thus did not include a primary lightcurve maximum or minimum, because the 6.5-hr gap was shorter than the duration of nearby maxima or minima, and the brightness gradient was positive on both sides of the 6.5-hr gap. The rotation period is thus considerably longer than 38 hr (1.58 days). An upper limit to the period can be estimated from the ~1-day interval between the apparent lightcurve maxima and minima near December 20.4 and December 21.4, 1992 (Fig. 5), both of which approach the extreme range of Toutatis' brightness. Primary maxima and minima are likely to be at least 1/4 rotation apart, giving an upper limit to the rotation period of about 4 days, though for safety we have searched for rotation periods up to 12 days.

Because of the rapidly changing viewing geometry during the December 1992–January 1993 observations, synodic effects should be considered in attempt to find the rotation period: the apparent rotation period during the close approach is likely to be different from the sideral period and is likely to change during the observations. The magnitude of the change will depend on the orientation of the rotation pole. If the pole is in the ecliptic plane, and the asteroid is in the ecliptic (a good approximation for Toutatis, which was within 4° of the ecliptic from December 19, 1992, till the end of January 1993), the apparent (synodic) rotation period will always equal the sidereal period (apart from a 180° phase shift when the pole passes though Earth), while if the angular momentum vector points north of the ecliptic plane (prograde rotation) the synodic period will be shorter than the sidereal period, and vice versa for retrograde rotation.

After December 20th the effects of changing viewing geometry on the lightcurve period should be relatively small. Ecliptic latitude varies little, between −3.6° on 1992/12/20 and −0.1° on 1993/01/28, so nearly all the change in viewing geometry can be expressed as a change in ecliptic longitude. The largest synodic effect on the period is seen when the rotational pole is perpendicular to the ecliptic, as discussed above. With this geometry, the maximum difference between the synodic and sideral

TABLE III
V Photometry: December 1992 and January 1993

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	$H(\alpha)$	H	First Observer
92/12/08	15:24	8.6417	0.9720	0.0243	121.4	200.1	1	12.80 ± 0.01	20.93	15.91	Tholen
92/12/09	09:50	9.4096	0.9761	0.0253	109.4	187.3	1	11.88 ± 0.05	19.91	15.67	MacConnell
92/12/09	15:00	9.6250	0.9773	0.0258	106.3	184.0	1	11.54 ± 0.01	19.53	15.47	Tholen
92/12/09	19:30	9.8125	0.9783	0.0262	103.6	181.3	1	11.42 ± 0.00	19.38	15.45	Birch
92/12/10	10:40	10.4444	0.9817	0.0281	95.2	172.9	1	10.79 ± 0.02	18.59	15.06	Wisniewski
92/12/10	11:43	10.4878	0.9820	0.0282	94.7	172.4	2	10.76 ± 0.01	18.55	15.05	Wisniewski
92/12/10	12:15	10.5104	0.9821	0.0283	94.4	172.1	1	10.73 ± 0.02	18.51	15.02	Wisniewski
92/12/10	14:16	10.5944	0.9826	0.0286	93.4	171.1	1	10.71 ± 0.01	18.47	15.02	Tholen
92/12/10	18:00	10.7500	0.9834	0.0291	91.6	169.3	1	10.70 ± 0.03	18.42	15.05	Birch
92/12/10	18:39	10.7771	0.9836	0.0292	91.3	169.0	3	10.66 ± 0.03	18.37	15.01	Noll
92/12/10	19:30	10.8125	0.9838	0.0293	90.9	168.6	1	10.61 ± 0.04	18.31	14.97	Birch
92/12/11	05:13	11.2172	0.9860	0.0309	86.4	164.5	1	10.78 ± 0.00	18.36	15.20	Lecacheux
92/12/11	07:16	11.3029	0.9865	0.0312	85.5	163.7	1	11.05 ± 0.04	18.61	15.48	MacConnell
92/12/11	08:25	11.3508	0.9868	0.0314	85.1	163.2	1	10.78 ± 0.04	18.32	15.21	MacConnell
92/12/11	09:33	11.3979	0.9871	0.0316	84.6	162.8	1	11.02 ± 0.04	18.55	15.46	MacConnell
92/12/11	10:37	11.4424	0.9873	0.0318	84.1	162.4	1	11.08 ± 0.02	18.60	15.52	Wisniewski
92/12/11	11:21	11.4733	0.9875	0.0319	83.8	162.1	2	11.17 ± 0.03	18.68	15.61	Wisniewski
92/12/11	12:28	11.5194	0.9877	0.0321	83.4	161.7	2	11.25 ± 0.01	18.74	15.70	Wisniewski
92/12/12	02:32	12.1057	0.9911	0.0347	78.0	156.9	1	11.90 ± 0.00	19.22	16.36	Lecacheux
92/12/12	05:00	12.2086	0.9917	0.0352	77.2	156.2	1	11.76 ± 0.00	19.05	16.22	Lecacheux
92/12/12	07:13	12.3008	0.9922	0.0356	76.4	155.5	1	11.73 ± 0.04	18.99	16.19	MacConnell
92/12/12	08:49	12.3675	0.9926	0.0359	75.9	155.1	1	11.66 ± 0.04	18.90	16.12	MacConnell
92/12/12	09:42	12.4042	0.9928	0.0361	75.6	154.8	1	11.70 ± 0.04	18.93	16.16	MacConnell
92/12/14	05:43	14.2383	1.0037	0.0455	63.5	145.1	1	11.11 ± 0.05	17.81	15.44	MacConnell
92/12/14	08:09	14.3396	1.0044	0.0461	63.0	144.7	1	11.09 ± 0.05	17.76	15.40	MacConnell
92/12/14	09:11	14.3825	1.0046	0.0463	62.7	144.5	1	11.07 ± 0.05	17.73	15.38	MacConnell
92/12/14	12:15	14.5104	1.0054	0.0470	62.1	144.0	1	11.23 ± 0.01	17.86	15.53	Tholen
92/12/14	13:30	14.5625	1.0057	0.0473	61.8	143.8	1	11.15 ± 0.01	17.76	15.44	Tholen
92/12/15	05:19	15.2212	1.0098	0.0510	58.6	141.5	1	10.78 ± 0.07	17.22	15.00	MacConnell
92/12/15	11:30	15.4792	1.0114	0.0524	57.4	140.7	1	10.72 ± 0.05	17.10	14.91	Wisniewski
92/12/15	23:43	15.9879	1.0146	0.0553	55.3	139.2	1	11.16 ± 0.03	17.41	15.29	Pravec
92/12/16	01:06	16.0462	1.0149	0.0557	55.0	139.1	1	11.25 ± 0.00	17.49	15.37	V.S. Shevchenko
92/12/16	05:36	16.2333	1.0161	0.0567	54.3	138.6	1	11.20 ± 0.05	17.40	15.30	MacConnell
92/12/16	07:29	16.3117	1.0166	0.0572	54.0	138.4	1	11.31 ± 0.05	17.49	15.40	MacConnell
92/12/16	21:34	16.8989	1.0204	0.0606	51.8	136.9	4	11.02 ± 0.01	17.07	15.04	Koshkin
92/12/16	23:38	16.9845	1.0209	0.0611	51.5	136.7	1	11.00 ± 0.00	17.02	15.01	Koshkin
92/12/17	00:12	17.0085	1.0211	0.0613	51.4	136.7	1	11.00 ± 0.00	17.02	15.01	V.S. Shevchenko
92/12/17	00:31	17.0217	1.0212	0.0613	51.4	136.7	2	11.03 ± 0.01	17.04	15.03	Koshkin
92/12/17	01:02	17.0433	1.0213	0.0615	51.3	136.6	1	10.85 ± 0.00	16.86	14.85	V.S. Shevchenko
92/12/17	01:03	17.0440	1.0213	0.0615	51.3	136.6	1	11.02 ± 0.00	17.03	15.02	Koshkin
92/12/17	07:15	17.3021	1.0230	0.0630	50.4	136.1	1	10.92 ± 0.02	16.87	14.89	Wisniewski
92/12/17	09:25	17.3924	1.0236	0.0635	50.1	135.9	1	10.95 ± 0.02	16.88	14.91	Wisniewski
92/12/17	11:00	17.4583	1.0240	0.0639	49.9	135.7	1	10.99 ± 0.02	16.91	14.94	Wisniewski
92/12/20	08:47	20.3659	1.0434	0.0815	41.5	131.0	3	12.22 ± 0.02	17.57	15.85	Young
92/12/20	09:43	20.4047	1.0437	0.0818	41.4	130.9	5	12.27 ± 0.03	17.62	15.89	Young
92/12/20	10:50	20.4512	1.0440	0.0821	41.3	130.9	2	12.24 ± 0.01	17.58	15.86	Young
92/12/20	11:25	20.4756	1.0442	0.0822	41.2	130.8	4	12.29 ± 0.03	17.62	15.91	Young
92/12/20	12:06	20.5039	1.0444	0.0824	41.1	130.8	1	12.27 ± 0.01	17.59	15.88	Young

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	$H(\alpha)$	H	First Observer
92/12/20	22:52	20.9525	1.0475	0.0852	40.0	130.2	8	11.74 ± 0.01	16.98	15.30	Blanco
92/12/20	23:24	20.9751	1.0476	0.0853	40.0	130.2	12	11.69 ± 0.02	16.93	15.25	Blanco
92/12/21	00:31	21.0212	1.0479	0.0856	39.9	130.2	15	11.64 ± 0.02	16.87	15.20	Blanco
92/12/21	08:28	21.3529	1.0502	0.0877	39.1	129.8	3	11.27 ± 0.03	16.44	14.79	Young
92/12/21	09:39	21.4023	1.0506	0.0880	39.0	129.7	3	11.26 ± 0.02	16.43	14.78	Young
92/12/21	09:60	21.4167	1.0507	0.0881	38.9	129.7	1	11.28 ± 0.01	16.45	14.80	Neese
92/12/21	10:55	21.4551	1.0510	0.0883	38.8	129.7	2	11.24 ± 0.02	16.40	14.75	Young
92/12/21	11:49	21.4922	1.0512	0.0885	38.7	129.6	1	11.25 ± 0.00	16.40	14.76	Young
92/12/21	12:28	21.5195	1.0514	0.0887	38.7	129.6	3	11.27 ± 0.02	16.42	14.78	Young
92/12/22	08:46	22.3652	1.0573	0.0940	36.8	128.7	2	11.83 ± 0.03	16.84	15.26	Young
92/12/22	09:51	22.4102	1.0577	0.0943	36.7	128.6	1	11.83 ± 0.01	16.84	15.25	Young
92/12/22	10:30	22.4375	1.0579	0.0945	36.6	128.6	2	11.88 ± 0.00	16.88	15.30	Young
92/12/23	06:25	23.2674	1.0638	0.0997	34.9	127.8	1	11.64 ± 0.02	16.51	14.98	Wisniewski
92/12/23	06:56	23.2891	1.0639	0.0998	34.8	127.8	1	11.61 ± 0.01	16.48	14.95	Young
92/12/23	06:60	23.2917	1.0639	0.0999	34.8	127.8	1	11.65 ± 0.02	16.52	14.99	Wisniewski
92/12/23	07:29	23.3115	1.0641	0.1000	34.8	127.8	4	11.67 ± 0.05	16.53	15.01	Young
92/12/23	08:00	23.3333	1.0642	0.1001	34.7	127.7	1	11.65 ± 0.02	16.51	14.99	Wisniewski
92/12/23	08:32	23.3555	1.0644	0.1003	34.7	127.7	1	11.69 ± 0.01	16.55	15.02	Young
92/12/23	09:25	23.3926	1.0647	0.1005	34.6	127.7	2	11.70 ± 0.04	16.55	15.03	Young
92/12/23	09:27	23.3941	1.0647	0.1005	34.6	127.7	2	11.69 ± 0.01	16.55	15.02	Wisniewski
92/12/23	10:24	23.4336	1.0650	0.1008	34.5	127.6	4	11.72 ± 0.03	16.57	15.04	Young
92/12/23	11:00	23.4583	1.0651	0.1009	34.5	127.6	1	11.74 ± 0.02	16.58	15.06	Wisniewski
92/12/23	11:43	23.4883	1.0654	0.1011	34.4	127.6	2	11.80 ± 0.02	16.64	15.12	Young
92/12/23	12:34	23.5234	1.0656	0.1013	34.4	127.6	2	11.85 ± 0.05	16.68	15.16	Young
92/12/23	13:24	23.5586	1.0659	0.1015	34.3	127.5	1	11.86 ± 0.01	16.69	15.18	Young
92/12/24	00:44	24.0305	1.0693	0.1046	33.3	127.1	1	12.09 ± 0.00	16.84	15.35	Krugly
92/12/24	01:13	24.0509	1.0694	0.1047	33.3	127.1	3	12.10 ± 0.03	16.85	15.36	Krugly
92/12/24	02:47	24.1162	1.0699	0.1051	33.2	127.0	3	11.99 ± 0.05	16.73	15.25	Krugly
92/12/24	03:33	24.1479	1.0701	0.1053	33.1	127.0	4	11.99 ± 0.03	16.73	15.25	Krugly
92/12/24	06:42	24.2793	1.0711	0.1061	32.8	126.9	4	11.75 ± 0.06	16.47	15.00	Young
92/12/24	07:38	24.3177	1.0713	0.1064	32.8	126.9	3	11.78 ± 0.02	16.49	15.02	Young
92/12/24	08:29	24.3535	1.0716	0.1066	32.7	126.9	4	11.77 ± 0.02	16.48	15.01	Young
92/12/24	09:32	24.3971	1.0719	0.1069	32.6	126.8	3	11.72 ± 0.02	16.42	14.96	Young
92/12/24	10:30	24.4375	1.0722	0.1072	32.5	126.8	3	11.70 ± 0.02	16.40	14.94	Young
92/12/24	11:41	24.4868	1.0726	0.1075	32.4	126.7	1	11.56 ± 0.01	16.25	14.79	Tholen
92/12/24	17:37	24.7342	1.0744	0.1091	32.0	126.5	1	11.58 ± 0.00	16.24	14.79	V.S. Shevchenko
92/12/24	18:34	24.7737	1.0747	0.1093	31.9	126.5	9	11.59 ± 0.01	16.24	14.80	V.S. Shevchenko
92/12/24	19:23	24.8076	1.0749	0.1095	31.8	126.5	6	11.59 ± 0.01	16.24	14.80	V.S. Shevchenko
92/12/24	20:16	24.8443	1.0752	0.1098	31.8	126.5	6	11.58 ± 0.01	16.22	14.78	V.S. Shevchenko
92/12/24	22:42	24.9460	1.0759	0.1104	31.6	126.4	2	11.58 ± 0.00	16.21	14.78	V.S. Shevchenko
92/12/24	23:40	24.9864	1.0762	0.1107	31.5	126.3	4	11.67 ± 0.02	16.29	14.85	Velichko
92/12/25	00:28	25.0192	1.0765	0.1109	31.4	126.3	4	11.69 ± 0.02	16.30	14.87	Velichko
92/12/25	01:24	25.0584	1.0768	0.1111	31.4	126.3	1	11.74 ± 0.04	16.35	14.92	Velichko
92/12/25	06:35	25.2744	1.0783	0.1125	30.9	126.1	4	11.81 ± 0.02	16.39	14.97	Young
92/12/25	07:25	25.3092	1.0786	0.1128	30.9	126.1	6	11.83 ± 0.02	16.40	14.99	Young
92/12/25	08:09	25.3398	1.0788	0.1130	30.8	126.1	2	11.87 ± 0.00	16.44	15.03	Young
92/12/25	21:45	25.9063	1.0830	0.1166	29.8	125.7	1	12.00 ± 0.02	16.49	15.11	Pravec
92/12/25	21:58	25.9154	1.0831	0.1167	29.8	125.6	1	12.01 ± 0.00	16.50	15.11	Krugly
92/12/25	22:06	25.9206	1.0831	0.1167	29.8	125.6	1	11.95 ± 0.00	16.44	15.06	Krugly
92/12/25	22:32	25.9392	1.0833	0.1168	29.7	125.6	1	11.97 ± 0.02	16.46	15.08	Pravec
92/12/25	23:44	25.9891	1.0836	0.1172	29.6	125.6	1	11.93 ± 0.02	16.41	15.04	Pravec
92/12/25	23:55	25.9962	1.0837	0.1172	29.6	125.6	3	11.96 ± 0.06	16.45	15.07	Krugly
92/12/26	00:32	26.0219	1.0839	0.1174	29.6	125.6	1	11.94 ± 0.02	16.42	15.04	Pravec

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	$H(\alpha)$	H	First Observer
92/12/26	01:25	26.0589	1.0841	0.1176	29.5	125.5	1	11.93 ± 0.02	16.40	15.03	Pravec
92/12/26	02:58	26.1238	1.0846	0.1181	29.4	125.5	1	11.94 ± 0.02	16.40	15.04	Pravec
92/12/26	04:05	26.1699	1.0850	0.1184	29.3	125.5	1	11.92 ± 0.02	16.38	15.01	Pravec
92/12/26	04:33	26.1898	1.0851	0.1185	29.3	125.4	3	11.93 ± 0.02	16.38	15.02	Green
92/12/26	05:02	26.2097	1.0853	0.1186	29.3	125.4	1	11.93 ± 0.02	16.38	15.02	Pravec
92/12/26	05:20	26.2219	1.0854	0.1187	29.2	125.4	6	11.93 ± 0.01	16.38	15.02	Green
92/12/26	06:31	26.2715	1.0857	0.1190	29.1	125.4	1	11.94 ± 0.02	16.38	15.02	Green
92/12/26	21:36	26.9000	1.0904	0.1231	28.0	125.0	8	12.59 ± 0.03	16.95	15.62	Krugly
92/12/26	22:26	26.9346	1.0907	0.1233	28.0	124.9	4	12.66 ± 0.02	17.02	15.69	Krugly
92/12/26	23:09	26.9645	1.0909	0.1235	27.9	124.9	2	12.78 ± 0.09	17.13	15.81	Angeli
92/12/26	23:25	26.9754	1.0910	0.1236	27.9	124.9	1	12.67 ± 0.03	17.02	15.70	Pravec
92/12/26	23:27	26.9770	1.0910	0.1236	27.9	124.9	4	12.69 ± 0.03	17.04	15.72	Krugly
92/12/26	23:60	26.9997	1.0912	0.1238	27.9	124.9	1	12.71 ± 0.02	17.06	15.74	Green
92/12/27	00:19	27.0132	1.0913	0.1239	27.8	124.9	3	12.73 ± 0.01	17.08	15.76	Green
92/12/27	00:47	27.0328	1.0914	0.1240	27.8	124.9	4	12.78 ± 0.01	17.12	15.80	Krugly
92/12/27	00:57	27.0397	1.0915	0.1240	27.8	124.9	1	12.74 ± 0.00	17.09	15.77	Angeli
92/12/27	01:05	27.0451	1.0915	0.1241	27.8	124.9	2	12.87 ± 0.02	17.21	15.89	Angeli
92/12/27	01:27	27.0605	1.0916	0.1242	27.8	124.9	6	12.81 ± 0.04	17.15	15.83	Krugly
92/12/27	01:36	27.0669	1.0917	0.1242	27.7	124.9	10	12.76 ± 0.01	17.10	15.78	Green
92/12/27	02:35	27.1073	1.0920	0.1245	27.7	124.8	5	12.78 ± 0.02	17.11	15.79	Krugly
92/12/27	02:54	27.1210	1.0921	0.1246	27.7	124.8	8	12.78 ± 0.01	17.11	15.80	Green
92/12/27	03:31	27.1464	1.0923	0.1247	27.6	124.8	3	12.87 ± 0.10	17.20	15.88	Krugly
92/12/27	04:25	27.1844	1.0926	0.1250	27.5	124.8	8	12.78 ± 0.01	17.11	15.80	Green
92/12/27	05:21	27.2227	1.0929	0.1252	27.5	124.8	1	12.81 ± 0.03	17.13	15.82	Mueller
92/12/27	05:34	27.2319	1.0929	0.1253	27.5	124.7	10	12.73 ± 0.03	17.05	15.74	Green
92/12/27	06:25	27.2671	1.0932	0.1255	27.4	124.7	2	12.78 ± 0.05	17.09	15.79	Mueller
92/12/27	06:34	27.2734	1.0932	0.1256	27.4	124.7	8	12.74 ± 0.01	17.05	15.75	Green
92/12/27	07:09	27.2979	1.0934	0.1257	27.4	124.7	1	12.70 ± 0.03	17.01	15.71	Mueller
92/12/27	22:35	27.9408	1.0983	0.1300	26.3	124.3	2	12.44 ± 0.01	16.66	15.39	Angeli
92/12/28	00:43	28.0298	1.0990	0.1306	26.1	124.2	1	12.49 ± 0.03	16.71	15.44	Pravec
92/12/28	01:42	28.0709	1.0993	0.1308	26.1	124.2	2	12.52 ± 0.00	16.73	15.46	Krugly
92/12/28	02:11	28.0910	1.0994	0.1310	26.0	124.2	1	12.49 ± 0.03	16.70	15.44	Pravec
92/12/28	02:27	28.1022	1.0995	0.1311	26.0	124.2	9	12.35 ± 0.10	16.56	15.29	Krugly
92/12/28	02:50	28.1181	1.0996	0.1312	26.0	124.2	2	12.44 ± 0.01	16.65	15.39	Angeli
92/12/28	03:26	28.1433	1.0998	0.1313	25.9	124.2	1	12.52 ± 0.03	16.72	15.46	Pravec
92/12/28	03:36	28.1503	1.0999	0.1314	25.9	124.2	1	12.15 ± 0.00	16.35	15.08	Krugly
92/12/28	03:37	28.1504	1.0999	0.1314	25.9	124.2	4	12.49 ± 0.06	16.69	15.43	Angeli
92/12/28	04:30	28.1873	1.1002	0.1316	25.9	124.2	1	12.53 ± 0.02	16.73	15.47	Pravec
92/12/28	04:34	28.1900	1.1002	0.1316	25.9	124.1	1	12.60 ± 0.00	16.79	15.54	Angeli
92/12/28	05:20	28.2220	1.1004	0.1318	25.8	124.1	1	12.55 ± 0.03	16.74	15.49	Pravec
92/12/28	20:37	28.8590	1.1053	0.1361	24.8	123.8	3	12.15 ± 0.08	16.26	15.04	Krugly
92/12/28	21:01	28.8756	1.1054	0.1362	24.8	123.7	1	12.13 ± 0.00	16.24	15.02	Krugly
92/12/28	22:39	28.9436	1.1060	0.1367	24.6	123.7	1	12.07 ± 0.03	16.17	14.95	Pravec
92/12/29	00:08	29.0056	1.1064	0.1371	24.5	123.7	1	12.04 ± 0.03	16.14	14.92	Pravec
92/12/29	00:19	29.0130	1.1065	0.1371	24.5	123.7	5	12.06 ± 0.04	16.15	14.93	Krugly
92/12/29	00:33	29.0229	1.1066	0.1372	24.5	123.7	1	12.23 ± 0.15	16.32	15.11	Hudecek
92/12/29	01:34	29.0654	1.1069	0.1375	24.4	123.6	5	11.99 ± 0.03	16.08	14.87	Krugly
92/12/29	01:49	29.0759	1.1070	0.1376	24.4	123.6	1	11.95 ± 0.03	16.04	14.83	Pravec
92/12/29	02:33	29.1062	1.1072	0.1378	24.4	123.6	5	12.00 ± 0.02	16.09	14.87	Krugly
92/12/29	02:35	29.1078	1.1072	0.1378	24.4	123.6	1	12.03 ± 0.03	16.11	14.90	Pravec
92/12/29	03:24	29.1417	1.1075	0.1380	24.3	123.6	5	11.98 ± 0.03	16.06	14.85	Krugly
92/12/29	03:37	29.1505	1.1075	0.1381	24.3	123.6	1	11.97 ± 0.02	16.05	14.84	Pravec
92/12/29	03:39	29.1521	1.1076	0.1381	24.3	123.6	3	11.81 ± 0.00	15.89	14.68	Angeli

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	H(α)	H	First Observer
92/12/29	04:15	29.1770	1.1078	0.1382	24.3	123.6	2	11.80 ± 0.00	15.87	14.67	Angeli
92/12/29	04:37	29.1927	1.1079	0.1383	24.2	123.6	1	11.96 ± 0.02	16.03	14.83	Pravec
92/12/29	16:58	29.7067	1.1118	0.1418	23.4	123.3	1	12.13 ± 0.00	16.15	14.97	V.S. Shevchenko
92/12/29	17:42	29.7378	1.1121	0.1420	23.4	123.3	5	12.18 ± 0.04	16.19	15.01	V.S. Shevchenko
92/12/29	18:35	29.7743	1.1124	0.1422	23.3	123.2	4	12.21 ± 0.01	16.21	15.04	V.S. Shevchenko
92/12/29	21:01	29.8758	1.1132	0.1429	23.2	123.2	1	12.36 ± 0.03	16.35	15.18	Pravec
92/12/29	22:07	29.9216	1.1135	0.1432	23.1	123.2	1	12.36 ± 0.03	16.35	15.18	Pravec
92/12/30	21:43	30.9047	1.1212	0.1499	21.6	122.7	1	12.22 ± 0.04	16.09	14.97	Kozhevnikov
93/01/01	01:39	32.0690	1.1304	0.1579	19.9	122.1	1	12.28 ± 0.04	16.02	14.96	Kozhevnikov
93/01/01	22:47	32.9496	1.1374	0.1641	18.6	121.7	1	12.36 ± 0.02	16.01	14.99	Pravec
93/01/01	23:43	32.9882	1.1377	0.1643	18.6	121.7	1	12.37 ± 0.02	16.01	14.99	Pravec
93/01/02	01:01	33.0426	1.1381	0.1647	18.5	121.7	1	12.39 ± 0.02	16.03	15.01	Pravec
93/01/02	02:20	33.0971	1.1385	0.1651	18.4	121.6	1	12.45 ± 0.02	16.08	15.07	Pravec
93/01/02	03:15	33.1356	1.1388	0.1654	18.4	121.6	1	12.47 ± 0.02	16.10	15.09	Pravec
93/01/02	04:46	33.1986	1.1393	0.1658	18.3	121.6	1	12.50 ± 0.02	16.12	15.11	Pravec
93/01/02	18:51	33.7858	1.1441	0.1699	17.5	121.3	3	12.76 ± 0.05	16.31	15.33	Velichko
93/01/02	19:10	33.7989	1.1442	0.1700	17.5	121.3	6	12.79 ± 0.02	16.34	15.36	Velichko
93/01/02	20:25	33.8505	1.1446	0.1704	17.4	121.3	6	12.82 ± 0.06	16.37	15.39	Velichko
93/01/02	21:37	33.9004	1.1450	0.1707	17.3	121.3	5	12.79 ± 0.04	16.33	15.35	Velichko
93/01/02	21:53	33.9118	1.1451	0.1708	17.3	121.3	1	12.73 ± 0.02	16.27	15.30	Pravec
93/01/02	22:30	33.9375	1.1453	0.1710	17.3	121.3	2	12.81 ± 0.04	16.35	15.37	Velichko
93/01/02	22:47	33.9493	1.1454	0.1711	17.2	121.3	1	12.72 ± 0.02	16.26	15.29	Pravec
93/01/02	23:37	33.9838	1.1457	0.1713	17.2	121.2	5	12.79 ± 0.01	16.32	15.35	Velichko
93/01/02	23:55	33.9962	1.1458	0.1714	17.2	121.2	1	12.69 ± 0.02	16.22	15.26	Pravec
93/01/03	00:24	34.0169	1.1459	0.1716	17.1	121.2	1	12.71 ± 0.02	16.24	15.28	Pravec
93/01/03	00:52	34.0360	1.1461	0.1717	17.1	121.2	3	12.74 ± 0.03	16.27	15.30	Velichko
93/01/03	01:32	34.0636	1.1463	0.1719	17.1	121.2	1	12.68 ± 0.02	16.21	15.24	Pravec
93/01/03	17:38	34.7344	1.1517	0.1767	16.2	120.9	1	13.22 ± 0.00	16.68	15.74	V.S. Shevchenko
93/01/03	18:32	34.7724	1.1520	0.1769	16.1	120.9	2	13.31 ± 0.01	16.76	15.83	V.S. Shevchenko
93/01/03	19:23	34.8076	1.1523	0.1772	16.1	120.9	3	13.33 ± 0.02	16.78	15.85	V.S. Shevchenko
93/01/03	20:33	34.8564	1.1527	0.1775	16.0	120.9	5	13.28 ± 0.02	16.73	15.80	V.S. Shevchenko
93/01/03	21:07	34.8796	1.1529	0.1777	16.0	120.9	1	13.24 ± 0.00	16.69	15.76	V.S. Shevchenko
93/01/03	22:30	34.9374	1.1534	0.1781	15.9	120.9	1	13.15 ± 0.03	16.59	15.66	Pravec
93/01/03	23:29	34.9784	1.1537	0.1784	15.9	120.8	2	13.07 ± 0.05	16.50	15.58	Pravec
93/01/04	00:32	35.0221	1.1540	0.1787	15.8	120.8	2	13.05 ± 0.02	16.47	15.55	Pravec
93/01/04	20:34	35.8572	1.1608	0.1847	14.7	120.5	2	12.70 ± 0.02	16.05	15.17	Pravec
93/01/05	00:57	36.0398	1.1623	0.1861	14.5	120.4	1	12.80 ± 0.02	16.13	15.26	Pravec
93/01/05	02:13	36.0921	1.1628	0.1864	14.4	120.4	1	12.86 ± 0.02	16.18	15.31	Pravec
93/01/05	03:09	36.1315	1.1631	0.1867	14.3	120.4	1	12.86 ± 0.02	16.18	15.31	Pravec
93/01/05	04:00	36.1669	1.1634	0.1870	14.3	120.4	1	12.88 ± 0.02	16.19	15.33	Pravec
93/01/05	05:01	36.2090	1.1637	0.1873	14.2	120.4	1	12.84 ± 0.02	16.15	15.29	Pravec
93/01/11	13:29	42.5618	1.2169	0.2354	6.7	118.3	1	13.44 ± 0.01	16.15	15.62	Spencer
93/01/11	14:29	42.6035	1.2172	0.2357	6.6	118.3	1	13.33 ± 0.01	16.04	15.51	Spencer
93/01/12	07:36	43.3167	1.2233	0.2414	5.8	118.1	1	13.06 ± 0.02	15.71	15.22	Spencer
93/01/12	08:41	43.3618	1.2237	0.2417	5.8	118.1	1	12.97 ± 0.02	15.61	15.12	Spencer
93/01/12	09:09	43.3812	1.2239	0.2419	5.8	118.1	1	12.96 ± 0.02	15.60	15.11	Spencer
93/01/12	21:20	43.8888	1.2282	0.2460	5.2	118.0	1	13.25 ± 0.04	15.85	15.39	Pravec
93/01/13	19:39	44.8190	1.2362	0.2535	4.2	117.8	4	12.90 ± 0.04	15.42	15.01	Velichko
93/01/14	23:22	45.9735	1.2462	0.2630	3.1	117.5	1	13.25 ± 0.00	15.67	15.34	Lecacheux
93/01/15	21:44	46.9056	1.2542	0.2708	2.1	117.3	1	13.17 ± 0.00	15.51	15.25	Lecacheux
93/01/15	22:50	46.9515	1.2546	0.2711	2.1	117.3	1	13.18 ± 0.00	15.52	15.26	Lecacheux
93/01/16	00:41	47.0282	1.2553	0.2718	2.0	117.2	1	13.23 ± 0.00	15.57	15.32	Lecacheux
93/01/16	01:12	47.0501	1.2555	0.2720	2.0	117.2	1	13.20 ± 0.00	15.53	15.28	Lecacheux

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	$H(\alpha)$	H	First Observer
93/01/16	21:12	47.8831	1.2627	0.2790	1.2	117.1	1	13.18 ± 0.00	15.44	15.26	Lecacheux
93/01/16	21:33	47.8983	1.2629	0.2792	1.2	117.1	2	13.03 ± 0.01	15.30	15.12	Barucci
93/01/16	22:09	47.9229	1.2631	0.2794	1.1	117.1	1	13.06 ± 0.00	15.32	15.15	Barucci
93/01/16	23:17	47.9705	1.2635	0.2798	1.1	117.0	2	13.04 ± 0.02	15.29	15.12	Barucci
93/01/17	00:16	48.0110	1.2639	0.2801	1.1	117.0	1	13.09 ± 0.00	15.34	15.18	Lecacheux
93/01/17	02:39	48.1102	1.2647	0.2810	1.0	117.0	3	13.01 ± 0.03	15.26	15.10	Barucci
93/01/17	03:31	48.1465	1.2650	0.2813	0.9	117.0	2	13.00 ± 0.00	15.24	15.09	Barucci
93/01/17	04:05	48.1703	1.2652	0.2815	0.9	117.0	1	13.09 ± 0.00	15.33	15.18	Lecacheux
93/01/17	04:24	48.1830	1.2654	0.2816	0.9	117.0	4	12.91 ± 0.04	15.15	15.00	Barucci
93/01/17	05:08	48.2141	1.2656	0.2819	0.9	117.0	3	12.94 ± 0.03	15.18	15.03	Barucci
93/01/17	20:12	48.8413	1.2711	0.2872	0.3	116.9	1	13.55 ± 0.00	15.73	15.65	Lecacheux
93/01/17	21:06	48.8792	1.2714	0.2876	0.3	116.9	1	13.54 ± 0.00	15.73	15.65	Lecacheux
93/01/17	21:13	48.8840	1.2715	0.2876	0.3	116.9	1	13.52 ± 0.00	15.71	15.63	Barucci
93/01/17	22:17	48.9286	1.2719	0.2880	0.3	116.9	1	13.57 ± 0.04	15.75	15.68	Pravec
93/01/17	22:19	48.9301	1.2719	0.2880	0.3	116.9	3	13.63 ± 0.04	15.81	15.74	Barucci
93/01/17	22:28	48.9361	1.2719	0.2881	0.3	116.9	7	13.56 ± 0.03	15.74	15.66	Velichko
93/01/17	23:24	48.9750	1.2723	0.2884	0.3	116.8	1	13.55 ± 0.00	15.73	15.66	Lecacheux
93/01/17	23:25	48.9758	1.2723	0.2884	0.3	116.8	2	13.72 ± 0.05	15.90	15.82	Velichko
93/01/17	23:42	48.9875	1.2724	0.2885	0.3	116.8	1	13.71 ± 0.00	15.89	15.82	Barucci
93/01/17	23:51	48.9940	1.2724	0.2886	0.3	116.8	8	13.76 ± 0.00	15.93	15.86	Blanco
93/01/17	23:55	48.9962	1.2725	0.2886	0.3	116.8	1	13.63 ± 0.04	15.81	15.74	Pravec
93/01/18	00:09	49.0062	1.2725	0.2887	0.2	116.8	1	13.61 ± 0.00	15.79	15.72	Lecacheux
93/01/18	00:11	49.0077	1.2726	0.2887	0.2	116.8	8	13.76 ± 0.01	15.94	15.87	Blanco
93/01/18	00:29	49.0204	1.2727	0.2888	0.2	116.8	10	13.76 ± 0.08	15.93	15.86	Velichko
93/01/18	00:43	49.0299	1.2728	0.2889	0.2	116.8	2	13.64 ± 0.00	15.82	15.75	Barucci
93/01/18	01:07	49.0462	1.2729	0.2890	0.2	116.8	4	13.61 ± 0.04	15.78	15.71	Velichko
93/01/18	01:45	49.0731	1.2731	0.2893	0.2	116.8	4	13.73 ± 0.03	15.90	15.83	Barucci
93/01/18	02:01	49.0844	1.2732	0.2894	0.2	116.8	1	13.59 ± 0.00	15.75	15.69	Lecacheux
93/01/18	02:16	49.0942	1.2733	0.2894	0.2	116.8	1	13.62 ± 0.04	15.79	15.72	Pravec
93/01/18	02:46	49.1153	1.2735	0.2896	0.2	116.8	1	13.66 ± 0.00	15.82	15.76	Barucci
93/01/18	03:34	49.1484	1.2738	0.2899	0.2	116.8	1	13.54 ± 0.00	15.71	15.64	Lecacheux
93/01/18	03:40	49.1528	1.2738	0.2899	0.2	116.8	1	13.46 ± 0.00	15.62	15.55	Barucci
93/01/18	03:48	49.1584	1.2739	0.2900	0.2	116.8	1	13.56 ± 0.04	15.72	15.65	Pravec
93/01/18	04:31	49.1882	1.2741	0.2903	0.3	116.8	2	13.41 ± 0.05	15.57	15.50	Barucci
93/01/18	20:30	49.8540	1.2800	0.2961	0.8	116.7	4	13.61 ± 0.02	15.71	15.59	Krugly
93/01/18	20:36	49.8585	1.2800	0.2961	0.8	116.7	2	13.70 ± 0.00	15.80	15.66	Lecacheux
93/01/18	20:45	49.8644	1.2801	0.2962	0.8	116.7	1	13.70 ± 0.04	15.81	15.67	Pravec
93/01/18	21:24	49.8919	1.2803	0.2964	0.8	116.7	2	13.60 ± 0.05	15.70	15.57	Krugly
93/01/18	21:28	49.8942	1.2803	0.2964	0.8	116.7	1	13.63 ± 0.05	15.73	15.59	Pravec
93/01/18	21:35	49.8992	1.2804	0.2965	0.8	116.7	65	13.68 ± 0.06	15.78	15.64	Dentchev
93/01/18	21:42	49.9043	1.2804	0.2965	0.8	116.7	1	13.70 ± 0.00	15.80	15.66	Lecacheux
93/01/18	22:08	49.9225	1.2806	0.2967	0.8	116.7	1	13.71 ± 0.00	15.81	15.67	Lecacheux
93/01/18	22:22	49.9318	1.2807	0.2967	0.8	116.7	73	13.64 ± 0.08	15.74	15.60	Dentchev
93/01/18	22:37	49.9422	1.2808	0.2968	0.8	116.7	3	13.63 ± 0.09	15.73	15.59	Krugly
93/01/18	23:25	49.9754	1.2810	0.2971	0.9	116.7	84	13.54 ± 0.04	15.64	15.49	Dentchev
93/01/18	23:32	49.9809	1.2811	0.2972	0.9	116.7	6	13.64 ± 0.07	15.73	15.59	Krugly
93/01/18	23:46	49.9902	1.2812	0.2973	0.9	116.7	3	13.55 ± 0.00	15.65	15.50	Blanco
93/01/19	00:18	50.0128	1.2814	0.2975	0.9	116.7	61	13.59 ± 0.06	15.68	15.53	Dentchev
93/01/19	00:25	50.0177	1.2814	0.2975	0.9	116.7	4	13.63 ± 0.05	15.72	15.57	Krugly
93/01/19	00:28	50.0193	1.2814	0.2975	0.9	116.7	7	13.55 ± 0.02	15.64	15.49	Blanco
93/01/19	01:18	50.0544	1.2817	0.2978	1.0	116.6	64	13.74 ± 0.08	15.83	15.67	Dentchev
93/01/19	01:33	50.0645	1.2818	0.2979	1.0	116.6	5	13.69 ± 0.02	15.78	15.63	Krugly
93/01/19	02:22	50.0989	1.2821	0.2982	1.0	116.6	2	13.66 ± 0.03	15.75	15.59	Lecacheux

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	$H(\alpha)$	H	First Observer
93/01/19	08:09	50.3393	1.2842	0.3003	1.2	116.6	1	13.66 ± 0.00	15.73	15.54	Tholen
93/01/19	10:25	50.4341	1.2851	0.3012	1.3	116.6	1	13.59 ± 0.00	15.65	15.46	Tholen
93/01/19	11:57	50.4981	1.2856	0.3017	1.3	116.6	1	13.54 ± 0.00	15.60	15.40	Tholen
93/01/19	13:37	50.5676	1.2862	0.3024	1.4	116.6	2	13.52 ± 0.01	15.58	15.37	Tholen
93/01/19	18:26	50.7680	1.2880	0.3041	1.6	116.5	5	13.21 ± 0.07	15.25	15.04	Krugly
93/01/19	19:34	50.8152	1.2884	0.3046	1.6	116.5	3	13.15 ± 0.11	15.18	14.96	Krugly
93/01/19	19:40	50.8196	1.2885	0.3046	1.6	116.5	1	13.22 ± 0.00	15.25	15.03	Lecacheux
93/01/19	19:44	50.8219	1.2885	0.3046	1.6	116.5	1	13.32 ± 0.02	15.35	15.13	V.G. Shevchenko
93/01/19	20:20	50.8474	1.2887	0.3048	1.7	116.5	1	13.25 ± 0.00	15.27	15.05	Lecacheux
93/01/19	20:28	50.8526	1.2888	0.3049	1.7	116.5	1	13.00 ± 0.03	15.03	14.81	Krugly
93/01/19	20:41	50.8616	1.2888	0.3050	1.7	116.5	2	13.33 ± 0.02	15.36	15.14	V.G. Shevchenko
93/01/19	21:15	50.8855	1.2890	0.3052	1.7	116.5	2	13.14 ± 0.03	15.17	14.95	Krugly
93/01/19	21:23	50.8912	1.2891	0.3052	1.7	116.5	2	13.27 ± 0.02	15.29	15.07	V.G. Shevchenko
93/01/19	22:01	50.9176	1.2893	0.3055	1.7	116.5	1	13.21 ± 0.00	15.23	15.00	Lecacheux
93/01/19	22:36	50.9417	1.2895	0.3057	1.7	116.5	2	13.30 ± 0.02	15.32	15.09	V.G. Shevchenko
93/01/19	23:37	50.9844	1.2899	0.3061	1.8	116.5	4	13.29 ± 0.02	15.30	15.08	V.G. Shevchenko
93/01/20	00:28	51.0191	1.2902	0.3064	1.8	116.5	6	13.32 ± 0.03	15.33	15.10	V.G. Shevchenko
93/01/20	00:28	51.0196	1.2902	0.3064	1.8	116.5	2	13.03 ± 0.02	15.04	14.81	Krugly
93/01/20	01:19	51.0549	1.2905	0.3067	1.8	116.5	1	13.18 ± 0.01	15.19	14.96	Krugly
93/01/20	01:38	51.0682	1.2907	0.3068	1.9	116.5	2	13.30 ± 0.02	15.31	15.08	V.G. Shevchenko
93/01/20	19:29	51.8118	1.2972	0.3135	2.5	116.3	2	13.66 ± 0.01	15.62	15.33	Barucci
93/01/20	21:08	51.8808	1.2978	0.3141	2.6	116.3	1	13.77 ± 0.00	15.72	15.43	Lecacheux
93/01/20	21:11	51.8826	1.2978	0.3141	2.6	116.3	2	13.74 ± 0.00	15.69	15.39	Barucci
93/01/20	22:48	51.9500	1.2984	0.3147	2.6	116.3	2	13.72 ± 0.01	15.67	15.37	Barucci
93/01/21	00:07	52.0049	1.2989	0.3152	2.7	116.3	1	13.67 ± 0.00	15.61	15.30	Barucci
93/01/21	00:23	52.0158	1.2990	0.3153	2.7	116.3	2	13.74 ± 0.00	15.68	15.37	Lecacheux
93/01/21	01:09	52.0479	1.2993	0.3156	2.7	116.3	1	13.74 ± 0.00	15.68	15.37	Barucci
93/01/21	02:48	52.1170	1.2999	0.3163	2.8	116.3	2	13.63 ± 0.03	15.56	15.25	Barucci
93/01/21	03:37	52.1507	1.3002	0.3166	2.8	116.3	1	13.69 ± 0.00	15.61	15.30	Barucci
93/01/21	04:03	52.1688	1.3004	0.3167	2.8	116.3	1	13.69 ± 0.00	15.62	15.30	Barucci
93/01/21	10:31	52.4384	1.3027	0.3192	3.1	116.2	4	13.54 ± 0.02	15.45	15.12	Nakamura
93/01/21	11:24	52.4753	1.3031	0.3195	3.1	116.2	5	13.54 ± 0.01	15.44	15.11	Nakamura
93/01/21	12:25	52.5175	1.3034	0.3199	3.1	116.2	5	13.53 ± 0.01	15.43	15.10	Nakamura
93/01/21	13:24	52.5586	1.3038	0.3203	3.2	116.2	5	13.55 ± 0.00	15.44	15.11	Nakamura
93/01/21	14:25	52.6004	1.3042	0.3207	3.2	116.2	5	13.54 ± 0.01	15.44	15.10	Nakamura
93/01/21	15:06	52.6292	1.3044	0.3209	3.2	116.2	2	13.54 ± 0.00	15.43	15.09	Nakamura
93/01/21	19:46	52.8236	1.3062	0.3227	3.4	116.2	2	13.61 ± 0.01	15.49	15.13	Nakamura
93/01/21	21:52	52.9109	1.3069	0.3235	3.5	116.2	2	13.86 ± 0.01	15.73	15.37	DeSanctis
93/01/21	22:21	52.9315	1.3071	0.3237	3.5	116.2	5	13.85 ± 0.00	15.72	15.36	DeSanctis
93/01/21	23:35	52.9826	1.3076	0.3242	3.5	116.2	2	13.88 ± 0.00	15.75	15.39	DeSanctis
93/01/22	00:40	53.0275	1.3080	0.3246	3.6	116.2	5	13.89 ± 0.01	15.75	15.38	DeSanctis
93/01/22	01:56	53.0807	1.3084	0.3251	3.6	116.2	2	13.90 ± 0.03	15.76	15.39	DeSanctis
93/01/22	02:42	53.1128	1.3087	0.3254	3.7	116.1	2	13.92 ± 0.01	15.78	15.41	DeSanctis
93/01/22	03:29	53.1453	1.3090	0.3257	3.7	116.1	2	13.92 ± 0.03	15.78	15.41	DeSanctis
93/01/22	05:32	53.2306	1.3098	0.3264	3.8	116.1	1	13.95 ± 0.02	15.80	15.42	Wisniewski
93/01/22	06:33	53.2729	1.3101	0.3268	3.8	116.1	1	13.98 ± 0.02	15.82	15.45	Wisniewski
93/01/22	07:32	53.3139	1.3105	0.3272	3.8	116.1	1	13.99 ± 0.02	15.83	15.45	Wisniewski
93/01/22	08:40	53.3611	1.3109	0.3276	3.9	116.1	1	14.02 ± 0.02	15.86	15.47	Wisniewski
93/01/22	09:47	53.4076	1.3113	0.3281	3.9	116.1	1	14.04 ± 0.02	15.87	15.49	Wisniewski
93/01/23	03:09	54.1312	1.3177	0.3348	4.5	116.0	1	13.67 ± 0.02	15.45	15.03	Wisniewski
93/01/23	04:15	54.1771	1.3181	0.3352	4.6	116.0	1	13.68 ± 0.02	15.45	15.03	Wisniewski
93/01/23	05:21	54.2229	1.3186	0.3357	4.6	116.0	1	13.67 ± 0.02	15.44	15.02	Wisniewski
93/01/23	06:34	54.2736	1.3190	0.3361	4.6	116.0	1	13.67 ± 0.02	15.44	15.01	Wisniewski

TABLE III—*Continued*

UT Date	UT Time	Decimal Day	Distance from Sun (AU)	Distance from Earth (AU)	Solar Phase α	Ecliptic Lon.	N	V	H(α)	H	First Observer
93/01/23	07:29	54.3118	1.3193	0.3365	4.7	116.0	1	13.66 ± 0.02	15.42	14.99	Wisniewski
93/01/23	08:34	54.3569	1.3197	0.3369	4.7	116.0	1	13.71 ± 0.02	15.47	15.04	Wisniewski
93/01/23	09:27	54.3937	1.3201	0.3373	4.7	116.0	1	13.71 ± 0.02	15.47	15.03	Wisniewski
93/01/23	10:21	54.4313	1.3204	0.3376	4.8	116.0	1	13.71 ± 0.02	15.46	15.03	Wisniewski
93/01/25	20:15	56.8439	1.3419	0.3607	6.7	115.7	2	14.14 ± 0.07	15.71	15.17	Angeli
93/01/26	00:41	57.0282	1.3435	0.3624	6.9	115.7	1	13.95 ± 0.10	15.52	14.97	Angeli
93/01/26	01:09	57.0482	1.3437	0.3626	6.9	115.7	1	14.12 ± 0.10	15.68	15.13	Angeli
93/01/26	02:40	57.1110	1.3443	0.3633	6.9	115.7	1	13.98 ± 0.10	15.53	14.98	Angeli
93/01/26	19:30	57.8123	1.3506	0.3701	7.5	115.6	1	14.62 ± 0.10	16.13	15.56	Angeli
93/01/26	20:07	57.8385	1.3508	0.3704	7.5	115.6	1	14.57 ± 0.10	16.08	15.50	Angeli
93/01/26	21:03	57.8770	1.3511	0.3708	7.5	115.6	1	14.53 ± 0.10	16.03	15.45	Angeli
93/01/26	23:32	57.9807	1.3521	0.3718	7.6	115.6	1	14.61 ± 0.10	16.10	15.52	Angeli
93/01/27	01:25	58.0592	1.3528	0.3726	7.7	115.6	2	14.44 ± 0.07	15.92	15.34	Angeli
93/01/27	03:08	58.1303	1.3534	0.3733	7.7	115.6	1	14.37 ± 0.10	15.85	15.26	Angeli
93/01/27	19:12	58.8003	1.3594	0.3800	8.2	115.5	1	14.19 ± 0.10	15.63	15.02	Wisniewski
93/01/27	21:13	58.8838	1.3602	0.3808	8.3	115.5	1	14.35 ± 0.10	15.77	15.16	Wisniewski
93/01/28	01:32	59.0639	1.3618	0.3826	8.4	115.5	1	14.25 ± 0.10	15.67	15.05	Wisniewski

Note. Observations within the same hour by the same observer have been binned together; the number of points in each bin is given by *N*. Photometric errors were assigned as described in the text; an error of 0.00 indicates that no error bar was provided for that point, but errors were estimated to be very small. Columns are the same as in Table II, except that "Decimal Day" is the time in fractional days since December 0.0, 1992; to convert to Julian date add 2448956.5.

rotational phases is equal to the change in ecliptic longitude during the observations: this is only 15° for the photometry taken after December 20 and only 7° after December 30. Furthermore, because the ecliptic longitude changes fairly linearly with time after December 20, the best-fit constant synodic rotation period will have maximum rotational phase errors of only 4° for the period after December 20 and only 1.5° after December 30. These rotational phase deviations, generally less than 1% of a rotation, are so small that the data during this period can be well represented by a single synodic period. For pole positions not perpendicular to the ecliptic, a single synodic period will fit even better, though the shape of the lightcurve will evolve due to the small (≤15°) variations in the sub-earth latitude.

The above discussion considers only viewing geometry, not illumination geometry, which changes more rapidly. Solar phase angle is −40° on December 20, −21° December 30, and +7° on January 25, and shadowing effects on an irregular object such as Toutatis are likely to change the lightcurve shape significantly over this range of illumination angles. However, again, the result should be a steady evolution of the lightcurve from rotation to rotation, particularly after December 30.

We have searched for a rotation period by assuming sideral rotation periods from 1.6 to 12.0 days, in 1% increments, and then plotting *H* as a function of apparent rotational phase [with respect to the Earth–Toutatis line, assuming obliquities of +90° (prograde), 0°, and −90° (retrograde)] for all observations at each assumed period. Because solar phase angle and, probably, sub-Earth latitude on Toutatis are also changing during the apparition, we do not expect identical lightcurves on successive rotations even when the correct period is chosen, but we do expect steady evolution of the lightcurve from one rotation to the next, with slower evolution as the apparition progresses and the geometry becomes more stable. However, visual inspection of all the lightcurves produced by this process did not find any period or pole orientation that resulted in smooth evolution of the lightcurve from one rotation to the next. The best lightcurve that we have found by this process assumes retrograde rotation with a sidereal period of 7.25 days, and is shown in Fig. 6. Prograde rotation with a 7.30-day period produces a very similar lightcurve. This rotation period aligns the five deepest minima in the curve fairly well, though not perfectly, suggesting that this period has some significance in Toutatis' rotation. However, the rest of the lightcurve has so much scatter and complex behavior that we doubt that there is simple rotation at something like a 7.25-day period.

As a check on the visual inspection technique, we have used the phase dispersion minimization (PDM) method of Buie and Bus (1992) to search quantitatively for periods

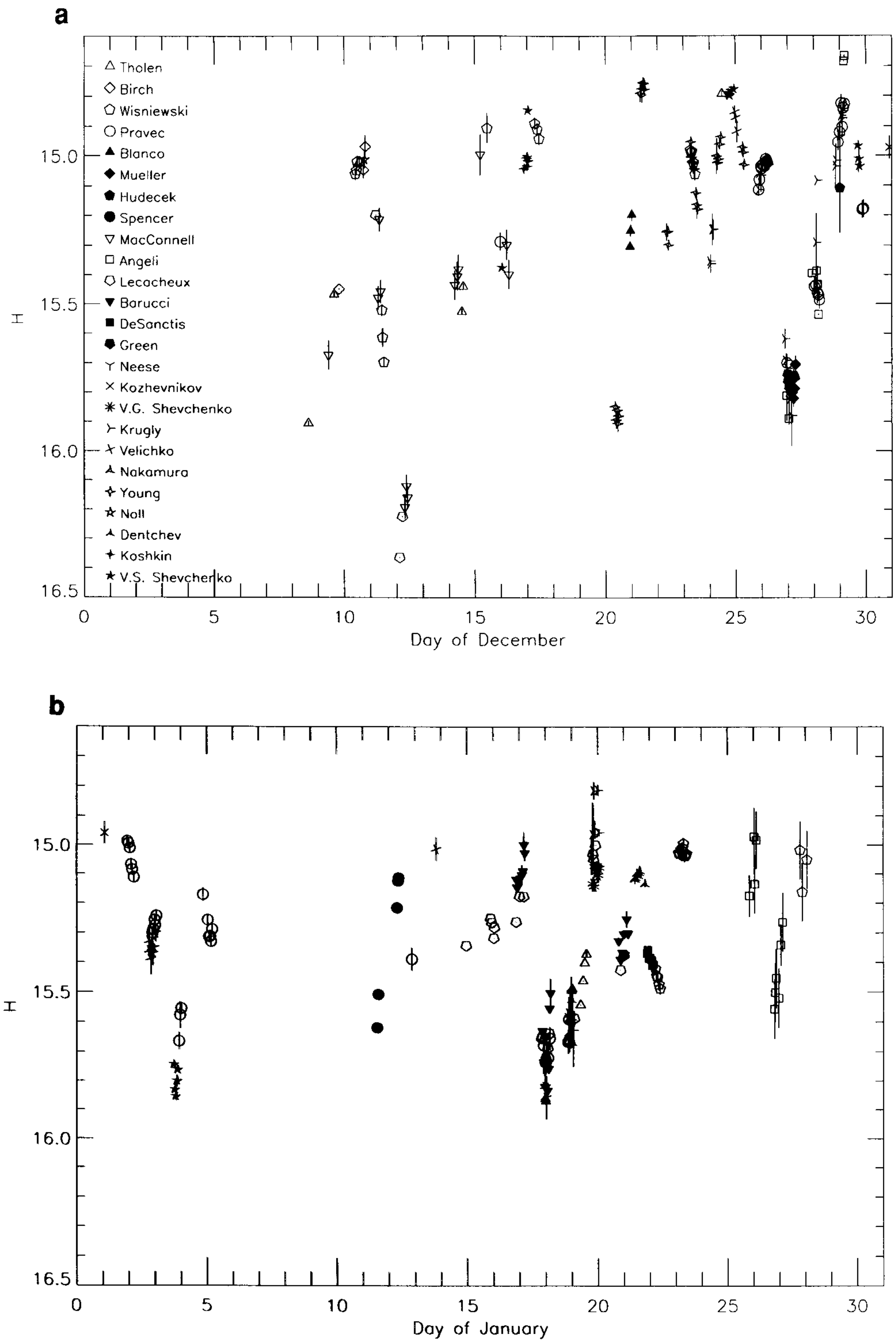

FIG. 4. All Toutatis *V* photometry obtained during the December 1992 (a) and January 1993 (b) period from Table II. Each observer is plotted with a different symbol, showing the generally excellent agreement between observers.

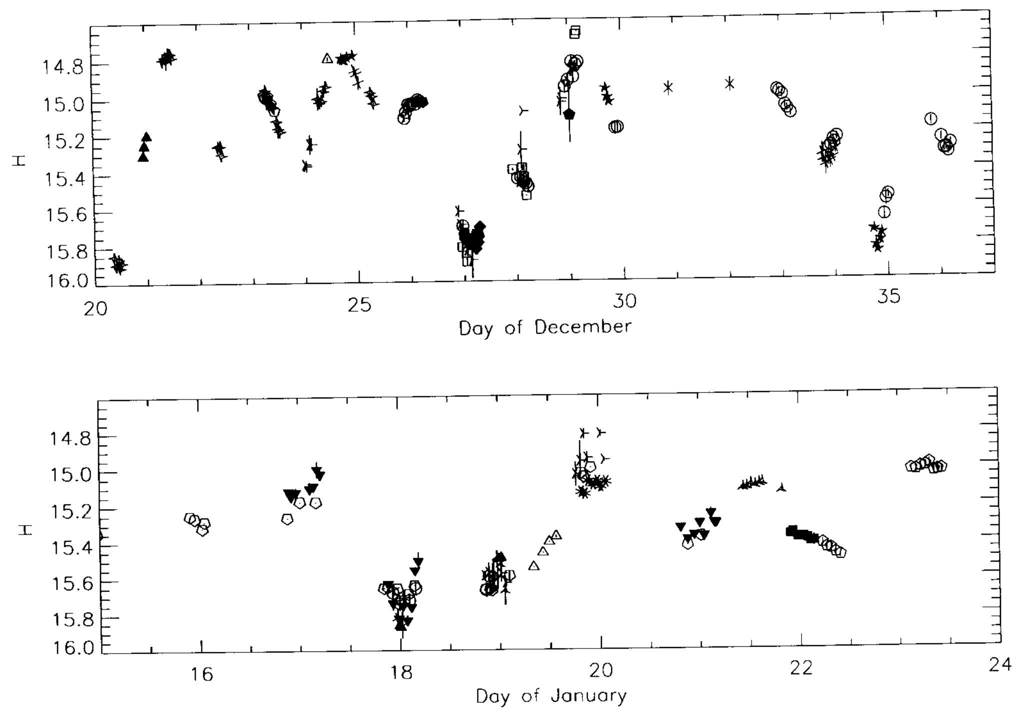

FIG. 5. An enlargement of two critical regions of the lightcurve shown in Fig. 4 (Top) From 1992/12/20 to 1993/01/06, the period with the best density and quality of data. Note the three deep minima with ~7.2-day spacing and the complexity of the lightcurve in the interval between the first two deep minima. (Bottom) From 1993/01/15 to 1993/01/24. Note the 38-hr period centered on January 21st in which no major lightcurve maximum or minimum occurs. Data from different observers are identified using the same symbols as Fig. 4.

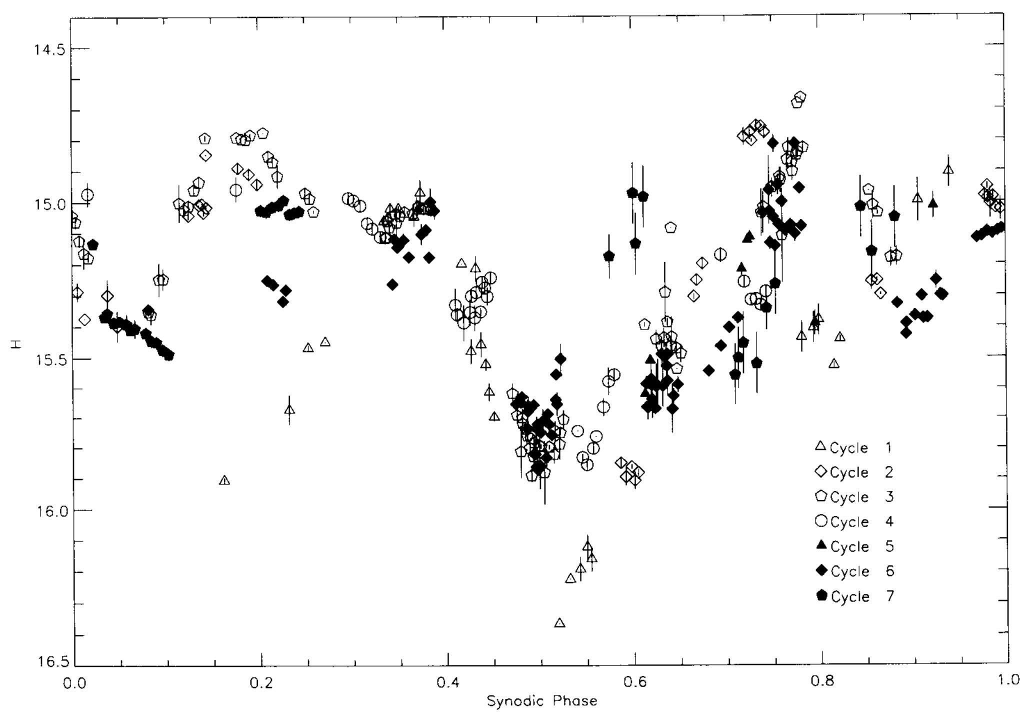

FIG. 6. The Toutatis lightcurve constructed from the December 1992/January 1993 data on the assumption of a retrograde rotation period of 7.25 days and a rotational pole perpendicular to the ecliptic. This period roughly aligns all the deepest lightcurve minima, but is unlikely to represent a true, simple, rotation period because the curve still shows large scatter and its shape does not evolve systematically between cycles. All other combinations of rotation period and pole orientation that have been tried produce lightcurves with even more scatter. This period is also unlikely because it requires an extremely complex lightcurve during a single rotation. See the text.

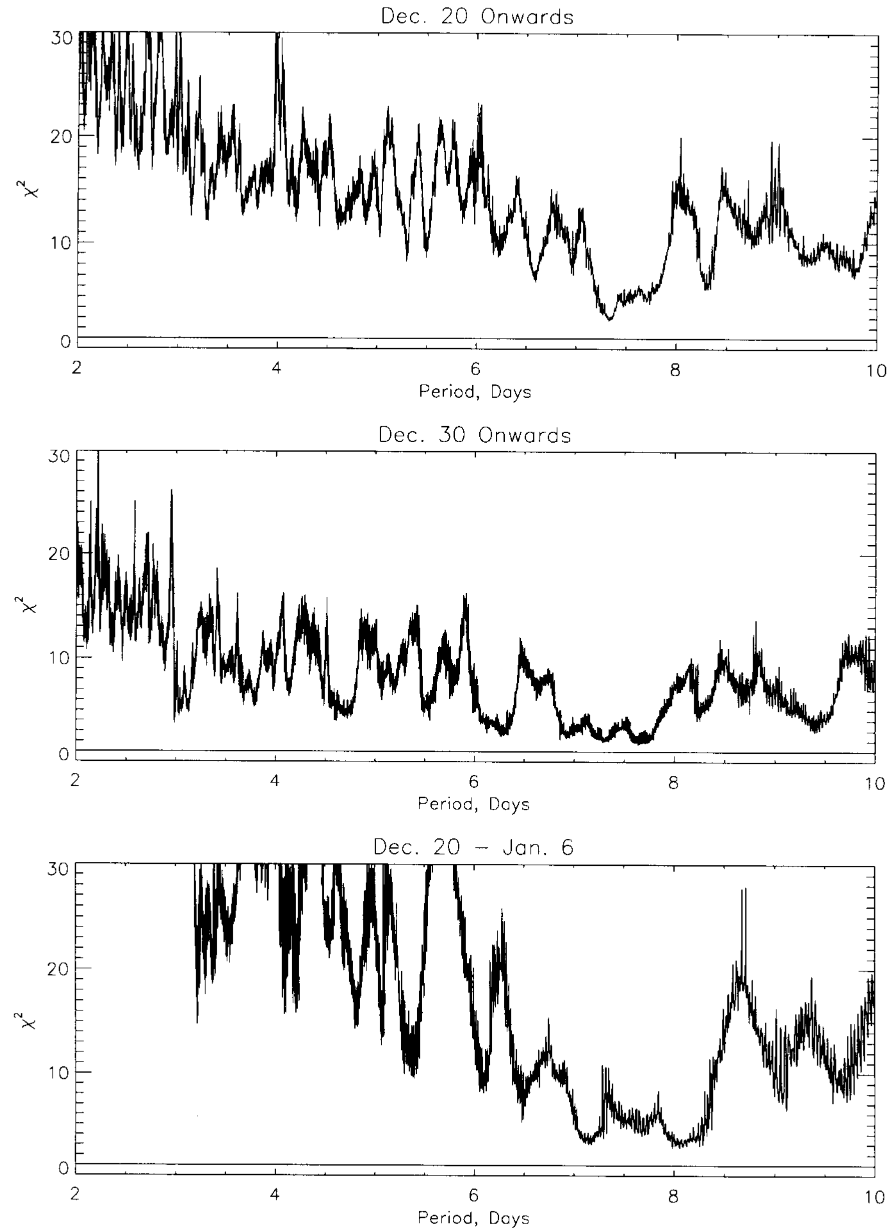

FIG. 7. χ^2 of lightcurve scatter vs rotation period for all observations after December 20 (top), after December 30 (middle), and between December 20 and January 6 (bottom). All show a minimum in the 7- to 8-day region, but for reasons discussed in the text this is unlikely to be a true, simple, rotation period. The $\chi^2 = 1$ level, indicating a "perfect" fit to the data, is highlighted by a horizontal line.

between 2 and 10 days in 0.016% increments, using all data after December 20 and also, to reduce the effects of changing geometry, the data after December 30 only. We have also looked at the period December 20–January 6, where the photometric coverage is particularly dense and of high quality. Constant synodic rotation period was assumed, as justified above. In this technique, a lightcurve is produced by interpolating between the mean magnitudes in each bin. The dispersion of the data around this mean lightcurve is measured by the reduced χ^2 of the residuals after this mean lightcurve has been subtracted: a χ^2 of 1.0 would indicate that the data are consistent with this trial period, if errors have been properly estimated. Results are shown in Fig. 7. Though there are several χ^2 minima, their asymmetry, the fact that x^2 is always significantly above 1, the visual appearance of the lightcurves at these periods, and the several minima at noncommensurate periods suggest that none of these minima represent a true rotation period. The lowest minimum in all three data sets is equivalent to the 7.25-day retrograde sideral period shown in Fig. 6.

The argument against simple rotation with a 7.25-day period is strengthened by considering the interval between December 20.4 and December 27.3 (Fig. 5), when coverage and data quality were particularly good. There are deep minima at the beginning and end of this period, which would be equivalent if the period were around 7 days. However, there are 4 maxima and 3 minima in the lightcurve between these two deep minima. The third deepest maximum/minimum pair, between December 22.4 and December 23.3, has an amplitude of at least 0.4 magnitudes, and the fourth largest, seen in data between December 25.9 and December 26.3, has an amplitude of at least 0.12 magnitudes. Most asteroids have only two maxima and minima per rotation, and only a few are known with three: 1580 Betulia shows the deepest tertiary maximum/minimum pair with an amplitude of 0.3 at 37° solar phase (Tedesco *et al.* 1978), comparable to the phase angle at the time of the Toutatis tertiary maximum. Asteroids 505 Cava (Young and Harris 1985) and 51 Nemausa (Gammelgaard and Kristensen 1991) show four maxima and minima, but the smallest (quaternary) maximum/minimum pair has an amplitude of only ~0.03 and 505 Cava and 0.04 for 51 Nemausa. If the Toutatis 7.25-day period is correct, then Toutatis shows deeper tertiary *and* quaternary maximum/minimum pairs than any other known asteroid. Such a complex lightcurve is probably physically impossible for simple rotation: more likely, either the 7.25-day period is wrong (and no other period gives a better lightcurve) or the rotation of Toutatis is not simple.

We must therefore consider the alternative that Toutatis does not rotate uniformly about a single rotational axis, but is rather in a more complex spin state, as is probably the case for the nucleus of Comet Halley (Peale and Lissauer 1989, Belton *et al.* 1991, Samarsinha and A'Hearn 1991) and possibly Schwassmann–Wachmann 1 (Meech *et al.* 1993). This possibility was first suggested by Ostra (in a talk to the Toutatis workshop, January 4, 1993, Tucson, AZ, and personal communication) on the basis of visual inspection of radar images of Toutatis (Ostro *et al.* 1993).

Two of us (DeSanctis and Caruso) have made a preliminary investigation of possible rotational components that are more rapid than the "best fit" 7.25-day rotation using a further elaboration of the PDM technique discussed above (Stellingwerf 1978). A best-fit period is found by PDM techniques and a mean lightcurve is constructed from binned data and subtracted from the original data, as in the Buie and bus (1992) technique. The residuals are then analyzed using a second iteration of the PDM technique to look for a possible second period P2. This method can find multiple periods if they are purely additive, but does not calculate the effect of multiple periods on the instantaneous orientation and projected area of a three-dimensional asteroid, so it is only a first attempt at a multiple-period model. Applying this algorithm to a particularly high-quality portion of the Toutatis lightcurve, between 92/12/20.9 and 93/01/2.3, there is a hint of the existence of two periods which are not correlated with each other: ~7.4 and ~3.1 days (or their multiples); these are also apparent in Fig. 7. The lightcurve could be the result of the superimposition of these two periods. Removing the period of 7.4 days from the data allows construction of a lightcurve with a period near 3.1 days (Fig. 8), though there is still considerable scatter. Whether the 3.1-day period represents a real rotation period is difficult to say without three-dimensional modeling of the rotation, but the relatively simple appearance of the lightcurve shown in Fig. 8 suggests an absence of rotation with periods much shorter than 3 days.

The July/August 1992 photometry is too sparse to use for an independent period determination, but it is interesting to check these data for consistency with the best-fit period from the close approach photometry (7.25 days, retrograde). Figure 9 shows that the July/August 1992 data are fairly consistent with this period, though the steady or increasing brightness near rotational phase 0.55, in the middle of a region of generally decreasing brightness, reinforces the impression from the close approach photometry that the lightcurve is probably too complex to be fitted with a single period near 7.25 days.

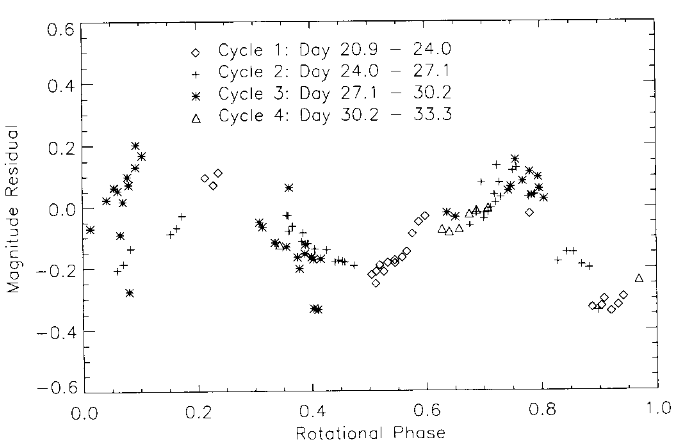

FIG. 8. Toutatis lightcurve from December 20.9 1992 to January 2.3 1993, with a mean lightcurve of period 7.4 days subtracted from the data. The residuals are roughly matched with a 3.1-day period.

DISCUSSION

Complex rotation may not be surprising, given the slow rotation of Toutatis. Harris (1994), adapting the

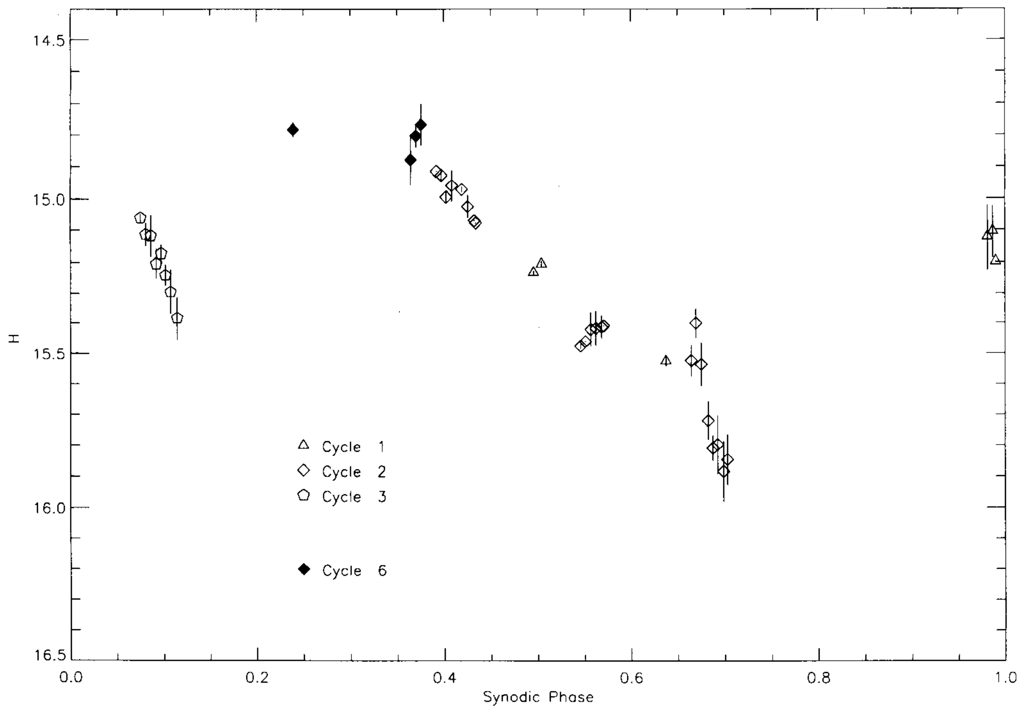

FIG. 9. The Toutatis lightcurve from July and August 1992, folded using the 7.25-day retrograde period also used in Fig. 6. The data appear fairly consistent with this period, but the slopes within each night's data suggest a complex lightcurve.

results of Burns and Safronov (1973), points out that while the collisional processes that control asteroid rotations will initially produce complex, tumbling rotation, the rotation will be damped to a simple state due to internal dissipation on a time scale τ which is given approximately by $\tau/(10^9 \text{ years}) \approx P^3/(4913D^2)$, where D is the diameter in km and P is the rotation period in hours. For a typical main-belt asteroid with $P = 10$ hr and $D = 50$ km, $\tau \approx 80{,}000$ years, so we are unlikely to see complex rotation in typical large asteroids. However, for Toutatis, with $P \approx 3$ days and $D \approx 2.5$ km (Spencer *et al.* 1993, Noll *et al.* 1995), $\tau \approx 1.2 \times 10^{10}$ years. So while the origin of the slow rotation of Toutatis is unknown (though it may simply result from the chance details of the collision that formed it, or subsequent collisions), complex rotation is highly likely given the slow rotation.

Toutatis is the first asteroid to show such strong photometric evidence for complex rotation, but Harris (1994, and personal communication) notes that the lightcurves for the slow rotators 1689 Floris-Jan and 3288 Seleucus are also difficult to reconcile with simple principle-axis rotation, and these asteroids are also complex rotation candidates.

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