ICARUS 73, 314–323 (1988)

Asteroid 45 Eugenia: Lightcurves and the Pole Orientation[1]

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Received February 20, 1987; revised September 18, 1987

Nine lightcurves of asteroid 45 Eugenia, three from 1969 and six from 1984, are given. In 1984–1985 the H_0 magnitude of Eugenia, corrected to the lightcurve maximum, was 7.47 and the slope parameter G_0 was 0.04. The north pole of Eugenia is within ±10° of ecliptic longitude 106° and latitude +26° (or 295° and +34°). This solution is consistent with an amplitude-aspect pole analysis. The sidereal period is 0.2374645 ± 0.0000002 day, or 5 hr 41 min 56.93 sec ± 0.02 sec and the sense of rotation is retrograde. When observations are closest to both the north and south poles (~30°) only one maximum and one minimum are present in the lightcurves; at other oppositions there are two of each. It is suggested that this is caused by albedo features on the surface of Eugenia. © 1988 Academic Press, Inc.

I. INTRODUCTION

Vesely and Taylor (1985) published the remaining useful lightcurves from our files with a comment that lightcurves of 45 Eugenia would be published separately. Those lightcurves, three from 1969, are given in this paper along with five lightcurves from 1984. We give Eugenia's 1984–1985 absolute magnitude H_0 and slope parameter G_0 derived from lightcurve maxima. We determine the asteroid's pole orientation, sidereal period, and sense of rotation. This paper represents continuing research in the application of photometric astrometry (PA) to asteroids. PA is a method for determining the pole orientation, sidereal period, and sense of rotation of an asteroid. The most recent capsule summary of PA can be found in Section I of Taylor *et al.* (1987). PA is explained in detail in Taylor (1979) and Taylor and Tedesco (1983). Our PA solution is compared to results of an amplitude–aspect pole analysis.

Eugenia is a 250-km U-type asteroid (Bowell *et al.* 1979). It is also grouped as a LASPA (large amplitude and short period) asteroid which leads Farinella *et al.* (1981) to suggest that Eugenia's shape may be a Jacobi ellipsoid in rotational equilibrium.

Eugenia was observed on four consecutive nights in May 1978 by Debehogne and Zappalà (1980). They refined the synodic period to 5 hr 41 min 56 sec, using a lightcurve obtained a month later by Harris and Young (1979). Eugenia was observed during the 1982 opposition by Debehogne *et al.* (1983) and by Weidenschilling *et al.* (1987). The latter group also obtained Eugenia lightcurves in the 1981–1982, 1983, 1984–1985, and 1985–1986 oppositions.

II. THE OBSERVATIONS

Figure 1 gives the Eugenia lightcurves from 1969. Figure 2 is a composite of those lightcurves using a 5 hr 42 min period. Figures 3 and 4 are 1984 lightcurves. All lightcurves are in Universal Time not corrected for light time. The vertical scale is the differential V magnitude in the sense of asteroid minus comparison star normalized to

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[1] Based in part on observations collected at the European Southern Observatory, La Silla, Chile.

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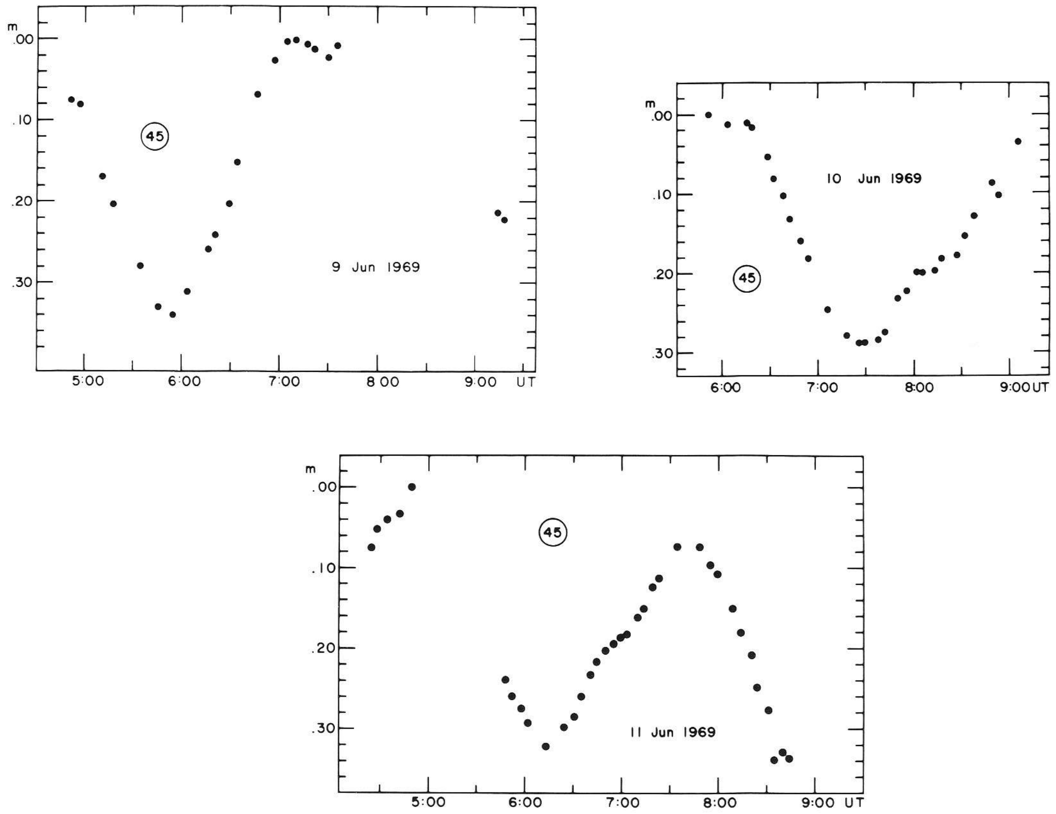

FIG. 1. 1969 lightcurves of Eugenia. $V_0(1,\alpha)$ = 8.37 for June 9 and 8.34 for June 11.

zero at the lightcurve maximum. Table I gives information about the comparison stars, the observers, and the telescopes they used. Table II gives the aspect data at the midtime of each lightcurve.

Table III gives the observed V magnitudes and colors of Eugenia in 1969 and 1984. $V_0(1,\alpha)$ represents each V magnitude corrected to both its lightcurve maximum and to unit distance from the Sun and the

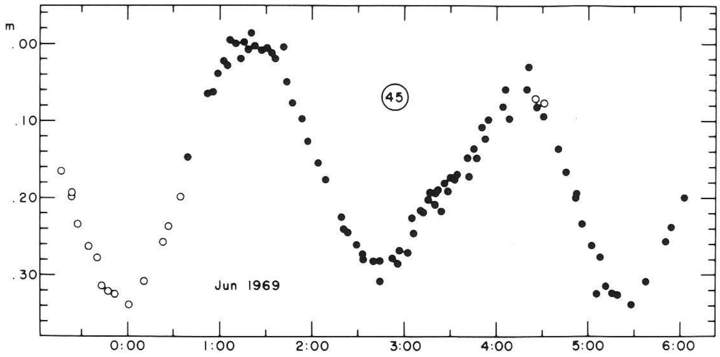

FIG. 2. Composite of the Fig. 1 lightcurves. The horizontal time scale in hours does not pertain to any specific night but is representative of one rotation period. Open circles are repetitions of points just one rotational cycle earlier or later.

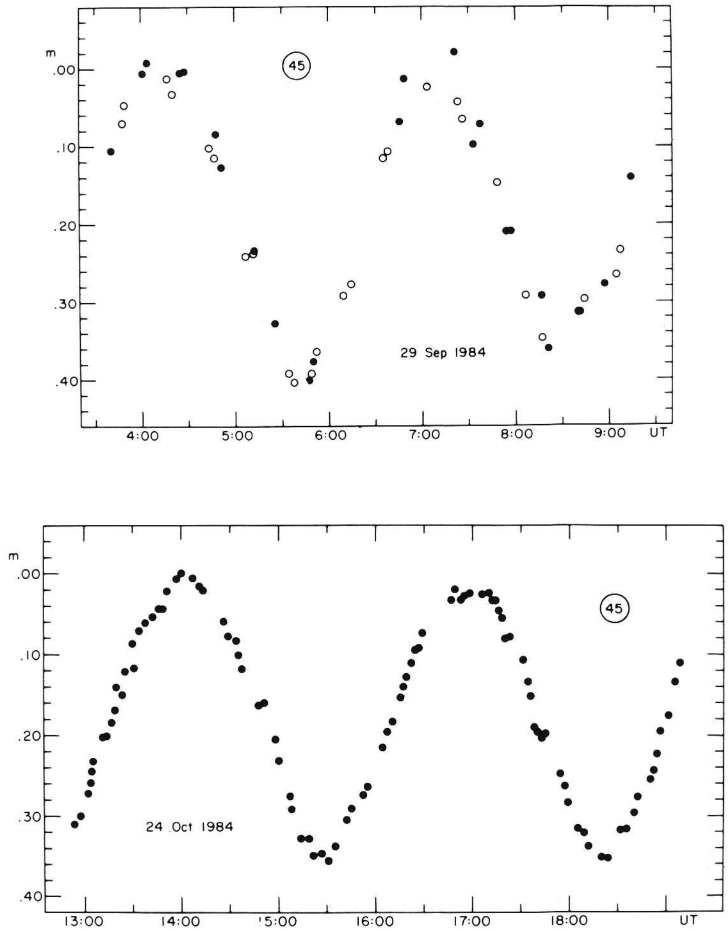

FIG. 3. 1984 lightcurves of Eugenia. In the upper lightcurve open circles are from September 28 and filled circles are from September 29. $V_0(1,\alpha) = 8.23$ for September 28, 8.22 for September 29, and 7.85 for October 24.

Earth. The absolute magnitude H_0 and the slope parameter G_0 were calculated using the 1984–1985 observations. Data from other oppositions are not included because precise axial ratios of Eugenia are not known and therefore aspect corrections cannot be applied accurately. The data are from Table III and the results, using the method of Tedesco (1986), are $H_0 = 7.47$ and $G_0 = 0.04$. Figure 5 shows the 1984 V-phase relation of Eugenia.

III. PHOTOMETRIC ASTROMETRY

The details of the photometric astrometry method will not be reproduced in this paper (see Section I for PA references). However, two refinements to PA are adopted and now discussed. First, in calculating the distance an asteroid moves across the sky ($\Delta\phi$) we use the distance between the phase angle bisectors rather than the distance between the sub-Earth points. The phase angle bisector concept was introduced by Harris *et al.* (1984). This routine is used in calculating the asteroid's angular velocity ($\Delta\phi/\Delta t$) across the sky in the estimated sidereal period analysis. Second, phase angle bisectors also replace "time shifts" in the basic PA Eq. (1) of Taylor and Tedesco (1983). Both of these refinements

TABLE I

COMPARISON STARS AND OBSERVERS

Fig. No.	UT Date	Observer	Comparison star	Observed V (mag)	Observed B-V	Observed U-B
1	1969 Jun 9	D	[a]	10.10 ± 0.02	+0.63 ± 0.02	
2	1969 Jun 10	D	[b]			
3	1969 Jun 11	D	[c]	12.04 ± 0.03	+0.82 ± 0.01	
5	1984 Sep 28	S	[d]	10.89 ± 0.02	+0.92 ± 0.01	+0.54 ± 0.01
5	1984 Sep 29	S	[d]	10.89 ± 0.02	+0.92 ± 0.01	+0.54 ± 0.01
6	1984 Oct 24	B	BD +2 348	10.03 ± 0.01		
7	1984 Oct 31	B	BD +2 348	10.08 ± 0.04		
8	1984 Nov 21	B	HD 12923	6.30 ± 0.02		
9	1984 Nov 27	B	HD 11037	5.92 ± 0.02		

Note. D, Dunlap at the Steward 91-cm telescope on Kitt Peak presently housing the Spacewatch Telescope; S, A. Pospieszalska-Surdej and J. Surdej at the European Southern Observatory 50-cm telescope. The observing and reduction procedures are described in Surdej *et al.* (1983); B, P. V. Birch at the Lowell–Perth 61-cm reflector.

[a] Comparison star not catalogued; 1950 coordinates are RA = 14 hr 36.6 min, and Decl. = −4° 45′.

[b] Same star June 9, 1969. No photometry done.

[c] Identification not available.

[d] Comparison star not catalogued; 1950 coordinates are RA = 2 hr 24 min 19 sec and Decl. = +5° 42′ 20″.

were used in the study of Herculina (Taylor *et al.* 1987). The results from the new and old techniques give identical results. However, we recognize that it is possible, given rarely seen relative positions of an asteroid with respect to its pole position, that discrepancies between the techniques could occur. The phase angle bisector is the more appropriate concept and therefore it is now a part of PA. Because of this change, the formulas (14) for the cycle corrections found in the Appendix of Taylor (1979) should be modified; the coordinates of the phase angle bisector rather than the sub-earth point should be used.

Table IV lists the time intervals of the

TABLE II

ASPECT DATA FOR EUGENIA

Observed UT date	RA (1950)	Decl. (1950)	Distance (AU) from the Sun	Distance (AU) from the Earth	Phase angle	Ecliptic Long (1950)	Ecliptic Lat (1950)
1969 Jun 9	$14^{\mathrm{h}}35^{\mathrm{m}}.5$	−4°41′	2.498	1.642	+15°.47	218°.0	+10°.0
1969 Jun 10	14 35.5	−4 41	2.498	1.645	+15.61	218.0	+10.0
1969 Jun 11	14 35.6	−4 40	2.498	1.649	+15.75	218.0	+10.0
1984 Sep 28	2 22.7	+5 37	2.916	2.014	−10.31	35.3	− 8.1
1984 Sep 29	2 22.1	+5 32	2.917	2.008	− 9.98	35.1	− 8.1
1984 Oct 24	2 3.5	+3 6	2.927	1.940	− 3.03	29.9	− 8.9
1984 Oct 31	1 57.7	+2 30	2.929	1.954	+ 4.42	28.3	− 8.9
1984 Nov 21	1 43.2	+1 23	2.935	2.075	+11.27	24.4	− 8.7
1984 Nov 27	1 40.5	+1 17	2.937	2.129	+12.99	23.7	− 8.5

TABLE III

MAGNITUDES AND COLORS OF EUGENIA

Observed UT date	$V_0(1,\alpha)$ (mag)	B-V (mag)	U-B (mag)
1969 Jun 9	8.37 ± 0.03	+0.68 ± 0.02	+0.29 ± 0.02
1969 Jun 11	8.34 ± 0.03	+0.67 ± 0.01	+0.27 ± 0.01
1984 Sep 28	8.23 ± 0.03	+0.65 ± 0.02	+0.24 ± 0.02
1984 Sep 29	8.22 ± 0.03	+0.67 ± 0.02	+0.23 ± 0.02
1984 Oct 24	7.85 ± 0.02	—	—
1984 Oct 31	7.86 ± 0.04[a]	—	—
1984 Nov 21	8.28 ± 0.03	—	—
1984 Nov 27	8.31 ± 0.03	—	—
1985 Jan 17	8.62[b]		

[a] Since the lightcurve maximum was not observed a 0.05 mag correction was applied (based upon an overlay of the Oct 24 and Oct 31 lightcurves).

[b] Observed at 19.50° solar phase angle. From Weidenschilling *et al.* (1987).

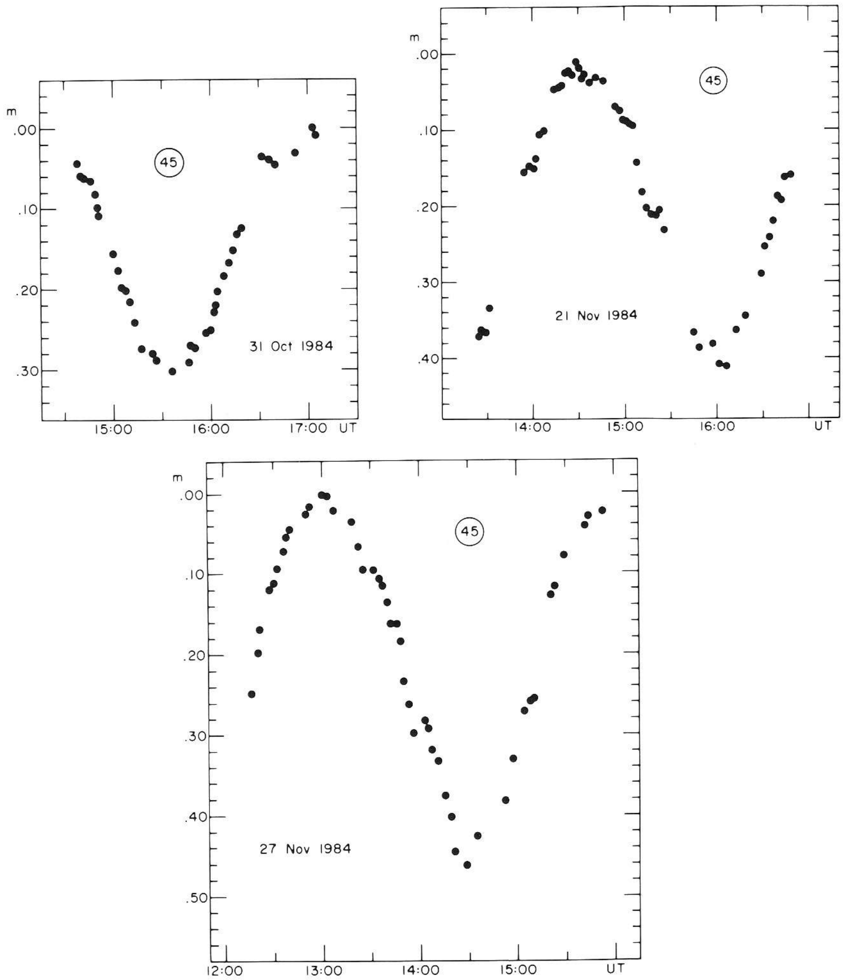

FIG. 4. 1984 lightcurves of Eugenia. $V_0(1,\alpha) = 7.86$ for October 31, 8.28 for November 21, and 8.31 for November 27.

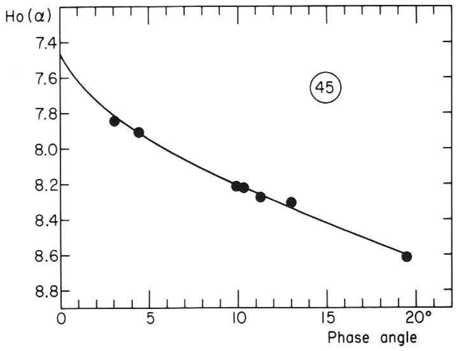

FIG. 5. The *V* phase relation of Eugenia at maximum light. The solid curve is the least-squares fitted Bowell–Lumme–Harris phase relation (Bowell *et al.* 1987).

1984–1985 lightcurves that were used to determine the "estimated sidereal period." Note that the times for January 17, 1985 are from the lightcurve of Weidenschilling *et al.* (1987). The synodic period when the angular velocity of the phase angle bisector ($\Delta\phi/\Delta t$) is zero is the sidereal period. Therefore, the least-squares solution of the ordered pairs ($\Delta\phi/\Delta t$, synodic period) gives the estimated sidereal period: 0.237464 day. The routine was done 10 additional times by varying the time intervals randomly by their estimated errors (the right column of Table IV). The results indicate that the error in the estimated sidereal period is ±0.000004 day (1σ). A negative slope from the least-squares routine indicates that if the asteroid is in the apparent retrograde loop of its orbit then the observed synodic periods are each larger than the sidereal period; a characteristic of a retrograde sense of rotation. The slope of the Eugenia solution is -0.00018 ± 0.00004, clearly implying that the sense of rotation of Eugenia is retrograde.

The mean synodic period (MSP) is a constant which represents the mean of all synodic periods over the orbit of an asteroid. It enables the number of synodic cycles to be counted between similar lightcurve features over long time intervals. Eugenia's lightcurves usually have two maxima and two minima per rotation period of 5 hr 41.9 min which do not create any difficulties in finding the MSP. However, in 1983 and 1985–1986 Weidenschilling *et al.* (1987) observed the Eugenia lightcurve to have essentially only one maximum and one minimum. Those lightcurves have the smallest observed amplitudes which imply that the observations were the furthest from the equator of Eugenia. The difference in ecliptic longitude between the two oppositions is approximately 180° so our first thought was that the single lightcurve minimum from

TABLE IV

INTERVALS FROM THE 1984–1985 DATA USED TO FIND THE ESTIMATED SIDEREAL PERIOD

Date	UT—Date	UT	$\Delta\phi/\Delta t$	Synodic periods (days)	Estimated error in overlays (± min)
Oct 24	16:00—Sep 29	6:11	−0.0207	0.237475	4
Oct 31	15:08—Sep 29	8:00	−0.0190	0.237479	3
Nov 21	15:00—Sep 29	9:41	−0.0108	0.237466	3
Nov 27	14:00—Sep 29	5:12	−0.0083	0.237464	4
Jan 17	5:00—Sep 29	6:17	+0.0551	0.237456	2
Oct 24	14:00—Nov 21	14:29	−0.0018	0.237453	4
Oct 24	15:00—Nov 27	14:00	+0.0057	0.237464	3
Jan 17	5:00—Oct 24	16:05	+0.0745	0.237453	5
Jan 17	7:00—Oct 31	15:29	+0.0824	0.237437	3
Jan 17	5:00—Nov 27	15:03	+0.1207	0.237453	3

TABLE V

EPOCHS AND PARAMETERS USED IN PHOTOMETRIC ASTROMETRY

UT date	Minimum $m1$		Minimum $m2$		Use	Source	Aspect[a] (degree)	Ampl. (mag)	Cycle corr.
	ID	UT	ID	UT					
Jun 9 1969	—	—	1	5:53	MSP	T	75.2	0.34[b]	—
Jun 10 1969	2	7:30	—	—	MSP, POLE	T	75.2	.34[b]	−1
May 4 1978	—	—	3	8:52	POLE	D	68.4	.31	+1
Jun 1 1978	4	6:30	5	9:26	MSP	H	72.9	.34[c]	—
May 21 1982	6	6:05	7	8:44	MSP, POLE	W	123.0	.20	+2
Jun 30 1983	8	7:01	—	—	MSP, POLE	W	34.0	.11	+3
Oct 31 1984	10	15:38	—	—	MSP, POLE	T	96.9	—[d]	+3
Nov 27 1984	—	—	9	14:32	MSP, POLE	T	93.1	.45	+3
Oct 20 1985	—	—	11	3:03	MSP	W	146.3	0.15	—

Note. T, this paper; D, Debehogne and Zappalà (1980); H, Harris and Young (1979); W, Weidenschilling *et al.* (1987).

[a] As measured from the 106° north pole solution.

[b] The amplitude is from the composite lightcurve (Fig. 2).

[c] From the composite lightcurve of 4 nights in Fig. 1 of Harris and Young (1979).

[d] The lightcurve does not cover the full rotation period.

each opposition represented the same surface feature on the asteroid. This is not true. In the MSP analysis it is apparent that the 1983 and 1985 lightcurves are switched with respect to each other. That is, the feature on the asteroid causing the single minimum in the 1983 lightcurve is not the same feature causing the single minimum in the 1985–1986 lightcurve. The two minima are separated by approximately 180° in rotational phase. This same phenomenon may occur with asteroid Herculina; a lightcurve switch is predicted for 1988 (see Section V of Taylor *et al.* 1987).

Table V gives the Eugenia lightcurve epochs of minimum light used in the derivation of the MSP. The epochs with even number identifications include 1983 and are designated $m1$. The odd number identifications $m2$, which include 1985, are one-half a rotation cycle from the $m1$ set. In the MSP analysis a time interval between two epochs from the independent sets $m1$ and $m2$ is used only if the epochs are within 20° solar phase angle of each other (see Section III of Taylor and Tedesco 1983), and the time interval is longer than the orbital period of Eugenia (~1640 days). The resulting intervals, from Table V, are 2–4, 2–6, 2–10, 4–8, 4–10, 1–5, 1–7, 1–9, 1–11, 5–9, and 5–11. Table V also identifies the epochs which are used in the pole analysis and a footnote column giving the source of each lightcurve epoch. The last three columns of the table are explained below.

By examining a few test cases it was found that, for retrograde rotation, a MSP is 0.000035 day smaller than the sidereal period it generates. Since the estimated sidereal period is 0.237465 day ± 0.000004 (1σ) then a search was made for a MSP within 3σ of the expected result, namely between 0.237418 and 0.237442 day. Only one MSP exists in that domain. The MSP of Eugenia, from both sets $m1$ and $m2$, is 0.2374296 ± 0.0000003 (1σ) day, within 1σ of the estimated value.

Table VI gives the time intervals, corrected for light time, used in determining the pole orientation and sidereal period of Eugenia. The identification numbers are the same as those found in Table V. The number of cycles is the quotient of the time interval and the MSP. The lightcurves were overlaid with similar minima superposed. Maxima are not used in this analysis be-

TABLE VI

TIME INTERVALS USED TO DETERMINE THE POLE ORIENTATION AND SIDEREAL PERIOD OF EUGENIA

ID of interval	Time interval (days)	Number of cycles	Error (min)
2– 4	3277.9588	13806	±3
2– 6	4727.9381	19913	4
2– 8	5132.9757	21619	5
2–10	5622.3371	23680	3
4– 8	1855.0214	7813	4
4–10	2344.3783	9874	4
1– 3	3251.1252	13693	2
1– 7	4729.1159	19918	5
1– 9	5650.3577	23798	3
1–11	5977.2923	25175	5
3– 9	2399.2324	10105	5
3–11	2726.1671	11482	±5

cause of the anomalies in the 1983 and 1985 lightcurves. The errors, in Table VI, are estimated uncertainties of each fit. We also estimate that the error in assuming lightcurve minima represent the same feature on the asteroid to be ±2° rotational phase, which for Eugenia is ±3 min. Equation (1) of Taylor and Tedesco (1983) was applied 20 times and for each trial the time interval was altered randomly by both uncertainties discussed above. PA results are given below; the "formal" pole error is the mean of the 20 angular differences between each trial pole and the adopted pole. The "approximate" uncertainty is our estimate based on the formal error.

Pole orientation
(ecliptic coordinates): 106° long
+26° lat
or
295° long
+34° lat
Pole uncertainty
(formal): 4.2 ± 2.7° (1σ)
(approximate): ±10°
Sidereal period: 0.2374645 ± 0.0000002 (1σ) day
Sense of rotation: Retrograde

In Table V the last column gives the cycle corrections needed for the 106° pole. It is an additional synodic cycle which is added for each orbital rotation of the asteroid (see Eq. (1) and Section V of Taylor and Tedesco 1983). The cycle correction is only listed for the epochs used in the pole analysis. In Table V the third from the last column gives the aspect angle which is measured between the 106° pole of the asteroid and the line of sight. The next column gives the lightcurve amplitude. A plot of amplitudes versus aspect (not shown) is internally consistent; they vary directly (see the next section).

IV. THE AMPLITUDE–ASPECT POLE SOLUTIONS

Combining all available photometric lightcurves of 45 Eugenia that have been recorded at phase angles $\lesssim 15°$ (cf. Table VII), we have applied the "revisited amplitude–aspect relation" in order to test the consistency of the pole solutions derived by PA. When doing so, we have first digitized all published "complete" lightcurves and measured the slope D_i of the normalized curves ($i = 1$ to 8 in Table VII) representing I_r^2 versus $\cos^2(\psi)$, where I_r is the relative intensity of a measurement observed at phase ψ. Under the assumption of a three-axis ellipsoid model, PSS[2] have shown that a simple but nonlinear relation does hold between the observed D_i, the ecliptic coordinates λ_i, β_i of the minor planet and the pole coordinates (λ_0, β_0) as well as the semi-axes ratios a/b and b/c of the best-fitted ellipsoid model. In this context, a set of at least four independent nonlinear equations must then be solved in order to determine the values of the four unknown parameters λ_0, β_0, a/b, and b/c. Since observations made at ecliptic longitudes 180° apart are photometrically equivalent, Table VII indicates however that 45 Eugenia has only been observed within three dis-

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[2] We refer the reader to the work by Pospieszalska-Surdej and Surdej (1985), referred to hereafter as PSS, for a comprehensive description of the amplitude–aspect (AA) method as well as for the exact meaning of the parameters t_M, D, R, and others used in the remainder of this section.

TABLE VII

Aspect Information and Characteristics of the $I_r^2 - \cos^2(\psi)$ Relation Used in the Amplitude–Aspect Analysis of Eugenia

Observed UT date	Ref.[a]	Ecliptic Long (1950.0)	Ecliptic Lat (1950.0)	Phase angle	t	D		R
1969 Jun 10	PP	217°.92	+10°.02	15°.7	$1^h.28567$	0.68053 ±	0.03977	0.932
1978 May 4	DZ	226.49	+10.79	4.5	4.60353	0.56598	0.01513	0.974
1978 Jun 1	HY	221.04	+10.51	12.0	8.01975	0.57853	0.03847	0.967
1983 Jun 30	W	294.81	+ 6.82	12.3	8.5[b]	0.07847	0.02522	0.511[b]
1984 Sep 29	PP	35.07	− 8.16	9.9	7.14971	0.95478	0.02869	0.978
1984 Nov 21	PP	24.44	− 8.69	11.3	14.53327	1.05685	0.03457	0.991
1984 Nov 27	PP	23.75	− 8.53	13.0	13.08204	1.21469	0.05085	0.988
1986 Jan 17	W	116.65	− 5.26	1.9	9.75[b]	0.07416	0.03216	0.592[b]

[a] References: PP, Present paper; DZ, Debehogne and Zappalà (1980); HY, Harris and Young (1979); W, Weidenschilling *et al.* (1987).

[b] This lightcurve seriously departs from an ellipsoidal one (only one maximum and minimum).

tinct longitude ranges, namely $\lambda_i \in$ [210–230°], $\lambda_i \in$ [20–40°], and $\lambda_i \simeq 295°$. As a consequence (see PSS), it is not possible to determine unambiguously the values of the four parameters λ_0, β_0, a/b, and b/c because one independent observation is missing. We have therefore chosen to calculate the solution of just three parameters (λ_0, β_0, a/b) as a function of the fourth one (b/c). While performing the calculations, we have furthermore assigned equal weight to each group of observations pertaining to one of the three distinct oppositions. The results of these calculations are illustrated in Fig. 6 where we have also indicated the PA pole solutions. As most usually (see PSS), we also find that there exist two equally probable sets of pole solutions (P_1 and P_2). Due to the nonellipsoidal character of some of the observed photometric lightcurves (cf. those recorded in 1983 and 1986), we conclude that there is an overall good agreement between the predicted PA and AA solutions.

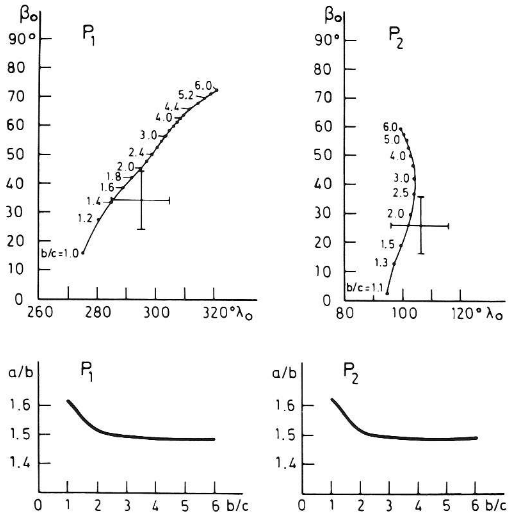

FIG. 6. Predicted amplitude–aspect pole solutions (λ_0, β_0, and a/b) as a function of the semi-axes ratio b/c (see Section IV). The PA pole solutions (see Section III) are indicated with crosses.

V. DISCUSSION

Lightcurves of Eugenia have been obtained from six oppositions; 1969, 1978, 1981–1982, 1983, 1984–1985, and 1985–1986. In four of the oppositions the lightcurves rather typically have two maxima and two minima. The relative amplitudes of the extrema do vary, but that in itself is not unusual. However, in 1983 and 1985–1986 the lightcurve shape changes. There are secondary variations but essentially the lightcurves have just one maximum and one minimum per rotation cycle (see Weidenschilling *et al.* 1987). The lightcurves of 1983 and 1985–1986 were both obtained by viewing approximately 30° from the 106° north pole solution and its corresponding south pole, respectively. Also, from the PA analysis we conclude that the lightcurves from those two oppositions are switched with respect to each other. That is, the feature on the asteroid causing the maxima in 1983 is causing the minima in 1985–1986, and vice versa. These phenomena were observed by Taylor *et al.* (1987) in the study of asteroid 532 Herculina. They suggested, as the simplest model, that Herculina might be a spheroidal body with two dark regions separated by approximately 180° in longitude. They demonstrated that such a model successfully reproduces the Herculina lightcurve amplitudes of each extrema. The Eugenia lightcurve anomalies might be explained by a similar model. Debehogne and Zappalà (1980) also suggest that Eugenia might have an albedo feature. Their 1978 lightcurves display maxima with nearly the same brightness but minima which reach different levels. The albedo conjecture is based on the fact that those 1978 observations were made at less than 5° phase angle. We urge that the possible albedo structure of Eugenia be tested with simultaneous visual and thermal infrared observations. Radar observations would also aide in the study of Eugenia's shape.

ACKNOWLEDGMENTS

We thank E. Tedesco for advice, R. Binzel for suggestions through his referee report, and the National Aeronautics and Space Administration for financial support. We are indebted to S. Weidenschilling and the Planetary Science Institute for providing us with their lightcurve data prior to its publication. We thank the Government of Western Australia for financial support, D. Harwood and C. Bowers for use of computer programs, and I. Nikoloff and I. A. Nikoloff for assistance with observations.

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