NO. 17. PHOTOMETRIC STUDIES OF ASTEROIDS. IX. ADDITIONAL LIGHT-CURVES*

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ABSTRACT

Fifteen asteroids were observed with the 36- and the 82-inch telescopes of the McDonald Observatory. Owing to the fast motions of the 36-inch, precise transfers to the *U, B, V* system could be made concurrently with the light-curve observations. Iris was observed nearly pole-on, at 8^h05^m right ascension and $+20°$ declination. Large obliquities often occur, and there apparently is some alignment of the poles. The ecliptic longitudes of eight asteroid poles were determined between 104° (284°) and 194° (14°), with none occurring between 14° and 104° or between 194° and 284°.

1. Introduction

This is the ninth paper in the series written by several authors under Dr. G. P. Kuiper's general direction. Three types of study have been undertaken in the series, namely, a general survey of *light-curves* (Papers I-IV, VII, IX, and X), the revision of *photographic magnitudes* (Papers VI and VIII), and photometry especially for *phase effects* (Papers V and XI). The full references are given at the end of the present paper. In addition, light-curves of Trojan asteroids are being observed.

The present observations are the first in this series obtained with the 36-inch reflector of the McDonald Observatory. The 36-inch is an ideal telescope for making magnitude transfers all over the sky because it slews fast and has precise setting dials. It was therefore considered feasible to make the transfers to *U, B, V* standards *during* the light-curve runs without causing appreciable gaps in the light-curves themselves. Compared with the method used previously, of making the transfers before and after the light-curve observations, the main advantage of the present method is in longer light-curves. Also, with standards especially chosen near the ecliptic, the precision can be improved, and a close check can be maintained on the constancy of the comparison stars.

The procedures of previous papers were used, but there are a few modifications, and we therefore describe the methods of observations and reductions (Sec. 2). The *U, B, V* standards were chosen in the Pleiades and Praesepe regions. New integrators and reduction templates were used, while the reductions were partly done with an electronic calculator. The plan of the present paper follows that of the others; a special section on the alignment of the poles (Sec. 5) is included.

2. The Observations

The photometer is the same as the one used before for most of the light-curves in this series; a photograph of the photometer has been published recently in a different context (Gehrels and Teska, 1960, Pl. I). The paper referred to also gives details of the Weitbrecht (1957) integrators, used for most of these observations, and of the use of magnitude rulers in the reductions. The main advantage of an integrator rather than an amplifier, even for bright objects, is that the readings on the Brown charts are straight lines and are easy to reduce. A disadvantage is that sudden pulses of very poor seeing, larger than the diaphragm, are not immediately recorded. One can, however, tell the presence of such effects from the poor repetition of the integrations. The multiplier phototube, RCA 931*A* (1P21 after September, 1958), is usually refrigerated with dry ice. The duration of each integration is about 30 seconds. The filters are standard for the *U, B, V* system (Johnson

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and Morgan, 1951); the light-curve observations all are with the yellow, V, filter.

The light-curve observations with the 36-inch are started as soon as it is clear and dark enough; no time is spent on standard stars before and after the run. The asteroid is identified by using predicted O–C's of position that are based on the O–C values in previous oppositions; these preparations were made by Mr. P. R. Davis, to whom we are indebted for his careful work. A nearby comparison-star is chosen, of approximately the same color and brightness as the asteroid, and the light-curve run is begun. The observations are in the following order: *A-A-S-A-A, C-S-C, A-A-S-A-A,C-S-C*, etc., where *A* is an integration on asteroid plus sky, *C* on the comparison plus sky, and *S* on the sky alone (close to asteroid or star).

the Praesepe stars are given. The magnitudes and colors are taken from the first two references, slightly modified on the basis of our own observations that were made on six different nights. No variability was found. The external probable errors of V, $B-V$, and $U-B$ in Table 1 are estimated to be ± 0.004, ± 0.003, and ± 0.007 mag., respectively. Paper VIII has a discussion of the possible use of asteroids as magnitude standards, for instance for the transfer of the U, B, V zero point to the southern hemisphere. For future reference we will list, in Table 2, the standard stars on which the present asteroid magnitudes are based.

As for the reductions, extensive use is made of magnitude rulers that give $m = 5 - 2.5 \log R$, where R is the reading on the Brown chart ($R = 100$ for a full-scale deflection). For the comparison star, m

TABLE 1

U, B, V STANDARDS MOST FREQUENTLY USED

Name	Catalogue No.	R.A. 1960	Dec. 1960	V (mag.)	$B-V$ (mag.)	$U-B$ (mag.)
Pleiades A......	H II 2484	$3^h47^m.5$	+24°05′	9.166	+0.169	+0.140
Pleiades B......	H II 1549	3 45.4	+23 25	8.800	+1.153	+0.837
Pleiades C......	H II 1234	3 44.6	+24 23	6.821	+0.021	−0.073
Pleiades D......	H II 1705	3 45.8	+24 51	6.461	+1.701	+2.074
Praesepe A......	KW 192=R 371	8 37.3	+19 26	10.966	+0.251	+0.093
Praesepe B......	KW 108=R 272	8 36.3	+19 36	10.008	+1.015	+0.785
Praesepe C......	KW 265=R 438	8 37.9	+20 07	6.607	+0.006	+0.013
Praesepe D......	KW 253=R 427	8 37.8	+20 09	6.388	+0.982	+0.839

Transfers to the U, B, V system are made, three or four times per light-curve, when the asteroid is near the meridian. A "transfer" is as follows: comparison; asteroid; first star; a short stretch of light-curve; second star; asteroid; comparison. Each object is observed with the color filters in the following order: *V-B-U*-skies-*U-B-V*; the comparison star, however, is not observed in the ultraviolet, and the asteroid has double integrations in the yellow (which are used also for the light-curve). The two stars are U, B, V standards, a red and a blue one, of widely different color indices.

Table 1 lists the standards that are primarily used. They were chosen near the northern ecliptic, within a cluster and bright enough to be easily identified and yet similar in brightness to the asteroids. The second column of Table 1 gives the identification numbers as used in the references, namely, by Johnson and Mitchell (1958) for the Pleiades stars and by Johnson (1952) for Praesepe. In addition, the identification numbers of Ramberg (1941) for

is plotted against time, and interpolation gives the comparison magnitude at the time of the asteroid observation. The difference with m for the asteroid, averaged over four integrations, gives a point on the light-curve. Close to the horizon, differential extinction corrections may be needed, and they are applied with $0.155\,\Delta \sec z$. The corrections may be as large as 0.017 mag., but they are usually smaller than 0.009 mag. Corrections for differential color extinction were found negligible ($q = 0.000$, see below). The values of sec z were computed with the IBM 650 at the Research Computing Center of Indiana University.

Further use of the IBM 650 was made for the reduction to absolute magnitude (Paper VIII, Sec. II) and for the transfers to the U, B, V system. The transfers were made either with adopted extinction coefficients or, when sufficient standard observations are available, by having the machine compute all coefficients, including those for the extinction. Both routines were programed by Dr. E. C. Olson, whom we should like to thank for his co-operation. The program with mean extinction coefficients is mostly used; it computes

$$V = m_{\text{yellow}} - 0.155 \sec z + q(B-V)\sec z + w + x(B-V),$$

where q is assumed negligible,

$$B-V = \frac{a + b(m_{\text{blue}} - m_{\text{yellow}} - 0.090 \sec z)}{(1 - 0.032 \sec z)},$$

and

$$U-B = c + d(m_{\text{ultraviolet}} - m_{\text{blue}} + L - 0.300 \sec z),$$

where the differences of m also include differences in gain steps. The correction L, for red leakage of the ultraviolet filter, is small; we found at most, for one of our phototubes, $L = 0.0045$ mag., for the very red standard Pleiades D (Table 1). The machine computes the transformation coefficients a, b, c, d, w, and x, by least squares, for each transfer separately.

Tables 2, 3, and 4 give a summary of the observations, while a detailed discussion of each asteroid is in Section 4. The tables are mostly self-explanatory, the column headings are the same as in Paper VII, with a few additions and remarks as follows. The observations of February 7, March 5, and March 9, 1958, were made with the 82-inch; all other observations were made with the McDonald 36-inch telescope. The observations were made by the first author (T. G.) and the reductions by the second (D. O.). "V of Zero" is the visual magnitude of the brightest part of the observed light-curve; it is found first from the transfer magnitudes of the asteroid and, second, carrying half-weight, from the transfer magnitudes of the comparison star. The latter requires a color correction, $x\Delta(B-V)$, where $\Delta(B-V)$ is the difference in color between the asteroid and the comparison star, and x is obtained from the U, B, V transfer. The estimated external probable errors of "V of Zero," $B-V$, and $U-B$, respectively, are ± 0.006, ± 0.005, and ± 0.009 mag. The probable errors of some of the other data are given under the first line of Table 3. The usual checks of the asteroid identification are always made, with the positions, the O−C of positions, and variation of the O−C values; during non-photometric nights some of these checks are made in advance. In addition, a careful watch is made for the relative motion of the asteriod during the night, and, when detected, "motion seen" is written on the Brown chart.

The "Range" in Table 2 is the greatest magnitude difference found along the light-curves of Figures 1-20. "Mean V" is determined such that the areas inclosed, by the observed part of the light-curve above and below the line of mean V, are equal. The reductions to zero phase and absolute magnitude $g(V)$ are made with the phase relation of Paper VI, Table 4. The absolute magnitudes are thus consistent with those adopted by the International Astronomical Union (Gehrels, 1958), except that the present ones are "V" magnitudes.

The aspect is given by the ecliptic longitude and latitude, $\cos\lambda = \cos\delta \cos RA/\cos\beta$, and $\sin\beta = 0.91741 \sin\delta - 0.39795 \cos\delta \sin RA$. The right ascension, RA, and the declination, δ, both listed in Table 3, are taken from the telescope dials and reduced to the middle of the run and corrected for refraction when necessary.

The "Scatter of Comp. Readings," in Table 4, indicates the quality of the night; it is the average deviation, deviating from a mean curve, of the single observations of the comparison star. No conclusive evidence of variability of any of the comparison stars used in this paper has been found.

3. *Axis and Period of Rotation*

From photographic photometry (Kuiper *et al.*, 1958), it was found that the asteroids in general have large obliquities. Of the 33 asteroids for which we presently have light-curves, none as yet has been surely established to have a pole perpendicular, or nearly perpendicular, to the plane of the ecliptic. Perhaps asteroids 4 Vesta and 15 Eunomia have small obliquities, but even these two cases need further confirmation.

Table 5 gives approximate pole determinations for asteroids that have been observed in more than one opposition. First listed are the ecliptic longitude, λ, and latitude, β, at the time of observation. The greatest amplitude, a_1, is given and also the second amplitude, a_2. In this section, the amplitudes are found from completely observed light-curves. When only part of the light-curve had been observed, the observation is not used, unless a_1 or a_2 could be clearly identified. As before in this paper, the absolute magnitude, $g(V)$, is based on the phase relation of Paper VI, Table 4. Next in Table 5 are three determinations of the longitude of the pole, λ_0, determined as follows.

An asteroid observed pole-on shows no rotational light-variation, while equatorially the greatest variation is observed. It is a projection effect, of a greatest possible amplitude, A, seen as the sine of the angle between the direction of observation and that of the rotational axis. We therefore adopt, in general, $a = A \mid \sin \gamma \mid$, where $\cos \gamma = \sin(-\beta) \sin \beta_0 + \cos(-\beta) \cos \beta_0 \cos(180° + \lambda - \lambda_0)$, and a is the amplitude observed at any one epoch.[1] The actually observed minimum and maximum may be distorted by irregular features of the asteroid body, newly exposed with change of phase or aspect, but the relation should be good for a first reconnaissance. Furthermore, the determinations in Table 5 are made from the *two*

TABLE 2

SUMMARY OF OBSERVATIONS

Ast. No.	Obs. Date 1958 U.T.	V of Zero (mag.)	$B-V$ (mag.)	$U-B$ (mag.)	Stds.*	Range (mag.)	Period	Mean V (mag.)	Mean $g(V)$ (mag.)	Figure
1....	Jan. 10	6.806	+0.720	+0.422	Prae.	0.04	....	6.829†	3.71	1, 2
3....	Jan. 14	8.152	.826	.482	Plei.	.16	$7^h18^m \pm 2^m$	8.207†	5.71	3
5....	Feb. 16	9.496	.823	.354:	Prae.	.21		9.60‡	7.40	4
	Mar. 5	9.774	.846	.396	Prae.	.....	....	....	.....	5
7....	Nov. 5	6.930	.836	.526:	Plei.	.04	....	6.947†	5.78	6
9....	Feb. 15	8.901	.844	.500	Prae.	.09	....	8.949†	6.53	7
18....	Feb. 15	10.166	.864	.504:	Plei.	.35	14^h	....	.....	8
	Mar. 9	10.617	.864:	.442	Other			10.73§	7.03	9
20....	Jan. 25	10.137:	.843	.480	Plei.	.24	....	10.25:§	6.94:	10
22....	Feb. 24	10.701	.713	.279	Other	.14	$4^h04^m \pm 4^m$	10.758†	6.86	11
30....	Jan. 28	10.770	.906	.467:	Prae.	.14	$13^h40^m.1$	10.84§	7.97	12
	Feb. 19	10.800	.865	.431	Prae.		± 0.15	10.86§	8.14	13
39....	Mar. 5	11.326:	.880	.658:	Other	.44	....	11.478:†	6.78	14
40....	Jan. 14	10.432:	.809:	.456	Other	.22	$9^h08^m.15$	10.553:†	7.61	15, 16
	Jan. 29	10.030	.841	.435	Prae.		± 0.04	10.144†	7.48	16
44....	Jan. 13	8.894	.699	.266	Prae.	.22	$6^h28^m \pm 2^m$	9.013†	7.12	17
60....	Feb. 7	10.617:	.852:	.455:	Other	.07	long	10.64‡	8.84	18
324...	Feb. 26	....	....	....	....	.07	8^h?	....	.....	19
511...	Jan. 26	10.449	+0.706	+0.391	Prae.	0.09	$5^h10^m \pm 1^m$	10.493†	6.58	20

* Prae. = Praesepe; Plei. = Pleiades; "Other" = U, B, V standards other than the ones of Table 1 were used.
† Mean over full period.
‡ Mean over night's run.
§ Mean over half-period.

TABLE 3

ASPECT DATA FOR THE ASTEROIDS

Ast. No.	Obs. Date 1958 U.T.	Phase Angle	log r	log ρ	Light-Time	R.A. 1958	Dec. 1958	λ	β
1.....	Jan. 10	3°.7	0.4155	+0.2121	$13^m.55$	$7^h50^m.2$	+30°11′	114°	+ 9°
		±0.1	±.0006	± .0010	±.03	±.1	± 2′		
3.....	Jan. 14	21.4	.3075	+ .0934	10.31	4 38.2	+ 0 43	68	−21
5.....	Feb. 16	12.1	.3204	+ .0643	9.64	8 10.3	+18 36	121	− 1
5.....	Mar. 5	19.5	.3198	+ .1013	10.50	8 05.4	+19 52	119	− 1
7.....	Nov. 5	7.8	.2639	− .0645	7.17	1 32.2	+18 25	28	+ 8
9.....	Feb. 15	5.1	.3580	+ .1154	10.85	10 34.4	+19 24	153	+10
18.....	Feb. 15	27.8	.3161	+ .2109	13.52	4 33.8	+11 20	69	−10
18.....	Mar. 9	27.8	.3277	+ .2835	15.98	5 01.6	+14 29	76	− 8
20.....	Jan. 25	27.4	.3204	+ .2158	13.67	3 02.5	+16 30	48	− 1
22.....	Feb. 24	6.9	.4620	+ .2900	16.22	10 55.8	+29 15	154	+21
30.....	Jan. 28	7.6	.3808	+ .1612	12.05	9 54.6	+12 03	147	− 1
30.....	Feb. 19	3.7	.3863	+ .1621	12.08	9 32.4	+13 34	141	− 1
39.....	Mar. 5	15.7	.4858	+ .3806	19.98	14 46.1	− 5 40	221	+10
40.....	Jan. 14	13.5	.3674	+ .1601	12.02	10 03.1	+16 36	147	+ 4
40.....	Jan. 29	6.6	.3685	+ .1378	11.42	9 52.1	+18 18	144	+ 5
44.....	Jan. 13	6.7	.3142	+ .0387	9.09	6 37.4	+20 06	99	− 3
60.....	Feb. 7	10.9	.2964	+ .0133	8.58	7 49.4	+14 42	117	− 6
324.....	Feb. 26	1.4	.5264	+ .3753	19.74	10 44.1	+ 4 41	161	− 3
511.....	Jan. 26	8.1	0.4580	+0.2873	16.12	10 14.4	+24 06	147	+12

[1] Dr. C. J. van Houten (personal communication) shows that, for a certain model, the proper relation is $a = A(1 - \cos \gamma)$.

TABLE 4

COMPARISON STARS AND QUALITY OF NIGHTS

Used for Asteroid No.	Obs. Date 1958 U.T.	R.A. 1958	Dec. 1958	V (mag.)	$B-V$ (mag.)	Scatter of Comp. Readings (mag.)	Remarks
1	Jan. 10	$7^h54^m.3$	+29°55′	6.818	1.406	±0.003	
3	Jan. 14	4 38.1	+ 0 29	8.566	0.085	.005	Poor seeing
5	Feb. 16	8 10.1	+18 39	9.111	1.015	.004	
5	Mar. 5	8 05.1	+19 45	11.539	0.648	.004	Isolated clouds
7	Nov. 5	1 31.8	+18 33	8.712	1.152	.003	Occasionally poor seeing
9	Feb. 15	10 34.2	+19 08	9.697	0.375	.003	
18	Feb. 15	4 32.9	+11 18	10.650	0.723	.003	Some dust
18	Mar. 9	{5 01.5 5 01.4	+14 29 +14 35	10.953 10.039	1.560 0.603}	.003	
20	Jan. 25	3 03.1	+16 49	10.019	1.303	.006	Cloudy
22	Feb. 24	10 56.0	+29 27	10.622	0.562	.004	Stopped by clouds
30	Jan. 28	9 54.5	+12 09	10.394	0.923	.004	Clouds at start
30	Feb. 19	9 32.1	+13 42	11.312	0.482	.009	Clouds and dust
39	Mar. 5	14 46.1	− 5 39	11.528	0.920:	.004	Clouds about
40	Jan. 14	10 03.3	+16 33	10.794	0.131:	.003	Poor seeing
40	Jan. 29	9 53.9	+18 09	10.138:	0.349	{.005 .007	Clear until 7:40 U.T. Cloudy and equipment trouble
44	Jan. 13	6 39.5	+19 49	9.353	0.458	.008	Hazy; asteroid passed two stars
60	Feb. 7	7 49.5	+14 38	11.183	1.005	.005	Clouds about 3:00 U.T.
324	Feb. 26	10 43.7	+ 4 39	....	....	.010	Poor seeing
511	Jan. 26	10 14.8	+23 53	10.210	0.570	±0.005	Stopped by clouds

TABLE 5

DETERMINATIONS OF ASTEROID POLES

AST. NO.	PAPER	OBS. DATE U.T.	OBSERVATIONS λ	β	a_1	a_2	$g(V)$	LONG. DET. FROM a_1	a_2	$g(V)$	WT. AVERAGE λ_0	β_0	A
1	{IV	1953 Jan. 30	64°	+ 1°	$0^m.04$	$0^m.02$	$3^m.58$	......	......	......	......	......	......
	IX	1958 Jan. 10	114	+ 9	.04	.01:	3.71	......	......	......	......	......	......
3	{II	1954 January	144	−13	.14	.05	5.66	......	......	......	......	......	......
	IX	1958 Jan. 14	68	−21	.16	.05	5.71	......	......	......	......	......	......
6	{IV	1953 July 11	294	+12	.16	.04	......	150°	133°	......	145°	15°	$0^m.30$
	XI	1959 Feb. 5	150	+ 2	.06	.04	......}						
7	{I	1950 August	271	+ 4	.29	.16	......	195	190	240°:	193	15	0.26
	I	1952 Jan. 28	118	− 7	.22	.12	6.02						
	VII	1955 Dec. 28	170	− 6	.08	.01:	5.96:						
	IX	1958 Nov. 5	28	+ 8	.04	.00:	5.78}						
8	......	......	......	......	......	......	......	......	......	......	157	10	......
9	{I	1949 Nov. 2	41	− 5	.10	.07	6.49	183	187	190	156	15	0.23
	II	1954 Jan. 16	95	+ 6	.25	.18	6.84						
	IX	1958 Feb. 15	153	+10	.09	.01	6.53}						
22	{IV	1953 February	152	+20	.14	.10	......	......	......	......	......	......	......
	IX	1958 Feb. 24	154	+21	.13	.09	6.86	......	......	......	......	......	......
39	{II	1949 May 9	232	+15	.41	......	......	128	132:	130	130	10	0.50
	I	1952 Jan. 29	96	−12	.19	.07	6.37						
	I	1953 Apr. 10	180	+ 7	.23	.12	6.44						
	VII	1955 December	25	−13	.50	.50	6.79						
	IX	1958 Mar. 5	221	+10	.32	......	6.78}						
44	{III	1949 November	18	− 6	.48	.33	7.28	100	118	97	105	30	0.48
	II	1954 January	52	− 5	.35	.33	7.17						
	IX	1958 Jan. 13	99	− 3	.22:	.15	7.12}						
433	Beyer	(1953)	......	......	......	......	......	......	......	......	173	+13	1.45
511	{I	1952 Jan. 26	112	+ 3	.06	.03	6.50	123	122	119:	122	10	0.25
	I	1953 Apr. 8	200	+22	.25	.21	6.73						
	IX	1958 Jan. 26	147	+12	0.09	0.06	6.58}						

amplitudes per light-curve, a_1 and a_2. A third determination of the poles is made from the change of absolute magnitude with change of aspect. The greatest brightness is seen when the asteroid is observed pole-on, while the mean brightness (the mean of the rotational light-curve) is the least when the asteroid is observed equatorially. The brightnesses depend on the mean projected area, with a cosine relation involved. In first approximation, $g = G\,|\cos\gamma| + c$, where g is the observed mean absolute magnitude observed at any one epoch, G and c are constants, and γ is as defined before.

The determinations of Table 5 were made by using master-curves of A sin γ, made for different values of A and β_0, plotted as a function of $(\lambda - \lambda_0)$. We assumed $\beta = 0°$, and when only two observations were available, we also assumed $\beta_0 = 8°$; it is seen that neither one of these assumptions strongly affects the determination of λ_0. The master-curves were superposed on longitude plots of a_1, a_2, and $g(V)$, respectively, and the resulting values of the longitude are given in Table 5. Finally, in Table 5, a weighted average is given of the determined longitudes for each asteroid pole, giving half-weight to the determinations from $g(V)$, as well as to poor determinations that are listed with colons. The value of the latitude of the pole, β_0, is estimated from the quality of fit to the observations by the different sets of master-curves. There is little precision to these latitudes, and no determination of the sign can as yet be made. The last column of Table 5 predicts the greatest amplitude, A, to be observed equatorially. The reasons why no poles were determined for asteroids 1, 3, and 22, are given in Section 4. No light-variation was found for asteroid 8 in Paper IV, and the observations therefore presumably were made pole-on. Asteroid 17 was not included in Table 5, because of uncertainties discussed in Paper VII, nor was asteroid 20 (see Sec. 4). Asteroids 4 and 15 were also left out of Table 5, even though they have been frequently observed. 4 Vesta has small amplitudes and probably is nearly spherical. 15 Eunomia either has small obliquity, or Eunomia has a pole near longitude 145° (325°); a single light-curve observed near that longitude will settle the ambiguity.

As a test case we computed the pole of Eros from five of the observations made by Beyer (1953), namely, on September 26 and December 14, 1951; February 12, March 14, and April 17, 1952. We obtained $\lambda_0 = 4° \pm 3°$; $\beta_0 = +22° \pm 6°$; and $A =$ 1.45 mag. ± 0.08; which is to be compared with Beyer's own determination, by a much more detailed method, given in Table 5. The agreement is good, especially considering that only one amplitude was used and no absolute magnitudes, that Eros has an extremely elongated shape, and that Eros was observed over a great range of phase. Similarly, the agreement is good with the pole for 39 Laetitia determined in Paper VII ($\lambda_0 = 115°$; $\beta_0 = +28°$).

As for the determination of accurate periods of rotation, it appears that the co-ordinates of the poles must be known with greater precision than we presently have. The parameters to solve for are the longitude of the pole, the latitude of the pole and especially its sign, and the direction of rotation (direct or retrograde), while irregularities of the asteroid's shape cause some uncertainty in the epochs. We have attempted for asteroids 7, 39, and 511 to solve for the above parameters, without finding a unique solution. The discussion of asteroid 39 in Paper VII demonstrates the difficulties. There sometimes are also errors of identification of the epochs.

The outlook for future work, however, is good. A few more epochs in some cases (we indicated a few in Sec. 4) may make it possible to determine the direction of rotation, etc. An electronic computer could be used to make least-squares solutions by trial and error, trying various polar co-ordinates. Such machine calculations allow the inclusion of all permutations, with suitable weights, between the epochs. The computed residuals would indicate which gives the better fit, direct or retrograde rotation.

4. *The Light-Curves*

The asteroids were selected from among those near opposition and having photographic magnitudes less than 13.0. Nine asteroids were chosen that had been observed before in this program, namely, asteroid numbers 1, 3, 7, 9, 20, 22, 39, 44, and 511. The purpose of observing these again is primarily to study the aspect variations for the asteroid's shape and orientation of its rotational axis. They usually were observed not longer than the known period of rotation, so that the best use of the photometric nights could be made. Two light-curves were obtained in the nights of January 14 (nearly 12 hours of light-curve), February 15 (11 hours), and March 5 (9 hours). Six asteroids were added to the survey; they are asteroid numbers 5, 18, 30, 40, 60, and 324.

The light-curves are in Figures 1-20. The abscissae are in Universal Time, without correction for light-time; the ordinates are in magnitudes. Open circles are used when the quality of the observations is low as compared with the nightly average, that is, when the scatter in the plot of the comparison star is greater than about three times the one listed in Table 4. Also in other cases of doubt, we have used open circles in the figures and colons in the tables. Summaries of the amplitudes and of aspect, including those of previous years, are in Table 5; additional discussion of the light-curves now follows.

Ceres, No. 1

Ceres was observed in 1953 by Ahmad (Paper IV), who found two maxima and minima, and $9^{h}04^{m}.7$ for the period. He also reviewed the previous observations by other observers. The present light-curve was obtained on January 10, 1958, and is plotted, in Figure 1, on the same scale as of the other asteroids in this paper. In order to make a closer comparison with Ahmad's results, we also made Figure 2, with averages of four consecutive points of Figure 1 and with the ordinates expanded by a factor of 4. Only one minimum and one maximum are clearly present. The difference with Ahmad's result may be due to aspect variation, but it could also be a secondary effect of the difference in phase (16°). No attempt was made in Table 5 to determine the pole, because of the phase difference and because of the small aspect variation. Our light-curve does not contradict Ahmad's period of 9 hours.

Quite contradictory results were obtained in 1956 by E. Fichera (1958), who observed Ceres during four nights with the 7-inch Fraunhofer refractor of the Capodimonte Observatory, Naples. One comparison star, HD 5959, was used; the effective wavelength was near 4000A. The repetition of the observations was very good. A light-curve with *three* maxima and minima was obtained, with a period of $2^{h}55^{m}03^{s}.6 \pm 0^{s}.9$. The greatest amplitude was nearly 0.10 mag., the secondary ones were about 0.03 mag.

The variations as published by Fichera would definitely have been detected by the methods of Papers IV and IX. One of his minima, for instance, lasts about 18 minutes and one of the maxima 12 minutes, while they differ by at least 0.07 mag. Such variation would be quite apparent in our light-curves. While different amplitudes at different epochs may be explained with aspect variation, the discrepancy of the periods cannot be explained in this manner.

An explanation of the discrepancy may be that HD 5959 is variable. (Ahmad did not use the same comparison star on different nights. No variability was found for the comparison star of January 10, 1958, in the three *U, B, V* transfers of that night.) HD 5959 was observed with the McDonald 82-inch telescope on August 22, 1960, but no variation larger than 0.015 mag., if any real variation at all, was detected. The conditions on August 22 were not good, however, and the run was only 2 hours; it therefore seems valuable to repeat the observations.[2] Even if HD 5959 were found variable, one would still have to explain why Fichera did not find a beat period caused by the variation of Ceres. However, Ceres' variation in 1956 may have been less than that in 1953 and in 1958 if the asteroid was observed more pole-on in 1956. As noted above, Ceres does show aspect variation. Crucial observations appear to be those of HD 5959, with respect to nearby comparison stars, at different times, and further observations of Ceres, at different aspects, especially that of Fichera's observations (near $\lambda = 9°$, or near 189°, as will be the case early in 1963).

Juno, No. 3

Juno was observed on 5 nights in 1954 (Paper II), and the period was determined at $7^{h}12^{m}.6 \pm 0.1$. The present light-curve, of January 14, 1958, is in Figure 3. The aspect differs by 76° from that of 1954, the shape of the light-curve differs a little, but neither the amplitudes nor the absolute magnitudes show much aspect variation. We have therefore not determined the pole. Either the obliquity is small, or the longitude of the pole is near 107°, or perhaps near 192°. Further observations are needed.

Astraea, No. 5

The present observations, on February 16 (Fig. 4) and March 5 (Fig. 5), 1958, are the first light-curves in this series for Astraea. The minima of Figures 4 and 5, when superposed, fit very well, and they therefore are probably the same. Their magnitude difference is found to correspond to differential *distance* correction, but then the phase factor would have to be nearly zero.

If an average phase factor is assumed, the two runs would imply three different minima, which would make this object rather unusual. Possibly some error in the magnitude calibration occurred on March 5. Additional observations are required.

[2]A 3-hour run with the Kitt Peak 36-inch telescope, November 10, 1961, showed no variation greater than 0.005 mag. of HD 5959 with respect to BD – 10°212.

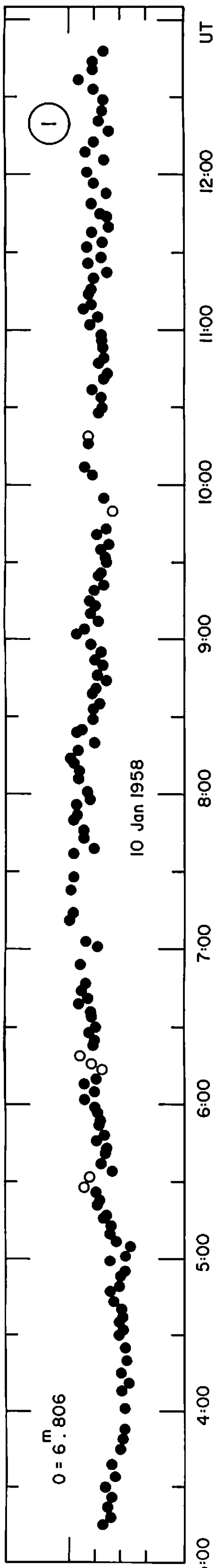

Fig. 1. Observations of 1 Ceres.

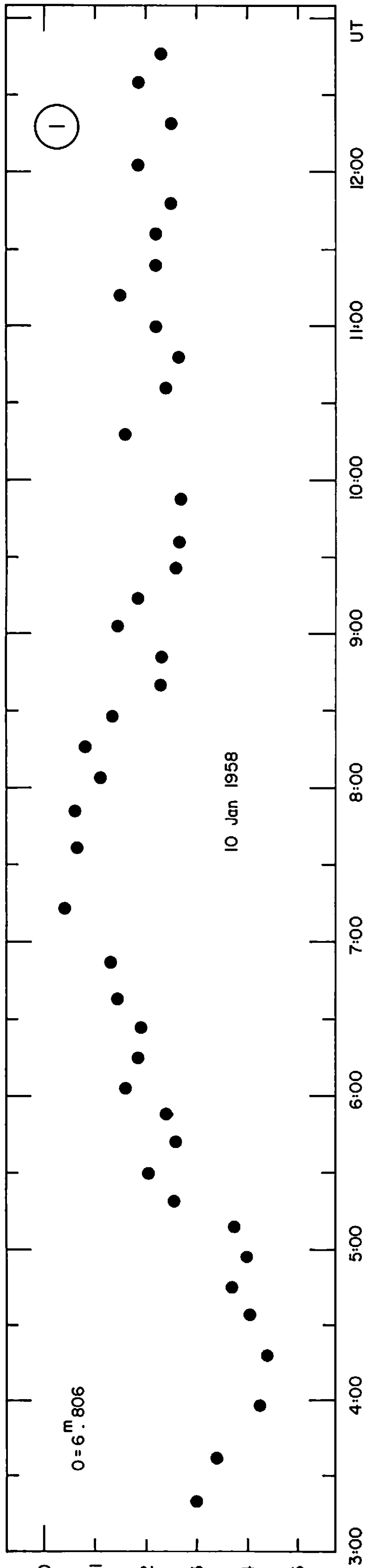

Fig. 2. Light-curve of 1 Ceres by normal points of Fig. 1.

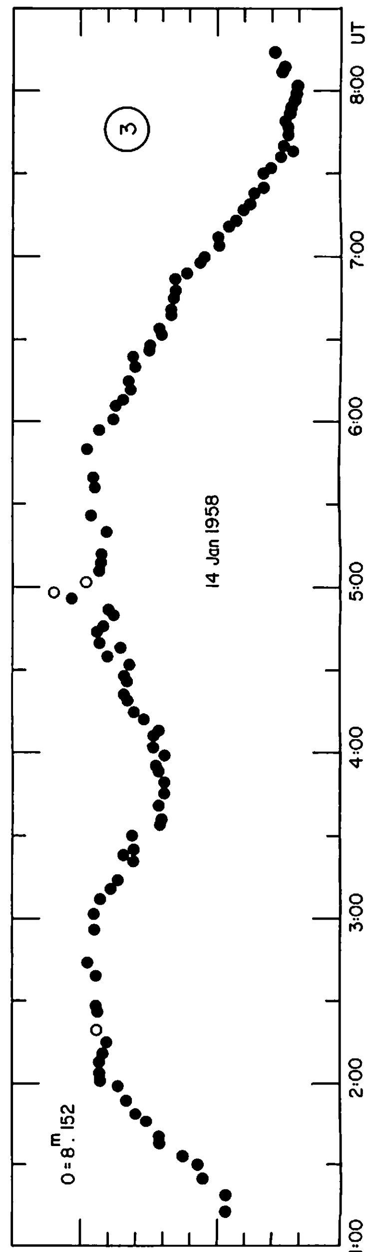

Fig. 3. Light-curve of 3 Juno.

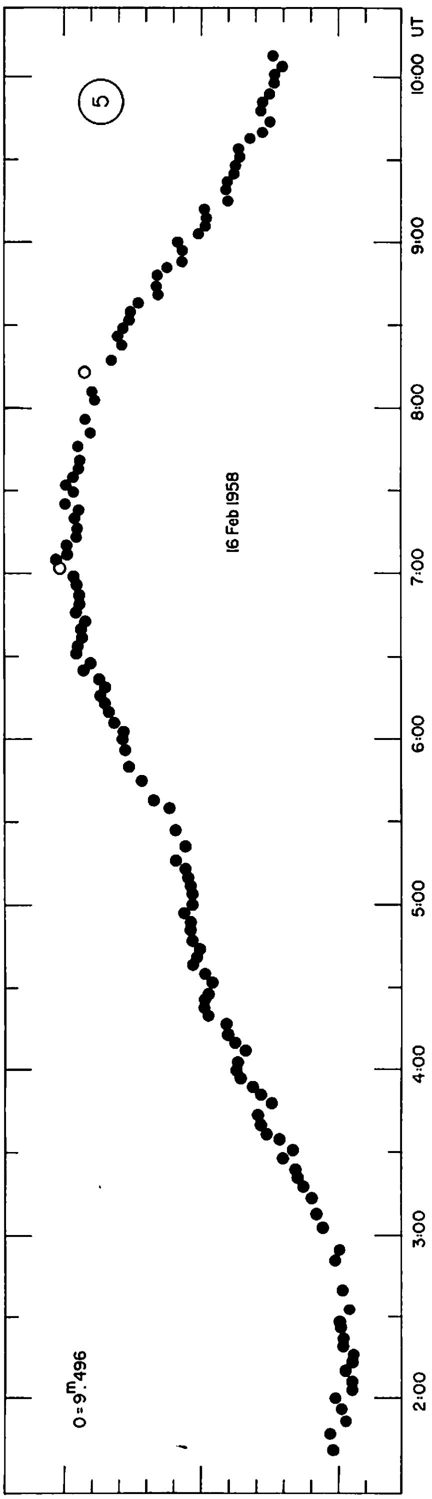

Fig. 4. Observations of 5 Astraea.

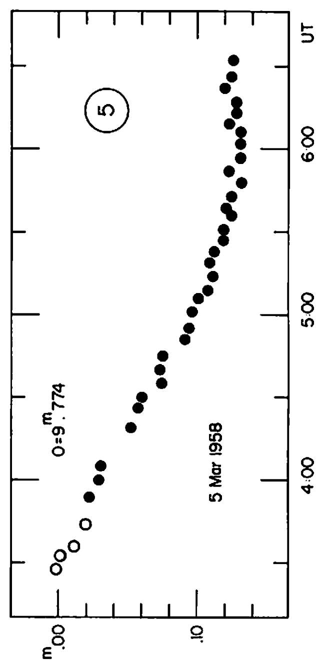

Fig. 5. Observations of 5 Astraea.

Iris, No. 7

Iris was observed in 1950 and 1952 (Paper I) and also in 1955/56 (Paper VII). The present observations were made on November 5, 1958, and are shown in Figure 6. It is noted that the apparent brightness was unusually great in 1958; this is due to being near perihelion of a rather strongly eccentric orbit.

The light-variation, that previously was as much as 0.29 mag., has almost completely disappeared. This apparently confirms the conclusion reached in Paper VII: "... the axis of rotation of the asteroid is considerably inclined toward the plane of the ecliptic ..." In fact, Iris is observed nearly pole-on near the present aspect.

The determination of the pole in Table 5 gives $\lambda_0 = 193° \pm 3°$(p.e.); the absolute magnitudes would have given $\lambda_0 = 240°$, with great uncertainty; we have therefore not included that determination. The amplitude appears to be greater ($A = 0.30$ mag.) near 283° than the one near 103° ($A = 0.22$ mag.). More observations are needed, in consecutive years, for the determination of the direction of rotation and of the sign and value of the latitude of the pole.

Metis, No. 9

Metis was observed in 1949 (Paper I) and in 1954 (Paper II). The present observations were made on February 15, 1958 (Fig. 7). As is seen in Table 5, the amplitude variation is large, which is

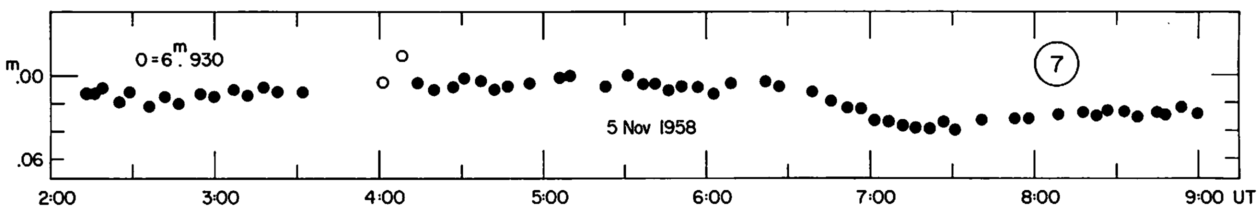

Fig. 6. Light-curve of 7 Iris.

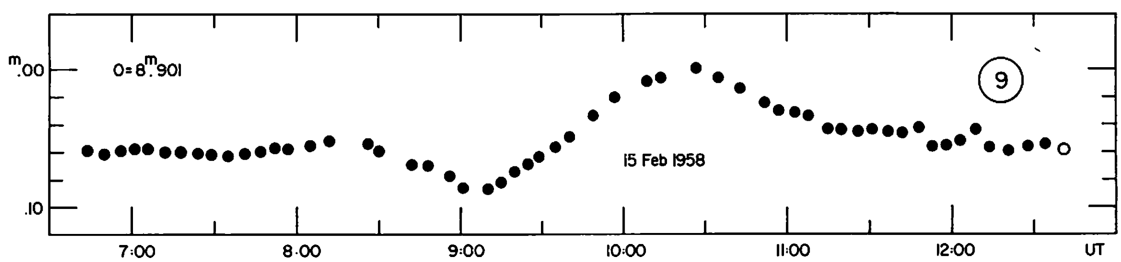

Fig. 7. Light-curve of 9 Metis.

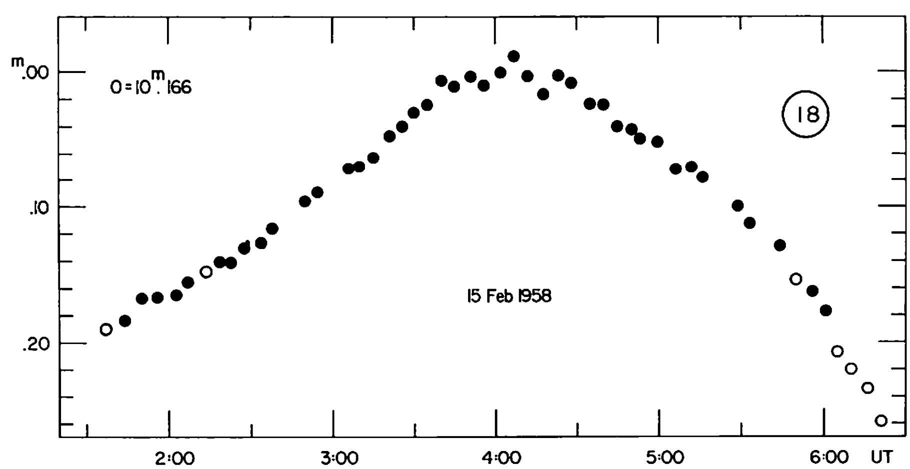

Fig. 8. Observations of 18 Melpomene.

again interpreted with large obliquity. With the analysis of Table 5 we find $\lambda_0 = 186° \pm 3°$ and $\beta_0 = 15° \pm 15°$. As for Iris, more observations are needed.

Melpomene, No. 18

Melpomene was observed, for the first time in this series, on February 15, 1958 (Fig. 8) and again on March 9 (Fig. 9). Short light-curves only could be obtained, as the asteroid set shortly after midnight. The asteroid moved close to a faint star at about 4:00 U.T. on March 9, but the light of this star was kept out of the diaphragm as much as possible, and the "hump" in the light-curve probably is real. Unless this "hump" is caused by aspect variation (the aspect changed by 8° between February 15 and March 9), we conclude that the maxima shown in Figures 8 and 9 are not the same. According to the usual corrections for distance, the maximum shown in Figure 8 should lie slightly above that of Figure 9 (the amplitude, then, is 0.35 mag.). The two curves then fit together such that the starting point of Figure 8, near 1:30 U.T., coincides with an extension point near 7:00 U.T. in Figure 9; the period is about 14 hours.

Massalia, No. 20

Massalia was observed extensively in 1955 (Paper V) at $\lambda = 181°$; the two amplitudes were about 0.20 mag. The present light-curve was obtained on January 25, 1958, and is shown in Figure

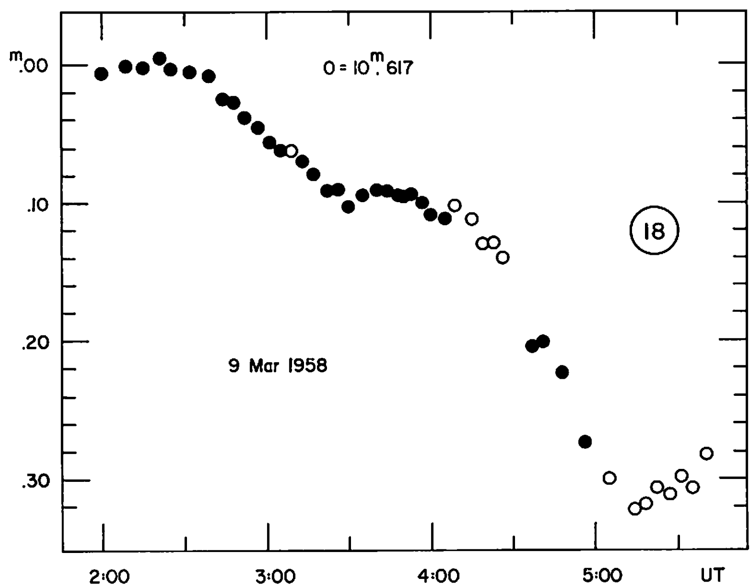

Fig. 9. Observations of 18 Melpomene.

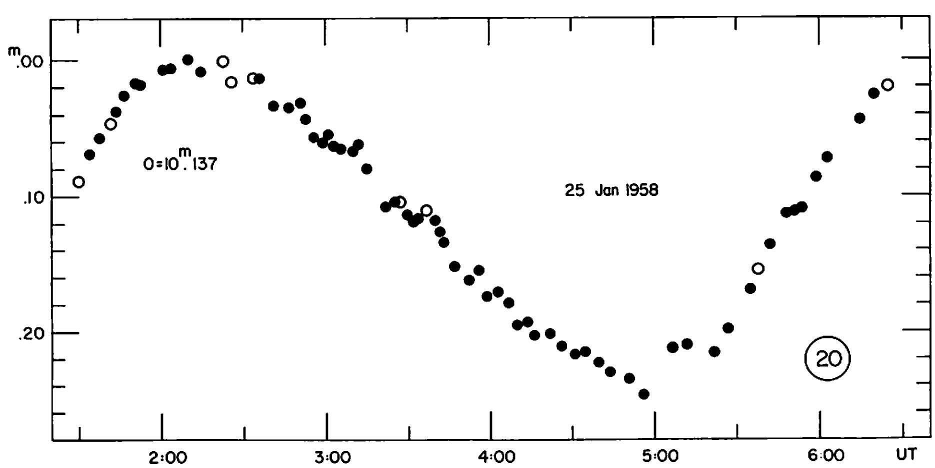

Fig. 10. Observations of 20 Massalia.

10. The aspect now is at $\lambda = 48°$, the amplitude is 0.24 mag. The amplitudes and the shape of the light-curve are rather the same in the two years. Either the aspect variation of Massalia is small, i.e., the rotational axis is nearly perpendicular to the ecliptic, or the two observations have aspects that are almost symmetric to the rotational axis. In the latter case, the pole is either at about 120° (300°) or near 30° (210°). For further analysis, observations near longitude 120° (300°) appear to be of crucial importance.

Kalliope, No. 22

The present observations of Kalliope, on February 24, 1958 (Fig. 11), are almost at the same aspect as that of Ahmad's observations in February, 1953 (Paper IV). The phase angle was 7°.4 for Ahmad's observation, and it is 6°.9 now, so that the phase difference also is small. We plotted our observations on Ahmad's scale and found close superposition. The only differences are for a part of the maximum, in Figure 11, near 7:40 U.T., which is 0.015 mag. lower than that in Paper IV, and for a

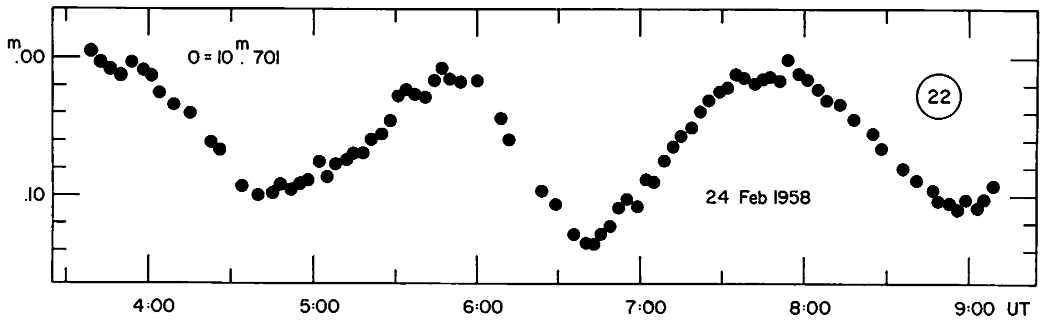

Fig. 11. Light-curve of 22 Kalliope.

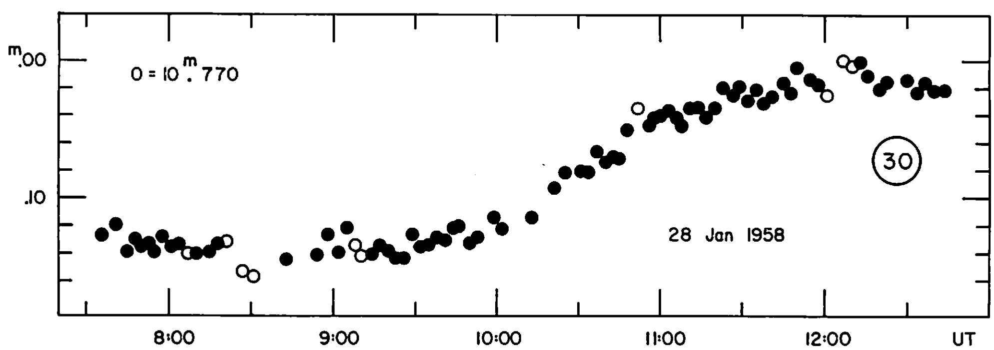

Fig. 12. Observations of 30 Urania.

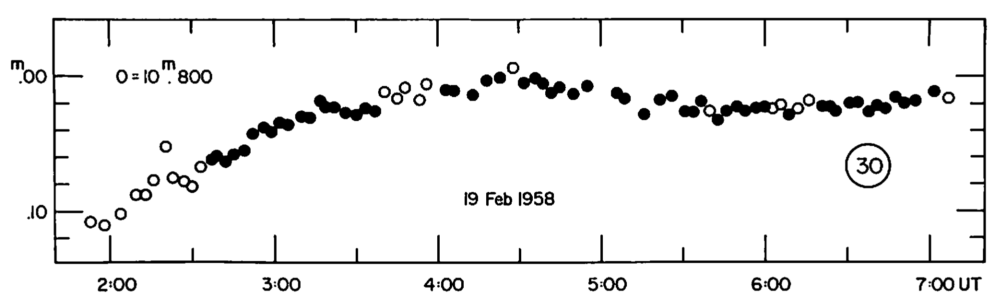

Fig. 13. Observations of 30 Urania.

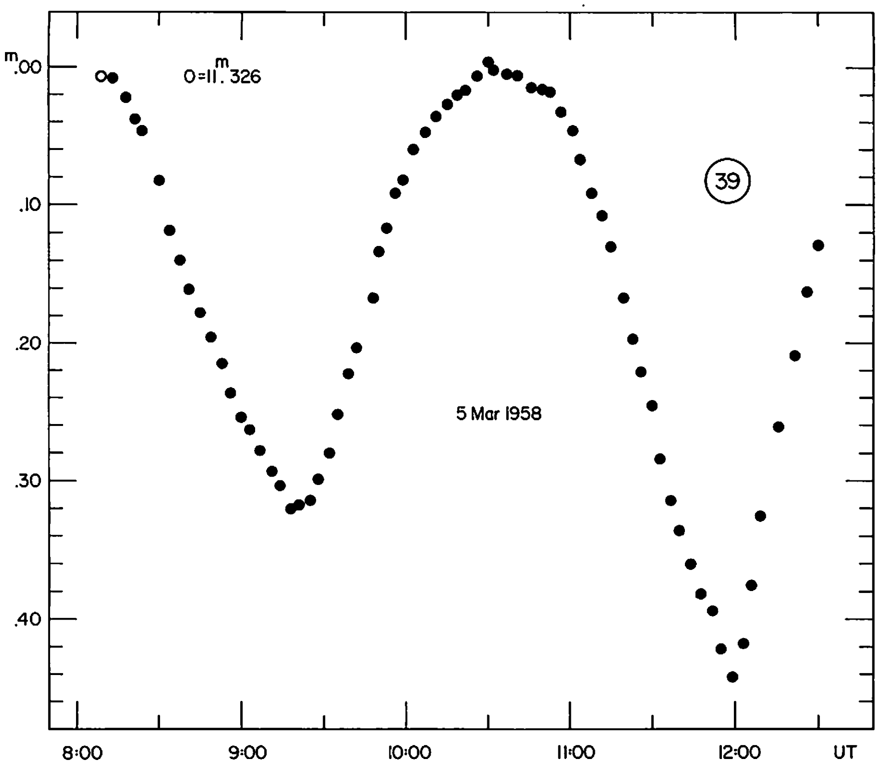

Fig. 14. Light-curve of 39 Laetitia.

part of the minimum near 5:00 U.T., which is 0.015 mag. higher than that in Paper IV. The night of February 24, 1958, was not very good, but the differences mentioned are probably real, because of the differential method used with close comparison stars. In any case, the general agreement of the two light-curves is close, after 5 years and after more than 10,000 revolutions. No determination of the orientation of the pole could, of course, be made in Table 5. The period is determined from the single light-curve of Figure 11 at $4^h04^m \pm 4^m$, which is compatible with Ahmad's determination of $4^h08^m.8$.

Urania, No. 30

Rigollet (1950) published a period of $13^h40^m.4$ for Urania. The first observations in this series were made on January 28, 1958 (Fig. 12), and Urania was also observed on February 19 (Fig. 13). There are two possibilities of fitting our two curves. First, the upward branches of the two figures are closely the same. A point at 11:00 U.T. on January 28 corresponds to one at 2:55 U.T. of February 19, and the amplitude is about 0.14 mag. The period would be $13^h40^m.1 \pm 0^m.15$, in good agreement with that determined by Rigollet. However, the phase factor between $3^\circ.7$ and $7^\circ.6$ phase would be only 0.002 mag/degree. The small phase factor is unlikely, but it may be a spurious value because the two observations are not on the same side of opposition (February 12).

The second possibility of fitting the curves is with the maximum of Figure 12 matching the flat part at the upper right in Figure 13. The shape of the composite light-curve would then perhaps be similar to the one found for 16 Psyche (Paper VII). A point at 9:39 U.T. of January 28 then coincides with one at 7:00 U.T. of February 19; the amplitude is greater than 0.22 mag.; and the phase factor is 0.031 mag/degree. The period closest to the one derived by Rigollet would be $13^h49^m.5$, which does not seem to be sufficiently in agreement with Rigollet's. Therefore, and because the phase observations were made on either side of opposition, we prefer the first solution.

Laetitia, No. 39

Laetitia is one of the most frequently observed asteroids, as is seen in Table 5. The present observations were made on March 5, 1958, and are shown in Figure 14. The longitude of the pole is well determined at $\lambda_0 = 130°$. The latitude of the pole is definitely small, but a determination can apparently be made only from observations near the longitude of the pole(s).

Harmonia, No. 40

A short run on Harmonia was reported in Paper I, the present observations were made on January 14 (Fig. 15) and January 29, 1958 (Fig. 16). Both nights had rather poor weather conditions, but fortunately the parts in between gaps overlap. Some of the January 14 observations were filled in, with crosses, in the curve of January 29. Even though the sky was of poor quality, the peculiar secondary maximum, such that Harmonia almost shows three maxima and three minima, is real. The interval between the two light-curves is $14^d20^h18^m \pm 1^m$; the approximate period derived from Figure 16 alone is $9^h06^m \pm 3^m$. The interval should therefore be divided by 39 cycles, which in turn gives an improved synodic period, $9^h08^m\!.15 \pm 0^m\!.04$ (8^h54^m for 40 cycles and 9^h23^m for 38 cycles appear to be ruled out). The phase factor between 6°.6 and 13°.5 is 0.045 ± 0.003 mag/degree. The greatest amplitude is 0.22 mag.

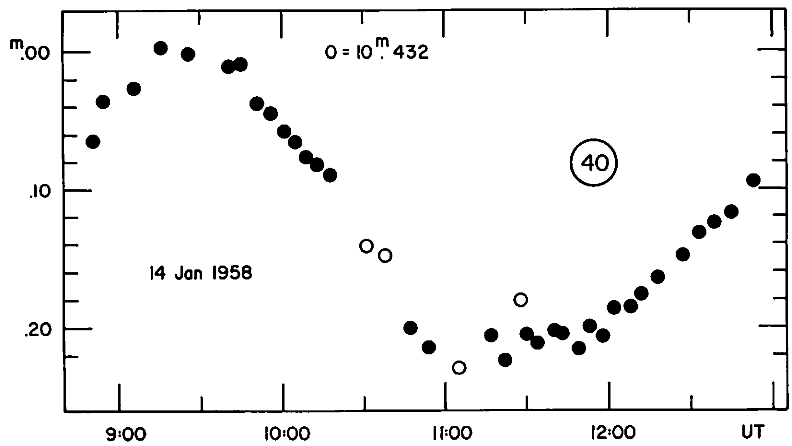

Fig. 15. Observations of 40 Harmonia.

Nysa, No. 44

Nysa was observed in 1949 (Paper III) and in 1954 (Paper II). The present light-curve was obtained on January 13, 1958, and is shown in Figure 17. The observations were in the crowded Milky Way; the asteroid passed two faint stars such that the run had to be interrupted. It is noted that the secondary maximum and the following minimum both are fainter by about 0.01 mag. than when they were first observed in Figure 17; it is not clear whether this is due to variability of the comparison star or perhaps to unnoticed faint stars within the diaphragm. The period, $6^h28^m \pm 2^m$, is in fair agreement with the determination in Paper II ($6^h25^m\!.2 \pm 0^m\!.1$). The greatest amplitude is 0.22 mag. This asteroid has large aspect variation. More observations, at longitudes outside the present range of 18°–99°, would be valuable to determine the pole orientation with precision. The preliminary analysis in Table 5 gives $\lambda_0 = 105°$.

Echo, No. 60

Echo was observed, for the first time in the series, on February 7, 1958 (Fig. 18). Very little variation is found, which may be due to being observed pole-on at this aspect ($\lambda = 117°$), or simply to the fact that the period is very long, or, of course, the asteroid may be nearly spherical. The period appears to be of the order of 30 hours.

Bamberga, No. 324

Bamberga also was observed for the first time in this series, on February 26, 1958, and the light-curve is shown in Figure 19. The night was of poor quality, and the run was stopped by clouds. The amplitude is about 0.07 mag.; the aspect has $\lambda = 161°$. The period may be of the order of 8 hours. Most of the scatter of the points must be due to poor seeing conditions. Incidentally, the "comparison star" listed in Table 3 is actually a narrow pair of stars.

Davida, No. 511

Davida was observed in 1952 and 1953 (Paper I). The present observations were made on January

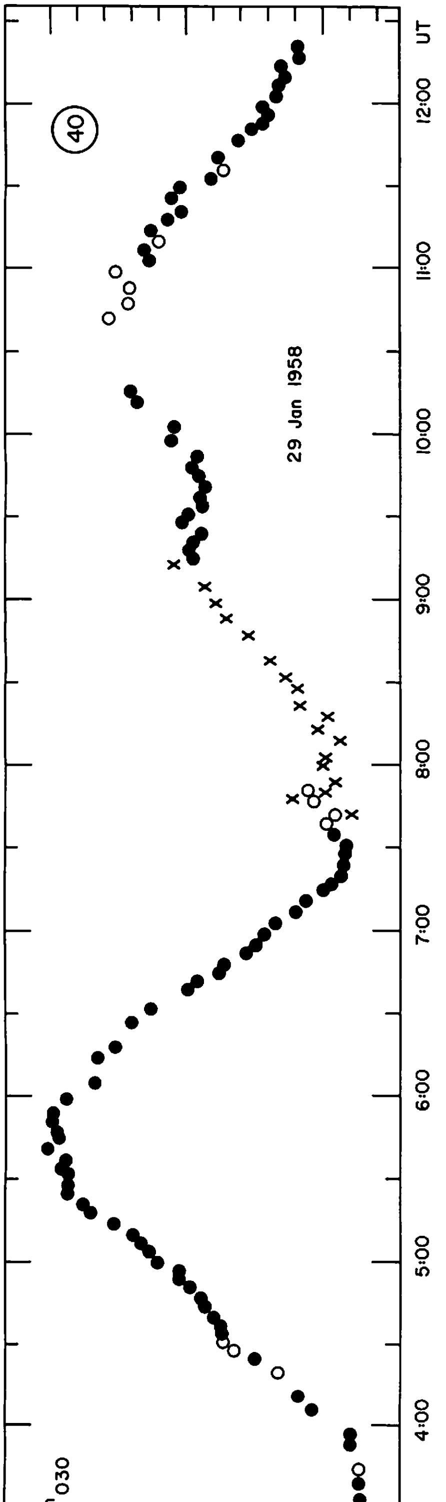

Fig. 16. Light-curve of 40 Harmonia. Crosses are for observations made on January 14, 1958.

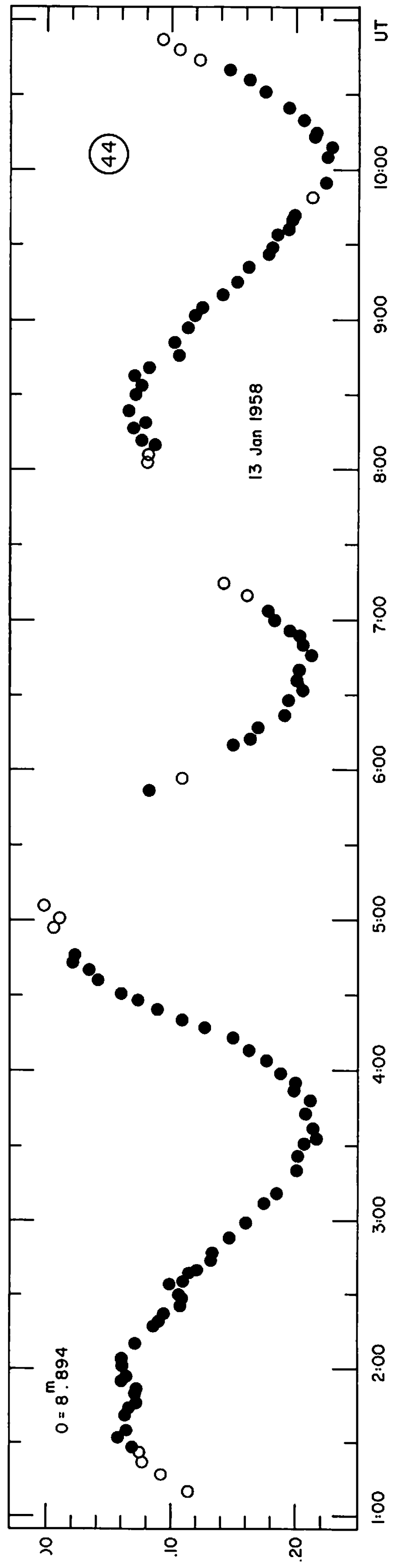

Fig. 17. Light-curve of 44 Nysa.

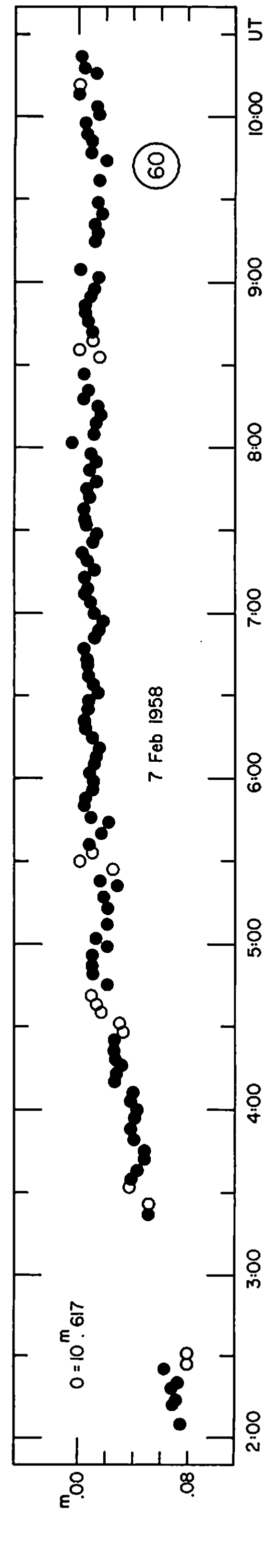

Fig. 18. Observations of 60 Echo.

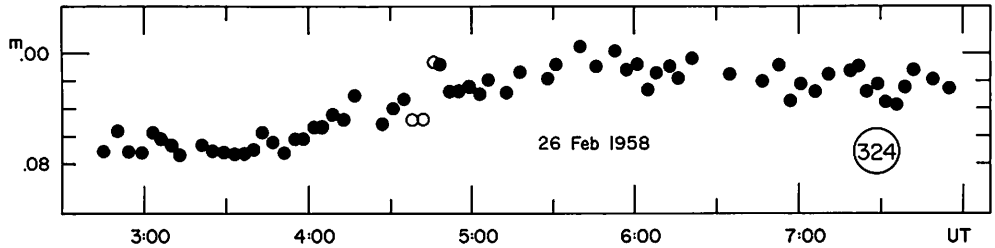

Fig. 19. Observations of 324 Bamberga.

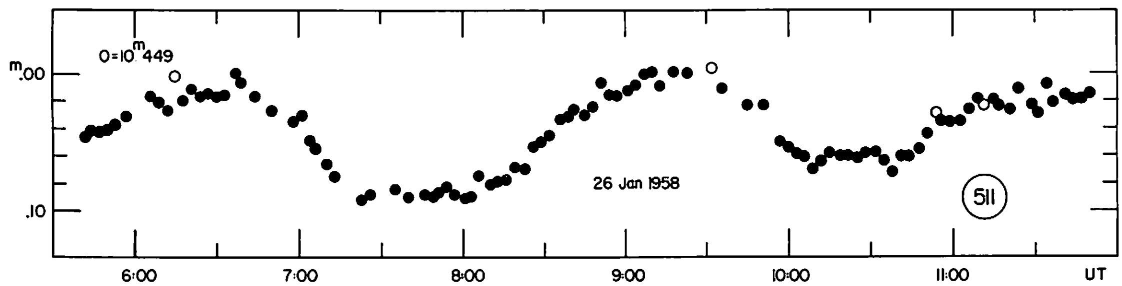

Fig. 20. Light-curve of 511 Davida.

26, 1958, and are shown in Figure 20. The determination of the pole is good, $\lambda_0 = 122°$. The period found from this one light-curve, $5^h10^m \pm 1^m$, is in good agreement with previously listed values.

5. *Distribution of the Poles*

The eight poles that have been derived thus far are listed in the last three columns of Table 5. All longitudes lie in one quadrant, between 104° and 194° (284° and 14° for the opposite poles), with none occurring between 14° and 104° or between 194° and 284° ecliptic longitude. Apparently, the asteroid poles show some alignment. This is also shown in Figure 21, where all light-curve amplitudes of this series have been plotted as a function of longitude. Actually plotted were only the amplitudes of full light-curves, and the largest amplitude was taken of each light-curve; asteroids 1 and 4 were omitted because of their often recurring small amplitudes. There are fewer points to the right of 200° because most of the observing runs were in the fall and winter. A considerable part of the scatter in Figure 21 is due to the fact that different asteroids have different shapes and therefore different maximum amplitudes. Even so, there is a marked trend with longitude in Figure 21. More asteroids than the eight of Table 5 appear to share the pole alignment: asteroid 97 showed little variation when observed near 12° longitude (Paper I), and the same holds for asteroids 10 ($\lambda = 117°$; Paper II), 60 ($\lambda = 117°$; Paper IX), and 324 ($\lambda = 161°$; Paper IX). This does not prove, of course, that these asteroids are non-spherical objects with strong aspect variation (viz., the discussion of asteroid 60 in Sec. 4). On the average, the asteroids have small amplitudes when observed near longitudes 150° (opposition in February) and 330° (August), and they have larger amplitudes when observed near longitudes 240° (May) and 60° (November). Only two cases, at present, appear contradictory; they are asteroid 14, which showed little variation near 71° longitude (Paper II), and asteroid 532 near $\lambda = 92°$ (Paper II). However, these observations are at only one epoch; further observations of asteroids 14 and 532 are needed. For illustration of the analysis of Table 5, the individual observations of asteroids 7 and 39 are marked in Figure 21. Asteroid 7 has a pole near 193°; asteroid 39 has it near 130° ecliptic longitude.

6. *Concluding Remarks*

Table 6 summarizes some of the results on the 33 asteroids observed to date. The colors will be discussed in Paper X; here listed is the average from all color observations in this series of papers. The

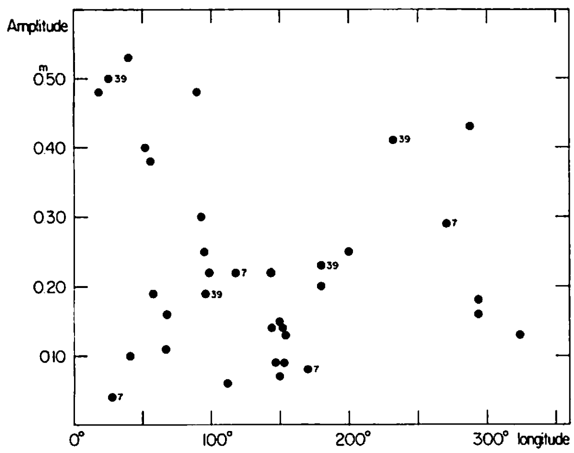

Fig. 21. Amplitudes of light-curves as a function of the ecliptic longitudes, at the time of observation, of the asteroids. The amplitudes of 7 Iris and 39 Laetitia are indicated.

greatest amplitude found for the asteroid is given under "Range," in the fifth column. The references mostly are numbers of the papers in the series; the actual references are at the end of this paper. Also referred to is the work by Stephenson (1951), Haupt (1958), Rigollet (1950), and Beyer (1953), while the "Survey" (Kuiper *et al.,* 1958) has some additional photoelectric colors in its Tables 9 and 10. The seventh column gives the number of hours of light-curves, published or about to be published in this series only. The total number of "light-curve" hours is 688. The eighth column contains the absolute photographic magnitude (Gehrels, 1958).

In future observations, the runs on known asteroids should be slightly longer than the period rather than, for the sake of economy, slightly shorter. It may be possible to reduce the scatter of points on the light-curves even more by using a precision timer (Weitbrecht, 1957). Since we list the comparison stars, in Table 4, it may be possible to use them again. For newly observed asteroids, the ideal arrangement of the observations appears to be with two light-curves in consecutive nights and a third some three weeks later.

TABLE 6

MISCELLANEOUS DATA ON ASTEROIDS

Ast. No.	Period	B−V (mag.)	U−B (mag.)	Range (mag.)	References	Hours	g(P₀) (mag.)
1.......	$9^{h}04^{m}.7$	+0.715	+0.436	0.04	II, IV, IX	29	4.00
2.......	11?	.652	.270	0.13	Survey, II, X	16	5.06
3.......	7 12.6	.827	.428	0.16	Survey, II, IX	20	6.33
4.......	5 20.5	.778	.478	0.13	Steph., Haupt, I, XI	46	4.22
5.......	18?	.834	.382	0.21	IX	12	7.90
6.......	7 16.5	.818	.402	0.16	IV, XI	60	6.60
7.......	7 08.1	.851	.461	0.16	I, VII, IX	37	6.74
8.......	13 36	.880	.480	0.04	IV, VII	24	7.38
9.......	5 04.6	.847	.496	0.26	I, II, IX	33	7.17
10.......	18?	.706	.400	0.10	Survey, II	15	6.45
11.......	10 40	.809	.403	0.09	VII, X	15	7.68
14.......	11 28.2	.815	.395	0.04	II, Rigollet	11	7.31
15.......	6 05.0	.824	.438	0.53	I, VII	29	6.19
16.......	4 18.2	.710	.250	0.12	VII	11	6.78
17.......	12 16.5	.845	.416	0.36	I, VII	32	8.59
18.......	14 12	.850	.398	0.35	Survey, IX	9	7.69
20.......	8 05.9	.830	.460	0.25	V, IX	39	7.38
22.......	4 08.8	.713	.279	0.14	IV, IX	12	7.37
25.......	9 56.7	.934	.520	0.18	I, VII	15	8.98
30.......	13 40.1	.877	.450	0.23:	Rigollet, Survey, IX	11	8.68
39.......	5 08.3	.893	.513	0.53	I, II, VII, IX	33	7.31
40.......	9 08.2	.850	.440	0.22	I, II, IX	12	8.35
44.......	6 25.2	.700	.247	0.48	II, III, IX	39	7.91
60.......	Long	.852	.455	0.07	IX	8	9.95
61.......	11 27	.850	.433	0.31	X	16	8.65
97.......	Long	....	....	0.07	I	8	8.57
110.......	....	.707	.309	0.19	XI	46	8.36
321.......	2 52.2	.82	.45	0.40	VII	9	11.26
324.......	8?	....	....	0.07	IX	5	8.11
354.......	4 16	.947	.563	0.15	II	9	7.47
433.......	5 16.2	.96	.56	1.50	Beyer, II	......	12.31
511.......	5 10	.713	.366	0.25	I, IX	20	7.02
532.......	17?	+0.83	+0.44	0.08	II	7	7.88

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