

Minor Planets. III. Lightcurves of a Trojan Asteroid

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Lightcurves for 624 Hektor were obtained in 1957 with the Radcliffe 188-cm, in 1965 with the Kitt Peak 213-cm, in 1967 with the Catalina 154-cm, and in 1968 with the Cerro Tololo 152-cm reflectors. The amplitudes of the lightcurves were respectively 0.8, 0.1, 0.4, and 1.1 mag. Hektor, therefore, is strongly elongated and its rotational axis is close to the plane of the ecliptic. The shape probably is that of a cylinder with rounded ends, the total length being about 110 km and the diameter 40 km. The reflectivity and the *UBV* colors are uniform over the surface. The sense of rotation is direct and the sidereal period is $6^h55^m21^s.115$ ($\pm 0^m004$ p.e.). The ecliptic longitude and latitude of the North Pole are (for 1950) 324° ($\pm 3^\circ$) and $+10^\circ$ ($\pm 2^\circ$).

THE Trojan asteroids, at about 4 a.u. from us during opposition, are fainter than the 14th magnitude, which probably is the reason why no photometry has as yet been published. Some reconnaissance of these objects is obviously important.

This paper is limited to the lightcurves of 624 Hektor, with one set of observations in 1968 for color differences over the surface. Little time was spent for *UBV* calibrations and the phase effects were not studied.

I. OBSERVATIONS

In 1957 the Radcliffe 188-cm reflector near Pretoria in South Africa was used; in 1960 an attempt was made at the McDonald 208-cm reflector, but it failed due to poor weather conditions; in 1965 the 213-cm reflector of the Kitt Peak National Observatory was used; in 1967 the 154-cm Catalina reflector of the Lunar and Planetary Laboratory, and in 1968 the 152-cm reflector of the Cerro Tololo Inter-American Observatory in Chile were used. We had standard *UBV* photometers and RCA 1P21 photomultipliers, cooled with dry ice. The observations were made by Gehrels and the reductions and analysis by Dunlap. The methods of lightcurves and reductions are described in Paper I (Gehrels 1967a).

Finding plates had to be taken immediately before the photoelectric observing. In South Africa they were obtained with the Franklin Adams Camera at Hartbeespoort and blinked at the Union (now Republic) Observatory in Johannesburg. At Kitt Peak they were taken with the 213-cm reflector in the early evening of

4 February 1965. In 1967, Dr. E. Roemer and Dr. G. Van Biesbroeck did the photographic work with the 154-cm reflector. At Cerro Tololo the Michigan Curtiss Schmidt was used.

Table I summarizes the observations of 624 Hektor. Preliminary *UBV* values in the *E* regions were kindly supplied by Dr. A. W. J. Cousins, and the *B*, *V* calibration of the comparison stars in 1967 was made by Dr. W. Wiśniewski. "Mean *V*" is determined by planimetry such that equal areas are enclosed by the lightcurve and by the line of "mean *V*" over a full cycle; half-cycles had to be used in the 1957 lightcurves. The "Range" is the largest amplitude of the observed lightcurve. "Mean *V*" is corrected to absolute magnitude *V*(1,0) as usual (Gehrels 1967b). "*V* of zero" is the magnitude of the primary maximum of the lightcurve and *g*(*V*_{zero}) is its absolute magnitude (see Sec. IV). Probable errors are included in the tables wherever possible.

Table II gives the aspect data for Hektor for the epochs of minimum in Table IV.

Table III gives various data for the comparison stars and the quality of the night. Under "Scatter" the average deviation from a smooth curve is given for a magnitude-time plot of the comparison star. On 1 May 1968 an unexplained discontinuity occurred, apparently in the tube response, at about 5:00 U. T.

Figures 1-8 show the various lightcurves for Hektor. The ordinates are in magnitudes and the abscissae in U. T. uncorrected for light-time. Each point is the average of four integrations (two in 1968) lasting about

TABLE I. Summary of observations of Hektor.

Date U. T.	Mean <i>V</i> (mag)	<i>B</i> - <i>V</i> (mag)	<i>U</i> - <i>B</i> (mag)	Range (mag)	<i>V</i> (1,0) (mag)	<i>V</i> of zero (mag)	<i>g</i> (<i>V</i> zero) (mag)	Figure
57.04.28	...	+0.81	+0.06:	...	...	...	...	1
57.05.05	14.70	0.81	0.20	0.800	7.92	14.41	7.63	2
57.05.31	14.59	0.75	0.43:	0.775	7.95	14.29	7.65	3
57.06.01	...	0.71:	0.29:	0.70:	...	...	...	4
65.02.04	14.281	0.760	0.25	0.113	7.70	14.20	7.62	5
67.03.07	14.454	0.752	...	0.398	7.81	14.26	7.63	6
68.04.29	...	...	...	1.088	...	...	...	7
68.05.01	14.640	+0.784	+0.23	1.055	8.05	14.28	7.68	8
	± 0.008	± 0.006	± 0.01	± 0.002	± 0.01	± 0.01	± 0.01	

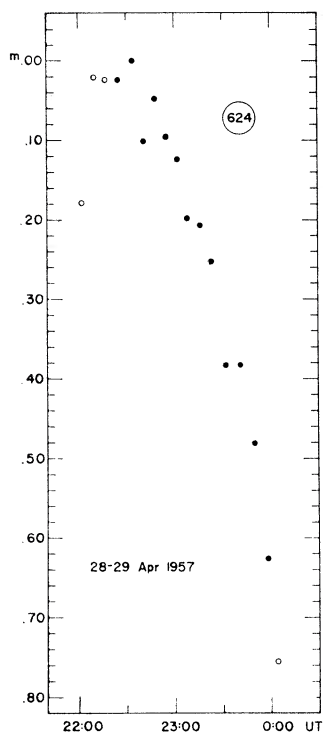


FIG. 1. Radcliffe observations.

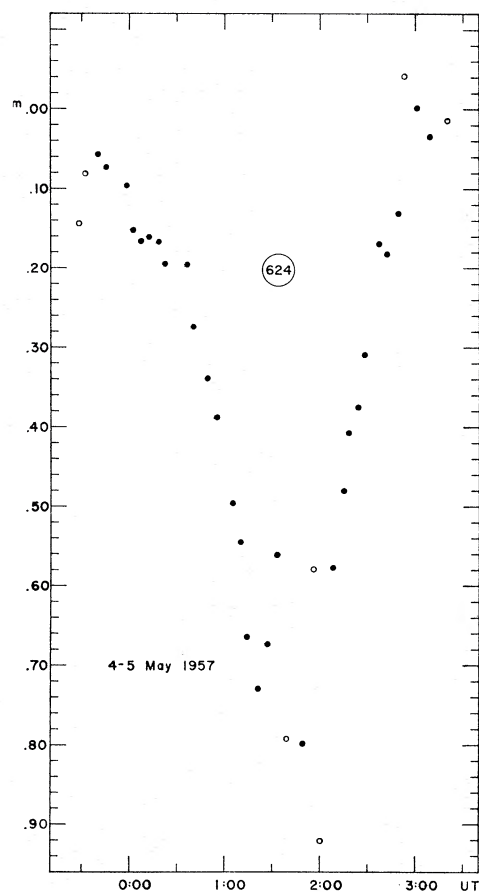


FIG. 2. Radcliffe observations.

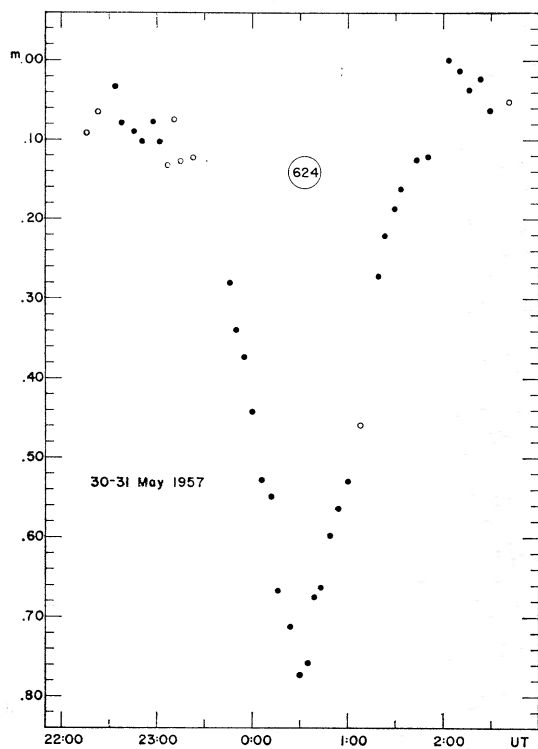


FIG. 3. Radcliffe observations.

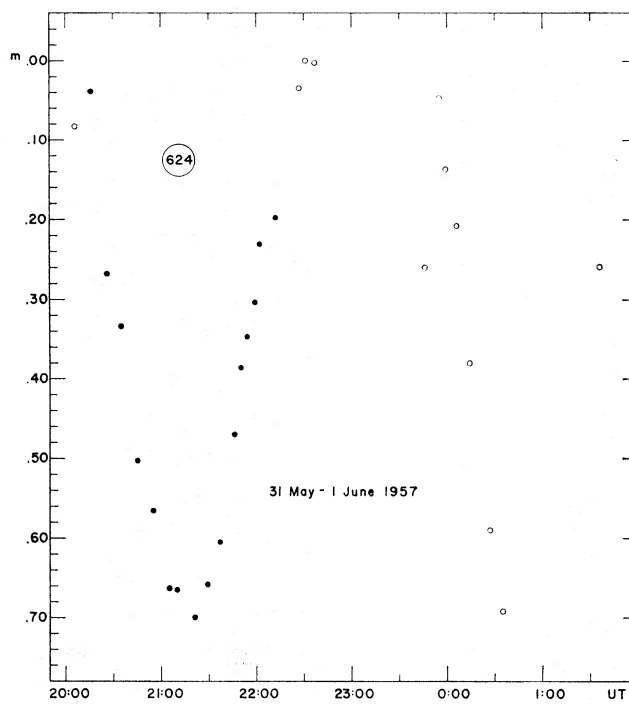


FIG. 4. Radcliffe observations.

TABLE II. Aspect data for Hektor.

Date U. T.	Phase angle	Distance from sun (a.u.)	Distance from Earth (a.u.)	Light- time	R. A.	1950 Dec.	Long.	Ecliptic 1950 Lat.
57.05.05	-6°22 ±0.03	5.091 ±0.001	4.216 ±0.001	0 ^h 02435 ±0.00001	16 ^h 13 ^m 5 ±0.1	-43°43' ±01	249°5 ±0.1	-22°1 ±0.1
57.05.31	+4.43	5.097	4.148	0.02396	15 55.9	-43 33	246.1	-22.6
57.06.01	+4.44	5.097	4.147	0.02395	15 55.1	-43 28	246.0	-22.6
65.02.04	+4.10	5.030	4.101	0.02368	8 21.1	+34 34	119.4	+14.7
67.03.07	-5.34	5.007	4.109	0.02373	12 31.9	-14 11	193.0	-9.9
68.04.29	+4.18	5.061	4.112	0.02375	14 26.5	-35 55	226.2	-20.2
68.05.01	+4.08	5.061	4.107	0.02372	14 25.2	-35 52	225.9	-20.3

TABLE III. Comparison stars and quality of nights.

Date U. T.	R. A.	1950 Dec.	V (mag)	B-V (mag)	Scatter (mag)	Remarks
57.04.28	16 ^h 17 ^m 0	-43°32'	12.22	1.40	±0.015	Stopped by clouds
57.05.05	16 13.8	-43 40	11.88	0.80	±0.008	Seeing poor
57.05.31	15 55.4	-43 34	12.09	0.72	±0.018	Clouds at start
57.06.01					±0.025	Cloudy
65.02.04	8 21.0	+34 34	14.126	0.498	±0.008	a
67.03.07	{ 12 31.9 12 31.7	{ -14 10 -14 11	{ 12.977 13.719	{ 0.633 0.590	±0.009	Cirrus?
68.04.29	14 26.6	-35 56	...	...	±0.009	
68.05.01	14 25.3	-35 51	12.776	1.622	±0.004	
	±0.2	±3	±0.008	±0.006		

• Trojan passed a star about 5^h U. T.; clouds at end of night.

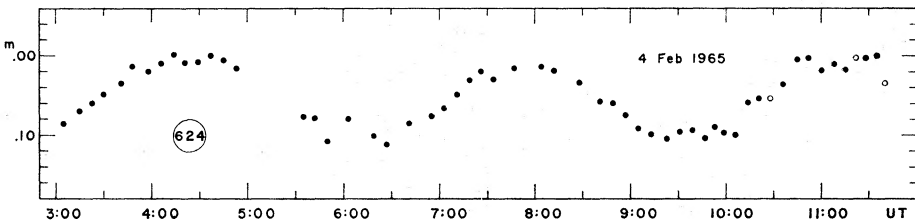


FIG. 5. Kitt Peak observations.

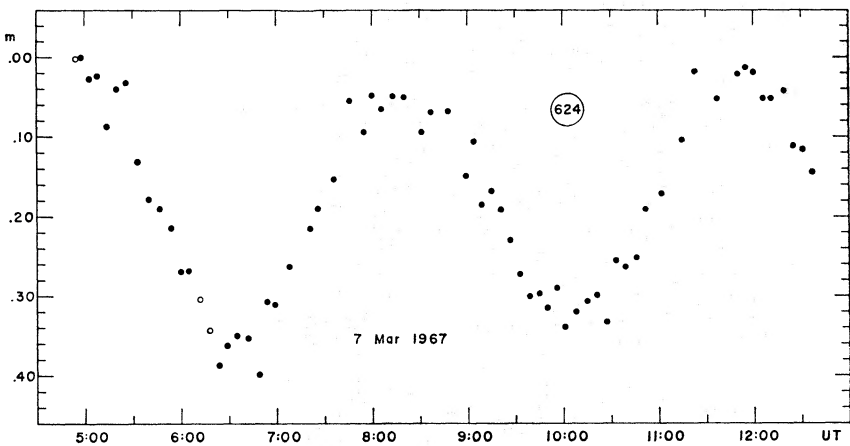


FIG. 6. Catalina observations.

25 seconds each (40 secs in 1965). Open circles are used when the probable error is larger than about 3 times the nightly average, or when successive integrations differ by more than about ±0.1 mag.

II. THE ROTATION OF HEKTOR

Table IV lists the epochs of minimum light (secondary minimum), their Julian Day numbers corrected for light-time and to Ephemeris Time, the interval and

number of cycles between adjacent epochs, and the synodic periods for each interval. The entries in Table IV were obtained in the following manner.

By careful inspection of the complete lightcurves it can be seen that the primary (deepest) minimum follows the primary (highest) maximum in time. It is then seen that every one of the figures has at least the secondary minimum (except April 1957), and the epoch of it is listed in Table IV. The 1968 lightcurves first give the approximate synodic period of $0^d2884 \pm 0.0002$. The remaining secondary minimum epochs and intervals in Table IV were obtained by superposing each lightcurve in turn on the 1968 lightcurves, keeping the maxima at about the same level (Sec. IV) and looking for the best repetition of distinguishable "humps" occurring on each lightcurve (due to the change in amplitude, exact superposition is not possible). With the above synodic period 0^d2884 , the number of cycles (90) was found for the next longest interval and its synodic period is 0^d28839 . The other periods in Table IV were found similarly. The probable errors are derived from the precision of determining the epochs; the systematic effects of aspect changes still have to be taken into account.

Figure 9 shows how the apparent number of cycles is changed as a function of longitude for four possible orientations of the pole (polar longitude assumed to be 90°). For 90° latitude of the pole, the number of cycles is steadily changed by an amount proportional to the longitude, from 0 to 0.5 cycles over 180° . On the other hand, for 0° latitude of the pole the 0.5 cycle change occurs at the longitude of the pole.

Figure 10 shows a plot of lightcurve amplitude as a function of orbital longitude (each filled circle was also plotted at $\Delta\lambda = \pm 180^\circ$). Since all observations were made at about the same phase angle, the variation is due to a change in aspect only. The variation is explained by assuming that Hektor is elongated and that the rotational axis is strongly inclined toward the ecliptic. The plot was folded along several longitudes near 140° until the superposed points lay on the smoothest curve (shown in Fig. 10). The additional locations of observed amplitudes are indicated with open circles. Minimum

TABLE V. Trials of various values of synodic period and sense of rotation.

Sense of rot.; best P_{sid}	N	Observed (see Table IV)		Computed ΔN (see Fig. 9)	
		P_{syn}	ΔN	for lat. 20°	for lat. 10°
Direct $0^d288439$	90	0^d28839	-0.015	-0.005	-0.002
	1459	0.288444	+0.025	+0.035	+0.020
	2638	0.288484	+0.410	+0.343	+0.405
Retrograde 0.288449	90	0.28839	-0.018	+0.005	+0.002
	1459	0.288444	-0.025	-0.035	-0.020
	2639	0.288374	-0.690	-0.343	-0.405

amplitude occurs near 141° longitude—thus the pole is near this position (or near 321°). The symmetry imposed by this folding technique is not strictly accurate for an object not on the ecliptic; 141° orbital longitude corresponds to about 142° ecliptic longitude.

Table V gives an example of the combination trials of synodic and sidereal periods, and the 141° longitude of the pole, in order to find the sense of rotation of Hektor. Since

$$\Delta JD(c)/N = P_{syn} \quad (1)$$

and

$$\Delta JD(c)/N \pm \Delta N = P_{sid}, \quad (2)$$

$$\Delta N = \pm N(P_{syn} - P_{sid})/P_{sid}. \quad (3)$$

The interval $\Delta JD(c)$ and the number of whole cycles N are taken from Table IV, while ΔN is the apparent cycle change as shown in Fig. 9. For intervals of increasing (decreasing) longitude, ΔN is positive (negative) for direct rotation and negative (positive) for retrograde. Several values of P_{sid} were tried for Table V and the ones giving the closest agreement of "observed" and computed (with Fig. 9) values of ΔN are tabulated. A consistent pattern emerges if the sidereal period is about $0^d288439$ and the motion is *direct*. A retrograde solution is not consistent with the values of N in Table IV and the ΔN values cannot be made in agreement with the aspect of the observations (other values of the latitude of the pole were also tried); translating the error in ΔN to the interval produces an error of about 150 times the probable error of the determination.

As a further check on the proper identification of epochs, the interval from 57.05.31 to 68.05.01 (two observations at nearly the same aspect) was used with various trial values of N to compute a series of possible sidereal periods: (a) for the epochs of Table IV, and (b) assuming a half-cycle error in epoch identification on the 68.05.01 lightcurve. These periods were then used with the time intervals of the shorter intervals (67.02.04–68.05.01 and 65.03.07–67.02.04) to compute $N \pm \Delta N$: (a) for the epochs of Table IV, and (b) with a half-cycle error in epoch identification in 65.03.07 and 68.05.01. (Earlier analysis had shown that if a half-cycle error was made, it had to occur in both 1965 and 1968 to suggest a retrograde solution.) For hypothesis (a), the results of the previous analysis are confirmed, with no

TABLE IV. Epochs, intervals, and synodic periods.

Date U. T.	Min epoch U. T.	JD(c) 2430000+	Interval $\Delta JD(c)$	Number of cycles	P_{syn}
68.04.29	5h50m ± 2	9975d7197 ± 0.0010			
			2^d019 ± 0.002	7	0^d2884 ± 0.0002
68.05.01	6 18	9977.7392	420.840	1459	0.288444 ± 0.000001
67.03.07	10 08	9556.8989	761.021	2638	0.288484 ± 0.000001
65.02.04	9 37	8795.8774	...	...	...
57.05.31	0 32	5989.4986	25.955	90	0.28839 ± 0.00002
57.05.05	1 37	5963.5434			

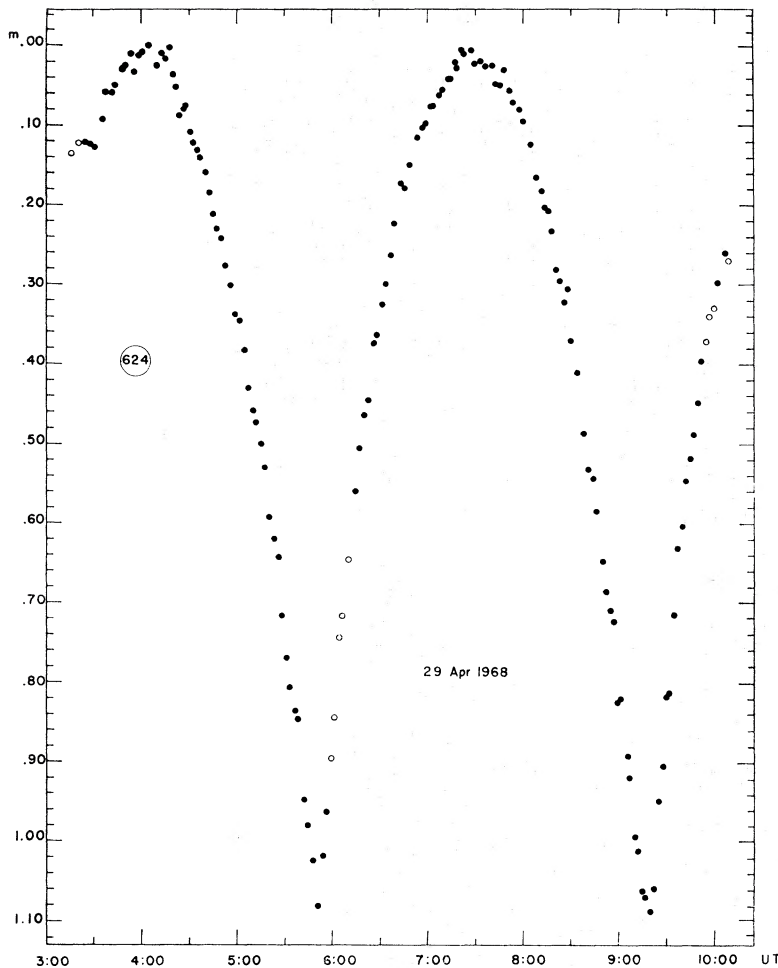


FIG. 7. Cerro Tololo observations.

retrograde solution suggested. For (b), no direct solution is seen, but two tentative retrograde solutions appear. First, with $P_{\text{sid}} = 0^{\text{d}}288366$, $(\Delta N)_1 = 0.11$ for 67–68 and $(\Delta N)_2 = 0.42$ for 65–67. Assuming the pole is near 140° or 320° ecliptic longitude, $(\Delta N)_1$ requires 90° latitude of the pole, whereas $(\Delta N)_2$ requires 10° latitude; this inconsistency rules out $0^{\text{d}}288366$. Second, if $P_{\text{sid}} = 0^{\text{d}}288345$, $(\Delta N)_1 = 0$ and $(\Delta N)_2 = 0.23$, both of which require a 90° latitude of the pole, which is inconsistent with the interpretation of Fig. 10. Thus hypothesis (b) is rejected.

For direct rotation then, and using the method of “photometric astrometry” developed in Paper I, the relation

$$\Delta \text{JD}(c) = \left[N + \frac{L' - L}{360} \right] P_{\text{sid}}, \quad (4)$$

where L and L' are relative longitudes on the planet, was applied to three long intervals in order to find a unique solution for the sidereal period and the ecliptic coordinates of the North Pole of Hektor. Table VI defines the epochs, intervals, and number of cycles used

for this determination. The intervals were selected for pairs of observations at nearly the same phase, and the phase correction was assumed negligible. The apparent cycle change $(L' - L)/360$ was obtained with a mechanical coordinate converter (Van Biesbroeck and Gehrels 1967).

Table VII contains some of our trials for direct rotation and for various latitudes and longitudes of the pole. The sixth column gives the weighted mean period for the three intervals, with weighting by the reciprocal of the square of the probable error of each period. The last column gives the weighted mean of the residuals, $|\bar{\Delta}|$. A minimum $|\bar{\Delta}|$ occurs for $\lambda_0 = 330^\circ$, $\beta_0 = 10^\circ$, and near 165° , 15° . The former solution is in good agreement with our interpretation of Fig. 10, while the latter is not.

TABLE VI. A second approximation to the sidereal period of rotation of Hektor.

Interval	Dates	$\Delta \text{JD}(c)$	N	P_{sid}
A	57.05.31–65.02.04	2806.43788	9729	$0^{\text{d}}288438$
B	57.05.05–67.03.07	3593.3555	12457	$0^{\text{d}}288438$
C	57.05.31–68.05.01	3988.2405	13826	0.288439

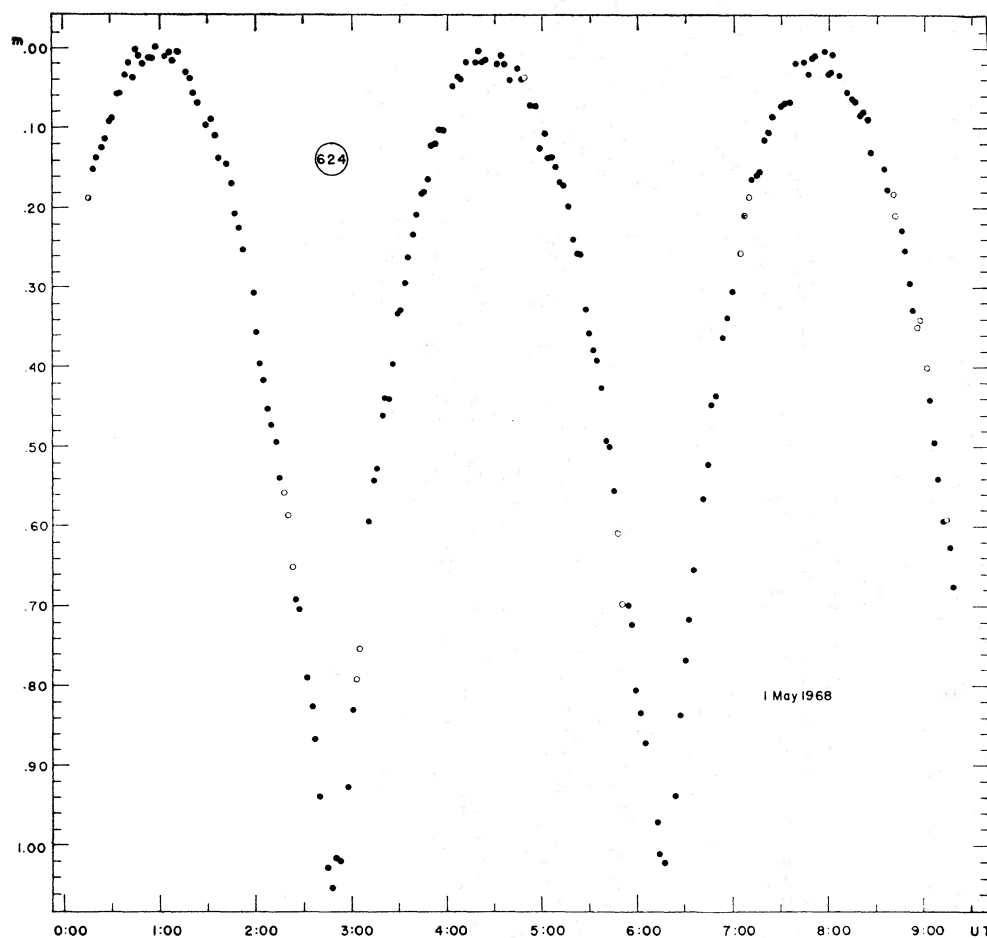


FIG. 8. Cerro Tololo observations.

For an independent determination of β_0 and λ_0 , Table VIII gives the latitudes B on Hektor computed with

$$\sin B = \sin \beta_0 \sin(-\beta) + \cos(-\beta) \cos(\beta_0) \times \cos(180^\circ + \lambda - \lambda_0). \quad (5)$$

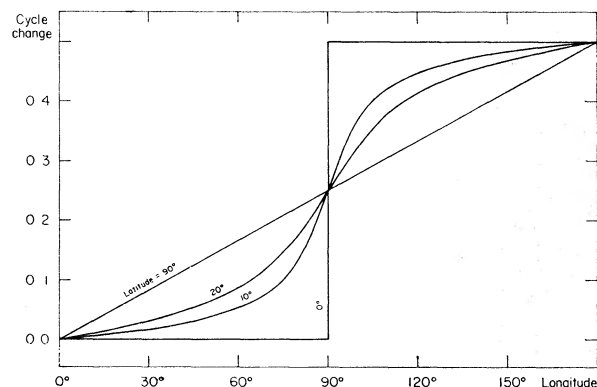


FIG. 9. The apparent change in cycle of asteroid rotation at various longitudes, plotted for four values of the latitude of the pole (90° longitude of pole).

The last column gives $\bar{d}$, the average of the differences between these and the latitudes computed with the observed amplitudes and the model of expression (11), below. The smallest value of $\bar{d}$ is seen near $\lambda_0 = 317^\circ$,

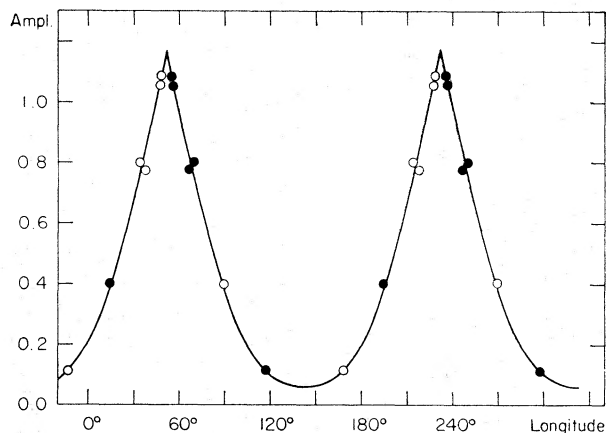


FIG. 10. The lightcurve amplitudes of Hektor plotted as a function of ecliptic longitude: with filled circles they are as observed ($\pm 180^\circ$), and with open circles after curve fitting.

TABLE VII. Period^a determinations for various latitudes and longitudes of the pole.

Lat. β_0	Long. λ_0	For the intervals of Table VI:			$\bar{P}$	$\bar{\Delta}$
		A	B	C		
5°	315	800	873	891	863	30
	320	859	865	887	873	12
	325	902	857	883	878	15
10°	325	858	892	892	884	12
	330	891	887	888	888	1
	335	919	885	884	892	11
15°	330	857	925	896	897	20
	335	883	926	894	903	17
	340	904	932	891	909	17
	345	928	939	890	916	22
15°	160	870	845	883	866	15
	165	866	870	887	876	9
	170	861	900	893	888	13
20°	155	815	857	887	860	23
	160	822	877	890	870	22
	165	822	901	895	880	27
25°	150	748	872	893	852	48
	155	767	887	897	863	45
	160	775	906	900	873	46

^a Only the last three digits are listed; 800 is 0^d28843800.

$\beta_0 = 10^\circ$, or 151° , 25° . Thus the closest agreement between Tables VII and VIII is for $317^\circ < \lambda_0 < 330^\circ$, and $\beta_0 = 10^\circ$. Changing the model dimensions within the limits imposed by Fig. 10 (see Sec. IV) does not significantly change the theoretical latitudes in Table VIII. The "photometric astrometry" of Table VII is model independent, but the difference between $\lambda_0 = 317^\circ$ and 330° may perhaps be attributed in part to the omission of a phase correction in Eq. (4). Also, Table VII reveals the strong dependence of the solution on interval A, while it is noted that B and C converge nicely near $\lambda_0 = 325^\circ$, $\beta_0 = 10^\circ$. Further observations near the polar aspect (in the Fall of 1970 and 1971) may improve the resolution of the longitude of the pole.

The solution suggested in Table VII at $\lambda_0 = 165^\circ$, $\beta_0 = 15^\circ$ is rejected for three reasons: the residual in

TABLE VIII. Latitudes on Hektor, for various combinations of latitude and longitude of the pole.

β_0	λ_0	68.05.01	57.05.31	57.05.05	67.03.07	65.02.04	$\bar{\alpha}$
5°	318	3.7	14.6	17.8	35.3	63.0	2.5
	319	4.6	13.7	16.9	36.3	62.3	2.2
	320	5.6	12.8	16.0	37.3	61.6	2.4
10°	316	3.5	14.2	17.4	33.9	60.3	1.6
	317	4.5	13.3	16.5	34.9	59.8	1.4
	318	5.4	12.5	15.6	35.9	59.2	1.6
10°	330	16.6	1.7	4.9	47.7	50.9	11.0
15°	313	4.2	12.1	15.1	31.4	52.8	2.4
	314	5.1	11.2	14.3	32.4	52.4	2.3
	315	6.0	10.4	13.4	33.3	52.1	2.4
25°	150	3.5	14.6	17.3	35.5	59.5	1.7
	151	4.3	13.7	16.4	36.2	58.6	1.5
	152	5.1	12.8	15.6	37.0	57.8	1.8
15°	165	20.5	2.2	0.7	52.7	46.0	14.9

TABLE IX. Average colors at maxima and minima on 1 May 1968.

Epoch	Mean time U. T.	$\langle B-V \rangle$ (mag)	$\langle U-B \rangle$ (mag)
Max I	1:20	0.783	0.218
Min I	2:49	0.748	0.285:
Max II	4:21	0.781	0.184
Min II	6:30	0.799	0.241
Max I	7:48	0.808	0.225
		± 0.005	± 0.010

Table VII is 9 compared with 1 for the first solution, the longitude of 165° is 24° from the minimum in Fig. 10, and the model agrees less well at this longitude than near 330° .

We adopt for the longitude of the pole

$$\lambda_0 = 324^\circ \pm 3^\circ \text{ (estimated probable error),} \quad (6)$$

for the latitude

$$\beta_0 = 10^\circ \pm 2^\circ, \quad (7)$$

and for the true period of rotation

$$P = 0^d 28843884 \pm 0^d 00000005, \text{ which is} \quad 6^h 55^m 21^s 115 \pm 0^s 004. \quad (8)$$

III. COLORS OVER THE SURFACE OF HEKTOR

During the lightcurve of 30 April 1968, sets of *UBV* color observations were made near each maximum and minimum for a total of 30 such observations. The *UBV* standards were observed only before and after the lightcurve, and there was an apparent change in equipment sensitivity during the night as determined from the photometry results when all the standards were used together. The *UBV* reductions were therefore made in two parts with the prelightcurve standards used for colors until 5:00 U. T., and the postlightcurve standards for colors afterwards. Table IX gives the average colors obtained at each epoch. These data suggest that the color differences are small, if real at all, which supports the contention that the lightcurve is caused mostly by shape rather than by a spotty surface.

The weighted averages of all our color observations of Hektor are

$$B-V = +0.778 \pm 0.005 \quad (9)$$

and

$$U-B = +0.237 \pm 0.005. \quad (10)$$

IV. THE SHAPE OF HEKTOR

Figure 11 shows a sketch of a model consisting of a cylinder with hemispherical caps. R is the radius of the cylinder and the hemispheres, and H is the height of the cylinder. If the angle between the rotational axis and the direction of observation [see Eq. (5)] is $(90^\circ - B)$, the area seen by the observer, at zero phase angle, varies between $(\pi R^2 + 2RH)$ and $(\pi R^2 + 2RH \sin B)$. For every aspect, a maximum epoch corresponds to the

same area ($\pi R^2 + 2RH$). Thus it is seen that for a constant phase angle, one expects from this model consistent values for the absolute magnitude if V_{zero} is used rather than mean V . Furthermore, a meaningful phase function would also have to be based on V_{zero} . This is evident in the data for Hektor [compare $g(V_{\text{zero}})$ and $V(1,0)$ columns of Table I] and for Eros (Beyer 1953). Assuming that the observed intensity is proportional to the area observed, the amplitude of a lightcurve at any aspect is

$$|\Delta m| = 2.5 \log \frac{\pi R^2 + 2RH}{\pi R^2 + 2RH \sin B}. \quad (11)$$

Equation (11) is used together with the amplitudes of Fig. 10 to give

$$H = 3.3R, \quad (12)$$

and it appears that the factor 3.3 could not be off by more than ± 0.2 . A discussion of the use of this model to predict the orientation of the pole is in Sec. II. Individual lightcurves obtained with such a model give sharp minima near the equatorial aspect, with the minima becoming more shallow as one approaches the polar aspect. Thus the proposed model is consistent with the observations of Hektor.

The sizes can be estimated using the absolute magnitude 7.64 and assuming that the reflectivity of Hektor is 28% (see review chapter, Gehrels 1969), and we find

$$R = 21 \text{ km}, \quad (13)$$

and

$$H = 70 \text{ km}. \quad (14)$$

These dimensions have about $\pm 25\%$ probable error because of the uncertainty in the reflectivity of Hektor.

V. CONCLUDING REMARKS

Section IV allows one to predict that a maximum amplitude of 1.2 mag could be observed near 54° and 234° ecliptic longitude, and a minimum amplitude of 0.05 mag near 144° and 324° .

If Hektor originated as a satellite of Jupiter, having the rotation synchronized with the orbital rotation, the present period of rotation might have been of the order of weeks instead of hours. The observed period being nearly 7 hours, however, does not rule out Hektor's origin as a satellite, because collisions after escape may have caused the fast rotation and the large obliquity.

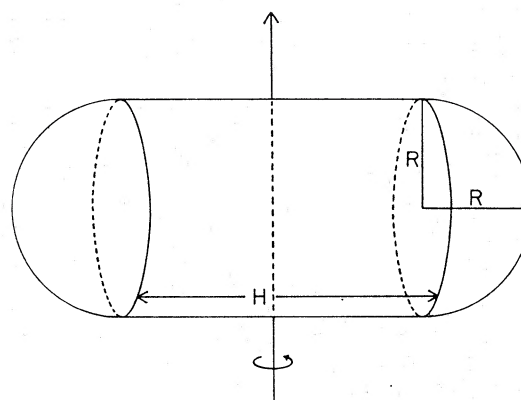


FIG. 11. A model of Hektor: $H = 3.3R$.

On the other hand, Dr. E. Rabe (personal communication, 1968) points out that so many Trojans are now known (29) that it appears unlikely that these all would be escaped satellites of Jupiter. Rabe's work indicates sufficient stability in the Lagrangian zones so that it is possible that the majority of the Trojans originated there.

Two other Trojans were observed in 1957 and 1968, but the lightcurves were of poor quality and the amplitudes are small (0.2–0.4 mag). 911 has a fairly short period (6–10 hrs) and 1437 has a longer one (18–24 hr).

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