

Minor planets and related objects. XIX. Shape and pole orientation of (39) Laetitia

R. E. Sather*

Lunar and Planetary Laboratory, The University of Arizona, Tucson, Arizona 85721

(Received 25 July 1975; revised 28 October 1975)

UBV photometry and lightcurves of Laetitia have been obtained between June 1968 and December 1974. The magnitudes at lightcurve maximum are consistent with a triaxial ellipsoidal figure of axial ratios 15 : 9 : 5 and a linear phase law with coefficient 0.026 ± 0.002 mag/deg. The lightcurves indicate a surface roughness on the order of 10 km. The pole determined by a new method of reducing the scatter in the magnitude phase relation lies near $\lambda_0 = 121^\circ \pm 10^\circ$ and $\beta_0 = +37^\circ \pm 10^\circ$. The absolute magnitude of primary maximum is then $V_0(1,0,90) = 6.56 \pm 0.03$ at 90° aspect and $V_0(1,0,0) = 6.01 \pm 0.03$ when viewed pole-on. Colors at zero phase are $B - V = +0.85 \pm 0.02$ and $U - B = +0.51 \pm 0.02$ with no substantial evidence of variation over the surface.

INTRODUCTION

LIGHTCURVES of Laetitia have previously been published by Groeneveld and Kuiper (1954), van Houten-Groeneveld and van Houten (1958), Gehrels and Owings (1962), and Wamsteker and Sather (1974). In addition to the lightcurves, these papers contain *UBV* data. Pole estimates have been given by van Houten-Groeneveld and van Houten (1958) and by Gehrels and Owings (1962). This paper combines the data presented in the previous papers with that presented here to obtain a physical model for Laetitia.

I. THE OBSERVATIONS

Photoelectric observations of Laetitia were made from 1968 to 1974 with the 41- and 91-cm telescopes at Kitt Peak and the 61-cm Air Force reflector at the Mauna Kea Observatory. The observation and the reduction of the data followed methods described in Paper I (Gehrels 1967). The lightcurves are made, with the *V* filter, relative to a nearby star selected at the telescope. This "comparison star" is chosen so that it will be as close to the asteroid in distance, brightness, and color as possible. The lightcurve points are obtained by subtracting the interpolated comparison-star magnitude from the asteroid magnitude. This tends to reduce the effect of short-term variations in sky conditions.

Table I lists the photoelectric observations of Laetitia. The Kitt Peak observations were made with standard *UBV* photometers. The calibration was done through the observation of standard stars before, between, and following the lightcurve observations. The standard stars are chosen from a list obtained at Kitt Peak (private communication) and a list published by Iriarte *et al.* (1965). $V_0(1,0,90)$ is $V_0(1,0)$ corrected for aspect effects as described in Sec. III. The Mauna Kea lightcurve (Fig. 8) was taken in the *y* filter of the *wby* system of Strömberg, which closely approximates *V* (Crawford and Barnes 1970, p. 979).

* Visiting Astronomer: Kitt Peak National Observatory, operated by AURA, under contract with the National Science Foundation.

The comparison stars are listed and the quality of the nights are described in Table II. The comparison stars are used only in the production of the lightcurve and are not to be considered as standards for the *UBV* calibration. The *V* and *B - V* columns refer to magnitudes of the comparison star calibrated by use of the standard stars discussed in the preceding paragraph. The "Scatter of comp." gives the average deviation from a smooth curve fitted to a plot of the comparison-star magnitudes versus time. If the assumption that this star is not an extremely short-term variable is correct, this deviation should be a measure of the quality of the night.

Table III gives the positional data for Laetitia, calculated for the midtime of the lightcurves.

II. THE LIGHTCURVES

The 1968 lightcurves of Laetitia are shown in Figs. 1 and 2. Repetition of small-scale features in Fig. 2 and in a lightcurve obtained 1 and 2 August 1968 published by Wamsteker and Sather (1974) has been noticed. The region of the lightcurve covered in Fig. 1 repeats the same features. There is only a suggestion of some of these features in Figs. 3-7. This is not too surprising since the large amplitude of the 1970 and 1972 lightcurves and the relatively few points per unit time of the 1971 lightcurve would tend to obscure any small-scale features that are present. Figures 8 and 9 also give evidence of small features in the lightcurve. Although the sizes of some of these features are not

TABLE I. Photometric observations of Laetitia.

Date ET	<i>V</i> of zero* (mag)	<i>B - V</i> (mag)	<i>U - B</i> (mag)	$V_0(1,0)$ (mag)	$V_0(1,0,90)$ (mag)	Figure
68.06.14	9.94	+0.88	+0.51	6.24	6.58	1
68.08.22	10.11	0.90	0.44	6.20	6.54	2
70.02.01	10.99	0.91	0.49	6.53	6.55	4
72.04.22	10.67	0.88	0.53	6.58	6.59	6
74.12.22	9.81	+0.87	+0.47	6.20	6.50	9
	± 0.02	± 0.02	± 0.02	± 0.02	± 0.02	

* Magnitude of the highest point on the lightcurve uncorrected for phase, aspect, or distance.

TABLE II. Comparison stars and quality of nights.

Date ET	R.A. 1950	Dec. 1950	V (mag)	B-V (mag)	Scatter of comp. (mag)	Remarks
68.06.14	19 ^h 21 ^m 9	8°45'	10.00	+0.68	±0.004	
68.08.22	18 37.4	-13 32	9.63	0.73	0.008	
70.01.31	3 23.9	+6 16	...	...	0.019	wind-dust
70.02.01	3 24.4	+6 24	9.57	0.42	0.006	some wind
71.04.03	9 45.6	+13 46	...	...	0.008	
72.04.22	15 29.8	-4 27	9.95	1.26	0.003	
72.04.23	15 30.7	-4 22	...	...	...	no filters
73.08.04	22 35.3	-6 14	...	...	0.001	
74.12.22	6 35.7	+9 02	8.63	+0.91	±0.013	clouds near
	±0.1	±1	±0.01	±0.01		

much greater than the probable error of the points, their repeatability attests to their reality. The small-scale features are suggestive of topographic elements such as peaks, scarps, or depressions which rather suddenly come into illumination. To produce a net photometric effect of 0.02 mag superimposed on the overall smooth lightcurve, the size of such an element or combination of elements must be on the order of 2% of the illuminated surface or 10 km in radius.

The general shape of the lightcurves of Laetitia varies greatly from one apparition to the next. The two maxima of a lightcurve are seen to be at the same height only near equatorial aspects, while the relative depths of the minima seem to be unrelated to aspect or phase angle.

III. MAGNITUDES AND COLORS

The first two columns of Table IV give the data used in the uncorrected phase relation for Laetitia shown in Fig. 10. This is a plot of the absolute magnitude of the lightcurve maximum, $V_0(1, \alpha)$, versus phase angle. It was clear that no meaningful phase relation could be obtained from this plot. However, it was noticed that the absolute magnitudes obtained at about the same phase and aspect angles agree, which suggests that the lightcurve maxima are related to aspect as well as phase and that the scatter can be reduced by properly allowing for aspect. This gives a new method to determine the pole orientation. The five lowest points on the plot were obtained from observations where the aspect

TABLE III. Positional data for Laetitia.

Date ET	Phase angle	Distance from Sun (AU)	Distance from Earth (AU)	Light time	R.A. 1950	Dec. 1950	Ecliptic	
							Long. 1950	Lat. 1950
68.06.14	-10°96	2.7023	1.7775	0°01027	19 ^h 21 ^m 5	-8°44'	291°	+13°
68.08.22	+17.26	2.6259	1.8632	0.01076	18 37.2	-13 33	279	+10
70.01.31	+21.78	2.6195	2.2711	0.01311	3 24.0	+6 16	50	-12
70.02.01	+21.82	2.6206	2.2838	0.01319	3 24.9	+6 24	51	-12
71.04.03	+14.25	3.0438	2.2873	0.01321	9 45.7	+13 46	144	0
72.04.22	-7.83	2.9893	2.0426	0.01180	15 30.7	-4 27	231	+14
72.04.23	-7.55	2.9885	2.0371	0.01177	15 30.0	-4 21	231	+14
73.08.04	-10.08	2.5053	1.5519	0.00896	22 35.1	-6 09	338	+3
74.12.22	-6.07	2.7418	1.7864	0.01032	6 37.6	+9 02	100	-14
	±00.01	±0.0001	±0.0001	±0.00001	±0.1	±01	±1	±1

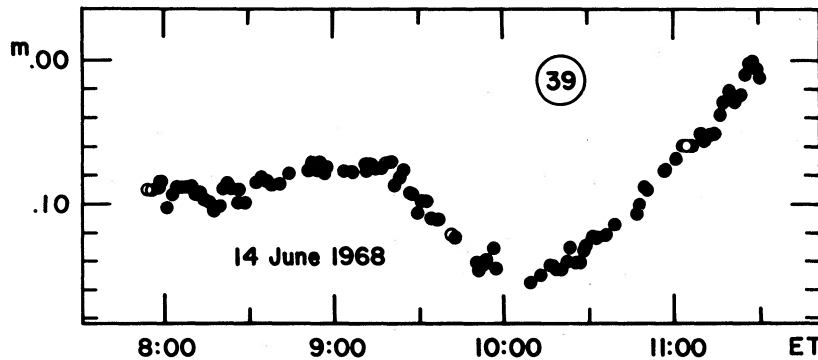


FIG. 1. Lightcurve of asteroid (39) Laetitia observed by J. L. Dunlap and R. C. Taylor at Kitt Peak 91-cm No. 2 telescope.

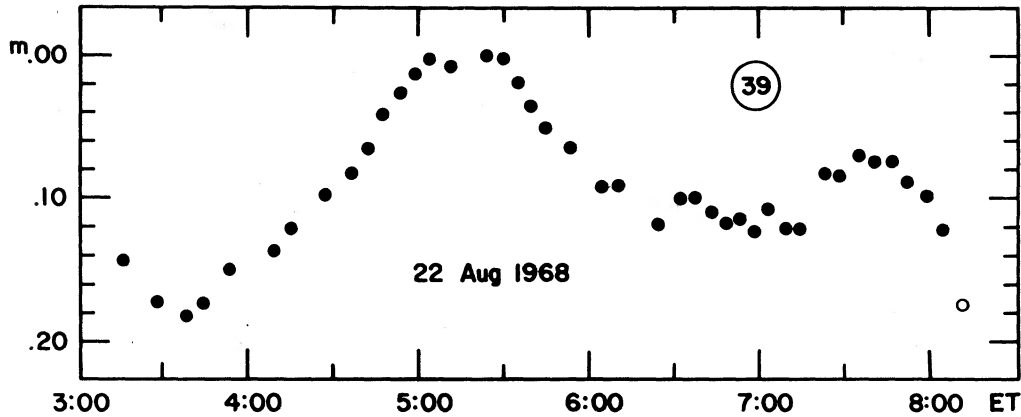


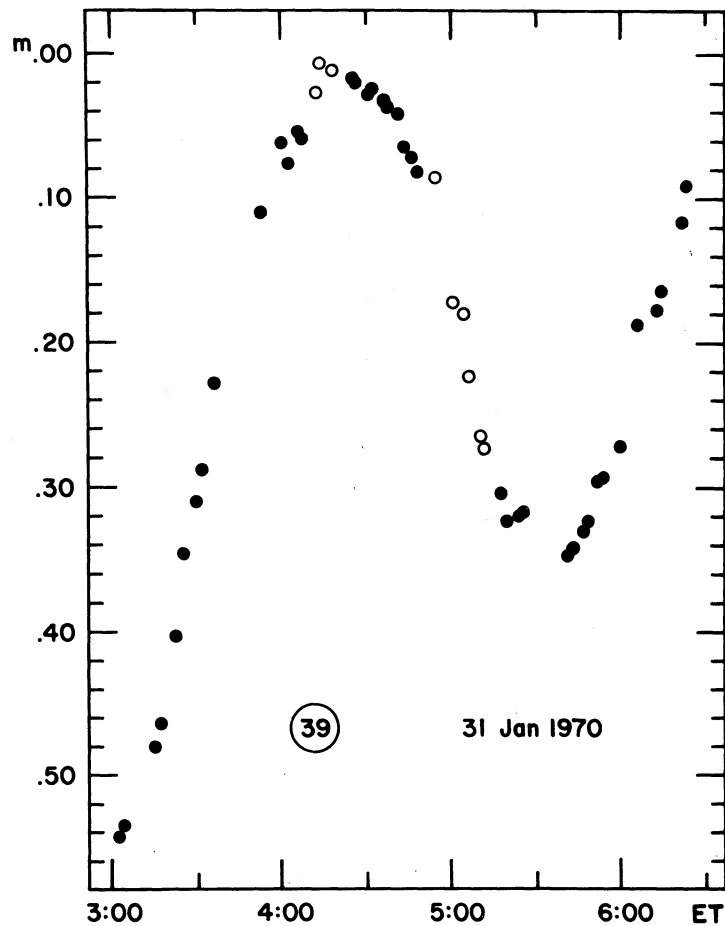
FIG. 2. Lightcurve of asteroid (39) Laetitia observed by J. L. Dunlap and R. E. Sather at Kitt Peak 41-cm No. 4 telescope.

angles were greater than 70° , based on a previously published pole near $\lambda_0=115^\circ$ and $\beta_0=19^\circ$ by Vesely (1971). Thus a correction to equatorial aspect would shift their position only slightly. The line plotted in Fig. 10 is a least-squares fit to these five points. The relation thus obtained is

$$V_0(1,\alpha) = 6.55 + 0.025|\alpha| \pm 0.02 \pm 0.002$$

An effort was made to correct all points on Fig. 10 to a 90° aspect. The simple model of a triaxial ellipsoid was chosen with the axes $a > b \geq c$, where c is considered to be the axis of rotation. It follows that the projected area at the lightcurve maximum varies directly with d as the aspect changes, where $d^2 = b^2 \cos^2 \xi + c^2 \sin^2 \xi$ and ξ is the aspect angle (the smaller of the two angles formed by the rotational axis and the line of sight).

FIG. 3. Lightcurve of asteroid (39) Laetitia observed by R. E. Sather at Kitt Peak 41-cm No. 3 telescope.



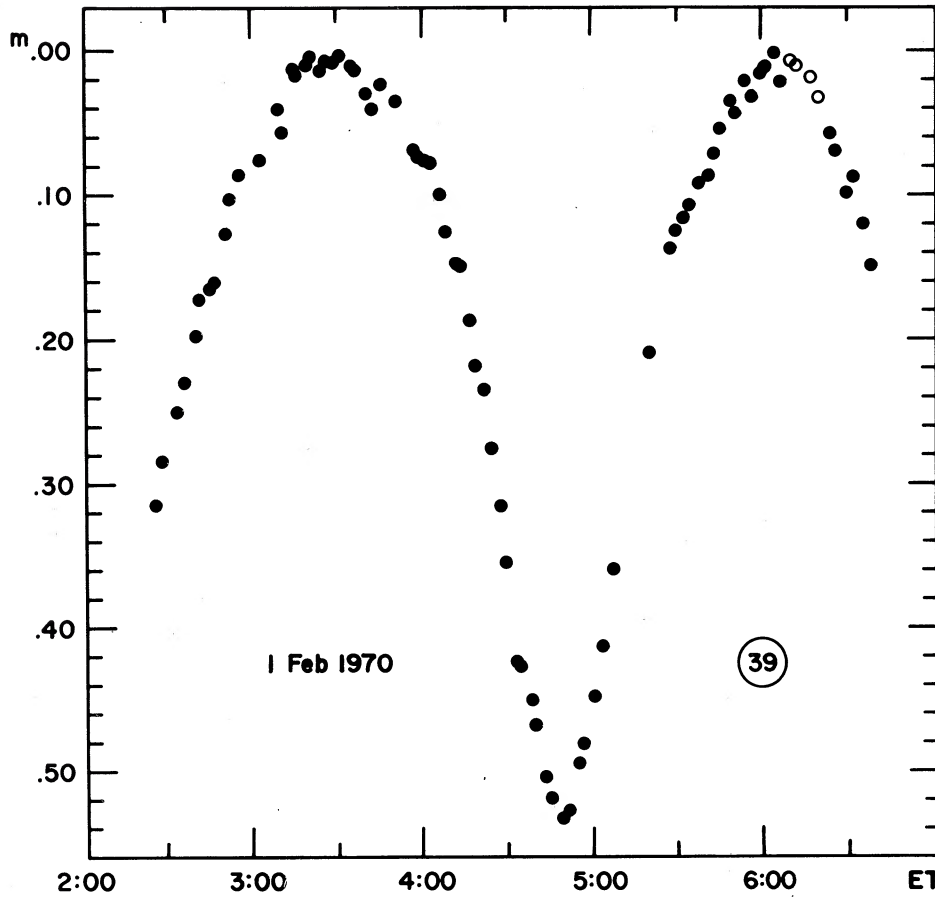


FIG. 4. Lightcurve of asteroid (39) Laetitia observed by R. E. Sather at Kitt Peak 41-cm No. 3 telescope.

No attempt was made to remove phase-dependent shadowing effects of the ellipsoidal shape. Ratios of b to c were taken from 1 to 2 at small intervals to obtain the d values which were then used to correct the $V_0(1,\alpha)$ magnitudes to $V_0(1,\alpha,90)$ found in the last column of Table IV. A linear least-squares fit was done on the $V_0(1,\alpha,90)$ magnitudes for various assumed poles for a 360° span in longitude and a 90° span in latitude. The ratio and pole which produced the minimum variance

were determined and the $V_0(1,\alpha,90)$ for each observation is plotted versus phase at the top of Fig. 11. This gives a phase relation of

$$V_0(1,\alpha,90) = 6.56 + 0.026|\alpha|, \\ \pm 0.03 \pm 0.002$$

not greatly different from the one obtained from the five points in Fig. 10. The pole and ratio which produced the corrections for Fig. 11 are $\beta_0 = +37^\circ \pm 10^\circ$,

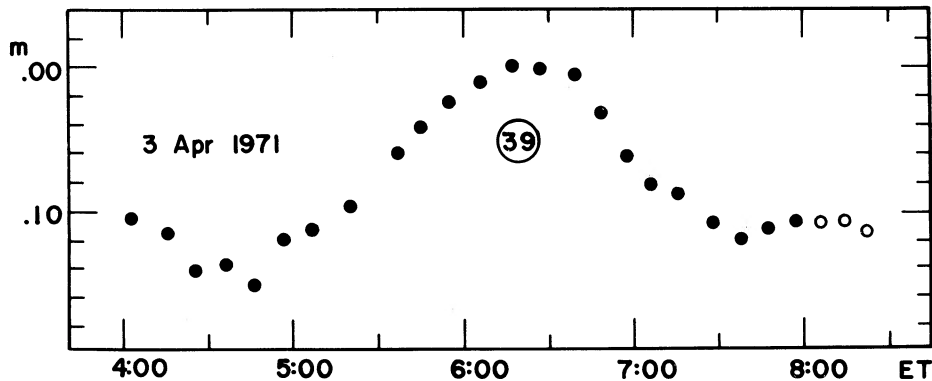


FIG. 5. Lightcurve of asteroid (39) Laetitia observed by R. E. Sather at Kitt Peak 41-cm No. 4 telescope.

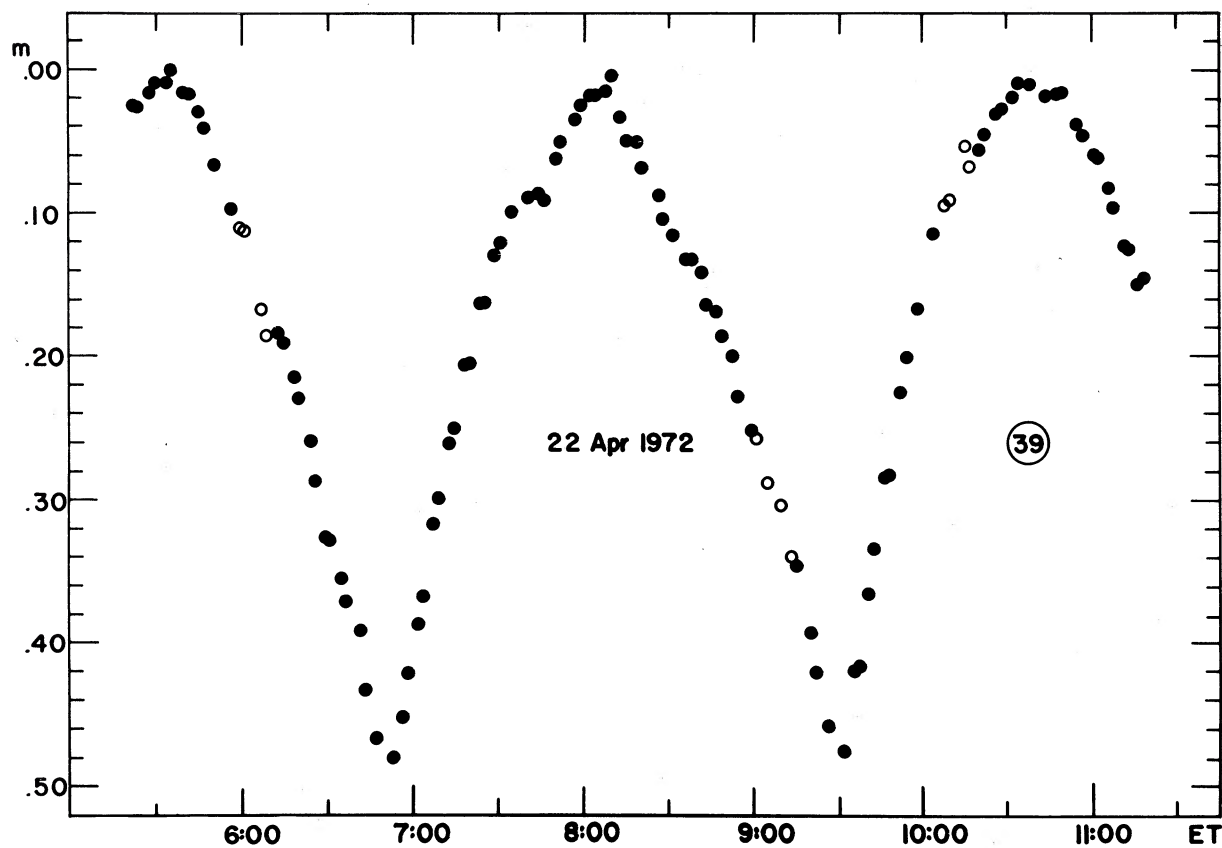


FIG. 6. Lightcurve of asteroid (39) Laetitia observed by M. L. Howes at Kitt Peak 41-cm No. 4 telescope.

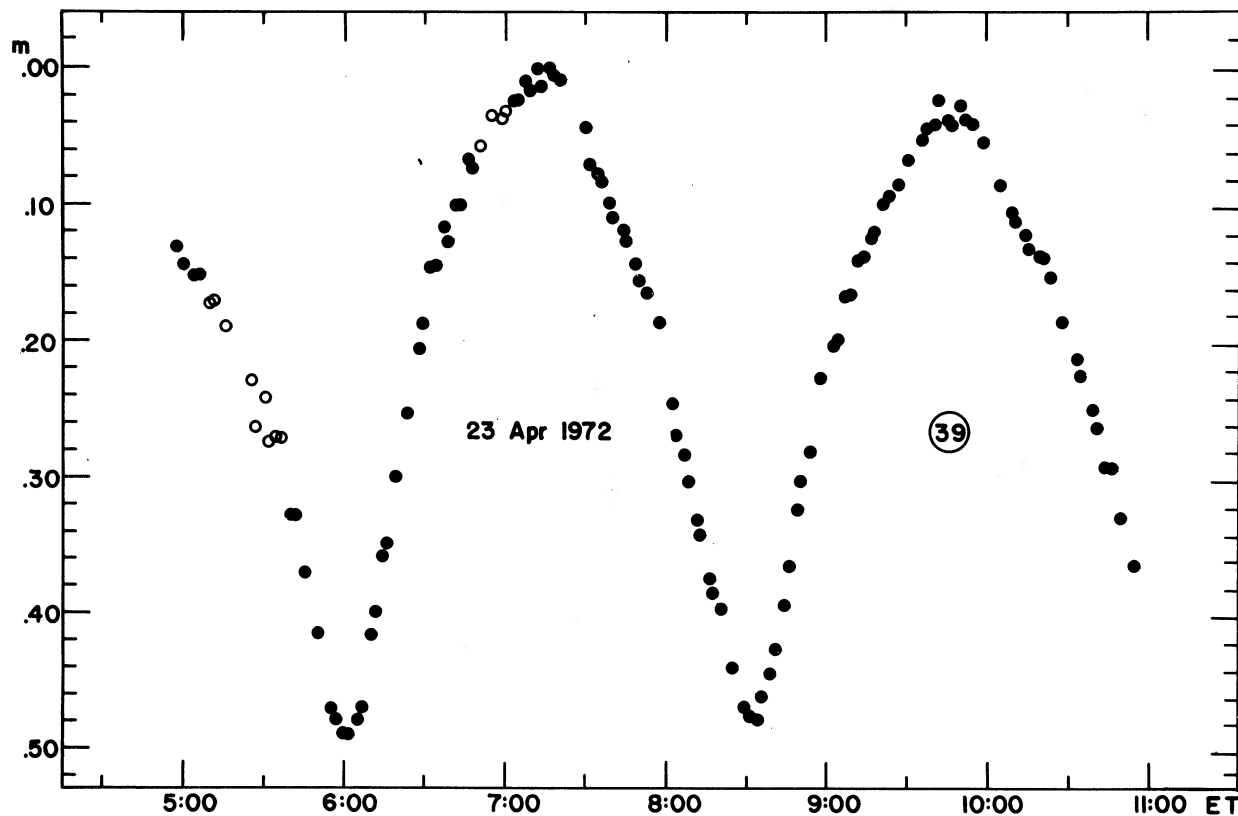


FIG. 7. Lightcurve of asteroid (39) Laetitia observed by R. C. Capen at Kitt Peak 41-cm No. 4 telescope.

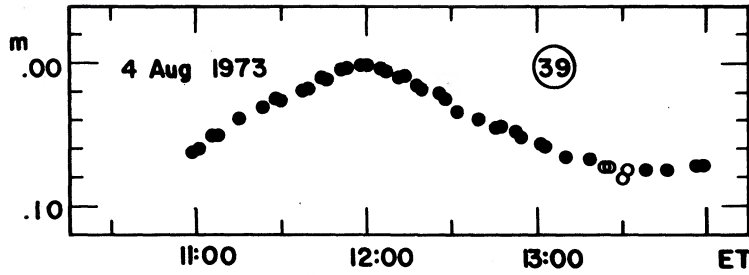


FIG. 8. Lightcurve of asteroid (39) Laetitia observed by L. B. Otten at Mauna Kea 61-cm Air Force telescope.

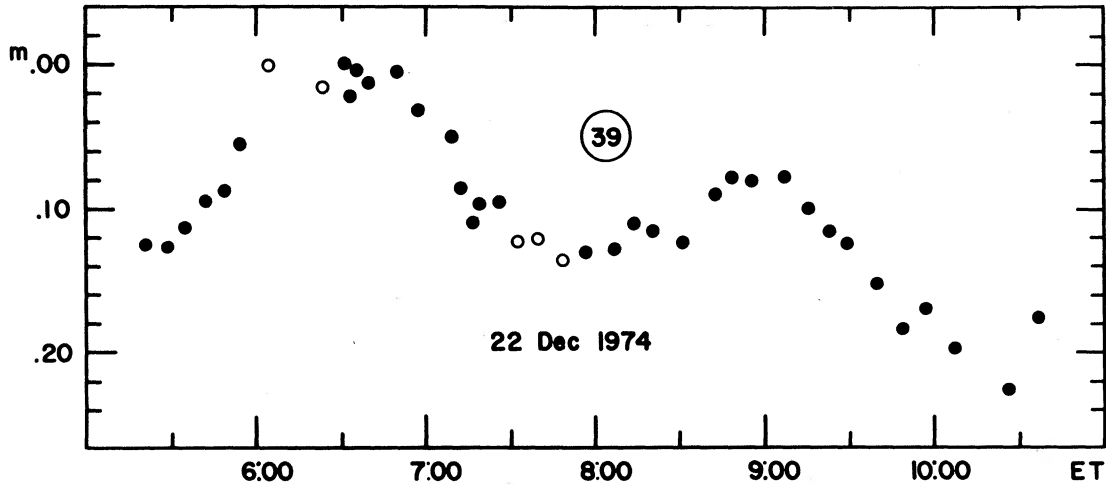


FIG. 9. Lightcurve of asteroid (39) Laetitia observed by R. E. Sather at Kitt Peak 41-cm No. 4 telescope.

$\lambda_0 = 121^\circ \pm 10^\circ$, and $b:c = 1.80$. In order to produce the amplitudes found in the lightcurves, $a:b = 1.64$. It should be noted that the observation at just slightly less than 11° phase is from Fig. 1. As may be seen, it is possible that the maximum had not been reached. Hence, this point could be somewhat higher. The mean $V(1,0)$ is 6.53. The colors are plotted at the bottom of Fig. 11. A least-squares fit to each of these plots gives the relations

$$B - V = 0.85 \pm 0.003 |\alpha| \pm 0.02 \pm 0.001$$

$$U - B = 0.51 - 0.001 |\alpha| \pm 0.02 \pm 0.001$$

TABLE IV. Aspect data for Laetitia.

Date ET	Phase angle	$V_0(1,\alpha)$ (mag)	Aspect angle	$V_0(1,\alpha,90)$ (mag)
52.01.29	+11°39	6.48	-54°	6.79
53.04.10	+ 6.85	6.44	-59	6.70
55.12.18	+20.00	7.03	+77	7.09
55.12.28	+21.45	7.06	+79	7.10
58.03.05	-15.83	6.99	+88	6.99
68.06.14	-10.96	6.53	+51	6.87
68.08.01	+11.18	6.54	+52	6.87
68.08.22	+17.26	6.66	+51	7.00
70.02.01	+21.82	7.10	-81	7.13
72.04.22	-7.83	6.73	+83	6.75
74.12.22	-6.07	6.36	-55	6.66

In order to determine the sidereal period of rotation and the orientation of the pole from the behavior of the synodic period over long time intervals ("photometric astrometry"; see Taylor 1971), it is necessary to have enough lightcurves during a single apparition for a confident count of cycles. Such an analysis cannot be made with the available data for Laetitia. From the lightcurves the period appears to be 0.21408 ± 0.00003 day. This is very close to that of 5 h 8.3 min given by van Houten-Groeneveld and van Houten (1958).

IV. THE SURFACE AND SHAPE OF LAETITIA

It has been shown that the lightcurve amplitudes and wide scatter in the observed magnitude, phase relation

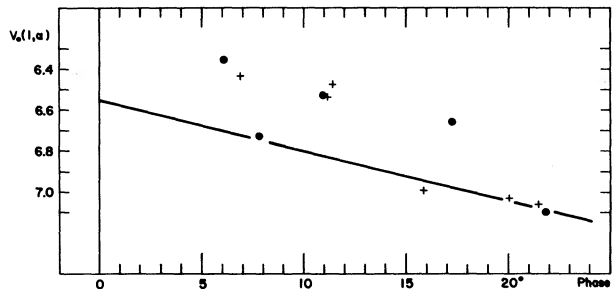


FIG. 10. First attempt to obtain the phase function for (39) Laetitia with $V_0(1,\alpha)$ uncorrected for aspect. The crosses represent data obtained from other papers.

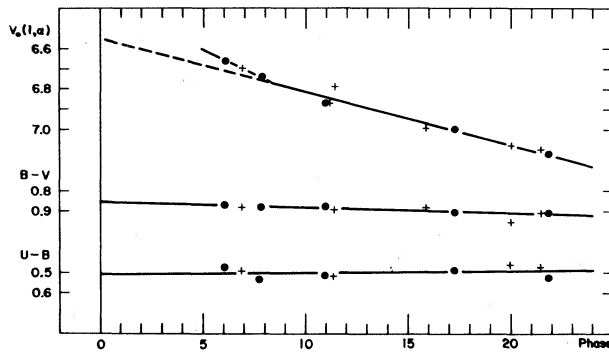


FIG. 11. Phase functions of (39) Laetitia with $V_0(1, \alpha)$ corrected for aspect. The crosses indicate data obtained from other papers.

can be explained by a triaxial figure with dimensional ratios near 15:9:5. The conclusions do not, of course, depend upon an exact ellipsoidal shape, and in fact major topographic structures are revealed by repetitive small-scale features in the lightcurves.

The surface of Laetitia seems to be optically rather uniform. Compositional variegation would be expected to show up in the UBV colors (e.g., Zellner *et al.* 1975), whereas in fact the observed colors show hardly detectable variations over rotation or aspect (Wamsteker and Sather 1974). Also, polarization observations at approximate effective wavenumbers in inverse micrometers of 1.93 and 2.30 (Zellner *et al.* 1974, and unpublished) repeat well enough to rule out major albedo differences. Thus, we appear to be on safe ground in attributing the lightcurve variations principally to shape.

The geometric albedo of Laetitia inferred from polarimetry by Zellner *et al.* (1974) is $p_V = 0.20$, which corresponds to dimensions of roughly $255 \times 150 \times 85$ km³ in our model. Thermal radiometry by Hansen (1975) implies dimensions roughly 25% larger. Finally,

we note that in spectrum and polarization Laetitia is a rather typical member of the S (stony or stony-iron) compositional type of asteroids (Chapman *et al.* 1975), and is one of a dozen or so largest of that type. Its shape, size, and composition are highly suggestive of a major collision fragment from a substantially more-massive differentiated parent body.

ACKNOWLEDGMENTS

I wish to thank the directors of the Kitt Peak National Observatory and the Mauna Kea Observatory for the use of their facilities. I would also like to recognize the aid in this work by B. Zellner and the observers mentioned in the figure legends. Our program is supported by the National Aeronautics and Space Administration.

REFERENCES

- Chapman, R. C., Morrison, D. L., and Zellner, B. (1975). *Icarus* **25**, 104.
 Crawford, D. L., and Barnes, J. V. (1970). *Astron. J.* **75**, 978.
 Gehrels, T. (1967). *Astron. J.* **72**, 929 (Paper I).
 Gehrels, T., and Owings, D. (1962). *Astrophys. J.* **135**, 906.
 Groeneveld, I., and Kuiper, G. P. (1954). *Astrophys. J.* **120**, 200.
 Groeneveld, I., and Kuiper, G. P. (1954). *Astrophys. J.* **120**, 529.
 Hansen, O. L. (1975). *Astrophys. J.* To be published.
 Iriarte, B., Johnson, H. L., Mitchell, R. I., and Wisniewski, W. K. (1965). *Sky Telesc.* **30**, 21.
 Taylor, R. C. (1971). *Physical Studies of Minor Planets*, edited by T. Gehrels (U.S. GPO, Washington, D.C.), NASA SP-267, p. 117.
 van Houten-Groeneveld, I., and van Houten, C. J. (1958). *Astrophys. J.* **127**, 253.
 Vesely, C. D. (1971). *Physical Studies of Minor Planets*, edited by T. Gehrels (U.S. GPO, Washington, D.C.), NASA SP-267, p. 133.
 Wamsteker, W., and Sather, R. E. (1974). *Astron. J.* **79**, 1465 (Paper XVII).
 Zellner, B., Gehrels, T., and Gradie, J. (1974). *Astron. J.* **79**, 1100 (Paper XVI).
 Zellner, B., Wisniewski, W., Andersson, L., and Bowell, E. (1975). *Astron. J.* **80**, 986 (Paper XVIII).