

B, V Photometry of Thebe (JXIV)

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Thebe (JXIV), a small inner moon of Jupiter, was discovered by Synnott in 1980 from Voyager images. It orbits in a severe environment of bombardment by high-energy charged particles trapped in Jupiter's magnetosphere and other contaminants originating on Io. Since Thebe is too small for its surface to be affected by endogenic processes, Thebe's surface is useful as a probe for the remote sensing of this environment.

B and *V* photometry of Thebe was obtained relative to Amalthea (JV). A TI 800 × 800 CCD chip was used with the USNO 61-in. astrometric reflector at Flagstaff. The results show Thebe to be 0.5 mag brighter in *V* on the leading side, near the eastern elongation, than on the trailing side, near the western elongation, suggesting synchronous rotation.

A mean opposition magnitude, $V = 15.7$, is obtained when combining these results with Millis' photometry of JV. The average albedo in *V*, 0.04, is similar to that of JV and agrees with Synnott's discovery observations. A $(B - V)$ of 1.3 makes Thebe one of the reddest moons in the Solar System and suggests that it too has been resurfaced by sulfur from Io. Contrary to expectations, Thebe is found to be 0.2 mag bluer than Amalthea, suggesting other contaminants.

Thebe also shares several photometric patterns with the Galileans and, thus, links the inner satellite system with the Galilean system. This suggests that the magnetospheric processes which have modified the surfaces of the Galileans have also modified the surfaces of the inner satellites. An implication of this conclusion is that the leading faces of the innermost satellites, Adrastea (JXV) and Metis (JXVI), should be darkened and reddened. © 1992 Academic Press, Inc.

I. INTRODUCTION

Thebe is a small moon of Jupiter discovered by Synnott (1980) from Voyager images. It has a radius of about 50 km and an orbital period of $16^{\text{h}} 11^{\text{m}}$. Its orbit lies at 3.1 planetary radii from Jupiter, between the orbits of Amal-

thea (JV) and Io (JI). In their survey of the inner satellites of Jupiter, Veverka *et al.* (1982) characterize the environment of these satellites as severe in terms of particle bombardment and they made the case for using these satellites as probes for studying this environment. They also predicted that the newly discovered satellites (JXIV, JXV, JXVI) would be found to be very red and dark—similar to JV. Although Thebe (JXIV) can be observed from the ground (Jewitt *et al.* 1981, Pascu and Seidelmann 1981), little new information on it has been obtained since Synnott's discovery from Voyager I images.

Along with other faint, inner satellites, we have observed Thebe for astrometric purposes since 1981. A CCD system on the USNO 61-in. astrometric reflector was used for the observations. Since photometric information results as a spin-off of our astrometric reductions, in 1987 we began observing Thebe relative to Amalthea in the *B*, *V*, *R*, and *I* passbands. Combining our relative photometry with Millis' (1978) photoelectric *B* and *V* magnitudes, we were able to obtain a $(B - V)$ and a *V* albedo for Thebe (Pascu *et al.* 1987a). Additional observations in 1988 made it possible for us to obtain a lightcurve for Thebe, showing a half-magnitude difference between eastern and western elongations (Pascu *et al.* 1990). We describe and present an analysis of the *B* and *V* data below. The *R* and *I* images will be reduced at a later time.

II. THE OBSERVATIONS

The observations were made with the U.S. Naval Observatory 61-in. astrometric reflector in Flagstaff, Arizona. A reimaging coronagraph was used together with a CCD camera housing a Texas Instruments 800 × 800 chip. This instrumentation is described in detail by Baum *et al.* (1981) and by Pascu *et al.* (1987b). The filters used

TABLE I
Observational Frames of JXIV (Thebe) and JV (Amalthea)

Date	Thebe at	V frames	B frames
9/16/87	Western elongation	3	3
9/17/87	Eastern elongation	3	4
9/19/87	Eastern elongation	4	2
10/13/88	Eastern elongation	5	5
10/16/88	Western elongation	4	4

Note. JV near western elongation in all frames.

were duplicates of the WF/PC filters: for *B*, F439W, and for *V*, F569W (see Harris *et al.* 1991).

Since Millis (1978) did his photoelectric photometry of Amalthea (JV) at western elongation, our strategy was to observe Thebe at both elongations relative to Amalthea only at the western. This configuration does not occur very often when Jupiter is near the meridian, but when it does, it lasts for several days due to the orbital periods of these moons. Amalthea's 12-hr period will place it in the same position each night, while Thebe's 16-hr period will place it on opposite sides of the planet on consecutive nights. In Table I above we list the configurational circumstances of the 37 frames that were measured and reduced.

The images of Amalthea and Thebe were modeled as two-dimensional Gaussians sitting on a halo background—quadratic in *x* and *y*. The intensity volumes of these Gaussian images, with the halo background subtracted, were taken as the photometric parameters. Magnitude differences between Amalthea and Thebe were computed for 19 *V* frames and 18 *B* frames. No extinction corrections were made since both satellites were near the same zenith distance and close to the same color. There was, however, a small (0.02 mag) correction to the magnitude difference for reduction to standard *V*, due to the small color difference between Thebe and Amalthea (Harris *et al.* 1991). Phase corrections could be made to the magnitude difference if the phase coefficients of both satellites were known. At present, only the phase coefficient of Amalthea is known (Veverka *et al.* 1981), but those authors argue for the similarity of surfaces for all the inner moons. Since the satellites were observed between phase angles of 6.5° and 8.0°, only a significant difference in phase coefficients can amount to a correction larger than 0.1 mag.

Aspect corrections were larger and more complex. Aspect corrections arise from the fact that both Thebe and Amalthea are ellipsoids and probably locked in synchronous rotation with their longest axis always pointed at Jupiter (Veverka *et al.* 1981). At elongation, both satellites are brightest—exposing their largest cross sections. Away from elongation, the declining brightness of Amal-

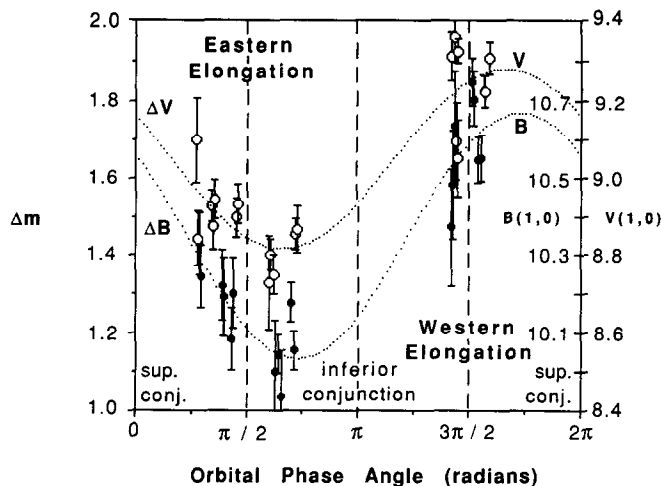


FIG. 1. *B* and *V* lightcurves for Thebe. The differences in *B* and *V* magnitude between Thebe (JXIV) and Amalthea (JV) are plotted against the orbital phase angle. The right-hand ordinate gives the absolute *B* and *V* scales computed by adding the absolute *B* (= +8.9) and *V* (= +7.4) of Amalthea to the left-hand scale. These observations were taken only when Amalthea was near western elongation. The color difference between Thebe and Amalthea is indicated by the clear separation of the *B* and *V* data. If Thebe and Amalthea were the same color, the *B* and *V* curves would overlap. The fact that the *B* curve is brighter indicates that Thebe is bluer than Amalthea. This figure demonstrates five photometric patterns: (1) an east/west magnitude difference in *B* of 0.7 (± 0.1) mag, (2) a smaller amplitude in *V* than in *B*, (0.5 mag), (3) a Thebe–Amalthea color difference, 0.2 (± 0.05) mag, on average, (4) an east/west color difference of 0.3 (± 0.05) mag on the leading side, and 0.1 (± 0.05) mag on the trailing side, and (5) a phase shift, 30° ($\pm 10^\circ$) lag angle (θ). Patterns 1, 2, 4, and 5 are in common with the Galilean moons.

thea will decrease the measured (Thebe–Amalthea) magnitude difference, while the reduced brightness of Thebe will increase it. Thus, the aspect correction for Amalthea was added to the measured (Thebe–Amalthea) magnitude difference, while that for Thebe was subtracted. In computing aspect corrections we modeled the satellites as ellipsoids with the dimensions given by Veverka *et al.* (1982). Since we could observe the satellites 45° away from elongation, the aspect corrections ranged from -0.1 to $+0.2$ mag but were generally just a few hundredths of a mag.

III. RESULTS

The 37 values are plotted in Fig. 1 against the corresponding orbital phase angle. This plot shows an east/west variation in both *B* and *V*. Thebe is about 0.5 mag brighter in *V* near the eastern elongation than near the western elongation. The variation suggests periodic rotation. A sine curve was fit to the data, although it is apparent that the variation is more complex. The formal solutions gave

TABLE II
B, *V* Photometry of JXIV (Thebe) near Both Elongations
 Relative to JV (Amalthea) near Western Elongation

Elongation	B_0	$V_0^{a,b}$	$B - V$	$V(1,0)^b$	A_V^c
Brightest (near eastern)	16.7 (± 0.1)	15.5 (± 0.1)	+1.2 (± 0.1)	+8.8 (± 0.1)	0.05 (± 0.01)
Faintest (near western)	17.4 (± 0.1)	16.0 (± 0.1)	+1.4 (± 0.1)	+9.3 (± 0.1)	0.03 (± 0.01)

Note. B_0 and V_0 are the mean opposition magnitudes of Thebe in *B* and *V*. $V(1,0)$ is the *V* magnitude of Thebe at unit distance from the Earth and Sun and at zero phase angle. A_V is the geometric albedo of Thebe in *V*, based on a mean radius of 50 (+10, -5) km (Synnott 1990).

^a Based on *V* photometry of Millis (1978).

^b Phase coefficient assumed to be the same as for JV (0.042 mag/deg) (see Veverka *et al.* 1981).

^c Assuming synchronous rotation.

$$\Delta B = 1.451 - 0.317 \sin(\text{orbital phase angle} - \text{lag angle } (\theta))$$

$$\Delta V = 1.648 - 0.233 \sin(\text{orbital phase angle} - \text{lag angle } (\theta)).$$

The orbital phase angle is measured from superior conjunction; θ , the phase shift or lag angle, is the angular difference between orbital elongation and the position of maximum/minimum light. An attempt was made to fit the data without a phase shift, but the residuals were significantly reduced by its inclusion and a value of about $30^\circ (\pm 10^\circ)$ was obtained for both *B* and *V*. The 30° phase shift is a lag angle at both elongations, although the solution at the western elongation was weak.

Combining the coefficients in these solutions with Millis' (1978) photoelectric work on Amalthea, Table II was constructed. The large error bars on the photometry are due primarily to the photoelectric photometry of Amalthea (Millis 1978) with which our relative values were combined. The larger error bars on the absolute albedo values are due primarily to the uncertainty in the dimensions of Thebe. The albedo difference between the leading and the trailing sides, as obtained from the relative photometry, is 0.019 ± 0.001 in *V*. This indicates a real leading/trailing albedo pattern.

IV. DISCUSSION

Figure 1 and Table II summarize our results. There are seven major features of this figure and table which are relevant to a model for Thebe's surface and its severe environment: (1) a very low albedo, $0.04 (\pm 0.01)$ in *V*, (2) a red color, $(B - V) = 1.3 (\pm 0.1)$, (3) an east/west magnitude difference in *B* of $0.7 (\pm 0.1)$ mag, (4) a smaller amplitude in *V* than in *B*, (0.5 mag), (5) a Thebe-Amalthea color difference, $0.2 (\pm 0.05)$ mag on average, (6) an east/west color difference of $0.3 (\pm 0.05)$ mag on the leading

side and $0.1 (\pm 0.05)$ mag on the trailing side, and (7) a phase shift, $30^\circ (\pm 10^\circ)$ lag angle (θ).

Of course, we have confirmed Veverka *et al.*'s (1982) prediction that Thebe would be dark and red, as is Amalthea. But Thebe also has four of the seven surface features in common with the Galilean moons (Nos. 3, 4, 6, and 7).

A. Rotation

Since Amalthea was found not to have an east/west magnitude difference (Veverka *et al.* 1982), Thebe's large brightness variation was unexpected, but proved useful in characterizing Thebe's rotation. If the variation were due to a different aspect (cross section) at the eastern elongation than at the western, the rotation could be periodic without being synchronous. Goldreich and Peale (1966) have shown that rotational periods of two-thirds and twice the orbital period are stable. For an elongated satellite with a uniformly reflecting surface, both of these periods can produce a configuration with a large cross section at one elongation and a small one at the other. It should be noted that the same effect can be produced by a satellite with the same cross section all around but with alternating bright and dark quadrants. Our data can rule out a rotational period of two-thirds, but not of twice the orbital period. Such a model will satisfy our lightcurve, but only at one apparition. The lightcurve will change from year to year and become flat in three years. The appearance that the 1987 and 1988 data fit together well is not strong enough evidence to reject this model, since the overlap of the 1987 and 1988 data is not good. Corroborating data from 1989 and 1990 would be necessary to reject it. With these caveats we suggest that the most likely model for Thebe is a synchronously rotating moon with the east/west magnitude difference due primarily to an albedo difference between the leading and the trailing sides. Of course, additional frames from 1989 and 1990 should be included to model the rotation conclusively.

B. Similarity of Photometric Patterns with Galileans

Thebe's red color suggests that it was resurfaced by sulfur from Io, as was Amalthea (Gradie *et al.* 1980). It appears that Thebe has a class 2 albedo/color pattern, as described by Veverka *et al.* (1986). In the Jovian system this pattern would be a "systematic variation of redness with distance from Io" (Veverka *et al.* 1986). Figure 1 indicates, however, that Thebe, which lies between Amalthea and Io (the source of reddening for both of them), is actually about 0.2 mag bluer than Amalthea. More precisely, Thebe's trailing side is 0.1 mag bluer than Amalthea's trailing side, while its leading side is 0.3 mag bluer than Amalthea's trailing side. This suggests that other contaminants may be involved, whose densities at Thebe's orbit are greater than at Amalthea's. The evidence is not strong that Thebe is redder on its trailing side, but such a pattern is certainly consistent with those found on Amalthea by Veverka *et al.* (1981) and on satellites I–III (Morrison *et al.* 1974). A smaller amplitude in *V* than in *B* for Thebe is also a feature in common with the other Galilean moons (Veverka 1977).

Thebe participates in what Morrison and Burns (1976) refer to as "regularities" in the photometric properties of the Galilean moons. Not only does Thebe have an albedo and color difference between the leading and trailing sides, but like satellites I–IV, the brightest and darkest faces lead or lag the elongation points. It has been claimed for some time that this lead/lag angle (called θ_{\max} and θ_{\min} in the literature) declines progressively for satellites I–III (Johnson 1969, Blanco and Catalano 1974). Veverka (1977), in his review of satellite photometry, demonstrates this phenomenon by a plot of the lead/lag angle for the Galilean moons against the distance from Jupiter. For Thebe this angle is about 30° and lags at both elongations (although the solution at the western elongation is not strong). A 30° lag angle fits Veverka's (1977) Fig. 9.13 very well for Thebe's distance and is further confirmation of the phenomenon.

C. Interaction with Magnetospheric Plasma

The similarity of the leading/trailing albedo pattern of Thebe with those of JI–JIV, combined with a strong indication that Thebe has been resurfaced, leads to the conclusion that the source of the variation is exogenic. Three mechanisms which have been associated with this pattern are bombardment by neutral meteoroids, bombardment by electrically charged micrometeoroids, and/or heavy-ion bombardment from the planetary magnetospheric plasma. In the first case, the leading and far sides of satellites would receive the heaviest bombardment (Cook and Franklin 1970, Bandermann and Singer 1973, Morrison and Burns 1976). In the second case, satellites JI–JIII will be preferentially impacted on their trailing

sides, but JIV will be preferentially impacted on the leading side (Hill and Mendis 1981, Wolff and Mendis 1983). For the ion-bombardment mechanism, Jupiter's magnetosphere rotates faster than Thebe revolves, so the trailing side will receive a heavier bombardment of ions, provided the gyroradii of those ions are small relative to Thebe's radius (Johnson 1990). In fact, the gyroradii need be no smaller than half the satellite radius for significant asymmetry in bombardment (Pospieszalska and Johnson 1989). The sulfur ions near Thebe have energies of about 40 keV, resulting in gyroradii of 25% of Thebe's radius (R. E. Johnson, personal communication, 1991), so ion bombardment is a feasible mechanism for explaining Thebe's leading/trailing albedo asymmetry. The fact that Amalthea exhibits little, if any, leading/trailing albedo difference supports the notion that interaction with charged particles in Jupiter's rotating magnetosphere is the leading cause of this asymmetry. This follows because Amalthea has the lowest velocity relative to the magnetosphere. If this is the case, the two innermost satellites, Adrastea and Metis, should have darkened leading sides, since they revolve faster than the magnetosphere rotates.

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