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RECOVERING THE ROTATIONAL LIGHT CURVE OF PHOEBE

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ABSTRACT

We present rotational light-curve data for Saturn's satellite Phoebe taken over the observing period prior to the *Cassini* mission's encounter with that moon. We find a rotation period of 9.2735 ± 0.0006 hr, a factor of 25 improvement in the rotation period's uncertainty over previously published data. This improved rotation period measurement allow s us to correlate previously observed spectral features and colors with albedo features observed by *Voyager* and to predict which side of Phoebe will be observed by *Cassini* during its 2004 June 11 encounter. The light curve, sampled at subobserver latitudes farther south than achieved by *Voyager*, shows evidence of surface features that cannot be explained by previously published shape models or albedo maps and that may be located in the regions in Phoebe's southern hemisphere that were unobserved by *Voyager*.

Subject headings: comets: general — Kuiper Belt — minor planets, asteroids — planets and satellites: individual (Phoebe) — solar system: formation

Online material: color figure

1. INTRODUCTION

On 2004 June 11, the *Cassini* spacecraft will make an unprecedented close (2000 km) flyby of the Saturnian satellite Phoebe. This object is not only interesting in its own right, but it may produce particles that are the source of the low-albedo, primitive material on one hemisphere of the enigmatic satellite Iapetus (Buratti et al. 2002). Furthermore, as an outer, retrograde, eccentric satellite, Phoebe is very likely a Kuiper Belt object (KBO) captured by Saturn as it migrated inward from the Kuiper-Edgeworth Belt. Accordingly, with the possible exception of the active, and therefore surface-altered, Jupiter family comets that have undergone spacecraft observations (e.g., Soderblom et al. 2004), the flyby of Phoebe may also represent the first encounter of a spacecraft with a KBO and mark the transition of the study of KBOs from discovery and gross physical characterization to close investigation.

The purpose of this Letter is to provide updated information on the rotational state of Phoebe and its geometric albedo and surface albedo distribution, particularly in regions not imaged by *Voyager*. We have obtained measurements of the current period and rotational epoch of Phoebe in support of the *Cassini* mission. Our results are based on nine nights of observations at Table Mountain Observatory (TMO) taken over a span of 3.5 months. Predictions regarding albedo patterns are especially valuable because they offer clues to the geologic history of Phoebe and volatile transport on its surface. Although its rotational period has been determined to be 9.282 ± 0.015 hr (Kruse et al. 1986), and the distant observations by *Voyager* provided data that yielded Phoebe's size and albedo (Thomas et al. 1983), no observations of Phoebe's rotational state have been published in the last 18 years. A particular concern to the *Cassini* mission is that Phoebe's rotational phase is entirely unknown, since the error in the Kruse et al. (1986) period propagated to the current epoch is greater than the period. Our results also enable the spectroscopic observations of different longitudes of Phoebe (Buratti et al. 2002; de Bergh et al. 2003) to be interpreted in the context of *Voyager* albedo maps, because the true longitude at the times of these observations was unknown (albedo maps of Phoebe indicate normal reflectances that vary by a factor of 2, from 0.06 to 0.13 at an effective wavelength of 0.48 μm; Simonelli et al. 1999). Finally, as most of our TMO observations were obtained under photometric conditions, they will provide the additional benefit of being a calibration benchmark early in the *Cassini* mission.

2. OBSERVATIONS AND ANALYSIS

On the nights of 2003 December 2–3, 2004 January 13–16, and 2004 March 14–16 (UT), we observed Phoebe's rotation light curve from the 0.6 m telescope located at Jet Propulsion Laboratory's TMO using the facility's Tek 1024 × 1024 CCD camera, with a pixel scale of 0″.523. We observed through a standard Johnson *V* filter (0.55 μm). The observations are summarized in Table 1.

Multiple-frame standard stars were selected to compare Phoebe's brightness over the course of each observing run. Landolt equatorial standard fields (Landolt 1992) were taken during each of the clear nights so that we could calibrate our frame standards. Saturn was at opposition in January, and so the coverage of Phoebe's light curve in our March data was less complete, although we still managed to obtain two brightness peaks. Phoebe was also considerably closer to Saturn in March (600″ west of Saturn, 100″ south), and scattered light was present over most of the frames. Our aperture background subtraction seemed to adequately remove the local background light, but the noise was noticeably greater in this last run's data than in the prior two when Phoebe was more than 1900″ away from Saturn.

The frames were bias-subtracted and flattened in the usual manner, and cosmic rays were removed from regions on the images near Phoebe or the standard stars. We used aperture photometry, with 8″ diameter apertures, on all of our objects, including the photometric standards and Phoebe frame standard stars. Images with cosmic rays directly in Phoebe's seeing disk, or where Phoebe was too close to background objects, were excluded from our photometry sample. Landolt standards were used to remove atmospheric extinction and adjust the nightly magnitude zero point. In most cases, the uncertainties were ~0.01 to 0.05 mag. Six maxima, listed in Table 2, were observed in the nine nights' data.

Rotation period fits, a solar phase-curve behavior analysis,

TABLE 1

PHOEBE OBSERVING RUNS AT TMO

Dates (UT)	JD − 2,450,000.0	$\langle\alpha\rangle$[a] (deg)	$\langle r\rangle$[b] (AU)	$\langle\Delta\rangle$[c] (AU)	$\langle m_V\rangle$[d]	Observing Conditions
2003 Dec 2–3 ………	2975.5–2976.5	3.2	9.04	8.18	16.32	Clear
2004 Jan 13–16 …….	3017.5–3020.5	1.7	9.00	8.05	16.26	Last night clear, otherwise thin cirrus
2004 Mar 14–16 ……	3078.5–3080.5	6.2	8.96	8.72	16.59	Clear

[a] Mean Sun-target-observer (i.e., solar phase) angle for the observing run.
[b] Mean heliocentric distance.
[c] Mean target-observer distance.
[d] Mean Phoebe *V*-filter magnitudes from the raw photometry data points.

and a comparison to known surface albedo features and shape models of Phoebe were conducted using the results of the photometry.

Rotation period.—An initial fit to the period of the rotational light curve was performed using the maxima observed on 2003 December 3 and 2004 January 14, which yielded results of 9.274 ± 0.002 hr. Using this initial fit, we aligned the light-curve data from each night by eye, correcting the magnitude offsets caused by any zero-point uncertainty, heliocentric and observer distance offsets, or phase-angle differences and the temporal offsets owing to light-travel time and viewing geometry. After the data were aligned, it was easier to see which individual points corresponded to the maxima in our combined data.

Selecting the exposure's midpoint times for the maxima points (see Table 2), we conducted a least-squares fit to the period, again accounting for the proper temporal offsets, arriving at a value of 9.2737 ± 0.0006 hr. We also applied a phase-dispersion minimization (PDM; Stellingwerf 1978) technique using the method described in Bauer et al. 2002. The PDM fitting results have a minimum for the χ^2 parameter at 9.2734 ± 0.0006 hr. We take as our final value the average of the periods determined using these two separate methods, $P = 9.2735(5) \pm 0.0006$ hr. Figure 1 shows the data rephased to this period value after removing the temporal offsets owing to light-travel time variances and viewing geometry. The error bars represent the statistical uncertainty for each image of Phoebe as formally derived from the photon noise and sky background statistics.

Phase-curve behavior.—From Figure 1, it is apparent that we had sufficient data to fit the light curve's shape, in this case using an eighth-degree polynomial function. We then subtracted this fit from each of the distance-corrected data points observed during the photometric nights. We used the magnitude dispersion in the nightly averages as the uncertainty for each of our phase-curve points shown in Table 3. Our data points yield a fit to a Lumme-Bowell–type phase function (Bowell et al. 1989), with parameter values of $G = 0.14 \pm 0.04$ and $H_V(1, 0) = 6.65 \pm 0.02$, which agrees closely with the value used by Kruse et al. (1986; $G = 0.15$). Using the mean radius for Phoebe of 110 km from Thomas et al. (1983), we find a geometric albedo value $p_V = 0.0821 \pm 0.0015$.

Comparison to known surface features.—Our subobserver latitudes (−19°; see Table 3) were considerably farther south compared to those of the *Voyager* images (23°; Simonelli et al. 1999) and to the Kruse et al. (1986) data (29°). In order to examine the possibility that additional surface features were present at unobserved southern latitudes, we calculated what shape of rotational light curve they would produce by Phoebe's known surface features. The *Voyager*-based albedo map from Simonelli et al. (1999) was mapped onto a triaxial ellipsoid shape model derived from *Voyager* images by Thomas et al. (1983). Two versions of the albedo map were used in our efforts to model the light-curve work, involving two different models of the appearance of the south polar region unobserved by *Voyager*. The first model (model A in Fig. 2) fills this region uniformly with Phoebe's average *Voyager*-derived normal reflectance from Simonelli et al. (1999). The second model (model B in Fig. 2) uses the Simonelli et al. (1999) map again and extends the southernmost features of the albedo map (averaged over the southernmost 3° of latitude) southward.

In projecting the albedo map onto the shape model, no limb darkening was included, as we expect these effects to be min-

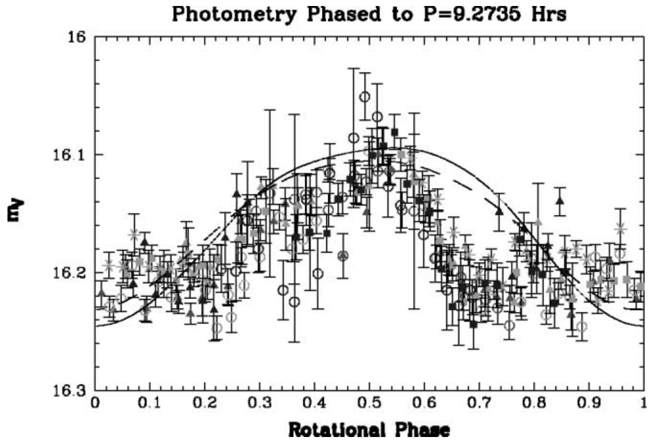

FIG. 1.—Rotationally phased light-curve data. Symbols and colors correspond to the observing night; red, green, and blue represent the December, January, and March data sets, respectively, and the circles, triangles, squares, and asterisks represent the first, second, third (where applicable), and fourth (where applicable) nights of each run. Magnitudes are plotted as a function of rotational phase, and the error bars represent the uncertainty in each point as derived from the photon noise and sky background statistics. The model curves are derived from the *Voyager*-based shape model and albedo map, using the mean albedo (*dashed curve*) and linearly projected feature (*solid curve*) methods. A rotational phase value of 0.5 corresponds to 0° longitude in the longitude system of Colvin et al. (1989; used in the albedo map of Simonelli et al. 1999). [*See the electronic edition of the Journal for a color version of this figure.*]

TABLE 2

PHOEBE'S LIGHT-CURVE MAXIMA

JD	α (deg)	r (AU)	Δ (AU)	Observing Conditions
2,452,975.969(5) ± 0.007 ……	3.277	9.039	8.183	Photometric
2,452,976.738(8) ± 0.007 ……	3.197	9.038	8.176	Photometric
2,453,017.685(5) ± 0.007 ……	1.517	8.999	8.042	Thin cirrus
2,453,018.854(2) ± 0.007 ……	1.653	8.998	8.046	Thin cirrus
2,453,078.737(9) ± 0.008 ……	6.222	8.964	8.702	Photometric
2,453,080.691(1) ± 0.008 ……	6.267	8.963	8.733	Photometric

TABLE 3

Solar Phase-Curve Points

Date (UT)	Latitude[a] (deg)	α (deg)	m_V[b]
2003 Dec 2	−17.35	3.29	16.54 ± 0.02
2003 Dec 3	−17.38	3.19	16.53 ± 0.02
2004 Jan 16	−19.11	1.88	16.43 ± 0.02
2004 Mar 14	−20.19	6.22	16.69 ± 0.04
2004 Mar 15	−20.19	6.25	16.69 ± 0.03
2004 Mar 16	−20.18	6.27	16.69 ± 0.03

[a] Subobserver latitude.

[b] Magnitudes are corrected to the mean heliocentric and geocentric distances of Saturn at opposition ($r = 9.54$ AU, $\Delta = 8.54$ AU).

imal relative to our light-curve observational uncertainties for such a dark object (and based on the appearance of the *Voyager* images). The resulting reflectance values, calculated for 360 subobserver longitudes (λ) and a subobserver latitude $\vartheta = -19°$, were converted to disk-integrated magnitudes as viewed from mean Saturn heliocentric and geocentric opposition distances and plotted over our phased rotational light-curve data (Fig. 1). In overlaying these model light curves, we assumed that the light-curve maximum in the telescope observations corresponds to the longitude at which the southern part of the *Voyager* albedo map is brightest; in the Colvin et al. (1989) longitude system used in the albedo map, this brightest longitude is approximately 355° ± 20° west. Note that it is this assumed correspondence of light-curve and albedo map maxima that allows us to extrapolate through time to predict the *Cassini* encounter longitudes at closest approach and to project which subobserver longitudes were seen during previous spectral observations.

3. DISCUSSION

The validity of the link of our light curve to the *Voyager* albedo map depends on the correspondence of the peak light-curve brightness to the albedo map's brightness features near Phoebe's equator. It should be noted that the difference in subobserver latitudes between current and *Voyager* epochs may adversely effect our longitudinal projections should significant new albedo or topographical features exist near the southern pole. Yet, some comfort may be taken that longitudinally isolated extremely bright features are unlikely to dominate the southern hemisphere as the amplitudes of our *Voyager*-based model and our light curve do nearly agree. Furthermore, we believe the larger amplitude reported by Kruse et al. (1986) is likely attributable to the apparent bright patch at $\lambda \approx 17°$, $\vartheta \approx 65°$ (Simonelli et al. 1999), visible at their epoch of observations but not ours, which would have been mostly hidden from our view (Fig. 2). There is some evidence of relatively weak, spatially constrained albedo features in our light curve near the expected light-curve minimum (Fig. 1). Specifically, from rotational phase values of 0.9 through unity and on to 0.1, corresponding to $\lambda \approx 144°$–$206°$, most of the observed light-curve points lie above the signal level (at 1–2 σ) expected from the Simonelli et al. (1999) albedo map and the Thomas et al. (1983) shape model. The true shape of Phoebe may also deviate from a triaxial ellipsoid, especially at latitudes unobserved by *Voyager*. A southern albedo or shape feature may better explain the light curve's steeper-than-expected drop-off of the peak brightness near the 0.65 rotational phase ($\lambda \approx 306°$). The shape of our light curve deviates from the Kruse et al. (1986) data as well, as their light curve does not differ greatly from a sine curve.

The rotation period was updated to sufficient accuracy to determine the average subspacecraft longitude at the time of *Cassini*'s closest approach, at 19:33 UT on 2004 June 11, to be $\lambda = 321(^{+12}_{-24})$ deg west (with a predicted subspacecraft latitude of $\vartheta = 15°$). The rotation period was also accurate enough to determine the subobserver longitudes of several published Phoebe spectral observations and thereby to see whether or not observed spectral bands might be associated with specific known surface albedo features. The correlation between surface albedo and spectral features is of particular interest to the study of minor planets in the outer solar system. Whether observed absorption bands in Centaur and KBO spectra (see, e.g., Brown 2000, Bauer et al. 2002, and Barucci et al. 2002) are caused by species that are intimately mixed or spatially variegated may not only significantly change the compositional fits to the spec-

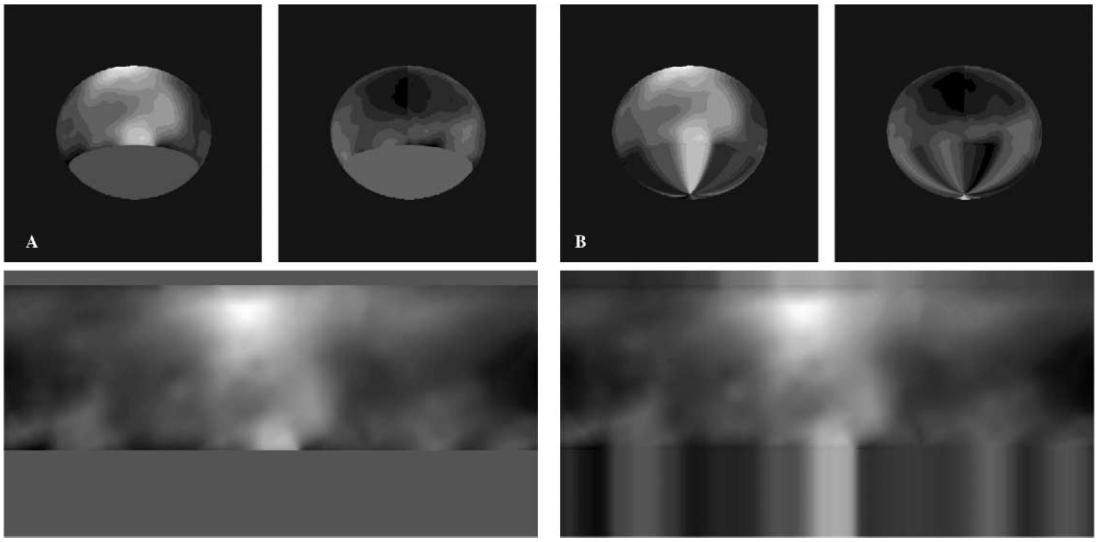

Fig. 2.—Two albedo and shape models (A and B) used in making model rotational light curves as described in the text. The bottom panels show how the *Voyager* albedo map was extended into the unobserved southern latitudes. The four top panels show the projection of the maps onto the Thomas et al. (1983) shape model for Phoebe, at subobserver latitude −19° and subobserver longitudes 0° and 180° west.

tra but may also provide clues as to whether these species are exposed or implanted by exogenic or endogenic processes (Hainaut et al. 2000; Owen et al. 2001). Color and albedo correlations have broader implications regarding the reported color bimodality or gradients among outer solar system small bodies (e.g., Tegler & Romanishin 2003; Bauer et al. 2003) and how to interpret these observed phenomena.

Two published near-infrared (NIR; over 1–2.4 μm) spectra of Phoebe in the literature show 2 μm water-ice absorption features (Brown 2000; Owen et al. 1999). In addition, de Bergh et al. (2003) have reported obtaining full NIR spectral coverage of Phoebe's surface, although these latter spectra have yet to be published. Buratti et al. (2002), observing at visible wavelengths (0.33–0.92 μm) and at two greatly differing subobserver longitudes, reported no spectral variation with longitude. We estimate subobserver longitudes of 327° and 176° west for the Buratti et al. (2002) spectra taken on 1998 November 14 and 15, respectively. Both have uncertainties of 111° in their absolute longitude values but less than 1° in their longitudinal difference, Δ_λ, of 150°. This longitudinal separation makes it unlikely that the brighter and darker regions of Phoebe differ in color at optical wavelengths, especially because the first of the two spectra may lie within 50° of the brightest region on the satellite. The two published NIR spectra that report water-ice features do not rule out a variegated surface, with localized water ice, entirely. For the most recent NIR data set (Brown 2000), taken on 1998 August 2, when $\vartheta = -31\overset{\circ}{.}5$ for Phoebe, our longitudinal estimates have an uncertainty of $\pm 118°$ and yield a predicted subobserver longitude for the Brown (2000) data of $\lambda \approx 186°$ west. The brightest longitude in the *Voyager* data, $\lambda \approx 17°$, would not have been visible to the observer, and it is unlikely in any case that the subobserver point was any closer than ∼50° to the brightest region, although a more southern, unobserved bright patch of surface ice may have been present. We project $\lambda = 207°$ (and $\vartheta = -19\overset{\circ}{.}1$) for the spectral observations shown in Owen et al. (1999). However, our longitude reference point uncertainty becomes unreliably large, with $\sigma_\lambda \approx 181°$, back to 1997 September 7, the time of the Owen et al. (1999) data. For the relative offset between the 1998 and 1995 NIR spectra, $\Delta_\lambda = 21° \pm 64°$, the uncertainty is considerably smaller. It is possible that the two spectra are sampling the same water-ice patch or patches.

In conclusion:

1. We have found Phoebe's rotation period to within 2.2 s (1 σ uncertainty): 9.2735($\pm$0.0006) hr. We predict that the subspacecraft longitude at *Cassini*'s closest approach on 2004 June 11 will be $321(^{+12}_{-24})$ deg west.
2. Our *V*-band phase-curve data points confirm the low–phase-angle brightness trends observed by Kruse et al. (1986), with a Lumme-Bowell–type phase-curve model fit of $G = 0.144 \pm 0.018$ and $H_V(1, 0) = 6.651 \pm 0.008$.
3. We project the subobserver longitudes for the known water-ice features observed in the NIR. The Brown (2000) NIR spectrum, at $\lambda = 186° \pm 118°$ west, correlates poorly with the hemisphere that contains the brightest albedo feature reported in Simonelli et al. (1999). The Owen et al. (1999) spectrum, with virtually no longitudinal constraints with respect to the *Voyager* albedo map, is offset by $+21°(\pm 64°)$ west relative to the Brown (2000) spectrum, covering virtually the same hemisphere.
4. Phoebe's rotational light curve shows evidence of more features, south of latitude $-30°$, albedo or topographical in nature, than revealed in the *Voyager* images.

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[1] See http://ssd.jpl.nasa.gov.

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