ESTIMATE OF TIDAL Q OF MARS USING MOC OBSERVATIONS OF THE SHADOW OF PHOBOS.

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Introduction: Phobos, the larger of the two small moons of Mars, is undergoing rapid orbital evolution due to tidal interaction with Mars. Phobos is very close to Mars, with a mean distance of only 2.8 R_{Mars}, within the synchronous orbital distance. Thus, Phobos's orbit is moving inward. The rate of this secular acceleration can give us information about tidal dissipation in the interior of Mars. Although Phobos has been extensively studied since its discovery in 1877, few new observations have occurred since 1990. We have used images from the Mars Orbiter Camera (MOC) to indirectly observe Phobos using its shadow on the surface of Mars. The observed position of Phobos's shadow agrees well with predictions based on the current orbital model, except that Phobos is getting slightly ahead of its predicted position, a result also found by Bills et al. using Mars Orbiter Laser Altimeter (MOLA) detections of the shadow of Phobos [1]. Using the MOC and MOLA datasets, we calculate a revised value for the secular acceleration of Phobos, and use this to estimate the tidal *Q* of Mars.

Martian eclipses: Because Phobos is so close to Mars and has a very fast orbital period (7.65 hours), solar eclipses occur frequently: ~3 per day over most of the year [2]. Because Phobos is so small in size (approximately 13 x 11 x 9 km), all solar eclipses on Mars are partial eclipses. The shape, size, and movement of the shadow of Phobos are described in detail in [2]. The shadow is roughly circular and ~30 km in diameter when close to the subsolar point. In MOC images, the ellipticity of the shadow is exaggerated due to the relative motion of Phobos and the spacecraft.

MOC observations: We found 360 shadow detections by MOC between 1999 and 2004. All are images taken with the MOC wide angle camera. Of these, 354 are from global image swaths with low resolution (~6 km/pixel), and 6 are medium resolution (~200 m/pixel). Examples of typical shadows are shown in Figure 1. For each shadow, we fit a two-dimensional Gaussian function to the shadow intensity to find the location of the center of the shadow (Figure 2). To properly make a comparison with the predicted location of Phobos's shadow, we actually need the shadow of the center of Phobos, which is only the same as the center of the shadow when Phobos is directly above the subsolar point, but we have ignored this discrepancy.

Orbital model: Because the corrections required are small, we can use a linear perturbation analysis and only adjust the parameters that determine the mean orbital longitude. The mean longitude as a function of time is written as:

$$\lambda(t) = L + n(t-\tau) + s(t-\tau)^2 , \qquad (1)$$

where L is the mean longitude at reference time τ, n is the mean motion, and s is half the secular acceleration. Following the analysis described in [1], for each shadow observation, we calculated the time that Phobos was ahead or behind its predicted location and then used this time offset to calculate a longitude residual using an initial estimate for the mean motion n. We then fit a quadratic expression to the longitude residuals to find the value of s (Figure 3).

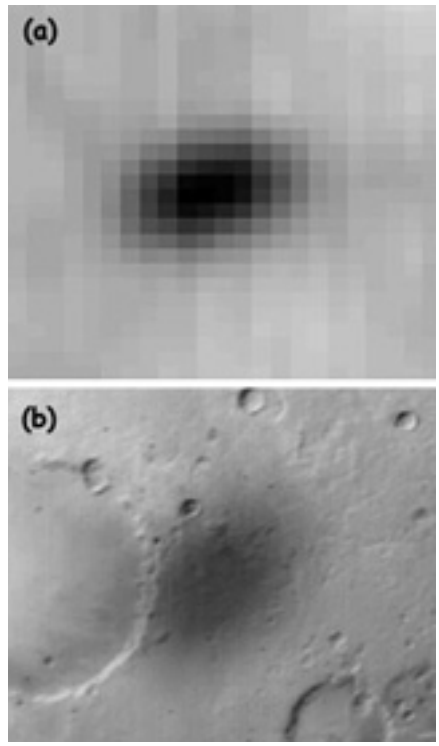

Figure 1. Typical images of the shadow of Phobos in (a) a low-resolution (~6 km/pixel) global image swath and (b) a medium-resolution (~200 km/pixel) wide angle image. In both images, the shadow is ~40 km across.

Results: Previous estimates for the parameters L, n, and s from the historical data in [3] are:

L = 138.003 ± 0.026 deg
n = 1128.844407 ± 0.000020 deg/day
s = 1.249 ± 0.018 × 10-3 deg/yr^2

Fitted values for the dataset which includes the MOC and MOLA observations plus historical values are:

L = 137.764 ± 0.015 deg
n = 1128.844411 ± 0.000013 deg/day
s = 1.334 ± 0.006 × 10-3 deg/ yr^2

Using observations of the shadow of Phobos from

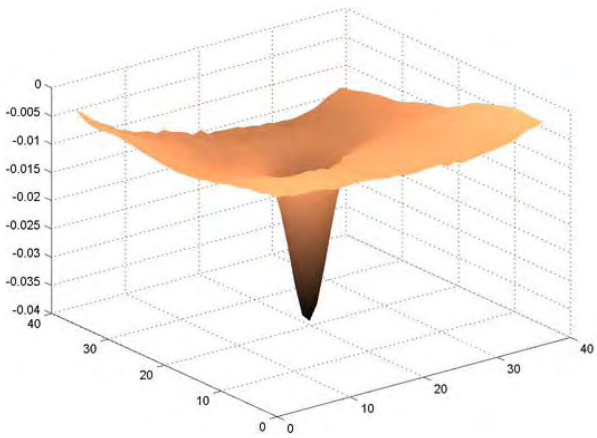

Figure 2. Intensity map of a typical image of the shadow of Phobos and surrounding area. The image covers an area ~150 km wide. To find the center of the shadow, a 2-D Gaussian is fit to this peak.

MOC and MOLA, we have not only refined the value of the secular acceleration, but also decreased the uncertainty associated with this value.

Tidal *Q* of Mars: Because dissipation occurs within Mars, the tidal bulge induced by Phobos on Mars is misaligned with Phobos's position by an angle γ. The secular acceleration of Phobos can be related to the phase shift γ by the following, derived in [5]:

$$\frac{2}{n}s = -3n\left(\frac{m_s}{M}\right)\sum_{j=2} k_j \left(\frac{R}{a}\right)^{2j+1} \frac{dP_j(\cos\gamma)}{d\gamma}, \quad (2)$$

where n is the mean motion, s is half of the secular acceleration, m_s is the mass of Phobos, M is the mass of Mars, R is the radius of Mars, a is Phobos's semi-major axis, k_j are the Love numbers of Mars, and P_j are Legendre polynomials. The phase shift γ is related to Q, the quality factor, by $1/Q = \tan(\gamma)$. Thus, using our fitted value of s, we can solve for k_j/Q. The higher order terms in this expression fall off quickly, but because Phobos is very close to Mars, higher-order terms are non-negligible (the k_3 term is around 20% of the k_2 term). A recent estimate of k_2 was given in [6]: $k_2 = 0.153 \pm 0.017$. No measurements exist of higher order k_j. However, using the k_2 term only, we can get a reasonable estimate for the tidal Q of Mars: $Q = 157.2 \pm 1.7$. The quoted uncertainty is mathematical and is not representative of the actual uncertainty since higher order terms were neglected. For comparison, the solid Earth (without oceans) has $Q \approx 280$ [7]. Thus, Mars appears to be more dissipative than Earth.

Conclusions: Using MOC images of the shadow of Phobos, we were able to substantially increase the existing dataset of Phobos observations. Using these MOC observations, we were able to refine the value of secular acceleration of Phobos's orbit and reduce the uncertainty associated with this value. We find that

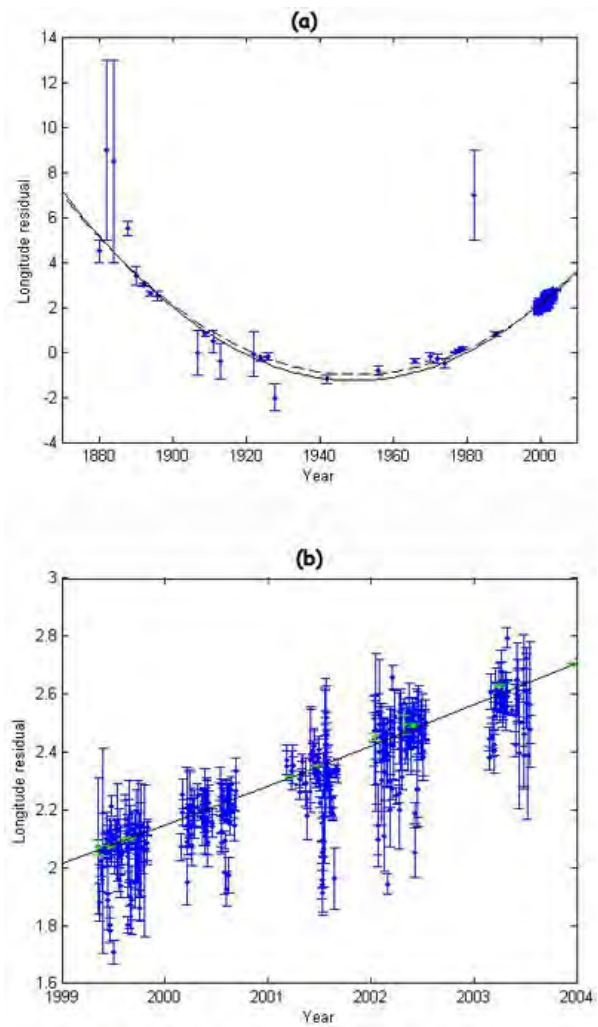

Figure 3. (a) Historical values of longitude residuals from [3] plotted with the MOC and MOLA values. The dotted line is the fit without MOC and MOLA data, and the solid line is the new fit. (b) Zoom in on the region of the plot in (a) containing the MOC and MOLA data. The blue data points are from MOC, and the green data points are from MOLA.

Phobos's acceleration is faster than previously estimated. We also find that Mars has a significantly lower value of Q than the solid Earth, implying that Mars is more dissipative.

References: [1] Bills B. G. et al. (2005) *JGR, 110*, doi:10.1029/2004JE002376. [2] Bills B. G. and Comstock R. L. (2005) *JGR., 110*, doi:10.1029/2003JE002209. [3] Jones D. H. P. et al. (1989) *Mon. Not. R. Ast. Soc., 237*, 15-19. [4] Jacobson R. A. et al. (1989) *Astron. Astrophys., 225*, 548-554. [5] Redmond J. C. and Fish F. F. (1964) *Icarus, 3*, 87-91. [6] Yoder C. F. et al. (2003) *Science, 300*, 299-303. [7] Ray R. D. et al. (2001) *Geophys. J. Int., 144*, 471-480.

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