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Solar eclipses of Phobos and Deimos observed from the surface of Mars

J. F. Bell III[1], M. T. Lemmon[2], T. C. Duxbury[3], M. Y. H. Hubbard[1], M. J. Wolff[4], S. W. Squyres[1], L. Craig[3] & J. M. Ludwinski[3]

The small martian satellites Phobos and Deimos orbit in synchronous rotation with inclinations of only 0.01° and 0.92°, respectively, relative to the planet's equatorial plane. Thus, an observer at near-equatorial latitudes on Mars could occasionally observe solar eclipses by these satellites (see ref. 1, for example). Because the apparent angular diameter of the satellites is much smaller than that of the Sun, however, such events are more appropriately referred to as transits. Transit data can be used for correcting and refining the orbital ephemerides of the moons. For example, Phobos is known to exhibit a secular acceleration that is caused by tidal dissipation within Mars[2–4]. Long-term, accurate measurements are needed to refine the magnitude and origin of this dissipation within the martian interior as well as to refine the predicted orbital evolution of both satellites[5,6]. Here we present observations of six transits of Phobos and Deimos across the solar disk from cameras on Mars aboard the Mars Exploration Rovers Spirit and Opportunity[7,8]. These are the first direct imaging observations of satellites transiting the Sun from the surface of another planet.

Transits of Phobos were observed indirectly from Viking Lander camera light-curve imaging of the martian sky[9,10] and from orbital imaging of the shadow cast by Phobos onto the planet[4,11–13]. The new transit observations reported here were made with the Pancam imaging system[8] carried by each rover. Pancam is a 1-cm-aperture, focal ratio *f*/20, $1,024 \times 1,024$-pixel charge-coupled device camera capable of acquiring images of the Sun at a spatial scale of 0.28 mrad per pixel using neutral-density narrowband blocking filters. All transit observations were made using an 880 ± 20-nm solar filter. We acquired images of four transits of Phobos and two transits of Deimos during March and April 2004 (Table 1). Four 'full' transits, two for Phobos and two for Deimos, were observed such that the standard contact point times could be derived; the other two observed transits were 'grazing' events for Phobos.

The first four events were observed from the Mars Exploration Rover MER-B rover Opportunity, which landed at 354.47417° E, 1.9483° S, and a radius of 3394.1482 km (Mars coordinates fixed by the International Astronomical Union, IAU, in 2000) and the last two events were observed from the MER-A rover Spirit, which landed at Mars coordinates of 175.4729° E, 14.5692° S, and a radius of 3392.2997 km (refs 14, 15). The positions of the rovers were modelled using the Jet Propulsion Laboratory (JPL) Navigation and Ancillary Information Facility (NAIF) spacecraft, planet, instruments, C-matrix, and events (SPICE) kernels mer1_ls_040128_iau2000_v1.bsp, mer1_surf_rover_0405181049.bsp, mer2_ls_040108_iau2000_v1.bsp, and mer2_surf_rover_0405172316.bsp (available at ftp://naif.jpl.nasa.gov/pub/naif/MER/kernels/spk). For each transit image acquired, rover flight software extracted a 63×63-pixel image centred on the solar disk, which is ~22 pixels

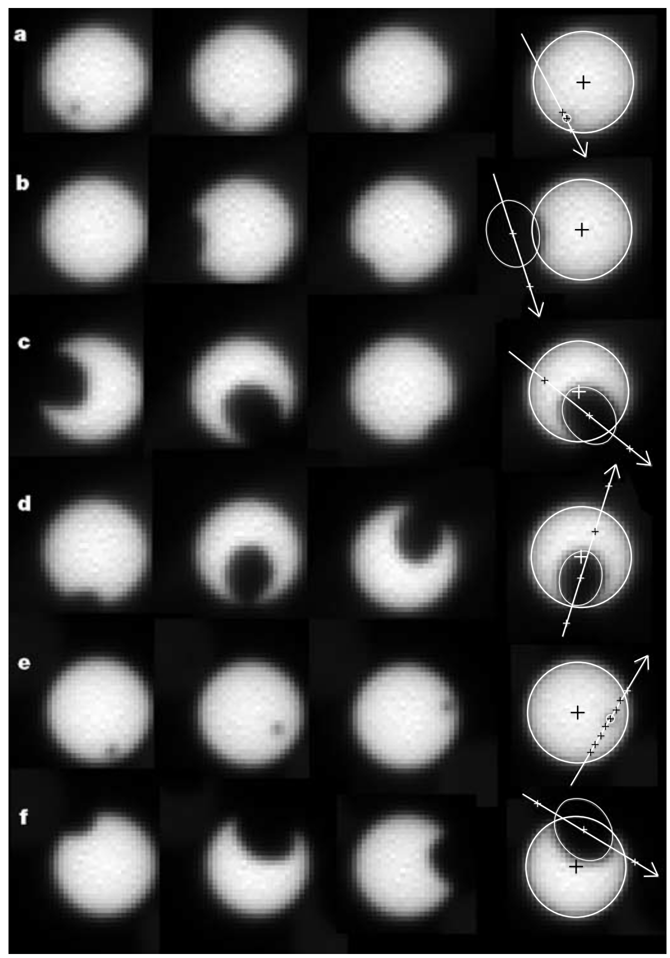

Figure 1 | Summary images of the transits observed by Spirit and Opportunity. Early contact or pre-contact images are shown in the first column, mid-transit images are in the second column, and late contact or post-contact images are shown in the third column. The fourth column shows our model of the path of the satellite during each event. **a**, MER-B Sol 39 Deimos transit of 2004-03-04. Images shown at 10 s spacing. The observations began near the middle of the event. **b**, MER-B Sol 42 Phobos grazing transit of 2004-03-07. Images shown at 10 s spacing. **c**, MER-B Sol 45 Phobos transit of 2004-03-10. Images shown at 10 s spacing. **d**, MER-B Sol 47 Phobos transit of 2004-03-12. Images shown at 10 s spacing. **e**, MER-A Sol 68 Deimos transit of 2004-03-13. Images shown at 30 s spacing. **f**, MER-A Sol 104 Phobos grazing transit of 2004-04-18. Images shown at 10 s spacing.

[1]Cornell University, Ithaca, New York 14853-6801, USA. [2]Texas A&M University, College Station, Texas 77843, USA. [3]Jet Propulsion Laboratory/Caltech, Pasadena, California 91109, USA. [4]Space Science Institute, Boulder, Colorado 80301, USA.

Table 1 | Summary of observed transit events

Event	Satellite	MER	Sol	Date (UTC)	d_{Sun} (arcsec)	α_{obs} (°)	α_{pred} (°)	Contact point times (UTC hh:mm:ss)				D_{obs} (s)	D_{pred} (s)	ΔT (s)
								I	II	III	IV			
A	Deimos	B	39	2004-03-04	1,241	0.11	0.16	03:03:02	03:03:10	03:04:25	03:04:33	91	66	−3
B	Phobos	B	42	2004-03-07	1,238	0.23	0.20	02:46:31	n/a	n/a	02:46:45	14	20	−3
C	Phobos	B	45	2004-03-10	1,235	0.04	0.06	07:36:32	07:36:43	07:36:49	07:37:01	29	31	−3
D	Phobos	B	47	2004-03-12	1,233	0.02	0.04	13:40:58	13:41:10	13:41:19	13:41:31	32	34	−3
E	Deimos	A	68	2004-03-13	1,232	0.11	0.15	00:04:24	00:04:31	00:05:39	00:05:47	83	68	−2
F	Phobos	A	104	2004-04-18	1,202	0.12	0.11	21:06:05	n/a	n/a	21:06:31	26	29	<9

'Sol' is the number of martian solar days (24 h 39 min 35.244 s) after the landing of each rover; d_{Sun} is the apparent angular diameter of the Sun in arcsec; α_{obs} is the observed phase angle of the transit, measured as the angular distance between the centre of the Sun and the mid-transit position of the satellite; α_{pred} is the predicted phase angle from currently-available ephemeris information; Contact point times are listed as hour:minute:second in Universal Time Coordinated (UTC); D_{obs} is the observed (modelled) duration of the transit in seconds; D_{pred} is the predicted duration from currently-available ephemeris information; ΔT is the estimated difference (due to clock drift) of the actual UTC time minus the UTC time as recorded on each rover, in sec. The uncertainty on ΔT is estimated to be between 2 to 5 s, but this is a systematic error that does not appear to introduce meaningful errors into our orbit-fitting procedure (see text).

across. Images were acquired every 10 s during each of the transit events, which is the fastest full-resolution frame rate possible for the rover imaging system. Because the satellites moved rapidly relative to the solar disk, the duration of the full transits were only 29 to 91 s and the partial transits lasted only 14 and 26 s, and so each event was captured in only two to eight images. Summary images of each of the events are presented in Fig. 1.

We used an image centroiding algorithm to determine the relative positions of the centre of the satellite and the centre of the solar disk for each image and used that information to generate a simple linear model of satellite position versus time. The model fit was then used to estimate the times of the four canonical transit contact points listed in Table 1. The Sun from Mars has an apparent angular diameter ranging from 1,160 to 1,400 arcsec because of the large eccentricity of the planet's orbit. At the time of the observed transit events, the Sun had an apparent angular diameter of ~1,200 arcsec (Table 1). Phobos, with a size of 27 × 22 × 19 km and a distance from the martian surface of ~5,984 km, has an apparent angular diameter at zenith of about 700 arcsec, but this decreases by ~32% if the satellite is near the horizon. Phobos was observed to transit at angles ranging from 24° to 56° from the zenith, and was approximated in our model as an ellipse with a semimajor axis of 5.7 to 7.0 pixels and a semiminor axis of 4.4 to 5.4 pixels, depending on zenith angle. Deimos, with a size of 16 × 12 × 10 km and a distance from the martian surface of ~20,060 km, has an apparent angular diameter at zenith of about 135 arcsec, decreasing by only ~14% with the satellite near the horizon. Because the two Deimos transits occurred at zenith angles of 22° and 33°, for this analysis the satellite was adequately approximated as a circle with a constant diameter of 1.6 pixels. The solar disk was modelled as a circle with a diameter of 20 to 22 pixels. Contact points were defined as occurring when any part of the modelled Deimos circle or Phobos ellipse intersected the modelled solar circle. The phase angle was defined as the angular distance between the centre of the modelled solar disk and the closest point on the best-fit linear model of satellite position versus time. Because none of the transits were observed with the satellites close to the horizon, the effects of differential atmospheric refraction on the relative positions of the moons and sun were negligible at the 1-km-level accuracy of the results presented here.

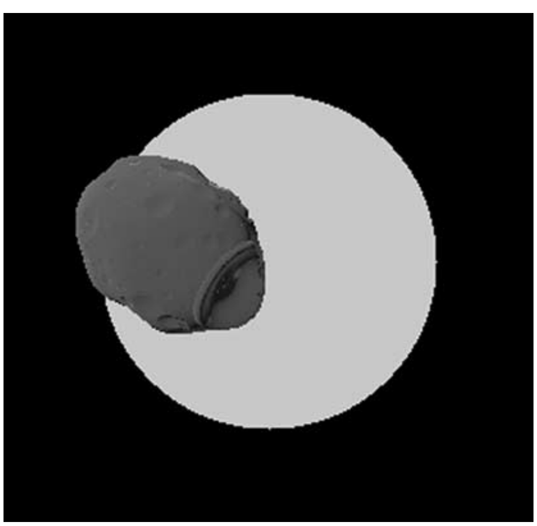

Figure 2 | Simulation of the position and orientation of Phobos relative to the Sun during the MER-B Sol 45 transit event of 2003-03-10 allowing both in-plane and out-of-plane orbit correction assessments.

The observed times of contact, corrected for systematic rover clock drift uncertainties, as well as the full images showing the moon positions during transit, were compared to the predicted times and images using the JPL Development Ephemeris mar033-7.bsp, which has not been updated since 1989 (refs 13, 16). Both local in-plane and out-of-plane orbit corrections were determined by matching simulated images to actual images (Fig. 1 shows the actual images and Fig. 2 shows an example of a simulated image).

Derived offsets between the predicted and observed positions of Phobos indicated that it was ahead of its predicted position by about 11 km (+0.071° in orbital longitude) and below by about 0.5 km (−0.003° out-of-plane). All 16 images analysed in the four Phobos events gave this same correction to the 1-km-level accuracy of the observations, providing confidence in the analysis methods and confirming that systematic effects like rover clock drift are being correctly incorporated in our model. The predicted Phobos position accuracy of the ephemeris is 10 km (1σ) at the times of the observations, in good agreement with the observed error. A similar comparison of the two Deimos events indicated that Deimos was about 38 km (+0.125° in orbital longitude) ahead of its predicted position and below by 25 km (−0.061° out-of-plane), also to the 1-km measurement accuracy level. The predicted Deimos position accuracy of the ephemeris was 20 km (1σ), also in reasonable agreement with the observed position correction.

The observed Phobos change is in the direction of increasing secular acceleration. If the observed longitude correction were attributed totally to orbital secular acceleration, then the current value of approximately 0.0013° yr^{-2} would have to be increased by 0.0002° yr^{-2} to match our observations. However, this small possible acceleration drift is comparable to the current uncertainty level of the orbital parameters. Indeed, within the uncertainties, the observed Phobos change could also be due to an error in the epoch orbital parameter values, or their secular rates (for example, mean anomaly or pericentre rate). Therefore, the variations observed in these new transit observations are not statistically significant enough to draw unique conclusions about potential variations in the secular acceleration value.

The limited number of observations, the small ranges in orbital longitude (less than 40° for the four Phobos transits and less than 20° for the two Deimos transits), and the fact that the observed satellite offsets barely exceed the 1σ errors from the propagated ephemerides, prevent us from more uniquely constraining the current orbit parameters, including secular rates. However, if additional observations can be obtained, either from more orbital shadow imaging[4,13] or possibly from the surface if the next transit seasons can be observed by the MER rovers in 2005 and/or 2006, then we will potentially be able to 'sense' the local epoch pericentre by having sufficient orbital longitude coverage, and then map the orbital longitude correction into mean anomaly and mean motion. The accuracy of the secular acceleration value would then be approximately 1 km (positional accuracy derived from transits) divided by $\sim$17 yr squared since the last ephemeris update, or approximately $0.00002^{\circ}\,yr^{-2}$. Thus, under the best-case scenario of additional surface observations spanning a wider range of orbital longitude, it should be possible to expand these results to include significantly improved constraints on satellite secular accelerations.

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