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Phobos mass determination from the very close flyby of Mars Express in 2010

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ABSTRACT

The global geophysical parameters $GM_{Ph} = (0.7072 \pm 0.0013) \times 10^{-3}$ km^3 s^{-2}, C_{20}, C_{22} and the bulk density $\langle \rho \rangle = (1862 \pm 30)$ kg/m^3 have been determined from the closest Mars Express flyby at the Mars moon Phobos on 3rd March 2010 at a distance of 77 km. The second degree gravity field of Phobos (C_{20}, C_{22}) could not be solved for at sufficient accuracy. The low bulk density suggests a high porosity and an inhomogeneous mass distribution but the large errors of C_{20} and C_{22} are still consistent with a homogeneous as well as an inhomogeneous mass distribution. The modeling of the moon's interior by a randomly selected mass distribution of given porosity and water ice content but constrained by the observed GM_{Ph} and $\langle \rho \rangle$ let a simulated C_{20} decrease with increasing porosity and water ice content indicating an increasingly inhomogeneous mass distribution. The high porosity together with an inhomogeneous mass distribution would be evidence that Phobos accreted in orbit about Mars from a debris disk and is not a captured asteroid.

1. Introduction

[1] The origin, composition and internal structure of the Mars moon Phobos remains a mystery. Many scenarios of its origin and formation have been put forward: asteroid capture by Mars (Burns, 1992), simultaneous formation with Mars, formation in orbit from a debris disk of a previously larger body destroyed by gravitational gradient forces near Mars (Singer, 2007), and re-accretion of impact debris blasted into Mars orbit (Craddock, 2011) are prominent among these.

[1a] Visible and infra-red (IR) spectra of the surface of Phobos are distinct from those of the Mars' surface (Giuranna et al., 2011). Infrared spectra of Phobos are more or less featureless as strong absorption bands are absent and evidence of a 3 μm water band are inconclusive. Vernazza et al. (2010) assert that these results suggest that Phobos is a captured object and not related to Mars. The observed surface material, however, may be altered or space weathered as the albedo and surface spectrum are emitted from the first micron or so of surface depth, and do not necessarily represent actual body composition and structure.

One faces a dilemma similar to the Rosetta mission at Asteroid (21) Lutetia: various spectral observations gave contradictory results concerning the classification of the asteroid. Only the determination of the global physical parameters (Pätzold et al., 2011; Sierks, 2011) supported conclusions regarding the internal structure (Weiss et al., 2011).

[2] Clues as to the origin of Phobos are found in the geophysical parameters mass GM_{Ph}, bulk density ρ_{bulk}, and the gravity field, where GM_{Ph} is the product of the gravitational constant G and the Phobos mass M_{Ph}. G is the least known natural constant at a relative error of $\sigma_G/G \approx 10^{-4}$. The product GM, however, may be determined at much higher precision.

[2a] Mass determinations from trajectory changes from spacecraft flybys began with the Viking mission in the late 70's and the soviet Phobos mission in 1988 (Christensen et al., 1977; Tolson, 1978; Williams et al., 1988; Kolyuka et al., 1990). The trajectory and velocity of a nearby spacecraft are perturbed by the attractive force of Phobos sensed through a change in Doppler shift of the radio tracking signal. Bulk density is derived from the ratio of mass to volume where the latter is determined from the shape of Phobos derived from imaging observations (Duxbury, 1991; Thomas, 1993; Willner et al., 2009). The detailed gravity field remained unknown as very close spacecraft flybys were not yet accomplished.

[3] The 2008 flyby of Mars Express (MEX) provided the closest flyby of Phobos in 20 years, leading to the most accurate direct mass determination of $GM_{\mathrm{Ph},2008} = (0.7127 \pm 0.021) \times 10^{-3}$ km^3 s^{-2} to date (Andert et al., 2010). The accuracy of the derived mass also depends on the quality of the ephemerides for Mars, Phobos, and the spacecraft. For comparison, the Phobos mass derived from

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the Mars Express flybys in 2006 at 450 km and 2008 at 275 km were based on the Phobos ephemeris from 2008 (Jacobson, 2008). Reanalysis of the 2008 flyby observations based on the 2010 Phobos ephemeris (Jacobson, 2010) yields a (only slightly changed but now actual) mass value of $GM_{\mathrm{Ph},2008} = (0.7132 \pm 0.022) \times 10^{-3}$ km^3 s^{-2}.

2. Gravity field determination

[4] The closest flyby to date by any spacecraft at Phobos occurred on 3 March 2010. While the planned flyby distance of MEX at Phobos was 62 km, over-performance of the trajectory maneuver before the flyby resulted in a closest approach distance at 77 km. The increase in distance caused a significant reduction of the expected C_{20} contribution close to the noise level. Close flybys provide the opportunity to determine details of the asymmetric gravity field. The expanded gravity potential of an elongated body is usually written as (Vallado, 2001)

$$\Phi(r,\theta,\phi) = \frac{GM}{r}\left\{1+\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{R_0}{r}\right)^{l} P_{lm}(\cos\theta)[C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi)]\right\} = \frac{GM}{r}+\frac{GM}{r}\left(\frac{R_0}{r}\right)^2 P_{20}(\cos\theta)C_{20}+\ldots \quad (1)$$

where r is the radial distance of a test particle to the center of mass M, the $P_{\mathrm{lm}}(\cos\theta)$ are the Legendre polynominals of degree l and order m, C_{lm} and S_{lm} are the expansion coefficients of degree l and order m, R_0 is the reference radius and r,θ,ϕ are the spherical coordinates.

[4b] The second degree gravity coefficient depends on a combination of the ellipticity and flattening of the body, and the internal mass distribution and is usually written as

$$C_{20} = \frac{1}{MR_0^2}\int\int\int_V \rho(r)P_{20}(\cos\theta)r^2\,\mathrm{d}V \quad (2)$$

[4c] Assuming a triaxial body of constant density and the known axial dimensions of the ellipsoid $a = 13.00 \pm 0.25$ km, $b = 11.39 \pm 0.25$ km and $c = 9.07 \pm 0.25$ km (Willner et al., 2010) embracing the shape of Phobos, the second order gravity coefficients are estimated from:

$$C_{20,\mathrm{shape}} = \frac{1}{5R_0^2}\left(c^2 - \frac{a^2+b^2}{2}\right), \qquad C_{22,\mathrm{shape}} = \frac{1}{20R_0^2}(b^2-a^2) \quad (3)$$

with

$$R_0^2 = \frac{1}{3}\cdot(a^2+b^2+c^2) = 11.270 \pm 0.140\ \mathrm{km} \quad (4)$$

[4d] According to the spherical harmonic function shape model to degree and order 17 (Willner et al., 2010), a body with the shape of Phobos and an assumed homogeneous mass distribution, and therefore constant bulk density ρ_{bulk} would have second degree gravity coefficients of

$$C_{20,\mathrm{shape}} = -0.106 \pm 0.01, \qquad C_{22,\mathrm{shape}} = -0.015 \pm 0.003 \quad (5)$$

[4e] The value $C_{20,\mathrm{shape}}$ will be used as a reference value. An actual $C_{20} > C_{20,\mathrm{shape}}$ would indicate an internal mass distribution and density increasing toward the center, typical of a differentiated body. $C_{20} < C_{20,\mathrm{shape}}$ would indicate an inhomogeneous mass distribution.

[5a] The velocity of a spacecraft flying by a body of sufficient size at a sufficiently close distant is perturbed by the attracting force of that body. The perturbed velocity is estimated from the Doppler shift of the transmitted radio signal as compared with the expected Doppler shift of an unperturbed trajectory (Anderson, 1971; Andert et al., 2010; Pätzold et al., 2010, 2011). The geometry of the MEX flyby at Phobos was excellent as a result of the planned close flyby distance and the geometric angle between the relative velocity and the direction to Earth. Dual-frequency radio signals transmitted by MEX at X-band ($f_X = 8.4$ GHz) and S-band ($f_S = 2.3$ GHz) during the flyby on 3rd March 2010 were recorded at NASA's Deep Space Network (DSN) 70-m ground station antenna near Madrid, Spain, from about 1 h before closest approach to 3 h after closest approach. Strong radio carriers at X-band and S-band were received for the full tracking period. The sampling time during the flyby was 1 s per sample.

[5b] The received carrier frequency from the flyby is compared with a prediction of a carrier frequency unperturbed by the flyby of Phobos. The latter is based on a complex force model that includes the gravitational forces from a 95° and order model for the gravity field of Mars (Konopliv et al., 2006), from the Sun and planets (Folkner et al., 2009) as post-Newtonian formulation (Moyer, 2000), the largest asteroids Ceres, Pallas and Vesta, and estimates of the non-gravitational forces acting on the spacecraft, e.g. solar radiation pressure and thermal planetary albedo and IR radiation relative to a spacecraft macro-model with known optical parameters of each plane and the solar panels and their orientation at each time step. Also required are precise knowledge of the location of the ground station antenna phase center, its behavior under distortions such as solid Earth tides and plate tectonics, and Earths rotation, precession and nutation (McCarthy and Petit, 2004). Relativistic propagation effects are considered through second order (Häusler et al., 2006). The frequency prediction is routinely computed for radio science data processing on the Mars Express and Venus Express missions (Pätzold et al., 2009).

[5c] The frequency shift resulting from the perturbed spacecraft motion caused by the attracting force of Phobos is extracted from the frequency observed at the ground station on Earth by subtracting the unperturbed frequency expected in the absence of Phobos. The difference between the observed perturbed and the predicted unperturbed Doppler shift are the raw frequency residuals due to the presence of Phobos (Fig. 1).

[5d] The raw frequency residuals contain a contribution caused by the propagation of the radio signal through the Earth's troposphere, where the propagation is mainly affected by the

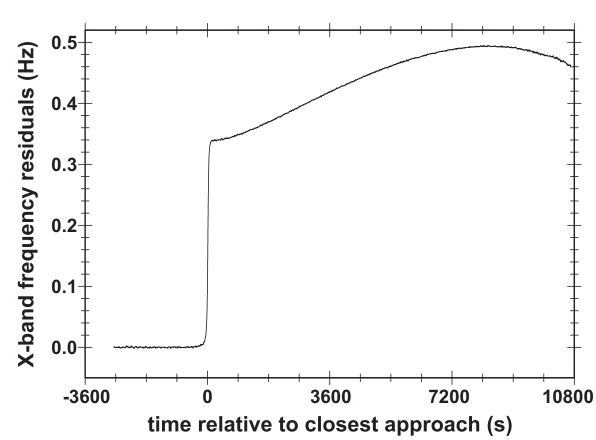

Fig. 1. Calibrated and filtered ($\Delta t = 5$ s) frequency residuals: observed sky-frequency minus predicted frequency at X-band (8.4 GHz) as a function of time during the Phobos flyby on 3 March 2010. Change in residual frequency around closest approach is the result of the attracting force of Phobos acting on the MEX spacecraft. The filtering reduced the noise level compared to the raw frequency residuals by a factor 3.