Geodäsie auf kleinen Welten – am Beispiel des Marsmondes Phobos

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Why Study Phobos?

• Phobos and Deimos discovery: 1877, Asaph Hall
• Phobos size: ~ 27 x 22 x 18 km; Deimos: ~ 15 x 12 x 10 km
• Origin of Phobos and Deimos uncertain:
  – Captured asteroid?
  – Reaccretion of Mars ejecta?
  – Primordial origin?
• Implications for origins other planetary systems
• Strong link with Mars
  – probably much Mars ejecta material trapped in Phobos regolith
• „Water-stop“ for future manned missions to Mars
Orbit and Rotation

• Near-circular near-equatorial orbit
  – Orbital period: \(\sim 7\ h, 40\ min\)
  – Deep in the gravity field of Mars, \(a = 9378\ km\)

• Locked rotation, i.e., rotation and orbit periods identical
  – one same hemisphere always facing Mars
  – leading and trailing hemispheres
  – implications for surface impacts
  – implications for mapping

• Phobos and Deimos exposed to tidal forces and drag:
  – Phobos will ultimately impact Mars
  – Deimos will ultimately escape
Phobos approaching Mars due to tidal drag, now moving close to the „Roche limit“

„Roche limit“: Distance within which a satellite will disintegrate due to tidal forces exceeding gravitational self-attraction

Phobos will disrupt within ~ 30 Mio years (Jacobson and Lainey, 2014)

Edouard Albert Roche,
French Astronomer, 1820 - 1883
Mars Express

- ESA’s mission first planetary mission, launched: June 2, 2003
- Entered Mars orbit: December 2003
- Mars Express in highly eccentric orbit; currently the only spacecraft at Mars to make close flybys of Phobos
- Currently, 166 close flybys < 2000 km
- HRSC obtained more than 800 high resolution images

Witasse et al., 2014
HRSC Camera

- High Resolution Stereo Camera, designed and built in Berlin, Germany
- PI: Gerhard Neukum, FU Berlin (retired), now Ralf Jaumann, DLR
- HRSC: Multiple line sensor (9 channels)
  - 9 channels, for high-resolution, stereo, and color mapping of the Martian surface
  - Best resolution: 10 m from range of 250 km
- SRC: (Super Resolution Channel)
  - Framing camera, 1k x 1k
  - Resolution: 2.5 m from range of 250 km
Phobos Geodesy and Mapping

Mars Express image samples

Jürgen Oberst – Intergeo 2014
Astrometric Measurements

- Phobos moving deep in gravity field of Mars – a sensitive indicator for various dynamic parameters of the Mars satellite system
  - Not so much affected by non-gravitational forces
  - Phobos orbit studies enjoy long observing history
  - Phobos gravitational shape
  - Tidal dissipation parameters

- Measurements of Phobos / Deimos positions
  - Oberst et al., 2006; Willner et al., 2008; Pasewaldt et al., 2012

- New Phobos / Deimos orbit models available (e.g., Jacobson and Lainey, 2014)

Observations of Phobos’ shadow on Mars (Willner et al., 2006)
Phobos control point network

... collecting tiepoints, screenshot

Oberst et al., 2014
Several realizations of control point networks available, based on Mariner, Viking Orbiter and Mars Express data. Shown here: Oberst et al., 2014
Phobos Shape Models

- 3-D control point cloud forms the basis for shape models
- Current networks typically have 600 – 800 data points (Willner et al., 2014; Oberst et al., 2014)
- Models through ellipsoidal and spherical function fits

Radii: $13.03 \times 11.40 \times 9.14 \text{ km}^3$
Volume: $5741.5 \pm 35 \text{ km}^3$
Moments of inertia $A, B, C : 0.3605, 0.4267, 0.4998$ (normalized)

- Principle axes in agreement with observed rotation pole and libration amplitude!

Willner et al., 2014
Measurements of Forced Librations

- Phobos ellipsoidal shape $\Rightarrow$ gravitational interaction with Mars ...
- ... expressed in terms of forced librations (small oscillations about its mean orbital period
- Amplitude of librations reveals gravitational moments ...
- ... which may be compared with shape models $\Rightarrow$ implications for internal structure
- Current estimates of libration suggest that Phobos largely homogeneous
High-Resolution Topographic Models

- Higher-resolution models through matching of stereo images, horizontal: 100 m, vertical: 2-25 m
- Regional stereo models are tied to the global control point network and are merged for global coverage

Giese et al., 2005

Jürgen Oberst – Intergeo 2014
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- Depths of ~20 craters can be resolved

Willner et al., 2014
Phobos Cartography

New (2012) SRC orthoimage mosaic in Simple Cylindrical projection (Wählisch et al., 2014)
Phobos Cartography

K. Shingareva et al., Moscow State University for Geodesy and Cartography, described in Wählsch et al., 2014.
Phobos Flybys, Radio Science, and Gravity Parameter Estimates

- Phobos flyby on March 3, 2010 at a distance of 77 km
- Deflection of the trajectory and measurements of radio Doppler effects
- $GM: \ (0.7072 \pm 0.0013) \times 10^{-3} \text{km}^3\text{s}^{-2}$
- Bulk density $\rho = (1862 \pm 30) \ \text{kg/m}^3$
- Second degree gravity field of Phobos ($C_{20}, C_{22}$) not resolved
- The low bulk density implies a high porosity, suggesting that Phobos accreted in orbit from a debris disk / not a captured asteroid (Pätzold et al., 2014).

- New radio science data from flyby on December 28, 2013 at a distance of 45 km currently being processed (stay tuned!)
Working Models for Phobos Gravity and “Dynamic Topography”

Phobos self-gravitation very weak. Centrifuge and tidal forces same order of magnitude!

Phobos topography referred to the best fit ellipsoid

Shi et al., 2011
Working Models for Phobos Gravity and “Dynamic Topography”

Need to introduce “Dynamic Topography” $H_d$

\[
H_d = \frac{W_0 - W_e}{g_r}
\]

$W_0$ and $W_e$: reference and effective potential at the surface
$g_r$: chosen reference gravity

\[
W_e = W_g + W_t + W_c
\]

$W_g$, $W_t$, $W_c$: gravitational, tidal, and centrifugal potentials

Gravitational potential computed from shape polyhedron models, assuming constant density

a: Topography referred to the best fit ellipsoid

b: Map of “Dynamic Topography”

c: Map of “Dynamic Topography”

Shi et al., 2011
Phobos Dynamic Topography Model

Shi et al., 2011
Phobos’ Evolving Tidal Environment

Due to “shrinking” Phobos’ orbit, associated tidal and centrifugal effects become stronger

(tidal and centrifugal accelerations, both at sub-Mars point)

Shi et al., in preparation, 2014
Phobos’ Evolving Tidal Environment

Shi et al., in preparation, 2014

Topography

Dynamic heights:

1.2 Ga

present
Evolving Tidal Environment and Triggering of Landslides on Crater Walls

Shi et al., in preparation, 2014
Phobos Cratering and Age

Schmedemann et al., 2014

- Old age of Phobos and Stickney (3-4 Ga) in stark contrast to Phobos’ short remaining life time (30 Ma, i.e., 1%)
- Phobos /Deimos may be remnants of an originally larger population of Mars satellites ...
Phobos Grooves

- Phobos covered with strikingly straight / parallel linear depressions, known as “grooves”
- Faulting from tectonic stresses? Ejecta from Stickney? Impact of ejecta from Mars?

Ramsley and Head, 2013; Murray et al., 2014
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Ramsley and Head, 2013; Murray et al., 2014
Phobos Past and Future Exploration

- Mariner mission (1971-73)
  - First resolved images
- Viking Orbiter Missions (1975-80)
  - First detailed shape models and maps
  - Discovery of Phobos grooves
- Phobos 1 / 2 (1988)
  - Both spacecraft failed on approach
- Mars Global Surveyor (1997-2006)
  - Unique high-res images of Phobos’ nearside
- Phobos Grunt sample return (2012)
  - Failed after launch
- Mars Express (this talk...)
- Various Phobos mission proposals being prepared
  - GETEMME
  - PHOOTPRINT
  - PhobEx

Duxbury et al., 2014
What about Deimos?

- Size: 15 x 12 x 10 km
- $a = 23,500$ km, orbit period: $\sim 1\text{d } 6\text{hrs } 18\text{min}$
  - Beyond Mars synchronous orbit
  - Due to idal interaction with Mars, Deimos will ultimately escape
- Imaging coverage rather limited
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Rare family portrait of Phobos / Deimos, captured by Mars Express
Conclusions

• New data from Mars Express available for Phobos: orbit, shape, mass, and rotation models, as well as new maps! Results currently in press ...
• Many open issues involving Phobos’ origin, evolution, associated time scales, ...
• .... interactions with Mars, and formation of unique surface morphology. In particular, the grooves
• New dedicated Phobos missions are being prepared by ESA / Roskosmos

• Stay tuned!
Conclusions

• New orbit, shape, and rotation models, as well as new maps available for Phobos
• Phobos mass estimates available
• Open issues involve Phobos’ origin and evolution, origin of grooves
• Mars
• New dedicated Phobos Missions being prepared
Bonus Material
Roche Limit

- Phobos approaching Mars due to tidal drag, now moving close to the „Roche limit“
- „Roche limit“: Distance within which a satellite will disintegrate due to tidal forces exceeding gravitational self-attraction
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Roche Limit

Gravity force: \[ F_G = \frac{Gmu}{r^2} \]

Tidal force: \[ F_T = \frac{2GMur}{d^3} \]

Gravity and tidal forces must balance:

\[ F_T = F_G = \frac{2GMur}{d^3} = \frac{Gmu}{r^2} \]

Mass can be expressed in terms of density:

\[ M = \frac{4\pi\rho_M R^3}{3} \quad m = \frac{4\pi\rho_m r^3}{3} \]

Hence, we have:

\[ d = r \left( \frac{2M}{m} \right)^{1/3} = r \left( \frac{2\rho_M R^3}{\rho_m r^3} \right)^{1/3} = R \left( \frac{2\rho_M}{\rho_m} \right)^{1/3} \]
Roche Limit

\[ d = R \left( \frac{2 \rho_M}{\rho_m} \right)^{1/3} \]

- Phobos density: 1.87 gr/cm³
- Mars density: 3.93 gr/cm³
- \( \Rightarrow d = 1.61 R \)
- (if density of Mars and Phobos were the same \( \Rightarrow d = 1.26 R \))
- radius of Mars = 3400 km \( \Rightarrow d = 5486 \) km
- observed Phobos distance: 9200 km

Note that Phobos rotation and centrifuge forces (60% of gravity force at equator!) must be taken into account

Material from the surface can easily be lifted into space!