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GRAVITY AND TOPOGRAPHY OF MOON AND PLANETS

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Abstract. Planetology serves the understanding on the one hand of the solar system and on the other hand, for investigating similarities and differences, of our own planet. While observational evidence about the outer planets is very limited, substantial datasets exist for the terrestrial planets. Radar and optical images and detailed models of gravity and topography give an impressive insight into the history, composition and dynamics of moon and planets. However, there exists still significant lack of data. It is therefore recommended to equip all future satellite missions to the moon and to planets with full tensor gravity gradiometers and radar altimeters.

Keywords: Gradiometry, gravity, moon, planets

1. Moon and Planets

Planetology serves two main purposes. First it is aimed at a deeper understanding of our solar system, its history, its characteristic features and its expected future development. Secondly, from comparison and from investigating similarities and differences, the study of planets helps in understanding our own planet. The major planets of our solar system are usually divided into two types. The outer planets, Jupiter, Saturn, Uranus and Neptune contain most of the mass of the planetary system. They have a large distance from the Sun, large diameters, low density, low surface temperature and well-developed satellite systems. The inner planets, Mercury, Venus, Earth and Mars, are referred to as terrestrial planets. They are much closer to the Sun, have small diameters, high density and less developed satellite systems or no moons at all. Compare Watts (2001).

The terrestrial planets are similar in many respects, yet there are significant differences among them. All four seem to be formed from mass accretion in the solar nebula. Active plate tectonics and the large height difference between the old continental crust and the young oceanic crust, however, are assumed to be unique features of the Earth. Mercury, and our Moon, have a continuous lithosphere, with their surface largely characterized by volcanism and impact craters. Typical for Mars is its hemispheric dichotomy. Its Southern hemisphere is densely cratered whereas the surface of the Northern hemisphere consists of lightly curved plains. Its surface is modified in its early history by atmospheric influences and flow of presumably water. Venus, the planet most similar to the Earth, is cloud covered; its surface is relatively hot. Also Venus is characterized by volcanism. See Schubert et al. (2001).

The primary sources of information about the planets are imaging of the surface (and telescope observations in the past) and orbit analysis from planetary fly-bys, as in the case of the outer planets and of a number of planetary moons or asteroids, or from elliptical orbits of planetary orbiters. For some planets, detailed topographic information exists, too, based on photogrammetric or altimetric measurements. Only in the case of Mars and Moon, rock samples could be analyzed in-situ or after being returned to the Earth, respectively. Gravity field information from fly-bys provides some elementary information such as mass, axiality and angularity; compare Kaula (1991). Already the combined use of images, displaying all characteristic surface features, and of gravity gives a wealth of information about the roughness or smoothness of the field and about the correlation of gravity variations with the topographic relief. The addition of topographic models is essential, however, for a deeper understanding of the evolution, thermal history, tectonics, the state of isostatic compensation and many more fundamental aspects of planetology. Planetology based on gravity and topography is in many ways comparable to a situation in solid Earth geophysics at the beginning of the 20th century.

2. Moon

The two typical visual features of the Moon's surface are the lighter looking, elevated highlands and the much darker maria. The latter are large impact basins, most of them filled by basalts. Another characterization results from the systematic difference in elevation between the far-side and the near-side. The far-side has much less and less flooded maria. Furthermore far-side elevations are systematically higher with the exception of the South-Pole-Aitken basin. The latter is a large impact basin with little basaltic fill. It is the lowest-lying region on the Moon. Topographic heights on the Moon range from −8 km to +8 km relative to a mean elevation. The evolution of the Moon can be divided into three phases: highland formation before 4 Ga (formed in the early Moon history and crystallized from a global magma ocean), mare formation between 3.8 and 4.0 Ga (bombardment resulting in many, large and deep basins, later filled by basalts, similar in composition to Earth oceanic basalts) and surface quiescence, (Schubert et al., 2001). It is assumed that after impact, the basins were filled with basalts to a hydrostatic level, which is above the original basin floors on the near-side and below basin floors on the far-side. Heating and weakening of the crust resulted in mantle rebound, in uplift of the crust-mantle boundary and in the generation of "plugs", (Konopliv et al., 1998).

3. Gravity and Topographic Models of the Moon

Rather detailed spherical harmonic topographic and gravity models exist for the Moon. Gravity models exist up to degree and order 165. They are based on data from Lunar Orbiters 1 to 5, Apollo 15 and 16, Clementine and, in particular, Lunar Prospector. In its final phase, the orbital altitude of Lunar Prospector was as low as 25 km. Examples of lunar gravity models are:

– Goddard Lunar Gravity Models 1 and 2 (GLGM-1 and 2)

– Lunar Prospector Models (LP75n, LP100n, LP165P).

See Figure 1 for the RMS gravity power per degree of LP165P and Floberghagen (2002).

A weakness of all existing lunar gravity models is the lack of directly observed far-side data. By means of a sophisticated approach based on the analysis of accelerations of orbit gravitational perturbations accumulated at the end of its occultations, the effect of lack of far-side data is somewhat

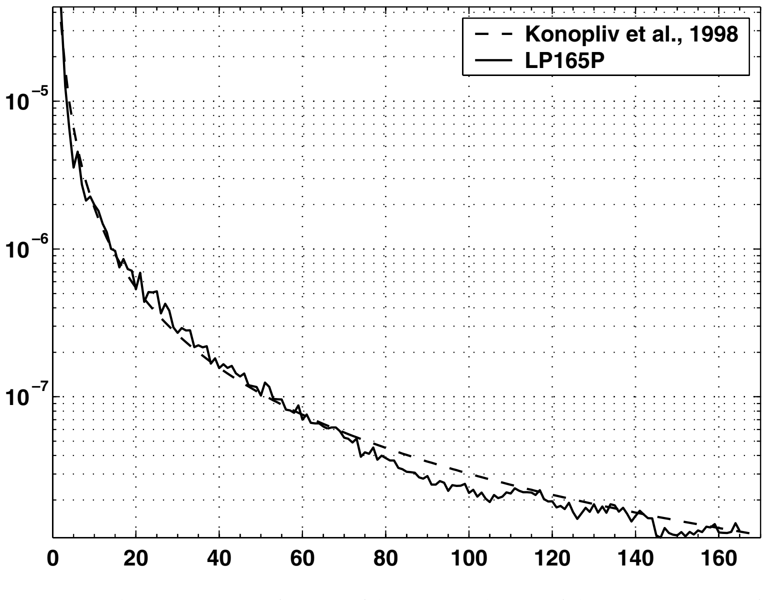

Figure 1. RMS gravity power per degree of lunar gravity model LP165P up to degree and order 165, as well as the power law by Konopliv et al. (1998).

diminished now-a-days, (Nerem, 1995; Konopliv et al., 1998). The empirical power law derived for the Moon gravity (Konopliv et al., ibid and Figure 1) is approximately

$$\sigma_n = 1.2 \cdot 10^{-4}/n^{1.8},$$

where σ_n approximates the RMS per degree

$$\sigma_n = \sqrt{\frac{1}{2n+1}\sum_{m=0}^{n}(\bar{C}_{nm}^2 + \bar{S}_{nm}^2)}.$$

It indicates that the Moon is closer to equilibrium than the Earth. Topographic models are based on Clementine lidar altimeter data and are developed up to degree and order 90. Based on the available gravity and topographic models, the degree of isostatic compensation can be inferred globally and locally for individual mares; compare Konopliv et al. (1998) and Watts (2001). Strong positive gravity anomalies are associated with mass concentrations in the near-side mare basins, the so-called mascons.

4. Mars

The surface of Mars is characterized by a wide variety of volcanic and tectonic structures. There are no indications of active plate tectonics like on Earth, but crustal magnetization indicates that plate tectonics may have occurred in early Mars evolution. The most striking characteristic of Mars is the clear division of its surface into the Southern highlands (densely cratered, rough, formed in its early history) and into volcanic plains that cover the Northern hemisphere (much younger, similar to volcanic plains on Venus). Martian thermal history can be divided into a very active early phase with accretional heating, core formation, strong mantle convection, and high surface fluxes of heat and magma and a second phase – the last 3.5 Gyr – marked by slow cooling. Mantle plumes play a major role in heat exchange. Very likely its core is completely fluid and non-convecting (Schubert et al., 2001).

5. Gravity and Topographic Models of Mars

Recent Mars gravity models are based on Doppler radio tracking of Mariner 9, Viking-1 and 2 and, primarily Mars Global Surveyor. Fields were developed by NASA GSFC and JPL and solved up to degree and order 80 or 85;

compare Smith et al. (1999) and Lemoine et al. (2001). Maximum values of free air anomalies are one order of magnitude higher (3000 mGal) than on Earth. The areoid exhibits a very distinct hemispheric East–West division with a range from −800 m to +2000 m, again more than an order higher in magnitude than on Earth. According to Smith et al. (1999), the approximate power law of Mars gravity field is, compare Figure 2:

$$13 \cdot 10^{-5}/n^2.$$

Topographic models are based on the Mars Orbiter Laser Altimeter (MOLA) with an elevation precision of about 13 m and an expansion up to degree and order 60, corresponding to 178 km. The topographic map shows the strong North–South dichotomy with a strong slope from South to North (Smith et al., 1999; Zuber et al., 2000).

Determination of Bouguer anomalies from gravity and topography provides a first look into subsurface Mars variations. Under the assumption of a single subsurface interface, a constant density contrast between crust and mantle and a radially uniform core and mantle density, Zuber et al. (2000) translated the Bouguer anomalies to crustal thickness. They found an average thickness of 50 km and variations in crustal thickness between 3 km and 92 km. A fundamental open issue is the formation of the northern lowlands. Based on the results of gravity and topography, they (ibid) consider an

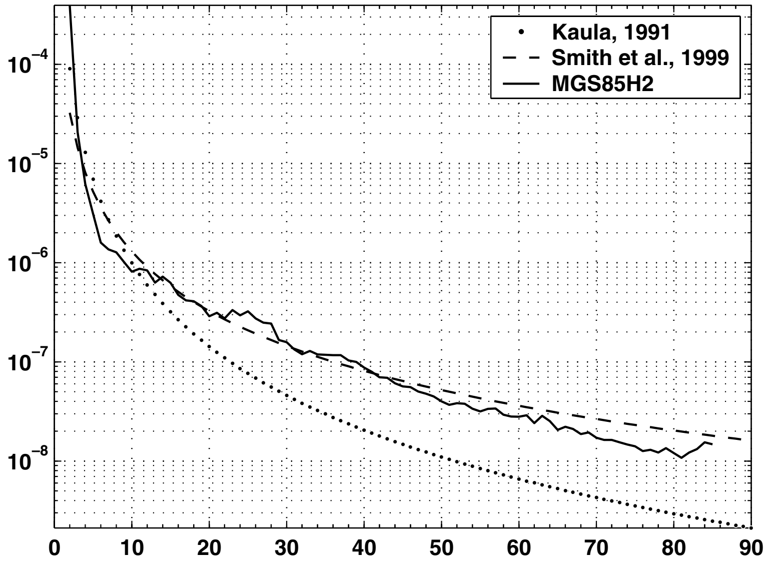

Figure 2. RMS gravity power per degree of the Mars Global Surveyor gravity model MGS85 1 + 2 up to degree and order 85 (Sjogren, 2002), as well as the power laws by Kaula (1991) and Smith et al. (1999).

impact hypothesis unlikely. Instead, either volcanic or sedimentary fill is favored. Furthermore Zuber et al. (2000) have come to the conclusion that negative gravity lineations as well as the geometric characteristics and the flow properties of these structures indicate either subaerial or subaqueous flow. Unlike the Earth, there is a high correlation between gravity and topography for Mars for the lower spherical harmonic degrees. Whereas ongoing geodynamic processes related to mantle convection, subduction and post-glacial rebound mainly determine the lower harmonics of the Earth's geoid, topographic signatures related to volcanic activity in the past like the Tharsis complex (Olympus Mons) seem to mainly determine the lower harmonics of Mars' areoid (Vermeersen, private communication).

6. Venus

Venus is the planet that most closely resembles Earth, in terms of size, mass and density. Yet there are substantial differences. Its surface topography is much smoother; Venus has a CO_2-rich atmosphere and surface temperatures of several hundred degrees. Gravity anomalies are smaller than those of Moon and Mars and they correlate better with topography than on Earth. This suggests at least partial isostatic compensation.

Venus has no intrinsic magnetic field. Schubert et al. (2001) suggest that the planet had a magnetic field until about 1.5 Gyr ago. Its absence today suggests an entirely liquid core, i.e. the absence of any core solidification. They (ibid) assume a sub-adiabatic, non convective core unable to sustain dynamo action.

Venus does not show signs of active plate tectonics. It is a one-plate planet. There are signs, however, of rifting, rift valleys and plateaus. Very characteristic features of Venus are coronae. These are quasi-circular topographic features with 100–2,600 km diameter. They consist of concentric ridges and interior plains, either topographic lows or highs. Coronae are often flanked by troughs. McKenzie et al. (1992) and Schubert et al. (1994) argue that they resemble subduction zones. Compare Schubert et al. (2001) and Watts (2001).

7. Gravity and Topographic Models of Venus

Venus gravity field models are based on the analysis of Venera, Pioneer Venus Orbiter and Magellan tracking data. For Magellan, the orbit was in 1993 circulized by aero-braking. This resulted in a significant improvement of gravity modeling (Nerem, 1995). Maximum resolution is degree and order

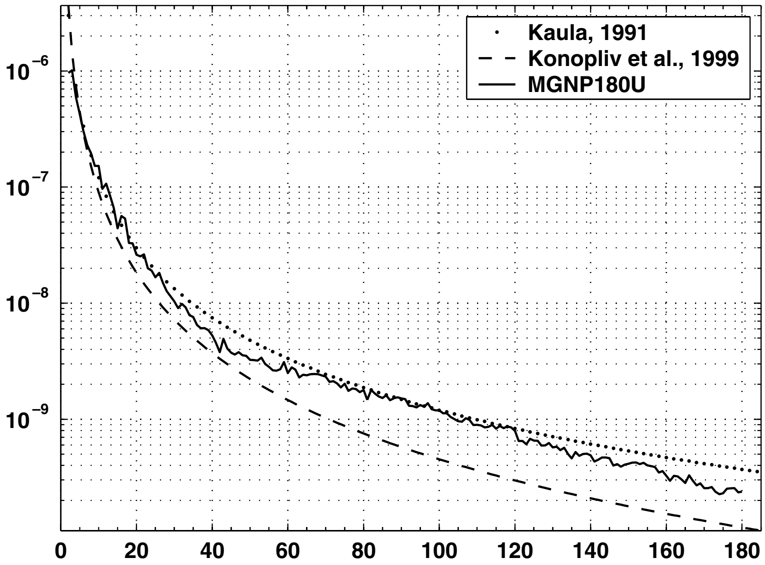

Figure 3. RMS gravity power per degree of the Venus gravity model MGNP180U (Sjogren et al., 1997), as well as the power law by Kaula (1991) and Konopliv et al. (1999).

180 (Konopliv et al., 1999), see Figure 3. The approximate power law of Venus gravity field is, due to Konopliv et al. (ibid),

$$1.8 \cdot 10^{-5}/n^{2.3}.$$

Very detailed topographic mapping has been obtained from Magellan, too; compare (Rappaport et al., 1999).

The key question addressed on basis of the available radar images, gravity and topographic models is the type of thermal evolution on Venus, (Kiefer and Potter, 2000; Schubert et al., 2001). Is there a vigorous mantle convection associated with a thin lithosphere and heat flow comparable to that on Earth, or is there a thick lithosphere with low heat flow? Schubert et al. (ibid) analyze the strong positive correlation of the "geoid" and topography at long wavelengths. It would result in compensation depths as deep as 200–300 km, while the actual lithospheric thickness is below 40 km. This suggests dynamic compensation by mantle convection. Kiefer and Potter (ibid) analyze gravity anomalies of several large shield volcanos. They use the superposition of several axis-symmetric Gaussian loads based on a least-squares fit to topographic data. The resulting elastic lithospheric thicknesses are between 10 and 22 km. These estimates are also strong functions of the lithospheric thermal gradient. Also their conclusions favor the hypothesis of a thin lithosphere for Venus.

Very limited information exists about Mercury, the outer planets, the moons of Mars, the moons of the outer planets and asteroids, compare (Nerem, 1995 and Schubert et al. 2001, ch. 14.1.1 and 15.9.4. and 5). In particular the terrestrial planet Mercury being a dead planet, the very active, though small Jupiter moon Io, Jupiter's moon Europa and Saturn's moon Titan would be of interest.

8. Conclusions

Radar or optical images of surface features (craters, coronae, plateaus, rifts, ridges, roughness versus smoothness), and detailed models of gravity and topography are the primary tools of modern planetology. The textbooks by Schubert et al. (2001) or Watts (2001) give an impressive insight into the wealth of information that can be deduced from this information about the current state-of-art of our planets.

Yet, the gravity models employed for these investigations exhibit serious deficiencies:

- Lunar gravity models suffer seriously from the lack of directly observed far side data,
- Gravity models of Moon, Mars, and Venus suffer to some extent from the spatial variations of the geometry of the connection Earth observatory to planetary orbiter and from the limited variety of orbit parameters of the orbiters. Despite the high spherical harmonic resolution of the gravity models, their actual significance does usually not exceed degree and order 20 or 30.
- Gravity information from all other planets, planetary sub-satellites and asteroids is derived from fly-byes or orbit perturbations. So far it only provides the most elementary gravity related information.

It is therefore recommended to develop dedicated gravity gradiometers for planetary missions. They should be full-tensor, nine component instruments that are capable of providing multidimensional gravity field information and are at the same time supporting positioning (orbit determination) and attitude determination.

The instrument should be robust, ambient temperature, and its precision tailored to the somewhat relaxed needs of planetary sciences. Ideally such a gradiometer should be accompanied by an altimeter, as altimetry is the second key quantity of planetology. Gravity gradiometers should simply be a standard equipment of any future lunar or planetary mission. Gradiometry is preferable to satellite-to-satellite tracking because of its compactness and because multi-spacecraft configurations add considerable complexity to planetary missions.

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