TIDES ON THE PLANETS MARS AND MERCURY

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ABSTRACT We have calculated tides on Mars and Mercury. In particular for Mars, we have used Roosbeek's tidal potential to calculate tidal displacements and gravity var iations. The tides are mainly caused by the Sun, the natural satellites Phobos and Deimos contribute about 8% and 0.08%, respectively. The Martian tidal displacements are about 1 centimeter and the tidally induced gravity changes on Mars are of the order of 1 μGal. These findings are important in the frame of the future geophysical experiment Netlander, which will measure station positions and gravity variations. For Mercury, the tidal signals are about 100 times larger, making future tidal measurements very interesting since they would offer the possibility to better determine the interior structure of this planet. The large tidal signal compared to Mars is caused by the proximity of Mercury to the Sun.

1. INTRODUCTION

Mars has no large natural satellites and due to its larger distance from the Sun and smaller radius, the ratio of the tidal potential U_T caused by the Sun on Mars to that on the Earth can be estimated as $(R_{\mathrm{M}}/R_{\mathrm{E}})^2(d_{\mathrm{M}}/d_{\mathrm{E}})^3 \approx 0.08$. Here, R and d denote mean radius and distance to the Sun, and subscripts M and E stand for Mars and Earth. Mercury has no natural satellites and the Sun is the only solar system body that causes important tides. Mercury's radius is almost 40% of the Earth's radius, and its mean distance to the Sun is also almost 40% of the Earth's mean distance to the Sun. Therefore, the tidal potential caused on Mercury by the Sun is about 2.5 times larger than the solar tidal potential on Mars.

The tidal potentials on Mars and Mercury induce periodic changes in station positions, lead to gravity variations that can be measured by a lander on the surface, and cause variations in the external gravitational potential fields of Mars and Mercury. The surface displacements can be estimated by the displacements of the equipotential surfaces near the surface of the planet, which are given by the ratio of the tidal potential to the gravity. For Mars, this gives tidal displaceme nts of about 3 cm, for Mercury of about 1 meter. The tidal contribution to surface gravity can be estimated as $2U_T/R$ and gives $\approx 1\mu$Gal for Mars and ≈ 0.3 mGal for Mercury.

Present technologies allow the determination of the position with an accuracy of a few centimeters, and of the measurement of gravity below 1 μgal. Tidal studies on Mars and Mercury can thus be undertaken. Tides can be extremely useful for better determining the interior structure of planets, as will be explained below. For Mars, several experiments of the space missions to Mars depend on accurate position or gravity determinations. The NetLander mission (Harri et al. 2000), which is planned to be launched in 2007, has a seismology experiment (SEIS)

and a geodesy experiment (NEIGE). Both experiments could be used to measure the tides on Mars.

2. TIDAL CALCULATIONS

Tides occur at various frequencies connected to the rotation of the planet and the periodically changing re lative positions between the planet and the bodies causing the tides. As for the Earth, the main tides of Mars and Mercury lie in diurnal, semi-diurnal, and long-period bands. Here, diurnal and subdiurnal have to be understood as with respect to the day of the planet defined by its rotation period about its axis. For Mars, a day is only slightly longer than on Earth, but on Mercury it is about 58 times longer. In addition to these period bands, Mars has also important tides with periods below half a day connected with Phobos, which revolves around Mars in about 8 hours.

A tidal potential for Mars has been calculated by Roosbeek (2000). For Mercury, a tidal potential has recently been calculated. These potentials form the starting point for tidal calculations as they give the gravitational forcing that is applied to the planets decomposed into periodic series.

Tidal displacements, gravity variations and external potential variations describe different reactions to the tidal forcing. They depen d on the interior of the planets. We have used different models of the interior structure of Mars and Mercury. We especially considered models with different core radii. These radii are not well known presently. For Mars, the core radius is believed to be between about 1300 and 1700 kilometers (see Van Hoolst et al 2000, for the models), for Mercury, the core radius is estimated as 1860km $\pm$ 100km. For Mars, it is moreover not known with certainty whether its core is (partly) liquid or not.

The reaction of planets to a gravitational forcing is most conveniently described by Love numbers. We have calculated Love numbers h and k for tidal displacements and external potential variations respectively. We also determined the so-called gravimetric factor δ for gravity variations. The tidal signals have then been calulated as a function of time for the different models.

3. RESULTS

For Mars, Love number h is about 0.2, three times smaller than th e values of 0.6 for the Earth. Love number k is about 0.1, also three times smaller than the Earth value. The reasons for the smaller Love numbers are that Mars is a smaller planet and that the liquid core is relatively smaller. The core radius is about 45 % of the planet's radius, compared to 55 % for the Earth.

Love numbers h are larger for a liquid core than for a solid core and increase when the core radius increases. For example, increasing the core radius by 200 km (about 14 %) increases the second-degree Love number $h^{(0)}$ by 25 %, and changing to a solid core decreases the second-degree Love number by 29 %. The Love numbers h, and therefore also the tidal displacements, are thus very sensitive to the dimension and state of the core. Love numbers k show a similarly large dependence on the core.

The tidal station displacements have been calculated by using expressions for a flattened planet as given in Mathews et al. (1995) and Dehant et al. (1999). All three components of th e displacement stay below 1 cm, and the radial component is about twice the tangential components. The NEIGE experiment to be sent to Mars in 2007 will determine positions of the NetLanders with an accuracy of about 5 cm (Barriot et al 2001). The tidal displacements fall below this threshold and can therefore not be observed with this experiment. However,

station position measurements can be corrected for the calculated tidal displacements before interpreting the results in terms of other time-varying phenomena such as nutations, polar motion, or length-of-day variations.

The external potential variations have been calculated according to an expression given in Dehant et al. (1999) for an ellipsoidal planet. For a satellite at an altitude of several hundred kilometers, the relative tidally induced potential variations are of the order of 10^{-8}. Atmospheric variations linked to the CO_2 cycle have an effect on satellites that is of the same order of magnitude (Smith et al. 1999), which is at the limit of dectectibility.

Also the gravitational acceleration of the attraction on Mars changes due to the direct attraction of the Sun, Phobos, and Deimos, to the gravitational attraction of the mass redistribution induced by the tides, to the change in station position, and to the accelerations induced by the tides (see Dehant et al. 1999). All these contributions appear in the definition of the gravimetric factor, which is defined as the ratio between the body tide signal measured by a gravimeter along the vertical and the gradient of the external potential along the perpendicular to the reference ellipsoid (see also Dehant et al. 1999).

We have calculated the gravimetric factors for all the tidal waves considered and computed the gravity variations. It was found that especially the gravity variations induced by Phobos are geophysically important. Although they are an order of magnitude smaller than the solar induced gravity variations, they do not suffer from the thermal effect which leads to a much higher noise level at the solar tides than at the Phobos tides. According to simulations of Lognonné et al. (1996), for long enough observation series, Phobos induced tides can be observationally determined with a precision of 1 nGal. The main ($l = 2, m = 2$) wave has an amplitude of 0.453μGal, two orders of magnitude above the measurement precision. Due to the high sensitivity to the core, precise gravity measurements of the main degree 2, order 2 Phobos induced tide can therefore yield important information on the core. As an example, we derived that a change in core radius of about 60 km corresponds to a 1 nGal change in amplitude of the gravimetric tidal signal.

For Mercury, the Love numbers h and k are about 0.8 and 0.4, respectively. These large values compared to Earth are a result of the large (partially liquid) core of Mercury. Mercury is believed to have a large core of about 1860 km, compared to a total radius of 2440 km. The core is assumed to be mostly solid with the uppe r few hundred kilometers liquid. We studied the sensitivity of the Love number k, which gives the external potential variations, to the core radius. Wu et al. (1995), using numerical simulations, showed that an orbiter-lander system with current technologies, can determine Love number k with a precision of 0.01. Using a set of Mercury models with varying core radius, we found that a change of 0.2 in k corresponds to a change of 120 km in our models. For a change in k corresponding to the Wu et al. (1995) measurement accuracy of 0.01, this gives a change in radius of only 6km. Evidently then, the extent of Mercury's core, presently derived with an error of $\pm$ 100 km, could be improved by a tidal experiment.

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