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Atmospheric angular momentum variations of Earth, Mars and Venus at seasonal time scales

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ABSTRACT

Atmospheric angular momentum variations of a planet are associated with the global atmospheric mass redistribution and the wind variability. The exchange of angular momentum between the fluid layers and the solid planet is the main cause for the variations of the planetary rotation at seasonal time scales. In the present study, we investigate the angular momentum variations of the Earth, Mars and Venus, using geodetic observations, output of state-of-the-art global circulation models as well as assimilated data. We discuss the similarities and differences in angular momentum variations, planetary rotation and angular momentum exchange for the three terrestrial planets. We show that the atmospheric angular momentum variations for Mars and Earth are mainly annual and semi-annual whereas they are expected to be "diurnal" on Venus. The wind terms have the largest contributions to the *LOD* changes of the Earth and Venus whereas the matter term is dominant on Mars due to the CO_2 sublimation/condensation. The corresponding *LOD* variations (ΔLOD) have similar amplitudes on Mars and Earth but are much larger on Venus, though more difficult to observe.

1. Introduction

The rotation of the Earth has been the principal time-keeper for most of history. With the precise time measurement tools of today such as hydrogen MASER or Cesium atomic clocks, this is not true anymore. On the news of 1 April 2009, French television channel France 3 mentioned that 238,500 wind turbines slow the rotation of the Earth due to atmospheric friction, increasing the length-of-day (*LOD*) hence our life expectancy.[1] The wind turbines do not have an observable effect on the Earth rotation in contrast to what is said in this 1st April joke, but it is true that the *LOD* increases at a rate of about 2 ms/century due to the solar/lunar tides (Mathews and Lambert, 2009; Mignard, 1986). It is known for more than a century that the Earth rotation is not constant in time, and many other phenomena influence the Earth rotation at an observable level at various time scales (see Wahr, 1988; Lambeck, 1980; Munk and McDonald, 1960). The study of Earth rotation is of major interest for astronomers and geophysicists (Dehant and de Viron, 2002). What is an error source for the astronomical observations becomes a fascinating subject for geophysicists as it provides information about the physical properties of the Earth's interior as well as on the dynamics of its geophysical fluid layers. Detecting small variations in the rotation yields also valuable information for other planets where the in-situ planetary measurements especially for the physical properties of deep interior are challenging.

The interaction between the solid and fluid layers of the Earth is the major cause of the fluctuations of the Earth rotation. In the absence of external forces, the total angular momentum of the Earth is conserved and any change in the atmospheric angular momentum yields a change in the solid planet's angular momentum. The same is true for Mars and Venus. Nevertheless, the causes and nature of angular momentum variations can be rather different. For all three planets, the dynamics of the atmospheres are principally affected by the incoming solar radiation which is affected by the planetary rotation. Moreover, for the Earth and Mars, the orbital eccentricity and obliquity lead to seasonal variations. Due to its very small eccentricity and obliquity, there are no seasons on Venus and the primary variability of the atmosphere is expected to occur over a mean solar day, which is close to the sidereal orbit period (see Table 1).

In this paper, we review the angular momentum variations and their consequences on the rotations of Earth, Mars, and Venus. The paper is organized as follows: Section 1 presents an overview

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[1] (http://www.france3.fr/STATIC/video/index-fr.php?titre=Eoliennes%20:%20impact%20sur%20la%20rotation%20de%20la%20terre&url=mms://a988.v101995.c10199.e.vm.akamaistream.net/7/988/10199/3f97c7e6/ftvigrp.download.akamai.com/10199/sgv/diff/videotheque/regions/lpc/infos/videoinfopoitiers/avrilhuit/avril09/B857B_eole.wmv&se).

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Table 1
Comparison of main periods of the Earth, Mars, and Venus. .
Data from Ahrens, 1995

	Sidereal rotation period	Sidereal Orbit period (days)	Mean Solar day (sidereal Earth days)
Venus	−243.02 days	224.695434	116.7490
Earth	23.93419 h	365.242190	1.002738
Mars	24.622962 h	686.92971	1.0274907

of the causes of the variations in rotation at seasonal time scales and the current precision in their observations for the three terrestrial planets. The governing equations for the atmospheric angular momentum and the mechanisms of exchange of angular momentum with the solid planet, i.e. the torques, are explained in Section 2. Section 3 presents the comparison of geophysical parameters of the Earth, Mars, and Venus that affect the variations of atmospheric angular momentum and rotation. In Section 4 equatorial and axial components of angular momentum variations are presented for the three planets. The future observations of the rotation of planets are discussed in Section 5.

2. Observations of the planetary rotations

The rotation of the Earth is perturbed by the combined action of multiple excitations (see Fig. 1). In particular, the interaction between the solid Earth and the other bodies of the solar system, as well as the interaction between the solid Earth and the geophysical fluid layers (i.e. the atmosphere, ocean, cryosphere, hydrosphere, and liquid core) generate fluctuations in the rotation. A marginal example is the contribution of climate change to the Earth rotation at the level of μs/year (de Viron et al., 2002b).

The Earth rotation variations can be separated in three main parts: (1) the changes in the rotation rate, commonly referred to as the variation of the length-of-day (ΔLOD), (2) the changes in the orientation of the rotation axis inside the Earth, which corresponds to the polar motion (PM), and (3) the changes in the orientation of the rotation axis in the inertial reference frame, corresponding to precession and nutation.

At very long time scale, tidal friction is responsible for a secular decrease in the Earth's rotation rate and thus for an increase in *LOD* (see for instance Brosche and Sündermann, 1978). Post-glacial rebound also contributes to the long-term trend in Earth rotation variations (Dicke, 1966; Peltier et al., 1986). At long period (decadal timescale), the core is commonly accepted to be the major source of excitation of the *LOD*. Ball et al. (1969) have shown that these variations are correlated with the variations of the geomagnetic field, suggesting that the fluid iron core is important at this time scale (see also Ponsar et al. (2002) and Dehant and de Viron (2002), for reviews). The decadal variations of the *LOD* associated with the core–mantle interaction are at the millisecond level. Interannual changes due to the El Niño-Southern Oscillation (ENSO) are observed with periods of 3–5 years. At shorter timescale, the atmosphere is responsible for most of the *LOD* fluctuations (e.g. Lambeck, 1980; Munk and McDonald, 1960; Rosen, 1993) and to a lesser extent, the oceans (see also Lambeck, 1980; Munk and McDonald, 1960; Marcus et al., 1998). The spectrum of all phenomena entering in the *LOD* variations of the Earth is presented in Fig. 2 (e.g. Eubanks et al., 1985; Rosen et al., 1990; Dickey et al., 1992; Salstein and Rosen, 1994; Hide et al., 1997; Huang et al., 1999). The atmospheric angular momentum (AAM) data are from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay et al., 1996; Salstein et al., 1993; Salstein and Rosen, 1997) while the oceanic angular momentum (OAM) are obtained from the oceanic model ECCO (Fukumori et al., 2002; Gross et al., 2004) forced by NCEP/NCAR reanalysis products. Polar motion is generated by the interaction of the crust with the ocean and with the atmosphere (see Ponte et al., 1998; Nastula and Ponte, 1999; Ponte and Stammer, 2000; Salstein, 2005). The present state of PM modeling is not good enough to reject the possibility of an effect of the core–mantle interaction, and our knowledge of the motion inside the core is even less complete. Additional variabilities in PM and *LOD* arise from variations in seasonal continental water storage change, i.e. hydrological angular momentum (HAM). Chen et al. (2000) showed that seasonal variability of HAM, which is of the same magnitude as the atmospheric pressure contribution, provides significant contributions to both polar motion and *LOD* variation. The precession and nutation are motions generated by the interaction between the planet and the other celestial bodies. The gravitational interaction between the Earth and close and/or massive celestial bodies (the Sun, the Moon, and to a minor extent the other planets of the Solar System) perturbs, on the one hand, the Earth's rotation, generating variations of its rotation period

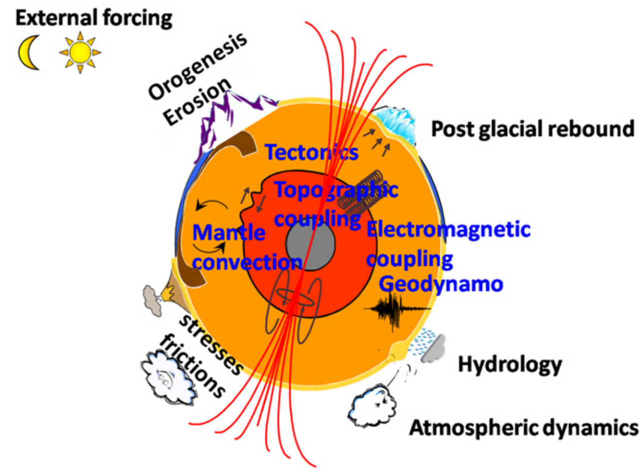

Fig. 1. Schematic of the geophysical phenomena affecting the Earth rotation.

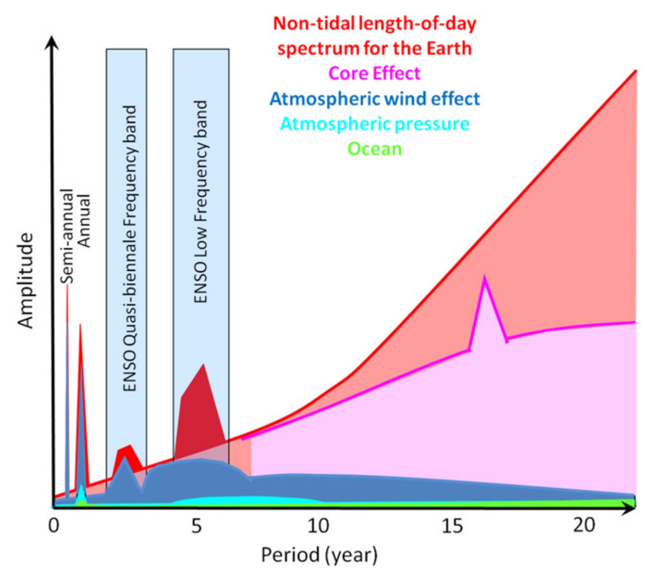

Fig. 2. Non-tidal spectrum of the contributions to Earth rotation (*LOD*) changes.

(and the associated *LOD*), and modifies, on the other hand, the orientation of its rotation axis both with respect to a given point at the pole on the terrestrial surface (polar motion) and with respect to the ecliptic pole in space (precession/nutation). The Earth rotation does not respond to these gravitational forces as a rigid body but as a deformable body containing different layers with different physical properties. Additionally, a nutation motion is superimposed to the response, stemming from the reaction of the atmosphere and ocean to the thermal excitation of the Sun. This complex response is nevertheless successfully modeled with a relatively simple model, as done by Mathews et al. (2002). A number of geophysical parameters are adjusted on the observation but the understanding of the influence of geophysical fluids remains rather incomplete (see Wahr and Sasao, 1981; Brzezinski, 1994; de Viron et al., 2001). Precession and nutation will not be further detailed in this paper as we concentrate on angular momentum changes at longer than the diurnal time scales for the Earth and Mars.

The Earth rotation variations are observed very precisely nowadays; not only the angular velocity of the Earth is monitored at the microsecond level or better, but also the rotation axis motion is detected at the millisecond of arc (milliarcsecond, mas) level or better (1 mas corresponds to 3 cm at the surface of the Earth). Very long baseline interferometry (VLBI) has been measuring Earth orientation and rotation for three decades. The rotation and orientation are obtained from the time delay between the arrivals of a signal from quasars at different stations as shown in Fig. 3. With the advent of global navigation satellite systems (GNSS) in the 1990s, *LOD* is known at about 0.10 mas (or 0.01 ms in time unit), and PM rate is determined to better than 0.3 mas/day. In addition, GNSS allows determining daily as well as sub-daily (2–6 h) values for these parameters. The precision of PM and *LOD* determined by GNSS ~0.10 mas) is much better than the precision of precession, nutation, and UT1 (Universal time) rotation angle derived from GNSS (~2.25 mas) (Dow et al., 2009). The low precision on orientation and rotation angles is due to the fact that satellite techniques are not able to determine UT1 in an absolute sense and that they are correlated with the orbital elements of the satellite; only the time derivative of the quantities related to angles is accessible to GNSS, while the angles themselves are obtained from VLBI. Therefore, it is important to consider the combination of these quantities obtained from different geodetic techniques. The latest Earth rotation parameters can be found on both the International GNSS Service (IGS), and the International Earth Rotation and Reference Systems Service (IERS) websites (http://www.igs.org; http://www.iers.org/.)

IERS Earth orientation parameters product center maintained at the Paris Observatory provides also online tools for the analysis of the observed *LOD* variations (http://hpiers.obspm.fr). As an example, Fig. 4 compares the observed excess of *LOD* (ΔLOD) as given by the IERS EOP 05 C 04 series, against the atmospheric contribution computed from the NCEP/NCAR reanalysis project (Kalnay et al., 1996; Salstein et al., 1993; Salstein and Rosen, 1997) with wind and pressure fields filtered out from diurnal variations. The daily *LOD* values of the IERS EOP 05 C 04 series are obtained by a weighted combination and smoothing of individual *LOD* series computed at different VLBI analysis centers. The oceanic contribution to *LOD* variations is presented in Fig. 5. The atmospheric and oceanic angular momentum data sets are made available through the Global Geophysical Fluid Center (GGFC) of the IERS. The atmospheric and oceanic angular momentum functions are filtered and sampled before comparison.

The parameters of the rotation of Mars have been first determined using radio Doppler and ranging measurements from the Viking landers (Yoder and Standish, 1997) and Mars Pathfinder (Folkner et al., 1997). These measurements were performed from an Earth tracking station to a lander on Mars and had a signature on the measured radio signal due to the rotation of Mars about its spin axis and to the changes in Mars' orientation. The rotation of the Earth and the relative orbits of the Earth and Mars must also be accounted for in these measurements, but in this framework, they can be considered as well known. Despite its short life, the Pathfinder radio system has allowed more accurate measurements than that of Viking, thanks to its higher radio frequency (X-band, ~8 GHz) which is less affected by the perturbations from the solar plasma than the frequency (S-band, ~2 GHz) used by Viking. Accurate radio tracking of Mars orbiters is being performed nearly continuously since the arrival of Mars Global Surveyor in 1997. Since then, the radio science data from orbiters (Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter) combined with the

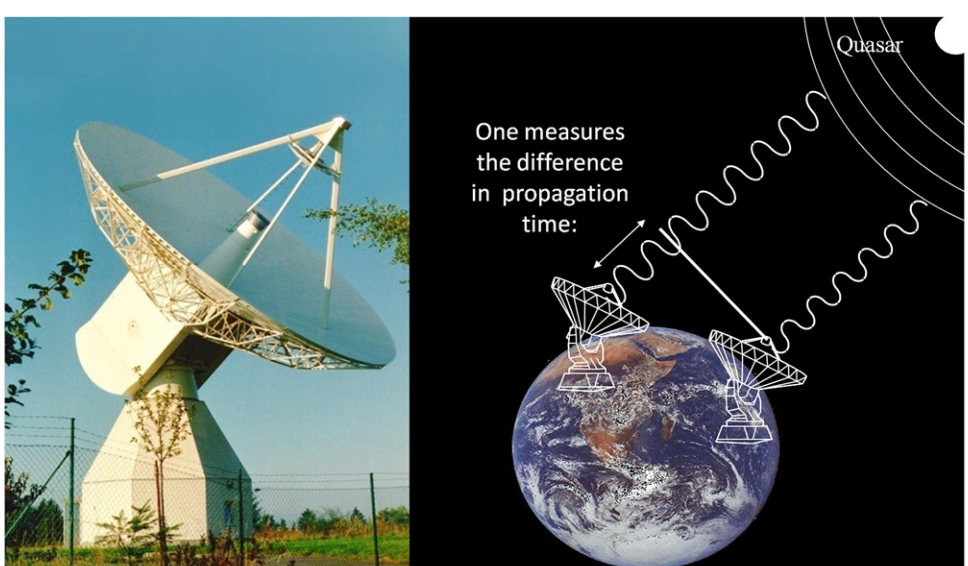

Fig. 3. VLBI antenna (left) and the measurement principle (right).

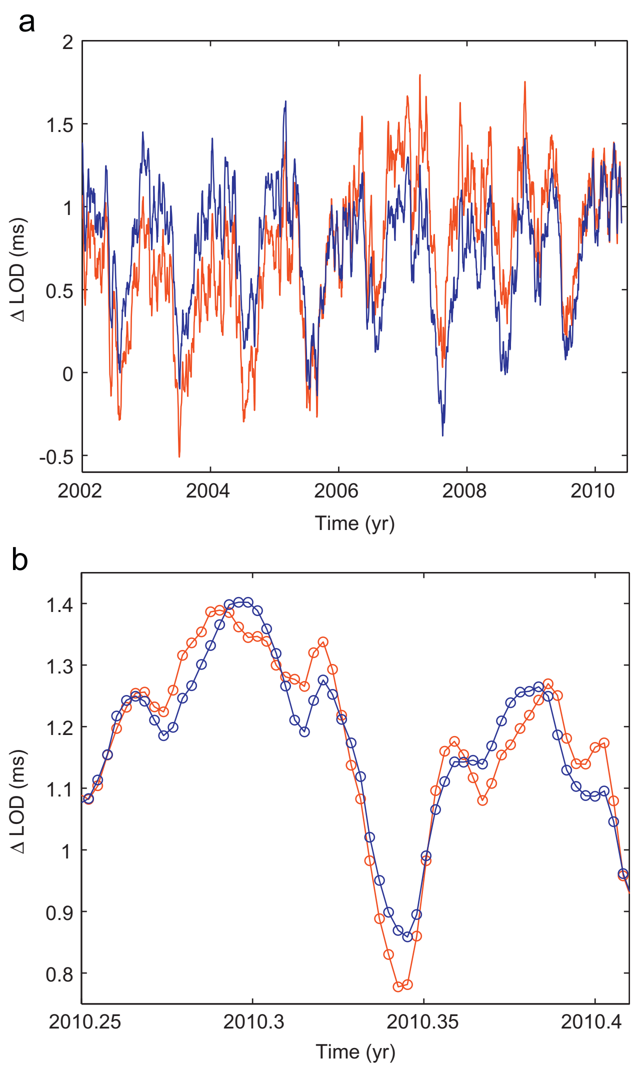

Fig. 4. Earth *LOD* changes observed by geodetic measurements (red) in comparison with modeled variations using the wind and pressure data (blue) for the periods 2002–2010 (a) and April–June 2010 (b) (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

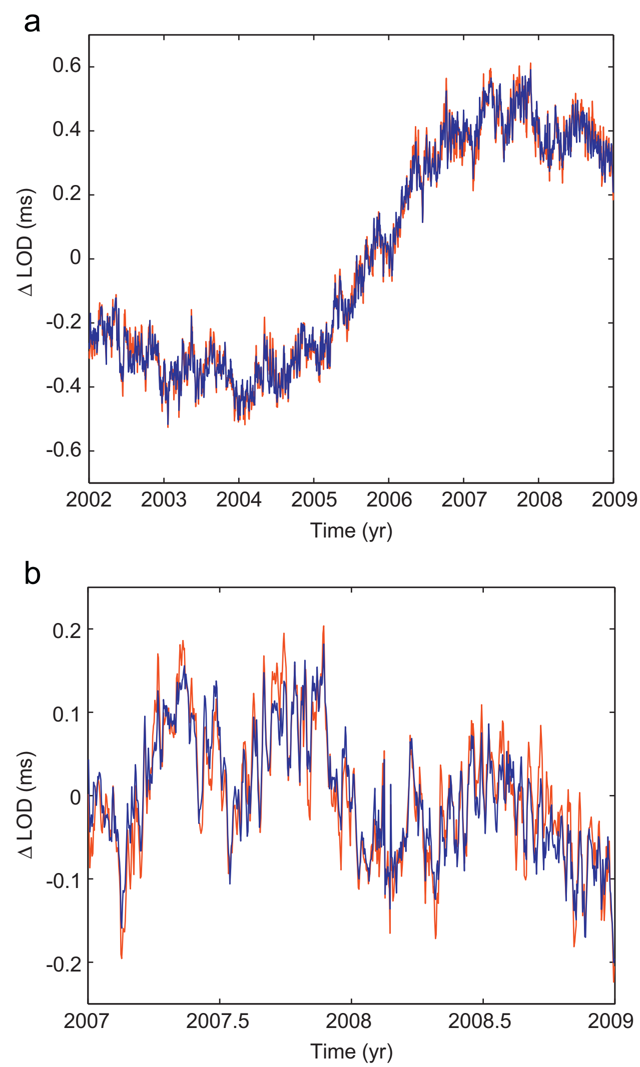

Fig. 5. Differences between the observed and the computed *LOD* from atmospheric and oceanic forcing (blue) and from only atmospheric forcing (red) for the periods 2002–2009 (a) and 2007–2009 (b) (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

data from Viking and Mars Pathfinder landers has been continuously improving the determination of the Mars rotation parameters (Konopliv et al., 2006, submitted for publication).

The changes in Mars rotation parameters are mainly caused by the condensation/sublimation of the CO_2 atmosphere at seasonal scales. Several authors (Cazenave and Balmino, 1981; Defraigne et al., 2000; Van den Acker et al., 2002; Sanchez et al., 2003, 2004; Karatekin et al., 2006) estimated the seasonal variations of *LOD* from Viking lander surface pressure measurements as well as from GCM data, which includes the wind contribution as well. The discrepancy between the observed and modeled *LOD* variations has decreased with time thanks to the continuous measurements of Martian orbiters as well as to the developments in numerical modeling of the Martian atmosphere. Fig. 6 shows that there is a good agreement between the observed and modeled ΔLOD.

Venus has a slow retrograde rotation. The rotation period of Venus and the direction of the planet's North pole have been determined by Davies et al. (1992) using the radar images of Magellan spacecraft and by Konopliv et al. (1993) from the radio tracking data of Pioneer Venus orbiter and Magellan spacecraft. The rotation periods given by the two studies are in good agreement but they do not indicate any variations in the rotation of Venus. Schubert (1983) suggested the possibility of having *LOD* variations on Venus several orders of magnitude larger than those observed for the Earth and Mars using an order of magnitude analysis based on analytical considerations. More recently, using the outputs of a GCM data (Lebonnois et al., 2010) Karatekin et al. (2008) showed that a ΔLOD around 10 s is plausible, indeed. This value is about the same order of magnitude as the uncertainties in the rotation period of Venus ($\approx$43 and $\approx$9 s) reported by Konopliv et al. (1993) and Davies et al. (1992), respectively.

3. Governing equations for the angular momentum exchange between the atmosphere and the solid planet

The angular momentum of a fluid particle in the atmosphere is given as

$$\vec{h} = \vec{r} \times \rho \vec{v}_T \tag{1}$$

where ρ is the density and $\vec{r}$ is the position vector with respect to the center of mass. The particle moves with the same angular

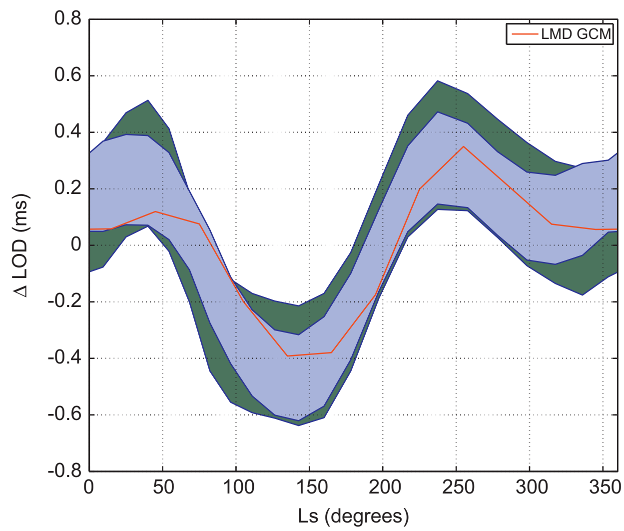

Fig. 6. Seasonal *LOD* variations of Mars given in *ms*. Computed ΔLOD from the GCM data (red line) compared with the observations from Konopliv et al. (2006) (dark green region) and Konopliv et al. (2010) (blue region). The thickness of the shadowed regions corresponds to the measurement uncertainties. The time-variable three-dimensional wind and pressure field provided used for the GCM data comes from Mars Climate Data Base of Laboratoire de Me´te´orologie Dynamique (LMD) (Forget et al., 1999) (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

velocity as the solid planet ($\vec{\Omega}$) and has a relative velocity $\vec{v}$ with respect to solid rotation ($\vec{v}_T = \vec{v} + \vec{\Omega} \times \vec{r}$). The total angular momentum of the fluid layer is given by the integral of the volume V of the fluid layer

$$\vec{H} = \int_V \vec{r} \times \rho \vec{v}\, dV + \int_V \vec{r} \times \rho(\vec{\Omega} \times \vec{r})dV \quad (2)$$

Using hydrostatic equilibrium assumptions $dp = \rho g\, dr$ (with g the surface gravity, and p the pressure) angular momentum can be expressed for a thin atmospheric layer with surface pressure p_s as

$$\vec{H} = \int_V \vec{r} \times \rho \vec{v}\, dV + \int_S \vec{r} \times (\vec{\Omega} \times \vec{r})\frac{p_s}{g}\, dS \quad (3)$$

The first term of the right-hand side is associated with the relative velocity of the fluid with respect to the solid planet, and is commonly referred to as the *motion term (or wind/current term)*. The second term corresponds to the angular momentum of a rigid rotation of the fluid with the planet, and is called the *matter term (or pressure term)*.

In the frame of Newtonian mechanics the time derivative of the angular momentum is equal to the total torque acting on the system. Consequently, if the system is isolated, its angular momentum is a constant. This property is commonly used to study the effect of the solid–fluid interaction on planetary rotation: the knowledge of the angular momentum variations of the fluid gives all the information on the changes of planetary rotation.

We can look at the angular momentum budget from another point of view: considering the solid planet as a physical system interacting with the fluid layer, we can compute directly the interaction torque due to the planet–fluid interaction (see r). The total torque can be decomposed into three main effects: (1) the *pressure torque* due to the action of fluid pressure on the planetary surface, (2) the *gravitational torque* due to the gravitational interaction between the masses inside the planet and the masses in the fluid layer, and (3) the *friction torque* associated with the relative motion of the fluid with respect to the surface. The total torque is computed from

$$\vec{\Gamma} = \int_S \vec{r} \wedge \vec{n}_T P dS + \int_S \vec{r} \wedge \vec{n}_E P dS + \int_S \vec{r} \wedge \vec{f}\, dS \quad (4)$$

where $\vec{n}_T$ is the unit vector normal to the planet surface, $\vec{n}_E$ is the unit vector normal to the equi-gravitational potential surface, and $\vec{f}$ is the friction drag, or the friction force by unit of surface. As shown in re equatorial components of the torque (associated with polar motion and nutation) are dominated by the effect of the planet's equatorial bulge: this *ellipsoidal torque* is the sum of the pressure torque and the gravitational torque acting on the equatorial bulge.

In most of the studies, the mass of the Earth's atmosphere has been assumed to be constant and the exchange of matter is ignored. Nevertheless, GCMs, which are subjected to various numerical errors, do not always perfectly conserve the mass and angular momentum. Although these errors originate mostly form discretization problems and are insignificant from a dynamical point of view, they contribute significantly to variation of the rotational parameters for Earth, more precisely to *LOD* as shown by de Viron et al. (2002a). Obviously in the case of Mars where there are significant seasonal atmospheric mass changes due to condensation and sublimation of CO_2, it is even more important to satisfy the mass and angular momentum conservations for an accurate calculation of rotational parameters.

The angular momentum approach has been shown to be more successful than the torque approach to estimate the effect of the fluid layers on the Earth's rotation (see de Viron and Dehant, 2000). The reason is that the angular momentum approach is based on a mean-like operation of well constrained quantities (large scale pressure and wind) that is quite insensitive to errors in the models, whereas the torque approach is based on delicate computation from less known quantities (local pressure and friction drag). Nevertheless, the torque approach has been shown successful to interpret the variation of the planetary rotation in terms of the interactions force between the fluid and the solid planet (see Rchez et al., 2003). Consequently, it is interesting to investigate the fluid effects on the rotation of a planet by both approaches in parallel.

4. Basic comparison of Earth, Venus, and Mars rotation variations from the fluid interaction point of view

The three terrestrial planets, Mars, Venus, and the Earth are comparable in many ways. We will discuss only the properties relevant to the angular momentum budget equation and the planetary rotation. These parameters are shown in Table 2.

The changes in *LOD* are associated with angular momentum variations of the solid planet along the axial axis (z-axis)

$$\frac{\Delta LOD}{LOD} = -\frac{\Delta H_{solid}}{H_{solid}} = -\frac{\Delta\Omega}{\Omega} \quad (5)$$

In the above equation, the changes in the polar moment of inertia C of the solid planet due to the deformations are neglected. Assuming that the system is isolated, the change in total angular momentum (the sum of the solid and atmospheric angular momentum) is zero. Therefore, we can write

$$\frac{\Delta LOD}{LOD} = -\frac{\Delta H_{atm}}{H_{solid}} \quad (6)$$

If the angular momentum of the fluid layer changes, it will induce a change in the planetary rotation that is inversely

Table 2
Comparison of the physical parameters of the Earth, Mars, and Venus associated with angular momentum.

	R (km)	C (kg m^2)	g (m s^{-2})	P_{atm} (atm)	Ω (s^{-1})	H_{solid} (kg m^2 s^{-1})
Venus	6052	6.24×10^{37}	8.87	92	2.99×10^{-7}	1.87×10^{31}
Earth	6371	8.03×10^{37}	9.81	1	7.29×10^{-5}	5.86×10^{33}
Mars	3396	2.70×10^{36}	3.71	0.007	7.09×10^{-5}	1.91×10^{32}

proportional to the polar moment of inertia C of the planet. The axial component of the angular momentum of the solid planet ($H_{solid}=C\Omega$) is directly proportional to the mean angular speed of the planet Ω. Since The Earth rotates much faster than Venus, its angular momentum is about 2 orders of magnitude larger than that of Venus. The radii of the Earth, Mars, and Venus normalized by the radius of the Earth are 1, 0.5, and 0.95, respectively. Since the moment of inertia is proportional to the 5th power of the radius, assuming similar mean density, moment of inertia of Mars is about a factor 20 smaller than the those of Venus and the Earth. Angular momentum of the three solid planets deduced from mean angular speed and polar moment of inertia are shown in Table 2. Since the angular momentum of the solid Venus is smallest, a given atmospheric angular momentum change would have a much larger effect on the rotation of Venus than on the rotations of the Earth and Mars.

In reality, none of the planets is rigid, and they deform under tidal forces and surface mass re-distributions. The angular momentum variations can be expressed equivalently by introducing the atmospheric angular momentum excitation function χ (Barnes et al., 1983)

$$\frac{\Delta LOD}{LOD}=(1+k'_2)\chi^{pressure}+\chi^{wind} \tag{7}$$

where k'_2 is the load Love number of degree 2. χ consists of the pressure (matter) and the wind (motion) terms. The matter term is due to the redistribution of the atmospheric mass while the motion term depends on the variations of the atmospheric zonal winds. The loading effect, represented by the non-dimensional Love numbers (Munk and McDonald, 1960) depends mainly on the elastic properties of the crust and the mantle. The load love numbers are 0 and -1 for the completely rigid and fluid planets, respectively. Earth's load Love number of degree 2 is -0.3 (Farrell, 1972; Rabbel and Schuh, 1986; van Dam and Wahr, 1987). Venus and the Earth have similar radius, mean density and k_2 tidal potential Love numbers (e.g. Lambeck, 1980; Yoder, 1995; Konopliv and Yoder, 1996). Load Love number of Venus is also expected to be close to that of the Earth (Correia and Laskar, 2003). In comparison, Mars has a much smaller load Love number $-0.05<k'_2<-0.13$ (Métivier et al., 2008). Consequently, the compensation of the mass term of the angular momentum is more significant for the Earth and Venus than for Mars.

It is likely that all the three planets have liquid cores. Then, the polar moment of inertia of the mantle C_m enters into the angular momentum equation and the resulting LOD variations of the solid planet are larger than for an entirely solid planet by a factor C/C_m, the ratio of the polar moment of inertia of the whole planet to that of the mantle. Consequently, ΔLOD is linked to the planet's interior through the parameters, C, C_m, and k'_2. The presence of liquid core generates a resonance (called "Free Core Nutation" (FCN)) in the transfer function of the nutation in the diurnal retrograde frequency band. The response to the forcing of the nutation at frequency close to this resonance is amplified to large extend. The FCN resonance is observed in the Earth nutation signal but not for the Mars and Venus. Its detection would provide significant constraints for the interior models (Dehant et al., this issue).

The surface atmospheric pressure corresponds to the weight of the air column. The air pressure on Mars' surface is about 0.007 atm, which is two orders of magnitude smaller than the surface pressure on the Earth (1 atm) and about 4 orders of magnitude smaller than that on Venus (92 atm). With the same gravity as on the Earth, the pressure on Mars would be at about 18 mbar, which is about 50 times smaller than on the Earth. As there is much less mass involved, it can be expected that, at equivalent dynamics, the Martian atmosphere would have a much smaller effect on the planetary rotation compared to the atmospheres of the Earth and Venus.

The atmospheric angular momentum is proportional to $\Omega R^4 p_s/g$ considering only the matter term. The angular momentum of the Earth's atmosphere is in the order of 10^{27} kg m^2 s^{-1}, Venus' atmospheric angular momentum is about half of that, whereas Mars' atmospheric angular momentum is about three orders of magnitude smaller. It is interesting to note that according to Eq. (6) only a few percent changes in the Earth's atmospheric angular momentum results in an LOD variation of 0.3 ms which is consistent with the observation. A similar change in the atmospheric angular momentum of Venus would cause much larger ΔLOD, at the order of 10 s due its slower rotation. The observed Martian ΔLOD however requires much larger angular momentum variations, which is provided by the sublimation/condensation of more than one fourth of the mass of the Martian CO_2 atmosphere.

5. Computation of the angular momentum of the terrestrial planets

The angular momentum variations of the Earth, Mars and Venus are investigated by using reanalysis and GCM data. The good agreement between the modeled and observed angular momentum variations of the Earth and Mars (Section 1) give confidence for the use of time-variable three-dimensional velocity and surface pressure fields provided by such data sets. The angular momentum variations of the Earth are calculated using the NCEP reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (http://www.cdc.noaa.gov/). For Mars, we use the Mars Climate Data base from Laboratoire de Météorologie dynamique de Paris (http://www-mars.lmd.jussieu.fr/mars.html). GCMs for Venus have larger discrepancies between modeled and observed aspects of the atmospheric dynamics mainly due to the incomplete understanding of the super-rotation phenomenon (Lebonnois et al., 2010). Nevertheless, the outputs of the LMD GCM can be used to illustrate the current understanding of the Venus atmospheric angular variability and an order of magnitude analysis for the expected LOD variations (Karatekin et al., 2008).

The angular momentum changes are shown in Fig. 7 for the Earth, Mars, and Venus, respectively. For the Earth, the matter term is dominant in the equatorial (X and Y) components, which are associated with the polar motion. The wind term dominates the axial (Z) component, which is directly proportional to LOD variations. For Mars, mass exchange between the ice caps and the atmosphere due to sublimation/condensation plays the principal role both for the LOD and PM. The wind variations on Venus are

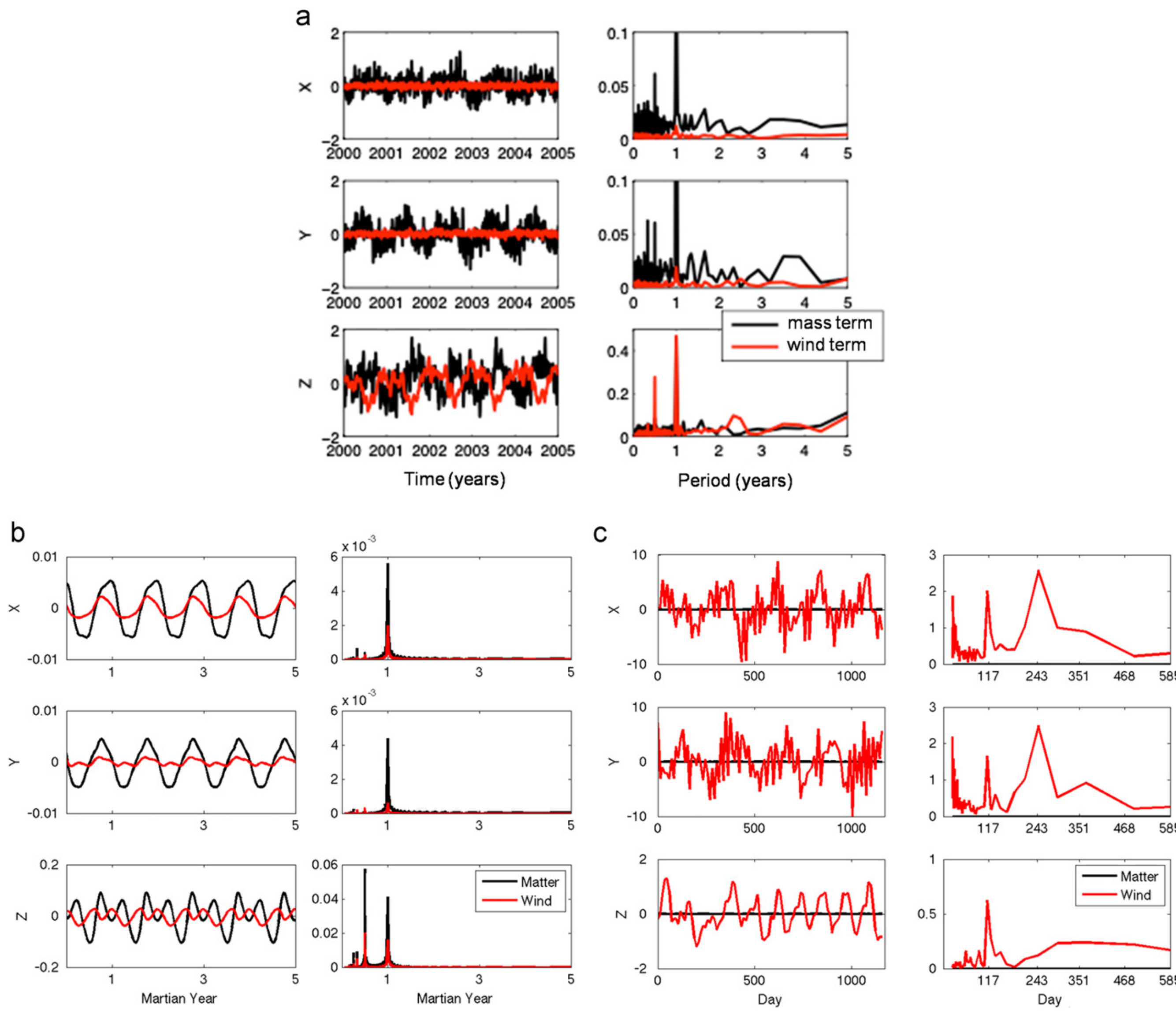

Fig. 7. Atmospheric angular momentum of the (a) Earth, (b) Mars and (c) Venus. Time variations are shown on the left (units in 10^{25} N m s) and the corresponding spectrum on the right. Matter (mass, pressure) and motion (wind) components are shown in black and red, respectively (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

expected to cause the major angular momentum changes The *LOD* variations on Earth and Venus are driven by the zonal wind variations whereas, on Mars, it is the seasonal changes in surface pressure that dominates the seasonal cycle of *LOD*.

Compared to the Earth, the equatorial and axial components of the Martian angular momentum variations have amplitudes about two and one order of magnitude smaller, respectively. Nevertheless, due to the difference in the planetary radius and the moment of inertia, the resulting annual ΔLOD amplitudes are similar for the two planets. The amplitude of the polar motion, though, is predicted to be smaller on Mars.

Although Venus and Earth have atmospheric angular momentum variations of the same order of magnitude, the resulting polar motion and *LOD* variations are expected to be larger on Venus due to its slower rotation rate. With the angular momentum of the solid planet about two orders of magnitude smaller and the *LOD* two orders of magnitude larger, from Eq. (6) it can be seen that for similar atmospheric angular momentum variability, the resulting ΔLOD is about 4 orders of magnitude larger on Venus. Its detection however is not straightforward as it corresponds to a surface displacement of only a few of meters due to the Venus' slow rotation.

The temporal variations of angular momentum of the different planets are directly related to the changes in the solar insolation and the atmospheric dynamics. On the Earth, the largest contribution to angular momentum comes from the annual excitation caused principally by the Mousson regime and the seasonal variations of zonal winds. The angular momentum signal contains also a large number of components with several predominant frequencies. This is mainly due to the presence of oceans and ocean-atmosphere interactions.

The angular momentum variability of Mars on the other hand is principally due to surface mass redistribution over seasonal time scales. Compared to Earth, Mars has a much more eccentric orbit. Consequently, the southern winter of Mars is about 30 days longer than the northern winter. This introduces an asymmetry between the seasons and a dominant semi-annual signal in axial angular momentum. In addition to diurnal and annual components there is also an additional component with a period of 6–7 days due to the planetary atmospheric waves. The temporal variation of angular momentum remains much smoother compared to that of the Earth. As a consequence, the amplification of the normal modes of the planet Mars due to the angular momentum is less significant compared to Earth. For both the Earth and Mars the diurnal angular momentum variations are smaller compared to the seasonal variations.

On Venus on the other hand, in the absence of seasons, the dominant change in the atmospheric dynamics is driven by the diurnal variations of the solar radiation with a period of 117 days. Diurnal changes in the incoming solar radiation causes atmospheric disturbances with periods shorter than both the orbital and rotation periods.

A schematic view of the atmospheric cells involved in the atmospheric dynamics of Earth, Mars, and Venus is presented in Fig. 8. For the Earth, there are three primary circulation cells known as the Hadley cell, the Ferrel cell, and the Polar cell (e.g. Holton, 2004; Thomson, 1998). The Hadley cell is a circulation pattern in the tropics with rising motion of the warm air near the equator and descending motion near 30° in the subtropics of both hemispheres. The Polar cell is composed of cold air moving towards the equator near the surface and poleward air motions in the high troposphere. The intermediate mid-latitude cell or the Ferell cell is driven principally by large scale eddies rather than the solar energy. The Coriolis force due to the planetary rotation deflects the winds and the cells in tending to conserve their angular momentum about the rotation axis, have both meridional and zonal wind components. The seasonal variations of zonal winds, e.g. trade winds (tropical easterlies), the mid-latitude westerlies, and jet streams (high-altitude currents circling the Earth at mid-latitudes at both hemispheres), are the primary cause of *LOD* variations on Earth (e.g. Salstein, 1993; Aoyama and Naito, 2000).

Mars has almost identical rotation period and obliquity to the Earth, hence it has similar seasonal insolation patterns, and exhibits comparable meteorological aspects to the Earth with the presence of mid-latitude westerlies, trade winds, and jet streams (e.g. Forget et al., 1999, 2008; Leovy, 2001). Martian GCMs predict jet streams with core speeds larger than 100 m/s at altitudes about 30 km. In comparison terrestrial jet streams are usually located near the tropopause (9–15 km) with wind speeds in the central core of jets stream often exceeding 50 m/s. The trade winds can extend to larger latitudes (up to 50°) on Mars whereas they are confined below 30° latitude on Earth. The large scale planetary disturbances, i.e. planetary waves in middle latitudes, propagate eastward with short periods of about 6–7 days and are considered as lower wave-number counterparts of similar weather systems on Earth. The Hadley circulation is similar to that on the Earth with two symmetrical cells about the Equator only during the equinox when the maximum heating is at tropics. In the rest of the year, circulation is dominated by a quasi-global Hadley cell extending from one hemisphere to the other with ascending branch in summer/spring hemisphere and the descending branch at the winter/autumn hemisphere. The Hadley circulation is stronger and wider during northern winter than southern winter due to large seasonal differences in heating resulting from the high orbital eccentricity. Similar to its terrestrial counterpart, the seasonal variations in the strength and in the extent of the Hadley cell are associated with the zonal winds variations. Although the seasonal variations of zonal wind speeds can be comparable to those on the Earth, the associated angular momentum variations are less significant due to lower atmospheric density of Mars. The matter term, i.e. the surface mass redistribution associated with the CO_2 cycle (not presented in Fig. 8), dominates the axial angular momentum variations.

Spacecraft observations on Venus suggest the presence of Hadley cells, reaching to about 50–65 km altitude above the surface and an anti-solar mesospheric circulation at the top of the atmosphere (e.g. Sevdhem, 2009). The effect of mesospheric circulation on atmospheric angular momentum variations is negligible and it will not be further discussed. The Hadley cells extend from the equatorial region up to about 60° of latitude in both hemispheres. The associated jets and polar vortices are larger and more energetic than their terrestrial counterpart. Despite significant discrepancies with observed zonal winds, Venus GCM can reproduce meridional circulations consisting of equator-to-pole cells, with the dominant cell located within the cloud layer (Lebonnois et al., 2010). Moreover, the role of thermal tides and the diurnal cycle n angular momentum transport and atmospheric angular momentum variations can be illustrated.

For Mars, dust also plays an important role on the atmospheric dynamics and planetary rotation. In addition, dust content of the

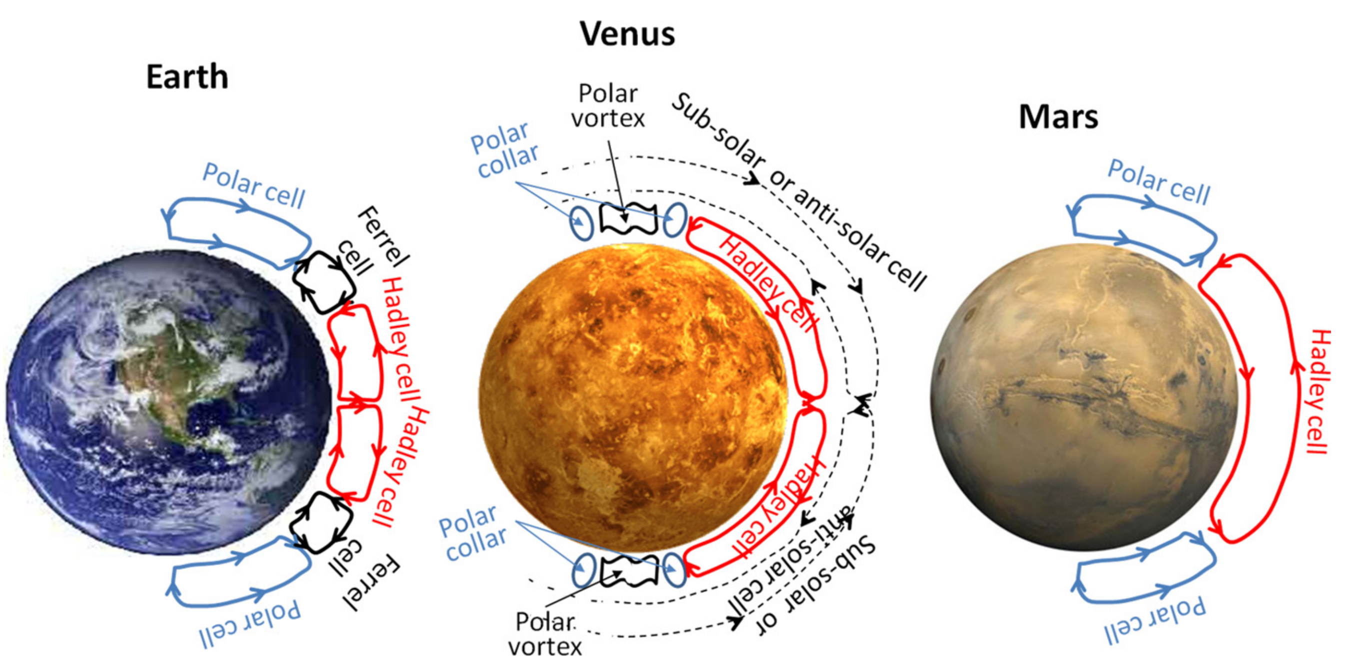

Fig. 8. Schematic of the general atmospheric circulations on the Earth, Mars, and Venus.

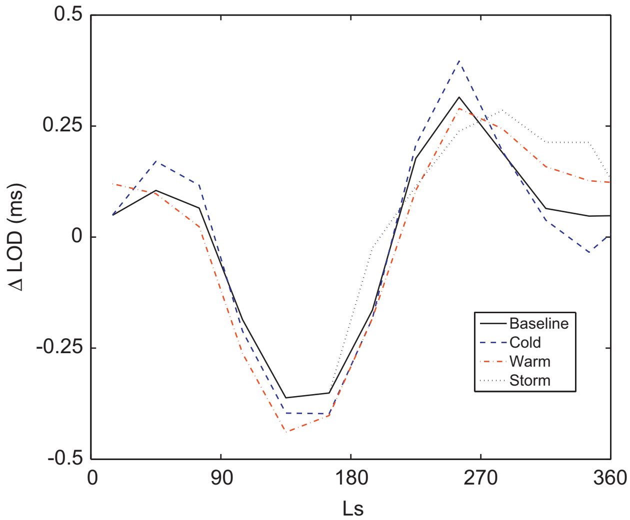

Fig. 9. Effects of a dust storm on the *LOD* variations of Mars. Data from LMD Mars Climate data base (Forget et al., 1999)

Martian atmosphere change from one year to another (Smith, 2010). Large dust storms, which cover the whole planet, have been observed, during which the atmospheric pressure, the wind speeds, and the pattern of the general circulation show changes. In Fig. 9 we show the effects of different atmospheric dust contents on Δ*LOD* estimated using the dust scenarios considered in the Martian climate data base (Forget et al., 1999). The largest variations in Δ*LOD* occur during the southern summer, when the planet is near perihelion.

6. Future observation of the rotation of terrestrial planets

Future improvements of the observations and measurements associated with the rotation and orientation of terrestrial planets will help to better understand the dynamics of the fluid layers and their interactions with the solid planet. The accuracy of Earth orientation measurements is expected to increase in a near future with the upcoming VLBI2010 project, the launch of improved global navigation systems (GALILEO, GPS2), the realization of more accurate spatial reference frames like the new ICRF2 (Ma et al., in preparation), and the constant effort within the IERS towards multi-technique combinations.

We can also expect that the tracking of present and future orbiters around Mars will be pursued to improve the present knowledge of the rotation state of Mars. Besides constraining the CO_2 cycle, in synergy with the time-variable gravity measurements, the variations of the zonal wind can be estimated. Seasonal zonal winds which are the primary cause of Δ*LOD* on Earth, are less important on Mars but still significant. Because of the lack of direct measurements, they are only estimated from Martian GCMs, which suggests, nevertheless, annual amplitudes as large as one third of the total Δ*LOD* (Van den Acker et al., 2002; Sanchez et al., 2003). In future, Martian meteorological data assimilation (e.g. Montabone et al., 2006) can be used to estimate the wind variations. Δ*LOD* amplitudes with an accuracy better than 2% were shown to be necessary to determine whether or not the core is liquid, and even better ($<0.5\%$) to constrain the core size (Karatekin et al., 2006). This kind of accuracy can be obtained more easily with Martian landers having direct radio (see Dehant et al., 2009, this issue, in the present issue) or Laser links to Earth (Degnan, 2009) than with orbiters. Observing polar motion and nutation would provide a step forward in our understanding of Mars, exactly as it did for the Earth a couple of decades ago. Compared to *LOD* variations, it is more challenging to detect the rotation variations associated with PM and nutations, principally due to their smaller signature. Nevertheless, an upper bound for the PM of Mars is given by Konopliv et al. (2006) from radio tracking of Mars orbiters and landers. The precision on the rotation parameters that can be obtained using a direct lander-to-Earth link depends on the lander location at the surface. For instance, Doppler from an equatorial lander will not be sensitive to PM (Le Maistre et al., submitted for publication). In the case of a radio link between the lander and an orbiter around Mars, determination of PM and nutation parameters would be more precise for whatever lander position, provided that the orbit of the spacecraft is well known. Having more than a single lander, i.e. lander network, would improve the determination of rotation parameters. In addition, determination of degree 2 and 3 load Love numbers would bring crucial information on the core properties (see Métivier et al., 2008). A lander could also detect the vertical surface displacements associated with the degree 1 loading deformations, which are directly related to time variations of the mass in the atmosphere and ice cap.

Determination of *LOD* variations of Venus would reveal the zonal wind variability and help to model the angular momentum exchange between the planetary surface and the atmosphere. Besides the atmosphere, Venus rotation could be excited also by other geophysical phenomenon such as the mantle convection, volcanic or seismic activity, resurfacing, or atmospheric changes. The measurements of planetary rotation could also reveal spin pole orientation, which is associated with the precession rate of the spin axis, a direct constraint on the moment of inertia of Venus. The expected *LOD* variations are close to the current *LOD* uncertainties reported from Magellan radar and the radio tracking data analysis (Davies et al., 1992; Konopliv et al., 1993). Although Δ*LOD* of Venus is likely to be large, corresponding surface displacement at the equator is only a few of meters due to the Venus' slow rotation. Therefore, the improvement of the current knowledge of Venus' rotation remains as a challenge for future planetary missions. As an alternative to spaceborne measurements (especially for Venus environment where the presence of a long-duration lander is challenging), ground-based radar can be used to study the rotational dynamics of the terrestrial planets (e.g. Holin, 2003; Margot et al., 2007).

7. Conclusion

In this paper we have examined the atmospheric angular momentum variations of the Earth, Mars, and Venus in seasonal time scales. We have shown that:

- AAM variations are mainly annual and semi-annual on Mars and Earth whereas they are expected to be "diurnal" on Venus (accounting for the diurnal rotation of Venus, this leads to long periods as seen from Earth).
- Wind terms have the largest contribution on the *LOD* changes of the Earth and Venus whereas the pressure term (matter term) is dominant on Mars due to its CO_2 cycle (about one third/fourth of the atmosphere sublimate and condensate in the ice caps with the seasons).
- *LOD* variations have similar amplitudes on Mars and Earth. They are expected to be much larger on Venus; this is due to the fact that the angular momentum of the solid part of Venus is much smaller compared to the Earth and Mars so that its rotation can be more easily excited.

  The future improvements on the knowledge of the rotational state and orientation of terrestrial planets will provide a better understanding of the dynamics of the fluid layers and insight into the mechanisms involved in the angular momentum exchange between the solid planet and its geophysical fluid layers.

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