JOINT COMMISSION MEETINGS

https://doi.org/10.1017/S1539299600009667 Published online by Cambridge University Press

JOINT COMMISSION I

Rotation of Solar System Bodies

Commission 19 with 10, 12, 15, 16 & 20
Chairman & Editor: *M. Feissel*

https://doi.org/10.1017/S1539299600009667 Published online by Cambridge University Press

ROTATION OF THE SOLAR SYSTEM BODIES

FOREWORD

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Solar System bodies are different. They have different sizes, from large planets to small asteroids, and shapes. They have different structure, from solid body to solid body with fluid atmosphere or core, to gaseous bodies, but all of them rotate. The Solar System is a big laboratory for studying rotation of solid and fluid bodies.

Different observational methods are applied to determine the rotation of the Solar system bodies. They depend on the position of the observer and on the structure of the bodies. The most accurate methods, laser ranging to the Moon and artificial satellites and Very Long Base radio Interferometry have been applied to the determination of the rotation of the Earth and the Moon. Their accuracy is better than 0.001", which on the surface of the Earth corresponds to about 3 cm. Radiotracking of artifical satellites have been used for Earth, Moon, Venus, Mars. In the case of Jupiter, Saturn, Uranus, Neptune and Pluto-Charon magnetic and photometric observations have been used respectively. Their accuracy is of the order of one tenth of a degree.

The high level accuracy of determinations of the rotation of the Earth allows to investigate its internal structure, e.g. size and shape of inner cores and angular momentum transfer between the atmosphere and the solid Earth, as well as to improve the theory of the rotation of the Earth with such complicated structure. It is a good example for demonstration how much we can learn about the internal structure of a body through precise determinations of the parameters of its rotation (direction of the rotation axis and rotational velocity) and the development of accurate theories.

The comparison of the rotations of the different solar bodies and their theories can be useful for developping further investigations in this field and might inspire future programs for planetary projects to improve our knowledge of the Solar System.

THEORY OF SOLID ROTATION

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The rotation of a rigid or non-rigid solid body satisfies the following equation (Moritz, 1980):

$$\frac{\partial \vec{L}}{\partial t} + \vec{\omega} \times \vec{L} = \sum_i \vec{N}_i = \frac{d\vec{L}}{dt} \qquad (1)$$

where $\vec{\omega}$ is the instantaneous rotational vector, $\vec{L}$ the angular momentum and where $\vec{N_i}$ represents the torques acting on the rotation.

In that case the above dynamical equation is written as follows (Goldstein, 1964):

J. Bergeron (ed.), Highlights of Astronomy, Vol. 9, 509–536.

$$\left(\frac{d\vec{L}}{dt}\right)_{\text{Space}} = \left(\frac{d\vec{L}}{dt}\right)_{\text{Body}} + \vec{\omega} \times \vec{L} = \sum_i \vec{N}_i \tag{2}$$

with:

$$\vec{\omega} = \dot{\alpha}\vec{\epsilon}_1 + \dot{\beta}\vec{\epsilon}_2 + \dot{\gamma}\vec{\epsilon}_3 = \begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{3}$$

where p, q, r are the components of $\vec{\omega}$ in the body-axes, and $\vec{\varepsilon_1}$, $\vec{\varepsilon_2}$ and $\vec{\varepsilon_3}$ three unit vectors representing three elementary rotations α,β,γ. Twelve different angular decompositions of such basic rotations can be used to locate a body-fixed rotating frame (*Oxyz*) relative to a fixed reference frame (*OXYZ*), both with the origin at the center of mass. The Eulerian sequence ψ, θ, ϕ called precession, nutation, *proper* rotation is only one of them (Gupta and Narchal, 1972). In analytical resolutions, the good choice of the sequence plays a non-negligible role in the facilities of treatment of the equations relative to the physical approximations of the problem (Bois, 1986, 1988). In numerical resolutions, using two sequences of different types with shifting rules (Bois, 1986) permits to avoid the singularities that occur in different positions of the body (Bois *et al.*, 1991, 1992). $\vec{L}$ and $\vec{\omega}$ are connected through a tensor of inertia *(I)*, as follows in the body-fixed axes:

$$\vec{L} = (I)\vec{\omega} \tag{4}$$

where *(I)* is composed of constant elements only when the body is rigid or assumed to be so. *(I)* is symmetric (products of inertia with respect to moments of inertia) and additive. As all symmetric tensors of order 2, *(I)* is diagonalisable by a choice of the directions *x*, *y*, *z*, so to speak making the body-fixed axes coincide with the principal axes of inertia. *(I)* is then only composed of three terms, the three principal moments of inertia *A*, *B*, *C*.

Non-perturbed rotation

The free rotation problem is represented by equations (2) written without right hand side. Without explicitly integrating such equations, the assurance of integrability of the problem can be obtained by some simple theoretical considerations. Indeed, whatever the triplet of generalized coordinates (α,β,γ) used, in order to describe the spatial attitude of a solid body in a fixed frame, the conjugate variables being (p_α, p_β, p_γ), one knows that there exists four prime integrals of the motion: the *H* Hamiltonian and the L_X, L_Y, and L_Z three components of the angular momentum. As a consequence of the general properties of the Hamiltonian systems, the problem is then integrable and even over-integrable.

Perturbed rotation

Let be a rigid body rotational motion submitted for instance to a potential U(*ψ*, *θ*, *ϕ*, *t*). The Hamiltonian of the system written in the Euler angles *ψ*, *θ*, *ϕ*, and in the conjugate Poisson variables Ψ, Θ, Φ, takes the following form (Boigey, 1972):

$$\begin{aligned} H(\psi,\theta,\phi,\Psi,\Theta,\Phi) = &\frac{1}{2A}\left[\frac{\sin\phi}{\sin\theta}(\Psi - \Phi\cos\theta) + \Theta\cos\phi\right]^2 \\ &+\frac{1}{2B}\left[\frac{\cos\phi}{\sin\theta}(\Psi - \Phi\cos\theta) - \Theta\sin\phi\right]^2 \\ &+\frac{\Phi^2}{2C} - U(\psi,\theta,\phi,t) \end{aligned} \tag{5}$$

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- When the three moments of inertia are different, A ≠ B ≠ C, there is no separation of the variables. It is then impossible to define some actions from the Eulerian angles and the conjugate Poisson variables ! The rotational motion problem is a difficult problem of Celestial Mechanics!

- If $A = B$ (solid of revolution), it is possible. (the ϕ angle disappears.). Fortunately, it is the case for the Earth! And unfortunately, it is not the one for the Moon!

Non-rigid body

In the non-rigid body case, there is a difficulty to keep the definition of the body-fixed axes, *(I)* is no longer constant and there exists a relative angular momentum $\vec{l}$, so that $\vec{L}$ is written as follows:

$$\vec{L} = (I)\vec{\omega} + \vec{l} \tag{6}$$

where *(I)* is variable. One then gets the equation of Liouville for the rotational motion of a non-rigid body:

$$\frac{\partial}{\partial t}\left[(I)\vec{\omega} + \vec{l}\right] + \vec{\omega} \times \left[(I)\vec{\omega} + \vec{l}\right] = \sum_i \vec{N}_i \tag{7}$$

- A method to treat equation (7) is obtained starting from the following writing:

$$\begin{aligned} \vec{\omega} &= \vec{\omega}_0 + \delta\vec{\omega} \\ (I) &= (I_0) + (\delta I) \end{aligned} \tag{8}$$

where (I_0) represents the best tensor obtained in the assumption of rigidity; (δI) being the variable part of the tensor.

- Moreover, it is possible to define some axes, called axes of Tisserand, so that $\vec{l} = \vec{0}$. They coincide with the minimum of the integral of the internal distortions, *i.e.* at the average of the deformations.

Let us now specify that two kinds of internal deformations may occur. Some of them are specifically due to the rotational motion (rotational deformations); the forces are stemming from a centrifugal potential (W_1). The other deformations are due to the tides (tidal deformations) and the corresponding forces are stemming from a tidal potential (W_2). Consequently, the tensor of inertia contains two parts as follows:

$$(\delta I) = (\delta I)^R + (\delta I)^T \tag{9}$$

These two kinds of deformations produce two kinds of librations in the rotational behaviour of the non-rigid bodies, *tidal librations* and *centrifugal librations* (Bois and Wytrzyszczak, 1990).

Let us recall the fundamental expression of the torque exerted on a body of potential V by a point mass m of position $\vec{u}$ (unit vector) with respect to the body, written as follows (Eckhardt, 1981):

$$\vec{N} = -m\vec{u} \times \nabla_{\vec{u}} V \tag{10}$$

The gravity field of the body is usually expanded through a spherical harmonic representation. For instance, if it is reduced to three oblateness coefficients, the second degree torque is then simply written as follows:

$$\vec{N}_2 = \left(\frac{3Gm}{a^3}\right)\left(\frac{a}{r}\right)^3 \vec{u} \times (I)\vec{u} \tag{11}$$

where a is the mean distance between the two bodies, while r is the instantaneous one. The non-rigidity of the body introduces the following additive potential:

$$\delta V = k\left(\frac{R}{r}\right)^j (W_1 + W_2) \tag{12}$$

where R is the mean radius of the body, and where, in the case of an elastic body, k is the Love number for the potential perturbation, and in the case of an anelastic body, k becomes a complex operator, *i.e.* the Love number with a phase shift. Knowing that for purely elastical deformations, its imaginary part $Im\,(k) = 0$, one gets from (7) the following relationship:

$$\vec{\omega} \times \delta\vec{L} = \delta\vec{N} \tag{13}$$

Consequently, the additive elastic torque is written as follows:

$$\vec{N}_{\text{el.}} = -\frac{\partial}{\partial t}[(\delta I)\vec{\omega}] \tag{14}$$

For anelastic deformations, $Im\,(k) \neq 0$, the torque is then written as follows:

$$\vec{N}_{\text{an.}} = -\frac{\partial}{\partial t}[(\delta I)\vec{\omega}] + \delta\vec{N} - \vec{\omega} \times \delta\vec{L} \tag{15}$$

Let us notice that in most practical cases, the second degree in spherical harmonics is sufficient and one may reduce δN to δN_2 as a function of (δI) as follows:

$$\delta\vec{N}_2 = \left(\frac{3Gm}{a^3}\right)\left(\frac{a}{r}\right)^3 \vec{u} \times (\delta I)\vec{u} \tag{16}$$

The libration, cause and nature

Starting from misunderstandings of the sense of some libration qualifications and considering the fact that each cause corresponds to its effect, its libration, a new classification and a new terminology of the librations connected to their nature and their cause have been proposed (Bois 1992, Bois and Wytrzyszczak 1990). This method and this vocabulary seem to be suitable for all the solar system solid bodies. That leads to identical qualifications for different bodies permitting to carry out some useful comparisons.

MARS

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Introduction

This paper reports on the state of our knowledge on the rotation of Mars and the geophysical significance of this knowledge. Section 2 deals with the rotational state of Mars, and section 3 deals with the variations in the rotation of Mars.

The rotational State of Mars

The rotational state of Mars is characterized by the direction of its spin axis and by the rotation rate.

Determinations of Mars' rotation rate and direction of spin axis

Mars' surface is much easier to observe than that of Mercury and Venus. The rotation rates of the latter planets were only established during our century. By contrast, the rotational period of Mars has been known since the golden age of astronomic observations, that is to say the 17th century. Modern determinations using data from the Mariner 9 and Viking missions have led to the most accurate knowledge of the rotation of Mars, compared to similar knowledge for the other planets.

Historical determination

When observed through a telescope, Mars shows dark and bright patches on its surface. By tracking the dark patches on the surface of Mars, Jean-Dominique Cassini obtained in 1666 a good value of the rotation of Mars (24 h 40 min instead of 24 h 37 min).

The orientation of Mars' axis of rotation was first determined by Schiaparelli in 1886 from observations of the polar caps. The obliquity of about 25° implies that Mars, like Earth, has seasons. Because Mars revolves around the Sun in about 687 Earth days, the Martian seasons are almost twice as long as ours. Seasonal changes on Mars are modulated by the relatively large orbital eccentricity $e = 0.093$. Winter in the southern hemisphere occurs when Mars is farthest from the Sun, which results in a larger southern polar cap. When spring comes in a given hemisphere, the polar cap shrinks and the regions at moderate latitudes darken. Astronomers in the 19th century, and in particular Percival Lowell, believed that the dark patches on the surface of Mars corresponded to the spreading and blooming of vegetation, helped by water released from the melting cap and flowing down the canals constructed once by intelligent Martians. Today, we know that a global dust storm starts at the end of the spring, and that the wind blows the fine, light-colored dust, exposing the darker terrain underneath.

Modern determinations

Numerous determinations concerning the rotation of Mars have been made in modern times. These determinations are based on different approaches.

(i) Earth-based optical observations of surface markings were analyzed by Wislicenus (see Michaux, 1967) to determine Mars' rotational period. Earth-based optical observations of Phobos and Deimos allowed Sinclair (1972) to determine the orientation of Mars' pole.

(ii) Radio tracking data of Mariner 9 were analyzed by Lorell *et al* (1972) to determine the orientation of the principal axis of the greatest moment of inertia, at the same time as the gravity field of Mars.

(iii) Radio tracking of the Viking Landers have allowed astronomers to perform the most precise determination of Mars' rotation rate and of the orientation of its rotation axis with respect to Mars' vernal equinox, as well as of the locations of the Landers (Michael *et al*, 1976; Mayo *et al*, 1977; Michael, 1979; Borderies *et al*, 1980).

(iv) Optical measurements acquired by Mariner 9 and Viking were used by Davies (1977 and 1978), Davies *et al* (1978), and Davies and Katayama (1983) to determine the angle measured from Mars' vernal equinox along the equator to the prime meridian (which passes through the center of the crater Airy-0).

The direction of the north pole of Mars adopted in the most recent IAU report (Davies *et al*, 1989) is that determined by Michael (1979) and with respect to the J2000 inertial coordinate system. The location of the prime meridian is from the most recent control network computation by Davies and Katayama (1983).

Geophysical interpretation

Unlike Mercury and Venus, Mars rotates relatively rapidly. This is because it has not been despun by tidal interaction with the Sun. This suggests the possibility of inferring the dimensionless moment of inertia $\lambda = C / Ma^2$ (where C is the greatest moment of inertia, M is the mass of Mars, and a is its mean equatorial radius) from the hydrostatic equilibrium theory (Hubbard, 1984).

Hydrostatic equilibrium

For a planet in hydrostatic equilibrium, the geometric flattening $f_g = (a-b) / a$, where b is the polar radius, is equal to the dynamic flattening $f_d = (3\, J_2 + q) /2$ to first order with respect to J_2 and ω^2, where J_2 is the harmonic zonal coefficient of degree 2 of the gravity field of the planet, $q = \omega^2 a^3 / GM$, ω is the rotation rate of the planet, and G is the gravitational constant.

Using $J_2 = 1.96045\ 10^{-3}$ from Balmino *et al* (1982); $a = 3389.92$ km from Bills and Ferrari (1978); $GM = 42828.3\ km^3\ s^{-2}$ from Null (1969), we derive $f_d = 523\ 10^{-5}$. On the other hand, using values for the axes of figures of Mars from Christensen (1975), we infer $f_g = 589\ 10^{-5}$. Since f_d and f_g are significantly different, we conclude that Mars is not in hydrostatic equilibrium. The roughness of Mars' areoid and the high correlation of the areoid contours with the topography (Christensen and Balmino, 1979) lead to the same conclusion.

The moments of inertia of Mars

Reasenberg (1977) noticed that the areoid could be reproduced, to a first approximation, by a spheroid and an extra bulge at the position of the Tharsis. He argued that the value of λ (0.377) which is derived from the Radau-Darwin formula is contaminated by the presence of the Tharsis, and he attempted to correct for this. His analysis is based on two main assumptions: (i) at an ancient epoch, the Tharsis bulge did not exist and Mars was in hydrostatic equilibrium; (ii) the formation of the Tharsis bulge occurred at a time when the rigidity of the underlying lithosphere prevented any substantial isostatic compensation. Under these assumptions, Reasenberg derived corrected values for f_d and f_g which are in better agreement than the uncorrected values, and inferred $\lambda = 0.3654$. This relatively large value, in comparison to 0.3335 for the Earth, and 0.4 for a homogeneous sphere, indicates that Mars is less centrally condensed than the Earth (Hilton, 1991).

Bills (1989) argues statistically that the bulge of the non-hydrostatic component of the planet had no reason to lie in the equatorial plane of Mars. Representing the non-hydrostatic component in a statistical way, he obtains $\lambda = 0.345$. However, Kaula *et al* (1989) support Reasenberg's (1977) approach, remarking that "statistical arguments should not prevail over physical sense". Reasenberg's value is used below.

Variations in the rotation of Mars

Variations in the rotation of Mars consist of several effects: precession of the axis of rotation, free and forced nutations, and variations in the rotation rate. All these effects have been predicted theoretically, but none of them have been measured. This is due to the fact that the available timelife of tracking data for the two Viking Landers is too short. The measurement of these effects is desirable because it would provide crucial information on the internal structure of Mars, on its meteorology, and on its climatic history.

Theoretical results

Precession rate

The theoretical value of the precession rate is $p = (3\, J_2\, n^2 / 2\, \lambda\omega) \cos K = 7.5''/\mathrm{a}$, where n is the mean motion and K is the obliquity. A more sophisticated theory (Hilton, 1991) leads to $p = -7.296'' \pm 0.021''/\mathrm{a}$.

Nutations

The rigid forced nutations of Mars have been studied by Struve (1898), de Vaucouleurs (1964), Lyttleton *et al* (1979), Reasenberg and King (1980), Borderies (1980), and Hilton (1991). The nutations of Mars are primarily driven by the Sun, and to a lesser degree by Phobos, Deimos and Jupiter. The larger nutation in longitude has an amplitude of 1.096"/a and a period of 343.41 days. The larger nutation in latitude has an amplitude of 0.516"/a and has also a period of 343.41 days.

Hilton (1991) studied the effect of a liquid core and of the elasticity of the mantle on the rotation of Mars.

Long term variations of the obliquity of Mars

Long periodic variations of the obliquity of Mars have been discovered by Ward (1973) and studied in subsequent papers (Ward, 1974a, 1974b,1979a, 1979b; Borderies, 1980; Ward, 1991). The obliquity of Mars undergoes periodic variations with an amplitude of about 10° around its mean value of about 25°, and with a period of 10^5 - 10^6 years. These variations are due to the fact that the spin axis precession rate is close to some of the frequencies characterizing Mars' orbital variations (Brouwer and Van Woerkom, 1950; Bretagnon, 1974; Laskar, 1988). Passages through spin-orbit secular resonances in the past history of Mars are likely (Ward, 1979b; Borderies, 1980; Ward, 1991).

In addition, Rubincam (1991) discovered that postglacial rebounds of Mars resulting from the large scale variations of its obliquity may have led to secular variations of the obliquity.

Seasonal variations in the rotation rate

Atmospheric pressure variations arising from the exchange of CO_2 between the polar caps and the atmosphere of Mars have been detected by Hess *et al* (1976). The variation in the moment of inertia of Mars associated with the growth and decay of the polar caps results in a modulation of Mars' rotation rate (Colombo, 1976; Williams, 1977; Philip, 1979; and Cazenave and Balmino, 1981). This modulation corresponds to a 5 m displacement at the equator.

Solid body solar tides also change the moment of inertia of Mars, and consequently modulate Mars' rotation rate. But this effect is expected to be an order of magnitude smaller than that due to the polar cap variations (Williams, 1977).

Geophysical implications

Precession rate

The precise value of λ is critical for determining the chemical composition of the Martian interior (Hubbard, 1984). The mantle density is especially sensitive the value of λ. Since the combination of the precession rate and of J_2 determines the value of λ, the determination of Mars' precession rate is crucial for constraining the models of internal structure for Mars.

Nutations

The models of internal structure for Mars are of two types, depending on the assumption that a liquid core is present (Okal and Anderson, 1978) or absent (Binder and Davis, 1973).

The measurement of some of the forced and free nutations could lead to an excellent determination of the size of the core. Hilton (1991) found that the effect of the internal structure of Mars on the precession and nutations is significant only for the case of a liquid core. Measurement of the nutations to ± 0.001" would give the core radius to ± 32 km. Measurement of the period of the Chandler wobble to ± 2 days would result in a determination of the core radius to ± 180 km, as long as it is greater than 1300 km. Finally, the free core nutation is a sensitive function of the mean core radius. The measurement of its period to an accuracy of ± 2 days would result in an uncertainty of ± 6 km in the core radius.

Long term variations of the obliquity of Mars

The large variations of Mars obliquity have led to climatic changes on the planet. The presence of layered deposits in the polar regions of Mars is generally explained by these climatic variations (Pollack, 1981). Channel formation could be explained by passages through resonances or by climatic friction.

The long-term theory of the rotation of Mars and the detailed secular orbit theory are very important for understanding the climatic history of this planet.

Seasonal variations in the rotation rate

The detection of seasonal variations in the rotation rate of Mars would provide valuable information on the exchanges of CO_2 between the atmosphere, the polar caps, and the regolith.

EARTH

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Introduction

The rotation of the Earth is prograde, its axis is inclined by 23° 27' on the plane of its orbit around the Sun. The duration of one sidereal revolution is 86 164.091 seconds of the SI (Système International d'unités), with variations between -10 ms and + 3 ms in the last four centuries. As it has been observed from its surface with increasing precision since the start of astronomy, its numerous irregularities have been extensively studied and progressively understood. However some of its features - large or small - remain to be explained.

The Earth is composed of concentric layers with various physical properties. The central part of the planet is the solid inner core, with a radius of 1290 km; the second layer is the liquid core, going up to the radius of 3470 km, from which the magnetic field is considered to origin. The next layer is the visco-elastic mantle. Floating on the mantle, at a 6360 km from the centre, is the crust, about 10 km thick, broken into slowly moving tectonic plates. The oceans cover a large part of the crust, with depths up to 10 km. The atmosphere is the most external enveloppe, about 12 km high.

The inner parts of the Earth have proper modes which, if excited, will perturb the Earth's rotation. Currents in the fluid components are compensated by changing rotation speed of the other part, according to the principle of conservation of the angular momentum. Secular and seasonal changes in the distribution of water and air masses create changes in the moment of inertia of the planet which reflect themselves as irregularities in the Earth rotation. The external luni-solar torque exerted on the fluid, non spherical, mantle gives rise to various perturbations.

Observations of the Earth's rotation and structure

The major source of observations of the Earth's rotation is the permanent monitoring of the direction of the rotation axis relative to the crust (two parameters) or in space (two parameters), and of the sidereal time, the angle of the Earth around its rotation axis. The observations are performed from stations on the crust, operated in Very Long Baseline radio Interferometry (VLBI) or in satellite geodesy (mainly satellite Laser Ranging, SLR). The present day measurements have an accuracy of about 0.0003" (equivalent to 1 cm at the surface of the Earth, 0.01 ms on universal time, or 0.1 ms on the duration of one revolution also called the length of day), with typically one value every three days. The observations are performed and analyzed in the framework of the IAU/IUGG International Earth Rotation Service (IERS). The knowledge of the Earth rotation in the first 80 years of this century is based on star transit observations. Back to 700 B.C. the variations of the

Earth rotation speed are known through the analysis of eclipses and occultations (Stephenson and Morrison, 1984). Historical and present day time series of measurements are available from the IERS Central Bureau, at Paris Observatory.

The winds and pressure in the atmosphere are monitored at 12h or 24h intervals, up to the pressure level of 100 or 50 hPa, in the framework of the world meteorological centres. Some information is available on the ground water storage (Kuehne and Wilson, 1991) and the load variations over the oceans (Benedict and Wilson, 1990).

The properties of the mantle are known from the propagation of seismic waves. Some information on the circulation in the core may be available from the analysis of the magnetic field. It should be noticed that the present knowledge of the solid part of the Earth is the result of highly developped modeling based on relatively little observation types.

For the dynamical effects of the Sun, Moon and planets, the spectrum of the perturbing potential is computed from the configuration of the celestial bodies relative to the Earth, while the response involves the physical properties of the solid Earth plus oceans, and the coupling or decoupling of the various layers for the frequencies considered.

A description of the irregularities in the Earth's rotation and of their causes is found in Lambeck (1980) and Munck and McDonald (1960). More recent findings are summarized in Cazenave (ed., 1986), or Hide and Dickey (1991).

Effects of the luni-solar torque

The torque exerted by the Moon, Sun, and to a lower extent by the planets, on the equatorial bulge of the Earth gives rise to periodic oscillations in space of the rotation axis, traditionally described as a precession (50.3"/a) and nutations. The principal term of nutation has a period of 18.6 years and an amplitude of 9.2". The latest development of nutation for a rigid Earth (Kinoshita and Souchay, 1990) includes the effect of Moon, Sun, Jupiter and Venus; it gives all components larger than 5 micro arc seconds (above 400 terms). The current model for a non-rigid Earth (Wahr, 1979) was adopted by IAU as a conventional model in 1980. Shortly after this date, VLBI and Lunar Laser Ranging (LLR) began to show evidence that some terms (with periods 18.6 a, 1.0 a, 0.5 a, and 14 d) have observed amplitudes which differ by a few milliarcseconds (mas) from the values in the model. Various attempts have been made to reconcile the theory and the observations by modifying some characteristics of the non-rigid Earth, such as the dynamical ellipticity of the liquid core or the characteristics of the core-mantle coupling (e.g. Herring, 1991; Dehant, 1990).

The lunisolar torque also gives rise to deformations of the Earth's polar moment of inertia which induce periodic variations in the rotation rate; the main terms are monthly and fortnightly with amplitudes of 0.8 ms in universal time, half-annual (4.8ms), annual (1.5ms) and with a 18.6 a period (0.16s); see Merriam (1982) for reference to the various models available. The study of the observed amplitudes is a tool to investigate the elasticity of the Earth (Nam and Dickman, 1990; Capitaine and Hefty, 1990). Although the oceans contain only $2\ 10^{-4}$ of the total mass of the Earth, their tides have detectable effects with periodicities from semi-diurnal to semi-annual (0.01 to 0.1 ms, see Brosche *et al.*, 1989).

The dominant effect in the long term is the braking of the Earth's rotation speed due to dissipation of energy in the oceans. The duration of one revolution is diminished by about 0.002s/century; angular momentum is transfered to the orbit of the Moon, which recedes by a few cm/a from the Earth. Although this deceleration dominates in the long term (centuries), for periods under a few tens of years it is dominated by larger variations with other causes.

Role of the atmosphere and groundwater

The general circulation and the mass distribution of the atmosphere have seasonal variations of opposite phases in the northern and southern hemisphere. Due to the prevalence of oceans in the southern hemisphere, the southern seasonal cycle is less pronounced. The resulting seasonal variations of the total angular momentum of the atmosphere is compensated, by virtue of the principle of conservation of angular momentum, by a seasonal change in the Earth rotation speed; the amplitude of this oscillation is 0.03 s peak-to-peak in universal time, or 2 ms in the length of day. Transient oscillations in the atmospheric angular momentum, with pseudo periods ranging from about 20 days to over 100 days, are also reflected in the length of day, reaching up to 0.6 ms peak-to-peak. The possible influence of the solar activity on the occurence of these oscillations has been invoked (Djurovic and Pâquet, 1989). In the lower frequencies, the Quasi Biennal Oscillation (QBO) of the upper strastospheric winds as well as the variations in the Southern Oscillation Index (SOI, related to the occurence of El Niño events) are also reflected in the Earth rotation speed, at the level of 0.4 ms peak-to-peak in the length of day (Eubanks *et al.*, 1985).

The seasonal imbalance of the air mass distribution moves the principal axis of inertia away from the rotation axis, which forces an oscillation of amplitude 0.1-0.2" peak-to-peak (3-6 m at the surface of the Earth) of the rotation axis relative to the crust. This polar oscillation is the second one in amplitude; it beats with the main term in polar motion, the Chandler wobble which has a period of 1.2 years. The seasonal and longer term variations in continental water storage have a detectable but not fully accounted for effect, according to Kuehne and Wilson (1991) and Vondrak (1990).

Role of the mantle and crust

The main signature of the mantle in the Earth's rotation is the Chandler wobble, a free oscillation of the polar axis relative to the crust. It can be considered as the result of random excitation of a single-period damped oscillator (Rochester, 1984). The period is near 435 days (1.2 years) and the amplitude has varied between 0.1" and 0.6" peak-to-peak in the last century. The observed Chandler period differs from that for a rigid Earth as a result of the decoupling between the liquid core and the mantle, of the elasticity of the mantle and the non-globality of the ocean (Smith and Dahlen, 1981). The damping time of the wobble gives information on the anelasticity of the mantle; unfortunately, as the sources of excitation are far from being elucidated, conclusions cannot yet be drawn in this respect from the 90 years of available observations. The dramatic diminishing of amplitude which took place around 1925 (Guinot, 1982) and the subsequent increase are not explained.

A slow random walk of the centre of the polhode (the beating circular track of the pole resulting from the addition of the seasonal and Chandler oscillations) is taking place; the mean velocity over the last 90 years is 1 cm/year roughly in the direction 80°W. It may

https://doi.org/10.1017/S1539299600009667 Published online by Cambridge University Press

be partially ascribed to slow changes in the inertia tensor of the mantle and crust that are associated to the post glacial rebound and to tectonic motions.

Role of the liquid core

According to the theories of the non-rigid Earth, the rotation irregularities include a normal mode due to the rotating, elliptical, fluid core: the Free Core Nutation (FCN) is a circular motion with a period of about 435 days in space. The detection of this term, smaller than 0.001", is rendered extremely difficult by the presence of the nearby annual component of nutation, nearly three orders of magnitude larger. However, using VLBI observations over 10 years and a geophysical model for nutation which inaccuracy in this frequency band is of a few milliarcseconds, the FCN circle has an estimated radius of 0.3 mas (Capitaine and Cazé, 1991; McCarthy and Luzum, 1991).

The core is also considered responsible for the so-called "decade fluctuations" in the length of day, which changes by several milliseconds at intervals that are irregular but longer than 10 years. Correlations between changes of the westward drift of the magnetic field (which reflects the circulation in the liquid core) with these large changes in the angular velocity of the Earth are explained by Le Mouël *et al.* (1991) as changes in the core angular momentum which are transmitted to the mantle then to the crust, where the Earth rotation observing stations are located. The nature of the coupling of the mantle with the core is not ascertained; it may involve the irregular topography of the upper core and/or the mantle conductivity (Rochester, 1984).

Conclusion

Among the rotating objects of the solar system, the Earth is obviously the one on which we have the largest information, by the length of observations (centuries), their time resolution (hours) and precision (better than 0.001"), as well as by the possibility to investigate directly or indirectly the detail of its structure and properties.

The layered structure and mechanical properties of its interior are known as a result of seismology and earth tides studies. The dynamics of the ocean and atmosphere are derived by modelling the *in situ* and satellite born observations. The continuous monitoring of the Earth's rotation provides strong external boundary conditions which help improve the knowledge of global features of our planet, such as the circulation in the liquid core, its shape, the characteristics of the core-mantle boundary, the amount of anelasticity of the mantle, interaction between mantle and ocean, interaction of the atmosphere with the ocean and solid earth, oscillatory modes in the atmosphere (see for example Brosche and Sündermann, eds., 1990).

The multidisciplinary research on Earth rotation has led to extensive modelling and understanding of the complex phenomena involved; the theories developped provide firm grounds for the understanding of the rotation irregularities of other planets.

MOON

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"Oh moon, lively moon, with thy beautiful face
Careering through the boundaries of space,
Whenever I see thee, I think in my mind,
Shall I ever, oh ever, behold thy behind."

Ascribed to Sir Edmund Gosse's maid

Astronomers from the Northern Hemisphere visiting Argentina should recognize that the "Man in the Moon" is upside down here. This observation reminds us that we are familiar with the face of the moon as seen by the naked eye. We only see one side of the moon, so it must rotate about a polar axis (which is more or less perpendicular to the plane of the ecliptic) at the same mean rate as it revolves about the earth. Even the most primitive people are and have been familiar with the face of the moon, but the earliest evidence that anybody surmised that the moon always has the same side turned toward the earth comes from Plutarch (46-120 AD) citing "opinions concerning the face of the moon that are current". Thus the principal feature of the rotation of the moon has been known for two millennia or more, even if it was not explicitly stated in terms of the relation between the lunar rotation and revolution. It is also possible (try it) to discern the librations in longitude and latitude with the naked eye, but they were not discovered until soon after the invention of the telescope.

The lunar libration in latitude was discovered by Galileo in 1632, and the libration in longitude was discovered by Hevelius in 1648. In the *Principia* (1687) Newton explained these librations in terms of the geometry of the setting: the moon rotates uniformly about a polar axis that is inclined to its non-circular orbit, and the mean rate of the orbit is the same as the rotation rate. Six years later, Cassini refined the geometry, noting that the lunar equator is inclined at a constant angle $i = 2.5°$ to the ecliptic, and that the descending node of the lunar equator on the ecliptic precesses in coincidence with the ascending node of the lunar orbit on the ecliptic. In 1748, Mayer determined the inclination to be $i = 1°29'$ which is only 3'7" less than the IAU (1976) value; from the earth this is an angular difference of only 1". Further observational improvements would require the resolution and measurement from the earth of libration effects of substantially less than 1". The incentive for more precise measurements came from Lagrange's *Theory of the Libration of the Moon*, published in 1780. Lagrange explained Cassini's "laws" in terms of the dynamical figure of the moon. He showed that, beyond the optical librations explained by Cassini, there must also be smaller forced physical librations and, possibly, free physical librations. Finding these terms, the largest of which has an amplitude of less than 0.5" as seen from the earth, was a major challenge. In 1839, Bessel introduced the application of the heliometer for determining the librations, and his technique endured for over a century. Bessel also introduced our current nomenclature for the moment of inertia ratio differences α, β, γ and for the mechanical ellipticity $f = \alpha/\beta$. (Because $\alpha-\beta + \gamma-\alpha\beta\gamma = 0$, there are only two independent dynamical parameters in the first order theory.) The heliometer observations were ultimately good enough to estimate I and β (strongly dependent on I) to about 1%, and to estimate f (strongly dependent on the physical libration in longitude) to about 10%.

From July 1969 through January 1973, Apollos 11, 14 & 15, and Lunakhods 17 & 21 placed retroreflectors on the lunar surface to serve as fiducial points for lunar laser ranging (LLR) experiments. Meanwhile, lunar libration theories - numeric and semi-analytic - were vastly extended using digital computers. Twenty years ago, LLR measure-

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ments were accurate to about 30 cm, and today they are accurate to about 3 cm. Even taking into account geometric dilution of precision (because the retroreflectors are not on the lunar limbs), this is a resolution of better than 0.01" on the moon; and it is equivalent to better than 0.00005" from the earth, over 1000 times better than could be done with the heliometer. The combination of improved measurements and theories, along with supplemental information concerning the lunar gravity field from lunar orbiters, is leading to major improvements in our understanding of lunar librations and their causes. The lunar parameters carried in the most recent LLR data analyses include the second, third and fourth degree harmonics of the lunar gravity field; for lunar tidal effects, the k, h, l Love numbers and a dissipation parameter related to a phase lag in k ; and, in effect, the amplitudes and phases of the three free libration terms. The most recent analyses performed by JPL indicate a 1056 day period free libration in longitude with an amplitude of approximately 1.0", and a Love number of $k = 0.027 \pm 0.006$. To geophysicists, this is evidence for the existence of a fluid core in the moon. Continued LLR analyses and measurements should help to resolve this and other issues concerning the physical properties of the moon.

This year, 1991, is the one hundredth anniversary of the birth of Sir Harold Jeffreys. Jeffreys made significant contributions in diverse fields of geophysics and astronomy, including lunar rotation. It is interesting in retrospect to note that in 1961 Jeffreys estimated i and f by averaging the results of heliometer studies reported over the previous decade. Using IAU Commission 17 Reports of 1952, 1955 and 1958, he took a weighted mean of ten estimates of I which were spread over a 3' range and calculated $i = 1°32'39 \pm 17"$; the current estimate from JPL results is $i = 1°32'32.2"$. Using Proceedings of the IAU from 1950 through 1958, he discarded one outlier and took an unweighted mean of the remaining 19 estimates of f which were spread over an 0.3 range and calculated $f = 0.639 \pm 0.014$; the current JPL estimate is $f = 0.6393 \pm 0.0007$. Thirty years ago, Jeffreys did remarkably well. (Indeed, 243 years ago, Mayer did extraordinarily well!). Still, with greatly improved analytic and measurement techniques that we now have, there is a lot more for us to learn concerning the rotation of the moon in the near future.

PLUTO

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*Abstract.*The determination of the axis of rotation and rotation rate of Pluto is reviewed. Early determinations based on observed light variations of Pluto have been superseded by analyses of the orbit of Pluto's satellite, Charon, and of the Pluto-Charon mutual events in 1985-90.

Pluto's 6.39 d light variations were first established by Walker and Hardie (1955) from observations in 1952-55 and ascribed to Pluto's rotation. Observations in 1964 by Hardie(1965), and in 1971-73 by Andersson and Fix(1973), showed an increasing amplitude of the light variations but with a decreasing mean brightness. Andersson and Fix interpreted this as being due to bright polar regions gradually turning away from the Earth, and isolated Pluto's north pole to a domain very close to the now accepted pole position.

On plates taken with the U.S. Naval Observatory's 155-cm telescope in Flagstaff in 1965, 1970, and 1978, Christy in 1978 discovered an elongation on Pluto's image consistent with a satellite in a synchronous orbit of 6.3867 d period. Christy and Harrington (1978) derived a circular orbit of radius a = 0.85" (about 20 000 km) and inclination i =105° with respect to the plane of the sky in 1978, and position angle N of the nodal line of 170° or 350°. The existence of this satellite, Charon, further complicated the interpretation of Pluto's light variations, but Charon also served as a kind of natural probe by means of which Pluto's mass, size, and pole position could be determined. An unexpectedly low mass of 0.0017 Earth masses resulted from an application of Kepler's third law given the observed period and radius of the satellite's orbit.

On the assumption that Charon's orbit lies in Pluto's equatorial plane, the spin axis of Charon's orbit will coincide with Pluto's spin axis.

Andersson (1978) realized that observable eclipses (actually occultations and transits) would take place between Pluto and Charon. He calculated that such mutual events would occur for a six-year interval centered on the time of the edge-on appearance of the orbit, in 1968 ± 5 a if N =350° or 1984 ± 4 a if N = 170°. Luckily, the latter case turned out to be the right one; otherwise one would have to wait some 115 years for the next series of such events! Occultations and transits follow one another every 3.2 days with 4-5 hours maximum duration.

It is easy to find roughly the times of these Pluto-Charon events by making the simplification that Pluto's orbital motion is perpendicular to the nodal line of Charon's orbit whose inclination will then on the average decrease by the yearly amount,

$$\frac{di}{dt} = -\frac{360}{248}\ °/a = -1.5\ °/a.$$

A central event must occur for i = 90°,while grazing events will occur when $i = 90 \pm \Delta i$, where

$$\Delta i = 57.3° \ \frac{R_p + R_c}{a} = 5.1\ °,$$

R_p and R_c being the radii of Pluto and Charon (see later table). Thus the first grazing event will occur for i = 85° and the last one for i = 95°, with a central event in the middle.

Since in 1978 i = 105° and di/dt = -1.5 °/a, we deduce that the series of mutual events should begin around 1985, become central in 1988, and end in 1991. In reality, these circumstances arose one year earlier than calculated here.

Speckle interferometric observations in 1980-85, pioneered by Bonneau and Foy (1980), led to a much improved orbit for Charon (Harrington and Christy 1981, Tholen 1985a) and improved mutual events predictions (Tholen 1985b, Tholen et al 1987 and 1988).

An exhaustive, but not yet quite final, orbital analysis by Tholen and Buie (1990) of the mutual events observed between January 1985 and July 1990 gave the results below:

Charon's Orbit Referred to the 1950.0 Earth Equator and Equinox:

Epoch = 1986 June 19 = JDE 2446600.5
a = 19640 ± 320 km
e = 0.00020 ± 0.00021
i = 98.9 ± 1.0 °
Ω = 222.407 ± 0.024 °
ω = 210 ± 31 °
P = 6.387246 ± 0.000011 d
λ = 259.96 + 56.3623195 (JDE - *Epoch*)

where λ is the mean longitude measured from the ascending node.

Other Fitted Parameters:

Pluto's radius: 1151 ± 6 km
Charon's radius: 593 ± 13 km

The right ascension α and declination δ of Pluto's north pole and the longitude W of the prime meridian are, according to the IAU convention, defined by

$\alpha = \Omega + 90°$
$\delta = i - 90°$
$W = 180° - \lambda$

Converting to the J2000.0 equator and equinox, Lieske (1991) finds

α = 313.02 °
δ = 9.09 °
W = 236.77 - 56.3623195 d

where d is in days from the epoch 2000 Jan 1.5 = JD 2451545.0 TDB.

JUPITER, SATURN, URANUS AND NEPTUNE

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Introduction

The giant planets, Jupiter, Saturn, Uranus, and Neptune, all have magnetic fields and magnetospheres where ionized particles are stably or quasi-stably trapped. To first order these fields are dipolar in form but there are significant higher order moments present. Energetic electrons moving in these magnetic fields emit radiation either by the cyclotron or synchrotron processes. The combination of highly beamed radiation and asymmetric magnetic fields causes the emitted radiation from these planets to vary significantly as they rotate. This radiation has now been detected from all of the giant planets, and from these data it has been possible to derive radio rotation periods. The methods used to translate

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the observed variations into rotational periods usually center around some type of spectral analysis or cross correlation technique. As no standard technique has been used, it is necessary to consult the original references in order to determine how specific periods were determined. Table 1 gives the derived values of the sidereal periods for the four giants planets. These periods are believed to represent the rotation rates of the magnetic fields, and by inference the rotation rates of the interiors of these planets.

Table 1. Radio rotation periods.

Jupiter	9h	55 min	29.711 s	± 0.04 s
Saturn	10h	39 min	24 s	± 7 s
Uranus	17.239 h			± 0.009 h
Neptune	16.105 h			± 0.006 h

The surface magnetic field strength of the planets determines the maximum cyclotron (gyro) frequency of emission. With the exception of Jupiter, the gyro frequencies are below the frequency range that penetrate our ionosphere, typically 5-10 MHz. Therefore the cyclotron radiation from Saturn, Uranus, and Neptune can only be observed from space. The Planetary Radio Astronomy (PRA) experiment on the Voyager spacecraft had a low frequency experiment which was ideally suited for making these measurements (Warwick *et al.*, 1977). To date, the rotational periods for these planets has been derived from PRA data exclusively. In the case of Jupiter, both its cyclotron and synchrotron emission can be observed from the ground as well as from space. Both PRA data and ground based have contributed to the rotation measurements of Jupiter.

Results

Jupiter

The rotation rate for Jupiter has been determined both from ground based and space based (PRA) observations. Because the data base for ground based observations extends for over 40 years, the uncertainty in the period derived from these observations is significantly better than that determined from the PRA data and for the other planets. However, it is imporatnt to note that these periods are derived using long time intervals, typically the Jovian year. The value of the rotation period known as System III (1965) was determined on the basis of a weighted average of four ground based radio periods determined in the early seventies (Riddle and Warwick, 1976, Seidelmann and Divine, 1977). The average included both decametric and decimetric (position angle, circular polarization, intensity) periods. The sidereal period deduced from the ground based data is 9 h 55 min 29.71 s ± 0.04 s (Riddle and Warwick, 1976). May *et al.* (1979) derived a new period based on ground based decametric data using an improved technique. They used histograms of occurence probability *vs* central meridian longitude obtained at the same frequency and observatory during apparitions about 12 years (one Jovian year) apart. The mean of their measurements gave a period of 9h 55min 29.689 s with a standard deviation of 0.005s. This is about 0.02 s or four standard deviations less than the System III (1965) value.

Desch and Kaiser(1981) analysed Jovian data obtained from the PRA experiment and obtained a period of 9 h 55 min 29.6 s ± 1.1 s. This is 0.1 s less that the System III (1965) period but consistent with the estimated uncertainty. Desch and Kaiser performed a spectral analysis to determine the period.

The current uncertainty from the ground based data is ± 0.04 s, estimated to be at the 95 % confidence level. It is interesting to note that published values of the decametric and decimetric periods differ by more than the 95% confidence limits (May *et al.* 1979, Riddle and Warwick, 1976). This raises questions regarding both the constancy of the period and about the assumption that the decimetric and decametric periods are the same. May *et al.* estimate that the rotation period was not changing linearly at a rate in excess of 0.03 s/a but note that the decimetric and decametric periods could be different.

The terrestrial magnetic field is at present moving gradually westwards, and over geologic times has shown variable drift rates and configurations. It has been suggested that the Jovian magnetic field may also drift and change its configuration, perhaps on shorter time scales than the earth. Such changes might be recognized as a change in the radio rotation periods. May *et al.* (1979) estimate that they might be able to detect a rate of change in rotation period as small as 0.002 s/a with continued monitoring over another Jovian year. This measurement would detect a long period drift but not changes over short intervals. Carr and Wang (1990) suggest that monitoring of hectometric emissions from space could result in high precision measurements over relatively short time spans.

Saturn

Saturn's sidereal rotation period was determined using measurements of the Saturn Kilometric Radiation (SKR) made by the PRA experiment onboard the Voyager spacecraft. The sidereal period deduced is 10h 39 min 24 s ± 7 s (Desch and Kaiser, 1981). The data used in the analysis covered 267 days, approximately 600 rotations of Saturn. The quoted uncertainty is believed to be a one standard deviation uncertainty. The technique used is identical to the technique Desch and Kaiser used for Jupiter spacecraft date analysis.

Uranus

Desch, *et al.* (1986) used both radio astronomy data and magnetometer data from Voyager 2 spacecraft to derive a rotation period of 17.24 ± 0.01 h. The radio astronomy (PRA) data alone yielded a value of 17.239 ± 0.009 h. The quoted uncertainty is believed to be a one standard deviation uncertainty.

Neptune

The two main radio components are analyzed. Sixty days of data around closest approach are used with the burst component. Fifteen days of data are used for the smooth component. Estimates are made for both components independently. The deduced value for the sidereal rotation period of Neptune is 16.105 ± 0.006 h or 16h 6.7 min ± 0.4 min. The quoted uncertainty is believed to be a one standard deviation uncertainty.

Discussion

A well know property of the solar system is the correlation of angular momentum density of the planets with mass (MacDonald, 1964). In particular, the angular momentum density, Cω/M, is proportional to M^x where x is approximately 5/6. The terms in this expression have following meaning:

C = moment of inertia about rotation axis;
ω = planetary rotation rate;
M = total planetary mass.

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Table 2 gives current values of the angular momentum density based on the radio rotation period measurements. Figure 1 shows the data for the giants planets. A least square fit to the data yields the following result:

$$C\omega/M = 1.52 \; 10^{13} \; M^{0.90}$$

It is seen that the angular momentum density for the major planets based on the radio data is consistent with earlier results.

Table 2. Angular momentum density of the giant planets.

Planet	C/MR^2	Mass (Earth=1)	rad cm^2/s
Jupiter	0.25 (1)	317.892 (3)	2.14 10^{15}
Saturn	0.22 (1)	95.184 (3)	1.23 10^{15}
Uranus	0.23 (1)	14.536 (3)	1.26 10^{14}
Neptune	0.29 (2)	17.148 (3)	1.53 10^{14}

Notes. (1) from Hubbard and Marley, *Icarus* **78**, 102-118, 1989;
(2) from *An Introduction to Planetary Physics* by William M. Kaula, John Wiley and Sons, 1968, page 211;
(3) from Miner, *Physics Today,* page 45, July 1990.

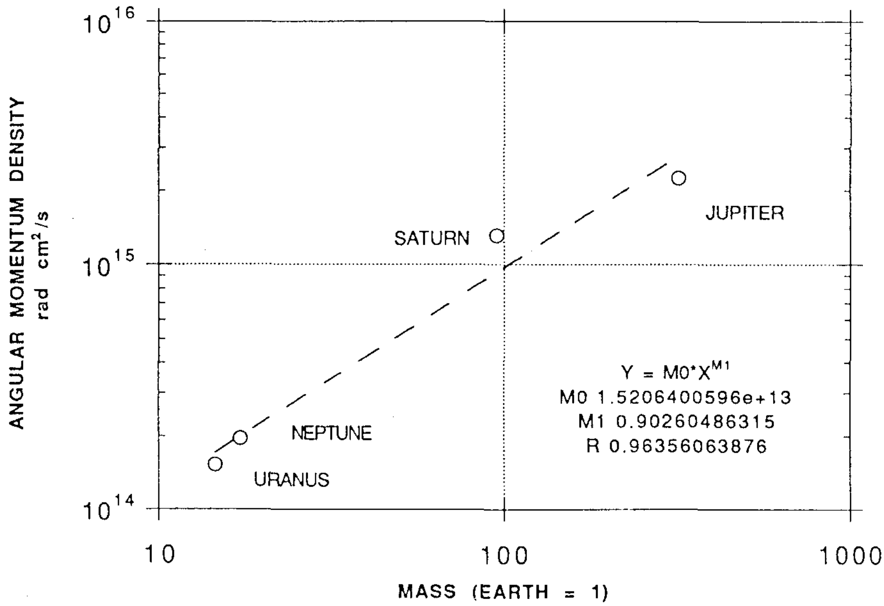

Figure 1. Angular momentum density as a function of mass.

Acknowledgement. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

MERCURY

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Abstract. Radar and space-craft measurements made since 1963 have shown that the axial rotation period of Mercury is 58.6461 days. Previous attempts to determine the period by visual means had been unsuccessful; thus F.W. Bessel derived a period of 24h 0min 53s, while in 1881 W.F. Denning preferred 25h. Careful studies made in daylight by G.V. Schiaparelli between 1881 and 1889, using 22cm and 49cm refractors, led him to believe that the rotation was synchronous, i.e. 88 days, so that apart from minor librations Mercury would have one sunlit hemisphere and one night hemisphere with only a narrow "twilight zone" between. Discounting the obviously spurious markings recorded by P. Lowell (canals) and T.J.J. See (craters), this was the general view up to 1963. In 1934 E.M. Antoniadi's important book summarized the situation, and regarded the synchronous rotation as unquestioned. Antoniadi's map was probably the best of its time; even so, it was highly inaccurate - for which he cannot be blamed. The general history of efforts to determine rotation have been summarized by Moore (1988).

The slow rotation may or may not be associated with effects due to the Earth; on the whole this is rather unlikely, though it is true that the coincidence is very close (2/3 of the sidereal period, so that when Mercury is best placed for observation from Earth the same hemisphere faces us). The rotational dynamics of Mercury, and the state of the core, have been summarized by Peale (1988).

ASTEROIDS

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Introduction.

The rotational motion acquired by bodies in the solar system as a result of collisions can be separated into two components, an *ordered component,* which arises from a slight vorticity in the velocity dispersion of surrounding particles as a result of three-body orbital motion, and a *stochastic component,* from the random off-center geometry of individual collisions. The former component is significant only if the dispersion velocity of colliding particles is less than the surface escape velocity of the target body. Thus it is significant only for major planets (see Lissauer and Kary 1991 for a recent review). The stochastic component is probably responsible for the obliquities of the terrestrial planets (Safronov 1969), and is certainly the dominant component of minor planet spins, as indicated by the apparently near-isotropic distribution of spin axis orientations.

Rotation data

Asteroid rotation periods are determined from lightcurve observations. Most determinations are quite reliable, although some bias against long period, low amplitude objects exists in the data. Harris and Lupishko (1989) summarize the techniques of observation. Binzel *et al.* (1989) present a recent review of rotation data. A summary table of rotation data appears annually in the *Ephemerides of Minor Planets*. Figure 1 is a plot of all reliable rotation rates published through 1989, *vs* asteroid diameter. The geometric mean rotation period of all 459 members of the sample is 9.726 hours.

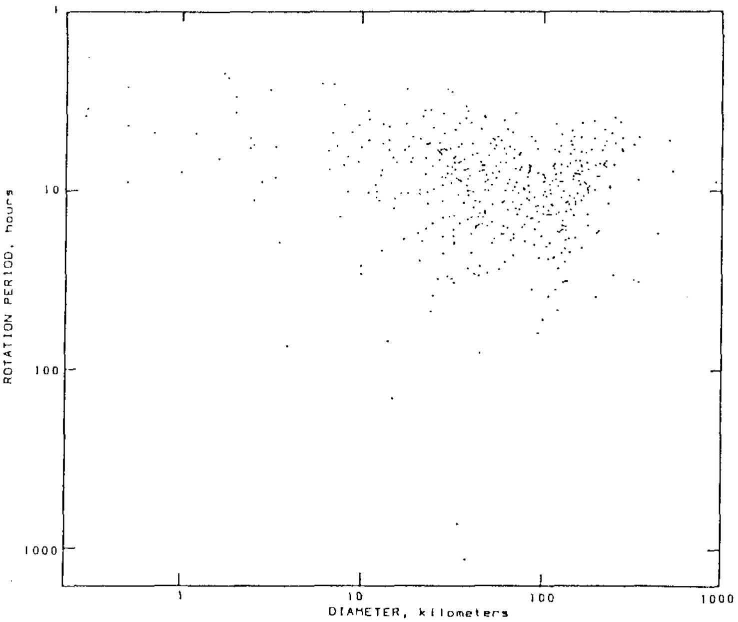

Figure 1. Rotation period of asteroids as a function of mass.

Collisional evolution of spin rates

Harris (1979) first applied the analysis of Safronov (1969) to the problem of asteroid spins. Consider the idealized case an inelastic collision between a target asteroid of mass m and radius r with a projectile of mass dm arriving at velocity v. If the orientation of the obliquity of each collision is randomly oriented with respect to the pre-existing spin, then the angular momentum h of the asteroid will grow as a random walk, that is, each new increment of angular momentum will add quadratically to the pre-existing angular momentum:

$$\mathrm{d}(h^2) = (dm)^2\, v^2\, l^2,$$

where l is the mean impact parameter, which turns out to be $r/\sqrt{2}$. Taking $h = 0.4mr^2$ and writing out the differential on the left, one can rearrange the equation to define the evolution of the mean spin rate:

$$\frac{\mathrm{d}\,\omega}{\mathrm{d}m} = \frac{5\,\omega}{2\,m}\left(\frac{5\,dm}{8\;m}\;\frac{v^2}{r^2\,\omega^2} - \frac{2}{3}\right)$$

The factor dm/m in the above equation indicates that the largest collisions are most important in determining the spin of the growing body. In fact, evaluating the "largest" collision size is key to the whole analysis. Harris (1979) suggests that for collisions in the present asteroid belt, hypervelocity collisions can be treated as inelastic collisions, followed by nearly isotropic ejection of matter, thus the above equation applies even though mass is being lost. Furthermore, he suggests that the quantity dm/m can be associated with the largest non-catastrophic collision possible, since still larger collisions break up the body rather than spin it up. The largest collision which can be absorbed without catastrophic disruption can be estimated to be that for which the kinetic energy of the collision is of the order of the binding energy of the target body. Two regimes can be recognized. Among large asteroids, gravitational binding energy exceeds material strength, so the kinetic energy of a barely catastrophic collision can be equated with the gravitational binding energy to obtain an expression for *dm/m*. Likewise, for strength dominated smaller asteroids, kinetic energy is equated with the material binding energy (S_0 per unit mass):

Gravity dominated:

$$\frac{1}{2} dm\, v^2 \sim \frac{3}{5} \frac{G m}{r} \implies \frac{dm}{m} \sim \frac{6}{5} \frac{G m}{r v^2}$$

Strength dominated:

$$\frac{1}{2} dm\, v^2 \sim S_0 m \implies \frac{dm}{m} \sim \frac{2 S_0}{v^2}$$

In both cases, the above relations can be regarded as only dimensional relations, since the efficiency of breakup is low. When these expressions for *dm/m* are substituted into the spin equation, we find equilibrium solutions for ω which are, in the gravitational regime constant with radius and proportional to the square root of the mean asteroid density, $\sqrt{\rho}$. For the strength dominated regime, ω is inversely proportional to r. There may be some indication in the rotation plot that this is so among the very smallest asteroids (diameter less than a few km). Even if so, it implies that asteroids are not very strong, *i.e.* they may be fractured "rubble piles" as a result of past catastrophic collisions. A valuable goal of future observations is to sample even smaller asteroids in order to determine where the real turn-up is, if at all.

Mean spin rate versus taxonotic class

Returning briefly to the regime of gravitationally bound asteroids, since $\omega = \sqrt{\rho}$, one can examine various sub-classes of asteroids, and relate differences in mean spin rate to differences in mean density between the subgroups. Fairly elaborate systems of taxonomy of asteroids exist, based on spectral features, albedos, etc. (e.g., Tholen and Barucci 1989). We can bunch the many classes into three groups, those believed to be primitive, undifferentiated bodies (C, G, B, F, D, P, T, X), those believed to be mineralogically evolved bodies (S, A, Q, E, V, R), and a lone class M, believed to be nearly pure iron cores of differentiated parent bodies. In table 1, we list for the entire sample and for each of the three sub-groups, the number in the sample, the geometric mean period of rotation with error estimate, and an inferred density. This density is scaled according to $\langle\rho\rangle \propto \langle P\rangle^{-2}$ and normalized to 3.0 for the entire sample.

This indicates that the primitive classes of objects are less dense than the differentiated classes, and that the M class are much more dense, consistent with a high content of iron.

Table 1. Mean rotation period and normalized density of asteroids

Classes	Number	$\langle P\rangle$	$\langle\rho\rangle$
All	459	9.726 ± 0.134	(3.0)
Primitive	192	10.416 ± 0.200	2.6
Differentiated	234	9.740 ± 0.199	3.0
M	27	6.951± 0.328	5.9

Additional structure in the spin rate distribution

There appears to be a modest dip in the mean spin frequency of asteroids in the diameter range near 100 km. One explanation of this (Dobrovolskis and Burns 1984) is that in this size range, typical ejecta velocities are about equal to the surface escape velocity from the asteroid. Thus collisions with bodies in this size range result in a preferential escape of ejecta in the prograde direction, producing an impulse opposing the pre-existing spin. Almost all ejecta escapes from small asteroids, and none from the largest ones, so no impulse results.

Another feature apparent in the rotation plot is the presence of an excess of asteroids with long periods. One can show that up to about 40 hours period, the distribution is approximately Maxwellian. Going to still longer periods, one can compute the probability that a given period represents an "outlier" of a distribution with a mean of about 10 hours. For the most extreme cases, the two with periods near 1000 hours, the probabilities are of the order 10^{-4} each, or 10^{-8} that two such outliers would exist among the present sample. Even the half-dozen or so with periods near 100 hours are improbable members of the main distribution. One explanation that has been suggested is that these objects are tidally evolved binary objects, like Pluto-Charon. This now seems unlikely, at least for some of them, as tidal evolution is incapable of yielding rotation periods longer than about 100 hours in the age of the solar system. The smallest objects, only a few km in diameter, have collisional lifetimes much shorter than that, so even periods in the 100 hour range are problematical. The problem of slow rotators must be regarded as still a mystery, meriting further study.

REFERENCES

Theory of solid rotation

Boigey, F., 1972: Une théorie des perturbations en variables angles-actions.Application au mouvement d'un solide autour d'un point fixe. Précession-nutation, *Journal de Mécanique* **11**, 521-543.

Bois, E., 1986: First-Order Theory of Satellite Attitude Motion - Application to HIPPARCOS, *Celest. Mech.***39**, 309-327.

Bois, E., 1988: Second-Order Theory of the Rotation of an Artificial Satellite, *Celest. Mech.***42**, 141-168.

Bois, E., 1992: On the Rotation Theory of Solid Celestial Bodies, submitted to *Astron. Astrophys.*

Bois, E., Oberti, P., Frœschlé, C., 1992: Gravitational Model of Comet Nucleus Rotation, submitted to *Celest. Mech.*

Bois, E., Wytrzyszczak, I., 1990: The Moon's Physical Librations - Part II: Non-Rigid Moon and Direct Non-Gravitational Perturbations, *Proceedings of the NATO Advanced Study Institute on: Predictability, Stability and Chaos in N-Body Dynamical Systems,* held in Cortina d'Ampezzo, Italy, Aug. 1990, Edited by Archie E. Roy.

Bois, E., Wytrzyszczak, I., Journet, A., 1991: Planetary and Figure-figure Effects on the Moon's Rotational Motion, submitted to *Celest. Mech.*

Eckhardt, D.H., 1981: Theory of the libration of the moon, *The Moon and the Planets* **25**, 3-49.

Goldstein, H., 1964: *Mécanique classique*, Presses Universitaires de France, p. 172.
Gupta, S.C. and Narchal, M.L., 1972: A note on Euler's angles, *Amer. J. Physics*, **40**, 345-346.
Moritz, H., 1980: Theories of Nutation and Polar Motion I, *Report No.***309**, *Dept. of Geodetic Science and Surveying*, The Ohio State University, p. 109.

Mars

Balmino, G., Moynot, B, and Valès N. 1982: Gravity Field Model of Mars in Spherical Harmonics. *J. Geophys. Res.* **87**, 9735-9746
Bills, B.G., and Ferrari, A.J. 1978: Mars Topography Harmonics and Geophysical Implications. *J. Geophys. Res.* **83**, 3497-3508
Bill, B.G. 1989: The Moments of Inertia of Mars.*Geophys. Res. Letters,* **16**, 385-388.
Binder, B.G., and Davis, D.R. 1973: *Phys. Earth Planet. Inter.*, **7**, 477.
Borderies, N., Balmino, G., Caster L., and Moynot, B. 1980: Study of Mars Dynamics from Lander Tracking Data Analysis. *The Moon and the Planets,* **22**, 191-200.
Borderies, N. 1980: La Rotation de Mars: Théorie analytique. Analyse d'observations de l'expérience Viking. *Ph. D. Dissertation,* Université Paul Sabatier, Toulouse, France.
Bretagnon, P. 1974: Termes à longues périodes dans le système solaire. *Astron. Astrophys.*, **30**, 141-154.
Brouwer, D., and Van Woerkom, A.J.J. 1950: The Secular Variations of the Orbital Elements of the Principal Planets. *Astron. Pap. Amer. Ephemeris Naut. Alm,* **13**, 81-107.
Cazenave, A., and Balmino, G. 1981: Meteorological Effects of the Seasonal Variations of the Rotation of Mars. *Geophys. Res. Letters*, **8**, 245-248
Christensen, E.J. 1975: Martian Topography Derived from Occultation, Radar, Spectral, and Optical Measurements. *J. Geophys. Res.,* **80**, 2909-2913
Christensen, E.J., and Balmino, G. 1979: Development and Analysis of a Twelfth Degree and Order Gravity Model for Mars. *J. Geophys. Res.*, **84**, 7934-7953.
Colombo, G. 1976: On the Spin Rate and Latitude Variations of Mars. *JPL Interoffice Memorandum* , **391**, 4-777.
Davies, M.E. 1977: The Prime Meridian of Mars and the Longitudes of the Viking Landers. *Sciences*, **197**, 1277.
Davies, M.E. (1978). The Control Net of Mars: May 1977. *J. Geophys. Res.* **83**, 2311-2312.
Davies, M.E., Katayama, F.Y.and Roth, J.A. 1978: Control Net of Mars: February 1978: *The Rand Corporation*, **R-2309-NASA.**
Davies, M.E., and Katayama, F.Y. 1983: The 1982 Control Network of Mars, *J. Geophys. Res.*, **88**, 7503-7504.
Hess, S.L., Henry, R.M., Leovy, C.B., Ryan, J.A., Tillman, J.E., Chamberlain, T.E., Cole, H.L., Dutton, R.G., Greene, G.C., Simon, W.E., and Mitchell, J.L. 1976: Mars Climatology from Viking 1 After 20 Sols, *Science,* **194,** 78-81.
Hilton, J.L. 1991: The Motion of Mars' Pole: I. Rigid Body Precession and Nutation. II. The Effect of an Elastic Mantle and a Liquid Core. *Ph. D. Dissertation*, U.S. Naval Observatory, Washington..
Hubbard, W.B; 1984: *Planetary Interiors*, Van Nostrand Reinhold Company.
Kaula, W.M., Sleep, N.H. and Phillips R.J. 1989: More About the Moment of Inertia of Mars. *Geophys. Res. Letters* **16,** 1333-1336
Laskar, J. 1988: Secular Evolution of the Solar System over 10 Millions Years. *Astron. Astrophys.***198**, 341-362.
Lyttleton, R.A., Cain, D.L. and Liu, A.S. 1979: Nutations of Mars. *JPL Publication,* **79-85.**

Lorell, J., Born, G.H., Christensen, E.J., Jordan, J.F., Laing, P.A., Martin, W.L., Sjogren, W.L., Shapiro, I.I., Reasenberg, R.D., and Slater, G.L. 1972: Mariner 9 Celestial Mechanics Experiment: Gravity Field and Pole Direction of Mars. *Science*, **175**, 317-320.

Mayo, A.P., Blackshear, W.T., Tolson, R.H., Michael Jr., W.H., G.M., Kelly, J.P., Brencke, and Komarek T.A. (1977: Lander Locations, Mars Physical Ephemeris, and Solar System Parameters: Determination From Viking Lander Tracking Data, *J. Geophys. Res.*, **82**, 4297-4303.

Michael, Jr. W.H., Tolson, R.H., Mayo, A.P., Blackshear, W.T., Kelly, G.M., Cain, D.L., Brenckle, J.P., Shapiro, I.I., and Reasenberg, R.D. 1976: Viking Lander Location and Spin Axis of Mars: Determination from Radio Tracking Data, *Science*, **193**, 803.

Michael, Jr. W.H., Mayo, A.P., Blackshear, W.T., Tolson, H.R., Kelly, G.M., J.P., Brenkle, Cain, D.L., Fjeldbo, G., Sweetnam, D.N., Goldstein, R.B., MacNeil, P.E., Reasenberg, R.D., Shapiro, I.I., T.I.S. Boak III, Grossim, M.D. and Tang, C.H. 1976: Mars Dynamics, Atmospheric and Surface Properties: Determination from Viking Tracking Data, *Science,* **194**, 1337-1339.

Michael, W.H. Jr. 1979: Viking Lander Tracking Contributions to Mars Mapping. *The Moon and the Planets*, **20**, 149-152.

Michaux, D.M. 1967: Handbook of the Physical Properties of the Planet Mars. *NASA Spec. Publ.*, **3030**, 31.

Null, G.W. 1969: A Solution for the Mass and Dynamical Oblateness of Mars. *Bulletin of the American Astronomical Society,***1**, 356.

Okal, E.A., and D.L. Anderson (1978). Theoretical Models for Mars and their Seismic Properties, *Icarus*, **33,** 514-528.

Philip, J.R. 1979: Angular Momentum of Seasonally Condensing Atmospheres, with Special Reference to Mars, *Geophys. Res. Letters*, **6**, 727-730.

Pollack, J.B. 1981: Atmospheres of the Terrestrial Planets. *The New Solar System,* Sky Publishing Corporation and Cambridge University Press.

Reasenberg, R.D. 1977: The Moment of Inertia and Isostasy of Mars, *J. Geophys. Res.*, **82**,369-375.

Reasenberg, R.D., and King R.W. 1979: The Rotation of Mars. *J. Geophys. Res.*, **84**, 6231-6240.

Rubincam, D.P. 1990: Mars: Change in Axial Tilt Due to Climate? *Science,* **248**, 720-721.

Sinclair, A.T. 1972: The Motions of the Satellites of Mars. *Mon. Not. Roy. Astron. Soc.*, **15**, 249-274.

Struve, H. 1898: *Mem. Acad. Imp. Sci. St Petersbourg,* **ser. VIII 3**, 66.

De Vaucouleurs, G. 1964: The Physical Ephemeris of Mars, *Icarus*, **3**, 236-247.

Ward, W.R. 1973: Large Scale Variations in the Obliquity of Mars, *Science*, **181**, 260-262.

Ward, W.R. 1974a: Climatic Variations on Mars. 1. Astronomical Theory of Insolation, *J. Geophys. Res.*, **79**, 3375-3386.

Ward, W.R. 1974b: Climatic Variations on Mars. 2. Evolution of Carbon Dioxide Atmosphere and Polar Caps. *J. Geophys. Res.*,**79,** 3387-3395.

Ward, W.R. 1979a: Present Obliquity Oscillations of Mars: Fourth-Order Accuracy in Orbital *e* and *I*, *J. Geophys. Res.*,**84**, 237-241.

Ward, W.R. 1979b: Past Obliquity Oscillations of Mars: The Role of the Tharsis Uplift. *J. Geophys. Res.*, **84**, 243-259.

Ward, W.R. 1991: Resonant Obliquity of Mars? *Icarus*, accepted for publication.

Williams, J.G. 1977: Seasonal Variations in the Rotation of Mars. *JPL Engineering Memorandum*, **315-14.**

Earth

Benedict, E., and Wilson,C.A., 1990: Dynamic redistribution of oceanic mass and the excitation of polar motion, *Trans. Amer. Geophys. U.*, **71**, 481.

Brosche, P., Seiler, U., Sündermann, J., and Wünsch J., 1989: Periodic changes in Earth's rotation due to oceanic tides. *Astron. Astrophys.* **220,** 318.

Brosche, P. and Sündermann, J., (eds) 1990: *Earth's rotation from eons to days.* Springer-Ferlag.

Capitaine, N. and Cazé, B., 1991: Deficiencies in the model for the celestial motion of the CEP , *Proc. IAU Coll.* **127**, Hughes, J.A., Smith, C.A. and Kaplan, G.A. (eds).U.S. Naval Observatory, p. 222.

Cazenave, A.,(ed.), 1986: *Earth rotation, solved and unsolved problems.* Reidel.

Dehant, V., 1990: On the nutations of a more realistic earth model. *Geophys. J. Int.* **100,** 477.

Djurovic, D., and Pâquet, P., 1989: A 120-day oscillation in the solar activity and geophysical phenomena. *Astron. Astrophys.* **218,** 302.

Eubanks, T.M., Steppe, J.A., Dickey, J.O., and Callahan, P.S., 1985: A spectral analysis of the Earth's angular momentum budget. *J. Geophys. Res.* **90,** 5385.

Guinot, B., 1982: The Chandlerian nutation from 1900 to 1980. *Geophys. J. Roy. Astr. Soc.* **71**, 295.

Hefty, J. and Capitaine, N., 1990: The fortnightly and monthly zonal tides in the Earth's rotation from 1962 to 1988. *Geophys. J. Int.*, **103,** 219.

Herring, T. , 1991: The ZMOA-1990 nutation series. *Proc. IAU Coll. 127*, Hughes, J.A., Smith, C.A.,and Kaplan, G.A. (eds), U.S. Naval Observatory, p.157.

Hide, R., and Dickey, J.O., 1991: Earth's variable rotation. *Science*, **53**, 627.

Kinoshita, H., and Souchay, J., 1990: The theory of the nutation for the rigid Earth model at the second order. *Celest. Mech.* **48,** 187.

Kuehne, J., and Wilson,C.R., 1991: Terrestrial water storage and polar motion. *J. Geophys. Res.*, **96**, 4337.

Lambeck, K., 1980: *The Earth's variable rotation. Geophysical causes and consequences.* Cambridge University Press.

Le Mouël, J.L, Courtillot, V., and Jault, D., 1991: Successful prediction of changes in the Earth's rotation rate. To appear in *Nature.*

McCarthy, D.D., and Luzum, 1991: Observations of luni-solar and free core nutation. *Proc. IAU Coll. 127.* Hughes, J.A., Smith, C.A., and Kaplan, G.A., (eds), U.S. Naval Observatory, p. 303.

Merriam, J.B., 1982: A comparison of recent theoretical results on the short-period terms in the length of day. *Geophys. J. R. astr. Soc.* **69**, 837.

Munk, W.H., and MacDonald, G.I.F., 1960: *The rotation of the Earth.* Cambridge University Press.

Nam Y.S., and Dickman, S.R., 1990: Effects of dynamic long-period ocean tides on changes in the Earth's rotation rate. *J. Geophys Res.* **95**, 6751.

Newhall, X X, Williams, J.G., and Dickey, J.O., 1990: Tidal acceleration of the Moon, *Earth's rotation from eons to days*, Brosche, P. and Sündermann, J.(eds),Springer-Verlag, p. 51.

Rochester, M.G., 1984: Causes of fluctuations in the rotation of the Earth. *Phil. Trans. R. Soc. Lond.* **A 313**, 95.

Smith, M.L., and Dahlen, F.A., 1981: *Geophys. J. R. astr. Soc.* **64**, 223.

Stephenson, F.R., and Morrison, L.V., 1984:Long-term changes in the rotation of the Earth: 700 B.C. to A.D 1980. *Phil. Trans. R. Soc. Lond.* **A 313**, 47.

Vondrak, J. 1990: Atmospheric and groundwater excitation of polar motion in case of variable Chandler frequency. *Bull. Astron. Inst. Czechosl.* **41**, 211.

Wahr, J.M., 1979: *The tidal motions of a rotating elliptical, elastic and oceanless Earth.* Ph. Thesis, University of Colorado.

Pluto

Andersson,L.E.,1978: Bull. *Amer. Astron. Soc.* **10**, 586.
Andersson,L.E. and Fix,J.D.,1973: *Icarus* **20**, 279.
Bonneau,D. and Foy,R.,1980: *Astron. Astrophys.* **92**,L1.
Christy,J.W. and Harrington,R.S.,1978: *Astron. J.* **83**, 1005.
Hardie,R.,1965: *Astron. J.* **70**, 140.
Harrington,R.S. and Christy,J.W.,1981: *Astron. J.* **86**, 442.
Lieske,J.D.,1991: *Private Comm.*
Tholen,D.J.,1985a: *Astron. J.* **90**, 2353.
Tholen,D.J.,1985b: *Astron. J.* **90**, 2639.
Tholen,D.J.,Buie,M.W. and Swift,C.E.,1987: *Astron. J.* **92**, 244.
Tholen,D.J. and Buie,M.W.,1988: *Astron. J.* **96**, 1977.
Tholen,D.J. and Buie,M.W.,1990: *Bull. Amer. Astron. Soc.* **22**, 1129.
Walker,M.F. and Hardie,R.,1955: *Publ. Astron. Soc. Pac.* **67**, 224.

Jupiter, Saturn, Uranus and Neptune

Carr, T.D., and Wang, L. 1990: Monitoring Jupiter's Hectometric Emission, from Low Frequency Astrophysics in Space. Ed. Kassim and Weiler, *Lecture Notes in Physics* **362**.
M. D. Desch and Kaiser, M. L. 1981: Voyager Measurements of the Rotation Period of Saturn's Magnetic Field, *Geophys. Res. Let.*, **8**, 253-256
Desch, M. D., Connerney, J. E. P., Kaiser, and M. L. 1986: The Rotation Period of Uranus, *Nature*, **322**, 42-43.
Lechacheux, A., Zarka, Ph., Desch, M. D., and Evans, D. R. 1990: The Sidereal Rotation Period of Neptune, *Magnetospheres of the Outer Planets,* Annapolis, Maryland, August 20-24.
MacDonald, G. J. F., 1964: Tidal Friction, *Revs. Geophys.*, **2**, 467-541.
May, J., Carr, T. D., and Desch, M. D., 1979: Decametric Radio Measurements of Jupiter's Rotation Period, *Icarus* **40**, 87-93.
Riddle, A. C. and Warwick, J. W. 1976: Redefinition of System III Longitude, *Icarus* **27**, 457-459.
Seidelmann, P. K. and Divine ,N. 1977: Evaluation of Jupiter Longitudes in System III(1965), *Geophys. Let.,* **4**,65-68.
Warwick, J. W., Pearce, J. B., Peltzer, R. G., and Riddle, A.C. 1977: Planetary Radio Astronomy Experiment for Voyager Missions, *Space Sci. Rev.* **21**, 309-328.

Venus

Dr M.E. Davies gave a talk on the rotation of Venus at the Joint Commission Meeting. Unfortunately, due to unexpected circumstances, he was not able to contribute to the proceedings of the meeting. The reader can refer to Peale (1989) for a survey of dynamics in the solar system, including Venus, and to Lago and Cazenave (1979) and Shen and Zhang (1988) for the dynamics of Venus's rotation.

Lago, B. and Cazenave, A., 1979: Possible dynamical evolution of the rotation of Venus since formation. *The Moon and Planets*, **21**, 127.
Peale, S.J., 1989: Some unsolved problems in evolutionary dynamics in the solar system. *Cel. Mech. and Dynam. Astron.*, **46**, 253.

https://doi.org/10.1017/S1539299600009667 Published online by Cambridge University Press

Shen, M., and Zhang, C.Z., 1988: Dynamical evolution of the rotation of Venus, *Earth, Moon and Planets*, **43**, 275.

Mercury

Antoniadi, E.M., 1934: *La Planète Mercure et la Rotation des Satellites*. Paris.
Moore, P., In Vilas, F., Chapman, C.R., and Mattews, M.S., 1988: *Mercury*, Tucson, p.3-5.
Peale, S.J., 1988: In Vilas, F., Chapman, C.R., and Mattews, M.S. (1988) *Mercury*, Tucson, p.461.

Asteroïds

Binzel, R.P., Farinella, P., Zappala, V. and Cellino ,A. 1989: Asteroid rotation rates: Distributions and statistics. *Asteroids II* (R.P. Binzel, T. Gehrels, and M.S. Matthews, eds.), Tucson: U. Arizona Press, pp. 416-441.
Ephemerides of Minor Planets (published annually) St. Petersburg: Institute of Theoretical Astronomy.
Harris, A.W., 1979: Asteroid rotation rates II. A theory for the collisional evolution of rotation rates. *Icarus* **40**, 145-153.
Harris, A.W. and Lupishko, D.F. 1989: Photometric lightcurve observations and reduction techniques. *Asteroids II* (R.P. Binzel, T. Gehrels, and M.S. Matthews, eds.), Tucson: U. Arizona Press, pp. 39-53.
Lissauer, J.J. and Kary, D.M. 1991: The origin of the systematic component of planetary rotation I: Planet on a circular orbit. *Icarus* (in press).
Safronov, V.S., 1969: *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets*. Moscow: Nauka Press (in Russian, English trans: NASA TTF- 677, 1972).

The meeting was organized jointly by Commissions 15, 16, 19, 20
Scientific Organizing Committee: A. Brahic, M.E. Davies, M. Feissel, A.W. Harris, J.W. Harvey, B. Kolaczek, E. Priest, R. West.
Editor: M. Feissel.