Long-term variations of the gravitational potential and of the geodynamical properties of a deformable Earth due to axial despinning

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Results described in this presentation in a significant extent are based on our common papers with Erik Grafarend written during the last twenty years.


The main source of long-term variations in gravity: the tidal friction

Content of the presentation

• The phenomenon of tidal friction
• The data
• The history of axial despining due to tidal friction
• The energy
• Variations in flattening
• Long-term gravity variations
Among the phenomena affecting the long-term evolution and dynamics of the solid Earth only one has an external origin: the long-term despinning of axial rotation due to tidal friction.
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$\beta = 6.8^\circ$ for Pz; $\beta = 1.5^\circ$ for Ptz
The data demonstrate: the axial despinning was constant over the last 600 Ma.
Historical data

Variation of LOD (astronomical data)

Late Babylonian tablet on the eclipse of 15.04.138 BC
Paleontological and paleo-sedimentological data
Internal growth lines in Clinocardium nuttalli compared to tidal predictions for the same epoch. (J.W. Evans, 1972).

Paleontological and paleo-sedimentological data
Paleontological and paleo-sedimentological data

The paleontological LOD data of Stoyko (1970) and Lambeck (1980) for the Pz
The data of Stoyko (1970) and Lambeck (1980) provide in average good agreement with geological data for the Pz. The regression line cannot be extrapolated into the more remote past, because it would lead for times around 3 Ga BP, to LOD < 1.15 hr (Poincaré limit) and to the Earth-Moon distance <18 500km (Roche limit).
Variation of l.o.d. during the Phanerozoic and Proterozoic (i.e. during the interval of time extending from the present to 2.5 eons in the past).

The unit of time ($t$) is Ga.

Paleontological and paleo-sedimentological data...
As a comparison: geomagnetic data for the last 3.5 Ga
LOD data for the time intervals
- from 0.570 Ga to present (above)
- from 2.500 Ga to 0.570 Ga (below).
The straight lines show the regression
LOD = a · t + b
with numerical values
a = (0.0054 ± 0.0006) h/Ma (Pz)
a = (0.00124 ± 0.00072) h/Ma (Arch+Ptz).

Dipolic geomagnetic moment values
- from 0.570 Ga to present (above)
- from 3.500 Ga to 0.570 Ga (below).
The straight lines show the regression
VDM = a · t + b
with numerical values
a = (-0.00019 ± 0.000284) A·m²/Ma (Pz)
a = (0.00019 ± 7.89 × 10⁻⁵) A·m²/Ma (Arch+Ptz).
The significance of slope estimate $a$ is verified using the $F$ statistical hypothesis test. Assuming identically normally distributed data the test statistics $T = a^2 / (\sigma_a)^2$ ($\sigma_a$ – standard error) follows $F$-distribution with $n$ degrees of freedom. Using a confidence level of $\alpha=5\%$ the null hypothesis $H_0: a=0$ the test supports that the slope is statistically significant if $F_{0.05}(1,n) < T$.

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>T</th>
<th>n</th>
<th>$F_{0.05}$</th>
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<td>LOD</td>
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</table>
ENERGY. The total rotational energy

\[ E_r = \frac{1}{2} C \omega^2 + \frac{1}{2} a_m^2 n_m^2 \cdot \left( \frac{M \cdot M_m}{M + M_m} \right) - G \frac{M \cdot M_m}{a_m} \]

The time derivatives should be replaced by the derivative of the Kepler’s law

\[ \frac{d a_m}{dt} = - \frac{2}{3} \cdot \frac{a_m}{n_m} \frac{d n_m}{dt} \]

The principle of conversation of momentum in the Earth-Moon system is

\[ C \cdot \omega + \frac{M \cdot M_m}{M + M_m} \cdot a_m^2 = \text{Const.} \]

A simple combination of the two last equations one gets:

\[ \frac{d \omega}{dt} = \frac{1}{3} \frac{M_m}{M + M_m} \cdot \frac{M a_m^2}{C} \cdot \frac{d n_m}{dt} \]

Using \( d a_m/dt \) and \( d \omega/dt \) together with the Kepler’s law leads to

\[ \dot{E} = C(\omega - n_m) \frac{d \omega}{dt} \]
It should be mentioned that \( C \cdot \frac{d\omega}{dt} \approx L \) (where \( L \) the tidal torque). From the cotidal map of Schwiderski (Schwiderski, 1980) for the tidal torque \( L = -5 \cdot 10^{16} \text{ J} \) was obtained (Varga, 1998) on the basis of numerical integration. Since \((\omega - n_m) = 7.026 \cdot 10^{-5} \text{ s}^{-1}\) the last equation gives \( \frac{dE}{dt} = 1.2 \cdot 10^{20} \text{ J/year} \). Similar value was obtained by Zschau (Zschau, 1986) \( \frac{dE}{dt} = 9.2 \cdot 10^{19} \text{ J/year} \). On the basis of paleontological and paleosedimentological data \( \frac{dE}{dt} = 1.1 \cdot 10^{20} \text{ J/year} \).
LOD, flattening and Earth-Moon distance during the last 2.5-3.0 Ga
Geometrical flattening ($f$) and the Earth-Moon distance ($c_m$) during the last 2.5-3Ga

\[
\frac{df}{dt} = \left(1 + k_s\right) \frac{R^3}{GM} \omega \frac{d\omega}{dt}
\]

\[
\frac{dc_m}{dt} = \frac{2(M + M_m)}{MM_m} C(c_m, n) \omega \frac{d\omega}{dt}
\]

$k_s$ - secular Love number ($\approx 0.96$)

$R$ - mean Earth radius ($= 6.371 \cdot 10^6 m$)

$G$ - gravitational constant ($= 6.673 \cdot Nm^2kg^{-2}$)

$M$ and $M_m$ – are masses of the Earth and the Moon
Concerning of LOD curves two questions must be answered:

• What is the accuracy of paleontological and paleosedimentological data?
• Are the changes reflected by this curve significant in statistical sense?
The diameter of the full Moon in our days and 2Ga BP
LOD, flattening and Earth-Moon distance during the last 2.5-3.0 Ga (cont.)

- Moons orbital radius remaining within about 90% of the present value 3 Ga BP
- This means: the development of the Earth-Moon system was probably slow
- A statistically significant low was found during the Mesozoic (0.35-0.15 Ga BP), which coincides with the time of Pangea, when probably the shelf areas of the continents were reduced.
Geometric flattening of the Earth over the last 2.5 billion years became smaller by 70%.
Accordingly
- absolute value of the gravitational field at the poles was reduced by 690 mgal
- the absolute value of the gravitational field at the equator increased by 2940 mgal
- at mid-latitudes (±50°) the annual variation is 2 ngal/year
Dear Erik,

a great happiness and experience of my life is that I could work with you together for more than twenty years on research problems of joint interest. I learned a lot from you.

Thank you,

Péter