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VARIATION IN THE ROTATION RATE OF THE EARTH AND THE GEOMAGNETIC FIELD

P Varga[1], Z Bus[1], B Süle[1], A Schreider[2], C Bizouard[3], D Gambis[3], C Denis[4]

[1]Seismological Observatory, Geodetic and Geophysical Research Institute, Meredek 18, H-1112 Budapest, Hungary, e-mail: varga@seismology.hu

[2]Shirsov Institute of Oceanology, Nahimovskiy prospekt 36, 117851 Moscow, Russia

[3]International Earth Rotation Service, EOP PC, Observatoire de Paris

[4]Musée National d'Historie Naturelle de Luxembourg and European Centre for Geodynamics and Seismology, 19 rue J Welter, 7256 Walferdange, Luxembourg

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In its first part this work focuses on connection of length of day (LOD) with centered and eccentric geomagnetic dipole fields described with the use of Gaussian coefficients derived from global geomagnetic observations is discussed for the epoch 1900–2000. The statistical comparison of temporal variation of earth magnetic and astronomical data shows close correlation of geomagnetic dipole momentum M_0 and ΔLOD. It should be mentioned that the time-correlation is closer when the centred geomagnetic dipole is used for statistical modelling. In the same time no relation was found between ΔLOD and the orientation variations of the geomagnetic dipole.

In the second part of present study the connection of geomagnetic field and the LOD is investigated in geological time-scale. A significant ΔLOD was found which coincides in time with the geomagnetic Mesozoic low. The reason of this coincidence is enigmatic.

Keywords: centered geomagnetic dipole field; earth rotation; eccentric geomagnetic dipole field; length of day

Introduction

The length of day (LOD) is connected with variations of geomagnetic field (VGF) in case of different frequency bands.

1. At periods longer than few years, extending to many tens of years, the so-called "decadal" LOD variations are chiefly influenced by processes of the liquid outer core, which can be observed at the surface of the Earth with the use of geomagnetic observations. One of the possible mechanisms to generate decadal changes in the LOD is the electromagnetic coupling (see e.g.

Yukutake 1972). Many earlier papers are dealing with relation of Gaussian coefficients and LOD (see e.g. Stephenson and Morrison 1984, Yokohama and Yukutake 1992). In the present contribution the correlation of physical components of the geomagnetic dipole field are compared with ΔLOD.

2. In case of long periods — in geological sense — the source of excitation of ΔLOD is enigmatic. The present author's aim is to show that in this case connection between variations of the axial speed and strength of the geomagnetic field also exists. Probably the physical background is distinct from the case of decadal changes. The interaction has most likely different consequences: contrary to the decadal case, it is not the ΔLOD which is generated, but supposedly it generates changes of the geomagnetic field. The proven with the use of robust estimation techniques minimum of despinning rate during the time interval 100–250 Ma BP (Zharkov et al. 1996) is compared with the virtual dipole moment (VDM) values obtained from paleointensity databases completed some years ago (Varga et al. 1997, Denis et al. 2002) and sufficiently extended recently by Schreider et al. (2005). The magnitude of the minimum in LOD during the Mesozoic is ∼0.3 hour while in the same time the VDM average value was the half of the average strength of the geomagnetic field. Due to the episodic character of Mesozoic low of LOD and VDM they cannot be explained by phenomena acting during the most of geological history, like formation of the inner core (Lay et al. 1998, Labrosse et al. 2001) or tidal friction due to the momentum exchange in the Earth-Moon-Sun system (Denis et al. 2002). During the time-interval 100–250 Ma BP different Earth' surface irregularities were observed (the mean speed of the continental speeds was reduced to $4\ \mathrm{cm} \cdot y^{-1}$ instead of average value of $6\ \mathrm{cm} \cdot y^{-1}$, the oceanic tidal torque was by $0.7\ \mathrm{J}\ 10^{16}$ less than $5.0\ \mathrm{J}\ 10^{16}$ — the average over the Phanerozoic) what can influence the surface geometrical flattening f and consequently the flattening at the core-mantle boundary (CMB) f_c what led to changes of size of the boundary surface. This way the amount of mechanical, electromagnetic core-mantle coupling (Yukutake 1972) can be altered and the heat flow across the liquid core boundary, which influencing in significant extent the strength of the geomagnetic dipole (Bloxham 2000), undergoes modifications.

Decadal variations of length of day and geomagnetic dipole field

Dependence of LOD from processes of the liquid outer core is especially strong in case of periods between 20 and 60 years. This phenomenon is determined first of all by core mantle interactions. These interactions can be of different kinds. Bloxham (2000) and Gubbins et al. (2003) described the sensitivity of the axial geomagnetic dipole to thermal interactions at the CMB. Mound and Buffett detected gravitational oscillations in the LOD. Yukutake (1972) and Yokohama and Yukutake (1992) explain the connection between sixty-year variation in length of day and magnetic field by the electromagnetic core-mantle coupling.

An extension of the range of the link between VGF and LOD in direction of

Table I

g/h	g10	g11	h11	g20	g21	h21	g22	h22	ΔLOD (ms)
1900.0	–31543	-2298	5922	–677	2905	–1061	924	1121	3.1391
1905.0	–31464	-2298	5909	–728	2928	–1086	1041	1065	4.1855
1910.0	–31354	-2297	5898	–769	2948	–1128	1176	1000	4.2438
1915.0	–31212	-2306	5875	–802	2956	–1191	1309	917	3.3492
1920.0	–31060	-2317	5845	–839	2959	–1259	1407	823	2.2468
1925.0	–30926	-2318	5817	–893	2969	–1334	1471	728	1.1443
1930.0	–30805	-2316	5808	–951	2980	–1424	1517	644	0.6905
1935.0	–30715	-2306	5812	–1018	2984	–1520	1550	586	0.4109
1940.0	–30654	-2292	5821	–1106	2981	–1614	1566	528	1.0983
1945.0	–30594	-2285	5810	–1244	2990	–1702	1578	477	1.2646
1950.0	–30554	-2250	5815	–1341	2998	–1810	1576	381	1.3146
1955.0	–30500	-2215	5820	–1440	3003	–1898	1581	291	1.2148
1960.0	–30421	-2169	5791	–1555	3002	–1967	1590	206	1.3022
1965.0	–30334	-2119	5776	–1662	2997	–2016	1594	114	2.4963
1970.0	–30220	-2068	5737	–1781	3000	–2047	1611	25	2.7002
1975.0	–30100	-2013	5675	–1902	3010	–2067	1632	–68	2.6128
1980.0	–29992	-1956	5604	–1997	3027	–2129	1663	–200	1.85554
1985.0	–29873	-1905	5500	–2072	3044	–2197	1687	–306	0.8653
1990.0	–29775	-1848	5406	–2131	3059	–2279	1686	–373	1.4220
1995.0	–29692	-1784	5306	–2200	3070	–2366	1681	–413	1.3712
2000.0	–29619	-1728	5186	–2267	3068	–2481	1671	–458	1.2920

shorter than 20 year periods is hardly possible because the worldwide geomagnetic data are available recently with a time step of 5 years. A more fundamental difficulty is related to the strong influence of the atmospheric angular momentum on LOD in case of annual/sub-annual periods (Abarca del Rio 2003), what hides the possibly existing core-mantle interactions. In case of longer, secular, periods we meet the problems of sparse LOD data and of the rogue definitions of dates for both the magnetic (archeomagnetic) and LOD data.

For the aims of present investigation in case of decadal variations the geomagnetic data were obtained from IAGA global spherical expansion database for the time-interval 1880–2000 with a five-year step. Lengths of day variation data for the same time-interval are given in form of mean annual values derived from long-term data set of JPL (Table I).

In spherical co-ordinate system expansion of the potential V of degree n and order m can be expressed as:

$$V(r,\theta,\varphi) = a\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}(g_n^m\cos m\varphi + h_n^m\sin m\varphi)P_n^m(\cos\theta)\,,$$

where a is the mean Earth radius, r gives the distance from the Earth centre, φ and θ are the geographical co-ordinates. Coefficients (so-called Gaussian coefficients) g_n^m, h_n^m are determined by magnetic observations.

The strength of the dipole field on the magnetic equator is

$$B_0^2 = (g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\,. \tag{1}$$

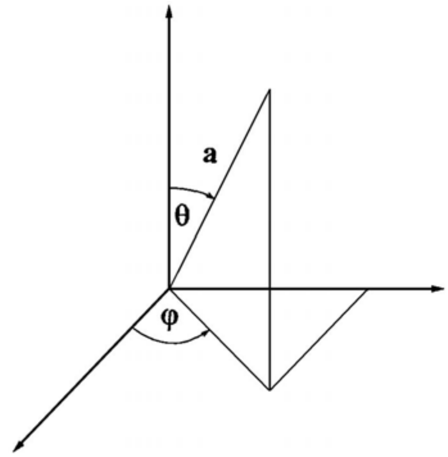

Fig. 1

The dipole moment M_0 (Fig. 1) is given by

$$M_0 = \frac{4\pi}{\mu_0} B_0 a^3 \,. \tag{2}$$

The angle between the geomagnetic dipole and geographic axes is θ_n, where

$$\cos\theta_n = -\frac{g_1^0}{B_0}; \quad \sin\theta_n = \frac{\sqrt{(g_1^1)^2 + (h_1^1)^2}}{B_n} \tag{3}$$

and the azimuthal angle is φ_n:

$$\cos\varphi_n = -\frac{g_1^1}{\sqrt{(g_1^1)^2 + (h_1^1)^2}}; \quad \sin\varphi_n = -\frac{h_1^1}{\sqrt{(g_1^1)^2 + (h_1^1)^2}} \,. \tag{4}$$

The interactions between M_0, θ, φ and ΔLOD are shown in Figs 2–4. The dependence of parameters describing the strength and the directions of centred geomagnetic dipole and ΔLOD is described by a polynomial of degree $n = 6$. We conclude that only the dipole moment (M_0) has significant fit with ΔLOD and the connection between these two vectors can be described with a polynomial of fourth degree.

The eccentric dipole has the same moment and orientation as the centred one, but located at the position $\xi \cdot a$, $\eta \cdot a$ and $\zeta \cdot a$ derived from the Gaussian coefficients. The distance of the dipole from the Earth centre is given by

$$\delta = \left(\sqrt{\xi^2 + \eta^2 + \zeta^2}\right) \cdot a \,.$$

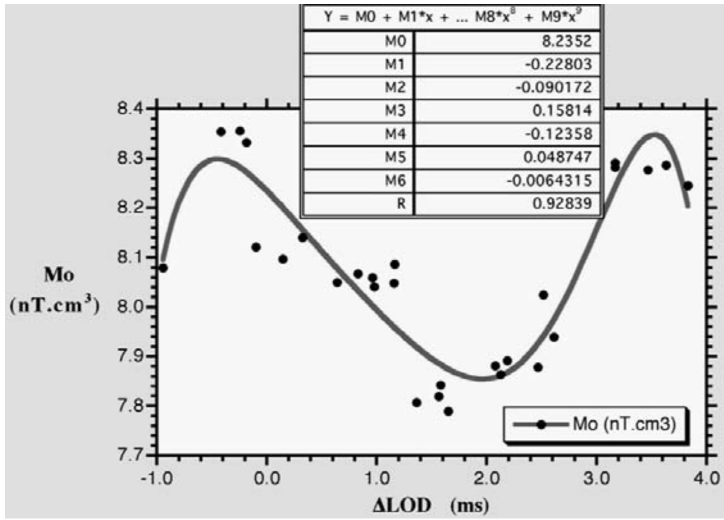

Fig. 2

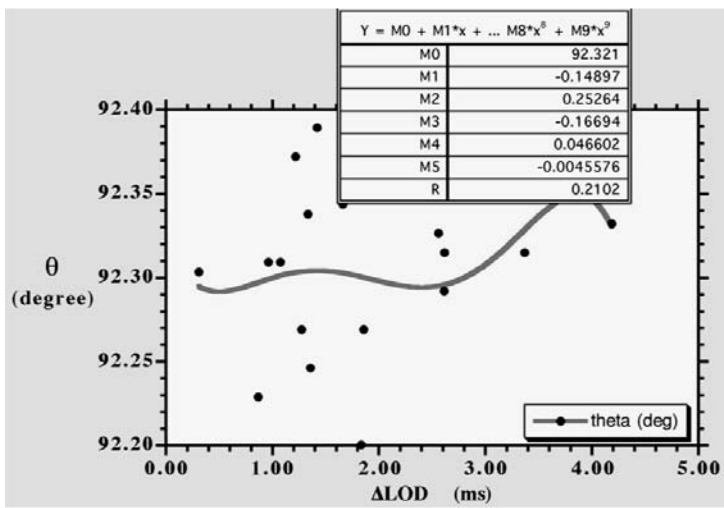

Fig. 3

The dimensionless co-ordinates ξ, η and ζ are given by auxiliary functions

$$\begin{aligned}\xi &= \frac{L_0 - g_1^0 \cdot E}{3B_0^2}\\ \eta &= \frac{L_1 - g_1^1 \cdot E}{3B_0^2}\\ \zeta &= \frac{L_2 - h_1^1 \cdot E}{3B_0^2}\end{aligned} \tag{5}$$

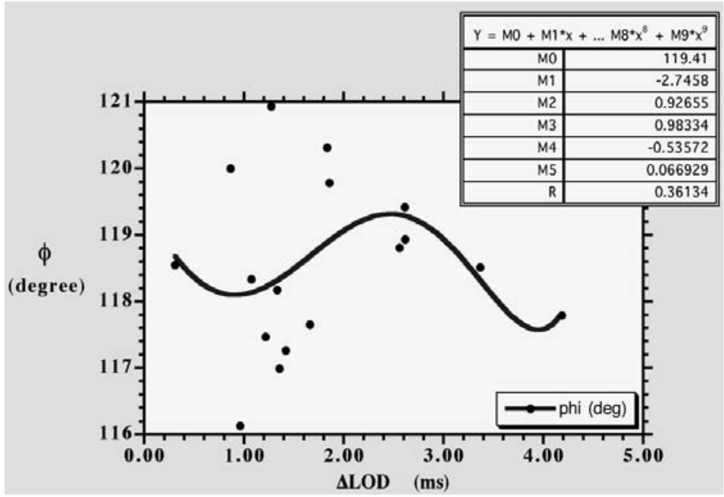

Fig. 4

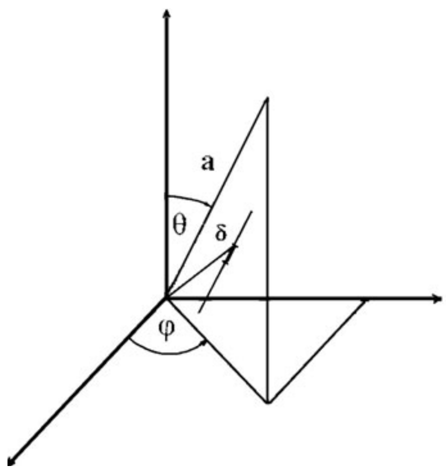

Fig. 5

where

$$L_0 = 2g_1^0 g_2^0 + \sqrt{3}\left(g_1^1 g_2^1 + h_1^1 h_2^1\right)$$
$$L_1 = g_1^1 g_2^0 + \sqrt{3}\left(g_1^0 g_2^1 + g_1^1 g_2^2 + h_1^1 h_2^2\right)$$
$$L_2 = h_1^1 g_2^0 + \sqrt{3}\left(g_1^0 h_2^1 + h_1^1 g_2^2 + g_1^1 h_2^2\right) \qquad (6)$$
$$E = \frac{L_0 g_1^0 + L_1 g_1^1 + L_2 h_1^1}{4B_0^2}\,.$$

From Eqs (6) the azimuthal angles θ_n and φ_n can be obtained and the geometrical position of the eccentric dipole are shown on Fig. 5.

The dependence of M_0, δ, θ, φ and ΔLOD are shown by Figs 6–9 respectively.

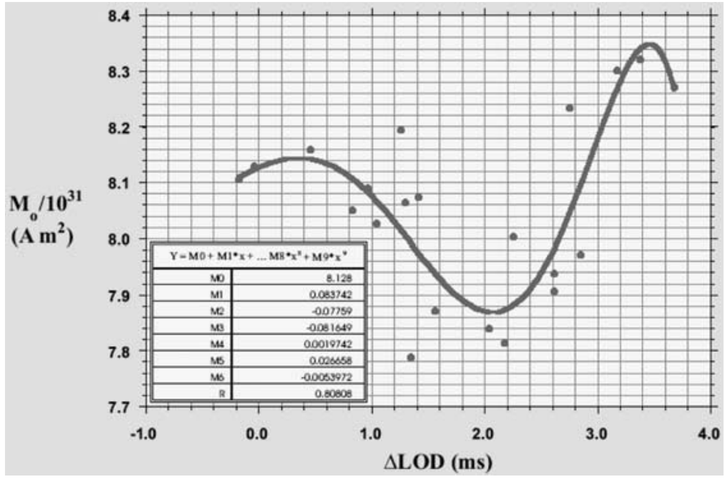

Fig. 6

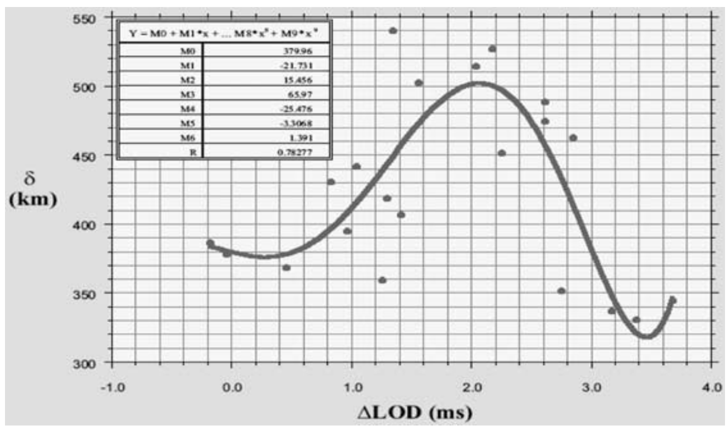

Fig. 7

Table II

	M_0	θ	φ	δ
Central dipole	0.928	0.210	0.361	
Eccentric dipole	0.808	0.612	0.740	0.703

In Table II the correlation coefficients both for three components of central geomagnetic dipole and for the four components of eccentric dipole field are collected together.

Correlation with ΔLOD in decadal time-scale is satisfactory in case of all components of eccentric dipole, while for central dipole the statistical link exists only

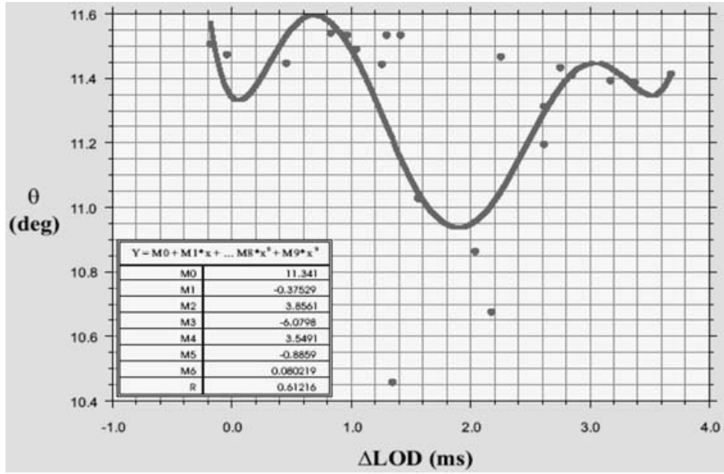

Fig. 8

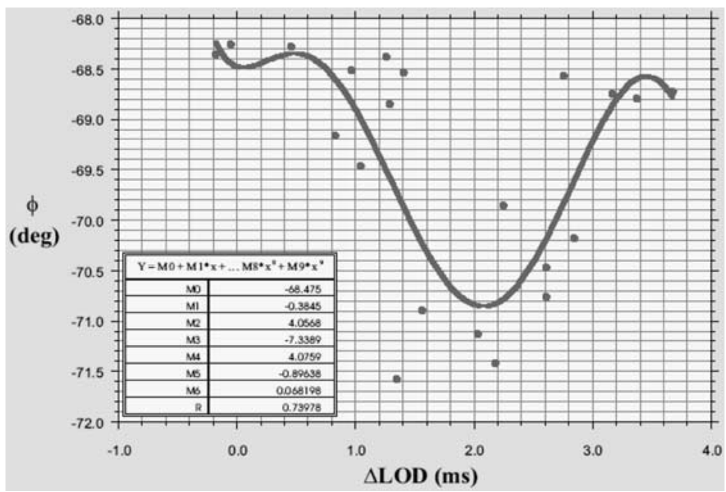

Fig. 9

between M_0 and ΔLOD. That means that for the study of interrelation of earth rotation and geomagnetic field the eccentric geomagnetic dipole is a more convenient tool.

From the data of Table I the fast attenuation of M_0 in the course of 20th century can be concluded (Fig. 10). This phenomenon is well known and it illustrates that at longer periods there is not evident correlation between VGF and ΔLOD. The 5%/century abatement of the geomagnetic dipole moment is of course an anomaly. This fast reduction of field strength holds in less extent for a more extended time-intervals too. To illustrate this on Fig. 11 M_0 values derived from archeomagnetic data (Schreider et al. 2005) are plotted from the present epoch till 12 000 BP (before

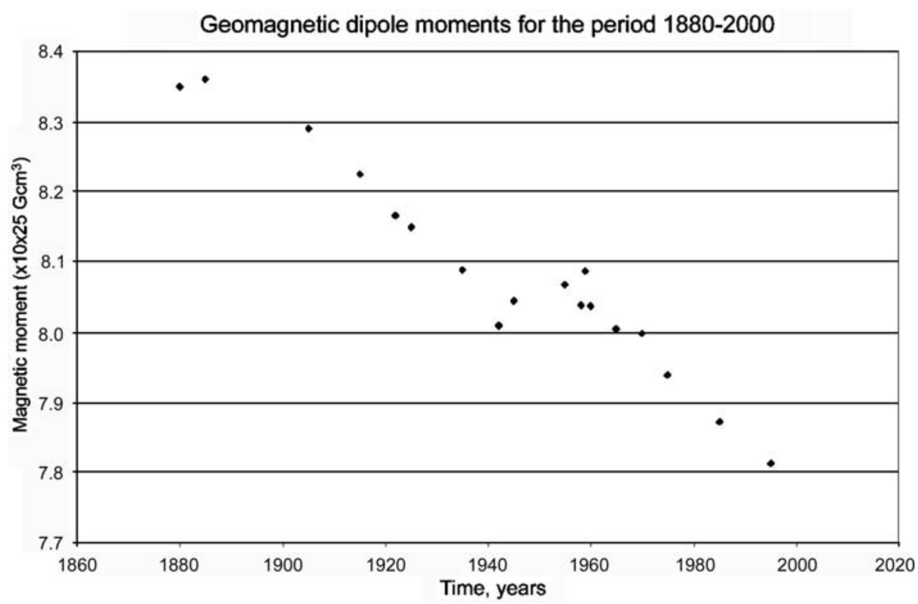

Fig. 10

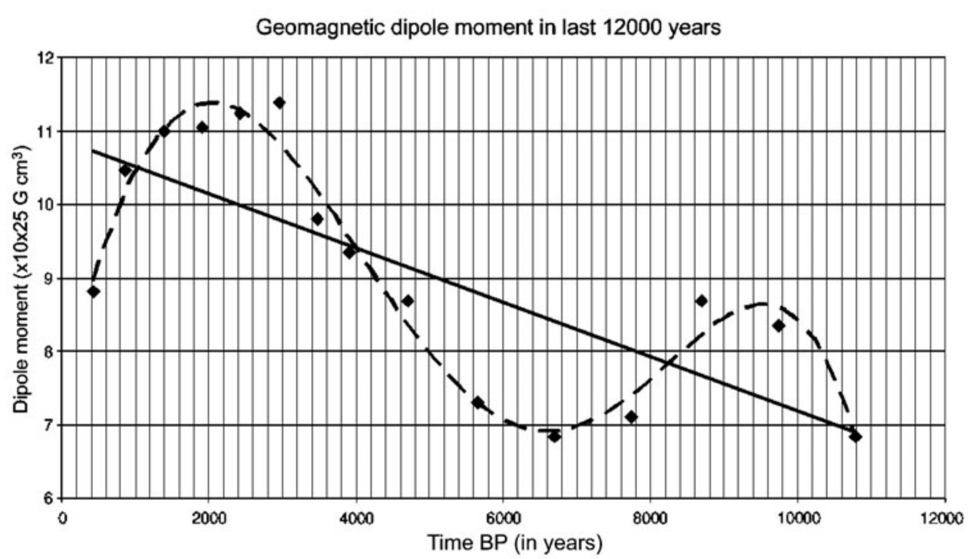

Fig. 11

present). In this case the dipole moment decrease is significantly smaller (0.4%), but in the light of history of geomagnetic field it is still a high value. It is remarkable that on linear trend of M_0 obtained with the use of archeomagnetic data a wave of 7700 year period is superimposed, what coinside with the period of the fundamental period of fundamental magnetohydrodinamical oscillation (Zharkov et al. 1996).

Variation of LOD and geomagnetic field during the geological history

The observed secular despinning of the Earth is generally explained in terms of tidal gravitational interaction with the Moon. LOD data plotted on Fig. 12 are sparse and were collected together from different sources in Denis et al. (2002) and Varga et al. (1997). Information comes from fossils of the Phanerozoic (0–570 Ma BP), from stromatolites and paleodeposits of the Proterozoic (570–2500 Ma BP). Concerning the LOD curve on Fig. 12 two questions must be answered:

— what is the accuracy of paleontological and paleosedimentological data used for determination of temporal variation of length of day?

— are the changes reflected by this curve significant in a statistical sense?

The error bounds of the age determination usually are not indicated by the authors quoted in Denis et al. (2002) and Varga et al. (1997). When they are published the typical errors are smaller than 10% and rarely approach 20%. An estimate of error in LOD can be obtained from a comparison of daily growth rings of recent corals and the astronomical datum. This way the relative error value of length of day data is around 2%.

To answer the second question on statistical significance of the nonlinearities in the despinning a robust statistical modelling was carried out which is a convenient statistical parameter estimation technique when the distribution of errors cannot be *a priori* supposed as normal. In case of paleontological and paleosedimentological data the Laplace-type estimations are suitable and the condition for modelling the paleorotation periods was that the deviation from the statistical model should be less than ± 0.25 hour.

The higher order robust estimation with the use of Laplace modelling ($n = 3, 4, 5$) of the residual of LOD (the linear trend is removed) allows us to conclude that a statistically significant minimum took place in the Earth despinning rate 250 and 100 million years ago i.e. during the Mesozoic a non-linear variation was superimposed on the overall linear trend of the Earth's rotation. The statistically significant Mesozoic low shown by Fig. 12 coincides with the time of Pangea when continents were gathered. It was shown by the paleotidal torque estimations calculated with the use of paleocotidal maps that around the time interval 350 and 150 million years ago the value of the oceanic tidal torque had this relative minimum, too (see e.g. Zharkov et al. 1996). It was shown by Zonenshain and Kuzmin (1997) that (100–250) Ma BP the mean speed of the continent plates was only 4 cm/y^{-1} instead of their average value 6 cm/y^{-1}.

The strength of the Earth's magnetic field during geological time is known only quite unsatisfactorily. This last statement is particularly valid for the Protorezoic and Archean (570–2500 Ma BP and 2500–4000 Ma BP). In contrast with the detailed knowledge of the directional behaviour of the geomagnetic field during geological and historic times paleointensity data are still scarce and often doubtful. Notorious difficulties are related to the nature of the primary remanent magnetisation and to the effects connected to many experimental difficulties. There are quite discordant

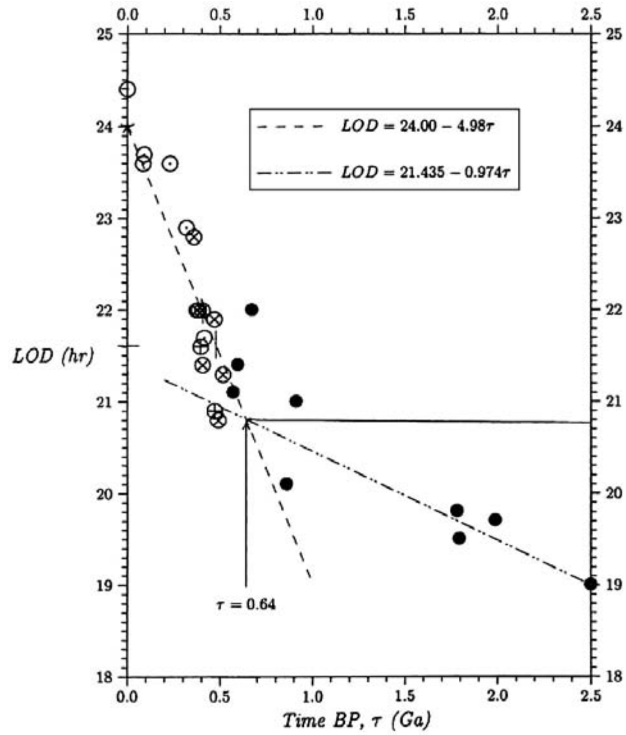

Fig. 12. Variation of LOD during the Phanerozoic and Proterozoic (i.e. during the interval of time extending from present to $2.5 \cdot 10^9$ year before present epoch. The star denotes the astronomical datum. The cycles with dot, X and + refer to bivalve, coral and brachiopod respectively. Full circle denotes information stemming from stromatolites or tidalites (Denis et al. 2002)

opinions concerning the reliability of the paleointensity data. Concerning Selkin and Tauxe (2000) beside the last 0.3 Myr there are no other significant changes in the distribution of dipole moment over the last 300 million year span of data. In contrast to this opinion Scherbakov et al. (2002) conclude that the overall paleointensity pattern in the time interval of 0–400 Ma revealed a series of higher and lower VDM (Virtual Dipole Moment) intervals. There is however a general agreement that the present day VDM value is high in a comparison with the values of remote geological past. Despite of these difficulties, the paleointensity database has grown over recent years although the predominant part of them come from the last 10–20 Myr and are restricted to a few locations on the globe. Some of the authors of present study completed in the course of last year a database of 2562 data (the last version of it is described by Schreider et al. 2005). With the use of the earlier version of this data set after careful selection a database of 297 values were completed, which are accurately described by Varga et al. (1997, 2002) (see Table III and Figs 13–14). In the selected database all the values were obtained with the use of Thelleir-Thelleir method and were published in international journals with strict reviewing process. The magnetic dipole moments are in relative units: the ancient value is divided

Table III. Paleointensity data for the Phanerozoic ((0.00–0.57) Ga BP) and for the Proterozoic + Archean ((0.57–4.00) Ga BP) (Data are in relative units, the ancient magnetic moment values are divided by $M_0 = 6.77 \cdot 10^{12}$ Am^2 (the present magnetic moment))

PHANEROZOIC (Number of data $n = 135$)		
(01–100) Ma BP	(100–250) Ma BP	(250–570) Ma BP
$n = 40$	$n = 56$	$n = 39$
Mean: 0.8962	Mean: 0.5385	Mean: 1.0408
RMS: ±0.0290	RMS: ±0.0267	RMS: ±0.0442

THE WHOLE PHANEROZOIC	
Mean:	0.7867
RMS:	±0.0190

THE WHOLE PHANEROZOIC WITHOUT MESOZOIC ((100–250) Ma BP)	
Number of data	79
Mean:	0.9735
RMS:	±0.0258

PROTEROZOIC + ARCHEAN ((0.57–4.00) Ga BP)	
Number of data	83
Mean:	0.9379
RMS:	±0.0541

by the present magnetic moment (M/M_0). The relative accuracy of the measured magnetic field values is generally comprised between 10% and 30% and in certain instances the error is larger than the intensity value itself. The error bound on the age determinations are as a rule smaller than 10%, and only rarely approach 20%. Altogether, the scatter in the data is quite large, and is probably not caused only by experimental problems. An essential part of the scatter obviously stems from the fact that the Earth's magnetic field undergoes large-amplitude short-periodic changes, too. Present study deals with paleointensities averaged over time scales of several million years.

Figure 14 shows VDM values for the most of Earth's history. There are no statistically significant changes in magnitude of VDM from Archean till the Present Epoch. (The slope of linear regression line on Fig. 14 has no significance). It should be mentioned here that there are doubts concerning the dipole character of geomagnetic field before 250 Ma BP (see e.g. Bloxham 2000).

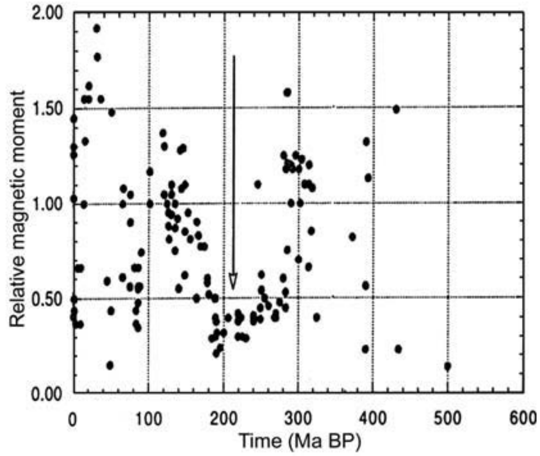

Fig. 13. Intensity of the geomagnetic field during the Phanerozoic. The arrow shows the position of the Mesozoic low (Varga et al. 1997)

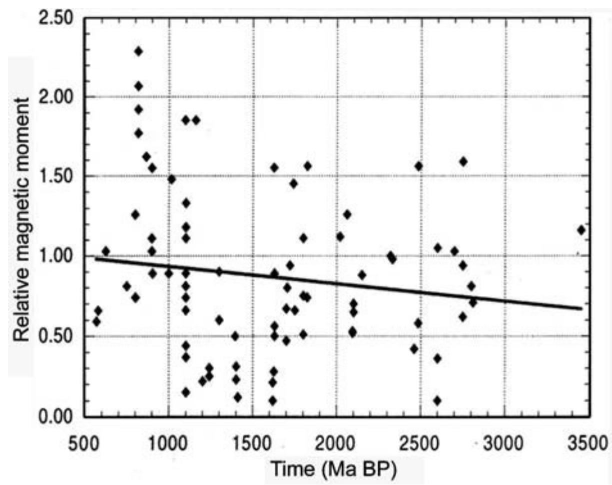

Fig. 14. Intensity of the geomagnetic field during the Proterozoic, Late and Middle Archean (Varga et al. 1997)

The Mesozoic low of the geomagnetic dipole (Fig. 13) coincides with anomaly of the oceanic tidal torque and of the angular speed values. In the same time took a relative minimum place in rates of lithospheric plate motion and in oceanic tidal torque. Presently there is no satisfactory explanation for the above coincidences. It should be mentioned however that during the most of Mesozoic all continental plates were gathered in one supercontinent Pangea. This circumstance generated diminution of the oceanic tidal displacements, which led to the minimum of the tidal torque, and — as a consequence — to an anomaly of the equilibrium figure of the Earth, and of the core-mantle boundary (CMB). The coupling phenomena at CMB (mechanical, electromagnetic, the heat flow through CMB) are influencing

Table IV. Flattening of the (f_0) Earth and the CMB (f_{CMB}) at the present, during early (250 Ma BP), middle (175 Ma BP) and late (100 Ma BP) Mesozoic

Epoch	f_0	f_{CMB}
Present	0.0033	0.0025
100 Ma BP	0.0037	0.0029
175 Ma BP	0.0038	0.0029
250 Ma BP	0.0042	0.0032

the LOD variations. Because the variation of coupling depends on the CMB surface variation the flattening (f_0) and the flattening at the CMB (f_{CMB}) were calculated for the present epoch, and for 100, 175 and 250 Ma BP. The surface value of the flattening for different epochs can be obtained with (Zharkov et al. 1996)

$$\frac{df_0}{dt} = (1 + k_s)\frac{R^3}{GM}\omega\frac{d\omega}{dt}\,, \tag{7}$$

where k_s is the secular Love number (~ 0.96), $R = (a \cdot b)^{1/2}$ is — as above — the equivolumetric mean radius (a – equatorial and b – polar radius), M is the mass of the Earth and G is the gravitational constant. To obtain f_{CMB} with the use of f_0 the Radou equation is needed (Denis 1989):

$$\eta = \frac{r}{f}\frac{df}{dr}\,. \tag{8}$$

In above equation r gives the distance from the centre of the Earth and according to the approximation introduced by Darwin (1899)

$$\eta = 2.5\left(1 - \frac{3}{2}\frac{C}{MR^2}\right)^2 - 1 \tag{9}$$

(C is the mean moment of inertia).

With the use of Eq. (7) f_0 can be computed for different epochs and with the use of these values with the differential equation of Radou (Eq. 8) f_{CMB} can be obtained for the geological past. For the numerical solution of Eq. (8) the following boundary conditions were used:

$$\frac{df}{dr} = f_0 \text{ – at the surface and}$$

$$\frac{df}{dr} = \frac{1}{4}\frac{f_c}{\varrho_c}\frac{d\varrho}{dr} \text{ – at the centre of the Earth.}$$

In the boundary condition for the centre of the Earth f_c and ϱ_c are the flattening and the density at $r = 0$. Results of solution of Eq. (7) and numerical integration of Radou's differential equation (Eq. 8) are given in Table IV.

After the removal of the long-periodic linear trend of f_{CMB} for the variation of the liquid core flattening one gets $\Delta f_{\mathrm{CMB}} = 6 \cdot 10^{-4}$. That means: the relative CMB surface variation due to Mesozoic LOD anomaly is $< 7 \cdot 10^{-4}$. This means that probably the CMB surface variation not causes significant influence on the coupling between the elastic mantle and the liquit outer core. Even less is the effect caused on the CMB by the surface load redistribution due to redistribution of continental plates during the Mesozoic.

Conclusions

1. It was found that the four components of the eccentric geomagnetic dipole (momentum, eccentricity and two angles of direction) are in close correlation with the LOD variations in the decadal time-scale. That means: the core processes and first of the entire coupling at the CMB being the causes of rotational speed variations in this frequency band. It is necessary to extend the investigations in direction of longer periods with the use of ancient Chinese and Babylonian eclipse information and selected archeomagnetic data.

2. In geological time scale a significant ΔLOD was found which coincides in time with the geomagnetic Mesozoic low. The reason of this coincidence is not clear yet. The calculations carried out until now could not prove that the flattening variations generated by LOD anomaly are able to influence processes in the outer liquid core.

3. The geomagnetic field intensity has rather significant oscillations during the lifetime of the Earth. There is no statistically significant evidence of variation of the geomagnetic dipole moment during the last 4 Ga.

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