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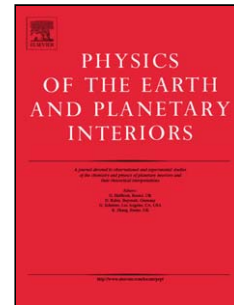
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How persistent is the present trend of the geomagnetic field to decay and, possibly, to reverse?

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Abstract

Recent studies provide evidence for a possible imminent change of polarity or an excursion of the geomagnetic field. In this paper we explore the possibility that the present trends are persistent, looking at the behaviour of some physical quantities of the recent geomagnetic field with particular attention to the last century. Analysis of the mean square value of the field over the last 400 years shows a linear decay that if extrapolated will be zero in around 1000 years, while if we extrapolate the field over Antarctica it will go to zero in around 300 years. The information content of the geomagnetic field has been decaying from around 1690, but began to decrease more rapidly at around 1775 and even more rapidly after 1900. An intermittent synchronicity between the exponential field decay and the increase latitudinal speed of the south geomagnetic pole with similar (decaying or growing) timescales can be interpreted as evidence for a present persistent turbulence of the geomagnetic field. From this work it emerges that the present situation is likely to persist further into the future, probably for another century, but longer predictions are not possible.

Keyword: geomagnetic field, geomagnetic reversal, persistent turbulence.

Introduction

The present geomagnetic field \mathbf{B} is rapidly decreasing in terms of its mean square value $\langle \mathbf{B} \cdot \mathbf{B} \rangle = \langle B^2 \rangle$ (Loves, 1966) and its dipole magnetic moment, so much so that some authors have suggested that the next geomagnetic reversal is imminent. For instance, Gubbins (1987) looking at local contributions to the surface integral that defines the axial dipole moment found that the southern hemisphere makes a larger contribution than the northern hemisphere and suggested that the decrease in the dipole moment is directly related to the intensification and southward movement of a pair of patches of reverse flux under South Africa, which could lead to a polarity reversal. Rajaram et al. (2002) related the rapid fall of the geomagnetic field in Antarctica to a possible imminent reversal. Newitt et al. (2002) found a recent acceleration of the North Magnetic dip pole and correlated it with geomagnetic jerks, which are rapid changes of the secular variation occurring all over the globe in a few years or even less. Opdyke and Meija (2004) show that the present Virtual Geomagnetic Dipole (VGD) as deduced from hypothetical present samples induced by a geomagnetic field such as the most recent IGRF model (e.g. Macmillan and Maus, 2005) has a dispersion typical of a reversal. Hulot et al. (2002) through an inversion of satellite magnetic data from the Magsat and Oersted missions centered at around 1980 and 2000, respectively, found a reverse magnetic flux under the southern hemisphere that could anticipate an imminent reversal. In an almost Earth-like dynamo simulation, Takahashi et al. (2005) found an analogous reverse flux that can explain the present anomalous aspect of the geomagnetic field in the Southern Atlantic, the so-called Southern Atlantic Anomaly (SAA), that could be a symptom of the next polarity reversal. If the present trend continues for the next years, the low in the field strength southwest of Cape Town (South Africa) will be reduced to zero in 235 years from now, and the SAA will cover about half the southern hemisphere at that time: all components of the geomagnetic field will be zero (Heirtzler, 2002; Heirtzler et al., 2002). A very recent paper (Gubbins et al., 2006) shows how special the current time is for the geomagnetic field, as the present decay started probably around

1840, confirming that the southern hemisphere contributes to it more than the northern hemisphere. Another recent paper (Constable and Korte, 2006) reviews some results in favour of or against the possibility of an imminent geomagnetic reversal, with more attention to those aspects of the geomagnetic field as deduced from paleomagnetic studies. They do not refer to a recent paper with a different approach to the problem that also favours to that possibility (De Santis et al., 2004).

In this paper, mainly based on the study of the intensity of the geomagnetic field and some related quantities, we will not analyse paleomagnetic data. They have been, and still are, fundamental for studying many aspects of the past geomagnetic field, especially the determination of the declination and inclination on geological timescales, and the reversals of polarity. However the estimation of the mean strength (and, in turn, the magnetic dipole moment) of the paleomagnetic field has always been rather problematic. For instance, on the one hand, an objection to a possible imminent geomagnetic reversal is that the mean magnitude of the dipole moment in the past was much lower than the present value, so now the field is simply tending toward its typical long-term mean value (Constable and Korte, 2006 and references therein). On the other hand, an opposing view has recently been proposed by Tarduno et al. (2006): the paleointensity results from single silicate crystals, which are likely to have been more protected from environmental magnetic contamination, reveal a higher mean field strength during the last 160 million of years, much closer to the present-day field value. According to these authors, “this higher mean implies that the present decay represents something more than a return to an average value”.

For the above reasons, in this paper we study the behaviour of some physical quantities of the geomagnetic field in the recent past when instrumental measurements were available. In particular we see that the mean square value of the geomagnetic field has decayed almost linearly during the past 400 years and when extrapolated into the future a zero mean square value is predicted around 1000 years from now. This effect is more pronounced over Antarctica where the mean square value of the field is predicted to be zero in around 300 years. We also find that the most recent global models based on satellite data confirm what was already found for the last 100 years concerning

Shannon information content (Shannon, 1948; Beck and Schlögl, 1993) which is linearly decaying supporting the idea of a chaotic regime for the dynamics underlying the generation of the geomagnetic field (De Santis et al., 2004). We find also that the linear decay of the information content probably started at around 1690, then it decreased more rapidly at around 1775; after 1900 it decreased even more rapidly with the same characteristics as the present information content (De Santis et al., 2004). Finally we show that, for the last century, a representative observational quantity contributing to the advective term in the magnetic induction equation is practically constant for some recent time intervals, supporting the idea of a persistence of the geomagnetic field to continue to have the same trend into the near future. Finally, some speculations based on these results are made.

In this paper we shall not investigate any of these persistent characteristics in the field over times longer than a few centuries; that will be the subject of a companion paper.

Mean square value of the geomagnetic field

Let us consider the mean square value of the geomagnetic field over the whole globe (Lowes, 1966, De Santis et al., 1995):

$$\langle B^2(t) \rangle = \frac{1}{4\pi} \int_0^\pi \int_0^{2\pi} B^2(\theta, \lambda, t) \sin \theta d\theta d\lambda = \sum_{n=1}^N (n+1) \sum_{m=0}^n (g_n^m)^2 + (h_n^m)^2 \quad (1)$$

where θ, λ and t are colatitude, longitude and time, respectively; g_n^m, h_n^m are the Gauss coefficients of the spherical harmonic expansion of the geomagnetic potential V , where $\mathbf{B} = -\text{grad } V$; m, n, N (where $m \leq n \leq N$) are the spherical harmonic order, degree and the maximum degree of the geomagnetic potential expansion, respectively. To have some idea of the behaviour of the mean square value of the field over a rather long period, we considered the GUFM1 model (Jackson et al., 2000) which is a time varying global spherical harmonic model of the geomagnetic field based on all known historical measurements from 1590 to 1990. Although there are some doubts about the

behaviour of the mean square value before 1840 (Gubbins et al., 2006), when we fit this quantity over the period of validity of the GUFM1 model, we find that this quantity will be zero around 1000 years from now (Fig.1a). The error bars shown are deduced by assuming a decreasing linear error of the Gauss coefficients from 5% at 1590 to 1% at 1990 and then applying the Gauss method of propagation of errors.

Fig.1b shows the same quantity for the last century as given by the global model IGRF and GUFM1. In the period 1900-1990 the mean square values from both models agree up to the third significant digit, so their points in the figure are practically overlapping. Each point is drawn without error, but this can be simply estimated as twice the largest relative error in one of the Gauss coefficients. For our purposes, attributing an error of around 1% to each of the Gauss coefficients, we can estimate the error associated with the mean square value to be around 2% of the value itself. Extrapolating linearly the behaviour of $\langle B^2 \rangle$, it can be estimated to become zero in around 1000 years, confirming the previous results obtained over a longer period. If at the moment of polarity reversal the field is 10% of the typical value (Jacobs, 1994), that means 1% of the typical mean-square value, this will happen in about 800 years from now.

Each region of the Earth's surface contributes differently to $\langle B^2 \rangle$. In the same way that Gubbins (1987) showed the different local contributions to the axial geomagnetic dipole, in particular that of the Southern Hemisphere, we can compute the local contribution to the mean square value (1) of the geomagnetic field over Antarctica. Choosing a spherical cap of half-angle θ_0 , we have:

$$\langle B^2(t) \rangle_{\theta_0} = \frac{1}{2\pi(1 - \cos \theta_0)} \int_{\theta_0}^{\pi} \int_0^{2\pi} B^2(\theta, \lambda, t) \sin \theta d\theta d\lambda \quad (2)$$

Using a spherical cap harmonic model for the Antarctic region below 60° S (i.e. a cap centred on the south geographic pole and with half-angle $\theta_0=30^\circ$), the so-called Antarctic Reference Model (ARM; De Santis et al, 2002a; Gaya-Piqué et al., 2006) we can estimate the quantity (2) with high accuracy during the temporal validity of the model, i.e. from 1960 to 2005 (Fig.2). Extrapolating

linearly the behavior of $\langle B^2(t) \rangle_{\theta_0}$ over Antarctica, we can predict its zero value around 340 years from now. This is much shorter than that predicted by considering the global contribution of $\langle B^2 \rangle$, confirming the origin of the present phenomenon of rapid geomagnetic field decay in the southern hemisphere and allowing us to recognise that a possible *imminent* reversal could be more *imminent* than previously expected. This same result can be found for the last century when we consider the mean square value over Antarctica from the GUFM1 model for the last 100 years (not shown).

The information Content, K-Entropy and a necessary condition for a geomagnetic reversal

The concept of Information Content $I(t)$ has been applied to the present geomagnetic field by De Santis et al. (2004). Here we summarize some of their most important results and update them with more recent data.

Let us define the information content $I(t)$ of the geomagnetic field $\mathbf{B}(t)$ characterized by a spherical harmonic expansion with maximum degree N , that is, characterized by N multipoles (De Santis et al., 2004):

$$I(t) = \sum_{n=1}^N p_n(t) \cdot \ln p_n(t) \quad (3)$$

where $p_n(t)$ is the probability of having a particular n -multipole rather than another:

$$p_n = \frac{\langle B_n^2 \rangle}{\langle B^2 \rangle} = \frac{(n+1) \sum_{m=0}^n (c_n^m)^2}{\sum_{n=1}^N (n+1) \sum_{m=0}^{n'} (c_n^m)^2} \quad (4)$$

and $(c_n^m)^2 = (g_n^m)^2 + (h_n^m)^2$; with $\sum_n p_n = 1$, and $p_n \ln p_n = 0$ if $p_n = 0$. We can also introduce an analogous probability p_n' for the secular variation $\dot{\mathbf{B}}$, as in (4) but using $(\dot{c}_n^m)^2 = (\dot{g}_n^m)^2 + (\dot{h}_n^m)^2$ instead of $(c_n^m)^2$.

As defined here, $I(t)$ is a negative quantity that measures our knowledge of the state of the system when we know only the distribution of probability p . In practice, it denotes our decreasing ability to predict the evolution of the system into the future. It can be related with the rate of loss of information, i.e the K-Entropy (Wales, 1991):

$$K = -\frac{dI}{dt} \quad (5)$$

We can also define a characteristic time $T = 1/K$ which is a sort of memory time after which the system behavior can no longer be predicted with sufficient accuracy.

There is a specific time when p_n and p_n' , and, consequently, the information content of \mathbf{B} and $\dot{\mathbf{B}}$, will be the same: it is the time of a geomagnetic reversal or excursion when the field will reduce significantly and it can therefore be assumed that (most of) the coefficients c_n^m will be (almost) zero. By chance or by some physical reason, the present geomagnetic field shows broad agreement between the two kinds of information content (De Santis et al., 2004). The corresponding value of the time T , between 400 and 800 years, can be interpreted as an estimate of the time until the next change of (global) polarity.

In order to evaluate the information content over a sufficiently long period of time, we applied the above analysis to the geomagnetic field defined by the GUFM1 model (Jackson et al., 2000). Fig. 3 shows that $I(t)$ started to linearly decay at around 1690 with characteristic time roughly typical of magnetic diffusion (of the order of 15×10^3 years; e.g. Section 4.5 of Moffat, 1978), then decreased more rapidly after 1775, with a shorter time scale of around 2000 years, and finally decreased more rapidly still after 1900 with a time scale of around 900 years. The latter time is close to that given by the IGRF, confirming the previous results. As in the case of the mean square value of the field, here also the error bars are deduced assuming a decreasing linear error of the Gauss coefficients from 5% at 1590 to 1% at 1990.

Regarding the present field, values from a recent model proposed by Olsen (2004) and based on magnetic data from Oersted and CHAMP satellites, lie on the same line as the previous IGRF

values, confirming the present linear trend of $I(t)$ (Figure 4 shows just the recent value at 2002). The figure also shows the expected value of $I(t)$ that would be possibly derived from the magnetic data expected from the planned multisatellite mission SWARM.

Persistence of the present trend towards a global geomagnetic change

Even though the system that generates the magnetic field may be irregular and possibly chaotic it is possible that some trend may be persistent. For instance, in some cases of turbulence, it is common for these to emerge vortices that persist for a significant time (e.g. McWilliams, 1984, Balle and Breidenthal, 2002). Based on this concept we have already defined the persistence times of each spherical harmonic of the geomagnetic field (De Santis et al., 2003) and explained the particular scaling of the temporal power spectrum of the geomagnetic observatory time series over the last 150 years. In the present work we wish to confirm the present persistence of the system to decay and possibly to tend toward a reversal or excursion.

Let us consider the equation of magnetic induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta_m \nabla^2 \mathbf{B} \quad (6)$$

which relates the secular variation of the magnetic field (left-hand side of the equation) with the advection and diffusion (right-hand side) of the field; \mathbf{v} is the fluid velocity in the outer core, η_m is the magnetic diffusivity and $\nabla = \partial/\partial x \mathbf{i} + \partial/\partial y \mathbf{j} + \partial/\partial z \mathbf{k}$, with \mathbf{i} , \mathbf{j} and \mathbf{k} the unitary vectors along the x, y, z Cartesian axes.

This equation is most important in understanding the geodynamo processes of magnetic field generation. Unfortunately, its solution is not easy to find since all quantities (velocity, magnetic field and its time derivative) must be estimated where most of the conductive fluid motions that generate the geodynamo processes occur, that is in the fluid core, with particular attention to the top of the core itself (radial distance from Earth's centre $b=3485$ km). The conventional way to

approach the problem is to fit magnetic observations on and above the Earth's surface and then to downward continue the field from the surface to the top of the core. However, even knowing the magnetic field at the level of these sources, the solution in \mathbf{v} is not unique. Hence, some additional constraints, often rather subjective, must be applied in order to finally estimate the velocity field. Here we have another objective: to find some characteristics of the field that are persistent in time, thus supporting the idea of some chaotic coupling within the outer core. To this end, we look for just one of the possible contributions to the velocity-magnetic field term $\mathbf{v} \times \mathbf{B}$ and then see whether it shows some particular aspects that can support the persistence of the present trend of the geomagnetic field.

It is known that most of the present decrease of the geomagnetic field originates in the southern hemisphere (Gubbins, 1987; Hulot et al., 2002). A good example of a *velocity-magnetic field* coupling term, here denoted by $\mathbf{v}_p \times \mathbf{b}_p$ (subscript p stands for *persistence* and *pole*), is to consider the latitudinal velocity \mathbf{v}_p of the south geomagnetic pole at the surface as contributing to that part of the velocity of the outer core plasma that tends to move this pole towards the geographic (rotational) pole, and the corresponding varying magnetic field observed at the same point, $\mathbf{B}_p = \mathbf{B}_0 + \mathbf{b}_p$, (see Figure 5), both as given by some global model over the last few centuries, and then to investigate the constancy of the term $\mathbf{v}_p \times \mathbf{b}_p$. Although \mathbf{v}_p and \mathbf{b}_p are evaluated at the Earth's surface, the constancy or otherwise of their product does not depend on this.

The choice of the latitudinal velocity is made because we can expect that it is this component that provides the best indication of the stability (or instability) of the field, since it is the one that points towards (or away from) the Earth's rotational axis. We shall see below how this component is more representative of the geomagnetic field dynamics. Concentrating on the south geomagnetic pole is justified because, although it is associated with a global process involving the longer spatial wavelengths of the geodynamo, i.e. the dipolar dynamics, it can be localised over a restricted area, i.e. part of the southern hemisphere.

Fig. 6 shows the motion of the geomagnetic pole as given by the GUFM1 model for the past 400 years. We again find that the epochs 1690, 1775 and 1900 exhibit significant changes of direction of the geomagnetic pole. Two other epochs, 1755 and 1815, also show distinct changes of direction though they were not significant for the information content. Fig.7 shows the behaviour of the total velocity, together with its latitudinal and longitudinal components, over the same period of time. The same epochs shown above are indicated with vertical lines. All these epochs seem to occur during periods of acceleration just after a relative minimum of velocity. Although the other quantities are rather erratic, the tendency of the latitudinal velocity to increase throughout almost all the period is noteworthy. Fig. 8 is a plot of the latitudinal velocity alone with a best fit line corresponding to an acceleration of around 0.016 km/yr^2 . The positive sign of the acceleration means that it has been always pointing toward the south geomagnetic pole. The value for the past century is almost an order greater, reaching about 0.1 km/yr^2 . For this reason, and also because we expect smaller involved errors, we will now restrict our attention to the last century only, considering the IGRF (Macmillan & Maus, 2005) from 1900 to 2005.

We can fit \mathbf{v}_p or \mathbf{B}_p with an exponential growth or decay. For both quantities we apply a nonlinear regression by means of the Marquard-Levenberger method for the period 1900-2005 (Figures 9 and 10). While for \mathbf{v}_p we find that an exponential growth fits all the data quite well, for \mathbf{B}_p we notice that we can fit the data with two exponential decays with same characteristics over two almost contiguous periods of time (1900-1950 and 1965-2005). It is really impressive that, within the estimated errors, the growth time scale (39.8 ± 8.6 years) of \mathbf{v}_p in Fig. 9 is practically the same as that of the decay time (41.7 ± 7.4 years and 39.4 ± 4.6 years) of the total intensity as given by IGRF in Figures 10b and 10c for the two successive intervals between 1900 and 2005. This finding has an important consequence. Since \mathbf{v}_p and \mathbf{B}_p are almost orthogonal, we will work with their scalar values.

Consider the equations:

$$|\mathbf{v}_p| = v_0 e^{(t-t_0)/\tau} \quad (7)$$

$$|\mathbf{B}_p| = B_0 + b_p = B_0 + A e^{-(t-t_0)/\tau} \quad (8)$$

with $t_0=1900$ and $B_0=62825$ nT in the period 1900-1950 and $B_0=57551$ nT in the period 1965-2005. A also changes with the period: $A(t=1900-1950)=2800$ nT and $A(t=1965-2005)= 26805$ nT. It is now clear that the term $\mathbf{v}_p \times \mathbf{b}_p$ is practically constant in each interval of 40-50 years:

$$|\mathbf{v}_p \times \mathbf{b}_p| = v_0 e^{(t-t_0)/\tau} A e^{-(t-t_0)/\tau} = v_0 A = \text{const} \quad (9)$$

Note that different conclusions would have been reached if we were considering the north geomagnetic pole (not shown), where the magnetic field oscillates somewhat.

We speculate here that this persistent aspect of the field at the southern geomagnetic pole is the local manifestation of a nonlinear coupling between velocity and magnetic field, as a consequence of the chaotic state of the geomagnetic field in the outer core. This can also be supported by another fact that is closely related to previous results. The characteristic time found does not come out of the blue. Already some years ago a similar time scale of around 40 years was found for the nondipolar geomagnetic field (Section 4.2 of Moffat, 1978). If this were true, the timescale found here appears as a natural effect of the coupling between the dipolar and nondipolar fields. It is also comparable with the memory time (50 +/-25 years) from the chaos analysis of the vertical component as applied by De Santis et al. (2002b) to time series of fourteen world magnetic observatories covering the past 150 years. Since the field at the geomagnetic pole is mostly vertical, is our result a coincidence or just the physical manifestation in the real world of the orbital divergence of the secular variation in phase space (see De Santis et al., 2002b)? Probably, this kind of intermittent synchronicity, in terms of multiple coincidence of time scales, could be interpreted as evidence of a persistent turbulence of the recent geomagnetic field.

Conclusions

This characteristic of coherent local coupling between two interacting quantities, in our case the plasma velocity (mostly the latitudinal part) and magnetic field in the outer core, is quite ubiquitous in turbulent fluid dynamics. It is because of this universal property of turbulence that physical signals detected from turbulent systems have temporal and frequency power spectra with related scaling exponents (Frisch, 1995) as found also in the case of the geomagnetic field (De Santis et al., 2003). It appears often during transitions between particular dynamical regimes with the emergence of specific almost stationary features in the form of cells, vortices, or other characteristic patterns (Haken, 1983); a well known example is the great red spot on Jupiter (e.g. Marcus, 1993) where the second law of thermodynamics can be used to understand the phenomenon (Bouchet and Sommeria, 2002).

On the basis of the above results, some speculations can be attempted.

i) The first concerns the velocity of the geomagnetic pole: it is clear that it cannot increase to infinity so the present trend must stop sometime in the future. On one hand, we can speculate that v_p will increase exponentially until it reaches its maximum value: if this value reaches the typical largest values as given by Voorhies (1995) or Hulot et al. (2002) of around 40 km/yr or 90 km/yr (values extrapolated to the Earth's surface: please remember that the velocity at the core surface is b/a times the one at the surface), respectively, the present trend of increasing speed of the geomagnetic pole will continue for other 100 years. On the other hand, another approach considers that if we square the latitudinal velocity observed at the Earth's surface and then divide by $2(a/b)^2$ we obtain the quantity $\varepsilon = v_p^2 / 6.684$ which has the dimension of energy/mass and would correspond essentially to the energy per unit mass that sustains the geomagnetic dipole dynamics in the fluid core. Looking at this quantity for the last 400 years as estimated from the GUFM1 (Figure 11) it seems that it has behaved as a series of intermittent bursts with maximum values which are decreasing linearly with time and reach zero value 300 years from now. If we interpret the series of bursts of successive exponential velocity growth as one of the contributions to the generation of the

geomagnetic field, this phenomenon is presently diminishing with time possibly suggesting a potential geomagnetic polarity change. By the way, from ϵ we can deduce a reasonable order of magnitude for the kinetic energy involved in the geomagnetic dipole dynamics, once we have estimated a mass that can be associated with this dynamics. Considering within the outer core a typical mass of 10^{20} kg (for instance a torus with external radius $L=10^3$ km and internal radius $L-d$, with $d=50$ km and a density of around 10^4 kg/m³), for a mean value of $\epsilon=40$ J/kg for the 400 years under considerations, we obtain a kinetic energy of around 10^{21} J which sounds reasonable, being comparable with the value of the magnetic energy ($3-6 \times 10^{20}$ J) estimated by Christensen and Tilgner (2004), although we recognise some peaks of involved energy over the past 400 years that even reached 10^{22} J. On the other hand, smaller kinetic energies can be found when considering smaller masses involved in the dipolar dynamics: this fact could be true if we consider that usually the kinetic energy is roughly three orders of magnitude less than the magnetic one (Glatzmaier and Roberts, 1997).

ii) Another speculation concerns the value of the ‘mean’ geomagnetic field at the pole of around 62,800 nT and then 57,550, in the two successive periods considered here. These are the values at which there is a fall to a lower level but with roughly the same time scale of around 40 years. In this way the process of field decay is accelerated.

iii) The last speculation concerns the timescale of around 40 years. Not excluding any possible coincidence, (but the fact that three different analyses and apparently different processes provide the same result is very difficult to explain simply as a rare coincidence) we can consider a unique source of the same timescale. That this value of time is associated with the generation and dissipation of the geomagnetic field is confirmed by a recent study of the ohmic dissipation in numerical and laboratory dynamos made by Christensen and Tilgner (2004) who estimated a value of 42 years for the timescale of dissipation for the geodynamo. An alternative explanation for this

timescale could be the presence of some persistent source of variability, for instance producing a torsional wave in the fluid core: this growth time scale of around 40 years is comparable with the growth timescales of 22, 46 and 55 years given by Bloxham et al. (2002) and with the timescales between 23 and 41 years given by Voorhies (1995). This kind of torsional wave is thought to be responsible for the occurrence of geomagnetic jerks (Bloxham et al., 2002).

In our picture of the dynamics of the geomagnetic field, the present regime is chaotic and this suggests an imminent reversal of polarity. All the aspects of the present geomagnetic field that we have found could be just consequences of this particular situation. Turbulent motions at the level of the outer core can show persistent features which have been called persistent turbulence (eg. Balle and Breidenthal, 2002): examples in the geomagnetic field of this characteristic are the intermittent coupling between velocity and field at the southern geomagnetic pole with same characteristic times, or the low anomalous field almost spatially stationary in the South Atlantic. Also the recent (past 100 years) apparent increase in the number of geomagnetic jerks could be just a consequence of this chaotic regime. In this scenario the geomagnetic jerks would appear as *elementary small local reversals*, in the sense that they are due to local changes of flows in the outer core, causing a change of secular acceleration. We expect that an increase of this kind of contribution is a typical characteristic of this special regime, representing a global geomagnetic change possibly going towards a polarity change or excursion.

In conclusion we can say that the present trend of the geomagnetic field looks persistent and we expect it will probably have the same tendency for the next few hundred years. What will happen after this period of time it is still too early to predict. What we can do in the near future is to follow as closely as possible the evolution of the quantities we have shown here to be good traces of the evolving dynamics of the geomagnetic field, that is, together with the *classic* quantities of the dipole moment and the mean square value of the geomagnetic field over the globe and/or over some particular regions such as Antarctica, we must focus our attention on the Shannon information content and on the term represented by the product of the geomagnetic south pole latitudinal speed

and the corresponding magnetic field, as well as the behaviour of ϵ . Also the careful and continuous monitoring of the South Atlantic Anomaly will constitute another significant way of investigating the state of evolution of the Earth's magnetic field, in particular if it is going toward a reversal of magnetic polarity or excursion. The planned ESA mission Swarm (launch planned in 2010), with the expected high accuracy magnetic data from its satellite constellation configuration, will provide a valuable contribution to follow and better understand this presently important topic in geomagnetism.

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FIGURES AND CAPTIONS

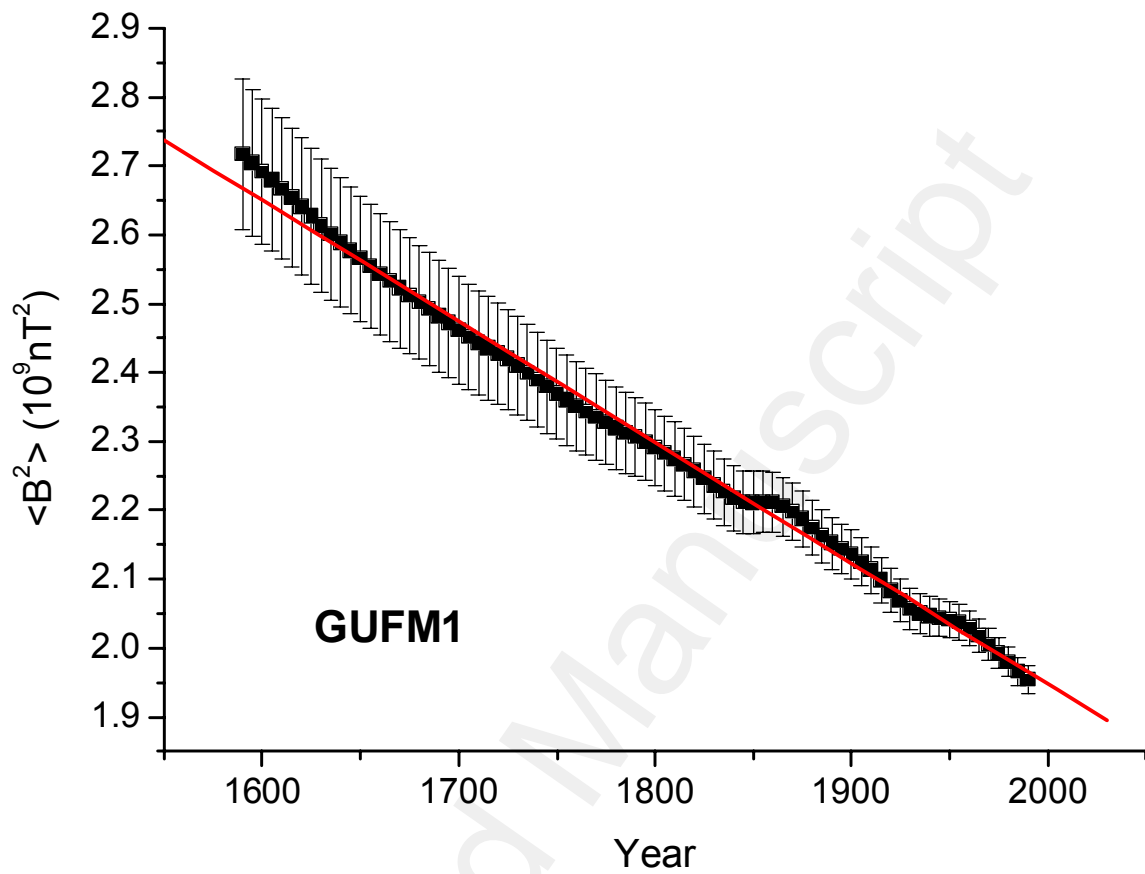


Figure 1a. Mean square value of the geomagnetic field over the whole globe from 1590 to the present as evaluated from the GUFM1 model (Jackson et al., 2000). Error bars are deduced assuming a decreasing linear error of the Gauss coefficients from 5% at 1590 to 1% at 1990. The figure shows also the best fit straight line over the period of validity of the model.

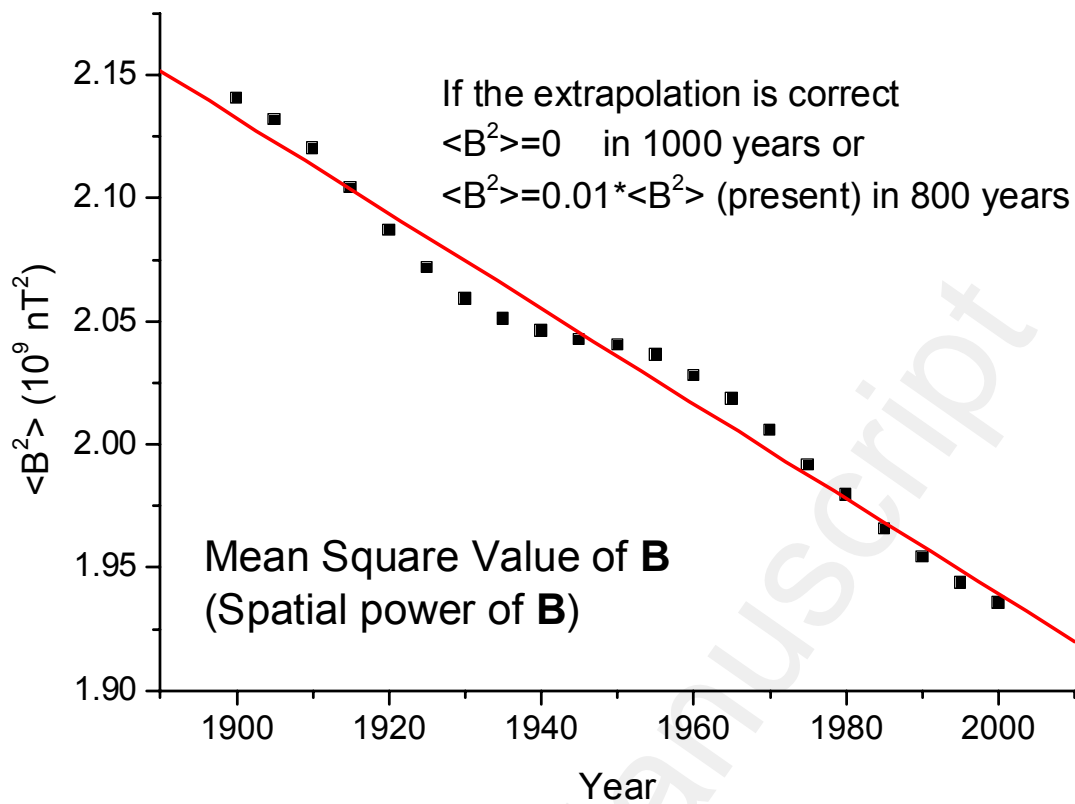


Figure 1b. Mean square value of the geomagnetic field over the whole globe for the last century as evaluated from IGRF and GUFM1 (the latter being valid up to 1990). In the period 1900-1990 the mean square values from both models agree up to the third significant digit, so their points in the figure are practically overlapping.

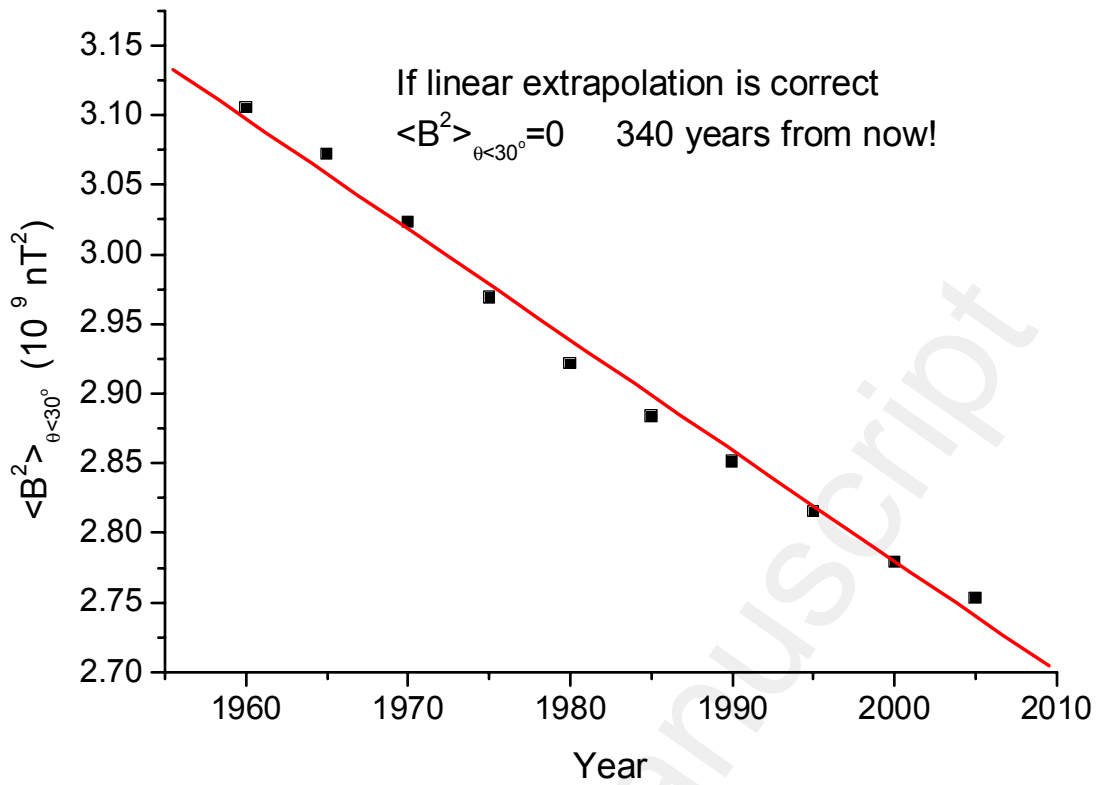


Figure 2. Mean square value of the geomagnetic field over a cap of 30° half angle over Antarctica from 1960 to 2000 as given by the Antarctic Reference Model (ARM) (De Santis et al., 2002a; Gaya-Piqué et al., 2006).

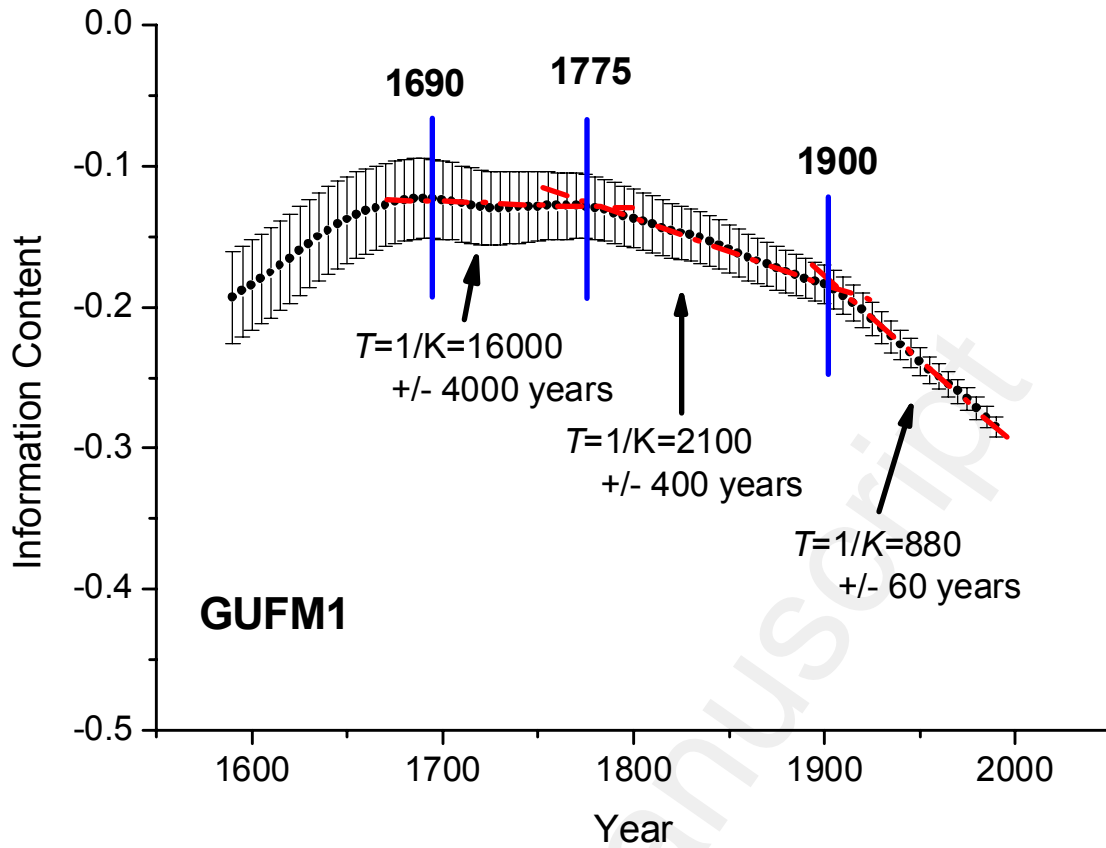


Figure 3. Information content $I(t)$ of the geomagnetic field from 1590 to the present as estimated from the GUMF1 model (Jackson et al. 2000). $I(t)$ started to linearly decay at around 1690 and decreased more rapidly at 1775 and even more rapidly after 1900. The latter characteristic time is similar to the one estimated from IGRF. Error bars are deduced assuming a decreasing linear error of the Gauss coefficients from 5% at 1590 to 1% at 1990. The characteristic times at the three periods after 1690 are given with errors of 25%, 20% and 7% respectively, which are the same relative errors given for the estimated slopes of the corresponding weighted fits.

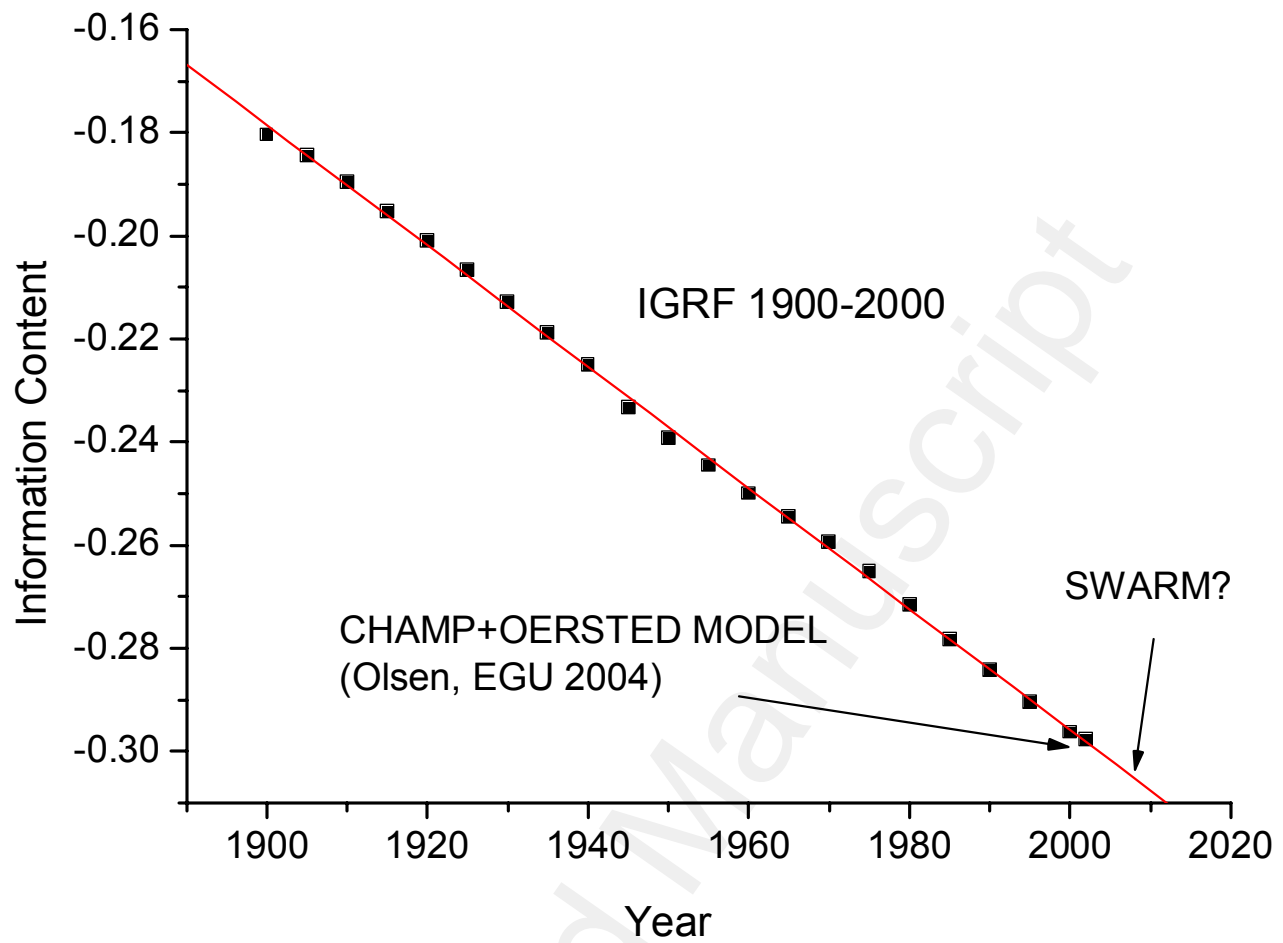


Figure 4. Linear decay of the Information content $I(t)$ of the geomagnetic field from 1900 to 2000 as estimated from the IGRF model. The most recent point at 2002 has been deduced from a model by Olsen (2004) that used a selection of CHAMP and Oersted satellite magnetic data.

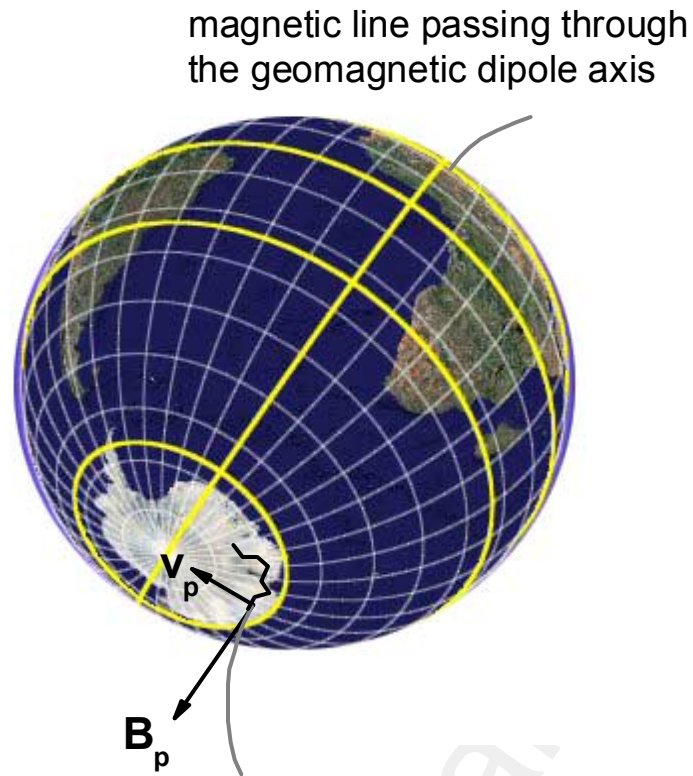


Figure 5. Sketch of the situation considered in the text: \mathbf{v}_p and \mathbf{B}_p are the latitudinal velocity of the south geomagnetic pole and the magnetic field there. The path of the south geomagnetic pole is hypothetical, being only for illustration. See Fig. 6 for correct path. (Earth's globe drawn with *Google Earth*).

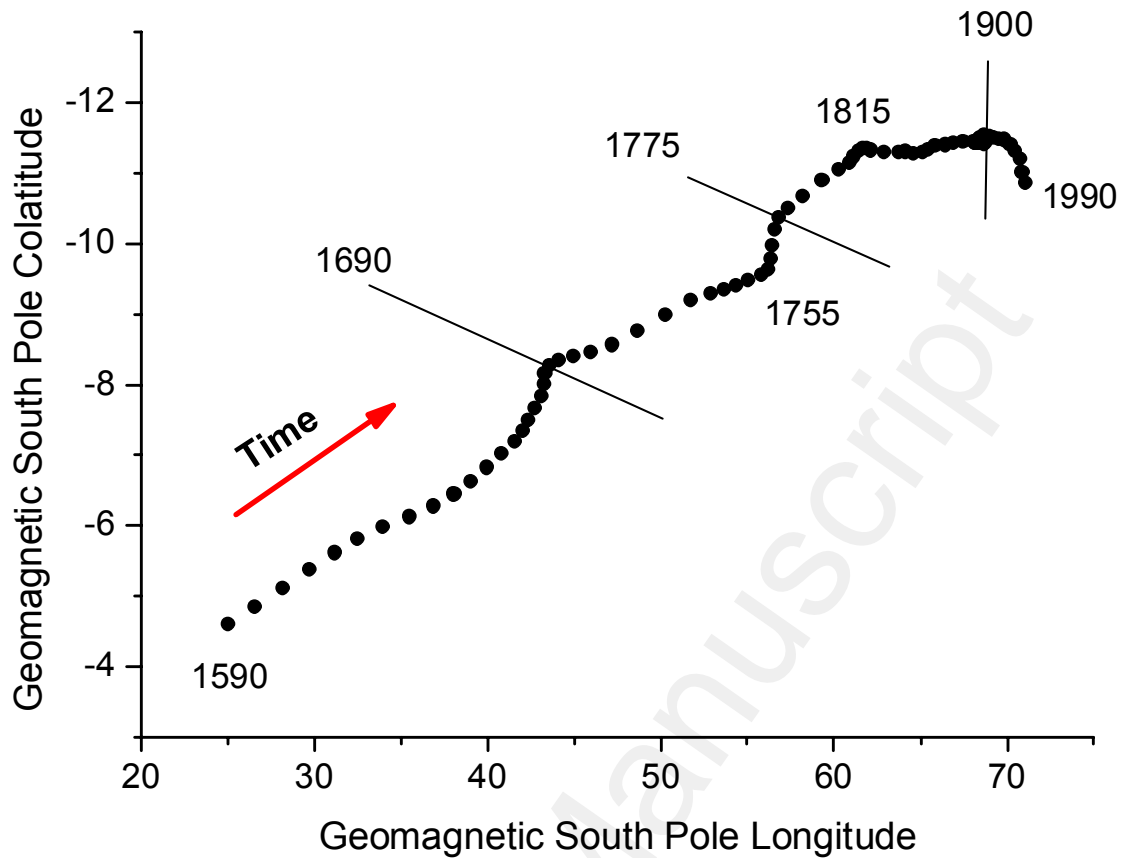


Figure 6. Geomagnetic south pole path from 1590 to 1990 as given by the GUFM1 model. Epochs are indicated when a significant change of direction occurs. The lines indicate the same epochs (1690, 1775, 1900) with significant change of slope of the information content (see Fig.3); two other epochs are also indicated (1755, 1815) which are not apparently important in terms of the information content.

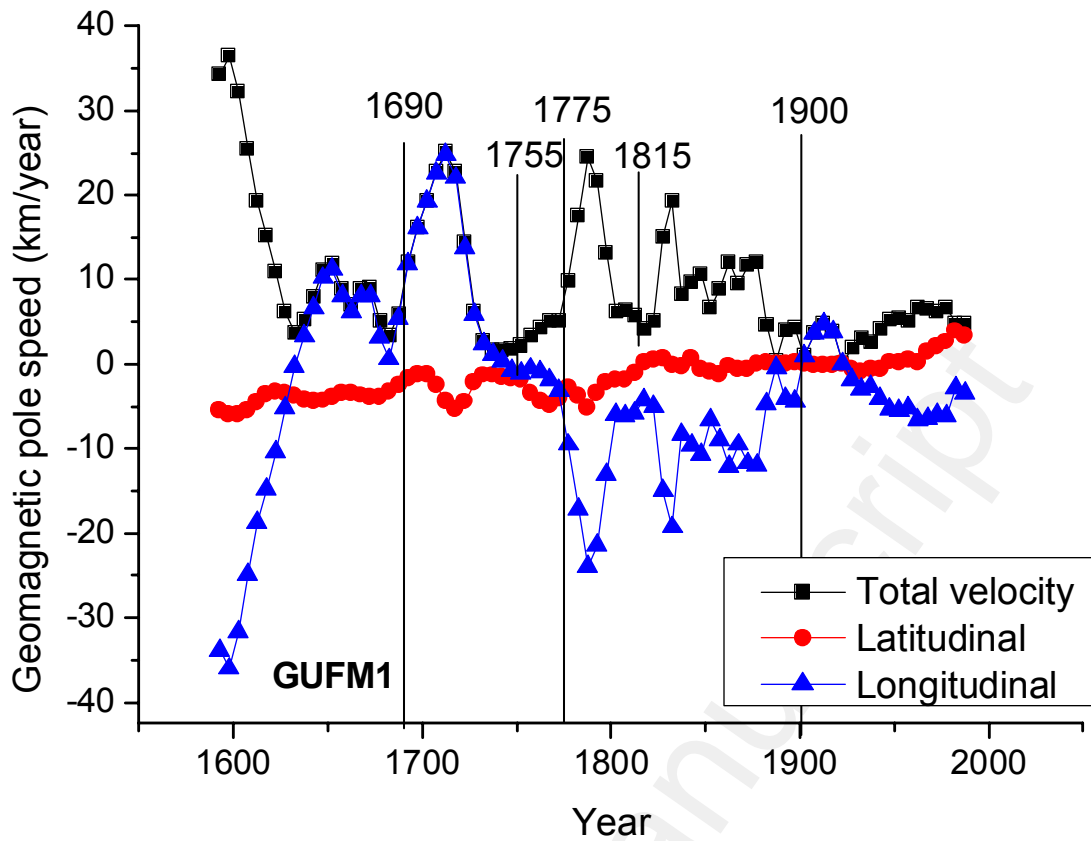


Figure 7. The total geomagnetic pole velocity and its latitudinal and longitudinal components from 1590 to 1990 as given by the GUFM model 1. The vertical lines represents the same epochs (1690, 1775, 1900) with significant change of slope of the information content (see Fig.3); two other epochs are also indicated (1755, 1815) which are not apparently important in terms of the information content. All the epochs occur during periods of acceleration just after a relative minimum of velocity.

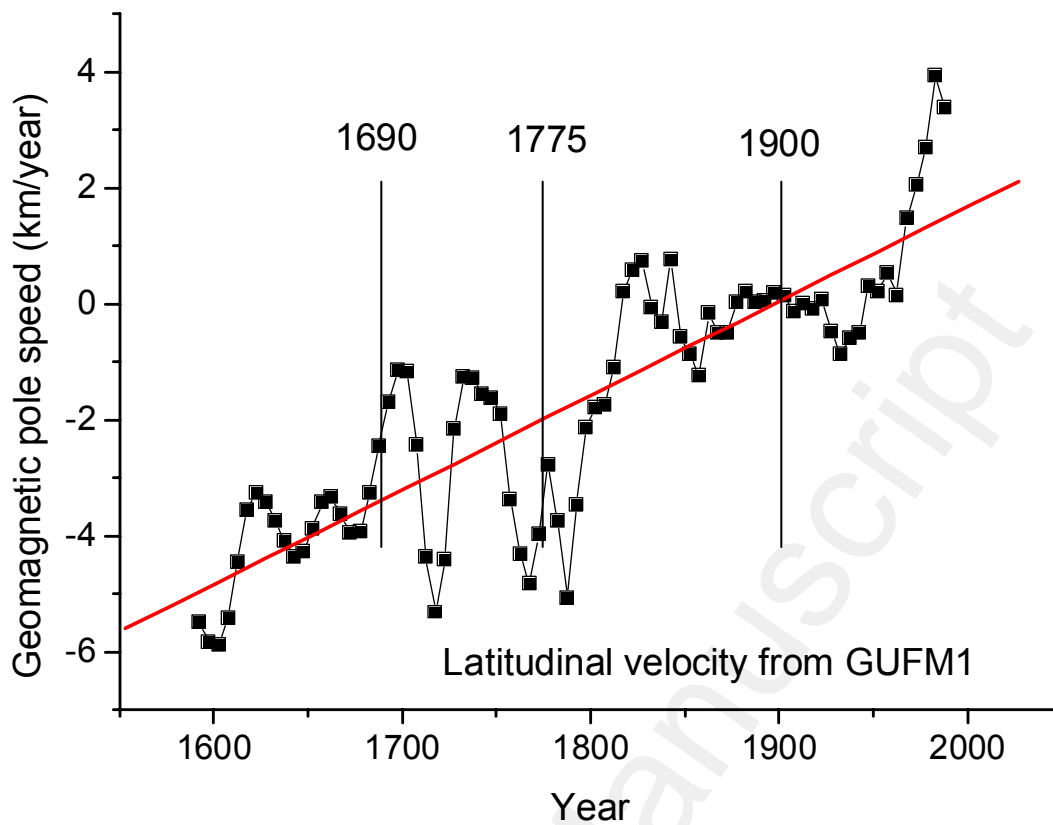


Figure 8. Geomagnetic pole latitudinal velocity with a linear fit from 1600 to 1990 as given by the GUFM1 model. The fit shows a mean acceleration of 0.016 km/yr^2 . The times of changes of information content as shown in fig. 4 are also indicated.

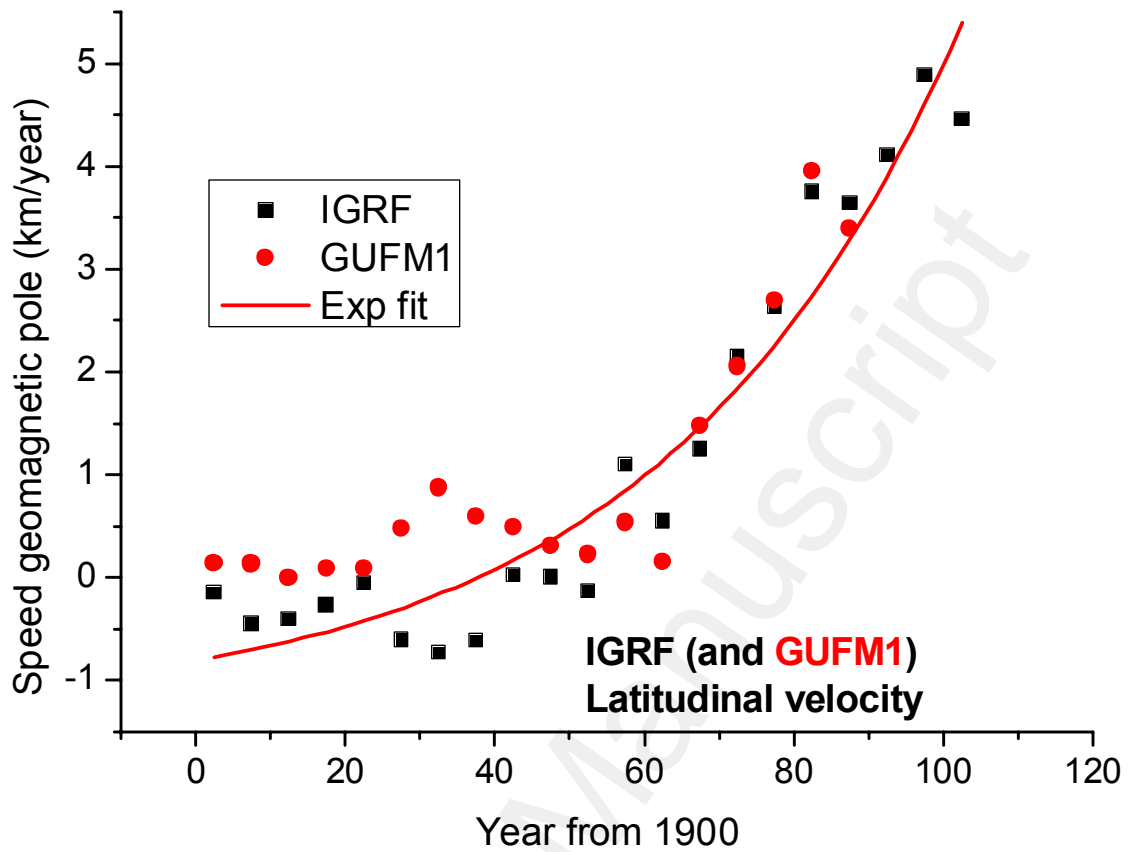


Figure 9. Exponential growth of the latitudinal speed of the south geomagnetic pole as given by the IGRF (squares) and the GUFM1 (circles) models from 1900 to 2005 and from 1900 to 1990, respectively. The exponential fit is estimated using the IGRF data only.

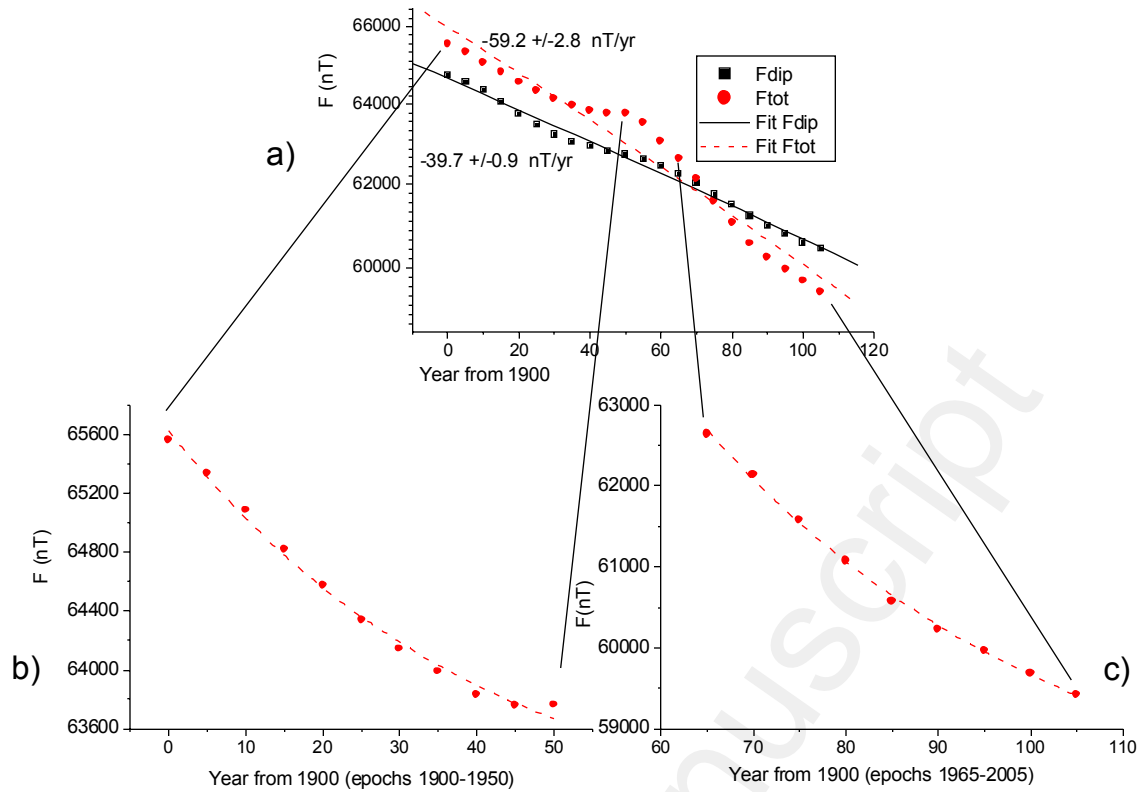


Figure 10. a) Total intensity of the geomagnetic field at the south geomagnetic pole as given by the IGRF from 1900 to 2005. The same quantity is shown in two almost consecutive periods: 1900-1950 (Figure 10b), and 1965-2005 (Figure 10c). The exponential decay in each period has the same time scale of around 40 years as the exponential growth of the latitudinal velocity (Fig.9). This could be a symptom of various attempts of the geomagnetic field to couple with the velocity field at successive times: sometimes it succeeds, at other times it loses the coupling and so only after a while (in this case after 15 years) does it regain the coupling with velocity field.

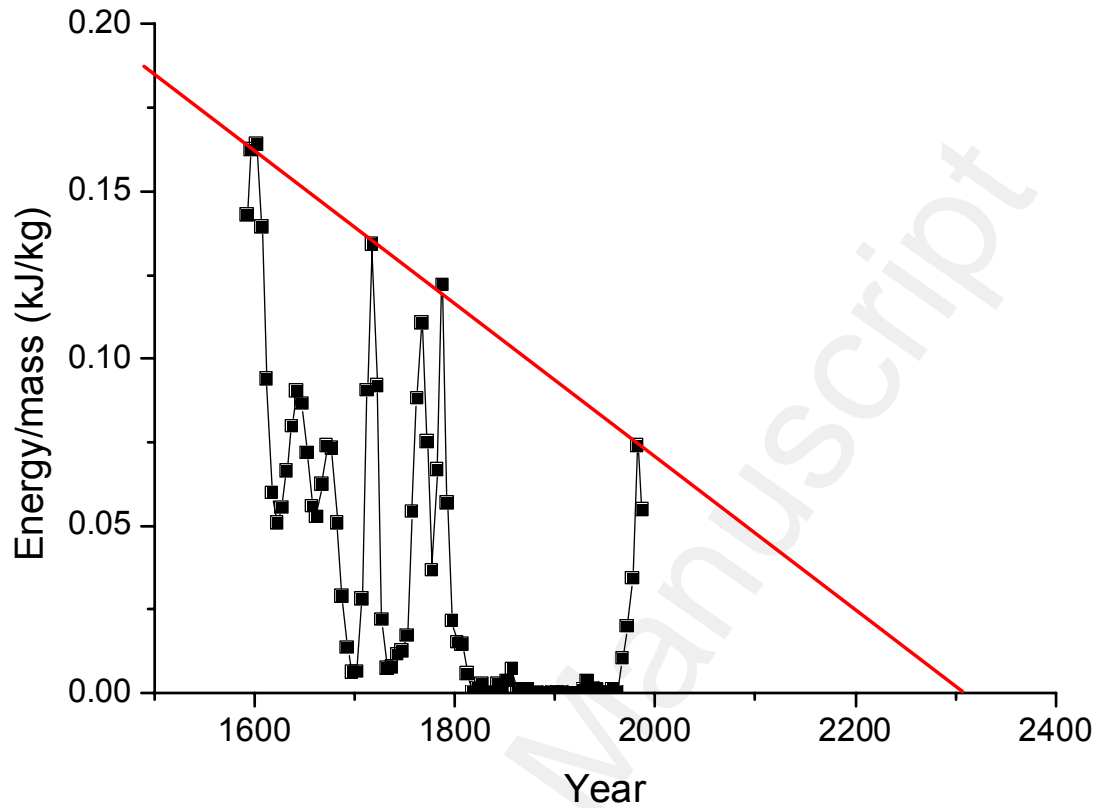


Figure 11. Squaring the latitudinal velocity observed at the Earth's surface and dividing by 2 we obtain a quantity $v_p^2/2$ which is an energy/mass. Further dividing by $(a/b)^2=3.342$ we estimate the same quantity at the core-mantle boundary. Plotting this quantity (called ε in the text) for the last 400 years as estimated from the GUFM1 model it seems as though the maximum value of this quantity is decreasing linearly with time, reaching zero around 300 years from now. If we interpret the series of bursts of successive exponential growths of the velocity as one of the contributions to the generation of the geomagnetic field, this phenomenon is presently diminishing with time.