# THE ORIGIN OF THE GEOMAGNETIC FIELD IN THE SECULAR TIME SCALE

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Los modelos del geodínamo suponen que el campo magnético terrestre crece de un campo "semilla" debido a la convección en el núcleo exterior, líquido, generada por una fuente de calor radial ubicada en la interfase entre el núcleo sólido y el líquido. Sin embargo, recientemente se han encontrado evidencias de que las fluctuaciones de largo plazo en la actividad solar controlan las variaciones en la longitud del día. Estas junto con las variaciones geomagnéticas seculares están vinculadas a movimientos en el núcleo.

Para profundizar en el estudio de estas relaciones analizamos las series temporales del promedio anual de la longitud del día y del numero de manchas solares desde 1657, y del índice geomagnético aa desde 1844. respectivamente, mediante un análisis multi-resuelto basado en las ondeletas de Morlet.

Encontramos que para escalas de tiempo mayores que los 40 años ciclos en la intensidad del campo dipolar solar excitan ciclos en la longitud del día cuando su longitud es similar al período de un modo propio de oscilación del sistema manto - núcleo.

Geodynamo models assume that the geomagnetic field grows from a seed field, due to the convective motions in the fluid core generated from a radial heat source localized at the solid-liquid core interface. However, evidence indicates that solar activity controls length of day variations. These variations, together with changes in the geomagnetic field, are linked to motions in the core.

To study in depth these relationships, we investigate the time series of Rz and LOD (1657-present) and the geomagnetic index aa (1844-present) by a multi-resolution analysis based on the Morlet wavelet transform.

We find that, for time scales larger than 40 years, cycles in the polar field of the sun excite cycles in the length of day, when the periodicity of the cycle matches that of a natural motion of the core-mantle system.

## I. INTRODUCTION

A relationship between secular geomagnetic variations, the Earth's core motion, and the rate of the Earth's rotation was discussed in the pioneering work of Vestine[1]. Understanding the causes of these secular variations may yield important clues to the understanding of Earth's dipolar field reversal and provide information about the physics of the Earth's interior[2, 3].

Le Moüel *et al.*[4] found a relationship between the length of the day (LOD) variations and the time derivative of the geomagnetic inclination - the last taken as a proxy data for the geomagnetic westward drift -. Currently, it is well established that this relationship is due to an exchange of angular momentum between mantle and core (see e. g. ref. 5 to 7).

However, the mechanism that facilitates the momentum exchange is still under discussion. Duhau and Martínez[8] presented a mechanism where the secular variations in solar activity, via controlling the geomagnetic storm intensity, may control the momentum exchange between the mantle and the core. Cross-correlating the five and the eleven years running means of LOD and the Zurich sunspot number, Rz, respectively, provided some empirical insight about this mechanism and results in new constrains to geodynamo theory[9-10].

Therefore, to test the results of a geodynamo theory based on the above finding, it is necessary to know the relationship between the geomagnetic storm time intensity and the geodynamo related variables in the different time scales.

In particular, the LOD variations may be directly measured. It is also the longest (since 1657) time series related to geodynamo processes. Also, Rz have been measured since 1650; Rz is a solar variable that is closely related to geomagnetic activity and the strength of geomagnetic storms (e.g. ref. 8). The geomagnetic index aa, with the first entry in 1884, is the longest measured index of geomagnetic activity

Fig. 1 shows the time series of Rz (Fig. 1a) and LOD (Fig. 1b). At a first, we see that both Rz and LOD contain cyclical and transient behaviors. For example, the values of Rz remain very small from 1650 to 1700 - during the so-called Maunder minimum[11]- Rz rises suddenly after that and the time series varies locally with the Schwabe cycle. On the other hand, the LOD time series show an isolated strong oscillation between 1850 and 1950. Hence, we need a tool capable of handling both transient and periodic phenomena so that we can analyze and gain insight into the temporal structure of LOD and Rz. The wavelet transform is such a tool (see e.g. ref. 15, and references therein)

In our analysis, we use the complex Morlet wavelet,

$$\Psi(t) = \pi^{-1/4} e^{t^2/2} (e^{jkt} - e^{k^2/2}),$$

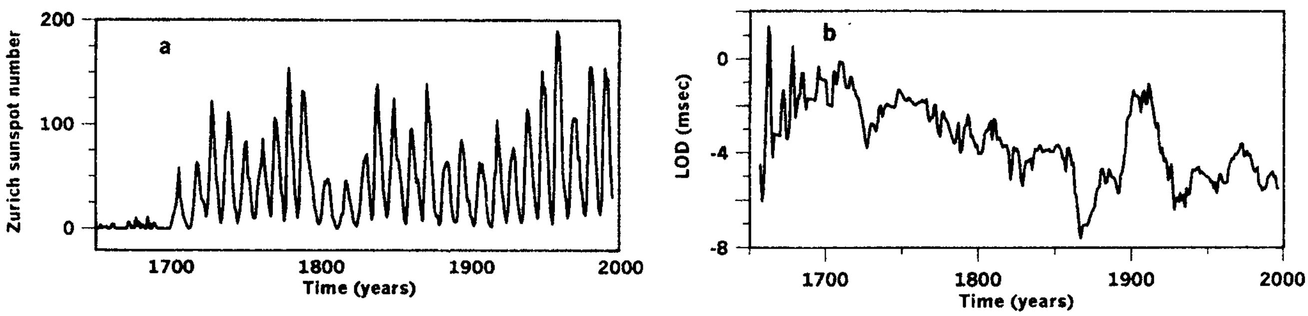


*Figure 1. The yearly average of: a) The Zurich sunspot numbers (Rz). The portion of the data from 1650 to 1700 is from Eddy[11]. The National World Data Center, Solar Terrestrial Division, provided the data after 1700. b) The variation of the length-of-day (LOD) The data from 1700 to 1976 is from McCarthy and Babcock[12] and from 1976 to the present is from Gross[13]. A linear decrease of 0.0211 ms/year has been removed from the data to take into account of tidal friction, post-glacial rebound, and atmospheric tides[14].*

here $j$ is the imaginary unit, $k$ is a scale parameter and $t$ is a location parameter. A Morlet wavelet is essentially a Gaussian wave packet. It has already been used to analyze geophysical and solar data. For example, the correlation between LOD and the atmospheric Southern Oscillation in the intraseasonal and interannual time scales[16]., transient solar influence on terrestrial temperature[17] and the 154 days cycle in sunspot areas[18].

In a companion paper[19] we introduce a multi-resolution analysis based on the Morlet wavelet transform and we use it to analyze the relationship between Rz and geomagnetic index aa to find the similarities and the differences between these two variables for time scales greater than 15 years. Wavelet analysis allows us to compare the characteristics of two signals at a specific time scale.

Furthermore, by comparing the wavelet coefficient, i.e., the wavelet transform waves, between two signals at a specific scale, we can determine the phase difference between the two signals.

Rz is a proxy data for geomagnetic activity. This solar terrestrial variable is directly related to sun's polar field strength that, in the long run, controls geomagnetic storm intensity. Time variations in this intensity leads, in turn, to core motions via the induction of electrical currents[8]. Hence, the relationship found between Rz and LOD must only be a consequence of the relationship that LOD should have with geomagnetic activity.

Therefore, we study further the relationship found by Duhau and Martinez between LOD and Rz[8], by comparing these indices, at each time scale, via a multi-resolution wavelet analyze, and comparing the results with that found for Rz and aa by the same procedure[19]

## II. A COMPARATION BETWEEN LOD, Rz AND AA INDEXES

### Rz and AA

We have decomposed the aa and Rz time series into 13 wavelets-transform waves. We did this by first detrending the data. We have selected λo = 2.833 years so that the third octave corresponds to T = 10.7 years, that is the average Fourier period of the Schwabe cycle for the time interval considered (1844 to 1997).

Fig. 2 shows, as a function of Fourier period, the cross-correlation coefficient, the slope of the regression line, and the phase difference between the wavelet transform waves of Rz and aa. In the figure, we show the results for the entire time series as well as for periods prior and after year 1910, where the relationship between aa and Rz has changed drastically (see ref. 19). Notice

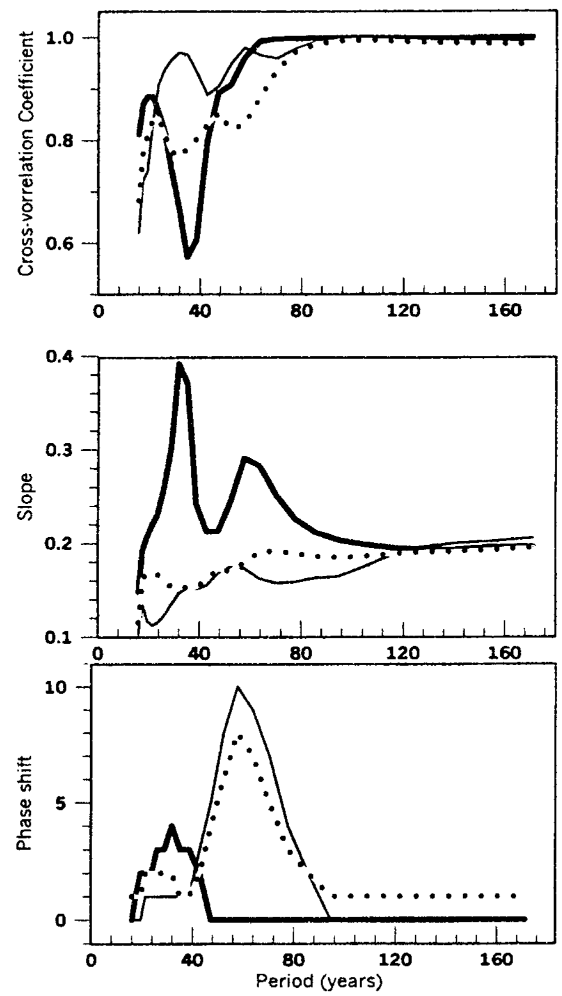


*Figure 2 The cross correlation coefficient (upper panel), the slope (middle panel), and the phase shift that leads to the best fits between aa and Rz (aa leading to Rz) (bottom panel), versus the Fourier equivalent of the wavelet scale. The thick, thin and dashed lines represent the result for the 1843-1910, 1911-1997 and 1843-1997 time intervals, respectively*

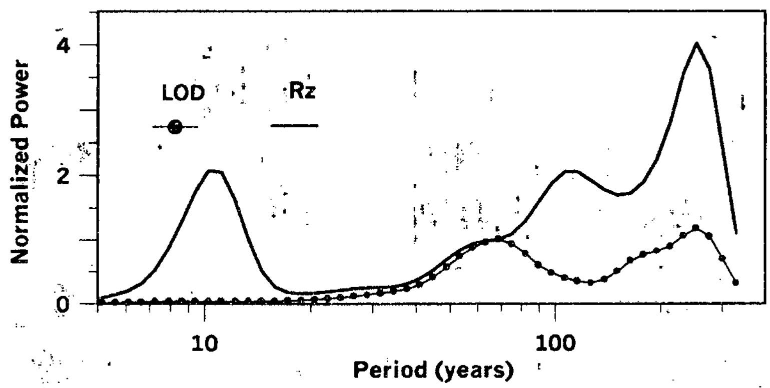


*Figure 3. The spectrogram of the data of Fig. 1 normalized to the amplitude at the period = 65-year. These spectra are the wavelet equivalent of the Fourier power spectra.*

that the three results are similar only for periods above 90 years.

The slope gives the relative amplitude of each aa wavelet wave with respect to the corresponding Rz wave. The correlation coefficient is larger than 0.8 for periods larger than 40 years. This indicates a relationship between the time series on the secular time scales. However, for periods below the 80 years one this relationship changes with time. For example, the slope of the regression line of the 60 years wavelet is 1.5 times larger after 1910 that in the previous period of time, and the time lag of aa with respect to Rz has a maximum of 10 years at this Fourier period.

In the case that LOD were related to aa instead of Rz[8], the above difference between aa and Rz must be noted when comparing Rz with LOD. (Note: a direct comparison between aa and LOD on the secular time scales is impossible because the phase shift between Rz and LOD has proved to be in the average of 94 years[8])

## Rz and LOD

We perform a multi - resolution analysis to the Rz and LOD time series in the 323 years time span covered by these two time series. We have selected 15 Fourier periods by the procedure outlined above. The first 13 periods are common with aa.

We present the spectrogram, the wavelet power spectrum, in Fig. 3. Similar to the Fourier spectrum, the scalogram represents the overall strength of the signal of at a given scale (Fourier period).

Fig. 3 reveals similarities as well as differences between the Rz and the LOD power spectrum. The Rz spectrum exhibits a peak at a Fourier period of 10.7 years, a signature of the Schwabe cycle, while the LOD spectrum does not. However, both time series focus their power in the long-period structures.

The Rz spectrogram present three peaks at a secular range of periods, at 65, 115 and 230 years, respectively. The 115 years peak is absent in the LOD signal. Also the power of the 65-year peak relative to the 230-year one is substantially smaller in Rz than in LOD (by a factor of 0.3).

We interpret the above differences in the light of the results shown in Fig. 2. We see that for Fourier periods larger than the 80 years Rz and aa wavelet transform waves are quite similar: they have a cross-correlation coefficient above 0.95 and the slope of the regression line and the phase shift are quite constant with time. Wavelet waves with periods around 115 years are quite similar between aa and Rz (see also ref. 19). Therefore we may interpret the lack of power in LOD around the 115, years periods by asserting that external signals with Fourier periods around 115 years are unable to excite motions in the core-mantle system.

With regard to the difference in the relative power between the 65-year and the 230-year peaks, the features

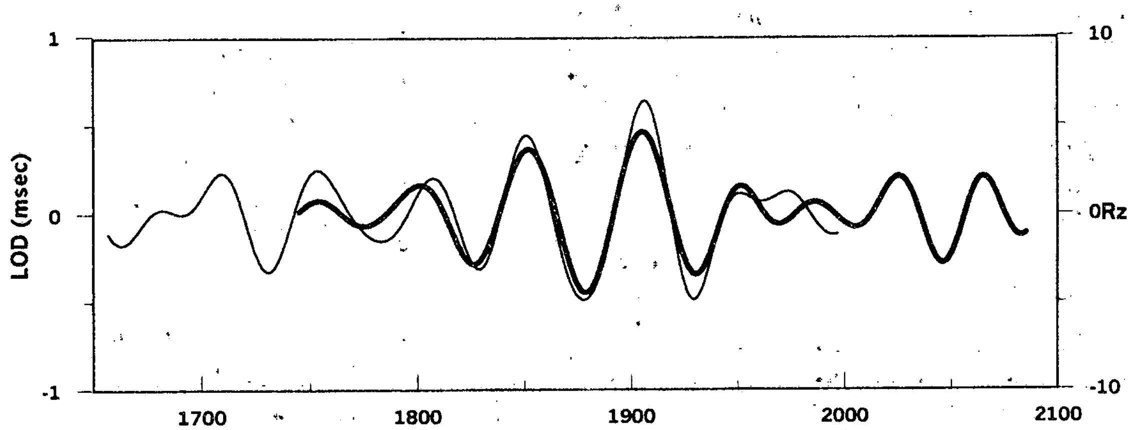


*Figure 4. The wavlet tranfrom wave of LOD (thin line) and Rz shifted 84 years ahead (thick line). Fourier period = 43. year*

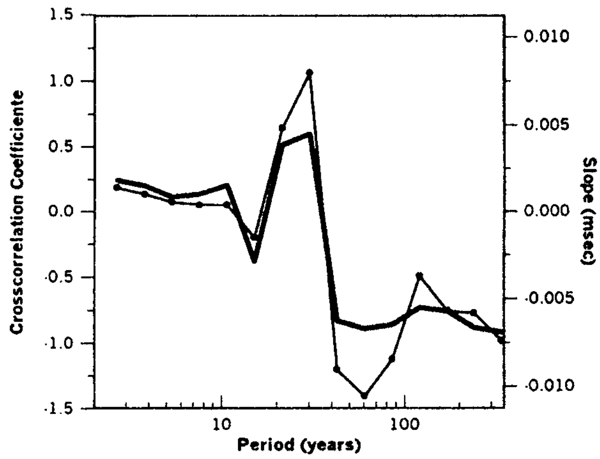


*Figure 5. The cross-correlation coefficient (thick line) and the slope of the regression line (thin line) between Rz and LOD. The points indicate the periods of the 15 wavelet transform waves.*

shown in the slopes of the regression line (middle panel in Fig. 2) indicate a difference on the aa and Rz time series. So, this feature might be only due to the fact that LOD is related to aa and not to Rz.

As we did with Rz and aa, we look for the phase shift between the wavelet waves at a given period such that the two waves correlate with each other. Fig. 4 shows an example for a particular Fourier period, and Fig. 5 shows, as a function of the Fourier period, the correlation coefficient and the slope of the regression line, respectively.

The cross-correlation coefficient changes sign at the 35-year period and has an absolute value larger than 0.8 for Fourier periods larger that 40 years. The slope has maximum absolute value at the 60-year Fourier period, its absolute value decreases to a minimum at 120-year period, and increases for larger values of the Fourier period. This again reflects the difference in the relative power of the peaks in Fig. 3.

The quotient between the amplitudes of the 60-year signal in LOD with respect to Rz is 1.4 larger than the

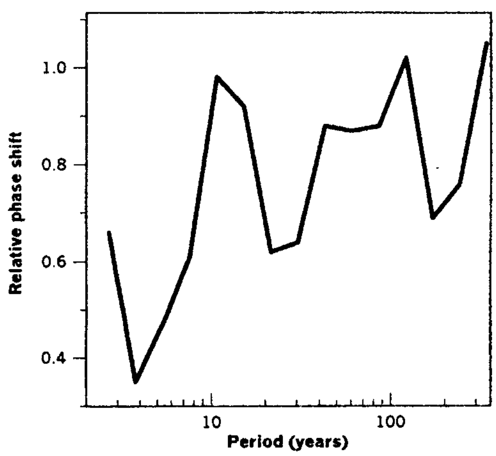


*Figure 6. The time lag of the wavelet transform waves that constitutes LOD with respect to that in Rz as a function of the Fourier periods of the wavelet waves, normalized to the amplitude at the 120 year Fourier period*

quotient between wavelet waves with longer periods. This difference is quite similar to that between aa and Rz for the same range of Fourier periods (see middle panel in Fig. 2). We conclude that the difference in the power of the 230 to the 65 year Fourier periods wavelet waves is due to a difference between aa and Rz, so reflecting the fact that LOD is related to aa instead to Rz

Fig. 6 shows the time lag of the wavelet transform waves of LOD with respect to that of Rz that gives the best fitting. The time lag at around 60 years is 10% smaller (about 10 years) than the time lag at the 85 years period. This, again reflects the fact that LOD is related to aa instead to Rz. Namely, aa is leading Rz by 10 years around the 65 year period (see Fig. 2 bottom panel). Again, we confirm that for secular time variations LOD is related to aa instead to Rz.

Note that, locking to the secular periods (larger than 40 years) the slope of the regression line between LOD and Rz time series (Fig. 5) has its minimum absolute value at the 120 years Fourier period. This feature do not appear in aa (see Fig. 2 middle panel) so confirming that external signals with Fourier periods of about 120 years are unable to excite LOD variations.

## III SUMMARY AND CONCLUSIONS:

We have compared the time series of Rz, LOD and aa and we have found that

- For Fourier periods above 40 years LOD is strongly related to aa. This geomagnetic index gives a measure of solar polar magnetic field and geomagnetic storm strength
- Strong signals with an average period of 65, 115 and 230 years are found in Rz but only the 65 and the 230-year signals are present in LOD.
- The comparison between aa and Rz indicates that the 115-year signal have the same strength in Rz than in aa. Therefore the lack of this signal in LOD indicates that this external signal is unable to excite LOD variations.

All these facts indicate that a cycle in the sun excites the corresponding cycle in the Earth's core only when the frequency of the solar cycle resonates with that of a natural motion of the core. In fact, geodynamo models predict that there are two kinds of natural motions of the core in the range of periods contained in the data: the torsional motions[20-22] (with a period of ~60 years) and the magnetostrophic wave[23, 25] (with a period of ~300 years). Therefore, our findings are not only highly consistent with geodynamo theory, but also support the suggestion of Duhau and Martinez[8] that the sun, via a non-linear mechanism, excites core motions.

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