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A STATISTICAL STUDY OF EARTH'S MAGNETIC FIELD REVERSALS SEQUENCES

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ABSTRACT. This paper presents an analysis of the distribution of periods between consecutive reversals of the Earth's magnetic field through a non-parametric statistics. The study analyzes whether data in different periods of reversal belong to the same distribution, the distribution type and whether the polarity states are equivalent. This analysis was performed for periods from 0 to 40 Ma, 40 to 80 Ma and 120 to 160 Ma. It was found that the data from the three periods show identical statistical characteristics which leads to the symmetry between the states of polarity and to a distribution compatible with a power law, which shows the possibility of a critical phenomenon acting on the geodynamo. The fact that the data obey a power law distribution prompted a comparison with synthetic data generated using two models based on criticality of reversals (one of them self-organized). These simple models reproduce some features of reversals as its temporal evolution and distribution of polarity intervals, and show a similarity with paleomagnetic data.

Keywords: geomagnetic reversals, power law, self-organized criticality.

RESUMO. Este artigo apresenta uma análise da distribuição de períodos entre reversões consecutivas do campo magnético da Terra através de uma estatística não-paramétrica. O estudo analisa se os dados dos diferentes períodos de reversão pertencem a uma mesma distribuição, o tipo de distribuição que eles obedecem e se os estados de polaridade são equivalentes. Esta análise foi realizada nos períodos de 0 a 40 Ma, de 40 a 80 Ma e de 120 a 160 Ma. Encontrou-se que os dados dos três períodos apresentam características estatísticas idênticas, o que leva à simetria entre os estados de polaridade e a uma distribuição compatível com uma lei de potência, o que mostra a possibilidade de um fenômeno crítico atuando no geodínamo. O fato dos dados obedecerem a uma distribuição de lei de potências motivou uma comparação com dados sintéticos gerados através de dois modelos de reversões baseados em criticalidade (um deles auto-organizado). Estes modelos simples reproduzem algumas características das reversões, como sua evolução temporal e a distribuição de intervalo de polaridade, e mostram uma similaridade com dados paleomagnéticos.

Palavras-chave: reversões geomagnéticas, lei de potências, criticalidade auto-organizada.

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INTRODUCTION

The Earth's magnetic field is extremely complex and it is constituted by many components. Usually, the dipolar magnetic component is predominant and it presents intensity and direction variations. The reversals of the directional component are considered the most dramatic variation. The timescales of reversals vary from thousands of years, the necessary time for a reversal, to millions of years. The mechanism behind the reversals and the mechanism of the wide polarity interval variation were not completely clarified. It is believed that they are associated to magnetohydrodynamic processes in the outer core (Merrill et al., 1996). The equation set that controls the core dynamics is symmetrical in relation to the field signal, that is, if B is a solution, $-B$ is an equally viable solution too. Therefore, the equations allow two stable solutions: a normal polarity, as it occurs nowadays, and a reverse polarity (Merrill et al., 1996). In spite of all theoretical and experimental progress, this equation set solution is extremely complex and the nature of the reversals is still an open problem.

A way to understand the reversal phenomenon is the statistical analysis of geomagnetic data (Mc Fadden, 1984). Kono (1987) showed the exponential distribution of the polarity lengths, a result that had already been suggested by Cox (1968). Naidu (1971) pointed out that the gamma distribution provides a better fit to the data than the exponential distribution. Mc Fadden (1984) suggested that the Poisson process is the one that results in the reversals instead of the gamma process. It was also found that the polarity interval distribution follows a power law with expoent –1,5 (Gaffin, 1989; Seki & Ito, 1993). In particular, Seki & Ito (1993) interpreted their results as indicating that the geodynamo is marginally stable and that the geomagnetic reversals are a kind of a critical phenomenon.

Figure 1 is a binary representation of the reversal sequence, according to Cande & Kent (1995). It can be noted that the process is statistically nonstationary, presenting periods with a high reversal rate and periods with low activity, presenting a few or no reversals. The non stationarity can be, for example, due to the manifestation of deterministic chaos within the geodynamo or a consequence of changes in the core mantle boundary conditions (Merrill & Mc Fadden, 1999). Some works have indicated a possible link between the long term changes in the reversal rate and the plume activity in the core-mantle interface (Courtillot & Besse, 1987; Gaffin, 1989), with changes in the inner-core/outer-core interfaces (Kent & Smethurs, 1998), or also with the arrival of cold material at the core mantle boundary (Gallet & Hulot, 1997). Nowadays it is accepted that the reversal rate changes reflect the evolution in spatial variability of some parameter, such as heat flux, at the core-mantle interface (Merrill et al., 1996; Glatzmaier et al., 1999).

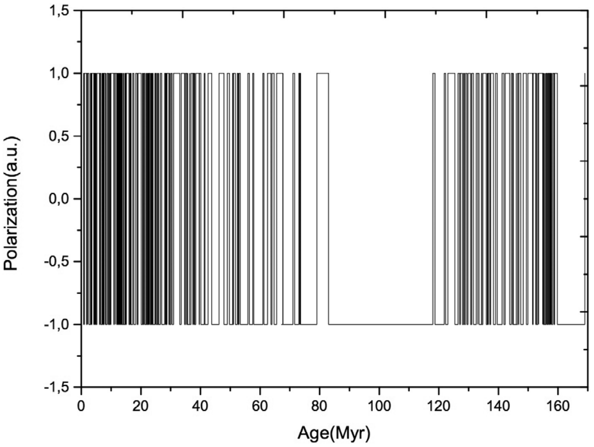

Figure 1 – Binary representation of the geomagnetic reversals from around 160 Myr to present. Arbitrarily we assigned –1 as the present day polarization. There was a particularly long period without reversals, from 120 to 80 Myr. The 165-120 Myr period was very similar to the period extending from 40 Myr to the present day (the number of reversals and the average reversal duration for both). The data were extracted from Cande & Kent (1995).

A difficulty to the statistical study of the reversal record of the Earth's magnetic field is the diversity of the geomagnetic scales proposed since 1960 (Heirtzler et al., 1968; La Brecque et al., 1977; Ness et al., 1980; Cande & Kent, 1995) due to the differences of data, suppositions and adopted approximations. Marzocchi & Mulargia (1990) carried out a comparative study of 11 geomagnetic polarity scales, searching for discrepancies and similarities among them. An additional obstruction is the length of these scales that are extremely short. The current scales comprise around 300 reversals, transforming the data statistical characterization into a hard task. An alternative is trying to simulate the reversal data through a physical model capable to generate synthetic data that can be used in the comparison and complementation of the actual data. The first and the most simple model created to simulate the geodynamo was proposed by Rikitake (1958). The model consists of two coupled Faraday disks and presents spontaneous reversals like the Earth's magnetic field reversals. After this model, many other contributions, mainly from magnetohydrodynamic models (Roberts & Glatzmaier, 2000; Kono & Roberts, 2002) could reproduce some reversal characteristics, although the geophysical parameters used in these simulations are very different from the Earth's parameters, turning the results distant from the geophysical reality. Besides, it takes too much time to carry out a simulation, turning it time consuming and expensive (see Jones' work (2000), for a discussion about dynamo models). Due to these hindrances some researchers have used alternative simulations to describe statistical properties of the geomagnetic data.

Seki & Ito (1993) proposed a stocastic model in which the turbulent vortices in the Earth outer core are approximated by magnetic spins in a critical phase transition state updated through the 2QR cellular automaton. In this simulation they found that the model polarity intervals follow a power law, in the critical state, with an exponent –0.5. Later they refined their model using a coupled lattice in which the elements evolve according to the Lorentz map obtained from the Rikitake model dynamics (Seki & Ito, 1999). This simulation presented an exponent closer to the value found for the actual data, nearly –1.5. Dias and collaborators (Dias et al., 2008) used a spin model in phase transition in which each current ring in the geodynamo was supposed to be a magnetic spin and the model magnetization was supposed to be proportional to the Earth's magnetic dipole. They found a polarity interval distribution in their model that follows a power law. Recently Nakamichi et al. (2011) presented a system that simulates the vortices through magnetic spins with short and long range interaction, reproducing some characteristics observed in the geomagnetic polarity intervals, like spontaneous reversals and power law of the model polarity intervals.

If a power law distribution indicates a critical phenomenon behind the geodynamo activity, some questions naturally arises:

(1) What is the meaning of the self-organization process in terms of boundary conditions in the outer core?

(2) Which is the smaller component in interaction: a portion of the fluid or a local vortex?

(3) What causes the discontinuous balance in the core?

(4) What is the dynamic state of the geodynamo?

(5) Are the reversals, the jerks and the secular geomagnetic variation distinctive phenomena or is there a dynamic link among them?

A theoretical study about the geodynamo may point out the possible answers to these questions and enhance the knowledge about its activity and structure, showing new directions to investigate this fascinating phenomenon, the planetary magnetism.

This paper is different from the works mentioned above in many important aspects. In relation to the used data, it is based only on the Cande & Kent scale (Cande & Kent, 1995), which is analyzed from a nonparametric statistics standpoint with the purpose to study the equivalence of the polarity states, the possibility of the activity periods present in this scale belonging to the same distribution and the possibility of the polarity interval distribution being a power law. In order to complement the available data, it were used synthetic data generated by two models produced by our group.

DATA AND METHODS

Presently the geomagnetic polarity intervals are distinguished through their duration: subchrons (10^5 years), chrons (10^6 years), or superchron 10^7 years (Merrill et al., 1996). In this paper this classification was not considered and all of them are simply referred as intervals. For the current study, the Cretaceous superchron was considered as an abnormal period of the geodynamo stability, different from the periods of the reversal occurrence, and it was excluded from this preliminary analysis.

Initially the data showed in Figure 1 were divided into three intervals: from 0 to 40 Ma, from 40 to 80 Ma and from 120 to 160 Ma. It can be noted that the process is statistically nonstationary as, for example, the average reversal frequency materially changes from one of the mentioned periods to the others. Due to this fact we could suppose that the process that generates the reversals is different in each period. This procedure was also carried out in other contributions (Naidu, 1971; Vogt, 1975; Phillips et al., 1975; Ulrych & Clayton, 1976) which described two intervals, before and after a discontinuity around 40-50 Ma. In the 80 to 120 Ma period the reversals ceased during the long Cretaceous normal isochron.

In most previous statistical works, the polarity interval distribution has been analyzed using a parametric statistics, in which it is presupposed that the data are well described through a specific distribution. In the case of the reversals, the Poisson distribution and the gamma distribution have been used with some success (Merrill et al., 1996). However, in this paper, due to the low number of available data in the used geomagnetic polarity scale, it was assumed that the data are not enough to show a single trend for the data statistical distribution feature, motivating the use of a non parametric statistical test. The non parametric statistics is an option once we do not know the data distribution and when the data quantity is statistically small, as is the case with the geomagnetic reversals.

Initially the three periods were analyzed through a non parametric hypothesis test to discover if the data belong to a same distribution. From the classic standpoint, to belong to the same distribution means that the data sets present similar averages and standard deviations. It was used the well known Mann-Whitney U test (Triola, 2005) to check if the data samples of the three intervals show significant statistical differences, indicating changes in the reversal process along the geologic time and asymmetry between the two polarity states.

The Mann-Whitney test is applied when two independent groups are compared and there is an ordinal variable.

Initially the data of each interval were separated in normal polarity and reverse polarity data groups, resulting in two groups for each period. Besides, to test the hypothesis of a sole distribution for the three periods, two groups with all data were formed. Statistically identical distributions constitute the adopted null hypothesis (H0) and different distributions constitute the alternative hypothesis (H1). If the null hypothesis is true, the polarity states must be equivalent.

Procedures used for the test accomplishment:

(a) n_1 and n_2 values are determined. Being n_1 the number of cases in the smaller group and n_2 is the number of cases in the larger group;

(b) The two group scores are put together, assigning to station 1 the algebraically smaller score. The stations will vary from 1 to N, where $N = n_1 + n_2$. The average of the corresponding stations will be assigned to tied observations;

(c) The U value is determined:

$$U\colon U = n_1 \cdot n_2 + \frac{n_1 \cdot (n_1 + 1)}{2} - R_1$$

where R_1 is the sum of the smaller group stations;

(d) The average and the standard deviation of the stations are obtained and the z value is calculated:

$$\mu_U = \frac{n_1 \cdot n_2}{2}$$

$$\sigma_U = \sqrt{\left(\frac{n_1 \cdot n_2}{N \cdot (N-1)}\right) \cdot \left(\frac{N^3 - N}{12} - \sum T\right)}$$

$$z = \frac{U - \mu_U}{\sigma_U}$$

where the sum of T (correction factor) is obtained through: $T = \frac{t^3 - 1}{12}$;

(e) Finally, the actual value of z is compared to the theoretical value. If the calculated z is smaller than the tabled z the null hypothesis cannot be rejected.

The test results for the three periods and for the sole group are shown in Table 1. Applying the test to the normal and reverse polarity distributions for each period with a confidence level of 5%, gives no result that leads to the refection of the null hypothesis, concluding that the data do not show any change in the reversal process during the geologic time neither any asymmetry between the polarity states.

Table 1 – U test statistical data for the geomagnetic data.

Period	0-40 My	40-80 My	120-160 My	Single distribution
n_1	71	19	46	138
n_2	72	20	47	139
z_{cal}	0.33	0.49	0.6	0.35
z_{tabled}	1.97	1.96	1.96	1.96

Figure 2 shows the logarithmic bin graph (the elements are classified into consecutive classes that increase the size proportionally to the consecutive powers of 2, see Fig. 2 caption) of the three periods used in the analysis. We can note that the distributions present a bell form with maxima in different periods of time and also that they are qualitatively similar. The quantitative analysis was carried out calculating the Pearson correlation coefficient, r, between each pair of periods. As we can expect due to the visual similarity they present in Figure 2 (and also for the duration, average duration of times between reversals and number of reversals), the best result was found for the correlation between the following periods: from 0 to 40 Ma and from 120 to 160 Ma $(r = 0.86 \pm 0.1)$. In the other two comparisons the result was nearly half of this value.

In an earlier work, Gaffin (1989) found that the polarity interval distribution follows a power law, identically to the result found by Seki and Ito (Seki & Ito, 1993). These works are supported by the interval distribution characteristics which present an extreme predominance of short intervals over long intervals, suggesting a heavy-tailed distribution (Sornette, 2000).

Figure 3 shows the frequency distribution for the geomagnetic data in a simple histogram with log-log scale, evidencing a possible power law for the data. The shown straight line is the best least squares fit with inclination –1.42 and error 0.14. This value is near the accepted value for the reversal distribution –1.5 and it is in accordance with values presented in previous contributions (Gaffin, 1989; Jonkers, 2003).

MODEL DATA

The possibility of the chron distribution obeying a power law has been interpreted in many contributions as indicating a critical phenomenon acting in the reversal process (Gaffin, 1989; Ulrych & Clayton, 1976; Consolini et al., 2000; Papa et al., 2013).

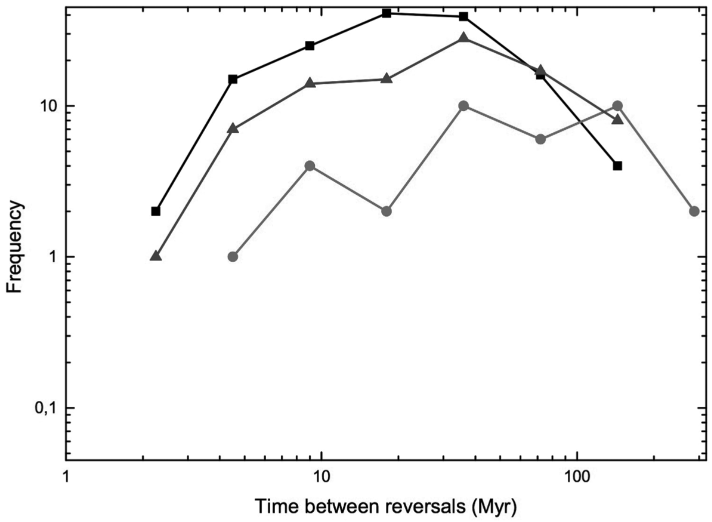

Figure 2 – Log-log graph of the interval distributions among consecutive reversals for the 0-40 Myr (squares), 40-80 Myr (circles) and 120-160 Myr (triangles) periods. We used logarithmic categories with sizes of $0.015 \times 2n$ Myr, where $n = 0$, 1, 2, 3, 4, 5, 6 and 7.

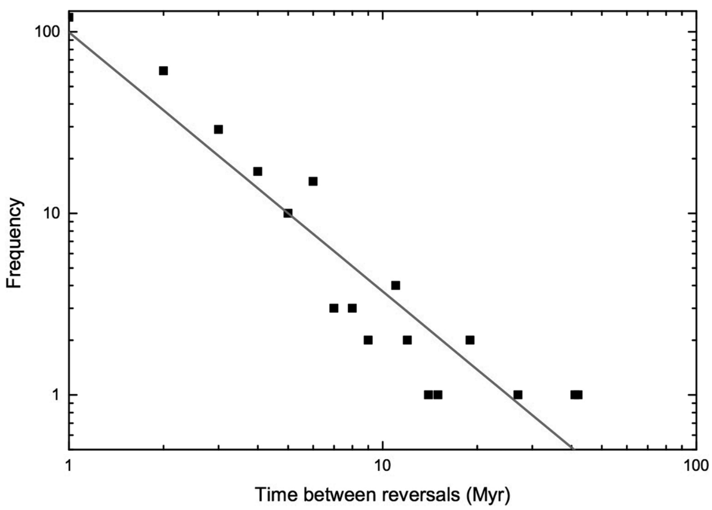

Figure 3 – Frequency distribution for the period extending from 160 Myr to the present day. The straight line is a linear fit to the data. It presents an inclination of -1.42 ± 0.14 (Myr)$^{-1}$.

This fact motivated a complement of the statistical study of the reversals through two simple dynamic models that hold few physical components but can reproduce the basic characteristics of the complex process that bears the geodynamo. The first model (Dias et al., 2008), that we will call model 1, takes the line of some works (Mazaud & Laj, 1989; Seki & Ito, 1993), that presented an interacting spin model, trying to simulate the reversals of the Earth's magnetic field. These models are based on the two-dimensional Ising model, near the critical temperature, and they show the similarity between the geomagnetic reversals and the criticality observed in the Ising model critical temperature. The second model (model 2), introduced by Papa et al. (2013), is based on the self-organized criticality of a model initially proposed by Bak (1996) for catastrophic events in ecology and subsequently adapted for other applications (da Silva et al., 1998; Sornette, 2000; Meirelles et al., 2010).

In model 1 each current ring was represented by a spin s, that is, the turbulent vortices behave as magnetic spins. In this model the magnetization is defined by:

$$M = \frac{1}{N} \sum_{i=1}^{N} s_i \tag{1}$$

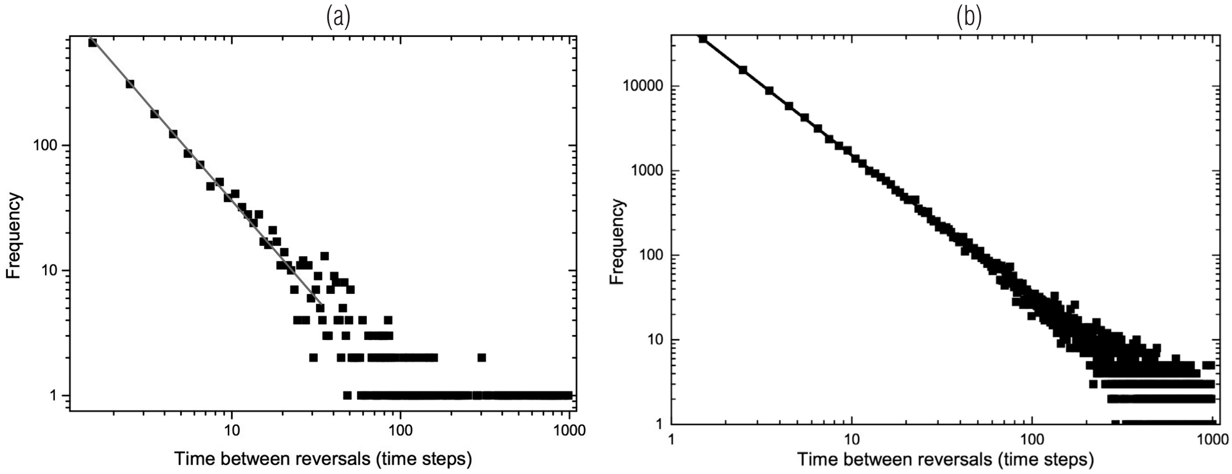

Figure 4 – Distribution functions for the times among reversals: a) for model 1; b) for model 2.

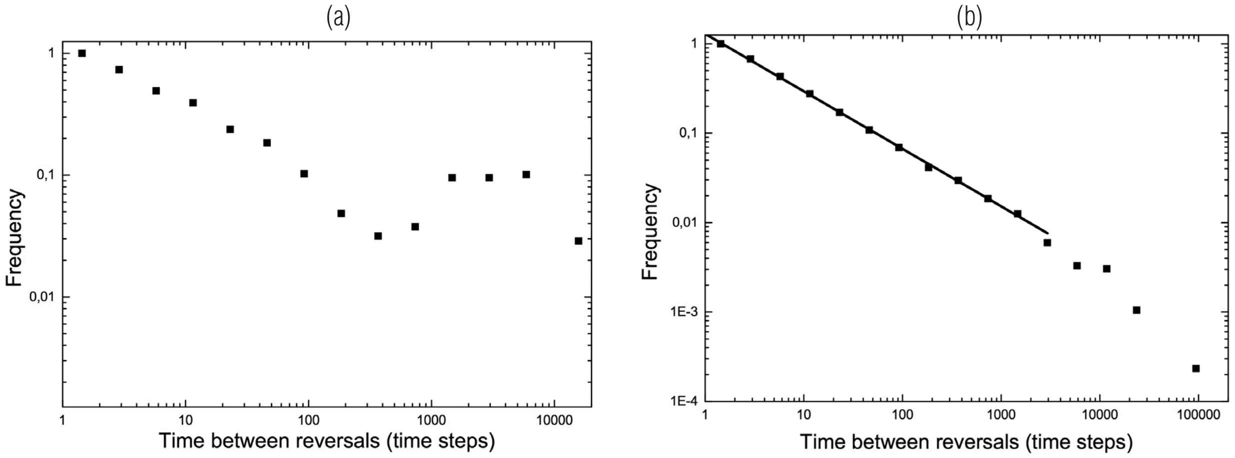

Figure 5 – Log-log graph of the interval distributions among consecutive reversals for simulations: a) in model 1, b) in model 2. Note the similarity among these graphs and the graph in Figure 3. As in Figure 2, we used logarithmic categories. The straight line inclination in b), which is a linear fit to the data, is –0.64 (0.01).

where the sum is performed considering all spins and M represents the geomagnetic dipole. In accordance with Dias et al. (2008), this model reversals were simulated, near the critical temperature, using a square lattice (50 × 50) that approximately represents the projection of the vortices in the terrestrial equator.

Model 2 consists of n random nodes, simulating the vortices in the Earth's liquid core that through a simple algorithm of temporal evolution converges into a self-organized critical state. In this model the geomagnetic polarity reversals were simulated through the changes in the magnetization of the node system in a 100 × 100 lattice. For both models the polarity interval distribution was determined and compared to actual data. From a practical perspective, it is expected with these models to generate synthetic data and overcome the experimental data limitation.

Figure 4 presents the distribution feature for the intervals among reversals for a model 1 and 2 simulation. The data follow a power law with inclination -1.56 ± 0.06, for the first model, and -1.6 ± 0.01 for model 2. These values are very close to the generally accepted value for the actual data –1.5 and also close to the value found in section 2 analysis.

To investigate the similarity between the actual and simulated data sets, the interval distributions among model 1 and 2 reversals were put in logarithmic bin graphs in Figure 5. We can note that the right side of the graph corresponding to model 1 presents traits identical to the actual data characteristics, however, Figure 3 graph does not present the left part of the graph in Figure 5. On the other hand, the graph corresponding to model 2 (in which the simulations were much longer) follows a power law almost perfect in all represented interval. From this comparison we assume that if the reversals obey a power law distribution, then this discrepancy may occur due to two possibilities (not mutually exclusive): the actual data sample is not enough extensive to show a trend in the data or there are many short intervals among the reversals that have not been documented yet in the used reversal scale.

DISCUSSION AND CONCLUSIONS

In this article it was carried out a statistical analysis of the geomagnetic reversal sequence, using the Cande & Kent (1995) geomagnetic polarity scale, through a non parametric statistics and scale laws. The analysis showed that the three geologic period data present identical statistical characteristics, concluding that the occurred geological changes in these periods did not modify the reversal process and that the polarity states are equivalent. These results are in accordance with many previous contributions and also with the magnetohydrodynamic theory of which equations are symmetrical in relation to the polarity states. A scale law analysis showed that the data present a power law as a possible distribution for the chrons and this could allow the existence of a critical phenomenon acting on the geodynamo. This implies that the outer core may be in a critical state in which the largest period duration among reversals is limited only by the system size, creating the possibility of the superchrons being generated by the same process of the other polarity intervals. This fact motivated the comparison between the reversal chronology of Cretaceous and Cenozoic with synthetic data of models based on the self-organized criticality. This comparison shows a considerable similarity between the actual and synthetic data. For the actual data frequency distribution, we found an inclination equal to $-1{,}42 \pm 0.19$. This value is -1.56 ± 0.06 for model 1 and -1.6 ± 0.01 for model 2.

The simple statistical analysis presented here cannot show the existence of a critical phenomenon acting on the Earth's outer core; it only indicates this possibility. More detailed studies, based on larger and more trustworthy data sets and also on new experimental evidences, shall lead to a more faithful characterization of the chron distribution. However, it is believed that the polarity scales, still subject to wide error margins, with many polarity intervals not registered yet, must be improved in the next years through new geophysical techniques of rock analysis, increasing the number of intervals in the geomagnetic chronology. Additionally, new computing simulations, mainly from the hydromagnetic dynamo models, will provide new and better synthetic data, leading to results closer to the geophysical reality.

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