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On the fractal structure of evolutionary trees

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Summary. We analyse in terms of a fractal tree the time sequences of major evolutionary leaps at various scales : from the scale of the "global" tree of life (appearance of life to homeothermy), to the distinct scales of organization of clades, such as sauropod and theropod dinosaurs, North American equids, rodents, primates including hominids, and echinoderms. We also apply this type of model to the acceleration observed in the economic crisis / no-crisis pattern in Western and pre-Columbian civilizations. In each case we find that these data are consistent with a log-periodic law of acceleration or deceleration, to a high level of statistical significance. Such a law is characterized by a critical epoch of convergence T_c specific to the lineage under consideration. These results support a description of evolutionary trees in terms of critical phenomena.

1 Introduction

The jumps between species [1,2] involve bifurcations allowing us to liken the general evolutionary process to a "tree of life" where "branch" lengths represent time intervals between major events. The question raised is whether this tree can be described by a mathematical structure, at least at a statistical level.

By analogy with real trees, we have tested as a first approximation the simplest possible law, i.e. a self-similar tree [3]. Such a law corresponds to discrete scale-invariance and log-periodic acceleration or deceleration, characterized by a critical point of convergence T_c which varies with the lineage in question. It has been suggested as describing various classes of phenomena [4-12]. The application of log-periodic acceleration models to life evolution has been anticipated by Meyer [13,14].

The physical model underlying the appearance of such laws is that of critical phenomena. The renormalization group approach [15,16] predicts both power law scale behavior and log-periodic corrections of such behavior [17,18,11] (see also [5,19] and Sec. 2 hereafter). Moreover, the critical behavior is *a priori* symmetrical around the critical value of the variable under consideration. Both log-periodic accelerations before the critical point ("precursors") and decelerations after it

("replicas") are expected, and they have been confirmed for spatial structures [20] and temporal structures (earthquakes [21,22], stock market crashes [23]).

2 Discrete scale invariance and log-periodic behavior

Let us give a simple theoretical argument [19] showing that a log-periodic behavior is naturally expected as a correction to standard self-similar fractal laws. Consider a scale-dependent "field" $\Phi(\varepsilon)$. The scale variable is identified with a resolution interval $\varepsilon = |T - T_c|$, where T_c is the date of crisis. Assume that Φ satisfies a renormalization-group-like first order differential equation,

$$\frac{d\Phi}{d\ln\varepsilon} - D \Phi = 0, \quad (1)$$

whose solution is a power law $\Phi(\varepsilon) \propto \varepsilon^D$. Now looking for corrections to this law, we remark that simply jumping to a complex exponent D would lead to large log-periodic fluctuations rather than to a controllable correction to the power-law. So let us assume that the right-hand side of Eq. 1 actually differs from zero, i.e. that:

$$d\Phi/d\ln\varepsilon - D \Phi = \chi. \quad (2)$$

We now apply the *scale-covariance* principle, according to which we require that the new function χ be solution of an equation that keeps the same form as the initial equation

$$\frac{d\chi}{d\ln\varepsilon} - D' \chi = 0. \quad (3)$$

Setting $D' = D + \delta$, we find that Φ is solution of a second-order equation

$$\frac{d^2\Phi}{(d\ln\varepsilon)^2} - (2D + \delta) \frac{d\Phi}{d\ln\varepsilon} + D(D + \delta) \Phi = 0. \quad (4)$$

This solution writes $\Phi(\varepsilon) = a \varepsilon^D (1 + b \varepsilon^\delta)$, and finally, the choice of an imaginary exponent $\delta = i\omega$ yields a solution whose real part includes a log-periodic correction:

$$\Phi(\varepsilon) = a \varepsilon^D [1 + b \cos(\omega \ln \frac{\varepsilon}{\lambda})]. \quad (5)$$

Such a function show peaks at discrete values of the time that accelerate toward the critical date (or decelerate from it) according to the log-periodic law $\ln[(T_n - T_c)/\lambda] = -n \ln g$, where $g = \exp(2\pi/\omega)$.

3 A fractal tree model

3.1 Constructing the evolutionary law

Let us consider a node in a tree where a branch divides into k sub-branches. Let us assume that the total cross-section before (level n) and after (level $n+1$) the node is preserved. If this section is bidimensional (as for example with conservation of sap flow), this is reflected in the relationship between radii: $k r_{n+1}^2 = r_n^2$. But a more general relationship can be considered by introducing a fractal dimension D : $k r_{n+1}^D = r_n^D$. If we now accept that the tree is fully self-similar (as a minimal simplifying assumption), the ratio of branch lengths will then be equal to the ratio of their radii, giving $g = k^{1/D}$. Since $g > 1$, the total length measured along a given lineage is therefore finite, since it is given by the converging infinite sum: $L_c = L_0 (1 + g^{-1} + g^{-2} + \dots) = g L_0 / (g - 1)$. For a temporal tree, these "lengths" are given by the time interval between two evolutionary events: $L_n = T_{n+1} - T_n$. Convergence of the above series therefore means there is a critical time, T_c , marking the end of the evolutionary process for a given lineage (or its beginning in case of deceleration).

If we now take as the time origin the final critical time T_c , self-similarity is preserved, because the time interval ratios relative to this origin are still given by g^n .

Finally, we recover the log-periodic law obtained in the previous section (by setting $\lambda = T_0 - T_c$):

$$T_n = T_c + (T_0 - T_c) g^{-n}. \quad (6)$$

This law is dependent on two parameters only, g and T_c , which of course have no reason a priori to be constant for the entire tree of life. Note that g is not expected to be an absolute parameter, since it depends on the density of events chosen, i.e. on the adopted threshold in the choice of their importance (namely, if the number of events is doubled, g is replaced by \sqrt{g}). Only a maximal value of g , corresponding to the very major events, could possibly have a meaning. On the contrary, the value of T_c is expected to be a characteristic of a given lineage, and therefore not to depend (within error bars) on such a choice.

3.2 Methodology

Our method of statistical analysis of the fit between the data and this law consists of using Student's t variable associated with the correlation coefficient in the graph [event rank n , $\log(T_c - T_n)$] as the statistical estimator. When T_c is given, the law of Eq. 6 becomes linear when it is expressed in logarithm form. Therefore we vary continuously the values of T_c , and for each of these values we compute the values of g by a least-square fit, then we determine the associated t (Student). Then we construct the curve $t(T_c)$ (see examples in Figs. 3 and 4 below). The optimized value of T_c is given by the peak of this curve, and the error bar on T_c is estimated from its half-width at half-maximum. Finally, Monte-Carlo simulations have been made to calibrate this estimator and define the associated probability, by applying the same analysis to dates chosen at random and arranged in chronological order (*Table 1*).

n	5	6	7	8	9	10	12	14	16
t (1‰)	100	50	46	42	37	38	44	50	52
t (1%)	34	28	27	27	26	30	32	37	40

Table 1. Values of the peak of the Student's t variable that corresponds to probability thresholds 1/100 (2.3 sigma) and 1/1000 (3 sigma), according to the number of dates in the sample.

3.3 Application to the evolution of species

We test this log-periodic evolutionary law at various levels of analysis: (i) the tree of life at a global level, from the first appearance of life to viviparity [24]; (ii) sauropod and theropod dinosaurs postural structures [25,27]; (iii) rodents families [28-29]; (iv) the North American equid genera [29]; (v) primates bauplans, including the hominids [12]; (vi) Echinoderms groups [32].

In each case we find that a log-periodic law provides a satisfactory fit for the distribution of dates, with different values of the critical date T_c and of the scale ratio g for different lineages. The obtained behavior may be an acceleration or a deceleration depending on lineage and time scale. The results are statistically significant.

We give in what follows (see also Fig. 1) the adopted dates (in Myrs before present) for the major jumps of the studied lineages. The error bars are typically $\delta T/T \approx 10\%$ or less, i.e., $\delta \log(T_c - T) \approx 0.04$. Since we are interested here in pure chronology, if several events occur at the same date (within uncertainties), they are counted as one. Then we give the result of the least-square fit of the log-periodic model and the associated Student variable with its corresponding probability to be obtained by chance. For each lineage we include in the analysis the common ancestors down to the origin of life (except for Echinoderms which show deceleration instead of acceleration). The obtained parameter values are compatible with those given in Fig.1, which result from a fit that does not include the ancestors of the lineage.

Global tree, from origin of life to viviparity (see the nature of the events in Fig. 1):

{-3500},{-1750},{-1000},{-570},{-380},{-220},{-120}

These events exhibit a significant acceleration toward:

$T_c = -32 \pm 60$ My; $g = 1.83 \pm 0.03$; $t_{St} = 36$, $P < 0.003$ (N = 7 events).

Primates including hominids

{prosimian bauplan : -65}, {simian bauplan : -40}, {great apes bauplan : -20},

{Australopithecus bauplan: -5}, {Homo bauplan: -2}, {H. sapiens bauplan: -0.18}

$T_c = 2.1 \pm 1.0$ My; $g = 1.76 \pm 0.01$; $t_{St} = 110$, $P < 0.0001$ (N = 14 events, including the "global" tree).

It has been recently suggested [33] that other events (actually minor ones) should also be taken into account for this lineage, leading to the following dates:

{-65, -53, -40, -35, -25, -20, -17, -10, -7, -5, -3.5, -2, -0.18}

The statistical analysis gives:

$T_c = 5.8 \pm 4.0$ My; $g = 1.23 \pm 0.01$; $t_{St} = 57$, $P < 0.001$ (N = 13 events).

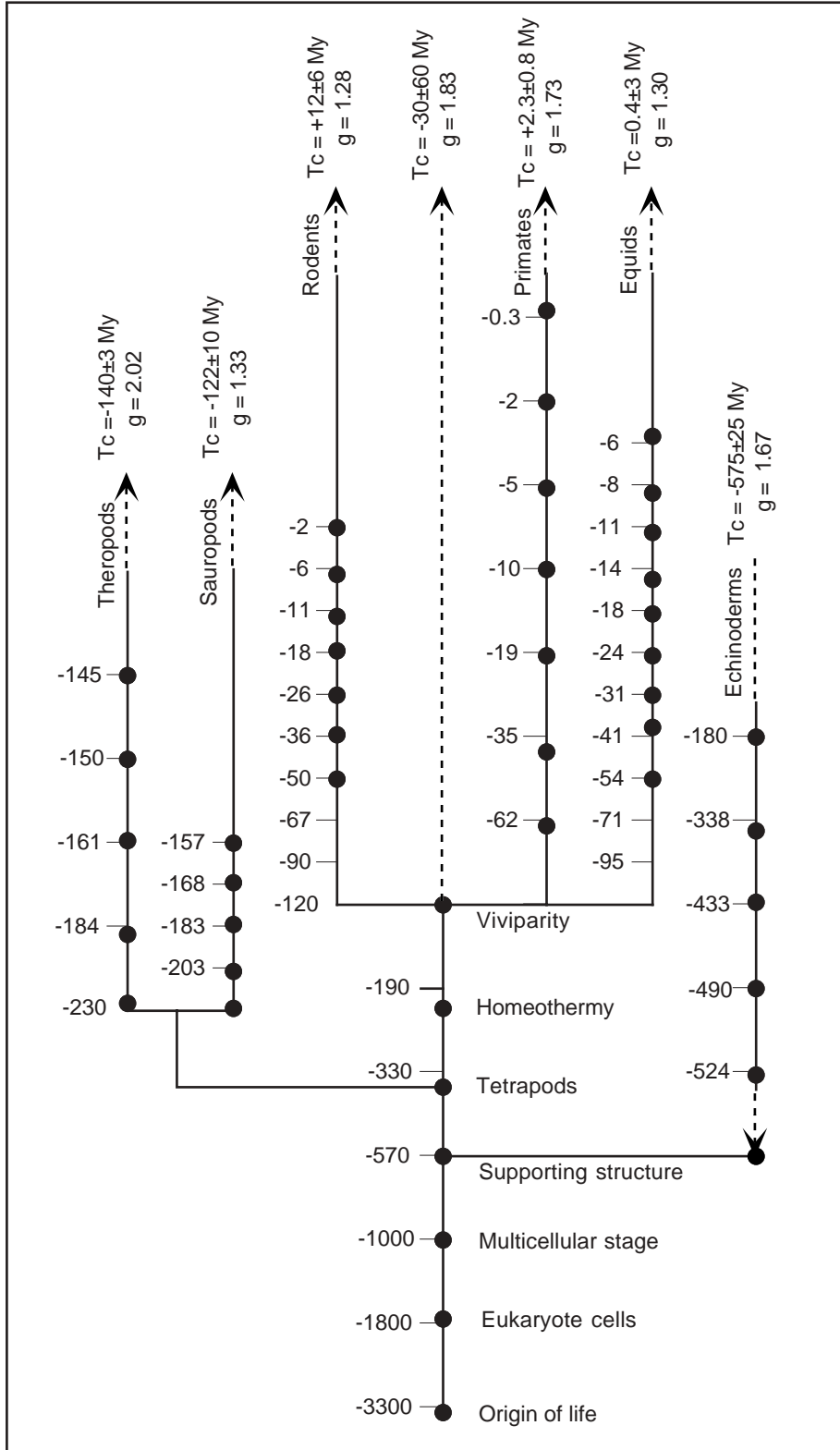


Fig. 1 The dates of major evolutionary events of seven lineages (common evolution from life origin to viviparity, Theropod and Sauropod dinosaurs, Rodents, Equidae, Primates including Hominidae, and Echinoderms) are plotted as black points in terms of $\log(T_c - T)$, and compared with the numerical values from their corresponding log-periodic models (computed with their best-fit parameters). The adjusted critical time T_c and scale ratio g are indicated for each lineage.

The result is still significant, and, moreover, the critical date agrees within error bars (to less than 1σ) with our previous determination. This confirms that T_c is characteristic of the lineage beyond the choice of the events. On the contrary the value of g , which depends on the density of dates, is not conserved, as expected.

Fossil North American equids

{*Hyracotherium*: -54}, {*Mesohippus*: -38}, {*Miohippus*: -31}, {*Parahippus*: -24}, {*Archeohippus*: -19}, {*Hipparion*: -15}, {*Protohipus*: -11}, {*Nannipus*: -9}, {*Plesippus*: -6}, {*Equus*: -2}

$T_c = -1.0 \pm 2.0$ My; $g = 1.32 \pm 0.01$; $t_{st} = 99$, $P < 0.001$ (N = 16 events, including the "global" tree, excluding *Equus*).

Rodents :

In the case of rodents, the analysis is different from the other lineages, since it is made on their whole arborescence, according to the data of Hartenberger [30]. We have plotted in Fig. 2 the histogram of the distribution of the 61 dates of appearance of rodent families. Well-defined peaks can be identified in this distribution. It is on these peaks that we perform our analysis. However, some uncertainty remains, in particular concerning the large peak after the date of first apparition of the lineage. Three different interpretations are considered.

In Fig. 1 we have used the mean value (-50 My) of the first peak. This yields a critical date $T_c = 12 \pm 6$ My in the future. One can also singularize the latest date, yielding:

{-56}, {-45}, {-34}, {-26}, {-18}, {-12}, {-7}, {-2}. One obtains:

$T_c = +7 \pm 3$ My; $g = 1.32 \pm 0.01$; $t_{st} = 78$, $P < 0.001$ (N = 15 events, including ancestors in the "global" tree).

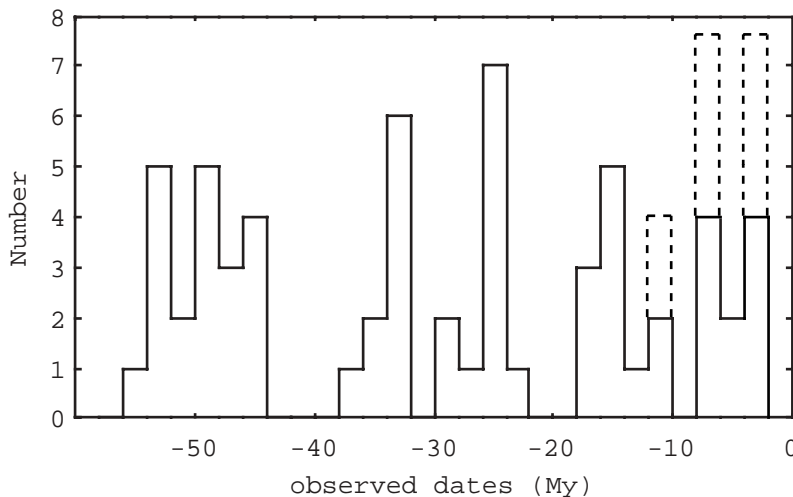


Fig. 2 Histogram of the distribution of the dates of appearance of families in the arborescence of the order of rodents, from the data of [30]. These data include only a subfraction of the events after -12 My, so that the amplitude of the last peaks is underestimated and has been extrapolated (dotted line).

But a closer scrutiny of the data suggests that the spurt of branching (that correspond to the sub-peaks inside the main first peak in Fig. 2) that followed the group's first

appearance actually decelerates. This would be in agreement with the interpretation of these structures in terms of critical phenomena. We find that the deceleration is issued from a critical point at $T_c = -62 \pm 5$ Ma, which agrees with the date estimated for the group's first appearance. Once this initial deceleration is allowed for, the following dates (-34, -26, -18, -12, -7, -2) exhibit highly significant acceleration toward $T_c = 27 \pm 10$ Ma ($t_{St} = 98$, $P < 10^{-4}$).

Sauropod dinosaurs :

Wilson and Sereno [26] have identified five well-defined major events in the evolution of their legs: {Sauropoda: -230}, {Eusauropoda: -204}, {Neosauropoda: -182}, {Titanosauriforms: -167}, {Titanosauria: -156}.

These events exhibit a marked log-periodic acceleration toward:

$T_c = -128 \pm 10$ My; $g = 1.41 \pm 0.01$; $t_{St} = 122$, $P < 0.001$ (N = 10 events, including ancestors from the "global" tree).

Theropod dinosaurs :

One can identify from the data of Sereno [27] the following main dates in the evolution of theropods (once again, several events having the same date within uncertainties are counted as one) : {Neotetanurae: -227}, {Coelurosauria: -187}, {Maniraptora: -160}, {Aves: -150}, {Euornithes: -145}.

There is a significant acceleration toward:

$T_c = -139 \pm 4$ My; $g = 2.02 \pm 0.02$; $t_{St} = 69$, $P < 0.001$ (N = 10 events, including ancestors down to the origin of life).

This supports the existence of a log-periodic acceleration for the whole group of *Saurischia* (Sauropods and Theropods). However, an analysis of the other large dinosaur group, *Ornithischia*, has given no statistically significant structure. This could indicate, either that the log-periodicity is not universal and characterizes only some particular lineages, or that the data are incomplete for this group.

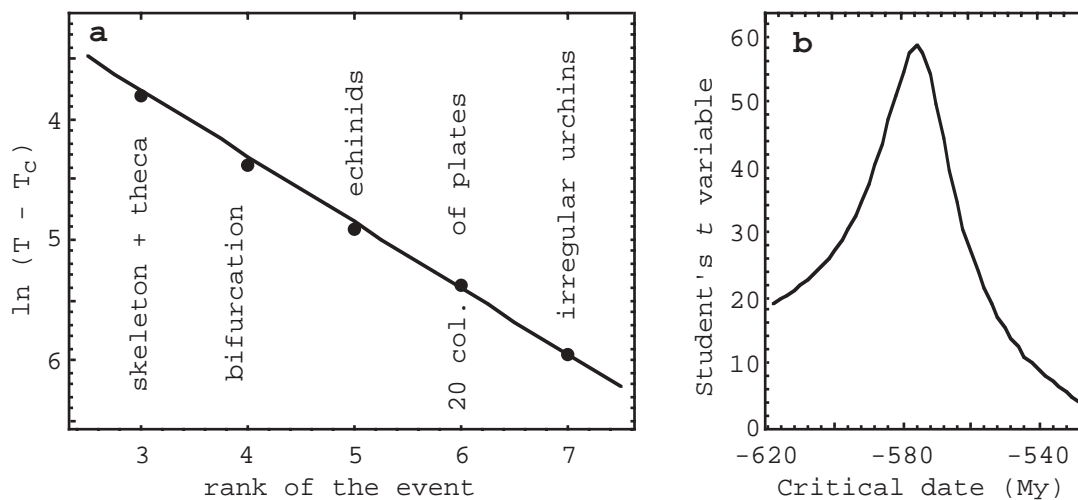


Fig. 3 Comparison of the main dates of the evolution of echinoderms with a log-periodic decelerating law of critical date $T_c = -575$ My and scale ratio $g = 1.67$ (figure a). Figure b shows the estimation of the critical date through the optimisation of the Student's t variable.

Echinoderms :

The critical phenomena approach to evolutionary process leads to expect not only acceleration toward a crisis date, but also deceleration from it. The echinoderm group supports this view. The major events that punctuate their evolution happen at the following dates, according to David and Mooi [32]:

{apparition:-570}, {-526,-520}, {-490}, {-430}, {-355}, {-180}.

Processing of this data shows that this group *decelerate* from a critical date $T_c = -575 \pm 25$ My (see Fig. 3). This epoch identifies, within error bars, with the first appearance datum around -570 My. We find:

$T_c = -575 \pm 25$ My; $g = 1.67 \pm 0.02$; $t_{st} = 58$, $P < 0.003$ (N = 5 events).

3.4 Application to the evolution of civilizations

Many observers have commented on the way historical events accelerate. In particular, a log-periodic acceleration has been anticipated by Meyer [13,14]. Grou [34] has demonstrated that the economic evolution since the neolithic can be described in terms of various dominating poles which are submitted to an accelerating crisis / no-crisis pattern, that we shall now quantitatively analyse.

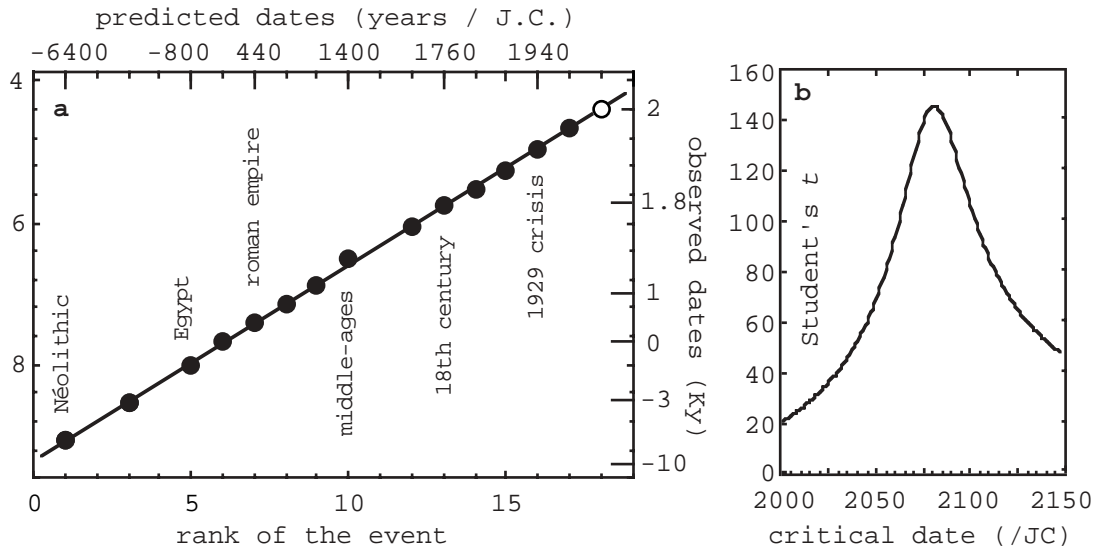


Fig. 4 Comparison of the median dates of the main economic crises of western civilization with a log-periodic accelerating law of critical date $T_c = 2080$ and scale ratio $g = 1.32$ (figure a). The last white point corresponds to the epoch (1995-2000), while the next crisis is predicted for (2015-2020). Figure b shows the estimation of the critical date through the optimisation of the Student's t variable. This result is statistically significant, since the probability to obtain such a high peak by chance is $P < 10^{-4}$.

3.4.1 Western civilizations

The median dates of the main periods of economic crisis in the history of Western civilization (as listed in [34-36] are as follows (we give the dominating pole and the date, in years / JC):

{Neolithic: -6500}, {Egypt: -3000}, {Egypt: -900}, {Grece: -100}, {Rome: +400}, Byzance: +800}, {Arab expansion: +1100}, {Southern Europ: +1400}, {Nederland:+1650}, {Great-Britain: +1775}, {Great-Britain: +1830}, {Great-Britain: +1880}, {Great-Britain: +1935}, {United-States: +1975}.

Log-periodic acceleration with scale factor $g = 1.32 \pm 0.018$ occurs toward $T_c = 2080 \pm 30$ (see Fig. 4). Agreement between the data and the log-periodic law is statistically highly significant ($t_{st} = 145$, $P \ll 10^{-4}$).

3.4.2 Pre-Columbian America

The historical evolution of pre-Columbian America provides an interesting opportunity to test the universality of the law proposed. The median dates of the economic crises of these civilizations are as follows (see [37]):

{Olmeques: -600}, {Classic: 500}, {Mayas: 1000}, {Tolteques: 1350}, {Azteques: 1550}.

A good agreement is obtained between these dates and a log-periodic law of factor 1.76 ± 0.02 and critical point $T_c = 1800 \pm 80$ ($t_{st} = 58$, $P < 5 \cdot 10^{-3}$).

4 Discussion and conclusion

Let us end this contribution by discussing possible biases and uncertainties in our analysis. There is a "perspective" bias, linked to observational data being fossil records observed at the present epoch only. This bias can manifest itself in two ways.

First, the uncertainty on the dates increases with the date itself, so that we expect that $\delta T/T$ be about constant, which could lead to alog-periodic behavior. We have discussed this bias in [3] and we have shown that it can not account for the observed structure. The additional information given here and in [37] that one observes also decelerations reinforce this conclusion. A second possible form of this bias [Sornette, private communication] could be an increasing number of missing events in fossil records for increasing dates in the past. Against such an interpretation, one can recall that the quality of the fossil records, concerning in particular their completeness, has been recently reaffirmed by Kidwell and Flessa [38]. Moreover, the number of missing links needed to compensate for the acceleration seems to be unreasonably large (the interval between major events goes from billion years at the beginning of life to million years now).

In addition, the bias about the choice of dates, in particular in defining which characters are considered to be major ones, has been analyzed here. The solution to this problem lies in the observation that, if the acceleration (or deceleration) is real and intrinsic to the lineage under study, its occurrence and the date of convergence T_c ought not to be dependent (within errors) on the limit applied as to the choice of which events count as important ones. However, there is nothing intrinsic about the scale factor g between intervals, as it decreases as the number of events allowed for increases. We have been able to test this stability of the critical date with the data for which we considered several possible choices (rodents, sauropods) as well as with choices suggested by other workers (primates). We conclude that this uncertainty cannot explain the observed law, which therefore seems to be a genuine one.

However, while log-periodic accelerations or decelerations have been detected in the majority of lineages so far investigated, the question of whether this behavior is systematic or not remains an open one (cf. the general tree for dinosaurs published by Sereno [27]).

Analysis of the values of the critical date for the various lineages leads us to interpret it, in the case of an acceleration, as a limit of the evolutionary capacity of the corresponding group. When a deceleration has been detected, it starts from the apparition date of the lineage. Let us finally stress the fact that the existence of such a law does not mean that the role of chance in evolution is reduced, but instead that randomness may occur within a framework which may itself be structured (in a partly statistical way). Such structures may find their origin in critical phenomena [37], or, in an equivalent way, in the geometry of intermittency [39].

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