A model of past Earth's climate from isotopic and biologic data and its relationship with orbits' expansion

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Abstract

The first model of the past hot Earth's climate consistently indicated by isotopic and biologic data is here established. This model, here named Evolving Climate Model (ECM), accurately matches a 3 Gy long compilation of $\delta^{18}O$ data. An important consequence of the model is the fast increase of oxygen atmospheric level between 2 and 1 Ga (Gy ago); this is a well-known but until now mysterious occurrence, the Great Oxygenation Event. A solution is presented for the two centuries old "dolomite problem" and new explanations arise for a number of long lasting problems, such as the origin of petroleum or of proto-continents. Differently from the usual climate scenarios, the ECM presents ideal conditions for the massive production of long organic molecules. Critical occurrences of life evolution, such as the Cambrian explosion, are explained and fitted by the ECM, exposing a previously unknown connection between the evolution of life and climate. The most likely cause for this hot past is the expansion of orbits; it is verified that this phenomenon can explain the ECM, the receding of the Moon and the water on early Mars for the same value of H_0 ($H_0 = 48$ km s^{-1} Mpc^{-1}), which, if not a coincidence, is a non-negligible result.

I. Introduction

The earliest and still most common conception of Earth's past assumes a climate similar to the present one because it has generally been considered that a different climate would not be suitable for life – neither for its origin nor its evolution. Then, some evidences portraying a warmer climate were found; it was considered that they trace abnormal warm periods of a past that, except for those periods, was still similar to the present. On the other hand, the standard solar model (SSM) predicts that solar activity was lower in the past and implies, considering only known phenomena, a past frozen Earth. However, the evidences supporting a hot past have been accumulating, questioning further and further the possibility of a past climate colder or even similar to the present one.

Most efforts to solve this difficulty consisted in looking for alternative interpretations of isotopic data in order to harmonize them with a past climate more similar to the present one (e.g., Kasting & Howard, 2006); however, the hot past is consistently indicated by all kinds of data and although some of them can support such reinterpretations, that is not the case of biologic data. However, how can a hot past be possible when the SSM implies that solar activity was considerably lower then?

A tentative answer to this question is the Snowball Earth theory[1], which considers that Earth has been fully frozen, from pole to pole, a number of times in the past and for long periods. Episodes of massive liberation of greenhouse gases led Earth out of glaciations and into hot periods, despite the lower solar activity. Therefore, Earth's past would have been an alternation of deep frozen and hot periods. This is a rather speculative theory but it is the only one available that can be compatible with standard physics. The alternatives are to consider that the SSM is wrong or that orbits expand (as space does). Unless Snowball Earth is considered a satisfactory theory, these alternatives must be carefully examined.

The possibility of orbits' expansion is especially relevant because it relates to an open issue: to know whether space expansion has local consequences or not. Standard space expansion models apply only in the absence of local gravitational fields but that is not a result, it is just a limitation of the validity of the theory (the concept of "local gravitational field" is itself questionable). In the absence of a theory able to deal with gravitational fields in expanding space (for instance, able to solve the two-body problem in expanding space), only observations can show how space expansion acts at local scale.

The more direct way to elucidate this issue is the analysis of ephemerides; however, several more years of measurements are required. The main difficulties are the complex treatment of measured values (see Pitjeva, 2013), the limited accuracy of measurements, especially for the determination of the variation of orbits (Folkner, 2010), the complexity of the model (more than 260 parameters, as mentioned by Pitjeva, 2011) and the absence of an acceptable theory supporting orbits' expansion. The calculations are performed to fit the only available model, where orbits are invariant; as the number of parameters is huge, the possibility of adjustment to invariant orbits is large within the present accuracy of data. Therefore, a conclusion about local space expansion will only be possible when the accuracy of the data becomes so high that the adjustment to invariant orbits becomes impossible. It is worth mentioning that Krasinsky & Brumberg (2004), considering that "the effects of expanding uniform Universe do not involve any measurable effects in the motion of the major planets", found an increase of 15 ± 4 m/cy in the Earth-Sun distance, a value that rules out invariant orbits.

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[1] http://www.snowballearth.org/

This value is too low for a cosmological orbital expansion but it was obtained considering the above paradigm.

One has to face the following: biologic data and isotopic data consistently indicate a hot past for Earth, with a sea surface temperature close to the boiling point until less than 3 Gy ago (Ga) (e.g. fig. 2 of Jaffrés et al., 2007). Alternative interpretations of the data were made in order to obtain lower temperatures but they were based on the assumption that high temperatures are not plausible; nevertheless, they were unable to produce a model of Earth's past climate compatible with current physics – which, truly, can only support a past frozen Earth. Therefore, the possibility of a hot Earth's past must be analysed because, methodologically, it cannot be ruled out just by a priori plausibility arguments and the alternative interpretations cannot be considered satisfactory. The most likely cause for such a hot past is orbits' expansion but no acceptable analysis of that past can be made without a viable theory or direct evidences of this phenomenon.

The above impasse changed with the self-similar dilation model (Oliveira, 2011), which predicts that orbits expand at the rate of $2H_0$ while being compatible with fundamental physical laws. Although not yet accepted, this model establishes the theoretical possibility of orbits' expansion without conflicting with laws and measurements, both cosmic and local, namely with the invariance of G. As the predicted rate of orbital expansion (twice the space expansion rate) implies strong and clear consequences, ruling it out or verifying it from evidences might not be too difficult.

Because the dilation model (see Appendix I for a summarized description of the dilation model) is not yet an acknowledged theory and the cited work only tests it with cosmic data, some local confirmation of the theory must be found before using it to analyse Earth's past climate. Luckily, two phenomena can be used to directly check the possibility of orbits' expansion at the predicted rate: the Moons' receding from Earth and the existence until 3.8 Ga of large bodies of water in early Mars. So, this paper starts with the analysis of these two cases, concluding that both are compatible with the predicted orbits' expansion.

Once the possible conflicts between expanding orbits and current knowledge are removed, one can consider the straightforward interpretation of biologic and isotopic data, i.e., that Earth's past climate was warm/hot. To model the past climate assuming so, a three-step procedure is used: first, a set of conditions is defined from clear evidences, outlining an empirical model; second, a theoretical model is built, considering the SSM and orbits' expansion; third, the theoretical model is adjusted to the empirical model, defining a value for H_0. A relevant result emerges: this value of H_0 is almost coincident with the values found for the two test cases (Moon's receding and Mars past water). The climate model is named Evolving Climate Model or ECM.

Once defined, the model must be tested. The 3 Gy long set of $\delta^{18}O$ data compiled by Jaffrés et al. (2007) is used to make the first test of the ECM model.

The ECM is rather different from what has been considered for Earth's past climate, and so it has new consequences and allows new explanations for known occurrences; to explore them is the following step of the testing. A particular attention is paid to life origin and evolution, which is the main terrestrial phenomenon.

The ECM is the first model of a hot past. The ECM is not a surprise, it reflects what evidences have been showing; the surprise is the possibility of modelling those evidences without conflicting with physical laws. With it, a new storyline of Earth and life evolution emerges, potentially explaining several – until now obscure or mysterious – occurrences.

II. The cases of Moon receding and of past climates

II.1. Moon receding

From the several hypotheses proposed to explain the increase of Moon-Earth distance (see e.g. Van Flandern, 1975), the only one that has not been ruled out is the Moon-Earth tidal effect. However, there is no theory on tidal effect that allows the quantification of the receding of the Moon, just a relationship between the receding and the increase of the day length, a slowing of Earth's rotation imposed by the transfer of the angular momentum from the Earth to the Moon. Is this relationship verified by measurements?

The Moon-Earth distance can be measured with an accuracy of some millimetres (although the analysis of data depends on about thirty parameters, some of them depending on the planetary model[2]) by Lunar Laser Ranging (LLR) since the 1990s. The current result from JPL (Jet Propulsion Lab) by Williams et al. (2008) is that the semi-major axis of the Moon's orbit increases 38.14 mm/yr; since this axis is 384,399 km long, its rate of increase is 0.992×10^{-10} yr^{-1}. The conservation of angular momentum in the context of tidal effect implies a negative acceleration component in Earth's rotation, which is usually quantified by the variation of LOD, defined as the difference between the astronomically determined length of the day and 86400 s; to the above rate of increase of Moon's orbit corresponds $\Delta\text{LOD} = +2.3$ ms/cy (e.g. Stephenson, 1997). Do evidences confirm this variation of the length of the day, supporting the tidal effect as the cause of the Moon receding?

Stephenson & Morrison (1995) analysed solar and lunar eclipses from 700 BC to AD 1600 and obtained $\Delta\text{LOD} = +1.70 \pm 0.05$ ms/cy; Pertsev (2000) found $\Delta\text{LOD} = +1.4$ ms/cy by analysing three centuries of telescope observations (in Dumin, 2002); and an analysis of a paleoclimate record from the eastern Mediterranean Sea over the past three million years (Lourens et al., 2001) yielded $\Delta\text{LOD} = +1.2$ ms/cy. To explain the difference between the value expected from tidal effect and the values from old records, the currently favoured theory is the isostatic adjustment, or post-glacial rebound (Wu & Peltier, 1984), with a calculated contribution of –0.7 ms/cy (Lambeck, 1977).

Therefore, there is a rather consistent explanation from standard physics, except for the following: since the 1970s,

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[2] http://wwwrc.obs-azur.fr/cerga/laser/laslune/presentation.htm

when high accuracy measurements of Earth's rotation began (www.iers.org), namely VLBI (Very Long Baseline Interferometry) measurements, there has been a decrease of LOD at a rate that can be as important as $\Delta\text{LOD} = -6$ ms/cy, as shown in Fig. 1 (graphic from the Earth Orientation Center[3]). VLBI uses extragalactic radio sources as reference; due to their distance, they can be considered an absolute reference to measure rotation.

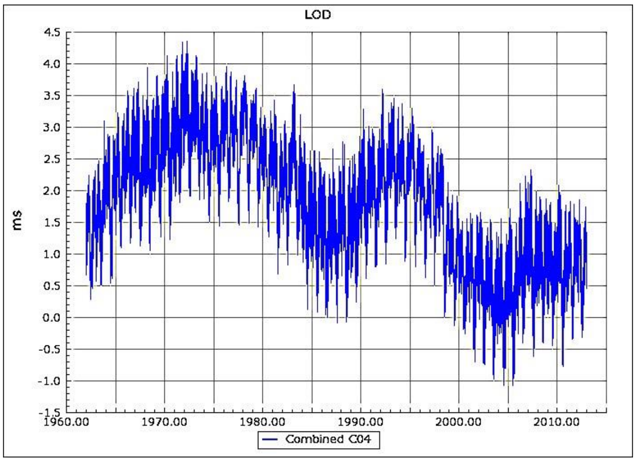

Fig.1. Plot of LOD (the difference between the length of the day and 86400 s) since 1962, from the Earth Orientation Center. The figure shows that Earth's rotation is dominated by phenomena with an intensity greater than the tidal effect, and with long time span. Instead of the increase of the LOD implied by the tidal effect, a decreasing trend is observed, the Earth's rotation being now faster than at four decades ago.

This highly accurate record is apparently a surprise, and the need to insert leap seconds has sometimes been understood as due to a slowing of Earth's rotation; however, it results from the definition of the second, too small for the present duration of the day (the second was defined in 1967, before VLBI measurements).

The data trace the existence of unknown phenomena influencing Earth's rotation, with amplitudes larger than the tidal effect and at least several decades long. The irregularity of Earth's rotation is not unknown (see, e.g., Hide, 1993).

This behaviour cannot be explained by phenomena of short duration because the acceleration displayed by the high-accuracy measurements has already four decades; its main cause might be tectonics or other phenomena of inner Earth, which can evolve at time scales of millions of years. Therefore, even if Earth's rotation has been slowing over the last thousands of years, it would possibly be a consequence of those unknown phenomena and not of the tidal effect due to the Moon and also to the Sun.

Examples of long-lasting phenomena (besides post-glacial rebound) that affect Earth's rotation are: the vertical oscillation of tectonic plates and the global oscillation of the mantle, which appear as a change of oceans' level with respect to a land benchmark (note that if oceans increase due to thermal expansion or ice melting, that contributes to slow Earth's rotation, while the sinking of the continents, by oscillation or other cause, has the opposite consequence); the variation of the internal temperature of the Earth which, although very small, affects the radius of the Earth (see, e.g., Tsuchiya et al., 2013) – a variation of a few millimetres per year is enough to explain the acceleration of Earth's rotation; other, less relevant, phenomena are the sinking of mantle's heavier components, the drag due to the higher rotation speed of the inner core, the variation of the rotation axis and the variation of water and atmosphere temperatures. There is also a small accelerative contribution considered by the self-similar model (≈ –0.5 ms/cy, due to the conservation of angular momentum in space units).

On the other hand, old data (telescope and naked eye data) have low accuracy and can be adjusted to invariant orbits, so the results of the mentioned analyses can only be valid if such a scenario holds. Furthermore, Kolesnik & Masreliez (2004) analysed about 240,000 worldwide optical observations of the Sun, Mercury and Venus, and found evidences of systematic errors in the data from the 18th and 19th centuries. Also, the JPL calculation of the Moon's orbit is not entirely satisfactory because there is an anomalous eccentricity rate (Williams et al., 2008), which cannot be explained by present models of dissipative phenomena, by published modified models of gravity or by a trans-Plutonian massive object (Iorio, 2011).

The above shows that one cannot expect to achieve conclusions about the tidal effect from measurements of Earth's rotation because this is affected by long-lasting phenomena more intense than the tidal effect. This conclusion does not question the existence of tidal effects but rules out the possibility that its quantification is adequately supported by the data on Earth's rotation.

II.2. Past climates

According to the Standard Solar Model (SSM), solar activity increases with the Sun's age. In case of an invariant Earth-Sun distance, the Earth should have been frozen during most of its past; the model that tries to comply with this scenario is the Snowball Earth (Hoffman et al., 1998; Arnaud et al., 2011). In spite of some evidences able to support the past occurrence of long-lasting and extensive glaciations, there are plenty of evidences indicating that Earth's past was hot. The idea that the Earth could have been alternating between frozen and hot periods has questionable support from evidences because the ones that imply a hot climate are not limited to some epochs. The first attempts to explain past hot or warm epochs considered the possibility of a greenhouse effect, but they were not consensual (for a review, see e.g., Kasting & Howard, 2006); the theory of Global Warming roots in those efforts to explain high past temperatures using the greenhouse effect. However, the discovery of the possible occurrence of large bodies of water in Mars as late as 3.8 Ga (McKay & Davis, 1991; Baker et al., 1991; Squyres & Kastings, 1994; Malin & Edgett, 2000; Perron et al., 2007; for a review see e.g. Carr, 2000) calls for an explanation for the warmer past of Mars as well; the carbon dioxide levels in Mars do not seem high enough to generate the required

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[3] http://hpiers.obspm.fr/eop-pc/index.php?index=analysis&lang=en

greenhouse effect (Chevrier et al., 2007). The fact is that there is no consensual greenhouse model able to explain high past temperatures considering the past solar luminosity predicted by the SSM. As an alternative, Sackmann & Boothroyd (2003) proposed a young Sun brighter than predicted by the SSM. Higher past irradiance is also suggested by the loss of large amounts of water in Mars (Krasnopolsky & Feldmann, 2001). Overall, there seem to be three possible explanations for this conundrum: either Earth had a generally frozen past (which agrees with current physics but conflicts with most data), or irradiance was higher in the past (which agrees with most data but has no explanation from current physics), or there is an unknown phenomenon that warmed up Earth and Mars in the past despite a lower irradiance. Either way, the past climates of Earth and Mars are a mystery, an unsolved problem within the framework of current physics.

III. Testing orbits' expansion: the receding Moon

The most direct test of orbits' expansion is the Moon's orbit around the Earth because it is the only orbit that can be measured with enough accuracy. As mentioned in section II.1, the semi-major axis of the Moon's orbit increases at a rate of 0.992×10^{-10} yr^{-1}. Within the framework of the dilation model, as the rate of orbital expansion is $2H_0$ [Eq. (AII.4)], the above rate corresponds to $H_0 = 48.5$ km s^{-1} Mpc^{-1} (if exclusively due to the dilation phenomenon). This value is lower than the one obtained from the supernovae test (Oliveira, 2011), which is $H_0 = 64$ km s^{-1} Mpc^{-1}; however, it is close enough to suggest that the receding of the Moon can be mainly due the expansion of the orbit predicted by the dilation model.

Given that the quantification of the tidal effect cannot be obtained (at least not yet) from the measurements of Earth's rotation (section II.1), it is possible that its consequences on the variation of the semi-major axis are at least one order of magnitude lower than has been considered. Contrarily to the tidal effect, the dilation model predicts a value for the increase of the Earth-Moon's distance, and the predicted value is not in conflict with measurements. This result allows us to proceed to the next test of orbits' expansion, the existence of large bodies of water in Mars until 3.8 Ga; for this test it is necessary to determine the planets' irradiance.

IV. Irradiance of planets considering orbits' expansion

The irradiance of a planet (defined as the power per unit area of solar radiation at the annual mean planet distance to the Sun) depends (mainly) on orbital radius and solar luminosity. Solar luminosity is calculated by the standard solar model (SSM), which is valid in the dilation model (in standard units). Since all calculations here are made in standard units, the *A* suffix used in the dilation model to identify these units is omitted.

From Eq. (AII.3), the irradiance $B(t)$ of a planet is given by

$$B(t) = B_0 L_{Sun}(t)\cdot\left(1+H_0 t\right)^{-4}, \qquad (4.1)$$

where $B_0 = B(0)$, and $L_{sun}(t)$ is the Sun's luminosity relative to its present value, i.e., $L_{sun}(0) = 1$ (the present moment is $t = 0$). According to the SSM, the Sun's luminosity was lower during early Earth, but exactly how much lower depends on the values chosen for the model parameters; however, published analyses (e.g. Lebreton & Maeder, 1986, 1987) present similar solutions, which are well fitted by the formula presented by Gough (1981):

$$L_{Sun}(t) = \left(1-\tfrac{2}{5}\cdot t/t_{Sun}\right)^{-1}, \qquad (4.2)$$

where t_{Sun} is the present age of the Sun in standard units; we will consider $t_{Sun} = 4.6$ Gy, as usual. Figure 2 displays the evolution of irradiance considering the expansion of orbits at the rate of $2H_0$. The irradiance curve indicates that the Earth's surface temperature was higher in a distant past and has been declining since. Depending on the value of Hubble's constant and on the real behaviour of the Sun, early Earth might have received as much irradiance as Venus does today. In this case, Earth's future will be what current physics estimates for the past, that is, in a very distant future, when Venus's temperature will converge to Earth's current temperature, Earth will become a snowball.

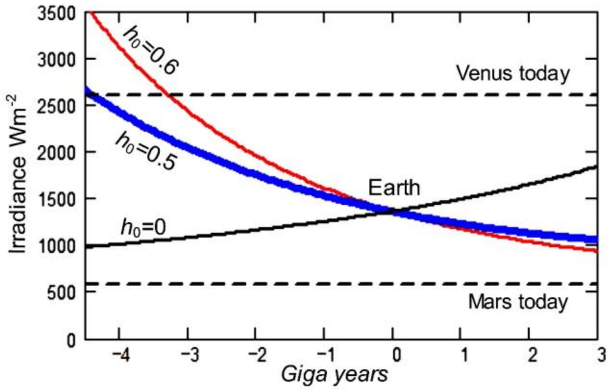

Fig. 2. Earth's irradiance calculated using Cough formula for solar activity and considering orbits' expansion at the rate of $2H_0$, for 3 values of the Hubble constant ($H_0 = 100\ h_0$ km s^{-1} Mpc^{-1}). In case of an invariant orbit ($h_0 = 0$), Earth's irradiance was lower in the past, implying a frozen past at least during most of the time. A value of $h_0 = 0.5$ or higher implies that early Earth's irradiance was higher than the one of Venus today. A past Earth's climate similar to the present one, as it is often assumed, would require a constant irradiance, which is not supported by any theory – the favoured scenario for Earth's past is the least likely.

V. Testing orbits' expansion: Mars water

As mentioned in section II.2, observations suggest that large bodies of water may have existed on Mars until around 3.8 Ga, when temperature should have been too low to support water at surface. Something had to be different at that time and a possibility is a greater irradiance than today. The question to address is: what is the required irradiance to support liquid water on Mars surface? To simplify the analysis, we will disregard both the eccentricity of Mars's orbit and the axial tilt of the planet.

The minimum condition to hold water in the liquid state is that the mean surface water temperature at the low latitude zone is 273 ºK; modelling this zone as a cylinder, considering no atmosphere, from the Stefan-Boltzmann law the surface temperature θ is:

$$\theta = \left(\frac{1-a}{e\sigma} \frac{B}{\pi} \right)^{1/4}, \tag{5.1}$$

where B is the irradiance, σ is the Stefan-Boltzmann constant, a is the albedo of water and e its emissivity (at this stage, the influence of atmosphere is not considered). The albedo of oceans varies with the incidence angle, being 3% at vertical incidence and around 10% at 70º (Jin et al., 2004); from these values, the mean albedo for the equatorial zone is around 5%. The emissivity of oceans is around 0.98 (Newman el al., 2005). Considering these values, from Eq. (5.1) the irradiance B_{273} required for an equatorial temperature of 273 ºK, neglecting the atmospheric influence, is:

$$B_{273} = 1.02 \times 10^{3}\,\mathrm{Wm}^{-2}. \tag{5.2}$$

One must now account for the secondary phenomena that influence the occurrence of liquid water. The two major ones are opposite. They are the greenhouse effect of the Martian atmosphere and the cooling of surface water by evaporation. In Appendix III a simple evaluation of the magnitude of these adjustments is made, which concludes that the overall contribution is close to zero; the error margins of this evaluation and of the dating of the moment of the last water on Mars surface are also estimated. Considering all this, the calculated value for the Hubble constant implied by the evidences of water on Mars is $H_0 = 48.5 \pm 3.5$ km s^{-1} Mpc^{-1}, as presented in Fig. 3.

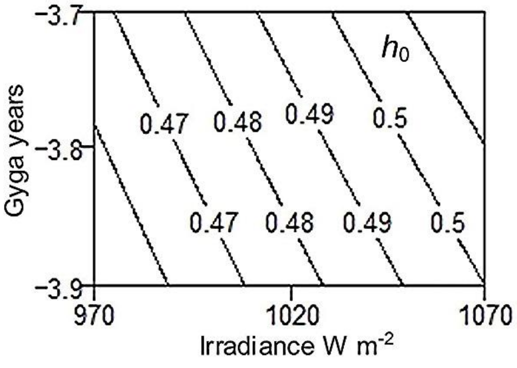

Fig. 3. The range of minimum H_0 values required for the occurrence of oceans in Mars until 3.8 ± 1 Ga. The irradiance that produces a 0 ºC surface temperature in the equatorial zone of Mars is calculated (see text) as 1020 ± 50 W m^{-2}; considering that the last appearance of liquid water in Mars was between 3.9 and 3.7 Ga, then $H_0 = 48.5 \pm 3.5$ km s^{-1} Mpc^{-1}.

This calculation has some limitations: the error margin of the moment when liquid water disappeared from Mars surface might be greater than here considered, the consequences of the orbit's eccentricity and of the axial tilt are not analysed, there is also an error margin associated with the values of albedo and emissivity, and Mars presumptive oceans and water flows were not confined to the equatorial zone. However, none of them changes the nature of the conclusion and, as there are contradictory effects, to consider them all can have very little influence on the value of H_0.

The fact that the same value of H_0 is obtained here and in section III for Moon receding is a coincidence, because it depends on data (mainly the moment of the last liquid water on Mars) and on theory (SSM and Cough formula) with unknown error margins. However, it does show that there is no conflict between the expansion of orbits and Mars data. Furthermore, as Fig. 3 shows, this value of H_0 strongly depends on the irradiance, which enhances the significance of this coincidence.

So, it is verified that the predicted expansion of orbits does not conflict with Moon's orbit and that it is able to explain Mars past water, which has no plausible explanation from current physics. The same value of H_0 was obtained in the two cases, which further supports the possibility that orbits expand as predicted by the dilation model.

Therefore, with no evidence against it from planetary ephemerides (section I), Moon's orbit (section II), Mars past climate (section IV), nor even from physical laws (Appendix I), we can now consider that orbits expand as predicted by the dilation model as a working hypothesis for the analysis of Earth's past climate.

To deal with a hot climate, a new concept, here called state temperature, is required and will be presented in the next section.

VI. State temperature

A higher sea surface temperature implies more water vapour in the atmosphere; this, in turn, raises atmospheric pressure and elevates the boiling point of water. Earth is a kind of pressure cooker: whichever the surface temperature, seawater will never boil because the pressure of water vapour prevents it. Given the amount of existing water, liquid water will simply enter the supercritical state when temperature exceeds 374 ºC, without ever boiling. The analyses of past data are based on formulas that were established with the present atmospheric pressure, but the past Earth had a much higher atmospheric pressure. How to apply those formulas in the past Earth's conditions?

Rather than the absolute value of the temperature as currently defined (whatever the units), what is relevant for the kind of phenomena under analysis is the quantification of the state of the substance. Water is in the liquid state between the freezing and the boiling points. The boiling point represents the same state whichever the pressure/temperature, and so it must be quantified by the same value; and the same reasoning applies to the freezing point. A simple way to quantify the liquid state is to generalize the original definition of Celsius temperature to any pressure; this quantification of the liquid state is here named **State Temperature**, represented by θ_S and defined as:

$$\theta_S = \frac{\theta-\theta_{freeze}}{\theta_{boil}-\theta_{freeze}}\times 100\% \cdot \qquad (6.1)$$

Differently from the definition of Celsius temperature, in the above definition the boiling and freezing temperatures are the ones at the pressure of the environment. The state temperature of water, given that $\theta_{\text{freeze}} \approx 0$ ºC whichever the pressure, is:

$$\theta_S \approx \frac{\theta}{\theta_{boil}}\times 100\% \quad \left(\text{for water; } \theta \text{ in } {}^{\circ}\text{C}\right)\cdot \qquad (6.2)$$

The state temperature is a quantification of the liquid state only. In this work, this concept is used mainly in the biological domain, applied to the cytoplasm; its properties are not exactly those of pure water but to account for the differences would complicate this analysis without significant improvements. So, the properties of pure water are the ones considered to calculate state temperature.

At the bottom of the oceans there are higher pressures than the critical pressure of pure water. No boiling occurs under such pressures but, as shown in Fig. 4, there is a fast change of density close to the critical point, a kind of “soft boiling”. Since the pressures considered in this analysis do not much exceed the critical pressure, the critical temperature is here used as the boiling temperature to calculate the state temperature at the deep seabed. This may be questionable, but the error margin of this simplification seems to be within the error margin of the considered data.

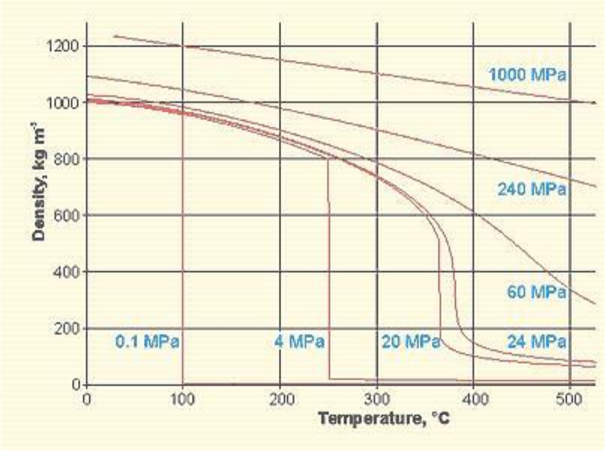

Fig. 4. Water density variation. This graphic from Chaplin M. (2014) shows that water density varies significantly at water critical temperature, even without an abrupt phase change. The estimated Earth’s surface pressure due to water is 26.6 MPa, therefore within the range of fast change of density around the critical temperature. This variation of density is the key to understand why the sedimentary rocks were formed after the temperature dropped below the critical temperature but not before.

This concept is decisive to understand the meaning of isotopic and biologic data. Yet, it requires experimental validation and there is none. Even if the concept is intrinsically valid, its formula may be more complex than here considered. However, the formula does not conflict with current knowledge, because at present Earth surface conditions there is no difference between θ and θ_S, and it leads to a consistent interpretation of δ^{18}O data, as shown in section X.

One shall note that there are other properties of water that depend on absolute temperature but not on pressure, namely viscosity; however, they seem to affect mainly the velocity of phenomena and not their nature.

VII. An empirical model of a hot past Earth’s climate

This work considers the hot past climate defined by the straightforward interpretation of the most important and consistent evidences. Note that this does not mean that some cold periods did not occur, but rather that they were due to sporadic phenomena not considered in the model, like sudden and strong fluctuations of solar activity.

The driving force of climate in this model is just the irradiance; because irradiance varies smoothly with time, so shall the temperature and we can expect that three or four points are enough to define the temperature curve for this empirical model. That temperature is not the mean global temperature but the equatorial one, because this is the one that can be simply related with irradiance, as in the case of Mars (section V).

The first point of the temperature curve is the current average equatorial temperature. Figure 5 displays the long term average oceans’ temperature in the tropical zone. What is relevant here is the maximum temperature in areas of significant size because lower temperatures reflect the influence of higher latitudes. It is apparent from the figure that a temperature of 29 ºC (302 ºK) can be adopted as the temperature corresponding to the effects of the present irradiance in the equatorial zone (one could discuss whether a value of 28 ºC or 30 ºC would be better but that is not important at this stage).

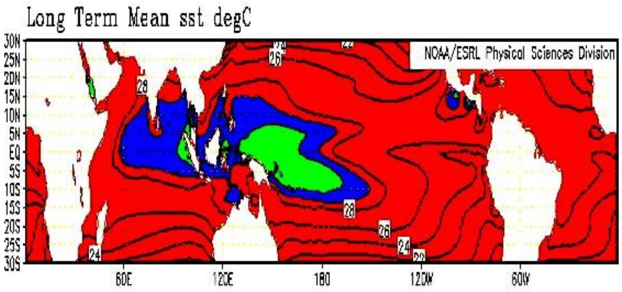

Fig. 5. Long term mean sea surface temperature 1971-2000. Blue above 28.5 ºC and green above 29 ºC. Maximum temperature is 29.48 ºC. Graphic from NOAA (proportions and colours processed for better readability) obtained from: http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html

There is a moment in the Earth' past that allows a good definition of its temperature: the moment when Earth cooled enough so that oceans began forming. Before that, if the amount of water was the same as at present (1.386×10^9 km^3; Shiklomanov, 1993), the pressure of the steam atmosphere was 26.6 MPa (266 bar, 263 atm) plus the pressure of other gases besides water vapour (Zahnle et al., 1988, estimated a pressure of around 270 bar), therefore above the water critical pressure of 22 MPa. Water was in supercritical state near the surface. The amount of water has varied, by addition and by loss, but the excess of about 20% seems large enough to compensate that variation and so one can consider that the pressure at the surface was above water critical pressure prior to the formation of oceans. The scenario was complex at this early phase but the important point is that liquid water appeared on Earth's surface, at a global scale, when the surface temperature dropped below the water critical temperature of 374 ºC, due to the high atmospheric pressure. To find out when this happened, one has to look for the oldest evidences of liquid water. One trace of liquid water is sedimentary rocks. Although water does not undergo a change of state at the critical temperature as it does at the freezing and boiling points, it still undergoes a fast variation of density (at the pressure that is being considered), as shown in Fig. 4, and the low density of supercritical water is possibly not enough to produce sedimentary rocks. In section XIII.1 an additional possible reason for the absence of sedimentary rocks when temperature was above 374 ºC is presented.

The oldest sedimentary rocks that are supported by some evidences date from around 3.825 Ga [found in Inukjuak[4] and Akilia (Manning et al., 2006)], following the >3.75 Gyr old evidences of a sea-floor in Isua, Greenland (Appel et al., 2001), which remains the most solid evidence of first oceans. The discovery of even older zircons provides some support to the idea that liquid water might have existed much earlier (e.g. Wilde et al., 2001; Nutman et al., 1997), and the δ^{18}O values of zircons may support the interpretation that temperature was already under 200 ºC as early as 4.4 Ga (Valley et al., 2002). However, it is unclear whether zircons could have been created in a supercritical water environment; on the other hand, salt water lakes should have existed before the beginning of global formation of oceans because salinity significantly increases the critical point of water – water with modern ocean salinity (3.2wt% NaCl solution) has a critical point of 298.5 bar and 407 ºC (Bischoff & Rosenbauer, 1988). Therefore, the existence of very old zircons is not unexpected and, as the number of samples is small and the dispersion of δ^{18}O values is large enough, different interpretations of the temperature at which they formed can be made, besides other considerations. The properties of old zircons can support a low temperature for early Earth but, so far, cannot rule out the hot scenario.

All this considered, it seems plausible that oceans began forming, i.e., that Earth's temperature dropped below 374 ºC, at least at 3.8 Ga but possibly not earlier than 3.9 Ga. Representing that moment by t_w, then $-3.9 < t_w < -3.8$ (t_w in Gy).

Having defined the extreme points of the temperature curve, we must now investigate the middle age of the Earth. The analyses of isotopes, either of δ^{18}O (Knauth & Epstein, 1976) or of δ^{30}Si (Robert & Chaussidon, 2006) indicate a sea temperature above 65 ºC, eventually close to 90 ºC, earlier than 2 Ga; a similar result is obtained from resurrected proteins (Gaucher & al., 2008). A particularly detailed analysis of available isotopic data is the one by Jaffrés et al. (2007); their conversion of mean carbonate δ^{18}O data to temperature shows a nearly linear increase in temperature toward the past, attaining 100 ºC at around 3 Ga. This and other estimates of paleotemperatures displayed in fig. 2 of the above cited paper are not considered plausible by its authors, who therefore develop a reinterpretation of isotopic data considering that they indicate a variation of seawater δ^{18}O and not a variation of temperature. All those analyses obtained temperatures that decrease rather steadily until present time, indicating that Earth did not cool quickly, but slowly. However, the results of those and other analyses are obtained from formulas and experiments made at present atmospheric pressure, with a boiling temperature of water of 100 ºC, which was not the case of past Earth. To deal with the increased pressure, the concept of state temperature defined in section VI is required.

Considering now the concept of state temperature, the conclusion from the above mentioned analyses is that the Celsius temperature at 2 Ga and before was between 65% and 90% of the boiling point of water (at the pressure at which the analysed samples were produced). Although apparently different, these two values may represent the same surface temperature because the state temperature decreases with depth (due to the increase of pressure), and can therefore result from different depths for the same sea surface temperature. As such, the portrayed situation is a sea surface temperature not lower than 90% of the water boiling point; as the atmospheric pressure was then much higher than today, the correspondent Celsius temperature of sea surface was above 100 ºC.

A different confirmation of the above understanding comes from the oldest life forms still living, which belong to the Archae. Most are thermophiles or hyperthermophiles and the temperatures they are able to withstand seem to be higher the older they are in evolutionary terms (e.g. Stetter, 2008). The first branches of the universal phylogenetic tree are hyperthermophiles (Stetter, 1994) and, according to Kandler (1994), the evidences point to a chemolithoautotrophic origin of life in an environment at about 100 ºC. All these evidences support the understanding that Earth's temperature during its first half age could have been close to the boiling point of water (a state temperature close to 100%) and we must consider it, rather than disregard it based on plausibility arguments. So, for the middle age of the Earth, the mentioned evidences consistently suggest a state temperature of not less than 90% at 2 Ga.

Another documented period is Cretaceous. Plenty of evidences indicate that mean temperature during Cretaceous was significantly higher – more than 10 ºC –

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[4] http://www.uqam.ca/nouvelles/2002/02-137.htm

than today (for a review, see e.g. Deconto et al., 2000), and greenhouse models have been used in attempts to explain what has been considered to be just a warm period. In our scenario, higher temperatures in the past are not the exception requiring abnormal conditions but, on the contrary, they are characteristic of the normal past climate; cold periods are the ones requiring a specific cause. The literature concerning the last 100 million years fairly consistently indicates an increasing mean sea temperature towards the past. The temperature reconstruction presented by Crowley & King, 1995 based on deep-sea benthic $\delta^{18}O$ records (Douglas & Woodruff, 1981; Miller et al., 1987) displays a trend of –7 ºC over the last 100 million years (-0.7×10^{-7} ºK yr^{-1}). The data supporting this trend is from several latitudes and depths, but whereas present water temperature decreases with depth and latitude, past warmer seawater depended less on these two factors because thermal amplitudes were lower due to the higher amount of water vapour in the atmosphere – at the epoch of the dinosaurs, the difference between polar and equatorial temperature was much smaller than today. So, the equatorial temperature decreased much less than the global one, which influenced the above data. This means that the value of the equatorial temperature trend has to be closer to zero than the above value.

Therefore, for an empirical model of Earth's equatorial surface temperature $\theta(t)$, the following conditions are defined (time in Gyr):

1) the function shall be steadily decreasing;

2) oceans began at 3.9-3.8 Ga
[i.e., $-3.9 < t_w < -3.8$ with $\theta(t_w) = 374$ ºC];

3) $\theta_S(-2) \geq 90\%$;

4) $0 > (d\theta_S/dt)_0 > -0.7\times10^{-7}$ ºK yr^{-1};

5) $\theta(0) = 29$ ºC.

The above conditions clearly rule out any possible explanation for past climate other than the expansion of the orbit (considering only known phenomena). The next step is to establish a theoretical model considering the expansion of Earth's orbit predicted by the dilation model and then see how it fits these conditions. A difficult obstacle emerges: estimating the greenhouse effect.

VIII. The greenhouse effect

Earth's surface temperature depends on Earth's irradiance and on the atmospheric greenhouse effect. The former was calculated in section IV, so we must now estimate Earth's greenhouse effect over the last 4 Gy.

The greenhouse effect is a complex phenomenon; however, an unexpectedly simple solution is here presented. This solution arises from considering that *the greenhouse effect is largely independent of the size and composition of an atmosphere able to support a stratum of clouds with a thickness dependent on temperature*. In other words, when there are enough clouds, their effect overrules the effect of greenhouse gases.

The above is established as a working hypothesis to investigate the relationship between surface temperature and irradiance, i.e., the function $\theta(B)$. The validity of the solution thus found is discussed at the end of this section; the test of the climate model obtained considering this solution also tests it.

What is known about the function $\theta(B)$ is its current value in Earth and in Venus, and some estimates of the irradiance sensitivity factor, $\gamma = d\theta/dB$, under present Earth conditions. There are several published analyses of climate sensitivity, but most are concerned with greenhouse gases; focused on the irradiance, is relevant the analysis of Shaviv (2005). Using data relative to periods from the last 550 million years, Shaviv obtains values of $\gamma = 0.35 \pm 0.09\,^{\circ}\mathrm{K\,W^{-1}m^{-2}}$ and $\gamma = 0.54 \pm 0.12\,^{\circ}\mathrm{K\,W^{-1}m^{-2}}$, depending on the inclusion or exclusion of the influence of the variation of the cosmic rays flux.

Shaviv's analysis concerns the irradiance over the last 550 million years but we need to estimate the sensitivity factor for the quite different early Earth's irradiance; how does the irradiance sensitivity vary with irradiance? In his calculation considering the cosmic rays flux, Shaviv concluded that the dependence of irradiance sensitivity on irradiance and temperature was undetectable, but one cannot assume the validity of this conclusion for the much different early Earth irradiance. We need a bridge between present and past values of Earth's irradiance. Fortunately, present Venus' irradiance is similar to the one of early Earth, which allows the analysis below.

According to NASA fact sheets, Earth's irradiance is 1367.6 W m^{-2}, the one of Venus is 2613.9 W m^{-2}, and Venus mean surface temperature is 464 ºC. For Earth, the equatorial mean surface temperature here considered is 29 ºC. So, the mean γ between Venus and equatorial Earth (the ratio between temperature difference and irradiance difference) is: $\bar{\gamma} = 0.35\,^{\circ}\mathrm{K\,W^{-1}m^{-2}}$. Why use equatorial temperature and not mean global temperature? The reason is that at high latitudes there is not enough water vapour in the atmosphere to support cloud regulation (the working hypothesis is that the greenhouse effect is ruled by clouds). The atmospheric system needs a minimum energy to operate efficiently; with lower irradiance, it has greater irradiance sensitivity (the transition between greenhouse effect and no effect). Therefore, it is expectable that the irradiance sensitivity of Earth's equator is lower than today's global Earth value.

The above result of $\bar{\gamma} = 0.35\,^{\circ}\mathrm{K\,W^{-1}m^{-2}}$, equal to the lowest value considered by Shaviv, is roughly what one could expect for Earth's equator. So, today's mean value of the irradiance sensitivity between Venus and Earth may be close to the value for Earth's equator today. This supports the hypothesis that γ may hold fairly independent of the atmosphere and of the irradiance (unless the above result is a coincidence), or that the different sizes of the atmospheres of Earth and Venus compensate for their different compositions (which is a coincidence). Although this latter case implies that the irradiance sensitivity of early Earth could be different from the value now obtained, as the variation of the composition of Earth's atmosphere is largely due to the variation of water vapour, which in turn is a function of the temperature and, so, of the irradiance, then Earth's irradiance sensitivity shall appear as a monotonic function of irradiance. Therefore, Earth's average irradiance sensitivity shall be either a constant, characteristic of all atmospheric systems with clouds, or a monotonic function of irradiance, specific of Earth's atmosphere.

The possibility that the greenhouse effect is ruled by clouds and is fairly independent of the greenhouse properties of gases seems to be at odds with present theories on greenhouse effect but it is not so. This result applies only to an atmosphere with enough clouds, which in present Earth only exists around the equator; at higher latitudes, with poor or irregular cloud coverage, the influence of greenhouse gases is no longer overruled by the cloud system. The greenhouse effect of greenhouse gases is not in doubt; the matter is that, according to the working hypothesis, a large enough cloud system overrules the greenhouse effect of gases. Clouds are the difficult issue of GCMs (General Circulation Models), differently taken into account in different models (see, e.g., Soden & Held, 2006). One must also note that GCMs predictions are supposed to meet IPCC criteria for selecting climate scenarios, and Criterion 1 is that they should be consistent with global warming projections based on the increasing concentrations of greenhouse gases[5], i.e., the predicted temperature increase due to the increase of greenhouse gases is not a necessary result of those models but a result defined a priori, constraining the role of clouds in those models.

Another aspect worth noting is the following: the independence of the greenhouse effect from the average atmospheric composition (as long as there is an operational cloud system) does not imply its independence from the variation of atmospheric composition. Namely, the amount of CO_2 may be fairly irrelevant for the greenhouse effect (when a cloud system is operating) but its variation may disturb the equilibrium of the system, producing first an increase of temperature (in case of an increase of CO_2 amount) and then a delayed cloud response, which will lead to a decrease in temperature. At small time scales, fast variations of the composition of the atmosphere and of the solar activity will drive delayed responses of the cloud system. In this case, the global temperature can depend more on the rate of variation of CO_2 than on its amount.

In short, an estimate of the mean irradiance sensitivity within the whole range of Earth's irradiance is the present mean value Earth-Venus; the fact that this value is close to what is expected for present Earth's equator supports the hypothesis that irradiance sensitivity may be fairly independent of atmosphere size and composition. Even if the above result were just a coincidence, one would expect it not to be dramatically different, just a slow varying function of the irradiance instead of a constant. One must also note that the above result is fairly in agreement with the fact that the climatic consequences of the present increase of CO_2 are not as predicted by the end of the 20th century.

IX. A climate model considering orbits' expansion: the Evolving Climate Model (ECM)

Considering an equatorial irradiance sensitivity that is constant or that can be expressed as a function of irradiance, Earth's equator temperature is given by:

$$\theta(t) = \theta_0 + \int_{B_0}^{B(t)} \gamma\left(B\right) dB \qquad (9.1)$$

where θ_0 is the current equator's temperature. As $\gamma(B)$ is a monotonic function of B, this temperature curve defines a climate model displaying an ever-evolving climate for Earth, driven by its expanding orbit and the variable solar activity; this model is here named Evolving Climate Model (ECM). The ECM temperature must satisfy the conditions defined for the empirical model, which constrains γ and B.

One way to analyse the model is to define first a simple configuration of its parameters, then analyse how this particular solution matches known evidences and to look for new evidences; this first analysis allows a subsequent refinement of the parameters.

In the next section a first solution of the ECM is proposed and named ECM1.

X. The ECM1

Calculating $B(t)$ using the Cough formula and considering orbits' expansion [Eq. (4.1) and Eq. (4.2)], the Eq. (9.1) becomes a function of irradiance sensitivity and of H_0. Now, considering that the irradiance sensitivity is constant for the reasons presented in section VIII, $\gamma = 0.35\ ^{o}\mathrm{K\ W^{-1}\ m^{-2}}$, then Eq. (9.1) depends on only one parameter, H_0. The temperature given by this equation must comply with the conditions of the empirical model (section VII). The condition that allows the clearest definition of H_0 is condition (2), the moment when oceans began, t_w; for the defined interval of t_w, $H_0 = 47.7 \pm 0.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. For a first configuration, it is adequate that we take the central value, $H_0 = 47.7\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.

The temperature function for this configuration, θ_{ECM1}, defined by Eq. (9.1), is (t in Gy):

$$\theta_{ECM1}(t) = 29 + 478.66\left[\left(1 - 0.4\frac{t}{4.6}\right)^{-1}\left(1 + 0.0487t\right)^{-4} - 1\right] \qquad (10.1)$$

The temperature curve of the ECM1 is displayed in Fig. 6.

From the temperature function, considering that Earth's initial liquid-gas system (after the formation of the initial crust) had the same atoms as today's liquid-gas system, one can compute the evolution of the oceans and of the atmospheric pressure at the surface. The results are presented in Fig. 7. For this calculation, the amount of carbon dioxide that existed in the atmosphere was not considered because it is only coarsely estimated and it decreased significantly during the first 2 Gy. The effects of salinity on the properties of water were not considered. The atmospheric pressure of the ECM1 is presented in Table 1.

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[5] http://www.ipcc-data.org/guidelines/pages/scen_selection.html

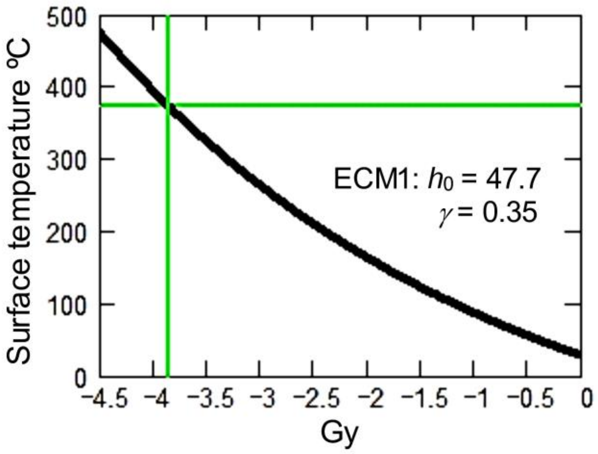

Fig. 6. Earth equatorial surface temperature according to the ECM1 ($H_0 = 47.7$ km s^{-1} Mpc^{-1}, $\gamma = 0.35$ ºK W^{-1} m^{-2}). This curve verifies the conditions imposed by data that trace a hot/warm past climate. The green lines identify the moment when the critical temperature of water was reached.

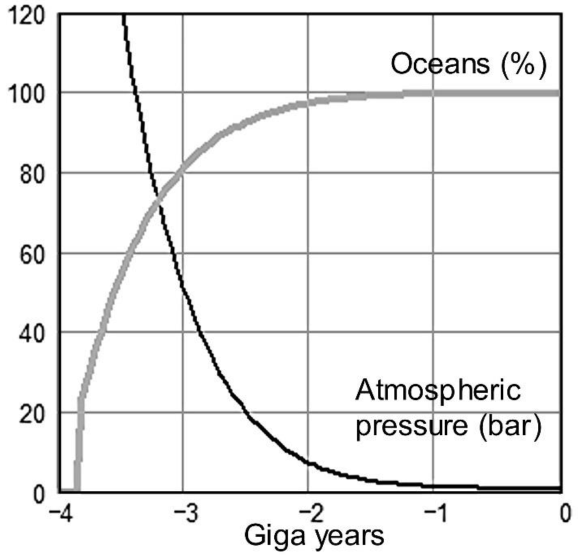

Fig. 7. The evolution of oceans and of atmospheric pressure in the ECM1.

Time (Ga)	0	1	2	3	3.85	4
Temp. (ºC)	29	88	165	265	374	396
Press. (bar)	1.0	1.5	7.6	51.5	221	----

Table 1. ECM1: the temperature and pressure at the surface of the oceans considering that oceans began at 3.85 Ga, for $H_0 = 47.7$ km s^{-1} Mpc^{-1} and $\gamma = 0.35^{\circ}\mathrm{K\,W^{-1}m^{-2}}$. The pressure at the Earth's surface prior to the formation of the oceans is 266 bar.

We now need to verify how the ECM1 meets the other conditions of the empirical model. The ECM1 temperature 100 million years ago is $\theta_{ECM1}(-0.1) = 34.2$ ºC, which adequately satisfies condition (4); the temperature at 2 Ga, $\theta_{ECM1}(-2) = 165$ ºC, corresponds to almost 98% of the boiling temperature of pure water at the pressure of water vapour plus the pressure of present dry air (i.e., a state temperature of 98%). This seems too high in relation to the established in condition (3); however, a pressure increase of 3 bar reduces this state temperature to 90%, which can be explained considering that the data are from some 30 meters below the surface; above all, there is a considerable error margin on the value of 90%. Therefore, the difference between condition (3) and the ECM1 is less relevant than its correspondence and does not question the model.

The conclusion is that the ECM1 roughly satisfies the conditions of the empirical model for a value of H_0 that is close to the values obtained for Moon receding and Mars past climate.

The ECM (for whichever values of the parameters) defines a very special scenario for early Earth. As the initial atmosphere certainly had a relevant amount of carbon atoms, there was a mix of H, N, O and C atoms forming several compounds and submitted to high pressure and temperature – a giant chemical reactor with several substances in supercritical state, slowly evolving. During the first hundreds of millions of years (until 3.85 Ga in the ECM1) the scenario was dominated by the presence of supercritical water, of compounds of H, C, N and O, combined with elements of the crust, namely metals. Even after the appearance of oceans, many substances remained in supercritical state, namely carbon dioxide (further 600 million years, until pressure dropped below 74 bar); this is particularly relevant because supercritical carbon dioxide has important properties for a number of geological and chemical phenomena. Many other substances were in supercritical state and until around 3 Ga, about one third of Earth's age, the atmosphere at the surface, with a temperature over 250 ºC and a pressure over 50 bar, was a huge chemical reactor with complex properties.

XI. The correspondence between predicted and measured values of δ^{18}O

Data on the oxygen isotope 18 show a decrease toward the past; it is known that a decrease of this isotope is associated with an increase of temperature. A detailed analysis of these data is made in Jaffrés et al. (2007), a paper used as a reference for the present analysis. The formula used therein to relate the paleotemperature with the oxygen isotope composition is:

$$\theta\left(^{\circ}C\right)=16.9-4.38\left(\delta_C-\delta_W\right)+0.1\left(\delta_C-\delta_W\right)^2, \tag{11.1}$$

where δ_c and δ_W are the isotope composition of calcite (relative to the Pee Dee Belemnite standard, or PDB) and of seawater (relative to Standard Mean Ocean Water, or SMOW) (cf. Shackleton & Kennet, 1975). This and other formulas relating the oxygen isotope with temperature were established from biotic data but that relationship is not independent of the isotope source (the isotope values of abiotic are different from those of biotic sources, and even between different biotic sources). In the cited work of Jaffrés et al., the abiotic data are increased by +2‰ because the authors considered that there is an average difference of 2-3‰ between the biotic and abiotic data they used.

The purpose here is not to estimate the temperature from the isotope data but rather the opposite: to verify whether the δ^{18}O composition of calcite calculated from the ECM1 temperature fits the data. First, we need to express δ^{18}O as a function of temperature. For the reasons previously presented, the temperature is the state temperature instead of the Celsius one. Making $\Delta\delta_C(t)=\delta_C(t)-\delta_W(t)$, then, from Eq. (11.1),

$$\Delta\delta_C(t)=5\left(4.38-\sqrt{4.38^2+0.4\left(\theta_S(t)-16.9\right)}\right). \qquad (11.2)$$

The ECM1 temperature is relative to the sea surface at the equator, while the calcite data is from a wide range of latitudes; Eq. (11.1) is adjusted to the global average sea surface temperature of 16.9 ºC and adequate to analyse data from all latitudes. For a prediction of the ECM1 to compare this data with, we need the global average sea surface temperature in the ECM1 scenario (θ_{G1}) and not the equatorial one. The simplest way to obtain the global temperature from the equatorial one is to linearly decrease the equatorial temperature to 16.9 ºC, starting at 500 million years ago (as shown in Fig. 10), which is roughly when the dependence of temperature on latitude began to be relevant (t in Gy):

$$\theta_{G1}(t)=\theta_{ECM1}(t)-(24.2t+12.1)\times(t<-0.5). \qquad (11.3)$$

The state temperature depends on depth; the formula used to calculate it is the following:

$$\theta_{W1}(t)=\frac{\theta_{G1}(t)}{\theta_{boil}\left(P_{ECM1}(t)+0.1d_W\right)}\times 100\%, \qquad (11.4)$$

where $\theta_{boil}(P_{ECM1}, d_W)$ is the boiling temperature of water at time t, when the atmospheric pressure was $P_{ECM1}(t)$, and at the depth d_W; the pressure is in bar and the coefficient 0.1 bar/m is the conversion factor for depth (m) to pressure (bar).

As the state temperature depends on depth, so does the value of δ^{18}O. Under present Earth conditions, δ^{18}O is known to vary with depth because water temperature varies with depth, but when the temperature was higher and uniform in most of the Earth, water temperature should have been rather uniform regardless of depth – that is why in Eq. (11.4) the Celsius temperature at depth d_W is the one of the surface, θ_{G1}; however, due to the dependence of state temperature on pressure, δ^{18}O data would also depend on depth. Therefore, data from near the surface, such as planktonic foraminifera or brachiopod data, differ from the bottom of the oceans, namely abiotic data (bulk rock calcite, dolomite). The extreme situations are the water surface, where the boiling temperature depends only on the atmospheric pressure, and the deep bottom of oceans, where the pressure is above the pressure of water's critical point; in this case we consider that the temperature of phase change is 374 ºC, as mentioned in section VI.

Fig. 8a shows how the δ^{18}O data compiled by Jaffrés et al. (2007) matches the near surface (10 m depth) curve and the deep bottom curve of the δ^{18}O values calculated by Eqs. (11.2), (11.3) and (11.4). The straightforward interpretation of the result is that brachiopod data, which dominated over the last 500 million years, are mainly from shallow waters, while rock calcite, mostly older than 500 million years, is from the bottom of oceans.

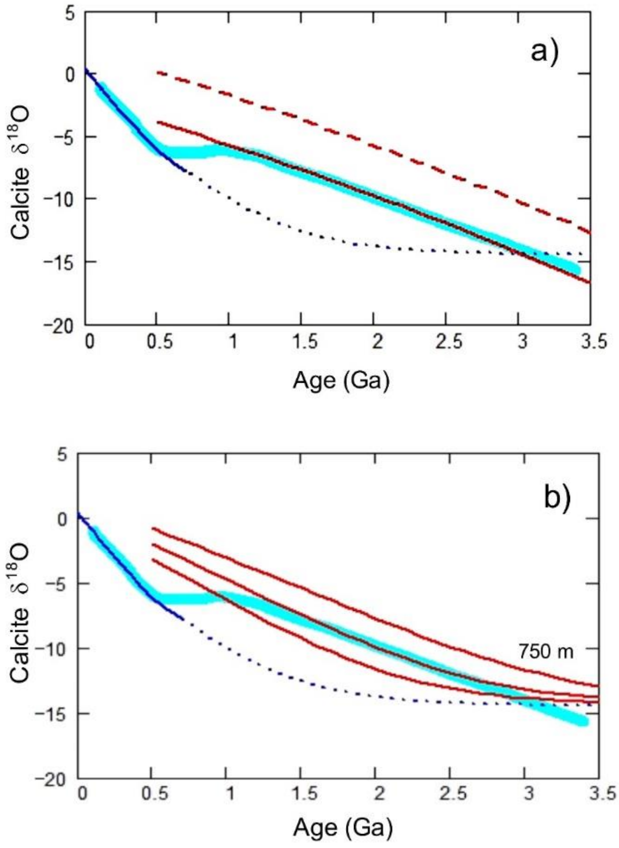

Fig. 8. Fitting Jaffrés et al. (2007) curve (Jaffrés curve) for mean values of bulk rock calcite and brachiopod δ^{18}O data - the thick cyan curve. The Jaffrés curve is from the fig. 9b of the cited paper. An important characteristic of the data is that the recent ones, until 0.5 Ga, are mainly biotic, while data older than 1 Gy is abiotic (bulk rock calcite); Jaffrés curve displays three distinct behaviours, tracing the dominance of each kind of data and the transition zone, where they are mixed. Blue and red lines are the ECM1 curves for biotic δ^{18}O at different depths. **a)** Top dashed red line is the ECM1 curve for the bottom of the oceans; the red solid line is this curve shifted by −4 ‰. The blue solid/dotted line is the ECM1 curve for 10 m depth. The biotic data is fitted by the blue ECM1 line and the abiotic data by the red one. **b)** An alternative explanation: the abiotic data is from several depths and the curve of Jaffrés represents their average; in the figure, the ECM1 curves for 750 m (top), 250 m and 100 m depth.

The curve of δ^{18}O is the one from fig. 9.b) of Jaffrés et al. (2007), where the abiotic data are shifted upward by +2‰; the fitting of the ECM1 biotic curve for the bottom of oceans with the abiotic data required a downward shift of –4‰, which suggests that the difference between bulk rock calcite and brachiopod δ^{18}O data at the same state temperature is –6‰.

Instead of considering that the abiotic data is from the deep bottom of oceans, one can consider that it is from different depths. Fig. 8b displays the curves for different depths, which can also fit δ^{18}O data considering the error margin of the data and of the calculation.

The analysis of Jaffrés et al. does not account for the depth at which calcite was originated because it does not use the concept of state temperature; however, it is this concept that allows the matching with the peculiar δ^{18}O curve.

This is just an elementary first analysis; however, given the quality of this fitting and the consistency with all the other results, a different conclusion is not expectable from a more detailed analysis, only a better understanding of the biotic and abiotic processes involved. A similar result is obtained using the formula of Erez & Luz (1983), concerning planktonic foraminifera.

The data interpretation proposed by Jaffrés and co-authors is that the $\delta^{18}O/\delta^{16}O$ ratio of sea water (the value of δ_W) has varied. If that is the case, the precise fitting here obtained is a meaningless coincidence. It is worth mentioning that Gregory (1991) presented evidences supporting an invariant value of δ_W.

XII. Three phenomenological evidences of the ECM

As seen in section X, the ECM defines for Earth a quite different scenario from the usually considered one; naturally, in this different scenario, phenomena occur that cannot happen in other scenarios. One phenomenon specific of the ECM that can be easily quantified is the fast increase of oxygen level in the atmosphere. This gives to this phenomenon a particular relevance as a test of the ECM. Another relevant one is the likely formation of dolomite, which solves the “dolomite problem”, one of the few problems without even a hypothetic solution. There is a third major consequence of the ECM: the fixation of nitrogen in great quantities and in large organic molecules. This section analyses these three phenomena.

XII.1. The Great Oxygenation Event (GOE)

One of the most puzzling events of the past is the significant oxidation of Earth’s surface around 2 Ga (Canfield, 1998), known as the great oxygenation event (GOE). It was first considered that atmospheric oxygen was absent or under 10^{-5} present atmospheric level (PAL) before the GOE, but some evidences of low levels of oxygen have been found at 2.5 Ga (Anbar et al., 2007) and 2.65 Ga (Scott et al., 2008). The picture today is that oxygen levels raised in two main steps, originating five stages in oxygen evolution; for Holland (2006), until 2.45 Ga the level of oxygen was irrelevant; between 1.85 Ga and 0.85 Ga it stayed between 0.02 and 0.04 bar, then raised close to present levels, at 0.54 Ga; during the last stage, it possibly rose to ≅0.3 bar and dropped to present levels.

Figure 9 displays Holland’s minimum and maximum curves of surface oxygen levels and the evolution of oxygen level in the ECM1; the calculation was done using the ideal gas model and a gas-liquid system with constant composition, which is the present amount of water, oxygen and nitrogen. The variation of the relative oxygen level is not due to the variation of the amount of oxygen but to the variation of the amount of water vapour, which decreased to form the oceans.

The correspondence between the calculated curve for the relative oxygen level and data (Holland’s analysis) shows that the GOE may be a consequence of a decreasing size of the atmosphere, due to water vapour condensation. That does not imply that the amount of oxygen has been constant throughout Earth’s history but its explosive increase is no longer required, since the varying size of the atmosphere is considered: observations trace the percentage of oxygen at the surface, and this percentage has varied because the size of the atmosphere has varied enormously.

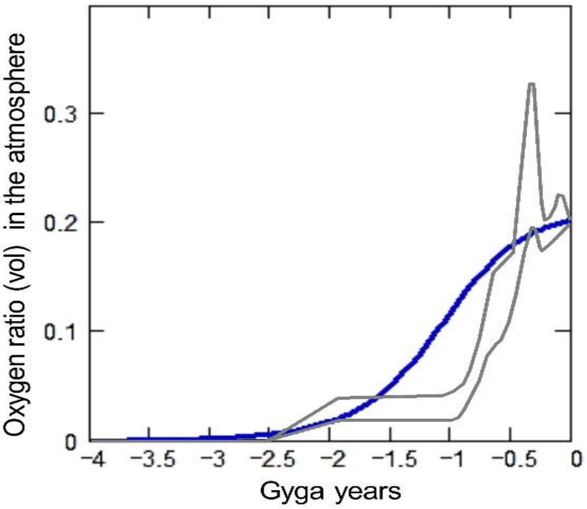

Fig. 9. The variation of Oxygen volumetric ratio in the ECM1 due to the variation of the size of the atmosphere, holding the amount of Oxygen constant (thick blue line). The grey lines represent the limits for the oxygen volumetric ratio (partial pressure in the atmosphere) estimated in Holland (2006).

Very likely, as discussed later in section XIII.3, free atmospheric oxygen was mainly produced in the first gigayears, which means a varying amount during that period. This is not considered in Fig. 9 but it is not relevant because the oxygen level then was extremely low due to the huge amount of water vapour. Note also that in the first 2 Gy the likely presence of an important amount of the heavier CO_2 may have further decreased the oxygen level at the bottom of the atmosphere.

XII.2. The "Dolomite Problem"

Dolomite is a sedimentary rock-forming mineral that can be found in massive beds all over the world. Identified in the 18th century, it has been a mystery for generations of geologists because it no longer forms on the surface of the Earth (only in very particular environments) while other sedimentary rocks form easily. Many theories have been presented but none has proved to be able to achieve massive production of dolomite considering surface conditions (Land, 1998). However, convenient growth of dolomite was obtained in reactors with temperatures above 115 ºC under appropriate pressure in a CO_2 atmosphere (Arvidson & Mackenzie, 1999). The growth velocity increases with temperature. Therefore, what is a mystery in current Earth conditions might have been trivial under past Earth conditions. In this case, the ECM explains how dolomite was formed and why it is no longer produced.

XII.3. The fixation of nitrogen in large organic molecules

There are two known kinds of methods to produce nitrogen compounds: one is by electric arcs or radiation; the other is by submitting an appropriate gas mixture to high pressure and temperature. The first method, used by Miller (1953) in his famous experiment, can produce nitrogen compounds but only in small molecules, as electric arcs or radiation destroy large molecules; furthermore, and despite some theoretical support (Navarro-González et al., 1998), the amount of lightning required for natural production may be a hindrance. The second method is used in common industrial processes for the production of synthetic fertilizers, namely the Haber-Bosch process: H_2 and N_2 are submitted to a pressure between 150 and 250 bar and a temperature between 300 and 550 ºC. These are just the kind of conditions that characterize early ECM atmosphere which, therefore, is an apparently ideal scenario for the production of large amounts of complex nitrogen compounds, namely long organic molecules.

XIII. New explanations for old problems

There are several phenomena to which a variety of explanations have been proposed without reaching a consensus. The reason is that each explanation has advantages but also drawbacks. The ECM provides conditions that were not considered before, allowing new explanations for those phenomena. As an example, new explanations are here presented for the origin of petroleum, proto-continents, oxygen and glaciations. These explanations require proper analysis by experts in those fields and the following is just as a call of attention for the new possibilities brought by the ECM.

XIII.1 Was the first ocean a petroleum ocean?

Earth's early atmosphere was a giant chemical reactor near the surface, where a mixture of atoms was submitted to high pressure and temperature; in this scenario, carbon and hydrogen atoms very likely combined into hydrocarbons. The production of synthetic fuel is made under these kind of conditions, namely by the Fischer-Tropsch process, requiring the mixing of carbon monoxide and hydrogen at high pressure and temperatures close to 340 ºC; or the Bergius process, combining carbon and hydrogen at 400 to 500 ºC and 20 to 70 MPa. Therefore, large amounts of petroleum could have been produced when water was still in supercritical state near the surface. As common varieties of petroleum might have been denser[6] than supercritical water, which, as shown in Fig. 5, has a density lower than 500 kg m^{-3} at the critical point and lower than 200 kg m^{-3} for a temperature above 400 ºC, petroleum layered the surface under supercritical water – the first ocean on Earth could have been a petroleum ocean. On the other hand, as mentioned in section VII, saline water lakes would have existed very soon, so this petroleum ocean was mixed with saline water. This thin petroleum ocean, together with saline water, was injected into the initial ductile crust or beneath it before the global formation of oceans, due to high atmospheric pressure, and can be found today in geological formations able to retain it. In this case, all the petroleum, or most of it, was produced in early Earth.

This may also contribute to explain why sedimentary rocks formed only when surface temperature dropped below 374 ºC: before that moment, petroleum might have covered the surface.

XIII.2. How proto-continents could have formed

During the cooling of a planet since its initial melted state, a crust probably forms that completely covers it. This is what happened in Mercury, Venus and Mars. However, that is not the case of present Earth: instead of a single kind of crust covering the whole planet, there are two: the thick continental crust, or sial, and the thin oceanic crust, or sima. Why is that so? There are theories to explain this phenomenon, but the ECM supports a new one, as follows.

Let us consider that, as observed in other planets, an initial crust covered all the Earth. With decreasing temperature, that crust contracted. This contraction necessarily fractured the crust, great canyons must have appeared, like in Mars (the famous Mars channels) and in Venus. However, early Earth had a relevant difference from those planets: a higher atmospheric pressure, three times (or more) the present Venus one, over 26 MPa. This pressure is close to or above the shear strength of main components of the crust, while in Venus the pressure is slightly below, as can be seen in Table 2. Applied to the long walls of the fractures, over hundreds of millions of years, early atmospheric pressure was able to widen the fractures, wrinkling and shrinking the thin crust. Furthermore, the presence of supercritical water and carbon dioxide lowers the melting point of igneous rocks (Grove at al., 2006; Dasgupta & Hirschmann, 2007) and so, during the first

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[6] For a table of the temperature and pressure dependence of crude oil see http://www.searchanddiscovery.com/documents/2006/06015powley/images/a09.htm

hundreds of millions years and possibly more (the temperature was over 300 ºC and the pressure over 80 bar until 3.3 Ga), the crust was not as stiff as today.

Material	Shear strength (MPa)
Granite	14-50
Diabase	25-60
Basalt	20-60
Slate	15-30
Quartzite	20-60
Sandstone	8-40
Shale	3-30
Limestone	10-50

Table 2. Most materials that form the Earth's crust are unable to withstand pressures over 26 MPa, exerted by the atmosphere on fracture surfaces of the primitive crust; furthermore, under early Earth conditions, rocks were softened by water and gases at high temperature and pressure (data made available by Tieyuan Zhu). This supports the possibility that the primitive crust was split into plates that were then compressed to form thick blocks - the proto-continents.

Some evidences of the process of compression of the initial crust led to or have been associated with theories on contracting or expanding Earth but they support the much simpler explanation presented above: the crust shrank as a consequence of high pressure on the surface of fractures and of other conditions that softened the crust. This process exposed the layer that was under the crust, on one hand, and, on the other hand, the thick crustal blocks thus formed pressed the molten material underneath, originating a variety of phenomena that altered the composition of the crust.

The absence of tectonic plates in Venus is usually explained considering that a thermal runaway caused extreme temperatures that hardened rocks by degassing them. According to the dilation model, Venus actually had past temperatures higher than the present one due to the higher past irradiance – discarding the need for the thermal runaway, which is a hypothetic phenomenon lacking empirical support. The increased irradiance also helps to explain why Venus lost its water, which could have been much less than in Earth from the beginning because in the planetary system the ratio between light and heavy elements increases with the distance to the Sun and so Venus would have had less hydrogen than Earth. Therefore, Venus' conditions were not likely to soften the crust but to harden it and atmospheric pressure was below the shear strengths of crust´s materials.

XIII.3. The origin of free oxygen

As explained in subsec. XII.1, the ECM predicts a very low level of atmospheric oxygen in the first 2 Gy even if its amount was the same as today. Therefore, one can face the problem of the production of the atmospheric free oxygen without the constraint of its atmospheric level.

There are two known natural ways of producing oxygen: by UV dissociation of H_2O and by photosynthesis. In the ECM, the former process was initially much more efficient than at present because of the huge amount of water vapour and of the greater intensity of UV radiation occurring then. The biological production of oxygen would have been important during the Archean, which ended at 2.5 Ga, therefore earlier than the GOE. The usual approach is to consider that the biologically produced oxygen was first combined with dissolved iron in oceans and only significantly released to the atmosphere later – a way to explain the delay between the presumed time of the biological production of oxygen and the rise of its atmospheric level. Here, there is no need to consider a delay – the biologically produced oxygen was dissolved in water and absorbed by the huge atmosphere without significantly changing its composition; the oxygen level increased only when the atmosphere significantly decreased due to the condensation of water vapour.

One can now consider that oxygen was produced in large amounts since the beginning, first from UV dissociation, at a rate that decreased over time, and very soon followed by biological production. In this case, there was an important amount of free oxygen in the atmosphere long before its atmospheric level started to increase significantly; and some potential evidences of it can be identified (for a review see Yamaguchi, 2005).

XIII.4. On Glaciations

It is usually considered that present climate is the normal situation and that past glaciations resulted from some particular phenomenon that disturbed the normal situation. The ECM establishes a new viewpoint.

According to the ECM, the continuous decrease of temperature necessarily leads to an oscillatory increase of the ice extent, i.e., glacial and interglacial periods with glacial periods of increasing length. Equilibrium in active systems is naturally oscillatory, not static. When an active system displays a static equilibrium, one must look for the particular phenomenon that prevents the oscillation, because those systems always have inertial properties that lead to oscillations. So, one must considerer that the alternation of glacial and interglacial periods is the normal situation at the present irradiance. The question is not the occurrence of an oscillation but its amplitude, which depends on the specific phenomena that are responsible for the oscillation. Of course, the mean ice extent and its maximum during glaciations tend to increase as the irradiance decreases due to the expansion of the orbit.

The fact that an oscillatory increase of ice is expectable in the scenario of the ECM does not mean that phenomena external to Earth do not contribute to the process and even trigger it, namely changes in irradiance due to variations of solar output power (other than the one accounted for by the SSM), or due to orbital characteristics or to some unknown phenomenon able to decrease Earth's irradiance.

This oscillatory process can only explain glaciations occurred during the last millions of years; older glaciations, if they really occurred, are necessarily due to a specific phenomenon able to produce a sharp decrease of Earth's irradiance.

XIV. Life and the ECM

The most relevant of Earth events is life, and no climatic model can ignore it. Life is one of the weaknesses of the Snowball Earth. And it is certainly crucial to check the compatibility of the ECM with life because this model defines a climate that greatly contrasts with the one generally assumed as suitable for life. This must be analysed by biologists, but the present work would be incomplete if it did not include at least a rough approach to this issue. Therefore, risking some insufficiency, a preliminary analysis of the compatibility of the ECM with life is presented in this section.

XIV.1. The cradle of life

Science should not aim to explain the origin of life based on some low-probability event that occurred in spite of adverse conditions (although that is not impossible). On the contrary, one should consider that life appeared because there were optimal conditions for it. However, the inadequacy of the current models of Earth's early climate to support the origin of life left no choice but to look for a different and more suitable environment, from the outer space to the submarine hot springs. There are also attempts to show the possibility of life creation in the low temperature scenario (e.g., Bada et al., 1994).

Here, we will try to establish the most basic conditions required to obtain the first molecules needed by life with acceptable probability and then verify if the ECM meets them. Note that there is a huge difference between explaining the origin of life and understanding the conditions required for it to happen, which is what is intended here.

Life requires a minimum specific organization of a considerable number of atoms. The probability of obtaining it from a random distribution is extremely low. However, a DNA molecule is made of a few different basic molecules: the four small compounds of nitrogen known as nucleobases – guanine (G), adenosine (A), thymine (T) and cytosine (C) –, a sugar called deoxyribose and a phosphate group; the nucleobases are associated in two pairs, A-T and C-G, so only two different basic molecules form the DNA, together with the sugar and the phosphate group. Now, the probability of obtaining some DNA molecule in an environment where its basic molecules are available is many orders of magnitude higher than the probability of obtaining it from random combinations of atoms. Therefore, life requires an environment where those molecules can be produced in huge quantities, followed by an environment where they can interact for a long time, producing many combinations so that the "right one" will eventually emerge. So, basically, we need to define these two environments.

As explained in subsec. XII.3, the only known way to obtain a large production of nitrogen compounds is to submit the appropriate gas mixture to high pressure and temperature. So, as far as we known, this must be the initial stage of life origin – and this corresponds to the early ECM, even before the beginning of oceans. Then, an environment where those molecules are no longer produced but where they have ideal conditions for combining is required. The characteristics of such an environment must be studied, but a basic one is provided by the ECM: a long-lasting and slowly cooling environment of huge dimensions, where a great amount of molecules can interact for hundreds of millions of years. One can also note that at such high temperatures water viscosity is much lower, so the velocity of the interactions between molecules much higher; this is important to increase the probability of formation of the right molecules during the available time window.

The ECM scenario for early Earth, described in section X, seems to fulfil not only the basic requirements but possibly many other requirements of the long pathway from basic nitrogen compounds to cells. There are theories for the origin of life requiring high temperatures, e.g. Huber & Wächtershäuser (1998) or the Ecopoesis model (Felix de Sousa, 2010). To study this process is beyond the scope of this paper, but the possibilities of the ECM scenario are appealing, with the phase with supercritical CO_2 at a decreasing pressure/temperature possibly playing a crucial role. An all-new class of lab experiments can be anticipated to test the potential of such an environment for the production of long organic molecules. The relevant aspect is that Earth's surface was a chemical reactor with apparently ideal conditions, as ideal as one can imagine with present knowledge, to produce the large molecules needed for life, a giant reactor operating at high speed for hundreds of millions of years.

One must note that the above said does not imply that life is just the result of random combinations in successive steps, but that the conditions required by at least some of the processes needed to originate life were available in early Earth.

It is usually considered that once created, life will naturally evolve in a climate like the present one, a different climate would be a challenge for life. That is not true, and to understand why it is first necessary to understand the links between climate and life. A first link is presented below.

XIV.2. The first link between temperature and life: the thermal window

Living cells are a kind of machine where the role of mechanical components is performed by proteins. Proteins are chains of amino acids that fold up to form complex three-dimensional structures; and, similar to a mechanical component, their form determines their function. These structures depend on hydrogen bonding, which can be easily disrupted by several stress agents such as heat. Proteins unfold – *denature* – outside their temperature window, and lose their function. The upper temperature of this window is called the melting temperature.

Temperatures above 41 ºC denature many of the complex proteins of human cells, but there are proteins that can withstand higher temperatures. The melting temperature of most proteins is between 41 ºC and 70 ºC (see, e.g., Franzosa et al., 2010; for a thermodynamic database for proteins see, e.g., Abdulla et al., 2004). There are also enzymes known as chaperones or heat shock proteins that assist proteins in the folding process and are able to increase their resistance to heat. Also, cells from thermophiles seem to have particular solutions to withstand heat. The general picture is that unicellular forms of life can endure almost any conceivable condition, simple differentiated life forms (i.e., organisms composed of cells specialized in different functions) require temperatures under 60–70 ºC, and animal cells need inner body temperatures below 50 ºC (the most primitive ones) or 40 ºC (hot-blooded animals). The more evolved an organism is, the more complex are its proteins and narrower the thermal stability window of its cells.

As mentioned, in the variable pressure environment of the ECM the state temperature is the relevant one, not the Celsius temperature; therefore, the simplest forms of differentiate life can only succeed at state temperatures under 60-70% and animals (the simplest forms) can only exist under state temperatures below 50%.

There is also a lower limit of temperature for proteins, below which cold denaturation occurs. The melting and the cold denaturation temperatures define the thermal window of the cell. Throughout evolution, these two temperatures converged to a temperature very close to 37%.

The thermal window of a species, i.e., the range of state temperatures of the environment that ensures that the organisms of that species can grow and reproduce, differs from the one of their cells, as shown next.

The minimum temperature that is relevant for the success of a species is not the cold denaturation but the fact that cells' activity slows down with decreasing temperature, which prevents the birth and survival of offspring under a certain minimum temperature.

On the other hand, the functioning of a cell produces heat. The more evolved the organism, the more complex the functioning of its cells and more heat is produced (in general); and this heat increases with the activity of the organism. The number of cells in a body depends on its volume, but the release of heat depends on body surface. So, a small animal can exist at an ambient temperature close to the higher limit of its thermal window but not a big animal, unless it has special processes of cooling, such as a body with a large surface/volume ratio. And, to be successful, i.e., to be able to develop the activity required for survival, an organism requires a difference between the ambient temperature and its maximum rest temperature that encompasses the dissipation of heat produced by its activity, which establishes the maximum temperature of the environment for the species.

From the above, the thermal window of a species is defined by the maximum and minimum environment temperatures that allow the organisms of that species to reproduce and to feed.

This link between temperature and life is important because the time interval during which each life form existed implies that its environment state temperature was within its thermal window. The sequence of thermal windows of the successively more evolved organisms defines maximum and minimum limits for Earth's temperature. In subsec. XIV.6 another link between temperature and life is analysed.

XIV.3. From the cell to the Cambrian explosion

From the organic molecules to the cell goes a giant step; but cells did appear and they needed an environment where their complex molecules remained stable, where they could get the atoms, molecules and energy required for their construction and functioning. There are two different environments in Earth's past where cells could obtain energy: the surface and the bottom of the oceans. At the surface, energy could be obtained from light and, on the seabed, from the substances released by submarine volcanic activity.

At the surface, one of the first important forms of life were cyanobacteria. These unicellular beings withstand very high temperatures and thrive in extreme environments, such as hot springs or salt works, and process the nitrogen and carbon dioxide using light energy to drive photosynthesis. They can withstand a state temperature close to 100%, which would confirm that surface state temperature was around 100% during the first gigayears if not for the fact that they seem able to adapt to almost any environment; nevertheless, it confirms cyanobacteria compatibility with the ECM.

According to the ECM1, surface state temperature was over 90% until around 1.4 Ga, too high for complex proteins. Therefore, water surface was not a friendly environment for more complex life forms than cyanobacteria. For differentiated life forms, the maximum state temperature must be 60-70% (subsec. XIV.2), which was available under the surface, but two limitations occur there: both light and dissolved gases vanish with depth.

Due to the cloudy atmosphere, there was less light at the surface in the past (the higher the irradiation, the higher the amount of water vapour and the lower the light intensity at the surface). Light is absorbed by seawater (over 50% within the upper first meter) except for blue light (minimum absorption at 418 nm). On the other hand, the solubility of gases and namely of carbon dioxide in water was then much lower than at today's temperatures[7]. Therefore, the conditions for differentiated life forms under the surface were worse than today due to the lower availability of dissolved gases and of light. Today, the simpler, light dependent, differentiated life forms able to live and reproduce at depth are the red algae, which can grow at about 75 m depth (McGrail Bank[8]) and possibly deeper. Considering the differences between past and present, the maximum depth in the past where enough light and gases were available for red algae would be significantly shallower than the present one.

The oldest fossils identified as of red algae were found in rocks with 1.2 Gy (Butterfield, 2000). At that time, the

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[7] http://www.engineeringtoolbox.com/gases-solubility-water-d_1148.html.

[8] http://oceanexplorer.noaa.gov/explorations/03mex/background/seaweeds/media/fig1_dive1763.html

state temperature at 30 m depth was 67.6% (ECM1), which is within the range of maximum state temperature for that kind of life forms; the 60% state temperature was available at 60 m depth and the maximum 70% at 24 m depth. So, according to the ECM1, red algae could exist 1.2 Ga, at depths compatible with their requirements of state temperature, light and gases. One can determine when red algae could have first appeared. At 30 m depth, the state temperature dropped below 70% at 1.26 Ga; this seems to be the most likely moment for the appearance of red algae and is in agreement with the age of the oldest fossil known.

A detailed study of red algae maximum state temperature and the availability of light and dissolved gases can accurately define the time window when their appearance could have happen. However, even without that, we can see that the time window is narrow: the earliest moment that can be a priori considered is when the 70% state temperature was available at 60 m depth, which happened at 1.48 Ga, less than 0.3 Gy earlier than the oldest fossil; and this is a very unlikely situation, given the limitations of light and dissolved gases at such depth and the high state temperature considered. So, this suggests that the ECM1 temperature is close to the maximum temperature compatible with the observed life evolution.

The state temperatures at various depths are displayed in Fig. 10, showing the correspondence between the oldest fossil of red algae known to date and the availability of conditions required by those life forms.

The subsequent evolutionary step is the appearance of animals. First, the Ediacara biota, around 0.6 Ga. The usual interpretation of the fossil record is that they were organisms having bodies with large surface to volume ratios (as expectable if they were animals living close to the maximum temperature they could withstand), and possibly related to cnidarians, which include jellyfish and sea anemones (Van Andel, 1994); but they could also have been giant marine protists (Seilacher at al., 2005) or lichenized fungi (Retallack, 2007). Ediacara biota radiated at the proposed Avalon explosion, 0.575 Ga (Shen, 2008). With the Cambrian, a little before 540 million years ago, new live forms (namely the coelomates) invaded shallow waters; most major animal phyla appeared then. An astonishing diversity of life forms became established within a short time interval, which justifies the designation of Cambrian explosion (or Cambrian radiation) for this occurrence.

Now, let us check the compatibility of this evolutionary step with the ECM1. Fig. 10 shows that at 30 m depth state temperature is low enough to allow the existence of these life forms since 760 million years ago (i.e., when state temperature became lower than 50%). As they were not photoautotrophs, an “explosion” of these life forms would require abundance of food, and algae are a suited food for animals with a digestive track. At that time, algae developed mainly close to the surface, where there was maximum availability of light and carbon dioxide at a comfortable state temperature – the most favourable depth should be around 10 m, just beyond the intertidal zone. So, one can expect that such an explosion occurred only after the state temperature decreased below 50% at 10 m depth, which happened 575 million years ago – at the Avalon explosion and only 0.03 Gy before the Cambrian.

Therefore, the ECM1 establishes an earlier limit for the appearance of animals in close correspondence with the date of the Cambrian explosion. Once again, one shall consider that this close correspondence is a coincidence because the accuracy of the values of the variables is not enough; nevertheless, as in all coincidences obtained in this work, the calculations are the simplest and most straightforward possible, therefore not prone to biasing. This correspondence between the evolution of life and of temperature, with life evolution following the temperature decrease with a time gap of just some millions of years (or less), supports the possibility that life evolution has been delayed by climate evolution and has happened as soon as temperature became low enough; such possibility is enhanced by the analysis of the evolution of life on land, in subsection XIV.5.

Now, let us examine what could have happened in the other possible environment for life, the bottom of the oceans. There, the pressure solves the temperature problem: the state temperature is under 50% since 2.2 Ga (considering that the bottom and surface Celsius temperature of the oceans were the same at that time). Furthermore, the volcanically active submarine zones would have been abundant in the past. Today, these zones are crowded with life and so we may think that in the bottom of the oceans life had good conditions to develop, in contrast with the surface. And, as those conditions became available very early, we can think that an initial population of chemoautotrophs soon supported heterotrophic and complex life forms – metazoans or animals. That is, at depth, it is possible that life evolution was not delayed by the lack of conditions. However, the conditions available at the bottom of the oceans were very different from the ones of the surface and so evolution was different. At the surface, the environment provides abundant resources, but at the seabed the energy came from specific sources (zones of volcanic activity, submarine vents) and so the organisms that were furthest from the sources had to feed on the ones that were close to them instead of feeding from the environment – they had to be predators.

Today, there are animals living around submarine vents. Are they just adaptations of surface animals to the depth? Or are they the result of life evolution at the bottom of the oceans? This latter possibility supports the following new explanation for the Cambrian explosion.

XIV.4. Came the animals from the ocean floor?

As it is well known, the Cambrian explosion of most major animal phyla, for which no link to previous life forms has yet been found, is one of the greatest difficulties of Darwin’s theory of evolution, as pointed out by himself; it is still the most extreme case of the lack of gradualism in evolution that seems to be a characteristic of the fossil record. Although this lack of gradualism may be only apparent and due to insufficiencies in fossil record, it can

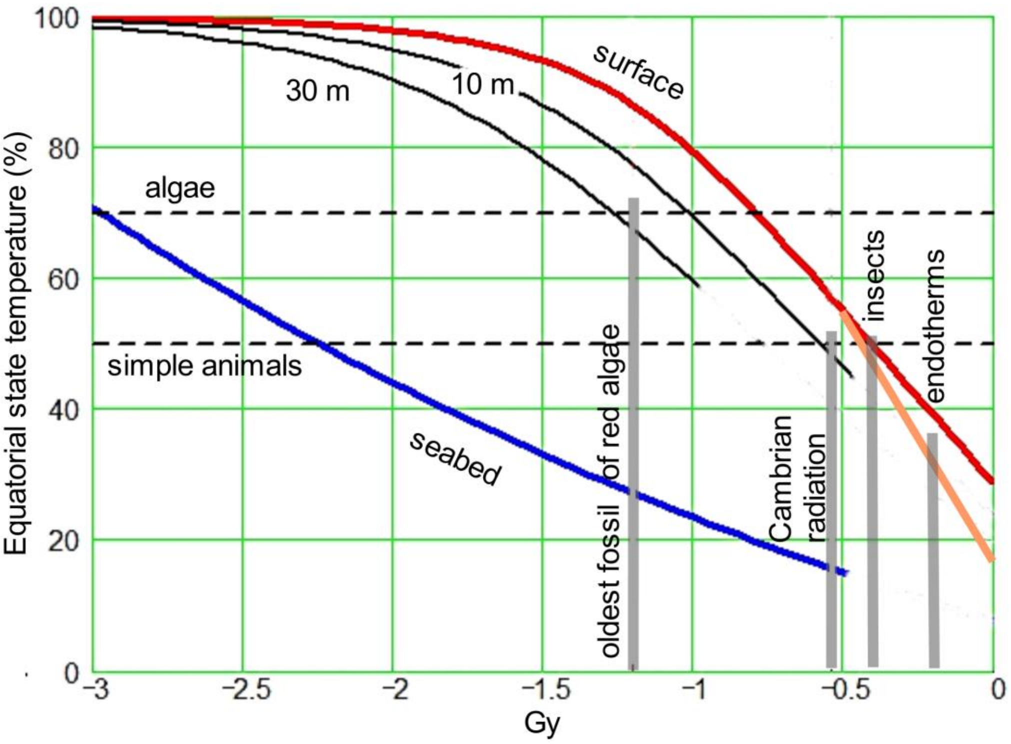

Fig. 10. State temperature (according to ECM1) and its relationship with the evolution of life. The solid lines represent the equatorial state temperature at various depths: 0 m (sea surface), 10 m, 30 m and deep bottom of the sea); the orange line from -0.5 Gy to 0 Gy represents the global average surface temperature, which departs from the equatorial one at -0.5 Gy. The dashed lines indicate the maximum temperature for simple organisms with differentiated cells (algae, around 70% state temperature) and for simple animals ($\theta_S \approx 50\%$). Major life events are represented by vertical grey bars: oldest red algae (-1.22 Gy), Cambrian radiation (-0.54 Gy), life on land (-0.4 Gy) and endotherms (-0.2 Gy). The figure shows that, according to the ECM, animals at the bottom of oceans near submarine volcanic zones can be older than 2 Gy, while in shallow waters they can exist since the last 0.56 Gy but not before; endotherms appeared when the global mean temperature dropped to near 30 ºC.

also be a characteristic of the evolution itself. The latter possibility led to the theory of punctuated equilibria (Eldredge & Gould, 1972). The ECM supports an unexpected explanation for the apparent evolutionary quantum leap of the Cambrian explosion: rather than belonging to the evolutionary line of the surface, those animals belong to the one of the ocean floor.

Surface life forms evolved into plants and possibly into cnidarians; Ediacara fauna belongs to this evolutionary line of the surface, i.e., the zone where there was enough light and gases to support photoautotrophs. This evolution occurred at the bottom of the light/gases zone, where state temperature was lower and so life could evolve earlier – first the multicellular algae, then Ediacara biota. The decreasing temperature allowed the invasion of the surface, where the resources were abundant, by algae; when the temperature allowed it, Ediacara biota appeared.

At the bottom of the oceans, life forms had been able to evolve since long, as said before, so they could have evolved to animal phyla in a more or less continuous way. The decreasing volcanic activity at the seabed reduced the availability of submarine sources and possibly many isolated colonies were formed, each with an independent evolutionary path, originating a huge diversity of animals. When surface state temperature became low enough, they managed to get to shallow waters and feed on the abundant surface life forms, originating the Cambrian explosion and the apparent leap in evolution. How did they go from the bottom of the oceans to continental shelves? Possibly as a result of movements of the bottom of the oceans, because it was a time of intense tectonic activity.

This hypothesis draws a new understanding of life evolution: algae and plants (and possibly the cnidarian) belong to the evolutionary line of the upper zone of the oceans, with enough light and dissolved gases, while most animals belong to the evolutionary line of the bottom of the oceans; the two lines met during the Cambrian.

The above description is just a rough hypothesis. It ignores relevant climatic occurrences that seem to have happened by the beginning and end of the Ediacaran Period. It is here presented merely as an example of the new possibilities offered by the ECM. This hypothesis on the Cambrian explosion does not contradict the theory of punctuated equilibria because it applies to this specific event only, which is unique in its gigantic evolutionary leap.

XIV.5. On life on land

A question concerning life is why it expanded so late on land, which provided more oxygen, carbon and light than oceans. Figure 10 supports an explanation: the state temperature at the surface corresponds to the state temperature at shallow waters with a delay of around 200 million years. Land organisms have to be more differentiated than algae, which implies that the thermal limit of land plants must be lower, close to the one of primitive animals. So, there was no life on land when the oceans were already crowded with life maybe because of the different state temperatures on land and at marine habitats, which were some meters below the oceans' surface and so had a lower state temperature. The evolution to terrestrial plants required a land state temperature similar to the one at marine habitats.

The analysis made until now has only defined the maximum state temperature compatible with the evolution of life, which is in close correspondence with the temperature of the ECM1; however, temperature could also be lower and life have evolved independently of temperature. The delay between the expansion of life on land and at sea is the first evidence that temperature was not lower because an excessively high temperature at land appears as the most likely explanation for the delay in the evolution and expansion of life on land.

On land, temperature could still have restrained evolution until recently. Humans could certainly not have appeared when state temperature was over 40% and the humidity was high.

A paradigmatic case is the one of dinosaurs and, ignoring many details not relevant in the present context, a simplified analysis is presented as follows. In evolutionary terms, dinosaurs probably stood between reptiles and "hot blooded" animals, with more evolved cells than reptiles, more complex proteins, implying a narrower thermal window, and with cells producing more heat than those of reptiles but less than of endotherms – their huge bodies would not be possible if their cells produced heat as endotherms do, in their warm environment. They were probably mesotherms and evidences of it were recently presented (Grady et al., 2014). On the other hand, they reproduced by eggs, which is adequate when the temperature of the environment is within the thermal window of the species. The fact that most present reptiles had to develop behaviours to keep their eggs warmer than the environment may trace a misfit between present temperature and the ones for which they were initially adapted. Big dinosaurs could not warm their eggs as birds do today, so their eggs fully depended on the temperature of the environment. If they had a narrower thermal window than reptiles, but were unable to warm their eggs, they were adapted to a temperature higher than today's Earth temperature since they appeared, more than two hundred million years ago. This shows that the well documented warm Earth epoch at almost one hundred million years ago was the typical climate, not an exceptional occurrence due to exceptional levels of greenhouse gases or other specific cause. On the other hand, a decreasing temperature would probably imply their extinction/evolution because their eggs would not succeed once the temperature dropped below their lower thermal limit; the sudden temperature decrease that followed the Cretaceous-Paleogene event may have contributed to their extinction.

So, very likely, dinosaurs could not have been "hot-blooded" animals because they could not have dissipated the internal heat generated by their huge bodies in their warm environment; but they were more evolved than reptiles, implying a narrower thermal window, with a higher minimum temperature. Apparently, dinosaurs were caught in the intersection of the decreasing Earth temperature and the increasing minimum temperature then required by evolution. The solution to the problem was the next evolutionary step, endothermic animals with forms of reproduction as independent as required/possible of external temperature. One shall note that endotherms could probably not have appeared without an intermediary step between them and reptiles – the dinosaurs; and that throughout Earth's history there was only a narrow time window of around two hundred million years when that intermediary step could have occurred because it requires a narrow thermal window around 37 ºC. After that, thermal amplitudes became too large; before that, temperature was too high. A curious thought: if, for some reason, endotherms disappear now, evolution will be stuck with reptiles, with no possible evolution because the climate no longer supports the following evolutionary step, the mesotherms.

According to the ECM1, endotherms could not have appeared earlier than two to three hundred million years ago because the temperature was too high. On the other hand, land animals less evolved than dinosaurs can survive with today's climate because their cells, although fitted for higher temperatures, as indicated by their metabolic rates and optimal temperatures for reproduction, have a wider thermal window that allows their survival with today's lower temperatures; even so, most of them developed adaptations and/or special behaviours, namely those concerning reproduction, to overcome today's colder environment – the need for those adaptations and behaviours suggests that they are suited for a warmer climate. Also, the fact that life is much more intensely expressed in the equatorial zone, where the climate is more similar to the past climate, suggests that Earth's mean temperature is now below optimal conditions for most present life forms. We usually perceive climate in relation to us, humans, and so we consider that polar climate is too cold and that mid latitude climates are temperate, while equatorial climate is above comfort conditions in temperature and humidity; that may be true for humans, but for most species on Earth (older than humans) climates other than the equatorial one require specific adaptations for survival.

If we let the imagination run a little wild, we can say that present climate is the one adequate for the on-going evolutionary step, the onset of the human society. We usually only consider the evolution of the organisms, but evolution occurs at several levels, the three main being the cell, the organism (which may be seen as a society of cells), and the society of organisms. The society of the human species is a new achievement of evolution, not just a scaling up of existing societies because it is able of evolution by itself and no longer genetically programed – it is a hybrid structure, partly genetic, partly outside genetics. And we can suspect that, as in the case of dinosaurs, there is a time window for it in this evolving universe, i.e., adverse conditions in the future may only be overcome by a sufficiently evolved society of humans. Note that adverse conditions are already in place because in the last glaciation, the level of carbon dioxide dropped close to the minimum level required by many plants to grow. Without the human society, next glaciation could be an ecological catastrophe. Earth is an evolving system and it is slowly but steadily drifting away from the comfort zone of life; the capacity of adaptation of life forms is large but limited. Humanity is the possible Nature's solution to the challenges ahead.

XIV.6. The second link between temperature and life: the importance of high temperature

Absolute temperature affects the processes related with life because it decreases water viscosity[9] and speeds chemical reactions (the relationship with absolute temperature is given by the Boltzmann factor[10]), namely metabolic rates. A lower temperature means that more time would be needed to achieve the required molecular combinations leading to life, and that evolution would be slower. There is a big difference between the time required to reach the present stage of evolution in the ECM scenario and in a scenario where the temperature is always similar to the present one.

The speed of evolution increases with absolute temperature, but evolution is limited by the maximum state temperature defined by the thermal window of living beings. So, the maximum speed of evolution is obtained in an environment where state temperature is always within the thermal window and absolute temperature is maximum.

In the ECM scenario, the ratio between absolute and state temperatures is maximum at the bottom of the oceans, and so is the velocity of chemical reactions; also, water viscosity there is minimum, which contributes to maximize the velocity of evolution.

From the above, evolution could have been fastest at the bottom of the oceans until temperature became too low. Then, the best thermal conditions became available at the surface, originating the Cambrian explosion. This further supports the hypothesis that the evolution leading to the appearance of animals occurred at the bottom of the oceans because the required state temperatures were available there around 2 Gy earlier than at the surface, and the ratio between absolute and state temperature was maximum.

In short, the high pressure and temperature of the ECM ensured low water viscosity and high speed of chemical reactions, maximizing the rate of combinations of atoms and molecules in the combinatory phase which originated life, as well as the velocity of evolution in the different environments of Earth. In comparison with the current climate, the ECM provides an environment (the bottom of oceans) where evolution could have been several times faster.

XV. Conclusion

This paper presents a solution for a major problem: the conflict between standard physics, which implies a frozen past for Earth, and the hot past indicated by most evidences. This conflict is a fundamental disagreement, apparently unsolvable within current conception of the universe. Earth's past climate was a riddle until now.

The model of Earth's past climate here established – the ECM – is significantly different from what has been traditionally considered. As a consequence, it opens new possibilities for the investigation of past phenomena, and some of those new possibilities are here suggested, particularly in what concerns life origin and evolution.

This paper is the second of a series of three. The first paper (Oliveira, 2011) establishes the dilation model and tests it with cosmic data, showing that it is better than alternatives because it has less parameters, but it does not present new results. Here, the dilation model is tested with local data and relevant new results are obtained, incompatible with standard physics; however, alternative interpretations of the data on Earth's past can still be made. The third paper to be published is on the large scale structure of the universe, being the one that finally ends this quest to know if the space expands or the standard length unit decreases.

This set of three papers is just the beginning, because, in spite of using the same fundamental physical laws, dilation model establishes a new conception of the universe with vast consequences.

Acknowledgements

I warmly thank to Hélder Velez the unyielding support and the enlightening discussions; without his enthusiasm, this work could never be known. I also thank the twenty years long support of my family, friends and colleagues. Finally, my very special thanks to those scientists that have send me a word of support and encouragement.

Appendix I – An essential description of the self-similar dilation model

This Appendix presents just a description of the essential aspects of the dilation model; its deduction, testing with cosmic data and implications for the concept of the universe were presented in Oliveira (2011).

The self-similar dilation model proceeds from the analysis of a fundamental question: ***does space expand or does the standard length unit decrease?*** A priori, both situations are possible because space expansion is such that it disappears with a simple change of length unit, from standard to comoving; however, the underlying phenomena are obviously different, leading to different physical models of the universe.

The intuitive answer may be that space expands, because a decreasing length unit would presumably not support current physical laws; yet, the analysis concludes, somewhat surprisingly, that it is not so: there is a system of units where space is invariant (and the standard length unit

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[9] http://en.wikipedia.org/wiki/Temperature_dependence_of_liquid_viscosity

[10] http://en.wikipedia.org/wiki/Metabolic_theory_of_ecology

decreases) and physical laws hold. Therefore, using the same well known fundamental laws, two different descriptions of the universe are possible, one using the standard length unit, where matter is invariant and space expands, and the other using a length unit where space is invariant and matter evanesces – the so-called comoving length unit. However, there is a first important difference between the two situations: while both systems of units are equally valid to model local systems, such as the systems on Earth, they are not so for systems at cosmic distances. To model cosmic data using comoving units, no unknown entities are required, no new parameters (just the Hubble parameter), while with standard units a set of unknown entities (dark energy and dark matter) and phenomena not describable by known physics (cosmic inflation, the Big Bang) is required. Furthermore, with comoving units there is no distinction between local and cosmic scales, with the same physics and the same entities at all scales. The standard system of units is called the Atomic or *A* system and the system that uses the comoving length unit is called the Space or *S* system (the name of the system identifies what is invariant in it, the atom or the space).

The description of the universe in *S* units is the following: in invariant space, matter transforms into field in a self-similar way (i.e., at a constant rate in *S* units), feeding field expansion through space. As a consequence of this phenomenon, matter and field evanesce while field expands since the moment when matter began. Matter and field appear as two aspects of the same entity, which evanesces while expanding.

One shall note that this is an expected phenomenon: from the characteristics of the Cosmic Microwave Background (CMB), we suspect that matter had a first moment; before it, there was no field, which started propagating then. So, since that moment, the field of each particle is expanding through space. We shall not assume that field expands at no cost, so something must feed field expansion; the only known entity able to do it is matter. Therefore, the evanescence of matter uncovered by the analysis of the above fundamental question is what must be expected because matter is the source of field, which is expanding through space.

Standard units must comply with the concept of reference-body, therefore matter is invariant when measured with them, i.e., standard units are units intrinsic to matter. However, because these units decrease in relation to space, we detect an expanding space, an isotropic and uniform expansion, a dilation, a perfect geometric transformation. This is the same kind of problem associated with the geocentric model of the universe: both the standard space expansion models and the geocentric Hipparchus/Ptolemy model are models of data as directly acquired by us, models of the universe in reference frames in which we are in some way invariant. The geometric motion of celestial bodies around us showed that we are not invariant in position and the geometric motion of celestial bodies away from us (space expansion) leads now to the discovery that we are not invariant in size.

The standard description of the universe, where space expands, or the new description, where space is invariant, can be supported in systems of units that differ only in the length unit, namely using *G*, ε and *c* as base units besides the length unit, which is the only base unit that, with this choice of base units, is different in the *A* and *S* systems.

The new model is called the dilation model, because in either system of units, *A* or *S*, a mathematical dilation is observed – a dilation of space with a scale factor >1 in *A* units and a dilation of matter with a scale factor <1 in *S* units.

The invariance of *G*, ε and *c* and the relationship between the two length units define the relationship between all other units in the two systems: the ratio between length units imply an identical ratio between time units for the invariance of light speed to hold, and the invariance of the other two constants imply the same for the units of mass and charge. Representing the ratios between Atomic (*A*) and Space (*S*) units of mass by M, of charge by Q, of time by T and of length by L, it is:

$$\mathsf{M}(t)=\mathsf{Q}(t)=\mathsf{T}(t)=\mathsf{L}(t). \tag{AI.1}$$

The ratio between the *A* and the *S* length units, L, decreases through time because the size of bodies decreases in *S* units, while the “size” of the space increases in *A* units − $\mathsf{L}(t_S)$ is the matter scale factor in *S* units, while $\mathsf{L}^{-1}(t_A)$ is the space scale factor in *A* units (the standard ones). This scaling has constant rate in *S* units (it is a self-similar transformation in *S*), so the scaling function, represented by $\alpha(t_S)$, is exponential in *S*:

$$\alpha\left(t_S\right)=e^{-H_0 t_S}. \tag{AI.2}$$

Naturally, $\alpha(t_S)=\mathsf{L}(t_S)$. Therefore, from Eqs. (AI.1) and (AI.2), mass, charge and the size of atoms decrease exponentially in *S* units, implying that atomic phenomena run faster at the inverse ratio (because light speed is invariant in *S* units), i.e., that the *A* time unit also decreases exponentially in *S*.

As the length and time units of *A* and *S* systems vary with respect to one another, the values of distance and time are different in *A* and *S*; from the above two equations, one obtains the following equations relating the values of local time and of proper distance in the two systems of units:

$$\begin{cases} t_A = H_0^{-1}(e^{H_0 t_S}-1) \\ r_A = r_S\cdot\left(1+H_0 t_A\right) \end{cases} \quad \begin{cases} t_S = H_0^{-1}\ln(1+H_0 t_A) \\ r_S = r_A e^{-H_0 t_S} \end{cases} . \tag{AI.3}$$

The time transformations show that the universe is time unlimited in *S* but has the age H_0^{-1} in *A* because $t_S \to -\infty \Rightarrow t_A \to -H_0^{-1}$; the moment $t_A=-H_0^{-1}$ is the “creation moment of the universe in *A* units”, the moment of the Big Bang of space expansion models, the moment before which there was nothing, no space and no time. In *S* units this has a trivial explanation: the *A* time unit becomes infinite at that moment, so it is a “moment” of infinite duration; the moment $t_A=-H_0^{-1}$ is a mathematical singularity, which withdraws physical meaning from the *A* description of the universe. The Big Bang as currently described is not a physical occurrence, it is just a mathematical singularity that is a consequence of the units used.

The length transformation shows that space expands linearly in *A* units; the standard expansion model concludes that space expansion is accelerating but that is not obtained from a direct measurement; instead, it is calculated within the framework of that model from the values of other parameters, one of them being the hypothetic dark energy.

Constants (all of them) hold invariant in standard (or *A*) units; in *S* units, the constants that depend on matter properties vary with the evanescence of matter, as determined by the respective dimensional function and by Eqs. (AI.1) and (AI.2), while field constants hold constant in *S* and, therefore, in both systems of units. The Hubble constant, the only time constant, is different from all other constants: it is constant in *S* but not in *A* (in *A*, the Hubble constant is just the present value of the Hubble parameter). Naturally, the dimensionless constants (such as the fine structure constant) are invariant in either system of units.

Something unexpected happens with physical laws. As they are valid in the absence of the dilation phenomenon (that is why they have the simplest form), one would expect that they could not maintain their simplest form in a scaling universe; but such is not the case. Local laws, such as Planck law, are not affected because they do not depend on time or space and so they hold the same in both systems of units. The laws for static field relate field and its source at the same moment; as both field and its source vary at the same ratio, their relationship holds invariant and so the laws are not affected – the classic static field laws are valid both in *A* and *S* units. The conservation of linear momentum and kinetic energy hold invariant provided that "mass" is replaced by "number of baryons" – and since the value of mass in standard (or *A*) units is proportional to the number of baryons, these laws hold the same in standard units. Electromagnetic induction laws can be used as local laws, therefore holding the same in both systems.

So far, in standard units (*A* units), all constants and mentioned physical laws are the same in the dilation model and standard physics. The two differences between those models that allow us to distinguish between them and to find the answer to the initial question are presented next.

The first difference is that, in *S*, the energy of electromagnetic waves during propagation decreases with the square of the scaling law; this is so because the energy of electromagnetic waves is proportional to the square of the field, which evanesces in the dilation model. In *A*, due to the relationship between *A* and *S* units, the energy of waves decreases at the inverse ratio of space expansion while the wavelength increases proportionally. This decrease of the energy of the waves (or of the photons) is a mystery for standard physics, a violation of energy conservation. The phenomenon is observed in the cosmic microwave background (CMB) because the temperature shift of a Planck radiation implies a decrease of the density of the energy of the radiation with the fourth power of the wavelength increase, while the expansion of space only accounts for the third power (this is perhaps the most significant problem of Big Bang models, seldom mentioned because no way of making this result compatible with standard physics is known).

The other difference is in the conservation of the angular momentum. The value of distance in this law (the value of curvature radius) is the *S* value, which varies through time differently of the *A* value, the one considered in standard physics; the *A* angular momentum being $\mathcal{L}_A = \mathbf{r}_A \times m_A\mathbf{v}$, the conservation law in *A* units is:

$$\left(\frac{d\mathcal{L}_A}{dt_A}\right)_0 = H_0\mathcal{L}_0 \, . \qquad \text{(AI.4)}$$

This means that the rotation speed of an isolated rotating body increases with time. For an *S* observer, this is the expectable consequence of the decrease of the size of the body, and the angular law applies as usual; an *A* observer can explain the increase of the rotation considering that it is due to the local expansion of space, which tends to drag the matter. The standard space expansion models do not apply locally, only non-expanding physics do, and they are incompatible with this result. The quantity $H_0\mathcal{L}_0$ may be undetectable by lab measurements but it has an important consequence: the expansion of planetary orbits (Appendix II).

Therefore, although the evanescence of matter and field is a quite different phenomenon from space expansion, in *A* units it has only two consequences not accounted for by standard physics: the decrease of the energy of electromagnetic waves and the increase of the angular momentum.

The dilation model is obtained by deduction from two consensual observational results (the space expansion and the invariance of constants in standard units); independent of hypotheses, it is a solid construction. However, the deduction path came across three nodes, where different options were possible, being assumed the ones that better comply with known phenomena. The first assumption is that the scaling law is exponential in *S* units, the second is that field evanesces as matter, and the third is that, in conservation laws, "mass" is the amount of particles and "distance" is the *S* value. The first and second assumptions were validated by the cosmic tests and by the characteristics of the CMB, while the third one is tested in this paper through its major consequence, the expansion of orbits. This completes the verification of the occurrence of a self-similar phenomenon characterized by an evanescence of matter/field, presumably supporting an expanding field; the full quantification of this phenomenon still requires the determination of the quantity, a constant in the relevant units, that represents the amount of matter plus field.

Only the classical fundamental physical laws have been considered because they are the ground on which the analysis of all physics can be made; nevertheless, the analysis of Special and General Relativity requires a particularly careful work because those theories are established in the observer's reference frame and one can now go beyond it; a preliminary work is made in Oliveira & Abreu (2002).

Appendix II – Orbital expansion

As explained in Appendix I, the dilation model uses two kinds of units: the *S* or Space units, in which space is invariant, and the *A* or Atomic units, which comply with the concept of reference-body and correspond to standard units.

The sole characteristic of orbital motion that is relevant for this paper is the rate of increase of mean orbital radius; so, a very simple calculation is here made, considering the case of a circular orbit of a body with negligible mass compared with the central body. As explained in Appendix I, Relativity has yet to be analysed, so we will use only the laws known to be valid in the dilation model. Taking r as the distance of the orbiting body to a central body of mass M, the conservation of the angular momentum and the centripetal acceleration define the following two equations:

$$\begin{aligned} v r_S &= v_0 r_0 \\ \frac{v^2}{r} &= G\frac{M}{r^2} \ . \end{aligned} \qquad \text{(AII.1)}$$

The absence of all suffixes in the second equation means that it is valid in both systems of units, i.e., with all variables measured in *A* or all measured in *S*; v has no suffix because it has the same value in both systems. The difference between these equations and the usual ones is that the conservation of angular momentum is in *S*, not in *A* (function of r_S, not of r_A). The calculation can be made in *S*, where $M_S = M_0\alpha$, or in *A*, where $r_S = r_A\alpha$; the solution in *S* is:

$$\begin{aligned} r_S &= r_0\alpha^{-1} \\ v &= v_0\alpha \ . \end{aligned} \qquad \text{(AII.2)}$$

In *A*, this is

$$\begin{aligned} r_A &= r_0\alpha^{-2} = r_0\left(1+H_0t_A\right)^2 \\ \varpi_A &= \varpi_0\alpha^3 = \varpi_0\left(1+H_0t_A\right)^{-3} , \end{aligned} \qquad \text{(AII.3)}$$

where ϖ is the orbital angular velocity. Therefore, in *A* (i.e., in standard units), there is an increase of orbital radius at the ratio of $2H_0$ and a decrease of angular velocity at the ratio of $3H_0$:

$$\begin{aligned} \left(\frac{\dot r_A}{r_A}\right)_0 &= 2H_0 \\ \left(\frac{\dot\varpi_A}{\varpi_A}\right)_0 &= -3H_0 \ . \end{aligned} \qquad \text{(AII.4)}$$

In spite of this enlargement of the orbital radius, it still is

$$\varpi_A^2 r_A^3 = \varpi_0^2 r_0^3 = GM_A = \text{constant}; \qquad \text{(AII.5)}$$

so, we have this surprising result: the gravitational law is the standard one, the value of GM is invariant (in standard units) and, yet, orbital radius increases. However, this is not at all unexpected in a scenario of local space expansion: G holds invariant while bodies are dragged by the expanding space. The novelty lies in the fact that the dilation model is able to account for the local expansion of space in standard units while the standard cosmological model is not.

Appendix III – Accounting for secondary phenomena on the calculation of irradiance for Mars

The calculation of the irradiance presented in sec. V only considers the simplest scenario and it is also necessary to account for the secondary phenomena that influence the result; there are two with major relevance.

The first one is the influence of the atmosphere; if Mars was warmer, there was an atmosphere with water vapour and, therefore, some greenhouse effect. This greenhouse effect decreases the intensity of the required irradiance. To estimate this effect, let us examine the effect of Earth’s atmosphere. First, let us calculate the low-latitude ocean temperature for Earth, considering no atmosphere, as done with Mars. For the current Earth’s irradiance, $B_E = 1368$ Wm^{-2}, and the values of oceans’ albedo and emissivity used in sec. V, the temperature from Eq. (5.1) is 22.3 ºC (in the absence of atmosphere and ignoring the effect of oceans in the distribution of heat). The temperature with atmosphere in the equatorial zone is assumed as 29 ºC (302 ºK), as explained in sec. VI. The irradiance required to produce this temperature in the absence of atmosphere would be, from Eq. (5.1), $B_{302} = 1529$ Wm^{-2}. Therefore, the equatorial effect of Earth’s atmosphere on sea surface temperature can be estimated as $\left(B_E - B_{302}\right)/B_{302} = -10.5\%$. This value has now to be scaled to the Mars’ atmosphere. We will simplify the problem considering that only the amount of water vapour is relevant. At 0 ºC, the water vapour pressure is 15% of the one at 29 ºC; Mars’ gravity is 38% of Earth’s (note that the value of the gravity of a planet in standard units is not affected by the dilation), which means that the amount of water vapour in Mars was around 40% of present Earth amount in equator. If the greenhouse effect of the atmosphere depended linearly on the amount of water vapour, then it would be about – 4.2%; however, according to the greenhouse theory, it has a logarithmic dependence, which means that the effect of Mars’ atmosphere at that time would have been between – 4.2% and – 10.5%, or – 7.4 ± 3.2 %. So, considering the atmosphere, the required irradiance is 7.4 ± 3.2 % less than the value calculated considering no atmosphere.

The second correction to be made arises from the fact that the mean water temperature under the surface must be slightly above 0 ºC to allow for the cooling provided by surface evaporation, even considering that the freezing point is a little under 0 ºC due to salinity. The profile temperature for the Greenland sea[11] displays a maximum temperature under the surface of ≈ 5 ºC for a near zero surface temperature; from Eq. (5.1), for 5 ºC, an irradiance 7.5% higher than for 0 ºC is required; the error margin of

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[11] http://en.wikipedia.org/wiki/Arctic_Ocean

this result will not be larger than the one due to a variation of 1 ºC, i.e., around 1.5%.

Adding both contributions, the result is +0.1 ± 4.7 %, which means that the irradiance calculated without considering both effects shall be similar to the one considering both of them with a roughly estimated error margin of 5%.

There is another aspect to be considered, the error margin of the dating of the disappearance of liquid water from Mars surface. This is rather inaccurate, a dating obtained from the analysis of the number of superimposed impact craters by analogy with Earth (see, e.g., Carr, 2000). In order to avoid speculative reasoning, only the error margin associated with the accuracy of the value of the date, i.e., ±0.05 Gy, rounded up to ±0.1 Gy will be considered.

The conclusion is that the estimated contribution to the value of irradiance of the two main secondary phenomena is 0 ± 5 %, which adds to an error margin of 0.1 Gy for the moment of last “large water flows / oceans”.

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