Research paper

Why did life develop on the surface of the Earth in the Cambrian?

CrossMark

Carlo Doglioni [a,*], Johannes Pignatti [a], Max Coleman [b,c]

[a] Department of Earth Sciences, Sapienza University, 00185 Rome, Italy
[b] NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[c] NASA Astrobiology Institute, USA

ABSTRACT

Life was limited for most of Earth's history, remaining at a primitive stage and mostly marine until about 0.55 Ga. In the Paleozoic, life eventually exploded and colonized the continental realm. Why had there been such a long period of delayed evolution of life? Early life was dominated by Archaea and Bacteria, which can survive ionizing radiation better than other organisms. The magnetic field preserves the atmosphere, which is the main shield of UV radiation. We explore the hypothesis that the Cambrian explosion of life could have been enabled by the increase of the magnetic field dipole intensity due to the solidification of the inner core, caused by the cooling of the Earth, and the concomitant decrease with time of the high-energy solar flux since the birth of the solar system. Therefore, the two phenomena could be responsible for the growth and thickening of the atmosphere and the development of land surface life.

© 2016, China University of Geosciences (Beijing) and Peking University. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The origin of life remains one of most challenging themes in science (Gould, 1989, 1995). We still do not know what exactly controlled evolution of life (Minelli, 2011), but we have started to have some reasonable indications (Miller, 1953; Russell, 2007). Chemical composition and pH of sea-water, thickness of the oceans and a number of physical parameters have constrained the initiation and degree of later development of life on Earth (e.g., Maruyama et al., 2013 and references therein). However, why did complex life start so late during the Earth's history? Why was life on Earth mostly dominated by single-celled Archaea and Bacteria for about 3 Gyr (Fig. 1)? Why only 4 Gyr after the Earth's origin had been the main development of ancestors to all modern phyla and the number of families increased so rapidly? Was this related to the widespread amalgamation of continental masses? The concentration and dispersal of continental blocks occurred several times during the Earth's history, so why it did not occur earlier than Rodinia? The delivery of vast amounts of nutrients to the oceans associated with the uplift of continental lithosphere, the

oxygenation level plus the sulfur and potassium concentrations have been correlated with the Cambrian explosion (Santosh et al., 2014; Zhang et al., 2014). The pre-existing period for limited life has been attributed to nebulae encounter, resulting in a catastrophe due to negative climate forcing and destruction of the ozone layer by enhanced fluxes of cosmic rays and cosmic dust particles (Kataoka et al., 2014).

In this article we discuss only the physical parameters that controlled the development of life. In particular we speculate on the interaction between ionizing radiation and the internal evolution of the planet. We infer a correlation between the persistent occurrence of the atmosphere, the solid inner core growth and the Sun's high-energy X-ray, gamma ray and UV flux decrease. The atmosphere was fed by volcanism, the Earth's natural degassing and oxygen increased due to photosynthetic activity. The Earth's surface and atmosphere evolved through time with the development and solidification of the Earth's inner core related to the secular cooling of the planet, which should have generated a protecting magnetic field while the high-energy solar flux was also reducing.

The solar wind has strong episodic flares, which hit and interact with the Earth's magnetic field. Moreover, the solar pressure on the magnetosphere was possibly higher in the past (Wood et al., 2002; Svensmark, 2006). The magnetosphere contributes to maintaining the atmosphere, preventing it from being
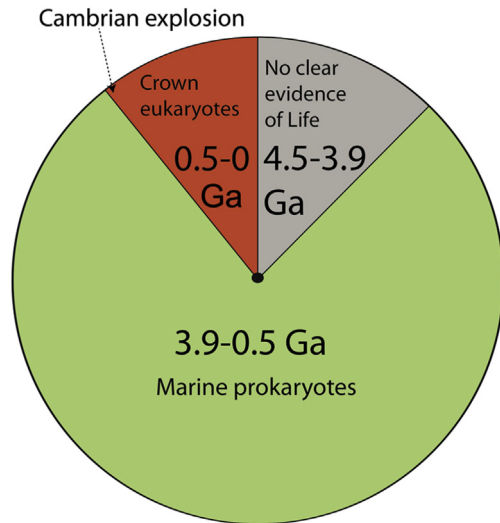
Figure 1. For much of its history, Earth was dominated by marine prokaryotes, protected by water from ionizing radiation.

stripped by the solar wind (Hunten, 1993; Lundin, 2001). Moreover, the solar wind influences atmospheric and climate evolution (Carslaw et al., 2002). The magnetopause shape is deformed by the solar wind (e.g., Tsyganenko, 1995). Therefore, a stronger magnetic field should partly deviate the solar wind, allowing growth of the atmosphere, which in turn protects the Earth's surface from high-energy gamma and UV radiation (e.g., Cockell, 2000). In fact the magnetosphere is one of the primary protections of the atmosphere and its oxygen content (Seki et al., 2001). Wei et al. (2014) and Meert et al. (2016) suggested a link between oxygen escape, the magnetic field and extinction. Edberg et al. (2010) have recently shown how the solar wind is blowing and eroding the thin Mars atmosphere. Mars likely had a thick early atmosphere, a stronger magnetic field (Jurdy and Stefanick, 2004) and an active hydrologic cycle. There is evidence for active volcanism, which contributed to atmospheric growth as well as a growing body of literature regarding the influence of water on Martian landscape evolution (Bibring et al., 2006). The scarce, present-day Martian atmosphere might be due to the disappearance of the planet's magnetic field, the lower gravity field with respect to the Earth, and the low level of magmatic and volcanic activity. The solar wind has been shown to remove the Martian atmosphere (Brain et al., 2015; Jakosky et al., 2015) and most likely erodes the atmospheres of planets in general (Edberg et al., 2010). In contrast, Venus, which has a dense atmosphere, also has a very weak magnetic field, approximately 5 orders of magnitude less than the Earth's. The Venusian magnetic field does not appear to have an active dynamo in part due to its very slow rotation (~6.5 km/h). Its origin has been related more to the interaction between the ionosphere and the solar wind, rather than by an internal dynamo like the Earth (e.g., Kivelson and Russell, 1995). Therefore the interaction between the magnetic field and planetary atmospheres is complex.

In the Archean, the early Earth may have experienced surface radiation levels (in the 200–300 nm wavelength range) several orders of magnitude higher than current levels. Any form of life that might have been present at Earth's surface 4–3.5 Ga must have been exposed to much higher quantities of damaging radiation than at present (Cnossen et al., 2007, and references therein). On the other hand, RNA and DNA are the most efficient of all known molecules for absorbing the intense ultraviolet light that

penetrated the early atmosphere and are remarkably rapid in transforming this light (Michaelian, 2011).

Variations or pulses in the solar wind may also have determined variations in the ionizing radiation hitting the Earth (Wood et al., 2002; Svensmark, 2006). Ionizing radiation in terms of effective dosing determines DNA damage, which may be repaired, mis-repaired (determining mutation), or destroyed provoking the death of organisms (e.g., Nikjoo et al., 1998). Periods of stronger ionizing radiation reaching the Earth's surface may have prevented surface life's existence there, or could have enhanced either mutations or extinctions.

Extinctions do not appear to be controlled by magnetic reversals (Glassmeier and Vogt, 2010). However, although a firm relationship between extinction and magnetic field reversals is difficult to trace, there are suggestions that they may be related. Wei et al. (2014) for example, discussed oxygen loss due to a weakened dipole and mass extinction and some authors (Bazhenov et al., 2016; Meert et al., 2016) recently recognized hyperactive reversals during the late Ediacaran. Magnetic reversals may be quite fast (e.g., Bazhenov et al., 2016; Driscoll and Evans, 2016), whereas long periods of low magnetic dipole intensity of the same polarity, may decrease the effect of the magnetic field protecting the atmosphere, which is the primary UV shield. UV radiation can destroy or deeply modify the DNA of organisms on the surface of the planet. Extinction can be due to increases in exposure to cosmic radiation during a weakened dipole strength. Rapid magnetic reversals are periods of overall weaker dipole, thinning the magnetosphere and thus decreasing the shield to cosmic radiation (Meert et al., 2016).

Life appears to be controlled by the chaotic, unpredictable interplay of independent chemical and physical parameters, within the Earth, at its surface, and from remote space. Among the most relevant are volcanic degassing and its contribution to various chemical inventories, the surface temperature and pressure, solar radiation, and cosmic rays. The fragile balance of all these parameters controls the system. If only one of these controlling factors is beyond a certain limit, life cannot evolve or it disappears. In this paper, we explore the relationship between the evolutionary development of the Earth's magnetic field in relation with the Earth's cooling, the solar ionizing radiation and the development of complex life.

2. Core evolution, geodynamics and life

The early Earth was a mostly undifferentiated hot aggregate of planetesimal bodies. Since the early recognition of mantle convection, it was proposed that descending currents would tend to leave some of their denser constituents at the base of the mantle while less dense components rose to form the crust (Runcorn, 1962a,b). The heavy elements, in particular Fe and Ni, started to sink to the core, where the higher temperature maintained its liquid state. Convection was proposed also for the core and it has been associated with nucleation (Jacobs, 1953) and growth (Buffett et al., 1992) of the inner core. Irreversible mass redistribution within the core is controlled primarily by inner core growth, which has been calculated to occur at rates between 0.2 and 0.7 mm/yr (Morse, 2002). Moreover, the Earth's internal temperature and dissipating heat flow are lower than previously estimated (Hofmeister and Criss, 2005), and the cooling of the planet generates internal irreversible stratification (Anderson, 2002). The spin rate of our planet is decreasing due to the tidal interactions between the Moon and Earth (Varga et al., 1998). The age of the inner core growth is still debated, ranging between early accretion, and 3.5 to 0.5 Ga. The law of conservation of energy, when applied to the Earth's core and integrated between the onset of crystallization of the inner core and the present, gives an equation for the

age of the inner core (Labrosse et al., 2001). The age of the inner core can be obtained as a function of the heat flux at the core-mantle boundary and the concentrations of radioactive elements. It is found that in the absence of radioactive elements in the core, the age of the inner core varies between 0.5 and 2.5 Ga and is most likely around 1 Ga (Labrosse et al., 2001; Labrosse and Macouin, 2003). Other authors proposed different time spans for the core evolution since 3.5 Ga: e.g., Gubbins et al. (2004) discussed ages as old as 3.5 Ga, whereas Hale (1987) proposed an age of about 2.8 Ga. Aubert et al. (2010) indicated ages between 750 Ma and 1.8 Ga. Smirnov et al. (2011) suggested that before 3.5 Ga the whole core was liquid and may have not hosted a geodynamo. They also inferred that cold subduction zones reaching the core-mantle boundary might have enhanced the cooling of the core. Moreover Smirnov and Tarduno (2004) argued for variations in the intensity of the dipolar field, suggesting that it was stronger during the Neoarchean with respect to the Proterozoic. Biggin et al. (2015) observed an increase in both average magnetic field strength and variability occurring between 1.5 and 1 billion years ago, and they interpreted these data as the best evidence for the nucleation of the inner core occurring during this interval. Magnetic data for the entire Earth's history are unfortunately quite scarce. The virtual axial dipole moment (VADM), or the natural remanent magnetization (NRM), or the paleointensity of the magnetic dipole are quite variable through time. For example, Perrin and Shcherbakov (1997) and Heller et al. (2002) recognized a Mesozoic low of the magnetic dipole. Similarly Juarez et al. (1998) recognized an average magnetic dipole moment of about 4.2×10^{22} Am^2, half the present magnetic-field intensity. Orbital oscillations (e.g., eccentricity, obliquity) have been shown to be responsible for short-term variations in the intensity of the magnetic field (Channell et al., 1998).

We assume that the rotation of the inner core relative to the outer core (Zhang et al., 2005) contributes to the production of the Earth's magnetic field and its dipolar component. In the absence of an inner solid core, we might expect a weaker, or at least structurally different magnetic field. The dynamic and gravitational couplings between inner core, outer core, and mantle are extremely complex processes (e.g. Aubert and Dumberry, 2011 and references therein). The differential rotation of the inner core with respect to the fluid in the outer core supports generation of a stronger magnetic field. In fact, Tarduno et al. (2010) reported an up to 50% weaker early Earth magnetic field during the Archean, predicting larger loss of the atmosphere. Other authors suggested a magnetic field of a quarter of the present-day intensity (Miki et al., 2009). According to Biggin et al. (2009), the late Archean (2.7 Ga) magnetic field intensity was about 60% of the present day field. Schreider et al. (2011) suggested that during the last 570 Ma the strength of the dipolar geomagnetic field has increased by ∼40%. Recently, Biggin et al. (2015) provided relevant evidence for paleomagnetic field intensity variations suggesting Mesoproterozoic inner-core nucleation. The pattern of secular variation of the magnetic field suggests a lower frequency of polarity reversals 2.5 billion years ago with respect to the Phanerozoic (McFadden et al., 1991; Christensen and Aubert, 2006). However, this may be related to the paucity of data of the earlier Earth's magnetic history. Nevertheless, the modification of the solid inner core growth at the expense of the liquid outer core should generate a different pattern and intensity of the geomagnetic field (Biggin et al., 2008, 2009). The intensity of the geomagnetic field had several fluctuations. For example, Driscoll and Evans (2016) and Meert et al. (2016) hint at a 180−200 Myr frequency in superchrons perhaps preceded by intervals of magnetic field hyperactivity. The time-averaged field over the past 300 million year is only half of that today, and therefore as 'low' as in the Archean (e.g., Biggin et al., 2009).

The magnetic field is a fundamental shield for containing the rocky planets' atmospheres. The atmosphere is the primary shield against UV radiation and its thickness and composition determine its effective protection (Meert et al., 2016). Before the solidification of the inner core, the faster relative rotation of it relative to the external liquid core was obviously absent. This variation in time in Earth's dynamics should have modified the dipolar component of the magnetic field, which may have allowed the formation of a thicker atmosphere, and eventually the Ediacaran biota and the Cambrian explosion of life, also called Cambrian Evolutionary Radiation (CER, Meert et al., 2016). A correlation between extinctions and magnetic dipole lows has been documented at the end of the Ediacaran period, about 550 Ma (Meert et al., 2016). Terrestrial ecosystems did not develop en masse until later in the Paleozoic, but if life existed on land earlier than that, it was likely very simple. Therefore, the development of life on the surface of the Earth could help to constrain the age of a stronger shield operated by the magnetic field, possibly related to the inner core solidification, or to a decrease of the high-energy (X rays, gamma rays and UV) solar flux (as opposed to the gradual increase in lower energy luminosity).

3. Life parameters and early evolution

The main chemical compounds allowing the development of life may be defined by the acronym CHNOPS, their constituent elements, i.e., carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur. On the other hand, the most important physical parameters controlling life as we know today can be synthesized in TWALPI, i.e., the narrow Temperature window, the occurrence of Water in the liquid phase, the presence of suitable Atmosphere, the solar Light and related radiation, an adequate Pressure (atmospheric and gravitationally controlled), and the Ionizing radiation which must be sufficiently low. Plate tectonics contributed to mantle degassing and atmosphere refueling. Therefore, life on Earth is the result of the chaotic combination of several independent parameters. One of them is the shield exerted by the atmosphere and the magnetic field against solar and cosmic ionizing radiation.

The presence of life on Earth prior to the Late Heavy Bombardment (Gomes et al., 2005) is a mystery unlikely to be answered due to the lack of rock record. Therefore the existence of life before 3.9 Ga is speculative, although Abramov and Mojzsis (2009) combined thermal metamorphism and genetic modeling to suggest that life survived the LHB. The bacterial clades that survived are unknown. Interestingly, there is some support from both theoretical models (Cavalier-Smith, 2006a,b) and broadly conserved protein-coding genes (Wu et al., 2009) indicating a basal or near-basal branching for some of the most radiation- and temperature-resistant bacterial clades (Hadobacteria: *Thermus* and *Deinococcus*). By 3.45 Ga well-preserved stromatolites attest to the likely existence of (not necessarily oxygenic) photosynthetic bacteria, established in submarine environments (Allwood et al., 2009). Subsequent evolution produced cells with a greater degree of organization, including a separate nucleus, i.e. putative eukaryotes, possibly but arguably at about 1.8 Ga (Cavalier-Smith, 2006b; Knoll et al., 2006a). The next major step was the evolution of multicellular organisms, found preserved as the first macrofossils, including some of the Ediacaran biota, the earliest of which occur in sediments dated at 610 Myr, almost 70 Myr before the beginning of the Cambrian period. Surface-living microorganisms may have existed only shortly after this time, aided by the development of biofilms (Frols et al., 2009) or waxy compounds which prevented their drying out when the evaporative sediments in which they lived became desiccated (Finkelstein et al., 2010). Another essential for living on the surface of the Earth is protection from destruction

by radiation (Cockell and Horneck, 2001) and oxidative stress (Ardini et al., 2013). The most abundant and readily available radiation shield is water (e.g., Simonsen and Nealy, 1991), as shown in Fig. 2.

The prokaryote-to-eukaryote transition (eukaryogenesis) was accompanied by the origination of complex genetic mechanisms, including syngamy, karyogamy, and meiosis (Fig. 3). As meiotic genes are present in all major eukaryotic lineages, meiosis (sex) may have preceded the diversification of basal eukaryotes. The rise in O_2 by 2.4 Ga was probably toxic to Archean biota and in synergy with other environmental stresses (reactive oxygen species, desiccation) may have led to the development of features such as the endomembrane system and the acquisition of the mitochondrion (Gross and Bhattacharya, 2010).

Although new fossil evidence from Paleo-Neoproterozoic time points to an early establishment of eukaryotes, there is still considerable debate surrounding the exact age for this diversification and/or the classification of the fossils. Various kinds of evidences (organic biomarkers, body and trace fossils, geochemistry, and molecular clocks) have been used in the attempt to pinpoint the origin of eukaryotes. In spite of growing data (e.g., Knoll et al., 2006b; El Albani et al., 2010; Javaux et al., 2010), the Precambrian record of body fossils, and the relationships of the more complex microfossils (acritarchs) and larger enigmatic taxa such as *Grypania* (1.9 Ga), *Horodyskia* (1.5 Ga), *Parmia* (~1.0 Ga), and *Sinosabellidites* (0.8 Ga) in respect to extant eukaryote groups has proved particularly elusive. Several of these fossils have been interpreted as early eukaryotes, but their assignment to recent lineages is highly contentious (Berney and Pawlowski, 2006; Cavalier-Smith, 2006a,b; Parfrey et al., 2011), possibly indicating distinct attempts towards multicellularity and eukaryogenesis, unrelated to that
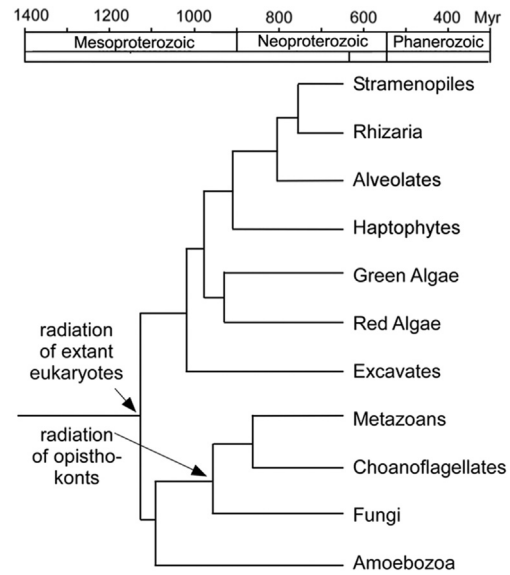

Figure 3. Robust molecular clocks constrain the early diversification of extant eukaryotes at not earlier than 1.2–1.1 Ga (simplified after Berney and Pawlowski, 2006).

leading to present-day eukaryotes. Alternatively, the first origin and the diversification of basal eukaryotes may not have been coincident because of physical factors (Yoon et al., 2004).

Whereas biomarkers (e.g., Brocks et al., 1999), molecular data (e.g., Yoon et al., 2004), and body and trace fossils have been often interpreted as indications of a much earlier origin for putative eukaryotes, some recent models integrating well-constrained fossil
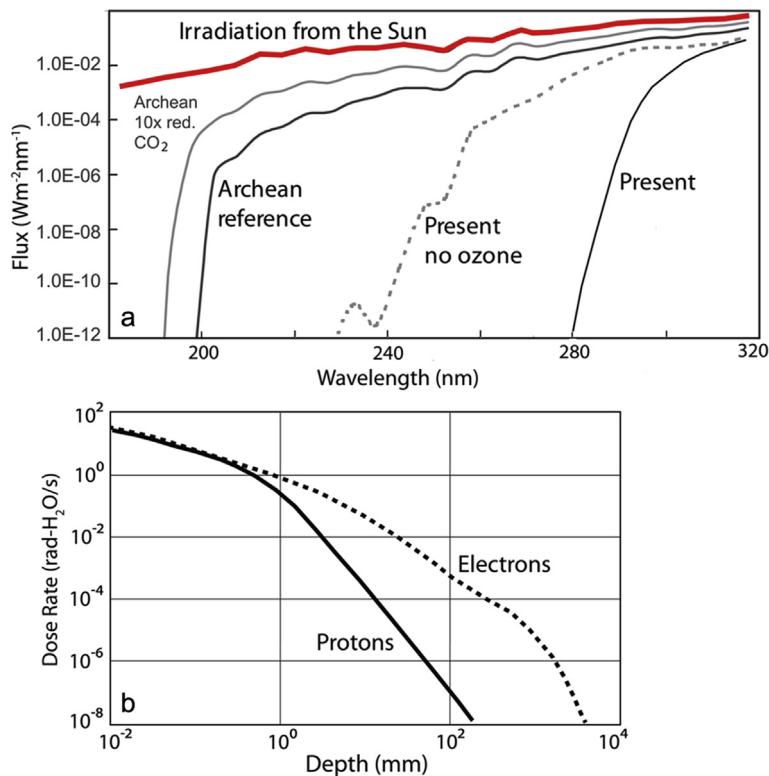
Figure 2. (a) Irradiation at the top of the atmosphere in the Archean and the surface irradiance for the Archean reference atmosphere and increasing CO_2 concentration, plus the present Earth with and without ozone (after Cnossen et al., 2007). (b) Attenuation of radiation at the surface of Europa by ice from Paranicas et al. (2002). The radiation environment of Europa is more extreme than an unshielded Earth. Note that deeper water is protected from radiation.
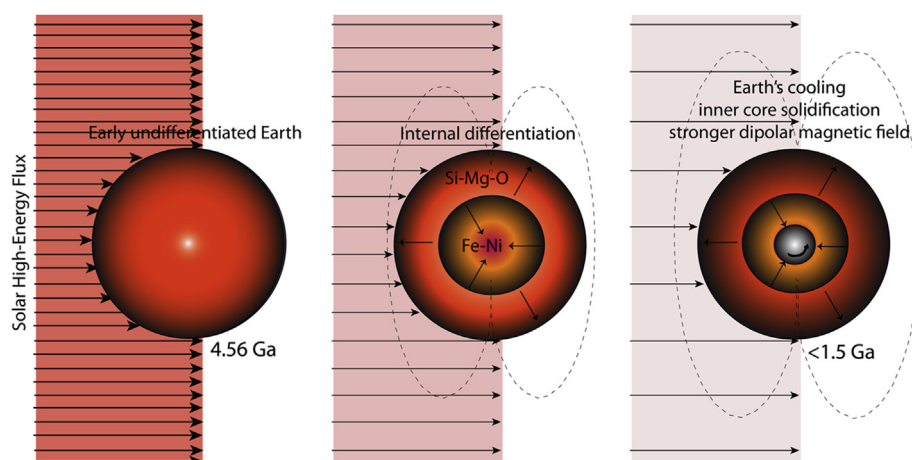
Figure 4. The early Earth was mostly undifferentiated, being a hot aggregate of planetesimals. The heavy elements started to sink, and the inner core initiated to solidify at about 1 (1.5−0.5) Ga due to the Earth's cooling. Since the solid inner core rotates faster than the external core, this possibly would have generated a stronger dipolar magnetic field and a thicker atmospheric shield. While the intensity of the magnetic dipole may have slightly increased, the high-energy solar flux hitting the Earth was decreasing. X rays and UV were 100−1000 times higher in the early stages with respect to the present solar radiation.

dates and robust molecular data suggest that the early diversification of extant basal eukaryotes did not occur earlier than 1.2−1.1 Ga, although molecular clock ages are somewhat contentious. By using the continuous microfossil record to calibrate eukaryote phylogeny, Berney and Pawlowski (2006) estimated that the basal split of extant eukaryotes into two main lineages, i.e. opisthokonts and amoebozoans vs. the remaining groups occurred near the Meso−Neoproterozoic boundary, ∼1.126 Ga (range of 948−1357 Ma) (Fig. 3). In this interpretation and using the systematic terminology of Berney and Pawlowski (2006), this basal radiation was shortly followed by the divergence of amoebozoans, opisthokonts and bikonts; interestingly, also other major eukaryotic lineages (animals, fungi, chromalveolates, red algae and green algae) radiated in the Neoproterozoic. Therefore, although their common root may be earlier, all major basal lineages of eukaryotes (Amoebozoa, Opisthokonta, SAR, Rhizaria, and Excavata) arose at about this time. In addition, the earliest fossils of putative non-marine eukaryotes are recorded in this timespan, between 1.2 and 1.0 Ga (Torridonian) (Strother et al., 2011). This is consistent with the idea that early eukaryotes should be associated with environments once exposed on the Earth's surface (Gross and Bhattacharya, 2010). The Archaea (archaebacteria) is one of the major groups among prokaryotes and may be considered as the sister group of eukaryotes. Therefore they should have had origin at about this time. The term Neomuran revolution has been proposed by Cavalier-Smith (2006a,b) to define this clade.

Thus, several lines of evidence suggest that the onset of the major phase of eukaryote basal diversification coincides with the formation of the Earth's solid inner core. In our interpretation, prior to this timespan, basal eukaryotes and bacteria were substantially affected by detrimental exposure to ionizing radiation, particularly in non-marine environments or in very few centimeter water-depth, possibly being counterbalanced by biofilm or waxy compound formation. After this early eukaryote (and possibly archaebacterial) diversification stage, between ca. 850−800 and 600−550 Ma, the Earth went through an extremely cold interval known as the Snowball Earth period (Kirschvink, 1992; Kopp et al., 2005), or Cryogenian. Four or five glacial periods, of which the severest and long-lasting was the Marinoan glaciation (650−635 Ma), affected the Earth prior to the appearance of the Ediacaran biota. In this timespan, the rise of oxygen levels (Holland, 2006) is correlated with increasing multicellularity (Payne et al.,

2009). Eukaryogenesis was thus gridlocked between ionizing, oxygen-poor and possibly ozone-less Archean and Proterozoic "Snowball Earth" conditions. There are disagreements about the divergence ages calculated from molecular clocks. However, since the error bars of the crystallization of the inner core age, the magnetic field intensity and the rate of ionizing radiation are even more uncertain, we consider this issue secondary for the topic of this research.

Oxygen is a fundamental parameter of life, but oxygen presence in the atmosphere is also an indication of life on Earth (Catling and Zahnle, 2002). Diatomic oxygen is primarily generated by oxygenic photosynthesis. Ancestral cyanobacteria are seen as major producers of free oxygen. The Earth's atmosphere is considered mostly anoxic before 2.3 Ga and life on the planet's surface also became protected from harmful ultraviolet radiation once O_2 levels exceeded 0.2−0.6%, causing an ozone (O_3) layer to form in the stratosphere (Catling and Zahnle, 2002). Variation in the size of fossil raindrop imprints has been used to constrain the past density of the atmosphere (e.g., Som et al., 2012).

4. Protection from radiation by water

Prior to the development of the stronger magnetic field, which protected the Earth from intense radiation, it is clear that life had evolved considerably and was abundant. This was possible only because of the radiation absorption powers of water allowing subaqueous microbial life to flourish. The main part of the radiation flux consists of electrons and protons from the solar wind, but also includes the most penetrating radiation, relatively heavy ions. The shielding effect of water can be demonstrated in a worst-case example. Jupiter has the most intense magnetosphere of all the planets in the solar system (Blanc et al., 2005), which focuses the solar wind particles in its vicinity. The surface of the Jovian moon Europa suffers intense radiation (Paranicas et al., 2007) and probably greater than that of an unshielded Earth. The depth of penetration in ice for Europa was calculated by Paranicas et al. (2002) and the intensity is attenuated by at least 6 orders of magnitude for even heavy ions in about 1 m depth of water (Fig. 2). For particles, attenuation is the same for both of ice and water. However, damaging electromagnetic radiation also would destroy life as demonstrated by the use of UVC light as a germicide. The longer wavelength UVB is also detrimental to life but all UV radiation is
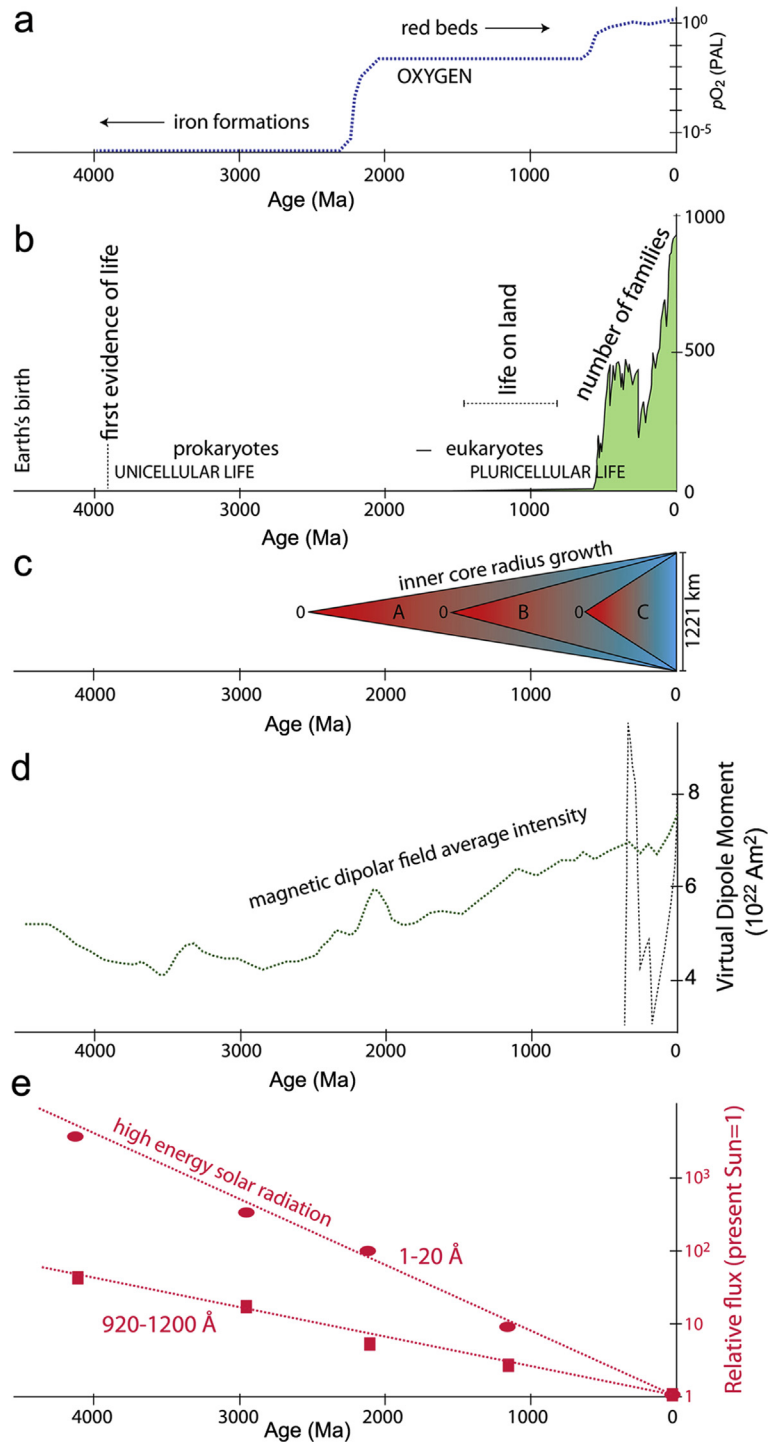
Figure 5. Comparison of a number of parameters. (a) Oxygen evolution (Catling and Zahnle, 2002; Lyons et al., 2014), *p*(O₂), atmospheric partial pressure of O₂, relative to the present atmospheric level (PAL). (b) Growth of the number of families (Labandeira and Sepkoski, 1993). (c) The initiation and thickening of the inner core development is still debated, ranging between either 2.5 (A) and 1.5 (B) or 0.5 (C) Ga (Labrosse and Macouin, 2003). (d) Modeled magnetic field average intensity (Roberts and Glatzmaier, 2001) or averaged virtual dipole moment for the last 400 Ma (Perrin and Shcherbakov, 1997). The magnetic dipole intensity is known to fluctuate, sometimes reaching zero, being the evolutionary curves only inferred average extrapolations. (e) Solar-normalized fluxes vs. age for different stages of the evolution of solar-type stars. Plotted here are the measurements for different wavelength intervals (filled symbols) and the corresponding fits using power-law relationships (after Ribas et al., 2005). The on-land fast growth of life occurred during or after the generation of the solid inner core that developed as a consequence of the Earth's cooling. In this interpretation, the dipolar magnetic field protecting the Earth's atmosphere from the solar wind, became more effective, and possibly even more important, the solar high-energy flux was decreasing.

attenuated by water although the extent of the attenuation depends on the depth and clarity versus lack of clarity of the water (e.g., Dunne and Brown, 1996). Its flux is reduced most dramatically in waters that have a high content of total dissolved organic

material, typical of life supporting marine waters. Furthermore, Glassmeier and Vogt (2010) noted that it is the interaction of solar protons with the upper atmosphere that may be more important in both thinning the ozone layer and stripping away oxygen (Wei

et al., 2014). Thus, solar radiation has a cascading effect on the biosphere rather than simply particle bombardment. Nevertheless, the shielding effects of water on UV-B radiation is important (Tedetti and Sempéré, 2006) and it would have allowed microbial evolution to occur under water while the Earth's core and magnetic field protection started to develop and at that stage near-surface non-marine life also became possible (Strother et al., 2011). Moreover, although generally interpreted as life-limiting, Snowball Earth conditions with snow and ice covers on the oceans may have favored radiation protection and enhanced photosynthesis (Cockell et al., 2002).

5. Discussion and conclusions

The evolution of complex life on Earth is a relatively recent phenomenon compared to the history of the planet. Prokaryotic organisms dominated the Earth for nearly 3 billion years. Some microbes are the organisms that are most resistant to ionizing radiation. Moreover they had a long evolutionary history. The solid inner core age is still unconstrained and it depends on the cooling gradient of the Earth.

The age of inner core nucleation is poorly constrained to sometime between 3.5 and 0.5 Ga (Labrosse et al., 2001; Aubert et al., 2010). Following nucleation, the growth of the inner core has proceeded at the expense of the liquid outer core (Runcorn, 1962a,b). If there is a relationship between the size of the inner core, the stability of the magnetic field and biological evolution, then we prefer an age of the inner core to be around 1 Ga.

Before the crystallization of the core, we hypothesize an average dipolar magnetic field of lower intensity than today's, since there was no relative rotation between inner and outer core. Moreover there was a thicker convective fluid core, all providing a weaker shield.

The solid inner core has a faster rotation rate toward the east relative to the mantle (Alboussiere et al., 2010; Dumberry and Mound, 2010). This should have generated a stronger and possibly more stable dipolar magnetic field (Fig. 4) counteracting a decreasing solar ionizing flux. The fast diversification of basal eukaryotes may have been triggered by a more stable atmosphere as a consequence of the stronger magnetic shield exerted by the newly developed rotating solid inner core and a weaker X-ray, gamma ray and UV flux (Fig. 5). Therefore we speculate that the development of life on Earth was significantly affected by the growth of the solid inner core and the natural evolution of our star. However, Aubert et al. (2010) argued that only small changes in the magnetic field occurred since the early Earth, too small to have major effects on magnetosphere shielding efficiency. The amount of the inner core rotation relative to the outer core is also questioned (Aubert et al., 2010). The strength of the magnetic field should increase in the core itself, possibly being related also to the tidally sheared liquid outer core (Buffett, 2010). Regardless of which hypothesis of evolution of the core is correct, the growth of the solid inner core necessarily determined a variation in the thickness of the fluid outer core and its internal convection pattern, plus the stability and intensity of the geodynamo (Roberts and Glatzmaier, 2001; Biggin et al., 2008). Moreover, Sun-like stars with ages of ~1 Gyr are observed to have more frequent and energetic X-ray flares than those of the current Sun (Telleschi et al., 2005). According to Tarduno et al. (2010), magnetic field and stronger solar wind strengths suggest important modifications during the first billion years of Earth evolution, possibly associated with a weaker thermal convection only driven dynamo. Studies of the evolution of Sun-type stars suggest that the Sun could emit high-energy flux (X-rays to UV) up to 1000 times stronger than the present flux during the early stages, gradually decreasing to 6 times 3.5 Ga, and to 2.5

times 2.5 Ga (Ribas et al., 2005, 2010). Therefore, besides the shielding effect of the Earth's magnetosphere, the Earth was hit by a much stronger ionizing flux in the past, which could have inhibited the evolution of surface life during the earlier stages of the Earth's history.

The rise of eukaryotes and explosion of life on Earth could help to constrain the development of the inner core age at an age <1.5 Ga due to Earth's cooling. At the moment is impossible to constrain the time lag between the generation of a habitable environment and the required biological time allowing families to differentiate. Regardless of whether our model is robust or not, there should have been a chemical-physical threshold which allowed the major pulse of eukaryote evolution and the Cambrian explosion of life in order to allow the diversification of life on land, once ionizing radiation became less damaging than in the early Earth.

References

Abramov, O., Mojzsis, S.J., 2009. Microbial habitability of the Hadean Earth during the Late Heavy Bombardment. Nature 459 (7245), 419–422.

Alboussiere, T., Deguen, R., Melzani, M., 2010. Melting-induced stratification above the Earth's inner core due to convective translation. Nature 466 (7307), 744–747.

Allwood, A.C., Grotzinger, J.P., Knoll, A.H., Burch, I.W., Anderson, M.S., Coleman, M.L., Kanik, I., 2009. Controls on development and diversity of Early Archean stromatolites. Proceedings of the National Academy of Sciences of the United States of America 106, 9549–9555.

Anderson, D.L., 2002. The case for irreversible chemical stratification of the mantle. International Geology Reviews 44, 97–116.

Ardini, M., Fiorillo, A., Fittipaldi, M., Stefanini, S., Gatteschi, D., Ilari, A., Chiancone, E., 2013. Kineococcus radiotolerans Dps forms a heteronuclear Mn–Fe ferroxidase center that may explain the Mn-dependent protection against oxidative stress. Biochimica et Biophysica Acta (BBA)-General Subjects 1830 (6), 3745–3755.

Aubert, J., Tarduno, J.A., Johnson, C.L., 2010. Observations and models of the long-term evolution of Earth's magnetic field. Space Science Reviews 155, 337–370.

Aubert, J., Dumberry, M., 2011. Steady and fluctuating inner core rotation in numerical geodynamo models. Geophysical Journal International 184, 162–170.

Bazhenov, M.L., Levashova, N.M., Meert, J.G., Golovanova, I.V., Danukalov, K.N., Federova, N.M., 2016. Late Ediacaran magnetostratigraphy of Baltica: evidence for magnetic field hyperactivity? Earth and Planetary Science Letters 435, 124–135.

Berney, C., Pawlowski, J., 2006. A molecular time-scale for eukaryote evolution recalibrated with the continuous microfossil record. Proceedings of the Royal Society (B, Biological Sciences) 273, 1867–1872.

Bibring, J.P., Squyres, S.W., Arvidson, R.E., 2006. Merging views on Mars. Science 313, 1899–2001.

Biggin, A.J., Strik, G.H.M.A., Langereis, C.G., 2008. Evidence for a very-long-term trend in geomagnetic secular variation. Nature Geoscience 1, 395–398.

Biggin, A.J., Strik, G.H.M.A., Langereis, C.G., 2009. The intensity of the geomagnetic field in the late-Archaean: new measurements and an analysis of the updated IAGA palaeointensity database. Earth, Planets and Space 61, 9–22.

Biggin, A.J., Piispa, L.J., Pesonen, E.J., Holme, R., Paterson, G.A., Veikkolainen, T., Tauxe, L., 2015. Palaeomagnetic field intensity variations suggest Mesoproterozoic inner-core nucleation. Nature 526, 245–248. http://dx.doi.org/10.1038/nature15523.

Blanc, M., Kallenbach, R., Erkaev, N.V., 2005. Solar system magnetospheres. Space Science Reviews 116, 227–298. http://dx.doi.org/10.1007/s11214-005-1958-y.

Brain, D.A., McFadden, J.P., Halekas, J.S., Connerney, J.E.P., Bougher, S.W., Curry, S., Dong, C.F., Dong, Y., Eparvier, F., Fang, X., et al., 2015. The spatial distribution of planetary ion fluxes near Mars observed by MAVEN. Geophysical Research Letters 42, 9142–9148. http://dx.doi.org/10.1002/2015GL065293.

Brocks, J.J., Logan, G.A., Buick, R., Summons, R.E., 1999. Archean molecular fossils and the early rise of eukaryotes. Science 285, 1033–1036.

Buffett, B.A., 2010. Tidal dissipation and the strength of the Earth's internal magnetic field. Nature 468 (7326), 952–954.

Buffett, B.A., Huppert, H.E., Lister, J.R., Woods, A.W., 1992. Analytical model for solidification of the Earth's core. Nature 356, 329–331.

Carslaw, K.S., Harrison, R.G., Kirkby, J., 2002. Cosmic rays, clouds, and climate. Science 298 (5599), 1732–1737.

Catling, D., Zahnle, K., 2002. Evolution of atmospheric oxygen. In: Encyclopedia of Atmospheric Science. Elsevier, pp. 754–761.

Cavalier-Smith, T., 2006a. Rooting the tree of life by transition analyses. Biology Direct 1, 19. http://dx.doi.org/10.1186/1745-6150-1-19.

Cavalier-Smith, T., 2006b. Cell evolution and Earth history: stasis and revolution. Philosophical Transactions of the Royal Society (B, Biological Sciences) 361, 969–1006.

Channell, J.E.T., Hodell, D.A., McManus, J., Lehman, B., 1998. Orbital modulation of the Earth's magnetic field intensity. Nature 394 (6692), 464–468.

Christensen, U.R., Aubert, J., 2006. Scaling properties of convection-driven dynamos in rotating spherical shells and application to planetary magnetic fields. Geophysical Journal International 166, 97–114. http://dx.doi.org/10.1111/j.1365-246X.2006.03009.x.

Cnossen, I., Sanz-Forcada, J., Favata, F., Witasse, O., Zegers, T., Arnold, N.F., 2007. Habitat of early life: solar X-ray and UV radiation at Earth's surface 4–3.5 billion years ago. Journal of Geophysical Research 112, E02008. http://dx.doi.org/10.1029/2006JE002784.

Cockell, C.S., 2000. Ultraviolet radiation and the photobiology of earth's early oceans. Origins of Life and Evolution of Biospheres 30, 467–499.

Cockell, C.S., Horneck, G., 2001. The history of the UV radiation climate of the earth—theoretical and space-based observations. Photochemistry and Photobiology 73, 447–451.

Cockell, C.S., Rettberg, P., Horneck, G., Wynn-Williams, D.D., Scherer, K., Gugg-Helminger, A., 2002. Influence of ice and snow covers on the UV exposure of terrestrial microbial communities: dosimetric studies. Journal of Photochemistry and Photobiology B: Biology 68, 23–32.

Driscoll, P.E., Evans, D.A.D., 2016. Frequency of proterozoic geomagnetic superchrons. Earth and Planetary Science Letters 437, 9–14.

Dumberry, M., Mound, J., 2010. Inner core–mantle gravitational locking and the super-rotation of the inner core. Geophysical Journal International 181 (2), 806–817.

Dunne, R.P., Brown, B.E., 1996. Penetration of solar UVB radiation in shallow tropical waters and its potential biological effects on coral reefs; results from the central Indian Ocean and Andaman Sea. Marine Ecology Progress Series 144, 109–118.

Edberg, N.J.T., Nilsson, H., Williams, A.O., Lester, M., Milan, S.E., Cowley, S.W.H., Fränz, M., Barabash, S., Futaana, Y., 2010. Pumping out the atmosphere of Mars through solar wind pressure pulses. Geophysical Research Letters 37, L03107. http://dx.doi.org/10.1029/2009GL041814.

El Albani, A., Bengtson, S., Canfield, D.E., Bekker, A., Macchiarelli, R., Mazurier, A., Hammarlund, E.U., Boulvais, P., Dupuy, J.-J., Fontaine, C., Fürsich, F.T., Gauthier-Lafaye, F., Janvier, P., Javaux, E., Ossa Ossa, F., Pierson-Wickmann, A.-C., Riboulleau, A., Sardini, P., Vachard, D., Whitehouse, M., Meunier, A., 2010. Large colonial organisms with coordinated growth in oxygenated environments 2.1 Gyr ago. Nature 466, 100–104.

Finkelstein, D.B., Brassell, S.C., Pratt, L.M., 2010. Microbial biosynthesis of wax esters during desiccation: adaptation or colonization of the earliest terrestrial environments? Geology 38, 247–250.

Frols, S., White, M.F., Schleper, C., 2009. Reactions to UV damage in the model archaeon Sulfolobus solfataricus. Biochemical Society Transactions 37 (1), 36–41.

Glassmeier, K.-H., Vogt, J., 2010. Magnetic polarity transitions and biospheric effects. Space Science Reviews 155, 387–410.

Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., 2005. Origin of the cataclysmic late heavy bombardment period of the terrestrial planets. Nature 435 (7041), 466–469. http://dx.doi.org/10.1038/nature03676.

Gould, S.J., 1989. Wonderful Life: the Burgess Shale and the Nature of History. W.W. Norton & Co., New York.

Gould, S.J., 1995. Paleontology - of it, not above it. Nature 377, 681–682.

Gross, J., Bhattacharya, D., 2010. Uniting sex and eukaryote origins in an emerging oxygenic world. Biology Direct 5, 53. http://dx.doi.org/10.1186/1745-6150-5-53. http://www.biology-direct.com/content/5/1/53.

Gubbins, D., Alfe, D., Masters, G., Price, G.D., Gillian, M., 2004. Gross thermodynamics of two-component core convection. Geophysical Journal International 157, 1407–1414.

Hale, C.J., 1987. Paleomagnetic data suggest link between the Archean-Proterozoic boundary and inner-core nucleation. Nature 338, 496–499.

Heller, R., Merrill, R.T., McFadden, P.L., 2002. The variation of intensity of earth's magnetic field with time. Physics of the Earth and Planetary Interiors 131 (3), 237–249.

Hofmeister, A.M., Criss, R.E., 2005. Criss Earth's heat flux revised and linked to chemistry. Tectonophysics 395, 159–177.

Holland, H.D., 2006. The oxygenation of the atmosphere and oceans. Philosophical Transactions of the Royal Society (B, Biological Sciences) 361 (1470), 903–915.

Hunten, D.M., 1993. Atmospheric evolution of the terrestrial planets. Science 259 (5097), 915–920.

Jacobs, J.A., 1953. The Earth's inner core. Nature 172, 297–298.

Jakosky, B.M., Grebowsky, J.M., Luhmann, J.G., et al., 2015. MAVEN observations of the response of Mars to an interplanetary coronal mass ejection. Science 350, 6261. http://dx.doi.org/10.1126/science.aad0210.

Javaux, E.J., Marshall, C.P., Bekker, A., 2010. Organic-walled microfossils in 3.2-billion-year-old shallow-marine siliciclastic deposits. Nature 463, 934–938. http://dx.doi.org/10.1038/nature08793.

Juarez, M.T., Tauxe, L., Gee, J.S., Pick, T., 1998. The intensity of the Earth's magnetic field over the past 160 million years. Nature 394 (6696), 878–881.

Jurdy, D.M., Stefanick, M., 2004. Vertical extrapolation of Mars magnetic potentials. Journal of Geophysical Research 109, E10005. http://dx.doi.org/10.1029/2004JE002277.

Kataoka, R., Ebisuzaki, T., Miyahara, H., Nimura, T., Tomida, T., Sato, T., Maruyama, S., 2014. The Nebula winter: the united view of the snowball Earth, mass extinctions, and explosive evolution in the late Neoproterozoic and Cambrian periods. Gondwana Research 25 (3), 1153–1163.

Kirschvink, J.L., 1992. Late proterozoic, low-latitude global glaciation: the snowball earth. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere: a Multidisciplinary Study. Cambridge University Press, Cambridge, pp. 51–52.

Kivelson, G.M., Russell, C.T., 1995. Introduction to Space Physics. Cambridge University Press, Cambridge, p. 567.

Knoll, A.H., Javaux, E.J., Hewitt, D., Cohen, P., 2006a. Eukaryotic organisms in Proterozoic oceans. Philosophical Transactions of the Royal Society (B, Biological Sciences) 361, 1023–1038.

Knoll, A.H., Walter, M.R., Narbonne, G.M., Christie-Blick, N., 2006b. The Ediacaran period: a new addition to the geologic time scale. Lethaia 39, 13–30.

Kopp, R.E., Kirschvink, J.L., Hilburn, I.A., Nash, C.Z., 2005. The Paleoproterozoic snowball Earth: a climate disaster triggered by the evolution of oxygenic photosynthesis. Proceedings of the National Academy of Sciences of the United States of America 102 (32), 11131–11136.

Labandeira, C.C., Sepkoski, J.J., 1993. Insect diversity in the fossil record. Science 261, 310–315.

Labrosse, S., Macouin, M., 2003. The inner core and the geodynamo. Comptes Rendus Geoscience 335, 37–50.

Labrosse, S., Poirier, J.-P., Le Mouël, J.-L., 2001. The age of the inner core. Earth and Planetary Science Letters 190, 111–123.

Lundin, R., 2001. Erosion by the solar wind. Science 291 (5510), 1909.

Lyons, T.W., Reinhard, C.T., Planavsky, N.J., 2014. The rise of oxygen in Earth's early ocean and atmosphere. Nature 506 (7488), 307–315.

Maruyama, S., Ikoma, M., Genda, H., Hirose, K., Yokoyama, T., Santosh, M., 2013. The naked planet Earth: most essential pre-requisite for the origin and evolution of life. Geoscience Frontiers 4, 141–165.

McFadden, P.L., Merrill, R.T., McElhinny, M.W., Lee, S.H., 1991. Reversals of the earths magnetic-field and temporal variations of the dynamo families. Journal of Geophysical Research 96, 3923–3933.

Meert, J.G., Levashova, N.M., Bazhenov, M.L., Landing, E., 2016. Rapid changes of magnetic field polarity in the Late Ediacaran: linking the Cambrian evolutionary radiation and increased UV-B radiation. Gondwana Research 34, 149–157.

Michaelian, K., 2011. Thermodynamic dissipation theory for the origin of life. Earth System Dynamics 2, 37–51.

Miki, M., Taniguchi, A., Yokoyama, M., Gouzu, C., Hyodo, H., Uno, K., Zaman, H., Otofuji, Y., 2009. Palaeomagnetism and geochronology of the proterozoic dolerite dyke from southwest Greenland: indication of low palaeointensity. Geophysical Journal International 179, 18–34.

Miller, S.J., 1953. A production of amino acids under possible primitive Earth conditions. Science 117, 528–529.

Minelli, A., 2011. Animal development, an open-ended segment of life. Biological Theory 6, 4–15.

Morse, S.A., 2002. No mushy zones in the Earth's core. Geochimica et Cosmochimica Acta 66, 2155–2165.

Nikjoo, H., O'Neill, P., Terrissol, M., Goodhead, D.T., 1998. Quantitative modelling of DNA damage using Monte Carlo track structure method. Radiation and Environmental Biophysics 38 (1), 31–38. http://dx.doi.org/10.1007/s004110050135.

Paranicas, C., Mauk, B.H., Ratliff, J.M., Cohen, C., Johnson, R.E., 2002. The ion environment near Europa and its role in surface energetics. Geophysical Research Letters 29, 18–1-18-4.

Paranicas, C., Mauk, B.H., Khurana, K., Jun, I., Garrett, H., Krupp, N., Roussos, E., 2007. Europa's near-surface radiation environment. Geophysical Research Letters 34, L15103. http://dx.doi.org/10.1029/2007GL030834.

Parfrey, L.W., Lahr, D.J., Knoll, A.H., Katz, L.A., 2011. Estimating the timing of early eukaryotic diversification with multigene molecular clocks. Proceedings of the National Academy of Sciences 108 (33), 13624–13629.

Payne, J.L., Boyer, A.G., Brown, J.H., Finnegan, S., Kowalewski, M., Krause Jr., R.A., Lyons, S.K., McClain, C.R., McShea, D.W., Novack-Gottshall, P.M., Smith, F.A., Stempien, J.A., Wang, S.C., 2009. Two-phase increase in the maximum size of life over 3.5 billion years reflects biological innovation and environmental opportunity. Proceedings of the National Academy of Sciences of the United States of America 106 (1), 24–27.

Perrin, M., Shcherbakov, V., 1997. Paleointensity of the Earth's magnetic field for the past 400 Ma: evidence for a dipole structure during the Mesozoic Low. Journal of Geomagnetism and Geoelectricity 49 (4), 601–614.

Ribas, I., De Mello, G.P., Ferreira, L.D., Hébrard, E., Selsis, F., Catalán, S., Garcés, A., do Nascimento Jr., J.D., De Medeiros, J.R., 2010. Evolution of the solar activity over time and effects on planetary atmospheres. II. κ1 Ceti, an analog of the Sun when life arose on Earth. The Astrophysical Journal 714 (1), 384–395.

Ribas, I., Guinan, E.F., Güdel, M., Audard, M., 2005. Evolution of the solar activity over time and effects on planetary atmospheres. I. High-energy irradiances (1-1700 Å). The Astrophysical Journal 622 (1), 680–694.

Roberts, P.H., Glatzmaier, G.A., 2001. The geodynamo, past, present and future. Geophysical and Astrophysical Fluid Dynamics 94, 47–84.

Runcorn, S.K., 1962a. Towards a theory of continental drift. Nature 193, 311–314.

Runcorn, S.K., 1962b. Convection currents in the Earth's mantle. Nature 195, 1248–1249.

Russell, M.J., 2007. The alkaline solution to the emergence of life: energy, entropy and early evolution. Acta Biotheoretica 55, 133–179.

Santosh, M., Maruyama, S., Sawaki, Y., Meert, J.G., 2014. The Cambrian explosion: plume-driven birth of the second ecosystem on earth. Gondwana Research 25 (3), 945–965.

Schreider, A.A., Schreider, Al.A., Varga, P., Denis, C., 2011. Variations of the Earth's magnetic field in the Phanerozoic. Oceanology 51 (3), 505–509.

Seki, K., Elphic, R.C., Hirahara, M., Terasawa, T., Mukai, T., 2001. On atmospheric loss of oxygen ions from Earth through magnetospheric processes. Science 291, 1939–1941.

Simonsen, L.C., Nealy, J.E., 1991. Radiation protection for human missions to the Moon and Mars. NASA Technical Paper 3079, 1–25.

Smirnov, A.V., Tarduno, J.A., 2004. Secular variation of the Late Archean-early Proterozoic geodynamo. Geophysical Research Letters 31, L16607. http://dx.doi.org/10.1029/2004GL020333.

Smirnov, A.V., Tarduno, J.A., Evans, D.A.D., 2011. Evolving core conditions ca. 2 billion years ago detected by paleosecular variation. Physics of the Earth and Planetary Interiors 187 (3–4), 225–231.

Som, S.M., Catling, D.C., Harnmeijer, J.P., Polivka, P.M., Buick, R., 2012. Air density 2.7 billion years ago limited to less than twice modern levels by fossil raindrop imprints. Nature 484 (7394), 359–362.

Strother, P.K., Battison, L., Brasier, M.D., Wellman, C.H., 2011. Earth's earliest non-marine eukaryotes. Nature 473 (7348), 505–509.

Svensmark, H., 2006. Cosmic rays and the biosphere over 4 billion years. Astronomische Nachrichten 327, 871–879.

Tarduno, J.A., Cottrell, R.D., Watkeys, M.K., Hofmann, A., Doubrovine, P.V., Mamajek, E.E., Liu, D., Sibeck, D.G., Neukirch, L.P., Usui, Y., 2010. Geodynamo, solar wind, and magnetopause 3.4 to 3.45 billion years ago. Science 327 (5970), 1238–1240. http://dx.doi.org/10.1126/science.1183445.

Tedetti, M., Sempéré, R., 2006. Penetration of ultraviolet radiation in the marine environment. A review. Photochemistry and Photobiology 82, 389–397.

Telleschi, A., Güdel, M., Briggs, K., Audard, M., Ness, J.-U., Skinner, S.L., 2005. Coronal evolution of the Sun in time: high-resolution X-ray spectroscopy of solar analogs with different ages. Astrophysical Journal 622, 653–679.

Tsyganenko, N.A., 1995. Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause. Journal of Geophysical Research 100 (A4), 5599–5612.

Varga, P., Denis, C., Varga, T., 1998. Tidal friction and its consequences in palaeogeodesy, in the gravity field variations and in tectonics. Journal of Geodynamics 25 (1), 61–84.

Wei, Y., Pu, Z., Zong, Q., Wan, W., Ren, Z., Fraenz, M., Dubin, E., Tian, F., Shi, Q., Fu, S., Hong, M., 2014. Oxygen escape from Earth during magnetic reversals: implications to mass extinctions. Earth and Planetary Science Letters 394, 94–98.

Wood, B., Muller, H., Zank, G., Linsky, J., 2002. Measured mass-loss rates of solar-like stars as a function of age and activity. Astrophysical Journal 574, 412–425.

Wu, D., 33 others, 2009. A phylogeny-driven genomic encyclopaedia of Bacteria and Archaea. Nature 462 (7276), 1056–1060. http://dx.doi.org/10.1038/nature08656.

Yoon, H.S., Hackett, J.D., Ciniglia, C., Pinto, G., Bhattacharya, D., 2004. A molecular timeline for the origin of photosynthetic eukaryotes. Molecular Biology and Evolution 21 (5), 809–818.

Zhang, X., Shu, D., Han, J., Zhang, Z., Liu, J., Fu, D., 2014. Triggers for the Cambrian explosion: hypotheses and problems. Gondwana Research 25 (3), 896–909.

Zhang, J., Song, X., Li, Y., Richards, P.G., Sun, X., Waldhauser, F., 2005. Inner core differential motion confirmed by earthquake waveform doublets. Science 309 (5739), 1357–1360.