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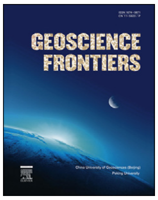

Research paper

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

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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.

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

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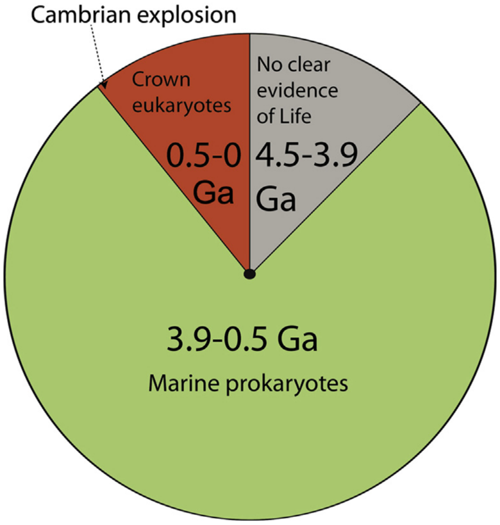

Figure 1. For much of its history, Earth was dominated by marine prokaryotes, protected by water from ionizing radiation.

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, misrepaired (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