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Milky Way Influenced Phanerozoic Cycles, Proterozoic Episodes, Global Catastrophes, Climate and the Evolution of Life on Earth: Review and Analysis

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Abstract

A compilation of many different kinds of natural scientific investigations and their interrelations as well as their collective interpretation are necessary to understand past, presence and future of the Earth's system adequately. This has been tried with somehow surprising results in this paper. Milky Way related cycles on Earth of 150 Myr duration as observed for the Phanerozoic Eon are obviously not dominant in the Proterozoic Eon. Only a very weak galactic signal due to periodic occurrences of phosphorous may be present that has entered the Earth from exploding stars. The Phanerozoic can be defined as an eon with very sensitive geophysical, geological, meteorological and biological reactions. The accelerated reactions from a 400 Myr to a 300 Myr cycle of mineral ages and continental tectonics include a generally high surface temperature with glacial interruptions, high oxygen and ozone values in the atmosphere, increase of the strength of the magnetic field and the rise of the asteroid impact rate witness those sensitives. It cannot be excluded after analyzing all related data that 1) Asteroid impacts stabilized and strengthened the Earth's magnetic field, 2) apparently the acceleration of geodynamic processes on Earth after weakening of the dynamics of Earth's core (geodynamo) is Milky Way supported, 3) the life spending biologically produced oxygen and its ozone derivative can influence Earth's climate significantly, and 4) somehow time coordinated events like asteroid impacts, Earth's core dynamics, nearby exploding stars, solar system pathway through dusty spiral arms, plate tectonics, a speculative companion of the Sun (or something else) and oxygen production via photosynthesis were essential ingredients for the remarkable success of life on Earth.

Keywords

Spiral arms, Supernovae, Asteroid Impacts, Magnetic Field, Phosphorous, Oxygen, Ozone

1. Introduction

> Study the past if you would define the future—Confucius

The history of the Earth is a history of cycles, episodes, catastrophes and of the ignition and the evolution of life. The evolution of life is severely influenced by geodynamic processes. It adopted their limitations and reacted as a co-driver in a complex feedback system. The most important ingredient of life became oxygen with its ability for sound chemical reactions. The history of oxygen on Earth is full of dramatic changes that altered the life and its geological, hydrological and atmospheric environment contemporaneously. This is partly demonstrated in **Figure 1**.

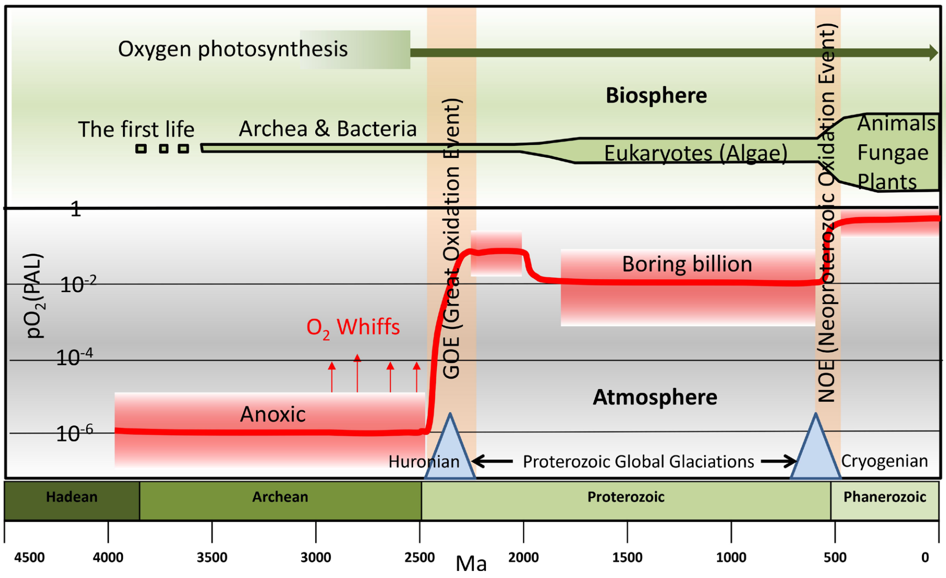

Figure 1. Evolution of life within the biosphere and Evolution of atmospheric oxygen levels relative to the present atmospheric level (PAL). Modified from [1].

Life requires only a selected subset of chemical elements. The major macromolecules of the cell account for the bulk of life's mass and are composed almost entirely of six elements (C, H, N, O, P, and S; abbreviated as CHNOPS), completed by ions (Mg, K, Na, Ca) together with a small but variable set of trace elements (micronutrients). The macromolecules include the DNA genome, RNA as genetic messenger (mRNA) and for protein synthesis (rRNA, tRNA) and regulation, and proteins [2].

The probable main origin of chemical elements are processes like big bang fusion, cosmic ray fission, dying low-mass stars, merging neutron stars, exploding massive stars and exploding white dwarfs, each one associated with a specific selection of elements of the periodic table (**Figure 2**). Birth and death of stars of the Milky Way are dominantly related to their location within the spiral arms. However, some cosmic marginal origins of chemical elements may also exist. As all chemical elements are available on Earth, all kinds of star deaths contributed to the composition of the interstellar cloud as source for the body of planet Earth. Later cosmic dust injections by near explosions of younger stars delivered further contributions to atmosphere, ocean and continents.

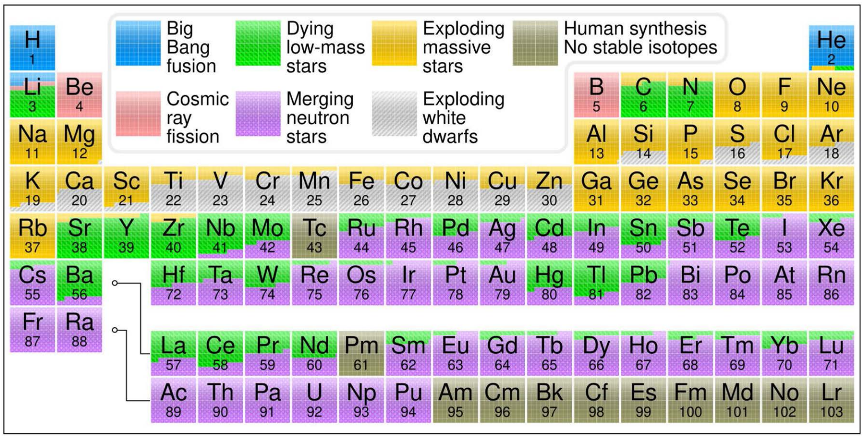

Figure 2. A version of the periodic table indicating the probable main origin of elements found on Earth. All elements past plutonium (element 94) are man-made. Reference: Cmglee—Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31761437, 2017.

Atmospheric oxygen has evolved from negligible levels in the Archean to the current level of about 21% through 2 major step rises: The Great Oxidation Event (GOE) in the early Proterozoic and the Neoproterozoic Oxygenation Event (NOE) during the late Proterozoic [3].

As oxygen levels in the atmosphere and ocean have changed dramatically over Earth history, it led to major impacts on marine life. Because the early part of Earth's history lacked both atmospheric oxygen and animals, a persistent co-evolutionary narrative has developed linking oxygen change with changes in animal diversity. Although it was long believed that oxygen rose to essentially modern levels around the Cambrian period, a more muted increase is now believed likely. Thus, if oxygen increase facilitated the Cambrian explosion, it did so by crossing critical ecological thresholds at low O_2 [4].

The long history of life on Earth has unfolded as a cause-and-effect relationship with the evolving amount of oxygen (O_2) in the biosphere. Oxygen deficiency characterized our planet's first 2 billion years, yet evidence for biological O_2 production and local enrichments in the surface ocean appear long before the first accumulations of O_2 in the atmosphere roughly 2.4 to 2.3 billion years ago [5].

Molecular oxygen in our atmosphere became the source for ozone (or trioxygen) is an inorganic molecule with the chemical formula O_3. Ozone is formed from O_2 with the help of ultraviolet (UV) light and electrical discharges within the Earth's atmosphere. The ozone layer formed with the early Proterozoic oxygenation. While oxygen itself has only minor radiative and climatic effects, the accompanying ozone has important consequences for Earth climate. Under a constant CO_2 level, the global-mean surface temperature decreases with decreasing ozone, with a maximum drop of ~3.5˚C at near total ozone removal. Therefore, the life itself keeps the Earth warm through the release of oxygen [6]. As part of a kind of balance the consumption of CO_2 by life cools the atmosphere down.

The survival of the life on Earth was not a given gift but depended on its gifted ability to get adapted to all the circumstances the planet Earth was dealing with. These circumstances were very slow to very fast changing environments due to geodynamic cycling, erratic episodes, and internal (e.g. volcanism) and external (e.g. asteroid impacts) catastrophes, which partly occurred periodically. One important topic of this paper is the question, whether the obvious Phanerozoic cycles had precursors in the Proterozoic and Archean Eons or are they unique. In the following chapters, the Phanerozoic cycles, the transition from the Proterozoic to the Phanerozoic Eon and Proterozoic episodes and cycles will be discussed.

To the knowledge of the author no similar compilation of geological, geophysical, meteorological, mineralogical, biological, and astronomical data and their collective interpretation concerning their significance for the Earth's history and future has been carried out so far. The novelty of the presented work will include new sights on the significance of asteroid impacts and of exploding life as one agent of Earth's sensitivities to (cyclical) galactic forces.

2. Phanerozoic Cycles

The explosion of life on Earth characterizes the Phanerozoic Eon with its specific cyclic, episodic and catastrophic geological environment. For example, the power spectrum of relative sea level change has been estimated over more than 15 orders of magnitude in frequency, from a frequency of about 1/(600 Ma) to a frequency of 1/(5 s) [7].

All these cycles include dominant geodynamic periods of about 600, 300, and 150 million years. They represent among others plate tectonic processes, sea level (**Figure 3**) and magmatic variations, fluctuations of the Earth's magnetic field (**Figure 4**), climate change, and the deposition of petroleum source rocks (**Figure 5**) [8]-[10]. Similar cycles have been detected by the analysis of the pathway of the solar system through the spiral arms of the Milky Way and their effect on the development of glaciation epochs on Earth (**Figure 6**) [11]-[13]. An interrelationship between the cycles of the Earth system and the ones of the Milky Way structure can convincingly be assumed (**Figure 7**) [14].

The spiral arms are preferred birth places of new stars, of which the larger ones have much smaller lifespans and die already within or close to their spiral arm. Their preliminary deaths ended quite often with explosions and selectively with the development of so-called white dwarfs, neutron stars or black holes. The times of the explosions of intermediate (sun-like) stars can be determined by measuring the present brightness of dwarfs. Not surprisingly the last two maxima of recordable near solar system star explosions took place during the presumably spiral arms driven glacial epochs in Eocene to present and Upper Jurassic times (**Figure 8** and **Figure 9**). Such near solar system star explosions may have been the source of intense neutrino showers, cosmic rays and star dust. This dust contained most likely all kinds of chemical elements, including phosphorus and uranium. Such cosmic phosphorus may have supported, through fertilizing, the distribution of life on Earth additionally to local phosphorus resources via bloom of biota in lakes and oceans and the enhanced growth of plants on land across all climatic zones [14].

By combining astrophysical, geophysical, geological, meteorological and biological data for a timespan of several 100 million years the evolution of the Earth during the Phanerozoic appears continuously and strongly related to properties of the Milky Way galaxy. This encompasses, coming from backwards, the deposition of energy resources like petroleum source rocks and coal, the bloom of biota ahead of that, the entry of cosmic dust in our atmosphere from the interstellar medium containing phosphorus and uranium among other elements, the detonation of long lived intermediate and short lived massive stars and the related production of heavy elements mainly within the spiral arms of the Milky Way galaxy, the wandering of the solar system through these spiral arms along a path around the Milky Way center, and the subsequent long term climatic effects on Earth with a 150 Myr periodicity [14].

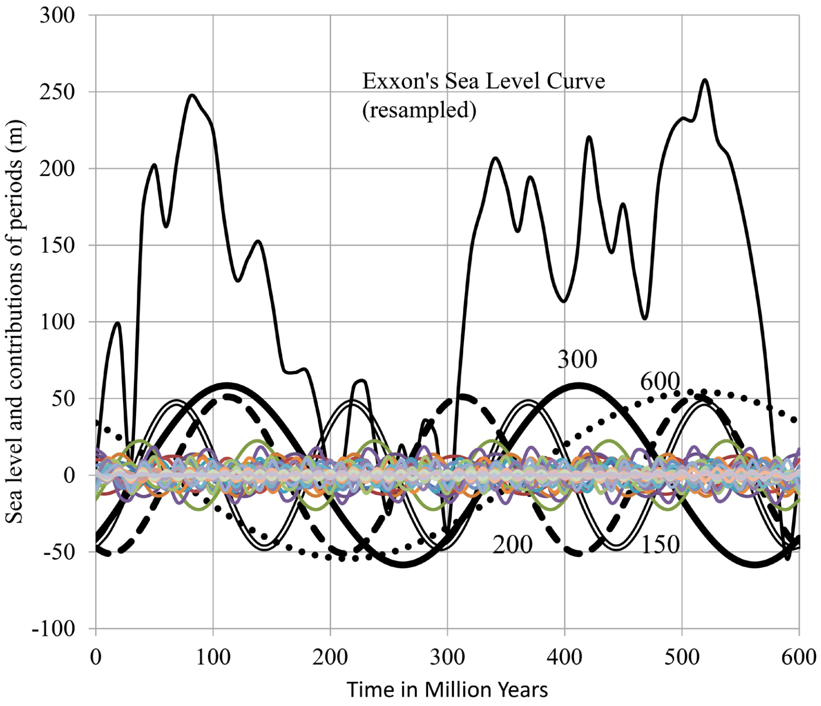

Figure 3. Analysis of Exxon's sea level curve by applying Fast Fourier Transformation (FFT), resulting in the resolution of contributing periods, their amplitudes and phases [7] [10].

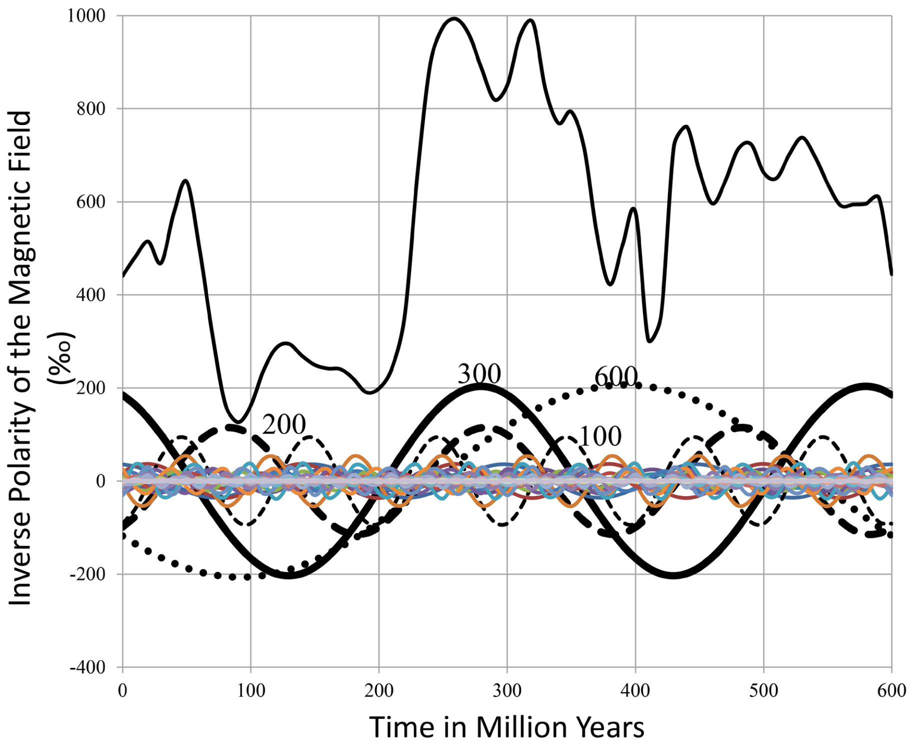

Figure 4. Historical polarity of Earth's magnetic field and its spectral Fourier analysis [10] [27].

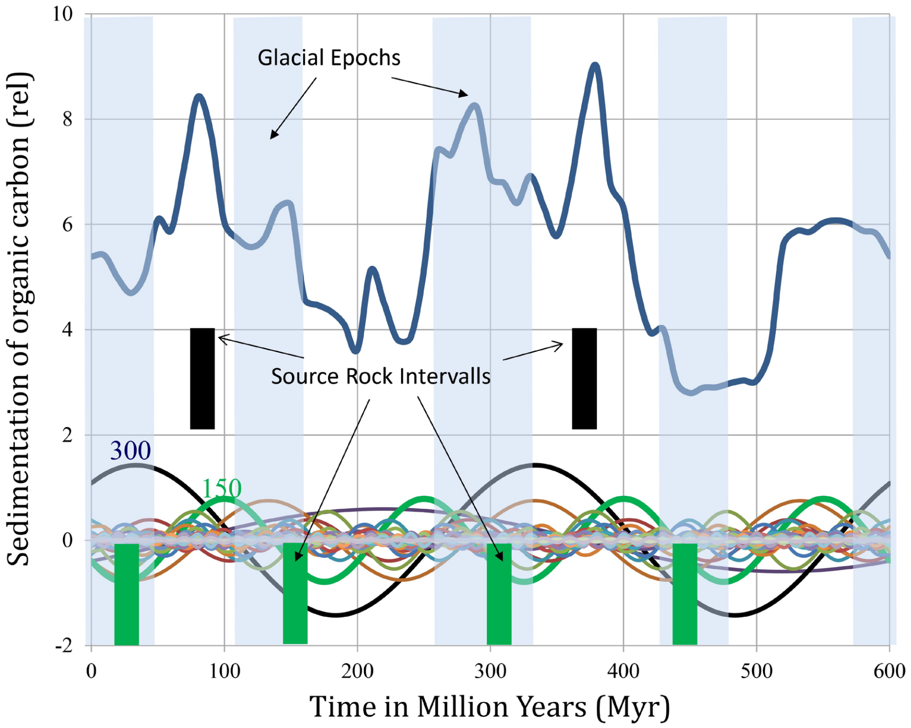

Figure 5. Fourier analysis of the sedimentation pattern of organic carbon after reference [28] and the dominant intervals for the sedimentation of petroleum source rocks after reference [29] that point to a 150 Myr (climate, Milky Way; green) and a 300 Myr cycle (sea level, magmatism; black) [10] [30].

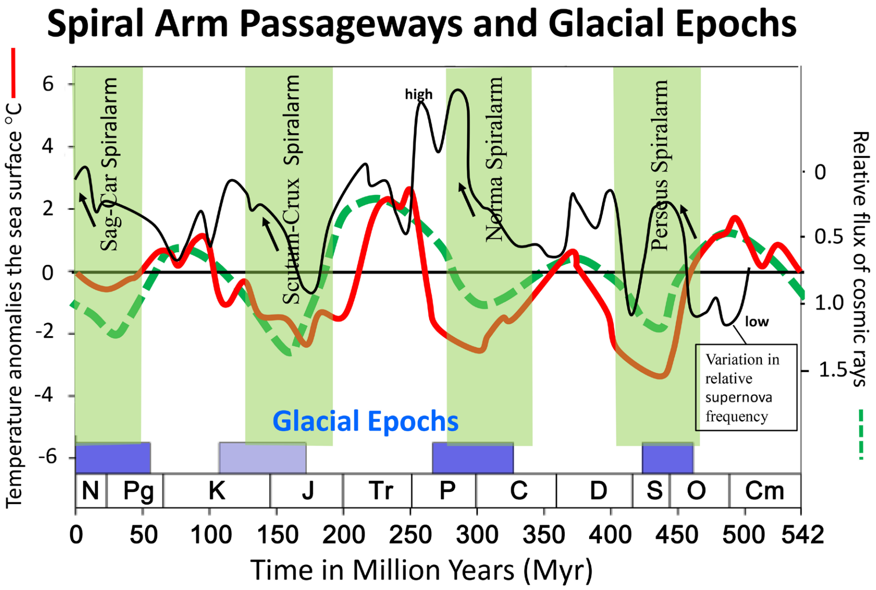

Figure 6. Phanerozoic cycles (~150 Myr) of the temperatures of the tropical sea surface (red curve) with the division of greenhouse and glacial-epochs and the flux of cosmic radiation (green shaded curve, scale inverted), that correlate with the passageways of the Earth through the spiral-arms of the Milky Way. The resulting increase in the cosmic-ray-flux enhances cloud-formation by the generation of condensation nuclei. This leads subsequently to a temperature decrease. Iron meteorites are regarded as medium of the signal for the cosmic-ray-flux [13]. The black curve represents the variation in relative supernova frequency presented by [31], which shows a weak graphical correlation with the other two curves. However, a generally increasing variation of supernova frequency (black arrows > derivative) may obviously correlate with the passageway of the solar system through the spiral arms of the Milky Way galaxy [10] [14].

Contemporarily to the orbiting around the center of the Milky Way the solar system executes oscillations with a cyclicity of approximately 60 million years (or less, [15]-[18]) which moves it out vertically from the Milky Way disk. Either it moves above the disk within the heading of the Milky Way towards the emitting galactic Virgo-cluster, or within the shadow of the Milky Way on the other side of the disk. In the first position, the solar system is the target of increased cosmic radiation due to an additional ray-flux. This movement is either regarded, or vehemently disregarded, as a cause for periods of increased extinction [10] [19]-[26].

The distribution of near-Solar-System white dwarfs [33] accompanying the Solar System with an assumed similar rotation speed around the galactic center, indicates a 150-Myr periodicity of maxima along the time axis of solar passages through the spiral arms of the Milky Way (**Figure 7**). Properties of the spiral arms may have therefore synchronized white dwarf development or initiated the intermediate status of stars in their supernova stage. The time span between birth and death for many of these stars should be shorter than 75 Myr (estimated residence time in a spiral arm). Short-lived stars are most likely less probable in the Milky Way than normal stars like the Sun. Probably due to their limited detectability;

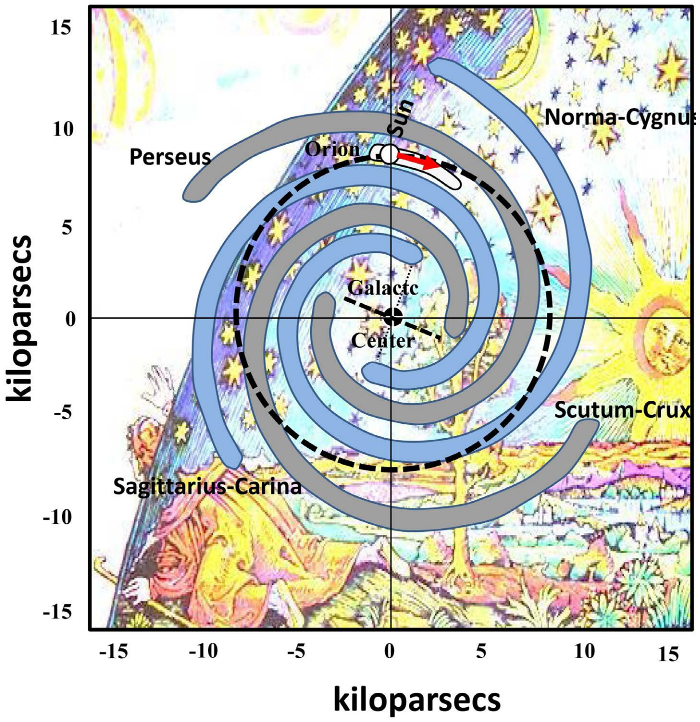

Figure 7. A depiction of the Sun's motion relative to the spiral arm pattern modified after references [22] and [24]. The Perseus and Scutum-Crux spiral arms should show a higher gas and dust-density, Sagittarius-Carina and Norma-Cygnus a more inferior [32]. Modified from [10]. Background: The Flammarion Woodcut is an enigmatic woodcut by an unknown artist. It is referred to as the Flammarion Woodcut because its first documented appearance is on page 163 of Camille Flammarion's L'atmosphère: météorologie populaire (Paris, 1888), a work on meteorology for a general audience. The colored woodcut depicts a man peering through the Earth's atmosphere as if it were a curtain to look at the inner workings of the universe.

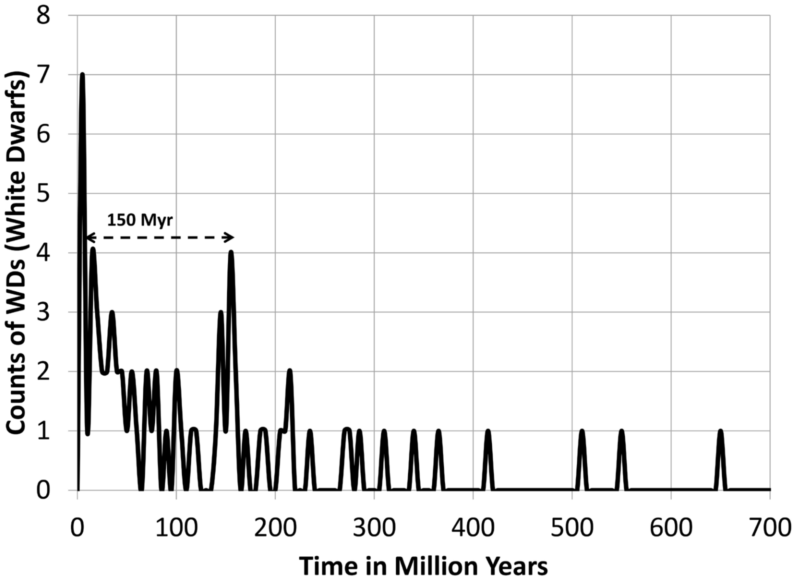

Figure 8. Counts of near-Earth white dwarfs per steps of 5 Myr, after [33], showing a 150 Myr periodicity (one repetition recognizable).

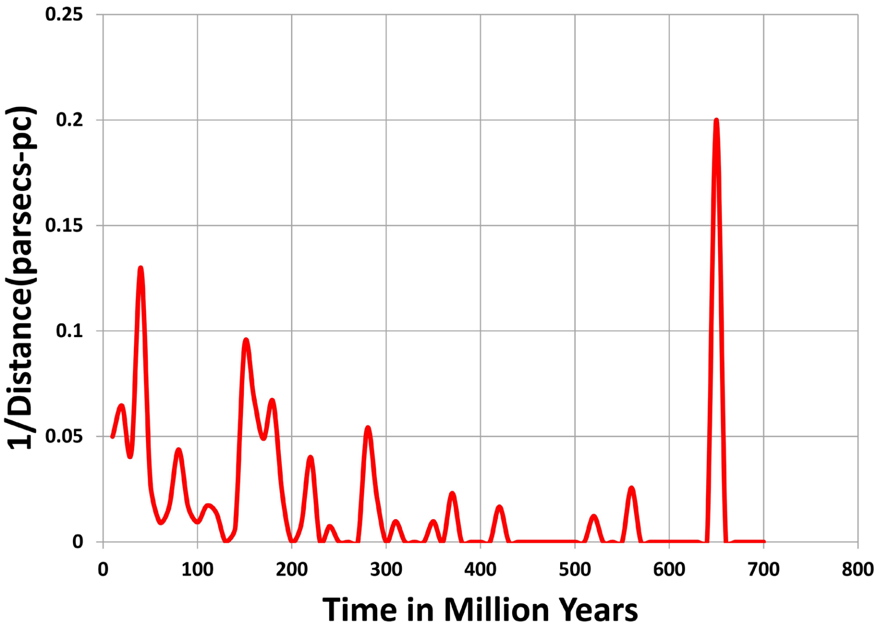

Figure 9. The inverse distances between the white dwarfs and the solar system as function of time, showing a general increase during the Phanerozoic Eon (1 pc ~3.26 light years). With time exploding stars got closer to the solar system, which may have subsequently induced higher asteroid impact rates. A very near explosion (~16 light years) took possibly already place in the late Pre-Cambrian during the transition phase between the Phanerozoic and Proterozoic Eons at about 650 Ma [33].

the number of older white dwarfs significantly decreases on the timeline. The importance of the spiral arms, especially their high-density regions, on passing stars has been investigated by [24], who investigated methanol masers as arm tracers. They revealed that asteroid/comet impacts on Earth are considerably grouped close to spiral arms and within specific locations of an average arm structure. The Permian-Triassic and Cretaceous-Paleogene boundary extinctions occurred during solar passages through small star-formation regions in two different arms. The origin of the Solar System occurred in a similar region in a third spiral arm [33].

3. Proterozoic-Phanerozoic Transition

To evaluate the transition between the Proterozoic and the Phanerozoic Eons the geodynamic cyclicities, changes of the magnetic field and the impact history are good sources for information including data about the oxygenation of the atmosphere, as already mentioned above. The study of these events will be outlined below.

3.1. Cyclicity Change

Coming from the Proterozoic and entering the Phanerozoic, the dominant cycle of mineral ages on Earth [34] of about 400 Mio years accelerated into a 300 Mio Years cycle (**Figure 10**). The processes behind this cycle got apparently synchronized with the dominant 300 Mio Year cycle of the solar system pathway through the Milky Way, supported by the Moon through its tidal effect [9]. At this transition the geodynamic processes of the previous cycles were obviously weaken by losing their strength and could therefore adopt the new rules. This observation is supported by the analysis of the plate tectonic history. The supercontinent cycle got contemporaneously accelerated from the sequence of the Sclavia & Superia and Nuna supercontinents to the one of Rodinia and Pangea, too [8]. The causes for this enforced change must be located within the depths of the Earth and include core and mantle. That the core is involved appears derivable from the strength behavior of the magnetic field with a smooth decline from the Archean and Proterozoic towards the transition and a strong increase afterwards (**Figure 11**). The time of the minimum of the magnetic field strength (protection shield for the life on Earth!) at the end of the Proterozoic opened the surface of the Earth for a greater influence of cosmic rays with their ability to enhance the mutation rate of biota. The following explosion of life in the Cambrian was accompanied by a dramatic increase of oxygen within the Atmosphere and Hydrosphere [1]. The oxygen converted partly into Ozone, which acted in the following times as shield against harmful cosmic rays and atmospheric heat loss. The temperature on Earth could therefore increase by about 3.5˚C [6] and converted the Phanerozoic Earth predominantly into a warm house, sensitively interrupted by Milky Way driven cyclic glaciation epochs about every 150 Mio years [10]-[13].

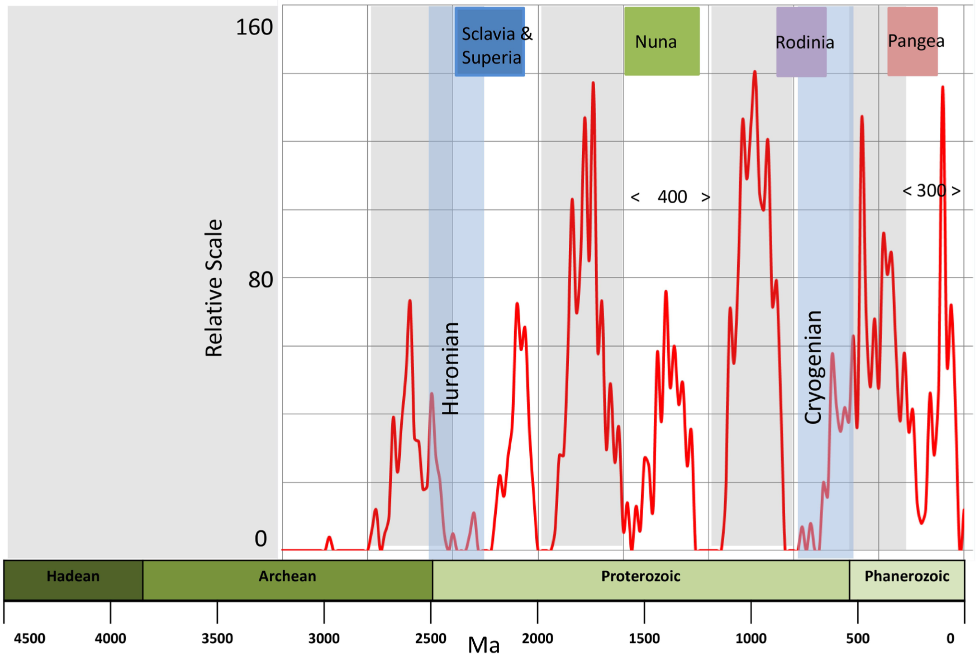

Figure 10. Mineral ages on Earth after reference [34], showing a Phanerozoic 300 Myr cycle and a preceding 400 Myr cycle [10]. Continental assemblies (upper row) Sclavia & Superia, Nuna, Rodinia and Pangea are taken from [8].

3.2. Magnetic Field Strength History

The extraordinary low magnetic field strength at the transition from the

Proterozoic to the Phanerozoic Eon suggest an anomalous field behavior, consistent with predictions of geodynamo simulations, high thermal conductivities and possibly an Ediacaran onset age of inner core growth. The contemporaneous Cryogenian glaciation epoch may indicate a second order correlation only, since the Huronian glaciation epoch shows apparently none [35].

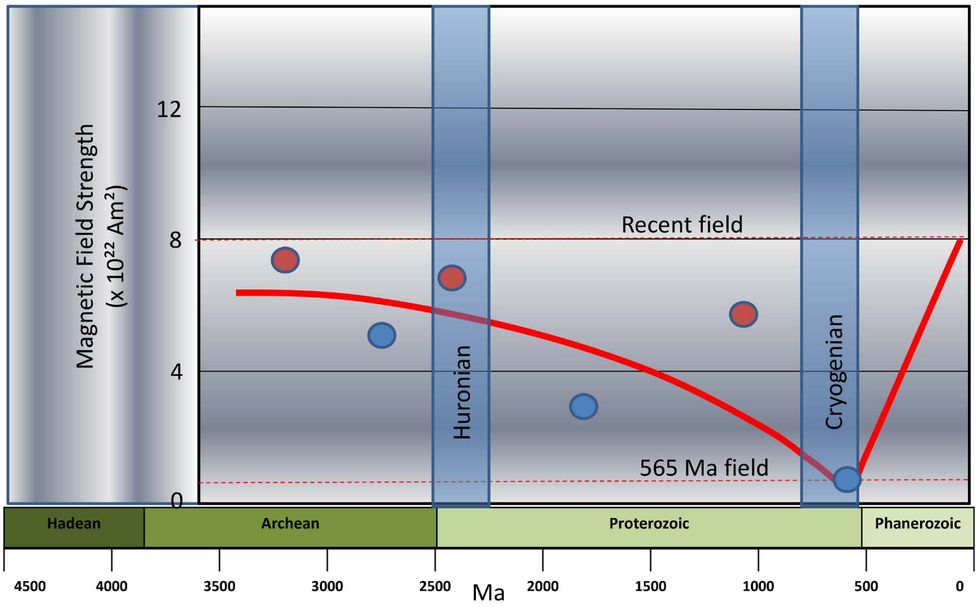

Figure 11. Paleointensity of the Earth's magnetic field since the Archean. Circles above the trend line indicate measured values of the magnetic field, which may realistically point to an increased strength. The trend line itself reflects a model with a freezing inner core that fits quite well the gathered data (extreme values: red circles (maxima), blue circles (minima). The field evolution model (3450 Ma to 565 Ma, left part of the red line) is a weighted second-order polynomial regression of Precambrian field strength data as taken from [35]. The line for the Phanerozoic represents the bulk of all younger data. Since the timing of the freezing of the inner core is heavily discussed ([36]-[38]), at least the cited model can be used as a guideline. Plausible yet contrasting core thermal conductivity values lead to models of inner core growth initiation ages that span 2 billion years, from ~0.5 to >2.5 billion years ago. Palaeomagnetic data provide a direct probe of past core conditions, but heretofore field strength data are still lacking for many ages.

The Earth's magnetic field was really in a highly unusual state when macroscopic animals of the Ediacara Fauna diversified and thrived (Ediacaran Period from ~635 Ma to the end of the Proterozoic Eon). Any connection between these events is exciting but unclear. Single crystal paleointensity data from pyroxenites and gabbros define a dramatic intensity decline, from a strong Proterozoic field like that of today, to an Ediacaran value 30 times weaker. The latter is the weakest time-averaged value known to date and together with other robust paleointensity estimates indicate that Ediacaran ultra-low field strengths lasted for at least 26 million years. This interval of ultra-weak magnetic fields overlaps temporally with atmospheric and oceanic oxygenation inferred from numerous geochemical proxies. This concurrence raises the question of whether enhanced Hydrogen ion loss in a reduced magnetic field contributed to the oxygenation, ultimately allowing diversification of macroscopic and mobile animals of the Ediacara Fauna at the End of the Proterozoic Eon [39].

On the search for the cause of the dramatic change of the magnetic field strength surprisingly cosmic events may have played a decisive role. It is postulated that asteroid impacts are able to enhance the Earth magnetic field in a significant way [39]. The best method to study the impact history of the Earth is now by analyzing impact spherules from the Moon as an unbiased data source (no geological erosions, no large oceans, and no plate tectonics). This has been done by [40]. The distribution of lunar impact spherules correlates significantly with the magnetic field strength of the Earth and shows a smooth decline in the Pre-Phanerozoic, a minimum in the transition phase and a strong increase during the Phanerozoic. These impacts may have partly maintained the Proterozoic magnetic field that otherwise would have decreased much faster, and supported apparently the rebuild of the field in the Phanerozoic (**Figure 11**). The distribution of the spherules has originally been used to explain the 26 Myr Phanerozoic extinction periodicity by introducing "Nemesis" as a companion of the sun.

3.3. Asteroid Impact History

Changes in the strength of the Earth's magnetic poles as described above and even reversal of the magnetic poles appear possible based on the mechanical effects of asteroid impacts [39]. Quantitative calculations show that the impact of the Chicxulub asteroid about 65 million years ago (K/T boundary) resulted in a rotation speed difference of 0.022 cm/s - 0.025 cm/s in the rotation speed of the Earth's core and mantle. This result is comparable in magnitude to the drift rate of the Earth's magnetic poles, which can cause variations in the strength of the Earth's magnetic field at the poles. Compared with the actual observation results, it is found that the meteorite impact event may have strengthened the Earth's magnetic field [39].

Like the Chicxulub event all six largest known impact craters of the last 250 Myr (≥70 km in diameter), which are capable of causing significant environmental damage, coincide with four times of recognized extinction events at 36 (with 2 craters), 66, and 145 Myr ago, and possibly with two provisional extinction events at 168 and 215 Myr ago. These impact cratering events are accompanied by layers in the geologic record interpreted as impact ejecta. Chance occurrences of impacts and extinctions can be rejected at confidence levels of 99.96% (for 4 impact/extinctions) to 99.99% (for 6 impact/extinctions). These results argue that several extinction events over the last 250 Myr may be related to the effects of large-body impacts [15] [16] (**Figure 12**).

Therefore comet and asteroid showers were likely the cause of mass extinctions occurring over the past 260 million years [17] [18]. Both impacts and extinction events are taking place every 26 million years. This cycle has been linked to periodic motion of the Sun and planets through the dense mid-plane of our Milky Way galaxy by [17] [18]. Theoretically gravitational perturbations of the distant

Oort comet cloud that surrounds the Sun lead to periodic comet showers in the inner solar system, where some comets strike the Earth. However, in this case the Paleozoic era and Proterozoic eon should have been affected similarly, assuming a Milky Way with a stable galactic plane full of dust and the potential to disturb the Oort comet cloud accordingly.

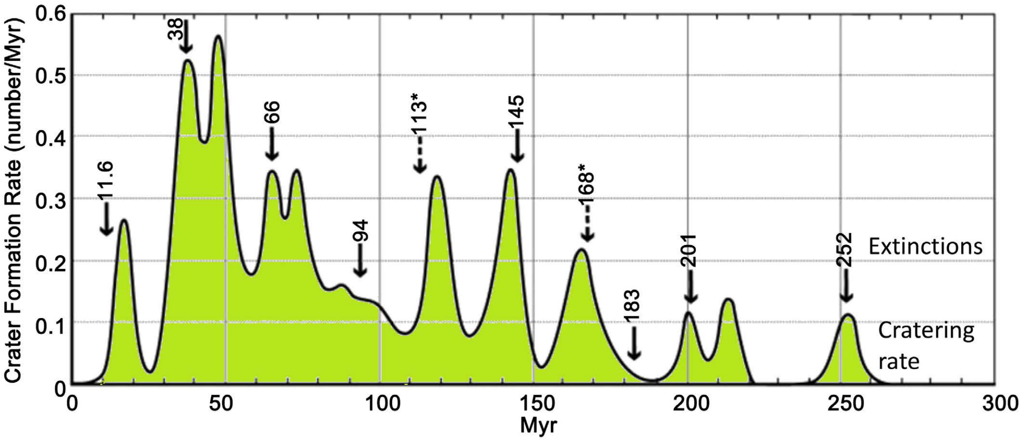

Figure 12. Probability distribution of crater-formation rate for the last 260 Myr. The probability distribution of 37 crater ages has been smoothed by a Gaussian window function of 3 Myr. Solid arrows indicate times of eight significant extinction events after [15] [16]. Broken arrows with asterisks indicate two additional potential extinction events at 113 Myr ago and 168 Myr ago. The impact crater ages show 11 peaks over the last 260 Myr, at least 5 of which correlate with significant extinctions events. Modified from [17] [18].

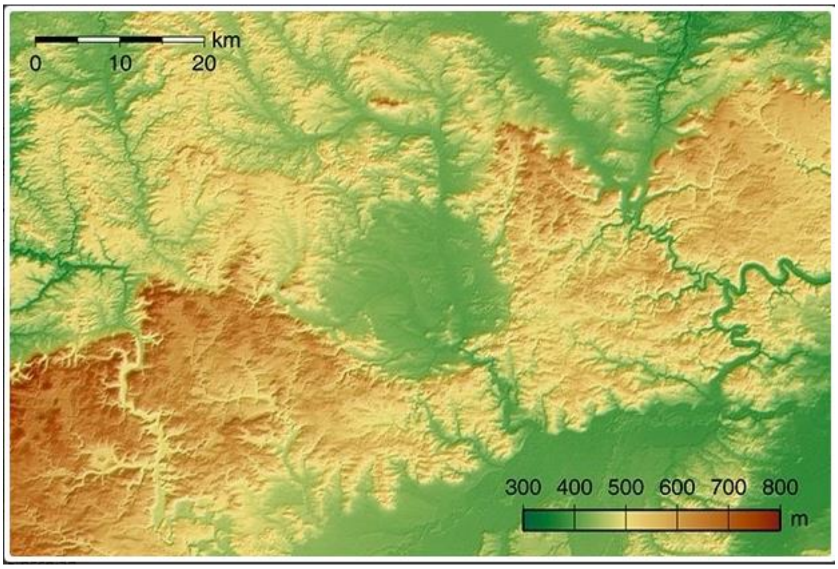

Figure 13. The youngest example of the listed asteroid impacts (**Figure 12**) is the Nördlinger Ries in Southern Germany with a diameter of about 20 km in Mesozoic strata and an age of about 15.1 Myr, which has been speculatively linked by [15]-[18] to the Miocene extinction of about 11.6 Myr that occurred roughly 3.5 Myrs later. However, a suitable younger crater may be somewhere hidden on Earth in the subsurface that is currently covered by sediments or ocean water or both. Weak indications for such asteroid impacts may already exist on the bottom of the Pacific ocean. Reference of map: ©San Jose/CC-by-SA 3.0.

The claims of periodicity in impact cratering and biological extinction events are controversial. A newly revised record of dated impact craters has been analyzed for periodicity, and compared with the record of extinctions over the past 260 Myr. A digital circular spectral analysis of 37 crater ages (ranging in age from 15 to 254 Myr ago) yielded evidence for a significant 25.8 ± 0.6 Myr cycle. Using the same method, a significant 27.0 ± 0.7 Myr cycle in the dates of the eight recognized marine extinction events over the same period was found. The cycles detected in impacts and extinctions have a similar phase [17].

The Nördlinger Ries/Germany (**Figure 13**) with a diameter of about 20 km is the impact crater (15.1 Myr) with a relation to the youngest listed mass extinction on Earth during the Miocene (11.6 Myr) despite of a time shift unequal to zero.

The impact of the large (>10 km diameter) comet or asteroid that took place about 65 million years ago, was most likely responsible for the great mass extinction at the beginning of the Tertiary [41]. This discovery became the outgrowth of the "Nemesis Theory". Studies of the fossil record by [15] and [16] show that this was not an isolated event, but one of several mass extinctions that appear to occur on a regular 26-million-year cycle as already mentioned above.

To analyze an unbiased solar system impact rate measurements of the ages of 155 lunar spherules from the Apollo 14 site representing such a rate suggest that the solar system impact rate over the past 3.5 Ga first gradually declined, and then increased starting at 0.6 - 0.5 Ga, back to the level it had been 3 Ga (**Figure 14**). A possible explanation is offered in terms of the Nemesis hypothesis, which postulated a solar companion star (red or brown dwarf star with possibly less than 50 Jupiter masses). A sudden change in the orbit of that star at the end of the Proterozoic Eon transformed a circular orbit (which does not trigger comet showers) into an eccentric orbit (which does). The Nemesis hypothesis is purely speculative but viable; contrary to prior assertions, the orbit appears sufficiently stable to account for the data [40]. The near solar system star explosion at about 650 Myr ago (**Figure 9**) may have escorted the transition from the Proterozoic into the Phanerozoic Eon with its neutrino, dust, and ray events and possibly with initiated asteroid impacts during the phase of weakness of the Earth interior.

Based on a current (as of September 2019) list of recommended ages for proven terrestrial impact structures (n = 200) and deposits (n = 46) an updated distribution is shown in (**Figure 15**) [42]. High-precision impact ages can be used to 1) reconstruct and quantify the impact flux in the inner Solar System and, in particular, the Earth-Moon system, thereby placing constraints on the delivery of extraterrestrial mass accreted on Earth through geologic time; 2) utilize impact ejecta as event markers in the stratigraphic record; 3) assess the potential link between large impacts, mass extinctions, and diversification events in the biosphere. This distribution of terrestrial impacts proofs the reliability of the distribution of lunar spherules. Detected large continental impact craters on Earth, which are only a subset of the total number of both, continental and oceanic impact events, are complementarily reflected by thorough amounts of spherules on the Moon (**Figure 14** and **Figure 15**).

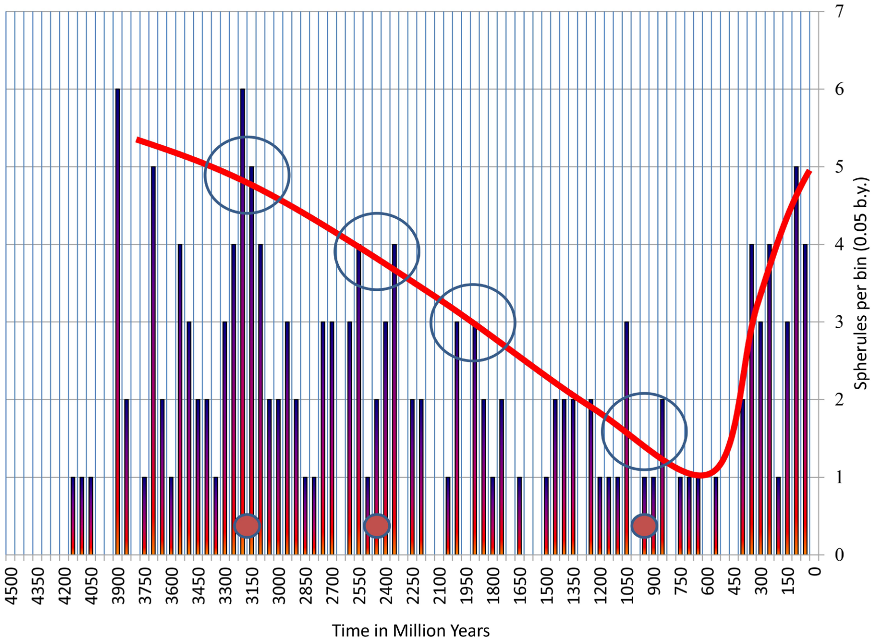

Figure 14. Relative frequency distribution of lunar spherules after [40]. Large blue open circles indicate longer lasting impact events on the Moon that correlate with the distribution of impact crater and ejecta on Earth (**Figure 15**). Small red circles indicate measured maximum values of the magnetic field, which may point to an increased strength at specific times. They coincide with 3 of 4 impact maxima at about 3200, 2500 and 1000 Ma. Apparently the large three cratering events Y, V and S (see **Figure 15**) at about 2000 Ma do not show up as anomaly of the magnetic field strength. This observation might be related to missing magnetic data of that specific time.

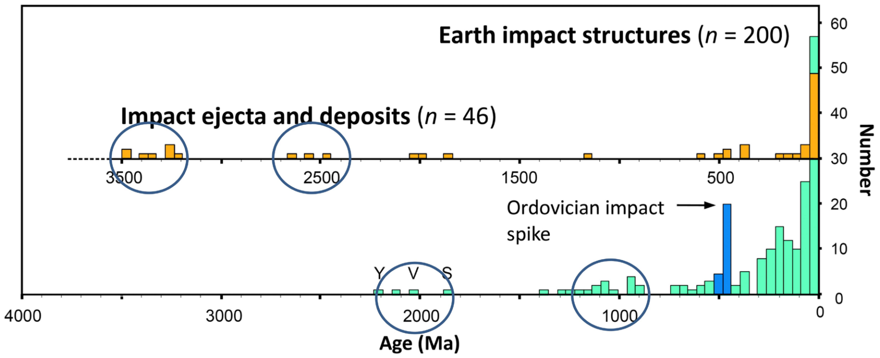

Figure 15. Histogram showing the age distribution of terrestrial impact structures (turquoise and blue) and ejecta deposits (orange). Ages are average ages. Note the distinct Ordovician impact spike around ~470 to 450 Ma (darker blue). S = Sudbury; V = Vredefort; Y = Yarrabubba. Blue circles indicate longer lasting impact events on Earth that correlate with the distribution of lunar spherules (**Figure 14**). Modified from [42].

The Permian-Triassic and Cretaceous-Paleogene boundary extinctions as mentioned already above occurred during solar passages through small star-formation regions in two different spiral arms [33]. In the light of the 26 Myr impact cycle these events may have been the results of at least two interfered and independent effects.

3.4. Nemesis Hypothesis

The transition from the Proterozoic to the Phanerozoic Eon is affected by astronomical events as assumed by [44]. The Nemesis theory postulates that the companion star to the Sun is orbiting at a distance of ~3 light years, with a period of 26 Myr. If this orbit has an eccentricity >~0.5, then it passes close enough to the Oort comet cloud to trigger a comet shower once per orbit. Such periodic showers could lead to periodic extinctions of life on Earth and to increases of the cratering rate on the Moon (**Figure 16**). Currently this theory could neither be verified nor falsified.

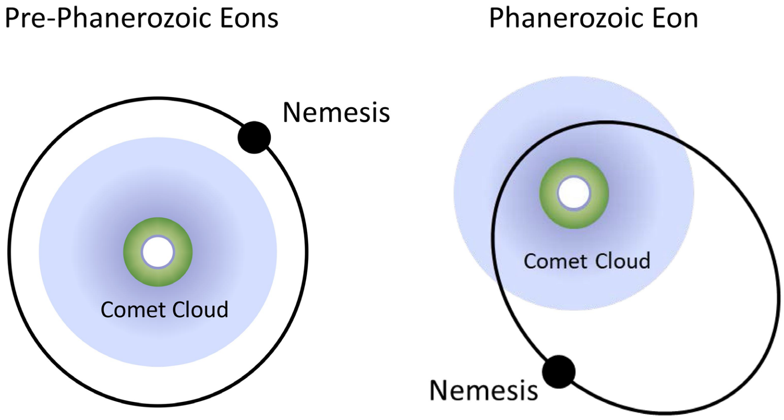

Figure 16. Hypothesized orbits of Nemesis. Left: Circular orbit with ~26 m.y. period around the solar system, hypothesized as orbit prior to 0.6 - 0.5 Ga. Right: Present orbit, with eccentricity 0.7. Change in eccentricity is attributed to close passage of star, as in calculations of [43]. Inner Oort comet cloud is depicted in blue. Expected duration of comet shower is few million years. Modified from [44].

Eight major episodes of biological extinction of marine families over the past 250 million years stand significantly above local background. These events are more pronounced when analyzed at the level of genus, and generic data exhibit additional apparent extinction events in the Aptian (Cretaceous) and Pliocene (Tertiary) Stages. Time-series analysis of these records strongly suggests a 26-Myr periodicity. This conclusion is robust even when adjusted for simultaneous testing of many trial periods. When the time series is limited to the four best-dated events (Cenomanian, Maastrichtian, upper Eocene, and middle Miocene), the hypothesis of randomness is also rejected for the 26-Myr period [15]-[18].

4. Proterozoic Episodes

Cycles of sea level, Earth’s magnetic field, deposition of black shales as petroleum source rocks, Milky Way related Earth’s surface temperatures and other geological properties are ruling agents of the Phanerozoic Eon. This can be demonstrated by a bulk of different data that do not exist for the preceding Proterozoic and Archean Eons due to the limited number of geological and biological remains. However, some useful information is still available on Proterozoic episodes that include temperature data, black shale distribution, cosmic data and mineral ages as well as the distribution of continents as already shown above.

4.1. Proterozoic Climate

The analysis of the Proterozoic climate should deliver a hint, whether the Milky Way structure has some influence similarly to the Phanerozoic climate. This can be done by merging different data sources of the Earth's climate [45]-[48] as presented in (**Figure 17**).

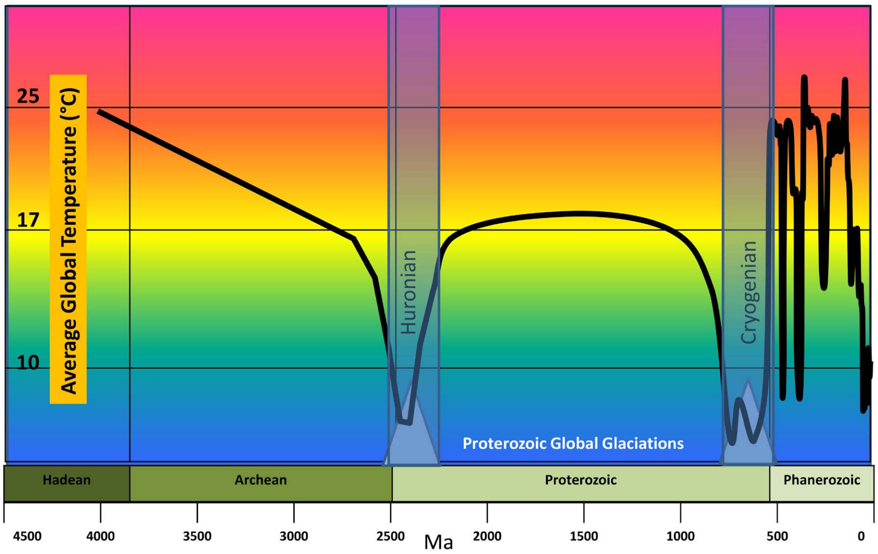

Figure 17. The temperature history of the Earth for the last 4000 Ma. The total range in temperature is surprisingly small—less than 30˚C. The oceans have neither evaporated nor frozen. There is a general cooling that has been going on for the last 50 Ma. Thus, it is empirically observed that over the history of Earth the excursions of the temperature from the mean are rather small, suggesting that there are negative feedback processes that bring the climate system back to the mean [45]-[48].

According to the reconstruction of the Earth's temperature of the last 4 billion years, Earth is now in one of the coldest periods in its history. No geological period has been as cold as our current geologic period, the Quaternary, for at least 250 million years. Temperature variations of more than 10˚C in either direction have been common. Using the average temperature of the Earth for the past 500 million years, the Earth experienced 50 million consecutive years of below-average temperature [45]-[48].

However, at the beginning and the end of the Proterozoic Eon the Earth cooled down to very low temperatures, apparently inducing total global glaciations (**Figure 1**), but no "high frequency" cycles similar to the Phanerozoic ones have been identified so far. This would be an indication that the Milky Way spiral arms, if at all, had only weakly control on the temperature variation on Earth and that the Phanerozoic remains a unique eon in this sense, too.

Over long time periods, changing solar luminosity and mantle temperatures have played important roles in regulating Earth's climate but both periods of climatic upheaval are associated with supercontinents. Enhanced weathering on the orogenically and thermally buoyed supercontinents would have stripped CO_2 from the atmosphere, initiating a cooling trend that resulted in continental glaciation. Ice cover prevented weathering so that CO_2 built up once more, causing collapse of the ice sheets and ushering in a warm climatic episode. This negative feedback loop provides a plausible explanation for multiple glaciations of the Early and Late Proterozoic, and their intimate association with sedimentary rocks formed in warm climates. Between each glacial cycle nutrients were flushed into world oceans, stimulating photosynthetic activity and causing oxygenation of the atmosphere [49].

During the two global glaciations mighty ice shields (about 5 km thick) covered the then present continents, changing the inertia of the Earth due to the change of material distributions. This could have reduced contemporaneously the Earth's rotation rate (Length of the day), what has been detected by the individual analysis of cyclic sedimentary patterns (**Figure 18**) [50] and [51].

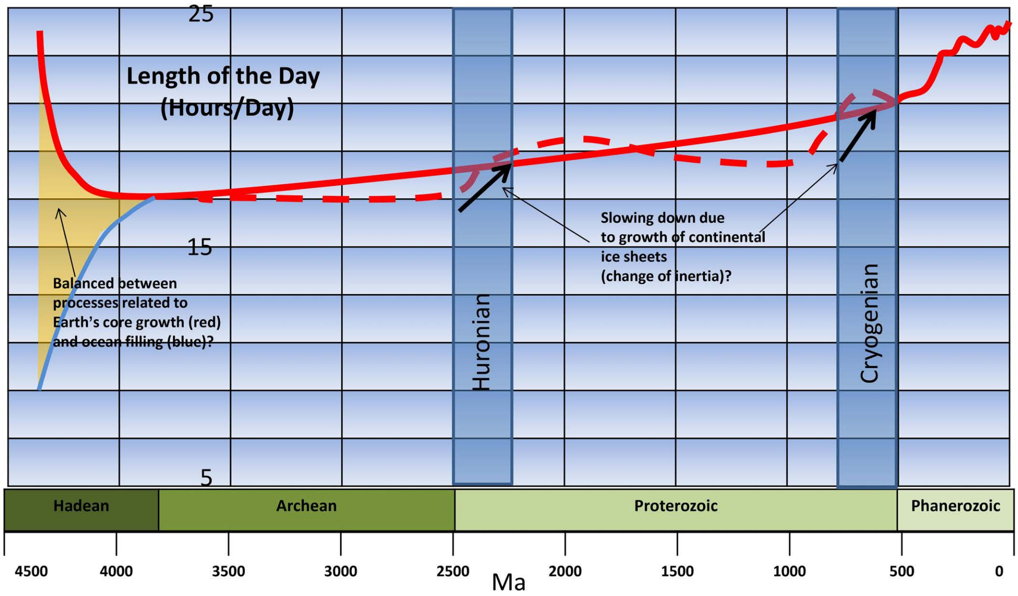

Figure 18. The length of the day (LOD) in hours/day since the Hadean Eon about 4.4 Ga ago. The red curve is a fit through the Precambrian Proterozoic and Archean LOD data points (Mean values only) and reflects the sum of the effects of core growth and tidal dissipation. The extended red solid line in the Hadean is based on the assumption that the core grows very fast very early, which would lead to a decrease of the LOD by about 6.57 h/day and therefore for an acceleration of Earth's rotation. The light blue line characterizes a decelerating tidal dissipation model for the early filling of the ocean during the Hadean Eon. The interrupted red line connects all available individual data points and shows two significant increases of the LOD during the two global glaciations. This would mean a slowing down of the Earth's rotation due to the change of the inertia by the growth of continental ice sheets. Modified from [50].

However, the temperature evolution of the Archean and Proterozoic Earth remains controversial. The "Faint Young Sun" paradox has been a long-standing problem, attempting to resolve evidence for oceans back to at least 4 billion years ago with knowledge that the Sun was likely significantly dimmer. Further, geochemical reconstructions based on δ^{18}O and δ^{30}Si data from cherts indicate warmer temperatures than today, over 30˚C throughout most of the Proterozoic, and exceeding 50˚C in the Archean and early Proterozoic. Isotopic analyses of phosphates point to hot Archean temperatures below 40˚C. These estimates are all higher than modern-day Earth's average temperature of ~15˚C. Similarly, a lack of evidence for glaciation in the mid-Proterozoic seems to validate the narrative of a warmer early Earth [51].

4.2. Proterozoic Black Shales

Earth has a prolonged history characterized by substantial cycling of matter and energy between multiple spheres. The production of organic carbon can be traced back to as early as ~4.0 Ga, but the frequency and scale of organic-rich shales have varied markedly over geological time. Black shales can record Earth's oxygenation process, provide petroleum and metallic mineral resources and reveal information about the driver, direction and magnitude of climate change [53] (**Figure 19**).

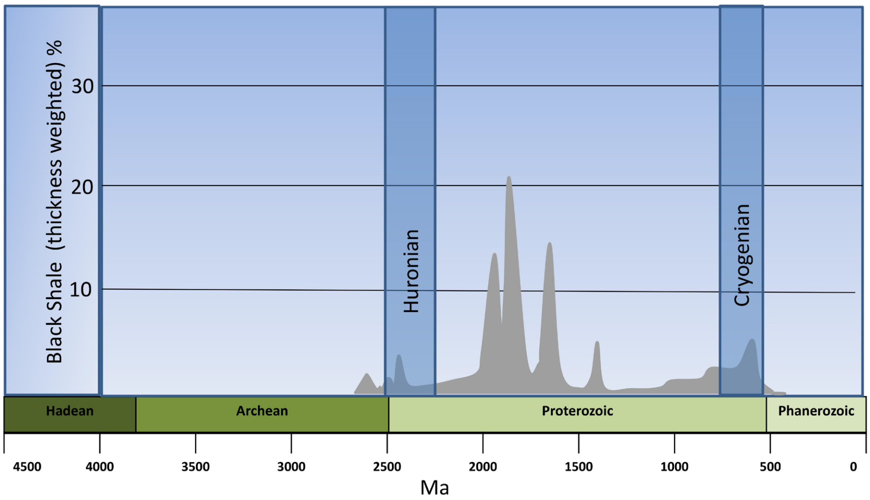

Figure 19. Time series of black shale that includes errors in ages. Three broad peaks are apparent in the Paleoproterozoic (at 1.7 to 2.1 Ga) and two maxima during the two global glaciations. Modified from [52].

4.3. Proterozoic Burial of Organic Matter

Black shales are the main geological archives of organic matter, buried in their mineral matrix. However, carbon's δ^{13}C as a measure for the existence of the effectiveness of life during the Pre-Phanerozoic Eons does not coincide with the distribution of black shales, pointing to a very complex relationship in life-representing environments.

A geochemical cycle fundamental for life is the carbon cycle. Due to the discrimination of ^{13}C relative to ^{12}C by photosynthesis, the isotope fractionation of δ^{13}C is a continuous biochemical record of former life processes preserved in sediments spanning almost 4 billion years [54]. A close relation between supernova rates and burial of organic matter represented by changes in δ^{13}C may demonstrate the importance of cosmic processes for the life on Earth. A simple model of the sources and sinks of carbon leads to an expression for the fraction f_{org} of organic matter buried in sediments [55]

$$f_{\text{org}} = (\delta_{\text{in}} - \delta_{\text{carb}})/(\delta_{\text{org}} - \delta_{\text{carb}}), \tag{1}$$

where the input of carbon from the mantle has $\delta_{\text{in}} = -5‰$, δ_{org} and δ_{carb} are the fractionations of organic sediments and inorganic carbonate sediments, respectively, which can be determined from measurements of Proterozoic Carbon Isotopes (**Figure 20**).

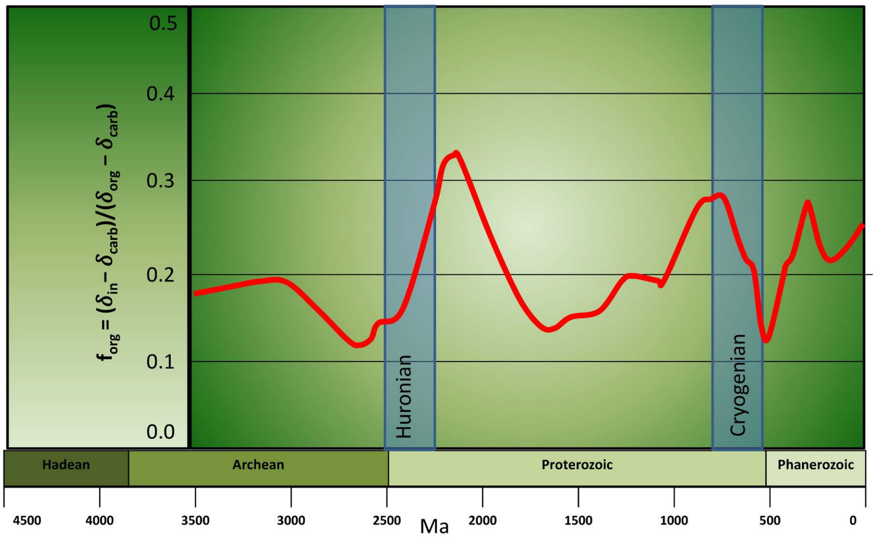

Figure 20. Fraction of carbon buried as organic matter in the sediments over the last 3500 Myr reconstructed from Equation (1). Major glaciations (blue) and geological time subdivision in eons are shown. Modified from [31].

Carbon isotope fractionation doesn't necessarily imply widespread photosynthesis. Unfortunately, many natural processes can cause changes in δ^{13}C. These processes include changes in: terrestrial weathering rates, ocean pH, temperature, tectonic activity, volcanic activity, availability of reduced metals, ocean depth, and ocean stratification, in addition to biological carbon fractionation [31]. Similar data have been published by [56] and [57].

4.4. Proterozoic Supernovae

Life on Earth has probably evolved under the influence of supernovae activity in the solar neighborhood. Supernovae frequency controls the flux of cosmic ray particles arriving at the Earth's atmosphere, where observed evidence supports a close connection between cosmic rays, clouds, and climate. Burial of organic matter in marine sediments follows cosmic ray variations for more than 3.5 Gyr and thoroughly during the last 500 Myr. The supernovae relation to the burial of organic matter may be due to climate-induced changes in the atmospheric and oceanic circulation affecting the availability of nutrients and the bioproductivity in the oceans. A higher bioproductivity then leads to a more widespread burial of organic matter. Support for this scenario comes from a proxy of nutrient concentrations in the ocean which coincide with the supernovae frequency. The results suggest a fundamental connection between supernovae rates and life on Earth [31]. See also reference [50] and [58].

There is no known geological proxy of GCR (Galactic Cosmic Ray) archived in sediments that can show variations over millions of years. Still, an alternative is to estimate the past frequency of supernovae from star formation in the solar neighborhood. The frequency of supernovae is relevant since they result in shock fronts in the interstellar media, which are the primary sources of GCR that ionize the Earth's atmosphere. Past star formation can be assessed using open stellar clusters. Open stellar clusters contain stars (typically ~103) that formed from the same gas cloud and bound together by gravity [59]. Measurements of distance from the solar system and assessments of ages of open stellar clusters are then processed to estimate the average number of massive stars that will end as supernovae in a given age interval. This information makes it possible to infer the GCR flux on Earth [60]. Reaching far back in time, it gets problematic to get information on the star formation in the solar neighborhood due to orbital diffusion [31].

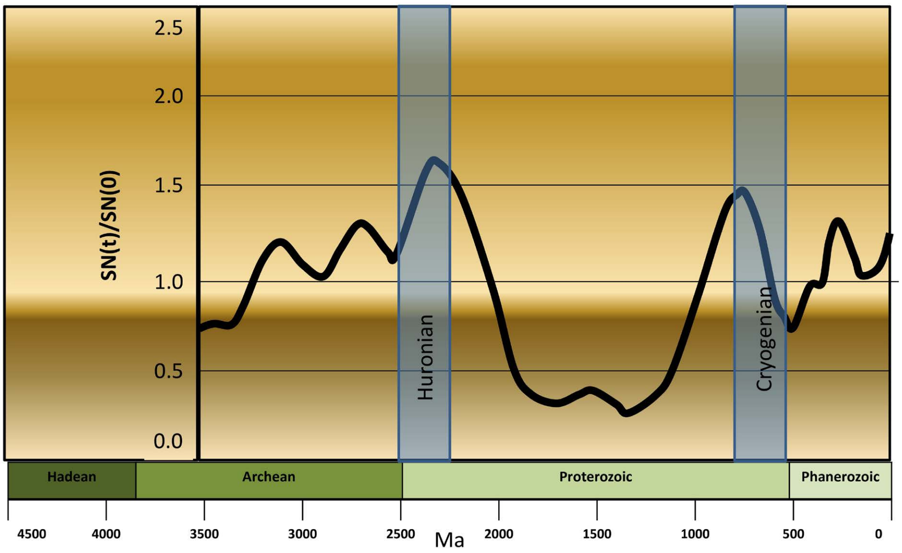

Figure 21. Reconstructed relative cosmic ray intensity over the last 3500 Ma. Based on star formation data [61] and [62], changes in solar evolution and open cluster data [60]. Modified from [31].

Therefore, on time scales longer than ~500 Ma, stars in the solar neighborhood reflect bursts of star-formation along the solar circle of the Galaxy. Reference [61] estimates star formation based on brown dwarf stars in the solar neighborhood and covering the life-time of the Galaxy. Using these results and correcting for solar evolution, it is possible to get a history of GCR over the lifetime of the Solar system [62]. Finally, combining the data of brown dwarf stars and the open stellar cluster data covering the last 800 Myr gives an estimate of the secular changes in GCR flux on Earth (relative to present-day values) in the last 3500 Myr. Most notable is the large maximum at −2300 Ma and the almost 1000 Ma hiatus between −2000 and −1000 Ma, followed by new maximum at −700 and −300 Ma. A burst of star-formation at −2200 to −2400 Ma, −550 to −770 Ma and at −300 Ma was also noted by [63] and [64] (**Figure 21**).

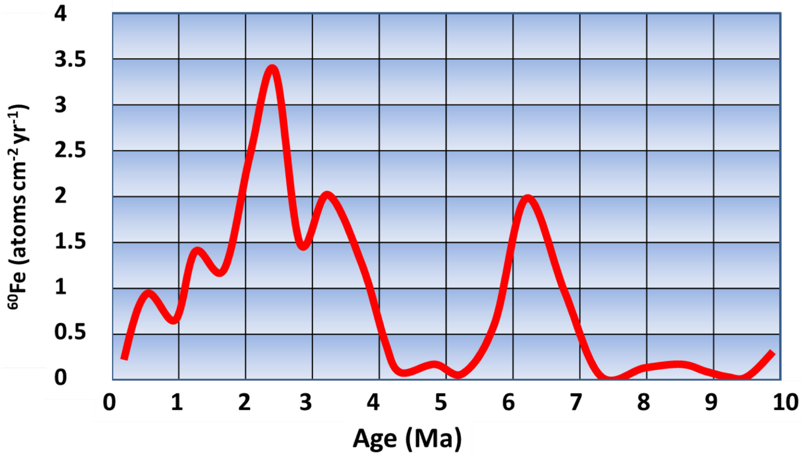

Figure 22. Influx of interstellar Fe and pulse durations. The absolute ages have an uncertainty of ~0.3 to 0.5 Myr. Modified from [65].

The presence of supernovae dust on Earth has recently been proven [65]. Remnants of cosmic particles have been detected in sedimentary probes from the sea bottom, which include the radioactive isotopes ^{60}Fe (iron, half-life: 2.6 million years) and ^{244}Pu (plutonium, half-life: 80.6 million years). Due to their half-life it can be excluded that these isotope samples have survived on Earth in one way or the other since her birth. The only known processes that could contribute to the deposition of those isotopes are cosmic processes like explosions of supernovae and merger of neutron stars, respectively. Their presence below a water column of several 1000 meters demonstrates quite well that the isotopes have undergone a complex distribution and deposition on Earth. Samples of undecayed ^{60}Fe in Antarctic snow confirm the global distribution, probes in lunar regolith and cosmic rays a source in the Milky Way galaxy. Recent explosions of at least two near-Earth supernovae have been identified as source of the mentioned radioactive isotopes [66]. The observed ^{60}Fe signals with maxima at 2.5 and 6.3 Ma confirm previous results in sediment, crust, and nodule samples. For samples between 4.2 and 5.5 Ma and for those older than 7 Ma the measured Fe level remained within the general background [65]. The detection of rare isotopes of iron and plutonium of exploding stars in a sedimentary environment at the bottom of the sea leads to the question: what has happened to all the other chemical elements simultaneously produced by the blast? As it will be hard to distinguish the stable isotopes of these chemical elements from the ones that have been present on Earth since the early days, however, their global distribution can be assumed, too. These include phosphorus as an essential element for life and uranium as a passive companion of biota, deposited in black shales and swamp plants that converted in course of the subsidence of sedimentary basins through the activity of microorganisms and under increasing temperature and pressure in petroleum source rocks [67] and minable coals [14] [68] (**Figure 22**).

5. Proterozoic Cycles

As already mentioned, the search for a Proterozoic cyclic activity may help to understand the Phanerozoic evolution and its relation to the Milky Way accordingly. However, one intrinsic cycle has been introduced previously.

5.1. Mineral Ages

Most igneous and metamorphic mineral dates indicate times of rock cooling, the preceding and causative thermal events of crustal adjustment. Accordingly, the distribution of mineral dates in time indicates the periodicity of such events and is related to cyclic orogeny and continental accretion (mantle convection processes) (**Figure 10**) [34].

Terrestrial magmatic activities and mineral ages of the Earth [34] show a significant 300 Myr correlation for the Phanerozoic time (**Figures 3-6**, **Figure 10**). Therefore, it appears justified to use mineral ages as indication for long term global thermal events as well. In pre-Phanerozoic times instead of the 300 Myr cycle a 400 Myr cycle may have been dominant, either as intrinsic process within the Earth or possibly as galactic process, or both. However, a galactic process appears very unlikely as properties of the pathway of the solar system around the center of the Milky Way (distance, velocity) would have changed then.

5.2. Phosphorous

The only very weak 150 Myr Milky Way signal that could possibly be identified so far is the phosphorous distribution of the Archean and Proterozoic eons. Phosphorous contents in black shales through time, but the black shale distribution (**Figure 19**) does not show any convincing and distinct cyclicity during the Proterozoic. The macronutrient phosphorus is thought to limit primary productivity in the oceans on geological timescales. A modified compilation of phosphorus abundances in marine sedimentary rocks spanning the past 3.5 billion years is presented after [69] and [70] in **Figure 23**. Evidence is demonstrated for relatively low authigenic phosphorus burial in shallow marine environments until about 800 to 700 million years ago. A series of small maxima may indicate a speculative 150 Myr cycle. Arrows indicate high-value data (roughly with values of about 10) in the Phanerozoic and the late Neoproterozoic that could not be represented on the figure. The Phanerozoic cyclicity appears obviously.

Phosphorus (P) is critical to modern biochemical functions and can control ecosystem growth. However, on the early Earth, P sources may have consisted primarily of poorly soluble calcium phosphates, which may have rendered phosphate as a minimally available nutrient or reagent if these minerals were the sole source. Phosphorus on Earth's early surface would have been present as a mixture of phosphate minerals, as a minor element in silicate minerals, and in reactive, reduced phases from accreted dust, meteorites and asteroids [71].

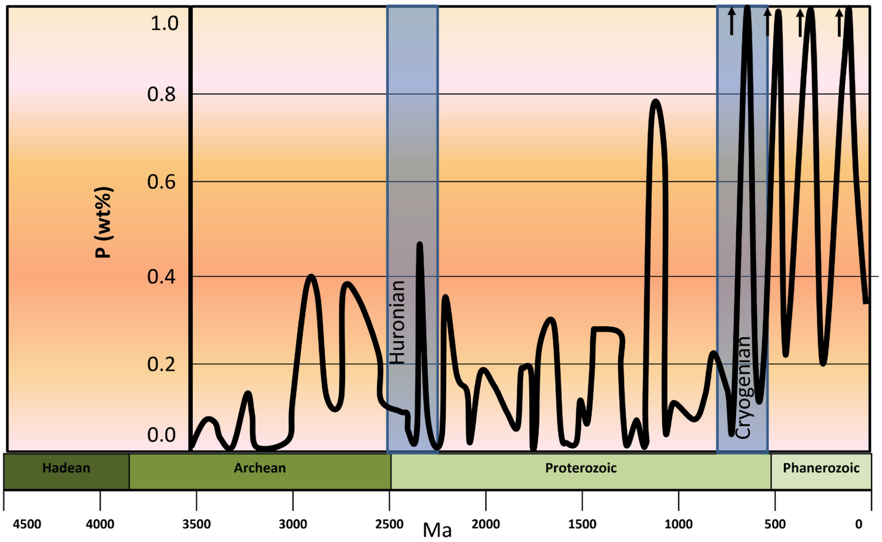

Figure 23. Modified phosphorous contents in black shales through time after [69].

5.3. Regional Glaciations

Regional glaciations as possible indications for passing of the solar system through the spiral arms of the Milky Way have not been recorded yet for the Proterozoic time span between the Huronian and Cryogenian global glaciations. However, during the Archean greenhouse gas concentrations were sufficient enough to offset a fainter Sun. Climate moderation by the carbon cycle suggests average surface temperatures between 0˚C and 40˚C, consistent with occasional glaciations (about 2.7 Ga: Glacial rocks in India and Montana, about 2.9 Ga: Glaciation, Pongola, South Africa, and about 3.5 Ga: Glacial rocks in South Africa [72].

6. Conclusions

Milky Way related cycles on Earth of 150 Myr duration as observed for the Phanerozoic Eon are obviously not dominant in the Proterozoic Eon. Only a very weak galactic signal due to the periodic occurrences of phosphorous generating exploding stars may be present. The Phanerozoic can be defined as an eon with very sensitive geophysical, geological, meteorological and biological reactions. The accelerated reactions from a 400 Myr to a 300 Myr cycle of mineral ages and continental tectonics include a generally high surface temperature with glacial interruptions, high oxygen and ozone values in the atmosphere, increase of the strength of the magnetic field and the rise of the asteroid impact rate witness those sensitives. To explain the 400/300 Myr event changes of the pathway of the solar system through the spiral arms (velocity, distance to the center of the Milky Way) appears unrealistic. Therefore, the 400 Myr cycle can be interpreted as an intrinsic process alone. Finally, it cannot be excluded that

- Asteroid impacts stabilized and strengthened the Earth's magnetic field. Therefore, future preventions of impacts could weaken the protective shield of the magnetic field against hazardous cosmic rays;
- the next asteroid impact with mass extinction potential will occur in about 15 Myr, either initiated by a red/brown dwarf companion of the sun or by the periodic crossing of the solar system through the dusty galactic plane or something else;
- the Milky Way supported apparently the acceleration of geodynamic processes on Earth after weakening of processes of the Earth's core (geodynamo) and the fertilizing of the biosphere with phosphorous by exploding spiral arm stars during related glaciation epochs;
- variable atmospheric fractions of the life spending oxygen and its heat enhancing ozone derivative can influence Earth's climate;
- the explosion of life on Earth during the Phanerozoic Eon might have apparently required for its success somehow time coordinated events like asteroid impacts, Earth's core dynamics, nearby exploding stars, solar system pathway through dusty spiral arms, plate tectonics, a speculative companion of the Sun and oxygen production via photosynthesis;
- and astronomical influences on life on Earth have already been archived in mankind's minds and religions like the memory on once existing dragons (extinct dinosaurs).

It is suggested to the geoscientific and astronomical communities that further work should be done at least for the study of the Proterozoic Eon. The densification of paleomagnetic measurements, length of the day investigations and asteroid impact studies may help to describe the sensitivities of the Earth's system to internal and external (periodical and episodic) forces (spiral arms, exploding stars) better than today. It could be an interesting scientific target either to verify or falsify the presented conclusions.

J.W.v.Goethe, Faust II
Nature with all her living, flowing powers
Was never bound by day and night and hours.
By rule she fashions every form, and hence
In great things too there is no violence.

Translation by George Madison Priest

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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