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ASTRONOMICAL AND ASTROBIOLOGICAL IMPRINTS ON THE FOSSIL RECORDS. A REVIEW

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1. The common frontier of astronomy and astrobiology

Both astronomy and astrobiology share a common frontier. Vertiginous progress in instrumentation such as novel microanalytical tools to study extraterrestrial materials, including those collected in space return missions, and availability of long ice cores and other fossil archives providing detailed records of the past terrestrial environment, can give deeper insights into the origin and history of life on Earth. The early stage of the Sun and other space-palaeoclimate conditions are relevant to the emergence of life on Earth.

The record of Earth’s condition in the past is studied by different scientific communities involved in space palaeoclimate research. A set of data derives from historical observations of the solar surface. Other data are based on laboratory studies of matter derived from the surface of planets, the Moon, meteorites and comets (Pepin *et al.,* 1981), which contain imprints due to past space weather conditions, such as implanted ions and radionuclides produced by nuclear reactions induced by high-energy cosmic rays. A final set of data derives from terrestrial archives, including tree rings, ice and marine sediment cores, corals, lake varves, manganese nodules and other crusts that grow slowly at the bottom of the ocean. All these systems contain a detailed record of proxies revealing Earth- and space-climate conditions in the past. Such information can be retrieved with advanced instrumentation, such as high sensitivity analyzers of stable and long-lived isotopes.

We shall focus our attention on space weather as a factor that is relevant for the origin and evolution of life on Earth. Then we will review possible changes in the evolution of life in general. Moreover, we will discuss possible clues contained in the fossil records of past life on Earth including some aspects of evolution, especially of humans, that may be due to space palaeoclimate. In general, the fossil record of the ancient Sun and of space palaeoclimate will yield insights into how our ecosystem may have evolved.

2. The impact of space climate and weather on living systems

During the early stages of the study of the origin of life (Oparin, 1953; Ponnamperuma and Chela-Flores, 1995) not enough attention was paid to the correlation between chemical evolution of Earth materials and variability of the early Sun (Messerotti, 2004) or remote events taking place in our galactic neighbourhood. Today, a meaningful study of the factors that may have led to an early onset of life on Earth begins to be possible due to the advent of a significant fleet of space missions and the possibility of performing experiments in the International Space Station (ISS). Our review lies within the scope of astrobiology (the study of the origin, evolution, distribution and destiny of life in the universe) and astronomy. Both disciplines should search analogous objectives, as we shall endeavour to illustrate with a few examples in this short review. Preliminary modelling of the Sun does not allow useful extrapolations into the distant past in order to study in detail the influence of solar physics on the emergence and early evolution of life on Earth (Jerse, 2006).

Electromagnetic and particle radiation that originate from the Sun, and from other space sources external to the solar system, are continuously impinging upon the Earth environment at different time scales and in a broad range of energies (Messerotti, 2004). The long-term evolution of the physical state of the space environment is referred to as *space climate*, whereas the short-term evolution is defined as *space weather (SpW)*. The interplay between the impinging energy carriers and the relevant impacts at the planetary level is determined by the complex physical couplings among the galactic, the solar and the terrestrial environments and the processes occurring therein. For instance, high-energy particles that originate from galactic sources, known as galactic cosmic rays (GCR), interact with the Earth atmosphere and generate showers of secondary particles such as muons and neutrons. It should be remarked that the flux of the GCR at the Earth depends on: a) the position of the Sun in the Galaxy, since during its revolution around the galactic centre our star crosses environments richer or poorer of GCR sources on a time scale of 225 million years; b) the activity level of the Sun. This contribution to the GCR flux is due to higher solar activity producing denser and faster solar wind. Hence, the particle flux is continuously accelerated by the star, which carries the solar magnetic field and fills up the interplanetary space by defining the region of space confined by the interstellar wind (heliosphere). When the solar wind is denser, it acts as a more efficient shield to the GCRs. Consequently, a lower GCR flux can reach the Earth; c) the strength of the Earth magnetic field, which acts as a further shield. Other materials reaching the Earth include meteorites, asteroids, comets and cosmic dust.

We can understand general trends of the influence of space climate and weather on the evolution and distribution of life. An important factor for understanding fully the origin and evolution of life on Earth is the evolution of the Sun and our galactic neighbourhood. We consider the constraints that present knowledge of our own star and its galactic environment imply for the emergence and evolution of life on Earth. This, in turn, will provide further insights into what possibilities there are for life to arise in any of the multiple solar systems that are known to date. Fortunately, the particles that have been emitted by the Sun or other galactic sources in the past have left a record in geologic samples in small bodies of the solar system in the Hadean (4.6 - 3.8 billion years before the present, Ga BP) and Achaean (3.8 - 2.5 Ga). In small bodies the geologic data has not been lost by metamorphism, as it has happened on the Earth. It is generally agreed that the latter period corresponds to the emergence of life, but we cannot exclude possible earlier dates for the onset of life on Earth.

The difficulty encountered in the simultaneous study of astrobiology and SpW is not insurmountable. Fortunately, considerable information can be retrieved from observations of extraterrestrial samples, either meteorites, or lunar material. Similarly, it is possible that we could retrieve bioindicators of the imprint that our galactic environment may have left on the fossil record of life on Earth. We will consider the fossils that represent an imprint of anomalous conditions in our environment since the Proterozoic. We have studied with special attention the records that may give some information on the factors favourable for life. Such data may be retrieved from the Sun during a period when fossils of animals were not available, during, or at the end of the Achaean. Such imprints are available in the upper layer of the lunar surface, on its regolith.

3. The possible role of space palaeoclimate in mass extinctions and planetary evolution

As suggested in the previous section, solar climate during the first Ga of the Earth was radically different. The earliest relevant factor was excessive solar-flare energetic particle emission, a phenomenon that has been recorded in meteorites (Goswami, 1991). These extraterrestrial samples provide information on events that took place during this early period after the collapse of the solar nebula disk. Gas-rich meteorites have yielded evidence for a more active Sun. A considerable number of young stars with remnants of accretion disks show energetic winds that emerge from the stars themselves. Similar ejections are still currently observed from our Sun. For this reason it is believed that some of the early Solar system material represented by meteorites could have retained the record of such emissions.

Information on the energetic emission of the Sun during this period can be inferred from data on X ray and UV emission (larger than 10 eV) from pre-main-sequence stars. We may conclude that during pre-main-sequence period, solar climate and weather presented an insurmountable barrier for the origin of life anywhere in the Solar system. In the Hadean, conditions may still have been somewhat favourable, especially with the broad set of UV defence mechanisms that are conceivable. The high UV flux of the early Sun would, in principle, cause destruction of prebiotic organic compounds due to the presence of an anoxic atmosphere without the present-day ozone layer (Canuto *et al.,* 1982; 1983). Some possible UV defence mechanisms have been proposed in the past, such as atmospheric absorbers and prebiotic organic compounds (Margulis *et al.,* 1976; Sagan and Chyba, 1997; Cleaves and Miller, 1998).

Inversions of the Earth's geomagnetic dipole represent a well-established geochronological framework. The most recent of these inversions, referred to as the Matuyama–Brunhes (M–B) transition, has been dated to about 780 ka ago.

During a geomagnetic reversal, the dipole field strength is believed to decrease by about an order of magnitude. During this time, galactic cosmic rays can more easily penetrate into the Earth's atmosphere and thus increase the production of cosmogenic isotopes, such as ^{10}Be. Evidence has been presented for enhanced ^{10}Be deposition in the ice at 3,160–3,170 m, interpreted as a result of the low dipole field strength during the Matuyama–Brunhes geomagnetic reversal. If correct, this provides a crucial tie point between ice and marine core records (Raisbeck *et al.,* 2006).

4. Traces of space-climate events in the geologic record

The solar corona is the outermost region of the Sun's atmosphere. Its expansion induces a flux of protons, electrons and nuclei of heavier elements (including the noble gases). These interplanetary particles are accelerated by the high temperatures of the solar corona, to high velocities that allow them to escape from the Sun's gravitational field. The wind contains approximately five particles per cubic centimetre moving outward from the Sun at velocities of $3x10^5$ to $1x10^6$ ms^{-1}; this creates a positive ion flux of just over 100 ions per square centimetre per second, each ion having an energy equal to at least 15 electron volts. The solar wind reaches the surface of the Moon modifying its upper surface or regolith. We have considerable information on the lunar regolith thanks to the Apollo Missions.

In the years 1969-1972 these missions retrieved so much material and made it available to many laboratories that influenced much of our preliminary understanding of the origin of life on the early Earth. These missions gave an opportunity for detailed studies of isotopic fractionation of the biogenic elements on the surface of the Moon. In general terms, the preliminary understanding that the Apollo Missions added to the work that was available at the time on meteorites was related to the fractionation of H, C, N and S on the lunar surface. In fact, the preliminary hint that was relevant for the origin of life was that the distribution range of ^{32}S/^{34}S appears to be narrower than the isotopic ratio of hydrogen, carbon or nitrogen. For this reason, it was suggested that the fractionation of S isotopes would be the most reliable parameter for estimating biological effects (Kaplan, 1975; Chela-Flores, 2007). Deviations of ^{32}S/^{34}S from meteoritic values discovered on the Moon by the Apollo missions can be understood by the fact that the solar wind modifies its structure leaving a tell-tale signal of how it changes over geologic time, since the Moon is an inactive body being modified only by the impacts of meteorites and asteroids.

Much more recently, the Genesis Mission was NASA's first sample return mission sent to space. It was the fifth of NASA's Discovery missions. Genesis was launched in the year 2001 with the intention to bring back samples from the Sun itself. Three years later, after crash-landing, the probe was retrieved in Utah, USA. Genesis collected particles of the solar wind on wafers of gold, sapphire, silicon and diamond. The amount of stardust collected by Genesis was about 10^{20} ions, or equivalently, 0.5 milligrams. Preliminary studies indicate that contamination did not occur to a significant extent. The objective is to obtain precise measures of solar isotopic abundances. By measuring isotopic compositions of oxygen, nitrogen, and noble gases we would have data that will lead to better understanding of the isotopic variations in meteorites, comets, lunar samples, and planetary atmospheres. This will lead to a deeper understanding of the early Solar system, and hence an additional opportunity beyond fossils for a closer approach to the mystery of the origin of life on Earth by being able to assess properly potential biomarkers that may be suggested from the point of view of biogeochemistry.

There will be also attempts to use Accelerator Mass Spectrometry (Tuniz et al., 1998) to detect a long-lived radionuclide of solar wind origin, for example such as ^{10}Be and ^{26}Al (Jull and Burr, 2006).

The Moon is depleted of volatile elements such as hydrogen, carbon, nitrogen and the noble gases, consistent with the fact that the most widely accepted theory of its formation is the impact of the Earth by a Mars-sized body during the accretion period. Exceptionally though, volatiles are abundant in lunar soils. The lunar surface evolved during the heavy bombardment period, adding material with a different composition to the Sun, and not derived from the Sun: The variability of ^{14}N and ^{36}Ar in grains (single mineral and glass) from a lunar soil were measured by laser extraction, to study the origin of trapped nitrogen in the lunar regolith (Wieler *et al.,* 1999). The ratio of N is very uniform relative abundances of Ar, Kr, and Xe trapped from the solar radiation observed in mineral grains from the same soil. This strongly suggests that, on average, some 90% of the N in the grains has a non-solar source. This seems to suggest that the non-solar N has not been trapped by ion implantation.

Ions from the solar wind were known to have been directly implanted into the lunar surface (Kerridge *et al.,* 1991). This component was detected during the Apollo missions. The isotopic composition of the noble gases in lunar soils has been established as being subsequent to the formation of the Moon itself.

The production of a long-lived radionuclide on the moon can provide information about the flux of galactic and solar cosmic rays in the past. This can also be done on meteorites from the moon (Gnos *et al.,* 2004).

To gain further insights into the early Solar system, evidence has been sought for a predominantly non-solar origin of nitrogen in the convenient source of information that is represented by the lunar regolith. This search suggests that, on average, some 90% of the N in the grains has *a non-solar source*, contrary to the view that essentially all N in the lunar regolith has been trapped from the solar wind, but this explanation has difficulties accounting for both the abundance of nitrogen and a variation of the order of 30 % in the ^{15}N/^{14}N ratio. The origin of the non-solar component remains a puzzle, but it presumably must have changed its isotopic composition over the past several billion years. The Moon regolith presents a very challenging geological phenomenon. It consists of a very large number of grains with a rich history regarding their exposure to the Sun. Two parameters are useful in the systematic study of the lunar regolith: firstly, its *'maturity'* namely, the duration of solar wind exposure and, secondly the *'antiquity'*, namely, how long ago the exposure took place.

For the maturity parameter a useful way to measure it is in terms of the abundance of an element from the solar wind that is efficiently retained. The element nitrogen is a good example. (Alternatively solar noble-gas elements can be used.) Both antiquity and maturity have been used to learn about the evolution of the early Solar system, especially the ancient Sun, the knowledge of which is needed for a comprehensive understanding of the problem of the origin of life on Earth. The exposure age to galactic cosmic rays produce certain nuclides in amounts proportional to the time the sample spends at the topmost part of the surface (some 2 meters). The contrast between the known low abundance of a certain nuclide and the one induced by cosmic rays produce an indicator of antiquity. The antiquity parameter has been discussed in detail (Kerridge, 1975). A related question is the search for live ^{244}Pu (half-life = 81 Ma) that is expected to be present in the interstellar medium (ISM) from ongoing nucleosynthesis. The use of resonant ionization mass is capable of detecting extremely low levels of this isotope that may have accreted onto Earth from the ISM (Ofan *et al.,* 2006).

5. Evidence in the geologic record of extinctions by impact of an asteroid or comet

5.1 EXTINCTIONS DUE TO EXOGENOUS SOURCES

Evidence for impact from the geologic boundary between the Cretaceous and Tertiary periods (the so called K/T boundary) is the Chicxulub crater in the Yucatan Peninsula in Mexico, and the global distribution of an anomalous iridium (Ir) layer (Keller and Stinnesbeck, 2000). In addition, impact ejecta such as pressure-shocked mineral grains support the meteorite impact hypothesis. Perhaps the better discussed evidence for the K-T impact at 65 Ma (million years ago) was the Ir-abundance coinciding with the geologic evidence of mass extinction. In spite of the very abundance of Ir in well-studied meteorites, the Ir-rich deposit may alternatively be interpreted as volcanic ejecta. In other words, the possibility remains that the layer could instead have been produced by volcanic Ir-rich eruptions.

The Permian period gave way to the Triassic at about 251 Ma. At that time the Earth experienced its greatest mass extinction known to us. Ninety percent of all marine species, including the trilobites, disappeared, while on land pervasive extinctions opened the way for the rise of the dinosaurs. But despite the magnitude of mass extinction its cause is a source of controversy (Kerr, 2001).

A new analysis of rock that marks the Permian-Triassic (P-T) extinction now suggests that it was caused by the hypervelocity impact of an asteroid or comet similar to the one thought to have led to the extinction of dinosaurs at the K-T boundary (Kahiho et al, 2001). There is some evidence for some catastrophic event that gave rise to the P-T extinction. Paleontologic evidence seems to suggest that a single event may have been responsible for the P-T transition. One such possibility shall be discussed in the next section.

Noble gases such as helium and argon apparently were trapped in molecular cages of carbon (fullerenes). This hypothesis follows the extraction of the gases from rocks at the P-T transition (Becker et al., 2001). Analyses of these gases show that their isotopic compositions are analogous to those found in meteorites, and are not typical of the Earth-bound abundances. This is some evidence that a major impact may have delivered the noble gases to Earth at the time close to the period when the extinctions did take place. Indeed, this suggestion provides an indicator for a P-T impact that is analogous to the earlier theory of the impact at the K-T boundary, an event that we saw above to have been supported by the Ir-data.

Fullerenes are also candidates for indicators of impact. Previous work by others showed that they are present in rock at the K-T boundary (Heymann *et al.,* 1994). Together these findings suggested that fullerenes are the product of the high pressures and temperature generated in the collision and are impact markers like iridium. That prompted Becker and her colleagues to look for the compounds in rock at the P-T boundary at the in South China, and in southwest Japan and reported the detection of fullerenes in boundary rock, but not in similar rock a few centimetres to meters above, or below the boundary. However, it should be kept in mind that fullerenes can be produced by, for instance, forest fires.

In the case of the K-T mass extinction shocked quartz was detected, (i.e., crystals containing distinctive lamellae made only in the extreme pressures of large impacts). Shocked quartz has not been identified with the same certainty at the P-T transition, but the noble gas indicators may offer additional evidence. Fullerenes can trap gas atoms. When the gases trapped in fullerenes from P-T-boundary rocks was analyzed (Becker et al., 2001), it was found that the abundance of helium-3 was significantly enhanced above what it was immediately above or immediately below the boundary. The ratio of helium-3 to helium-4 was typical of meteorites. Besides the ratio of argon-40 to argon-36 in boundary fullerenes is likewise analogous to that of meteorites.

5.2 EXTINCTIONS DUE TO ENDOGENOUS SOURCES

The warming caused by volcanoes through carbon dioxide emissions would not be large enough to cause mass extinctions by itself. That warming, however, could set off a series of events that may have led to mass extinction. During the P-T extinction 95 percent of all species on Earth became extinct, compared to only 75 percent during the K-T when a large asteroid apparently caused the dinosaurs to disappear.

Volcanic carbon dioxide would cause atmospheric warming that would, in turn, warm surface-ocean water. Normally, the deep ocean gets its oxygen from the atmosphere at the poles. Cold water there soaks up oxygen from the air and because cold water is dense, it sinks and slowly moves equator-ward, taking oxygen with it. The warmer the water, the less oxygen can dissolve and the slower the water sinks and moves toward the equator (Kump *et al.,* 2005).

The constant rain of organic debris produced by marine plants and animals, needs oxygen to decompose. With less oxygen, fewer organics are aerobically consumed. In the Permian, if the warming from the volcanic carbon dioxide decreased oceanic oxygen, especially if atmospheric oxygen levels were lower, the oceans would be depleted of oxygen. Once the oxygen is gone, the oceans become the realm of bacteria that obtain their oxygen from sulphur oxide compounds. These bacteria strip oxygen from the compounds and produce hydrogen sulphide. Hydrogen sulphide kills aerobic organisms. Humans can smell hydrogen sulphide gas, the smell of rotten cabbage, in the parts per trillion range. In the deeps of the Black Sea today, hydrogen sulphide exists at about 200 parts per million. This is a toxic brew in which any aerobic, oxygen-needing organism would die. For the Black Sea, the hydrogen sulphide stays in the depths because our rich oxygen atmosphere mixes in the top layer of water and controls the diffusion of hydrogen sulphide upwards. At the end-Permian, as the levels of atmospheric oxygen fell and the levels of hydrogen sulphide and carbon dioxide rose, the upper levels of the oceans could have become rich in hydrogen sulphide catastrophically. This would kill most the oceanic plants and animals. The hydrogen sulphide dispersing in the atmosphere would kill most terrestrial life. Another aspect of this extinction is that hydrogen sulphide gas destroys the ozone layer. Once this process has started, methane produced in the ample swamps of this time period has little in the atmosphere to destroy it. The atmosphere becomes one of hydrogen sulphide, methane and ultra violet radiation.

Biomarkers of photosynthetic sulphur bacteria in deep-sea sediments were recently reported in shallow water sediments of an age comparable to the P-T transition (Grice *et al.,* 2005). These bacteria live in places where no oxygen exists, but there is some sunlight, as it may have happened at the end of the Permian. Confirming the evidence for these microorganisms would suggest hydrogen sulphide to have been the cause of the mass extinctions. The question remains however whether the extinction may have been the effect of another underlying process.

6. Are there possible traces of catastrophic space-climate events in the hominid fossil record?

The role of cataclysmic events in the evolution of life on Earth has been discussed in recent times. Tobias has suggested the possible causal connection between large impacts such as the Vredefot impact structure in the Free State (it is the latest World Heritage Site to be listed in South Africa). Its reconstructed diameter of 250-300 km was made by a projectile estimated at 10-15 km in diameter, which collided with the Earth at 2.1 Ga (Tobias, 2005).

This impact coincided with two significant events in the evolution of life on Earth, namely the oxygenation of the atmosphere and the first appearance of the eukaryotes. Although Tobias attempts to make a causal connection between the large impact and these two events, an approach that he calls catastrophism, there are alternative explanations as discussed by others: in the case of the oxygenation of the atmosphere (Abelson, 2007), and the first appearance of the eukaryotes (Chela-Flores, 1998). But even if the alternative explanations are maintained, what is true is that the Vredefot impact illustrates the major implications that extraterrestrial events, not only SpW, as illustrated in this paper, but even planetary sterilizations going back into the Phanerozoic and extending back to the Hadean.

Tobias insists that milder environmental impacts might have been relevant in the evolution that led to *Homo sapiens*. For instance, about 2.6-2.5 Ma marked climatic changes in Africa that were associated with uplift of its southern and eastern parts. The ensuing cooler and dryer weather was accompanied with significant changes in the paleontological record:

(a) Extinction of the small-brained hominids *Astralopithecus africanus.*
(b) The earliest appearance of *Homo* of the species *Homo habilis.*
(c) The first signs of the enlargement of the hominid brain, as compared with the smaller brains of the australopithecines.

The possibility of a supernova explosion near the Solar system has been discussed for a long time (Ruderman, 1974; Reid *et al.,* 1978; Ellis and Schramm, 1995). Such a nearby supernova explosion can be confirmed by the detection of radioisotopes on Earth that were produced and ejected by the supernova. A measurement of a well-resolved time profile of the ^{60}Fe concentration in a deep-sea ferromanganese crust showed a significant increase 2.8 Ma (Knie et al., 2004). The amount of ^{60}Fe is compatible with the deposition of ejecta from a supernova at a distance of a few 10 pc. The well-defined time of the supernova explosion makes it possible to search for plausible correlations with other events in Earth's history. Other possible radionuclides for tracing supernova explosions are 182Hf (8.9 Ma) (Vockenhuber et al., 2004), 244Pu (81 Ma) (Winkler *et al.,* 2004).

The profile of the ^{60}Fe concentration in the deep-sea ferromanganese crust has been considered in terms of the environmental changes that were relevant for *Homo* evolution (a-c) According to the authors (Knie *et al.*, 2004), at the time of the supernova explosion there was an increase of the cosmic radiation of a few percent that lasted for some thousand years. They claim this might have triggered climate change in Africa, causing significant developments on hominid evolution. This effect would in any case be superimposed on other phenomena causing climate change, such as tectonic activities (like those that gave rise to the Great Rift Valley in Africa), as well as other global phenomena.

Besides, this event could have a significant effect on the ozone layer. Hence it may have had an effect on the natural UV filter that led to the present Earth biota. Improved tools for detailed modelling of atmospheric chemistry have been developed to calculate ozone depletion, and advances have been made also in theoretical modelling of supernovae and of the resultant gamma-ray spectra. In addition, we now have better knowledge of the occurrence rate of supernovae in our galaxy and of the spatial distribution of progenitors to core-collapse supernovae. The results of two-dimensional atmospheric model calculations estimates (Gherls *et al.,* 2003) are interesting in this respect, since they take as input the spectral energy distribution of a supernova, adopting various distances from Earth and various latitude impact angles. In separate simulations there is an estimate of the ozone depletion that is due to cosmic rays. These calculations suggest that for the combined ozone depletion from these effects roughly to double the "biologically active" UV flux received at the surface of the Earth, the supernova must occur at 8 pc. Based on the latest data, the time-averaged galactic rate of core-collapse supernovae occurring within 8 pc is 1.5 Ga.

In principle, high-energy galactic cosmic rays could be also responsible for genetic changes related to human evolution. Some groups have been searching for discrepancies in the production rate of stable cosmogenic radionuclides, such as ^{21}Ne and radioisotopes with different half-lives such as ^{10}Be, ^{26}Al and ^{53}Mn that might indicate time variation in the galactic cosmic-ray flux within the solar system. The existing data do not support major variations in cosmic ray intensity within the past 5 million years, crucial period for the evolution of the *Homo* species (Moniot, *et al.,* 1983). A huge asteroid collided with the Earth in South East Asia around 780 thousand years ago, with devastating environmental effects. Magnetic properties of rocks formed at that time show that the impact of the extra-terrestrial body might have caused the Brunhes-Matuyama magnetic reversal. Tonnes of tektites—obsidian-like pebbles produced by the fusion of sediments during the impact—were launched into the air and scattered all over South-east Asia and Australia. Some scholars connect this environmental disaster to the introduction of advanced Acheulean-like technology in Asia during this period.

More recently it has been suggested that a comet or asteroid exploded over North America 13,000 years ago. This event wiped out a Stone Age culture known as Clovis, as well as the mammoth and the mastodon. This event may have caused a major shift in the climate, the well-known Youger Dryas cooling event. The cooling produced may also have affected humans in Europe and Asia (Firestone *et al.,* 2007). A detailed analysis of the sediments corresponding to 13 ka ago reveal a high concentration of extraterrestrial (ET) markers such as glass-like beads, soot and fullerenes, materials that are absent in other layers of the stratigraphy. The glassy beads could only be produced by melting carbon at 4000 degrees C. Electron microscope analyses show the glassy spherules are reach in micro-diamonds. Diamonds are produced in the interior of the Earth by compressing carbon at the pressure of several gigapascals. These conditions could be produced on the surface of the planet only by the impact of a massive extraterrestrial body.

Finally, we should mention that the evolution and dispersion of the *Homo* species during the last 2 million years was strongly conditioned by the variable climate of Earth, driven by changes in the Earth's orbit around the Sun as proposed by Milankovitch in the 1920s. Three variations of the Earth's orbit are considered, eccentricity, obliquity and precession, which affect the quantity of sunlight hitting the Earth's surface. They are the main cause of the ice ages during the Pleistocene, characterised by periods of about 100,000, 40,000 and 20,000 years, respectively, as confirmed by the ice fossil record in sea sediments.

7. Beyond the Sun: influence of our galactic environment on life on Earth

In this section we shall discuss two possible sources of SpW factors that may have influenced the evolution of life on Earth and such factors may be reflected in the fossil record: gamma ray bursts (GRBs) and cosmic rays.

Firstly, GRBs are powerful explosions that produce a flux of radiation detectable across the observable Universe. These events possibly originate in distant galaxies, and a large percentage likely arises from explosions of stars over 15 times more massive than our Sun. A burst creates two oppositely directed beams of gamma rays that race off into space. If a GRB were to take place within the Milky Way we would have to consider the possibility of mass extinctions comparable to the other known sources, such as the meteoritic collision with the Earth (cf., the next section), or a singular abundance of sulphur in the atmosphere due to the causes that are reviewed below. Mass extinctions have eliminated a significant fraction of life on Earth. For example, the most severe extinction of the past 500 million years occurred in the Late Permian (Erwin, 1994). The large masses of the first stars suggest that they may have produced supernovas at the end of their relatively short lifetimes. Such events may in principle be detectable as GRBs at very large red shifts, which may be detectable with the SWIFT satellite (Hartmann, 2005; Markwardt *et al.,* 2005).

A number of other astrophysical objects also produce GRBs, such as quasars and neutron stars. Quasars were also forming at around z~6, so part of the challenge is to identify the proper GRB source (Xu *et al.,* 2005). GRB, together with meteoritic collisions, or an atmosphere that has gone through a transition unfavourable to the Earth biota are three likely causes that need to be discussed together, as we have attempted to do in the present review.

The Ordovician is the second oldest period of the Palaeozoic Era, thought to have covered the span of time between 505 and 440 million years before the present Ma BP. The late Ordovician mass extinction took place at approximately 440 Ma BP may be at least partly the result of a GRB. Due to expected depletion of the ozone layer arising from the incoming energetic flux, the solar ultraviolet radiation that is normally shielded would give rise to a severely modified ecosystem. It is known that all marine animals suffered mass mortalities during the Late Ordovician Mass mortalities at the close of the Cambrian and late in the Ordovician resulted in the unique aspects of the Ordovician fauna.

The Swift mission, launched in November 2004, contributes to determine recent burst rates. During evolution of life certain events triggered large-scale extinctions. We consider one of the most remarkable possible candidates. The Late Ordovician extinction created new opportunities for benthic and planktonic marine fauna. Biological radiation during post-Ordovician glaciation led to many new taxa typical of the Silurian. GRBs within our Galaxy have been repeatedly suggested to be a possible threat to life on Earth (Thorsett, 1995; Scalo and Wheeler, 2002; Melott *et al.,* 2004).

Some effects similar to those due to a nearby supernova should be expected. GRBs are less frequent than supernovae, but their greater energy output results in a larger region of influence, and hence they may pose a greater threat. It is likely (Melott et al., 2004) that in the last billion years (Ga), a GRB has occurred close enough to have dramatic effects on the stratospheric ozone, leading to detrimental effects on life through increases in solar ultraviolet (UV) radiation, which is strongly absorbed by ozone. A major question has been the timescale for atmospheric chemistry: most of the GRB influence comes in seconds or minutes as compared to months for the case of supernovae.

There is no direct evidence that such a burst activated the ancient extinction. The conjecture is based on atmospheric modelling (Thomas *et al.,* 2005). The main conclusion to be derived from these calculations is that gamma-ray radiation from a relatively nearby star explosion, hitting the Earth for only ten seconds, could deplete up to half of the atmosphere's protective ozone layer. Recovery could take at least five years.

With the ozone layer damaged, ultraviolet radiation from the Sun could kill much life on land and near the surface of oceans and lakes, and disrupt the food chain. Nevertheless it is important to recall, as we shall do in the next two sections based on the fossil record that there are two other competing theories for mass extinctions during earlier geologic periods, such as the suggested Ordovician mass extinction.

A related issue of SpW besides GRBs is whether cosmic rays may have left their imprint in the fossil record**.** To answer this question we may recall some recent research related to the rationalization of observed cycles in the fossil diversity (Kirchner and Weil, 2005).

As the Earth’s solar system travels around the centre of the Milky Way galaxy, it also wobbles up and down from the galaxy’s disc. U.S. scientists found that these swings take about 62 million years to complete—thus, may expose the Earth to higher doses of dangerous cosmic ray that may also cause mass extinctions. One complete orbit around our galaxy takes the solar system about 225 million years to complete. So, we go through about four of these cycles above and below the galactic plane during one orbit around the galaxy. (The galactic plane as the plane that is contained within the equator of the Milky Way galaxy, with the centre of the galaxy being the origin of this galactic coordinate system.) . The modulation of the cosmogenic nuclide production expected from the galactovertical motion of the solar system was evaluated earlier (Vanzani *et al.,* 1987). The time distribution of ^{10}Be concentration predicted by the model appears to be consistent with the data of deep-sea sediments.

The translation between the northern and southern sides of the galactic plane happens due to mass and gravity. When the solar system is on the northern side of galactic plane, the galactic mass located in the southern part uses its gravity to pull the solar system back down. Similarly, the northern galaxy mass, through the gravitational force, displaces the solar system from the southern side. A large amount of fossil data that covered an era of over 500 million years has been published (Sepkoski, 2002). Further studies suggest that living things on the Earth have been at their greatest risk of extinction every 62 million years or so for the past 542 million years (Rohde and Muller, 2005).

This suggests that living in the south side of the galactic plane of the Milky Way may be safer for humans and all living things here on the Earth. Cosmic rays strike the Earth on their travels from a large cluster of galaxies in the direction of the Virgo constellation (Medvedev and Melott, 2007). Our own galaxy is moving toward the Virgo constellation in the northerly direction. So, when the solar system is on the north side of the Milky Way's plane, we are being bombarded by more cosmic rays from the Virgo constellation. The more cosmic rays that hit the Earth, the more that these energetic particles could possibly cause various problems such as changes in weather and climate, damage to DNA within humans and other animals, and mass extinctions. This work suggests that mass extinctions may very likely correspond to peaks in cosmic rays when the Earth is at its maximum northerly distance from the galactic plane.

8. Discussion and Concluding Remarks

The main thesis that we have maintained in this work is that solar activity, space climate and astrobiology should be brought within a unified framework that would include contributions from other disciplines relevant to the past of environments in the solar system. This approach naturally leads us to the suggestion of exploiting instruments and methods from somewhat dissimilar sciences (astronomy and astrobiology) with a unified objective (Messerotti and Chela-Flores, 2007a; 2007b).

We have attempted a preliminary comprehensive discussion of how research in the conditions of the early Sun combine with observations in several disciplines giving insights into the factors that lead to the emergence of life in a given Solar system: biogeochemistry, lunar science, cosmochemistry, chemical evolution, palaeontology, palaeoanthropology, palaeoecology, geochronology and oceanography, amongst others. These considerations are necessary for a holistic approach to understand the conditions that allow life to emerge and evolve elsewhere in the universe.

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