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Solar Activity and Life: a Review

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Abstract

During the early stages of the study of the origin of life, not enough attention was paid to the question of the correlation of chemical evolution on Earth and the all-important evolution of the still-to-be understood early Sun. Today, due to the advent of a significant fleet of space missions and the possibility of performing experiments in the International Space Station (ISS), a meaningful study begins to be possible concerning factors that led to an early onset of life on Earth. We wish to review and update recent work concerning the frontier between Space Weather (SpW) and Astrobiology. We argue that the present robust programs of various space agencies reinforce our hope for a better understanding of the bases of Astrobiology. Eventually, with a more realistic model of the Sun, more reliable discussions of all the factors influencing the origin of life on Earth, and hence Astrobiology, will be possible.

Key words: Space Weather, Astrobiology, solar activity, early solar system, solar missions.

1. WHY SHOULD ASTROBIOLOGY BE INCORPORATED INTO THE STUDIES OF SPACE WEATHER?

In the new science of Astrobiology (Oparin 2003, Miller 1953, Ponnamperuma and Chela-Flores 1995) the question of the correlation of chemical evolution on the Earth and the all-important evolution of the still-to-be understood early Sun requires more attention (Messerotti 2004). Today a meaningful comprehensive study begins to be possible. The present review concerns the frontier between Space Weather (SpW) and Astrobiology (Messerotti 2004, Messerotti and Chela-Flores 2007a, b, Chela-Flores and Messerotti 2008, Chela-Flores *et al*. 2008).

Solar climate and weather during the first billion years (Gyr) of the Earth was entirely different from the present. The early atmosphere arose from collisions during the accretion period, the so-called heavy bombardment period of the surface of the Earth during the early Archaean (before 3.8 Gyr BP). Planetesimal impacts increase the surface temperature affecting the formation of either a proto-atmosphere or a proto-hydrosphere by degassing of volatiles. The earliest relevant factor from solar physics that may have influenced the origin of life conditions 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 we believe that some of the early Solar System material must keep 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 ultraviolet (UV) emission (larger than 10 eV) from pre-main-sequence stars (Lal and Ligenfelter 1991). We may conclude that during the pre-main-sequence period, solar climate and weather presented an insurmountable barrier for the origin of life anywhere in the Solar System. This is the main input that has encouraged us to search for a unified approach to both Astrobiology as well as Space Weather (SpW). In the most remote times of the Archean eon (2.5-3.8 Gyr before the present, BP), and in the Hadean (earlier than 3.8 Gyr BP), conditions may still have been somewhat favorable, especially with the broad set of UV defense 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*. 1983). Some possible UV defense mechanisms have been proposed in the past, such as atmospheric absorbers and prebiotic organic compounds. We expect that the early microbes must have used various means of avoidance of radiation damage, including inhabiting in deep subsurface environments (Gold 1992). Some of these are attenuation by the water column of their aquatic habitats by the presence of some UVR absorbing substance. It is known that water itself does not protect life. Indeed, UVR is known to penetrate the water column up to at least 50 meters. But if the water contains iron, or nitrogenous salts, UVR is efficiently screened. In addition, related relevance of

SpW on the origin of life is demonstrated with two sets of experiments have established that UV radiation plays a significant role in the synthesis of some of the precursors of the biomolecules, especially the amino acids (Bernstein *et al*. 2002, Munoz-Caro *et al*. 2002).

Solar systems originate out of interstellar dust, namely, the dust constituted mainly out of the fundamental elements of life (Ehrenfreund and Charnley 2000), such as C, N, O, P, S and a few others. We refer to this set as "the CNOPS elements". Just before a star explodes into its supernova stage, all the elements that have originated in its interior out of thermonuclear reactions are expelled, thus contributing to the interstellar dust. Recent work has some implications on the question of SpW. Our Solar System may have been triggered over 5 Gyr BP by the shock wave of a supernova explosion. Indeed, there is some evidence for the presence of silicon carbide (carborundum, SiC) grains in the Murchison meteorite, where isotopic ratios demonstrate that they are matter from a type II supernova (Hoppe *et al.* 1996). Around 4.6 Gyr BP on the nascent planet, the organic compounds may have arisen at the end of accretion when they would have been incorporated or delivered by small bodies, both comets and meteorites. Then, planetary processes, such as those that may have occurred close to hydrothermal vents, may have synthesized organic compounds. Comets are another source of CNOPS elements which develop gaseous envelopes when they are in the close vicinity of the Sun. Gas leaves the comet, carrying some of the dust particles. On the other hand, the Earth's biosphere is that part of this planet where life can survive; it extends from a few kilometers into the atmosphere to the deep-sea vents of the ocean, as well as into the crust of the Earth itself. The Delsemme model is based on the assumption of the cometary origin of the biosphere (Delsemme 2000). According to this viewpoint, an intense bombardment of comets has brought to the Earth most of the volatile gases present in our atmosphere and most of the carbon extant in the carbonate sediments, as well as in the organic biomolecules. With the measuring ability that was available throughout last century, molecules have been identified by their spectra in a wide range of wavelengths, and even by in situ mass spectrometry during spacecraft flybys of comet P/Halley. These measurements provided composition of parent volatiles and dust, properties of the nuclei, and physical parameters of the coma. Besides the Halley comet already mentioned, two other comets were particularly useful objects for remote sensing measurements: Hale-Bopp and Hyakutake (Campins 2000). These comets led to the detection of HCN, methane, ethane, carbon monoxide, water, as well as a variety of biogenic compounds.

The Big Bang model tells us that as time t increases, the Universe cools down to a certain temperature, which at present is close to 3 K which is equivalent to a temperature of –270°C), in less than one million years after the beginning of the general expansion, the temperature T was already sufficiently low for electrons and protons to be able to form hydrogen atoms. Up to that moment these elementary particles were too energetic to allow atoms to be formed. Once "recombination" of electrons and protons was possible, due to falling temperatures, thermal motion was no longer able to prevent the electromagnetic interaction from forming hydrogen atoms. This is the "moment of decoupling" of matter and radiation, when the primordial high temperature had decreased sufficiently, not only hydrogen atoms were formed and helium atoms arose from the combination of deuterium with itself. This expansion generated a fraction of deuterium. It is estimated that this cosmic ratio of D/H had an upper bound of some 30 parts per million (ppm). Deuterium cannot be created *de novo*. So the variable presence of D/H is a marker for understanding various aspects of the evolution of solar systems. Since deuterium can react easily inside stars, it is not surprising that its abundance in interstellar matter be smaller than the original cosmic abundance. Yet, in Jupiter the value is higher than in interstellar matter, reflecting its abundance in the proto-planetary nebula. The Jupiter abundance is of the order of 20 ppm, closer to the expected cosmic abundance. In the Earth's seawater, this ratio is about 8 times the value of the solar nebula. The D/H ratio is known in three comets: Halley, Hyakutake and Hale-Bopp (HHH). This work on the D/H ratio suggests that cometary impacts have contributed significantly to the water in the Earth's oceans. However, because the D/H ratio observed so far in comets is twice the value for Earth's oceans, it may be argued that comets cannot be the only source of ocean water.

2. SIGNATURES OF THE EARLY SOLAR SYSTEM THAT ARE RELEVANT FOR SPW AND ASTROBIOLOGY

The early Earth was much more dynamic geologically and most of the records of large impacts were deleted, but the same geological activity was most likely responsible for partial out gassing of a secondary atmosphere, the exact nature of which can be inferred from the isotopic composition of the noble gases: It has been shown that comets are capable by themselves of providing noble gases in the correct proportions provided that the laboratory experiments duplicate the conditions for cometary formation (Owen and Bar-Nun 1995). Besides, the temperatures had descended to about 1000 C, or below, by about 4.4 Gyr before the present (BP). This scenario for planetary origin allows the possibility of an early origin and evolution of life on Earth. However, it should be remembered that the lunar record demonstrates that some difficulties may arise in this scenario since the Imbrium basin on the Moon was formed by a large impact as late as 3.8 Gyr BP. This implies the persistence of catastrophic impacts for life on Earth, since our planet has a larger effective cross section than our satellite (Sleep *et al.* 1989).

Yet, in this harsh environment photosynthesis of prokaryotes did arise. It is evident from fossils of the stromatolitic-forming cyanobacteria. But the best evidence comes from geochemical analyses of the ancient rocks that militate in favor of the presence of bacterial ecosystems in the period that we are discussing in this section, namely 3.8-3.9 Gyr BP. The question of the metamorphism to which the Isua samples have been subjected remains controversial (Schidlowski *et al*. 1983). Stromatolites consist of laminated columns and domes, essentially layered rocks. Prokaryotic cells called cyanobacteria form them. In addition, they are users of chlorophyll-a to capture the light energy that will drive the photosynthetic process. We remind the reader that chlorophyll is a pigment that is present in chloroplasts that captures the light energy necessary for photosynthesis. Chlorophyll-a is the most common of five such pigments absorbing well at a wavelength of about 400-450 nm and at 650-700 nm. The reason that there are so many pigments in photosynthesis is that each pigment absorbs light more efficiently in a different part of the spectrum. Cyanobacteria are mat-building communities. Right back into ancient times such mats covered some undermat formation of green sulphur and purple bacteria. Such underlying microorganisms are (and were) anaerobes that can actually use the light that impinges on the mat above them by using bacteriochlorophylls that absorb wavelengths of light that pass through the mat above them (Schopf 1999). Stromatolites have persevered practically without changes for over 3 billion years. The exact date for the earliest stromatolitic fossils is at present under discussion (Brasier *et al.* 2002, Schopf *et al*. 2002). They have been dated at around 3.5 Gyr BP (Schopf 1993). If the fossils are accepted, life's origin must be in the Archean, or even earlier, considering the complexity of a cyanobacterium itself.

Another signature of the early Sun is provided by isotopic fractionation of the five stable noble gas elements, namely, He, Ne, Ar, Kr, and Xe. The early atmosphere arose from collisions during the accretion period, the so-called heavy bombardment of the surface of the Earth. Planetesimal impacts increase the surface temperature affecting the formation of either a proto-atmosphere or a proto-hydrosphere by degassing of volatiles (Matsui and Abe 1986).

Thus, life emerged on Earth during the Archean (3.8-2.5 Gyr BP). From the point of view of SpW, we should first of all appreciate the magnitude of the ionizing radiation that may have been present at that time. According to some theoretical arguments the origin of life may be traced back to the most remote times of this eon (3.8 Gyr BP). Indeed, isotopic and geologic evidence suggests that photosynthesis may have been already viable by analysis of the biogeochemical parameter delta 13 C (Schidlowski *et al.* 1983). Besides, in the Archean the atmosphere was to a large extent anoxic. As a result the abundance of ozone would not have acted as a UV defense mechanism for the potential emergence of life. UVB (280-315 nm) radiation as well as UVC (190-280 nm) radiation could have penetrated to the Earth's surface with their associated biological consequences (Cockell 1998, Elster 1999). If the distribution of life in the Solar System took place by transfer of microorganisms between planets or satellites (the Panspermia Hypothesis), knowledge of SpW becomes fundamental during the early stages of its evolution, to have some constraints on the possible transfer of microorganisms, as investigated extensively (Cockell and Horneck 2001). The most radiation resistant organism known at present exhibits a remarkable capacity to resist the lethal effects of ionizing radiation. The specific microorganism is a non-spore forming extremophile found in a small family known as the Deinococcaceae. In fact, Deinococcus radiodurans is a Gram-positive, red-pigmented, non-motile bacterium. It is resistant to ionizing and UV radiation. All known members of the genus are radioresistant: D. proteolyticus, D. radiopugnans, D. radiophilus, D. grandis, D. indicus, D. frigens, D. saxicola, D. marmola, D. geothermalis and D. murrayi; the latter two are also thermophilic. Various groups have studied these microorganisms (Battista 1997, Daly *et al*. 2004, Levin-Zaidman *et al*. 2003). Members of this bacteria taxon can grow under large doses of radiation (up to 50 grays (Gy) per hour). They are also known to recover from acute doses of gamma-radiation greater than 10,000 Gy without loss of viability. Such microorganisms demonstrate that life could have survived at earlier times when the Earth surface was more exposed to solar radiation.

3. RELEVANCE OF SOLAR MISSIONS FOR AN INTEGRATED STUDY OF SPW AND ASTROBIOLOGY

Space climate and Space Weather are also fundamental for understanding the early evolution of life. The DNA repair mechanisms that extremophilic organisms evolved in response to a continuously changing space environment. The Sun has been considerably changing its temperature and luminosity, key factors for Astrobiology that require better understanding, so that we would be in a position to ***predict*** with a certain degree of confidence what were the conditions like during the first Gyr of evolution of the Solar System. The violent eruptions of solar flares during its earliest stage (T-Tauri) soon gave way to a very broad range of physical conditions that have to be clarified by further research. There are several reasons to raise the question: Why do we need improved understanding and predictions of solar activity? One reason arises from theoretical modeling of the earliest organisms. Predictions range broadly in their claims. Improved understanding of solar activity in the first billion years of the Earth would provide essential clues. Additional aspects of astrobiology, such as the question of the distribution of life in the Solar System, also depend on further research outside the frontier of Astrobiology, namely by acquiring improved understanding of solar activity, such as the preliminary information that has been possible to retrieve from the ISS.

Much progress has been achieved since the 1990s missions for studying the Sun. Firstly, remarkable progress has been possible with the Solar and Heliospheric Observatory (SOHO), a joint NASA-ESA spacecraft. SOHO was concerned with the physical processes that form and heat the Sun's corona, maintain it and give rise to the expanding solar wind. A second mission launched in the last decade is Ulysses with measurements of the Sun from a polar orbit and had been active to the present. Ulysses has returned a wealth of data that has led to a much broader understanding of the global structure of the Sun's environment: the heliosphere. It is also dedicated to interplanetary research, especially with interplanetary-physics investigations, including close (1992) and distant (2004) Jupiter encounters. More recently, the Transition Region and Coronal Explorer (TRACE) is giving information on the three-dimensional magnetic structures that emerge through the photosphere, defining both the geometry and dynamics of the upper solar atmosphere. In this respect, STEREO (Solar TErrestrial RElations Observatory), a mission launched in October 2006, employs two nearly identical space-based observatories – one ahead of the Earth in its orbit, the other trailing behind – to provide the first-ever stereoscopic measurements to study the Sun and the nature of its coronal mass ejections, or CMEs, which in spite their significant effect on the Earth, their origin, evolution or extent in interplanetary space remains as a challenge. Persevering with the solar missions like Ulysses should be useful, especially in the future when we should address an important question: whether in the past 2-3 Gyrs similar events may have produced space climate and weather, harmful or beneficial for the evolution of life in the Solar System. The focus of Space Weather from the point of view of Astrobiology gives us a hint for persevering with Ulysses-type of missions. Jupiter's moon Io is emitting volcanic particles at passing spacecraft. The dominant source of the jovian dust streams is Io's volcanoes (Graps *et al*. 2000). In September 2004 Io emitted dust particles whose impact rate was recorded by the Cosmic Dust Analyzer on board of Ulysses. The discovery of this phenomenon dates back to 1992 when a stream of volcano dust hit Ulysses as it approached within 1 AU from the Jupiter (Grun *et al*. 1993). Cassini's dust detector is more capable than the instrumentation on Ulysses when faced with a similar event (Srama *et al*. 2000). In addition to mass, speed, charge and trajectory, Cassini measured elemental composition finding sulfur, silicon, sodium and potassium, whose origin is volcanic. This raises a question that inevitably will deserve further attention from both astrobiologists as well as Space Weather researchers in the future.

4. CONCLUDING REMARKS ON THE SIGNIFICANT OVERLAP OF SPW AND ASTROBIOLOGY

In the present review, we have attempted for the first time to make a compelling case for the insertion of Astrobiology as a prominent topic in SpW research. In our earlier attempts we only succeeded partially. Now with the present review we believe that we have not only brought together partial evidence published in various papers, some of which are not easily accessible to the readers of this journal, but by bringing them together we now have argued in favor of an integrated study of two disciplines of the space sciences that up to the present have largely ignored each other, notwithstanding their significant overlap.

The main thesis that we have maintained in this work is that solar activity, Space Weather and Astrobiology should be brought within a unified framework. This approach naturally leads us to the suggestion of exploiting instrumentation from somewhat dissimilar sciences (astronomy and astrobiology) with a unified objective. We have attempted a preliminary comprehensive discussion of how research in the conditions of the early Sun combines with observations in several disciplines to give us insights into the factors that lead to the emergence of life in a given Solar System (biogeochemistry, lunar science, micropaleontology and chemical evolution). These considerations are necessary to approach the evaluation of conditions that will allow life to emerge anywhere in the Universe.

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