SIGNATURES OF THE ANCIENT SUN CONSTRAINING THE EARLY EMERGENCE OF LIFE ON EARTH

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ABSTRACT/RESUME

A factor for understanding the origin and evolution of life on Earth is the evolution of the Sun itself, especially the evolution of space climate and weather. Many aspects of the Sun's history remain to be understood. We reconsider constraints that knowledge of our own star implies for the emergence of life on Earth. This provides further insights into what may happen in other solar systems. Fortunately, particles emitted by the Sun in the past have left a record in geologic samples, but on this bases we cannot exclude earlier dates for the onset of life on Earth. A very early origin of life has to take into account the imprints of solar energetic particles during the first billion years (Gyr) after the formation of the Sun, approximately from 4.6 till 3.6 Gyr before the present (BP). Our review includes the isotopic fractionation of the noble gases, the depletion of volatile elements on the Moon and constraints for the origin of life on Europa, the icy moon of Jupiter.

1. ESTIMATES FOR THE AGE OF THE FIRST APPEARANCE OF LIFE ON EARTH

The rationalization of the lunar cratering record provides some guidance for estimating the possibility of life first arising on Earth. Distinct temporal possibilities for the earliest possible time for the first appearance of life are possible with additional inputs from closely related scientific areas. The lunar record may be supplemented with information retrieved from firstly, biogeochemistry (namely with data related to the fractionation of the stable isotopes of the biogenic elements). Secondly, associated with the earliest fossils of stromatolites our current understanding of micropaleontology leads to further possible constraints on the first appearance of life on Earth. However, various theories of the evolution of the early Sun will further constrain the origin of the earliest life on Earth.

1.1 Lunar record constraints (4.4–4.2 Gyr BP)

Although the processes taking place during this period are not represented in the geological record, the current scenario of planetary origin gives us a means of inferring the activity that may have frustrated or encouraged emergent life. During the first 100 million years the flux of impactors would have set up the conditions for the separation of iron and silicate, giving rise to a metallic core. During this formation of the planetary embryo a major impact with another planet-size body would have given rise to the expulsion of a large amount of matter from the embryonic Earth and given rise to the Moon (Canup and Asphaug, 2001). The satellite cooled quickly, but did not form an atmosphere, possibly due to the smaller cross section than the Earth. Another significant effect of the Moon-forming impact was to blow away the original atmosphere that the embryonic Earth had captured from the solar nebula (Kasting and Catling, 2003). The planet 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 100 degrees Centigrade or below by about 4.4 Gyr BP (Schwartz and Chang, 2002). 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).

1.2 Biogeochemistry constraints (3.8-3.9 Gyr BP)

The photosynthesis of prokaryotes includes the stromatolitic-forming cyanobacteria, formerly called blue-green algae. In this process a specific enzyme that leads in several steps to the synthesis of glucose captures carbon dioxide. But the carbon dioxide in the environment and nutrients contain the two stable isotopes of carbon ^{12}C and ^{13}C. The process of photosynthesis favours ^{12}C over ^{13}C. Geologic process partitions the stable isotopes in opposite ways; for instance limestone is depleted in ^{12}C and enriched in ^{13}C. The fossil records of organic matter that have been enriched in ^{12}C can be traced back in sedimentary rocks right back to some of the earliest samples such as the 3,800 Myr-old metamorphosed sedimentary rocks from Isua, West Greenland. These geochemical analyses of the ancient rocks militate in favour of the presence of bacterial ecosystems in the period that we are discussing in this section, namely 3.8-3.9 Gyr BP (Schidlowski, 1988; Schidlowski et al., 1983). The question of the metamorphism to which the Isua samples have been subjected has raised some controversy in the past (Hayes *et al.,* 1983).

1.3 Stromatolitic constraints (3.5-3.6 Gyr BP)

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. These microorganisms are mat-building communities. At present they are ubiquitous, even in the Dry Valley lakes in Antarctica mat-building communities of cyanobacteria have been well documented (Parker et al, 1982). 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). Not only has the cyanobacterium spread worldwide, but it has also extraordinary temporal characteristics. 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). Hence, the origin of life if the fossils are accepted, must be in the time interval discussed in this section, or even earlier considering that the cyanobacterium itself is already quite a complex cell.

2. ISOTOPIC FRACTIONATION OF THE NOBLE GASES ON EARTH

A 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). This generated a 'steam atmosphere'. One of its consequences was a rapid hydrodynamic outflow of hydrogen, including some of its compounds such as methane, carrying along heavier gases in its trail (Hunten, 1993). The mechanism postulated is that of aerodynamic drag. The upward drag of noble gas atoms of similar dimension competes with an opposite force due to gravity. Hence, since the various isotopes of these gases have different masses the net result is the occurrence of a mass-dependent fractionation of the various noble gas isotopes. For even heavier atoms, the gravity effect can be stronger than the aerodynamic drag and such atoms would not show the remarkable fractionation typical of the noble gases.

By looking at other main-sequence stars at equivalent early periods of their evolution, we became aware of an associated larger output of solar EUV radiation. With the early Sun such an ultraviolet excess radiation is a possible factor that can trigger the phenomenon of mass fractionation in the noble gases. The case of the $^{22}Ne/^{20}Ne$ ratio is an example, since its value is larger than in the Earth's mantle, or in the solar wind. The observed fractionation of the noble gases can be taken as a signature of two aspects of the early Sun: firstly, the presence of the postulated escape flux, and secondly (more relevant for the main topic of this paper), as evidence for the solar energy source that drives the outward flux of gases. The emergence of appropriate conditions for life on Earth has to wait until the decrease of solar radiation that characterizes the terrestrial accretion period. The beginning of such a favourable period begins once accretion has ended. The surface heat flux diminishes, leading to the steam atmosphere raining into a global ocean (Kasting 1993). This splitting of a primitive atmosphere into a hydrosphere and a secondary atmosphere leaves behind carbon and nitrogen compounds that will be ingredients for subsequent steps of chemical evolution and, eventually, the dawn of life.

3. DEPLETION OF VOLATILE ELEMENTS ON THE MOON

The Moon is depleted of volatile elements such as hydrogen, carbon, nitrogen and the noble gases, possibly due to 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. Ions from the solar wind are directly implanted into the lunar surface (Kerridge, 1975; 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. But nitrogen has a special place in the research for the nature of the astrochemistry of the early solar system. Unlike some of the other biological elements (CHNOPS or carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur), in lunar soils it is estimated that between 1.5 and 3 Gyr there was an increment of some 50 % in the ratio $^{15}N/^{14}N$. This result has been abundantly confirmed. By performing single grain analyses Wieler and co-workers have searched for evidence of a predominantly non-solar origin of nitrogen in the lunar regolith (Wieler et al, 1999). There have also been attempts to analyze trapped N in the lunar regolith (Hashizume, 2000). These works suggest 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 per cent in the $^{15}N/^{14}N$ ratio. The origin of non-solar component is an open problem. Indeed, Ozima and co-workers propose that most of the N and some of the other volatile elements in lunar soils may actually have come from the Earth's atmosphere rather than the solar wind (Ozima et al, 2005). This hypothesis is valid provided the escape of atmospheric gases, and implantation into lunar soil grains, occurred at a time when the Earth had essentially no geomagnetic field. This is a valuable approach since it could clearly be tested by examination of lunar far-side soils, which should lack the terrestrial component. This question is not just pertinent to the astrogeological aspects of the evolution of the Moon, but by giving us a solid grasp on the evolution of the early Earth atmosphere, those factors that influenced the conditions favourable to the onset of life on Earth will be clearer. Hopefully with the availability of new missions, such STEREO involving two spacecraft in heliocentric orbit to study coronal mass ejections (CMEs), further measurements of the isotopic N-abundances may contribute to sorting out the astrochemical signatures of the early solar system that are awaiting to be deciphered. Such knowledge of N, one of the most intriguing of the six CHNOPS elements, will be considerable progress in the study of the origin of life on Earth.

4. PREPARING THE SOLAR SYSTEM FOR THE EMERGENCE OF LIFE

Various processes may have contributed to an early onset of the phenomenon of life, solar activity being one of the most relevant. The more intense solar wind of the early Sun would have a dramatic effect on the possibilities of preparing the Solar System for the emergence of life. In fact, the shock wave of the encounter of the intense solar wind with the spreading accretion disk blows away the residual gas and fine dust still present in the disk. Some evidence for this assertion may be found in meteorites (Bertout et al, 1991). In spite of the fact that the processes taking place from that moment onwards are not represented in the terrestrial geologic record, the current scenario of planetary origin gives us a means of inferring the activity that may have frustrated, or encouraged, the emergence of life. During the first 100 million years the flux of impactors would have set up the conditions for the separation of iron and silicate, giving rise to a metallic core. During this formation of the planetary embryo a major impact with another planet-size body gave rise to the expulsion of a large amount of matter from the primitive Earth, giving rise to the Moon. Our satellite cooled quickly, but it did not form an atmosphere. This may have been due to the smaller lunar cross section compared to the Earth. The original atmosphere that the Earth had captured from the solar nebula must have been largely blown away by the intense solar wind of the T-Tauri phase of the solar evolution. The planet 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. This remark has been confirmed by laboratory experiments duplicating the conditions for cometary formation (Owen and Bar-Nun, 1995). Temperatures had descended to about 100 degrees Centigrade after the end of accretion at 4.4 Gyr BP. This scenario for planetary origin allows, in principle, the possibility of an early origin and evolution of life on Earth, provided that the solar climate and solar weather were sufficiently clement. 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, for instance, was formed by a large impact as late as 3.8 - 3.9 Gyr BP (Hartmann et al, 2000). This was a real cataclysmic spike in the cratering record. This event is known as the Late Heavy Bombardment (LHB). This implies the persistence of catastrophic impacts for the emergence of life on Earth, since our planet has a larger effective cross section than our satellite (Sleep et al, 1989). Recent discussions of the origin and intensity of the late heavy bombardment is further supported by more recent work (Gomes *et al.,* 2005) that suggests that the LHB was triggered by the rapid migration of the giant planets. This phenomenon produced major changes in the space weather conditions. But even more, it triggered a massive delivery of planetesimals into the inner Solar System. Those conditions were an impediment for the emergence of life. Alternatively, if life had emerged before the LHB, it would most likely have been annihilated and started again after the major perturbations of the LHB had faded out. The analogous problem of bombardment of terrestrial-like planets in extra-solar systems is the subject of further recent attention (Levison et al., 2003).

5. EFFECTS OF RADIATION

As astrobiology studies the origin, evolution, distribution and destiny of life in the universe, in the present section we shall discuss in turn the four stages at which solar and extra-solar physics have a frontier in common with astrobiology.

5.1 Solar radiation as a factor in the origin of life

The incidence of non-ionizing UVR on the early surface of Earth and Mars to a large extent can be inferred from observations. Ionizing radiation, mainly due to nuclear and atomic reactions is relevant: X-rays are emitted spanning the whole spectrum of hard X-rays to soft X-rays (0.01-10 nm); gamma rays are present too. The primary components affecting space climate are: galactic cosmic rays and solar cosmic radiation. To these we should add events that contribute to solar weather, such as solar particle radiation consisting of the low-energy solar-wind particles, as well as more energetic solar burst events consisting of solar particles that arise from magnetically disturbed regions of the Sun. These events vary in frequency according to the eleven-year cycle. However, scenarios for an early onset of life that have been proposed in the past have to deal with space weather that was radically different in the early Sun. Knowledge of the prehistory of solar particle radiation can be approached with a combined effort from observations of present-day emissions, together with studies of energetic solar particles recorded in extraterrestrial materials, notably the Moon material that became available with the Apollo missions, as well as with the study of meteorites. First of all we consider the magnitude of the ionizing radiation that may have been present at the time when life emerged on Earth, during the Archean (3.8 - 2.5 Gyr BP). According to some theoretical arguments (Mojzsis et al, 1999), the origin of life may be traced back even earlier, during the Hadean (4.6 - 3.8 Gyr BP). Indeed, these authors argue that the simplest interpretation of carbon isotopic data may point to the presence of diverse photosynthesizing, methanogenic, and methylotrophic bacteria on Earth before 3,85 Gy BP. Isotopic and geologic evidence suggest that in the Archean the atmosphere was anoxic (Walker et al, 1983). 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 (Margulis et al, 1976; Cockell, 1998).

5.2 Extra-solar radiation in the evolution of life

Gamma ray bursts are powerful explosions that are known to 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. The Swift mission, launched in November 2004, contributes to determine recent burst rates. Such data allows the evaluation of life's robustness during the Ordovician (510 - 438 million years ago). During this geologic period there was a mass extinction of a large number of species (440-450 million years ago). This was the second most devastating extinction in Earth history. Present evidence has led to the conjecture that the extinction was triggered by a gamma ray burst (Thomas et al., 2005). There is no direct evidence that such a burst activated the ancient extinction. The conjecture is based on atmospheric modelling. 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, UVR from the Sun could kill much of the life on land and near the surface of oceans and lakes, and disrupt the food chain.

5.3 Solar radiation in the distribution of life

To illustrate further the necessity for a comprehensive approach to influence of space weather on the origin of life, we should consider the underlying presence of variable, and to some extent, incompletely known output of solar radiation during its first Gyr. Experiments have been performed in the recent past at the ISS. We should keep in mind that during the early life of the Sun, the UV flux was much higher than it is today. The relevant wavelength regions are the XUV and soft X rays. These wavelengths are absorbed at the top of the atmosphere. Research at the ISS has been supplemented with laboratory tests. Several problems related with early biological evolution have been discussed in the past under the simulation of the early solar radiation environment (Lammer et al, 2002). Work on space weather influence on biological systems include the implications for the biosphere of magnetic field reversals (Biernat, et al, 2002); the influence on biological systems of solar flares (Belisheva, et al, 2002), and some work on uracil dosimetry to estimate the possible preservation of the molecules of life (Bérces, et al, 2002). If the distribution of life in the solar system took place by transfer of microorganisms, knowledge of solar weather is needed for the early stages of its evolution, to have some constraints on the possible transfer of microorganisms, as investigated extensively by Horneck and co-workers (Horneck and Cockell, 2001 for references). *Bacillus subtilis* is a Gram-positive harmless bacterium. It is capable of producing endospores resistant to adverse environmental conditions such as heat and desiccation and is widely used for the production of enzymes and specialty chemicals. The inactivation of *B. subtilis* spores has been studied in the Earth's orbit under different simulated ozone-column abundances to provide quantitative estimates of the potential photobiological effects of such an early ozone-free atmosphere (Horneck and Cockell, 2001). These authors find that the spectral sensitivity of DNA increases sharply toward shorter wavelengths from the UVB to UVC region. They conclude that this is the primary reason for the observed high lethality of extraterrestrial UV radiation that could provide a barrier to the distribution of life in the solar system. However, it should be kept in mind that 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* (whose name comes from the Greek for "terrible berry that withstands radiation") is a Gram-positive, red-pigmented, non-motile bacterium. It is resistant to ionizing and UV radiation. Several authors have studied these (Battista, 1997, Daly et al. 2004 and Levin-Zaidman et al. 2003). Members of this Family can grow under chronic radiation [50 grays (Gy) per hour] or recover from acute doses of gamma radiation greater than 10,000 Gy without loss of viability. Survivors are often found in cultures exposed up to 20,000 Gy. Seven species make up this Family, but it is *D. radiodurans,* whose radio-resistance appears to be the result of an evolutionary process that selected for organisms that could tolerate massive DNA damage. For the sake of comparison, the bacterium *E. coli* is approximately 200 times less resistant to gamma radiation, whereas humans cannot tolerate radiation of up to 5 Gy. Independent of the various UV defense mechanisms discussed in Sec. 2, the surface of the Earth is largely protected from cosmic radiation by the atmosphere itself. The annual dose of cosmic radiation for Germany is 0.3 mGy/year at sea level and 25 mGy/year at an altitude of 15 Km (Baumstark-Khan and Facius, 2001). Besides, also for comparison, we know that the survival fraction for mammalian cells in radiotherapy becomes negligible for a dose of 500 Gy (Kassis and Adelstein, 2004). It appears that the capacity of extremophiles to withstand ionizing radiation is due to adaptation to desiccation, as both environmental challenges (lack of water and excessive radiation doses) lead to similar massive DNA repair mechanisms. In this context, cyanobacteria have extraordinary ability to withstand desiccation and then rapidly absorb water when it becomes available. For example, a cyanobacterial population in gypsum quickly regains its ability to photosynthesize after addition of water (Van Thielen and Garbary, 1999). Possibly the radiation resistance ability of *D. radiodurans* may be due to its genome. (It assumes an unusual toroidal morphology that may contribute to its radio-resistance.)

5.4 Solar radiation as a factor in the destiny of life

The question of solar radiation also has a frontier with the fourth aspect of astrobiology. In about 4-5 billion years the brightness of the Sun will increase and its radius will increase (Sackmann et al. 1993). The consequence of the Sun abandoning its present steady state will lead to a swelling of its outer atmosphere. At the same time while the radius is increasing helium atoms will be at such a temperature that fusion into beryllium and carbon will occur. This is known in nuclear physics as the triple alpha point. This process lasts a few seconds. The energy from this ‘helium flash’ will lead to a sequence of events that will largely increase the emission of solar wind, carrying away a large fraction of the solar mass. This stage is well known to us. Indeed, there are many known examples of the stellar mass that the increased solar wind will take away (this is the planetary nebula stage). These events will set definite constraints of the destiny of life in our own solar system. Our knowledge of other stars mapped on a Hertzsprung-Russell diagram gives us enough confidence with the later stages of the evolution of our own Sun as it leaves the Main Sequence. These phenomena set strong constraints to the destiny of life in the solar system. But some further work on the models of the sun is necessary before making definite predictions on the period following the departure from the Main Sequence.

6. DISCUSSION AND CONCLUDING REMARKS

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 combine 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 conditions that will allow life to emerge in a given solar system anywhere in the universe.

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8. REFERENCES

Battista, J.R. (1997). Against all odds: The survival strategies of *Deinococcus radiodurans.* Ann. Rev. Microbiol. 51, 203-224.

Baumstark-Khan, C. and Facius, R. (2001). Life under conditions of ionizing radiation, in: *Astrobiology the Quest for the Conditions of Life,* G. Horneck and C. Baumstark-Khan (eds.). Springer, Berlin, pp. 261-284.

Belisheva, N.K., Semenov, V.S., Tolstyh, Yu. V. and Biernat, H.K. (2002). Solar Flares, Generation of Solar Cosmic Rays, and Their Influence on Biological Systems, ESA SP 518, 429-430,

Bérces, A., Kovács, G., Kerekgyarto, Rontó, Gy., Lammer, H., Kargel, G., and Kömle, N.I. (2002). Uracil Dosimetry in Simulated Extraterrestrial Condition, ESA SP 518, 431-432.

Bertout, C., Basri, G. and Cabrit, S. (1991). The Classical T-Tauri Stars: Future Solar Systems? in: *The Sun in Time,* C.P. Sonett, M.S. Giampappa and M. S. Matthews (eds.), The University of Arizona, Tucston, pp. 683-709.

Biernat, H.K, Erkaev, N.V., Penz, T., Lammer, H., Manrubia, S.C., Selsis, F., Vogl., and Muhlbachler, S. (2002). Magnetic Field Reversals on Earth: Possible Implications for the Biosphere, ESA SP 518, 433-434.

Brasier, M.D., Green, O.W., Jephcoat, A.P., Kleppe, A.K., Van Kranendonk, M.J., Lindsay, J.F., Steele, A. and Grassineau, N.V. (2002). Questioning the evidence for Earth's oldest fossils, Nature 416, 76-81.

Canup, R. M. and Asphaug, E. (2001). Origin of the Moon in a giant impact near the end of the Earth's formation. Nature 412, 708 - 712.

Cockell, C.S. (1998). Biological Effects of High Ultraviolet Radiation on Early Earth - A Theoretical Evaluation, J. theor. Biol. 193, 717-729.

Daly, M. J., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Zhai, M., Venkateswaran, A., Hess, M., Omelchenko, M. V., Kostandarithes, H. M., Makarova, K. S., Wackett, L. P., Fredrickso, J. K. and Ghosal, D. (2004). Accumulation of Mn (II) in *Deinococcus radiodurans* Facilitates Gamma-Radiation Resistance, Science, 306, 1025-1028.

Gomes, R., Levison, H.F., Tsiganis, K. and Morbidelli, A. (2005). Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets, Nature 435, 466-469.
Hartmann, W.K., Ryder, G., Dones, L. and Grinspoon, D. (2000). The time-dependent intense bombardment of the primordial Earth/Moon system, in: *Origin of Earth and Moon,* R.M. Canup and K. Righter (eds.), University of Arizona Press, Tucson, pp. 493–512.

Hashizumi, K., Chaussidon, M., Marty, B., and Robert, F. (2000). Solar Wind Record on the Moon: Deciphering Presolar from Planetary Nitrogen. Science **290,** 1142-1145.

Hayes, J.M., Kaplan, I.R. and Wadeking, K.W. (1983). Precambrian organic geochemistry, preservation of the record, in Schopf, J.W. ed. Earth Earliest Biosphere, Princeton University Press, Princeton, pp. 93-134.

Horneck, G. and Cockell, C.S. and (2001). The History of the UV Radiation Climate of the Earth—Theoretical and Space-based Observations, Photochemistry and Photobiology, 73, 447–451.

Hunten, D. M. (1993). Atmospheric Evolution of the Terrestrial Planets, Science 259, 915-920.

Kassis, A.I. and Adelstein, S.J. (2004). Radiobiologic Principles in Radionuclide Therapy, The Journal of Nuclear Medicine 45, 1-4.

Kasting, J. F. (1993). Earth's Early Atmosphere, Science 259, 920-926.

Kasting J. F. and Catling, D.C. (2003). Evolution of a habitable planet, Annual Reviews of Astronomy and Astrophysics, 41, 429-463.

Kerridge, J. F. (1975). Solar nitrogen: evidence for a secular increase in the ratio of nitrogen-15 to nitrogen-14, Science 1975, 162-164.

Kerridge, J. F., Signer, P, Wieler, R., Becker, R.H., and Pepin, R.O. (1991). Long term changes in composition of solar particles implanted in extraterrestrial materials, in: *The Sun in Time,* C.P. Sonett, M.S. Giampappa and M. S. Matthews (eds.), The University of Arizona, Tucston, pp. 389-412.

Lammer, H., Hickel, A., Tehrany, M.G., Hanslmeier, A., Ribas, I., and Guinan, E.F. (2002). Simulating the Early Solar Radiation Environment: X-Ray Radiation Damage Experiments, ESA SP 518, 469-470.

Levin-Zaidman S, Englander J, Shimoni E, Sharma AK, Minton KW, Minsky, A. (2003). Ringlike structure of the *Deinococcus radiodurans* genome: a key to radioresistance? Science. 299, 254-256.

Levison, H. F., Agnor, C. (2003). The Role of Giant Planets in Terrestrial Planet Formation, Ap. J. 125, 2692-2713.

Margulis, L., Walker, J. C. G. and Rambler, M. (1976). Re-assessment of the roles of oxygen and ultraviolet light in Precambrian evolution, Nature 264, 620-624.

Matsui, T., and Abe, Y. (1986). Evolution of an impact-induced atmosphere and magma ocean on the accreting Earth. Nature 319, 303-305.

Mojzsis, S. J., Krishnamurthy, R., and Arrhenius, G. (1999). Before RNA and after — Geophysical and geochemical constraints on molecular evolution, *in* Gesteland, R., et al., eds., RNA world, 2nd ed.: Cold Spring Harbor, New York, Cold Spring Harbor Laboratory Press, p. 1–49.

Owen T., Bar-Nun, A. (1995). Comets, impacts and atmospheres, Icarus 116, 215-226.

Owen T. and Bar-Nun, A. (1995). Comets, impacts and atmospheres, Icarus 116, 215-226.

Ozima, M., Seki, K., Terada, N., Miura, Y. N., Podosek, F. A. and Shinagawa, H.(2005). Terrestrial nitrogen and noble gases in lunar soils, Nature 436, 655-659.

Parker, B., Simmons, Jr., G., Wharton, Jr., R. Seaburg, K.G. and Love, F. (1982). Gordon Removal of organic and inorganic matter from Antarctic lakes by aerial escape of bluegreen algal mats, J. Phycol. 18, 72-78.

Sackmann, I.-J. Boothroyd, A. I. and Kraemer, K. E. (1993). Our Sun. III. Present and Future, Astrophysical Journal, 418, 457-468.

Schidlowski, M. (1988). A 3.800-million-year isotopic record of life from carbon in sedimentary rocks, Nature 333, 313-318.

Schidlowski, M., Hayes, J.M. and Kaplan, I. R. (1983). Isotopic Inferences of Ancient Biochemistries: Carbon, Sulfur, Hydrogen, and Nitrogen, in Earth's Earliest Biosphere its Origin and Evolution, J. William Schopf (ed.), Princeton University Press, Princeton, New Jersey, pp. 149-186.

Schopf, J.W. (1993). Microfossils of the Earth Archaean Apex Chert: New evidence of the antiquity of life, Science 260, 640-646.

Schopf, J.W. (1999). Cradle of Life: The Discovery of Earth's Earliest Fossils, Princeton University Press, Princeton, New Jersey, pp. 186-190.

Schopf, J. W., Kudryavtsev, A. B., Agresti, D. G., Wdowiak, T. J. and Czaja, A. D. (2002). Laser-Raman imagery of Earth's earliest fossils, Nature 416, 73-76.

Schwartz, A.W. and Chang, S. (2002). From Big Bang to Primordial Planet- Setting the Stage for the Origin of Life, in Life's Origin, Schopf, J.W., ed., University of California Press, Berkeley, pp. 78-112.

Sleep, N., Zahnle, K., Kasting, J.F., and Morowitz, H.J. (1989). Annihilation of ecosystems by large asteroid impacts on the early Earth, Nature 342, 139-142.

Thomas, C. H., Jackman, A. L., Melott, C. M., Laird, R. S., Stolarski, N., Gehrels, J. K. Cannizzo, and Hogan, D. P. (2005). Astrophysical Journal Letters, 622, L153.

Van Thielen, N. and Garbary, D.J. (1999). Life in the rocks- endolithic algae, in: *Enigmatic microorganisms and life in extreme environmental habitats.* J. Seckbach (ed.), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 245-253.

Wieler, R., Humbert, F. and Marty, B. (1999). Evidence for a predominantly non-solar origin of nitrogen in the lunar regolith revealed by single grain analyses, Earth and Planetary Science Letters 167, 47-60.