

## GEOCHEMICAL AND ASTROBIOLOGICAL CONSTRAINTS ON FAST EVOLUTION OF COMPLEX LIFE ON EXOPLANETS

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The Earth originated about 4.56 Gyr ago (Allègre et al., 1995) and accreted most of its mass from planetesimals within the first 100 Myr. After this formation process, the Earth was subject to a phase of heavy bombardement, which lasted about 700-800 Myr, sterilizing the surface and frustrating the evolution of life in this early stage of the Earth's history (Sleep et al., 1989; Halliday, 2001). Presumably, the formation of the Moon due to the collision with a Mars-sized object took place during this era (Halliday, 2001). Since the gravitational attraction of the Earth is higher, impacts on Earth occurred more often and were more energetic than on the Moon, producing rock vapor atmospheres with temperatures of up to 2.000 K, which lasted probably for several thousand years (Sleep et al., 2001). At about 3.8 Gyr, most of the planetesimals and meteorites remaining from the protoplanetary nebulae were removed out of the solar system by impacts or due to gravitational interaction mainly with the gas giants. Surprisingly fast after the end or even during the last stages of the late heavy bombardement, the first simple life forms developed. Mojzsis et al. (1996) inferred from ion-microprobe measurements of the carbon-isotope composition of carbonaceous inclusions within grains of apatite from the oldest known sediment sequences, the 3.8 Gyr old banded iron formation from the Isua supracrustal belt, West Greenland, that life on Earth appeared more than 3.85 Gyr ago. Woese et al. (1990) established a universal phylogenetic tree of life based on 16/18S rRNA sequence comparison, which shows that hyperthermophiles are represented by short and deep phylogenetic branches, forming a cluster around the phylogenetic root. The idea of a hyperthermophilic origin of life is also supported by newer works (e.g., Schwartzman and Lineweaver, 2004). A hyperthermophilic origin may took place at hydrothermal vents or in subsurface rock, both environments, which were sufficiently protected against the last impacts of the late heavy bombardement so that life could evolve there. It is also possible that life evolved much earlier, but was annihilated again by the sterilizing influence of a large impact on early Earth. The rapid occurrence of life on Earth was analyzed by Lineweaver and Davis (2002) in a mathematical way, where they showed that from a statistical point of view it is very likely that life can also emerge on other habitable planets in a geological short period of time. The first appearance of cyanobacteria, which produced oxygen due to photosynthesis, is reported for about 3.46 Gyr ago (Schopf, 1993). Nevertheless, oxygen remained a trace element in the atmosphere until about 2.2-2.4 Gyr before present (Farquhar et al., 2001). This time delay is one of the big unresolved questions in the study of the biogeochemistry of early Earth. There are various theories trying to explain the lack of oxygen in the atmosphere between 3.5 and 2.4 Gyr, including hydrogen loss to space due to methane produced by methanogenesis (Catling et al., 2001), a change in the redox state of volcanic gases from late Archean and earliest Paleoproterozoic magmatism during a period of mantle overturn and/or intense plume activity (Kump et al., 2001), or even the statement that the reason for the rise of oxygen remains problematic (Towe, 2002). However, soon after the initial increase of the oxygen level in the atmosphere, Mitochondria and organisms with more than 2-3 cell types appeared (Hedges et al., 2004). The appearance of mitochondria was possibly caused by endosymbiosis (Margulis, 1993). Mitochondria were

free living anaerobe bacteria, adopted by some ancestral host cell leading to the formation of eukaryotes. This process was driven by the hostile environmental condition produced by free oxygen in the atmosphere. Where the bacteria, which became the mitochondria afterwards, was absorbed by a phagocyte, and survived inside this cell. Due to the mitochondria, the eukaryotes were able to perform aerobic respiration, giving 18 times more energy than anaerobic respiration. This large amount of energy available for the eukaryotes led to a more complex structure of this early life forms. Therefore, the initial increase in complexity may have been a response to both, energy availability (oxygen) and the ability to extract it (mitochondria). According to Hedges et al. (2004), the second increase in cell types at 1.5-1 Gyr occurred immediately following the acquisition of the plastids, again suggesting a relationship with oxygen. Plastids provided eukaryotes with the ability to generate their own oxygen, benefiting those species directly and their ecosystem partners indirectly. Therefore, it seems reasonable that the atmospheric oxygen concentration triggers the evolution of complex life forms, but we have seen that it took a long time until the oxygen concentration reached values necessary to trigger this transitions. Is it possible that on habitable exoplanets this time span can be decreased and complex life forms may develop more rapidly?

We assume that most of the oxygen produced by early photosynthetic life forms was used for the oxidation of iron and sulfur ions as well as reduced volcanic gases. Catling et al. (2001) showed that large oxygen inventories are included in the continental crust and mantle. The continental crust's excess oxygen mostly resides in altered and metamorphosed igneous rocks. Kump et al. (2001) argued that 75% of the oxygen generated is consumed by weathering of reduced compounds in rocks, predominantly organic carbon, pyritic sulfur, and ferrous iron in shales. Therefore, the rise in oxygen can start only after most of the reducing fractions are oxidatively weathered and the oxygen is bound in the continental crust or the upper mantle. It is necessary to take into account, that oxidation in the oceans and at mid-ocean ridges does not influence the oxygen balance over long times, since the oceanic crust is subducted quite rapidly and the oxygen is released again by volcanic actions. Therefore, the most effective way to shorten the anoxic time period is to reduce the amount of material which can be oxidized, mainly reduced rocks of the stable continental crust, which are than a reservoirs for the oxygen. From numerical simulations of the late stage planetary accretion, focusing on the delivery of volatiles (primarily water) to the terrestrial planets, it was found that it is very likely that most of the terrestrial exoplanets formed with a water content between 1-100 Earth oceans (Raymond et al., 2004). If most of the exoplanets are formed with a higher water inventory, it is very likely that large parts of the exoplanets are covered with oceans. In such a case, only a small amount of oxygen is needed to oxidize the continental crust, and the atmospheric oxygen content may rise much earlier in the history of the exoplanet. A linear approximation leads to the rough conclusion that if only 1/10 of the Earth continent surface is present at an Earth-like exoplanet with a higher water inventory, the time span for the oxidation can be reduced from more than 1 Gyr to more than 100 Myr, which may lead to a much faster evolution of complex life forms.

Another variant for the fast removal of oxygen is connected with the idea of Catling et al. (2001) that hydrogen loss into space is important. If methanogenesis takes place, methane is produced which can be transported into the upper atmosphere, namely in the region of the exobase. For low mass K stars, there is observational evidence that their XUV energy fluxes stay active over longer time periods than for our Sun. In this case, the exospheric temperatures are probably quite high (Lammer et al., 2004), removing even more hydrogen, which was formed by the photolysis of methane, and the exoplanet can be oxidized even faster, because the more hydrogen is lost, the more oxygen is left for the oxidation of the planetary surface and the accumulation in the atmosphere may start earlier. If the exosphere temperature is higher, also more particles are lost by Jeans escape, since the tail of the Maxwell-Boltzmann distribution is broader in this case. For low mass K stars, the outer edge

of the habitable zone is already in a region where tidal locking is not important anymore, therefore the atmosphere of such an exoplanet can be protected by an internal magnetic field. If there is a dense carbon dioxide atmosphere, IR-cooling is important for the exospheric temperature, leading to a smaller loss rate. But if the carbon dioxide is removed from the atmosphere in a reasonable time, these exoplanets may evolve an oxidized atmosphere faster than on Earth. An additional candidate for such loss processes are non-magnetized exoplanets, whose atmospheres are subject to non-thermal loss processes in a much larger amount (Penz et al., 2004). These processes are probably very efficient in removing atmospheric compounds at the interaction region with the stellar wind. All three scenarios contribute to increase the probability that life evolved on other planets.

## References

- ALLÈGRE, C. J., MANHÈS, G., and GÖPEL, C. (1995), The age of the Earth, *Geochim. Cosmochim. Acta* **59**, 1445-1456.
- CATLING, D. C., ZAHNLE, K. J., and MCKAY, C. P. (2001), Biogenic methane, hydrogen escape, and the irreversible oxidation of early Earth, *Science* **293**, 839-843.
- FARQUHAR, J., BAO, H., and THIEMANS, M. (2000), Atmospheric influence of Earth's earliest sulfur cycle, *Science* **289**, 756-758.
- HALLIDAY, A. N. (2001), Earth science: in the beginning ..., *Nature* **409**, 144-145.
- HEDGES, S. B., BLAIR, J. E., VENTURI, M. L., and SHOE, J. L. (2004), A molecular timescale of eukaryote evolution and the rise of complex multicellular life, *BMC Evolutionary Biology* **4:2**.
- KUMP, L. R., KASTING, J. F., and BARLEY, M. E. (2001), Rise of atmospheric oxygen and the "upside-down" Archean mantle, *Geochem. Geophys. Geosyst.* **2**, 2000GC000114.
- LAMMER, H., KULIKOV, YU. N., PENZ, T., LEITNER, M., BIERNAT, H. K., and RIBAS, I. (2004), The evolution of the stellar radiation and particle environment and its implication for planetary habitability, *Celest. Mech.*, submitted.
- LINWEAVER, C. H., and DAVIS, T. M. (2002), Does the rapid appearance of life on Earth suggest that life is common in the universe?, *Astrobiology* **2(3)**, 293-304.
- MARGULIS, L. (1993), *Symbiosis in Cell Evolution* (Freeman, New York), 2nd Ed.
- MOJZSIS, S. J., ARRHENIUS, G., MCKEEGAN, K. D., HARRISON, T. M., NUTMAN, A. P., and FRIEND, C. R. L. (1996), Evidence for life on Earth before 3,800 million years ago, *Nature* **384**, 55-59.
- PENZ, T., LAMMER, H., BAUER, S. J., BIERNAT, H. K., and HANSLMEIER, A. (2004), Solar wind induced atmospheric and water loss over the Venusian history, *Geophys. Res. Lett.*, submitted.
- RAYMOND, S. N., QUINN, T., and LUNINE, J. I. (2004), Making other earths: dynamical simulations of terrestrial planet formation and water delivery, *Icarus* **168**, 1-17.
- SCHOPF, J. W. (1993), Microfossils of the early archean apex chert: new evidence of the antiquity of life, *Science* **260**, 640-646.
- SCHWARTZMAN, D. W., and LINWEAVER, C. H. (2004), The hyperthermophilic origin of life revisited, *Biochem. Soc. Trans.* **32(2)**, 168-171.
- SLEEP, N. H., ZAHNLE, K. J., KASTING, J. F., and MOROWITZ, H. J. (1989), Annihilation of ecosystems by large asteroid impacts on the early Earth, *Nature* **342**, 139-142.
- SLEEP, N. H., ZAHNLE, K. J., and NEUHOFF, P. S. (2001), Initiation of element surface conditions on early Earth, *Proc. Natl. Acad. Sci. USA* **98**, 3666-3672.
- TOWE, K. M. (2002), The problematic rise of oxygen, *Science* **295**, 1419.
- WOESE, C. R., KANDLER, O., and WHEELIS, M. L. (1990), Towards a natural system of organisms: Proposal for the domains Archaea, Bacteria, and Eukarya, *Proc. Natl. Acad. Sci. USA* **87**, 4576-3672.