CONSTRAINTS FOR THE EVOLUTION OF HABITABLE PLANETS: IMPLICATIONS FOR THE SEARCH OF LIFE IN THE UNIVERSE

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Abstract

Since 1995, more than 150 extrasolar planets were detected. This led to the question if Earth-like planets and consequently also life could exist outside our Solar System. Until now, the resolution of the methods used to detect these exoplanets do not allow the detection of Earth-like planets. But several missions are planned in the next ten years, having the capability to find twins of the Earth. However, it seems to be necessary to discuss in which cosmic environments the discovery of Earth-like planets and possible life is most likely. Therefore, we discuss the constraints implied by different host star types, as well as the influence of the planetary atmosphere evolution on the habitability. Additionally, we investigate the impact of high energetic particles on biological systems on the surface of the Earth as an analogue for terrestrial exoplanets. Also unconventional habitats in the Universe are discussed.

1 Introduction

The mankind at the beginning of the 21^{st} century is in a lucky position. Since more than 10 years, it is empirically known that planets exist orbiting around other stars than our Sun. This is again a great leap forward in a chain of physical and philosophical revolutions started 500 years ago. Due to the ideas of Copernicus, the Earth moved from the center of the Universe to an orbit around its host star, the Sun. Later, it became part of the outer rim of the Milky Way galaxy, one within myriads of other galaxies. The Big Bang hypothesis revealed that all points in our Universe are equal, followed by the hypothesis that our Universe is just one out of many. Not even the matter from which we are created seems to be dominant in the Universe, compared with the large amount of dark matter and energy proposed in modern cosmology. But this shift from speciality to generality gives us the opportunity to think about other places for life in the Universe. If we are not special anymore, there is no reason, why there should not be thousands of Earth's with life on it. Right now, we are on the cusp to answer this question empirically.

Since the first detection of an exoplanet orbiting a main-sequence star (Mayor and Queloz, 1995), the number of known exoplanets is increasing with astonishing speed. In spring 2005, we know more than 150 giant exoplanets. Recently, the first non-Jupiter-class

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exoplanet with a mass of about 14 $M_\oplus$ orbiting a solar-like G-type star at about 0.1 AU was discovered (Santos et al., 2004). This detection represents the first discovery of a planet with a mass slightly smaller than that of Uranus. Right now (June 2005) a press release of the University of California in Berkeley reports the detection of a possibly rocky planet with about 7.5 $M_\oplus$ in the Gliese 876 system. In fact, also Earth-mass planets where detected orbiting the pulsar PSR1257+12 (Wolszcan and Frail, 1992), but it is very unlikely that life can be found in such a harsh environment. The discoveries of such low-mass exoplanets strengthen the major question, which has to be answered in the future, namely if life may have evolved on a habitable Earth-like exoplanet outside our Solar System. Therefore, space missions like ESA's Darwin and NASA's Terrestrial Planet Finder (TPF-C, TPF-I) and their precursor photometry missions like CoRoT (CNES) and Kepler (NASA) are currently under development. The CoRoT space observatory is planned to be launched in 2006 and will be able to find exoplanets with sizes above 2 $R_\oplus$ by using high-precision photometry and will be the first mission in this series dedicated to discover small exoplanets at orbital distances of up to about 0.5 AU (e.g., Rouan et al., 2000).

Although the necessary conditions for the emergence, survival, and evolution of life are still unknown, one requirement is widely accepted as an unavoidable necessity: liquid water. The presence of liquid water, far from being a sufficient requisite for biology, allows the identification of potential extraterrestrial habitats or, more rigorously, to exclude dry environments, where the presence of life may be ruled out. In the Solar System, and with the exception of Earth, liquid water is expected in the subsurface of Mars, on icy satellites like Europa and Callisto and in the Venusian clouds, that does not imply that life is likely to be found there, but that life may be absent elsewhere. One should also note that there are strong indications that microbial life is widespread at depth in the crust of the Earth, and life has been identified in numerous ocean vents. This life-forms do not dependent on solar energy and photosynthesis for their primary energy supply, and they are essentially independent of the surface circumstances. Biosignatures in the atmospheres of exoplanets will probably help to answer the question if life may exist on exoplanets.

2 Habitable Zones in the Universe

Probably the most crucial parameter for the formation of terrestrial exoplanets is the generation of heavy elements and the metallicity of the protoplanetary cloud (Santos et al., 2003). If the metallicity is too small, no terrestrial planets can form, because the necessary chemical elements are not available in a reasonable abundance. A low metallicity is leading to the formation of small terrestrial planets, whereby Gonzalez et al. (2001) estimated that at least half of the Sun's metallicity is needed for the formation of terrestrial planets. If the planets are too small, the heat flow and associated geophysical processes like plate tectonics and strong intrinsic magnetic moments can not be maintained over sufficient time periods, leading to efficient atmospheric loss processes. Since the metallicity is decreasing away from the center of a galaxy, a region is defined where life most likely can evolve. This region is called the Galactic Habitable Zone (GHZ). Additional constraints, like an environment free of life-extinguishing supernovae, and a time span allowing the emergence of complex life were introduced in the definition by Lineweaver et al. (2004).

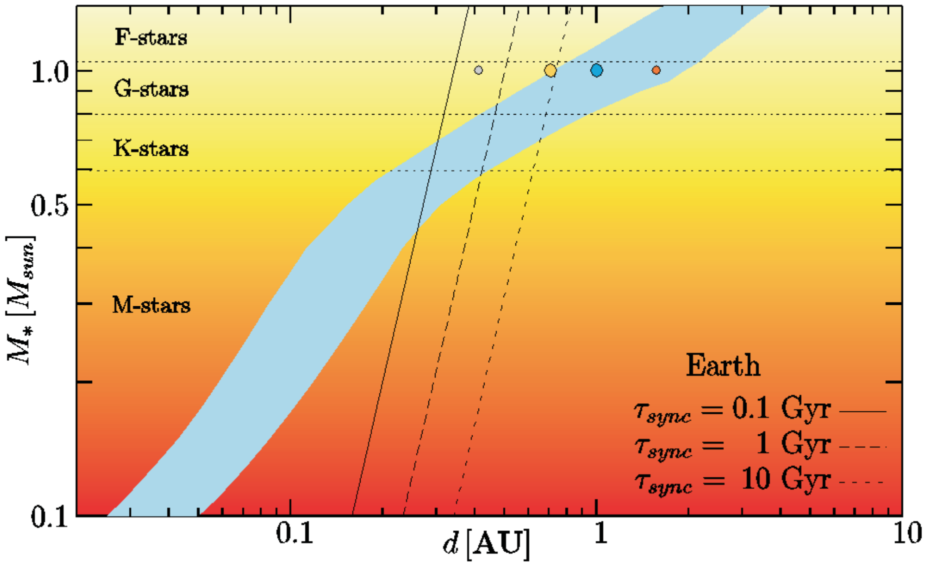

Figure 1: Continuous circumstellar habitable zone from 0.5 Gyr after Zero Age Main Sequence to 90% of the main sequence as a function of stellar mass. The straight lines give the tidal-locking limit at which an Earth-mass planet become synchronized after 0.1, 1 and 10 Gyr (courtesy of F. Selsis and J.-M. Grießmeier).

From their arguments it is obvious that habitable planets can be found most likely in the inner galactic disk, like, of course, our Earth.

Since the Earth is located in the GHZ of the Milky Way, biogenic elements should be abundant in our galactic neighbourhood, and heat sources are available. Thus, the most crucial question regarding the evolution of an Earth-like biosphere and surface habitability of terrestrial planets is the presence of liquid water on the planets surface. Therefore, the circumstellar habitable zone (HZ) is defined as the region, where a planet can maintain surface conditions that allow liquid water to exist. Two important parameters, which influence the HZ, are the energy emitted by the host star and the atmospheric composition of the planet (e.g., Kasting et al., 1993). The influence of the emitted energy of the host star is easy to describe. On the outer boundary of the HZ, the energy input is too small to maintain liquid water on the surface, while the inner boundary is defined as the distance, where water escapes rapidly to space. Since the energy output of the star increases over time, the location of the HZ also changes and will move outwards. Additionally, the energy output of a star is related to its mass. Since stars with masses of more than 2 $M_\odot$ have lifetimes of less than 2 Gyr, it is probably unlikely that complex life forms will evolve on a planets surface during this short time frame. Furthermore, a more massive star has a higher energy output compared to a low-mass star. Therefore, for stars with masses of 1.5 $M_\odot$, the HZ is centered at about 2.5 AU, while the HZ of a star with 0.5 $M_\odot$ is centered at about 0.3 AU (Fig. 1). Additionally, low mass stars evolve more slowly, thus the location of the HZ does not change significantly during several Gyr (Kasting et al., 1993).

The second parameter influencing the possibility to keep water liquid is the atmosphere composition. The most important atmospheric parameter for the surface temperature is the abundance of greenhouse gases, like CO_2, CH_4, and H_2O. If there is a dense CO_2 atmosphere, the surface temperature can be raised by several 100 °C, therefore the HZ can be farther away from its host star. However, for large orbital distances, condensation processes for CO_2 and surface cooling more than heating, due to enhanced Rayleigh backscattering of the incoming stellar radiation to space, shift the outer boundary inside. The inner boundary of the HZ is found at the distance, where a runaway greenhouse effect (Kasting, 1988) can occur, resulting in vaporization of water, that starts to increase the surface warming and thus enhance the evaporation in a positive feedback process. This results in a H_2O-rich atmosphere with surface temperatures above 100 °C, in which H_2O vapor reaches the upper atmosphere, where it can be photolyzed. Within a period of the order of 10 to 100 Myr, the planet loses its hydrogen to space and becomes dry. Therefore, appropriate conditions for the evolution of surface life are found only in a small region of a solar system (Fig. 1).

3 The Evolution of Planetary Water Inventories

Water can be accreted by terrestrial planets through planetesimals and planetary embryos (e.g., Morbidelli et al., 2000). The level of hydration of planetesimals and embryos depends on the heliocentric distance at which they are formed. A threshold distance is the so-called snowline, beyond which water condensates as ice. It is believed that, at the time of planetesimal formation in the Solar System, the snowline was at about 4 - 5 AU. Icy snowballs formed at the snow line could have drifted inwards by gas-drag and be incorporated by growing planetesimals in the inner Solar System (Cyr et al., 1998). Additionally, accretion of icy planetary embryos delivers a substantial mass in the form of water (Morbidelli et al., 2000; Raymond et al., 2004). The location, mass, number, and eccentricity of gas giants outside the HZ are important for the occurrence of impacts and the delivery of water and volatiles to terrestrial planets (Wetherill, 1994; Raymond et al., 2004).

Earth-like planets can evolve into a habitable world if they keep their atmospheres and water inventories during the period of heavy bombardment by asteroids and comets and during the host stars active X-ray and extreme ultraviolet (XUV) radiation fluxes and stellar wind periods. It can be inferred that the early Sun, a representative of G-type stars, have had strong X-ray and extreme ultraviolet (XUV) emissions up to several 100 times stronger than the present Sun (Zahnle and Walker, 1982; Lammer et al., 2004; Ribas et al., 2005). Since the stellar XUV radiation affects the thermosphere and exosphere temperatures of the exposed planets, the evolution of planetary water inventories must be understood within the context of the evolving stellar energy and particle fluxes. If IR-cooling of the thermosphere can not balance the incoming stellar XUV radiation anymore, the excess thermal energy is directly converted into kinetic energy and hydrodynamic escape occurs. An interesting effect may appear at a terrestrial water-rich planet inside the HZ of a dwarf star emitting high XUV fluxes over longer time periods then a G-type star. High CO_2 levels in a planet's early atmosphere may prevent extreme hydrodynamic escape conditions like on early Earth. But after the CO_2 is removed from the atmosphere due to chemical weathering in a humid environment (Pollack et al., 1987), N_2 like on present Earth may become the dominant constituent in the atmosphere. So, the upper atmosphere is heated and large escape rates develop, which can evaporate the whole planets H_2O inventory.

It seems very likely that complex surface life is strongly coupled to geochemical processes like the carbon cycle, which itself depend on the planetary water inventory. The conventional theory is that CO_2, in the form of H_2CO_3 dissolved in water, could be removed by reactions with exposed continental rocks to produce carbonate alteration products that were, in turn, transported to the oceans by rain and river flows for final burial in deep-sea sediments. Ultimately, the latter would be removed into the mantle by subduction of the sediment-coated oceanic crust. Plate tectonics plays an important role in the recycling of CO_2 in the atmosphere; the subducted carbonate is resupplied to the atmosphere through volcanic eruptions (Kasting and Catling, 2003). If there is too less water near the planetary surface, plate tectonics will not work and the carbon cycle will cease. It will also cease if the water gets evaporated, since no weathering can take place anymore. Therefore, it is very likely that geological processes, like plate tectonics and surface weathering, are essential for the long-term habitability of Earth-like exoplanets.

4 Habitability of Exoplanets in Close-In Habitable Zones

Especially the surface habitability of terrestrial exoplanets orbiting around low-mass M and K stars requires a detailed investigation, because dwarf stars constitute about 75 % of all main sequence stars in the Universe. Joshi (1997) applied a climate model to exoplanets orbiting M stars in synchronous rotation, and showed that the climatic changes may not rule out the evolution of life, if the atmosphere is thick enough, which was confirmed by Heath et al. (1999). An additional study by Joshi (2004) showed that planets inside M star HZs may even establish a biosphere with atmospheres of about 1 bar, depending on the available land-mass and water covered surface. The HZ of low-mass K and M stars is at orbital distances of 0.5 AU, where the planets become tidally locked on time scales of less than 1 Gyr (see Fig. 1). Due to slow rotation, tidally locked Earth-like planets will have weak magnetic dynamos resulting in weak intrinsic magnetic moments, which are decreased by about two orders of magnitude (Grießmeier et al., 2004). Thus, these planets will develop only small magnetospheres, which are compressed by the stellar wind at close orbits at least during the active stellar periods. Thus, the planetary atmospheres may build a Venus-like obstacle for the stellar wind interaction, leading to an enhanced atmospheric loss (Grießmeier et al., 2004).

Additionally, the continuous occurrence of Coronal Mass Ejections (CMEs) during the first 2 Gyr of the M star evolution may further enhance the atmospheric loss rates and remove planetary atmospheres of several tens of bars during short time periods (Lammer et al., 2005). A sketch of this continuous interaction between the planetary atmosphere and CMEs is shown in Fig. 2. These results indicate that only terrestrial exoplanets in tidal-locking zones with intrinsic magnetic moments $M_{pl} > 10^{-1} M_{\oplus}$ can develop extended magnetospheres, so that their atmospheres can be protected against hitting CMEs and related atmospheric erosion processes. However, it should be noted that the Earth would not build up such strong magnetic moments at orbits inside close-in HZs, so the atmosphere of an Earth's twin would not be protected against CME-erosion (Khodachenko et al., 2005). Also the stellar wind experiences large change over time. Wood et al. (2002)

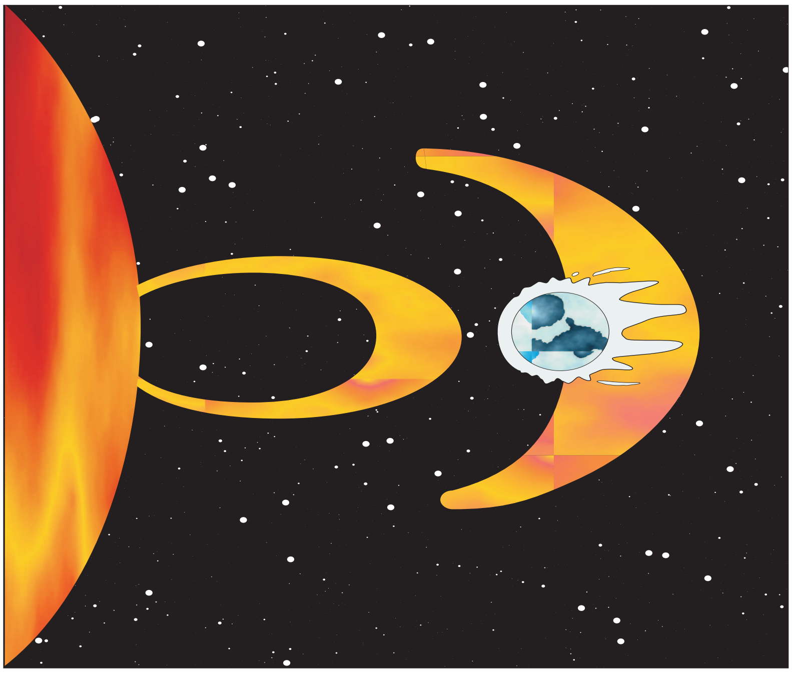

Figure 2: Sketch of the interaction between a close-in exoplanet and a star with nearly continuous CME activity.

showed that solar proxies have a 100 to 1000 times denser particle environment during the early stage of their evolution. This has similar consequences than CMEs, especially for non- or weakly-magnetized planets, which establish a Venus-like stellar wind-atmosphere interaction, leading to erosion of the planetary atmosphere by various non-thermal loss processes.

5 High Energetic Particle Impact on Biological Systems on Planetary Surfaces

Earth-like planets orbiting young or active stars are subject to large ionizing fluxes of stellar flares. During these events high energetic particles interact with the atmosphere, producing secondary energetic particles, like pions, and muons (Fig. 3), where some of them can reach the surface causing Ground Level Enhancements (GLE) of secondary cosmic particles. This has effects on the biological activity through direct mutational enhancement or sterilization (Smith et al., 2004). Such events may especially influence Earth-like planets orbiting low-mass stars, since they are known for high flare activity (e.g., Haisch et al., 1991; Smith et al., 2004; Khodachenko et al., 2005). Furthermore, due to tidal locking, the protecting magnetospheres may be reduced (Grießmeier et al., 2005). Smith et al. (2004) studied the transport of ionizing radiation in Earth-like exoplanetary atmospheres inside orbits of low-mass M stars and concluded that biological activity and atmospheric chemistry should be strongly influenced by the exposure to such intensely fluctuating radiation environments, although the nature and efficiency of the effects remains to be estimated.

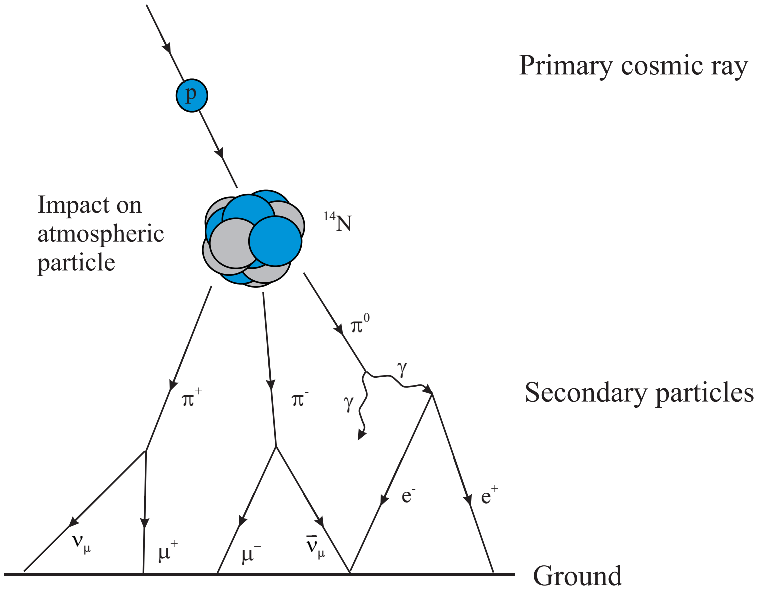

Figure 3: The collision of a primary cosmic ray and an atmospheric particle causing a cascade of secondary particles, which is called a cosmic–ray shower.

One may expect that a large increase of solar secondary cosmic radiation on the Earth's surface due to the Great Solar Proton Events (GSPE) will also produce biological effects in living systems. The role of secondary solar cosmic radiation near Earth's surface for simple bio-systems was discovered and studied after the GSPE associated with GLEs, which occurred during 1989 (Belisheva et al., 1995; Grießmeier et al., 2005). Experiments on three different cell cultures, growing in-vitro (Belisheva et al., 1995), were carried out during the second largest GLE (Reeves et al., 1992) in September and October 1989. It was found that during the increase of the energetic proton fluxes observed by the GOES-7 satellite (Reeves et al. 1992) in Earth's orbit, the cell fusion dynamics in all cells had a significant correlation with energetic particle and proton fluxes. Fig. 4 shows examples of biological effects on cell cultures studied during and after the GSPE in 1989. Simultaneously, in diverse cell-lines, gigantic nuclei, nuclei association, chromatin fragmentation, dispersion of cell and nuclei matter, micro-cells, micro-nuclei and separate chromosomes emerged. The left panel in Fig. 4 shows intracellular nuclear associations, which are coupled with cell fusion. The right panel shows gigantic nuclei, which occurred either by cell nuclear fusion or by abortive cytokinesis usually observed after X-ray irradiation. One should note that similar distortions in diverse biological systems were found in biological experiments during spacecraft flights in Earth's orbit. Earth-like exoplanets at orbital distances of about 0.2 AU with an atmospheric pressure of about 1 bar may experience the same biological effects as observed at Earth's polar region during the GSPE in 1989 over 100 % of its surface (Grießmeier et al., 2005). In particular, it is unknown whether such a mutationally rich environment would enhance or suppress the rate of evolution even in simple population genetic models.

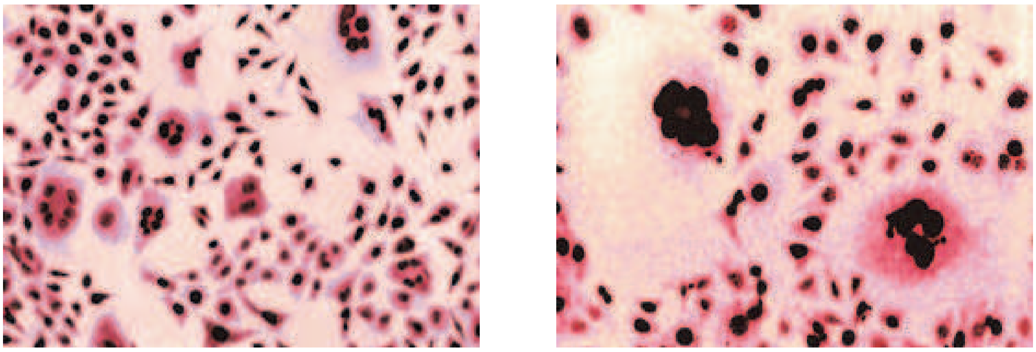

Figure 4: Biological effects caused by secondary solar cosmic radiation on simple genetic systems observed in cell cultures in Apatity, Russia (Lat.: 67.57°; Long.: 33.40°), during the high energetic solar proton event in 1989.

6 Other possibilities for extraterrestrial habitats

From the discussions above one can see that exoplanets orbiting massive K and solar-like G and F stars are more favorable to develop an Earth–like biosphere. However, the definition of the HZ does not tell the whole story about planetary habitability, because it is based on the idea that only starlight is the energy source providing liquid water on a planet. Additionally, the definition in Sec. 2 proposes that liquid water must be present on the planetary surface to harbor life, and therefore atmospheric stability, of course, is a requirement. But even on Earth there exist habitats, where these restrictions are not valid. This includes ecosystems at hydrothermal vents, living without sunlight, but using chemical energy provided by chemical reactions between hot water and the surrounding rocks (e.g., Zierenberg et al., 2000). Additionally, there are life forms dwelling deep inside the continental and oceanic crust, living completely independent from Earth's surface (e.g., Gold, 1992; Krumholz et al., 1997). Their energy supply comes from chemical sources, due to fluids that migrate upwards from deeper levels inside the Earth. In mass and volume, this biosphere may be comparable with all surface life. Such microbial life may account for the presence of biological molecules in all carbonaceous materials in the outer crust, and the inference that these materials must have originated from biological deposits accumulated at the surface is therefore not necessarily valid. Subsurface life may be widespread among the planetary bodies of our solar system, since many of them have equally suitable conditions below, while having totally inhospitable surfaces. One may even speculate that such life may be widely disseminated in the universe, since planetary type bodies with similar sub-surface conditions may be common as solitary objects in space, as well as in other solar-type systems. If there is some other energy source, like gravitational interactions or internal radioactivity, keeping water liquid, subsurface life may flourish even without a star. Also potential chemical energy sources such as hydrogen and iron oxides are common in planetary environments.

One place in our Solar System where other heat sources are available may be the subsurface oceans of icy satellites like Europa and Callisto (Khurana et al., 1998). In this case,

the heat source is the gravitational interaction between the icy satellite on one side, and the planet (Jupiter) on the other side. Due to this heat source, the ice layer is molten below 3 - 30 km, giving rise to several possible habitats, including the ice layer, the brine ocean, and the seafloor environment (Marion et al., 2003). In other stellar systems, terrestrial planets may form far from their host stars, which might not need gravitational interactions to maintain a deep ocean. According to numerical models (e.g., Raymond et al. 2004), rocky planets could form at distances between two to four times the Earth's orbit. Since the stars heat input would evaporate less water during their formation, such distant planets would likely have deeper oceans than Earth. Internal heat sources alone can melt any ice layer deeper than 14 km below the surface on an Earth-sized planet (Vogel, 1999). Furthermore, Lger et al. (2004) have shown that massive ice-rich planets possibly form in external regions of protoplanetary disks and migrate inward. Depending on their distance to the star and properties of their atmospheres, some of them may form a surface water ocean. Such an ocean of liquid water can have a thickness of about 100 km. The results of these studies lead to the plausible conclusion that planets with deep oceans underneath ice layers may exist which provide all conditions necessary for life.
An additional scenario is proposed by Lissauer (1987), because many planetary embryos form quickly by runaway accretion during the origin of a stellar system. Some of these embryos may merge but others may be scattered into escape trajectories from the stellar system by proto-giant planets. Stevenson (1999) pointed out that such free-floating interstellar planets may also develop large oceans protected by dense atmospheres. Probably, life has much more time to evolve on such interstellar planets compared to planets in stellar systems. The expanding stars annihilate all life on planets inside the HZ after some Gyr, but an interstellar planets internal heat may keep life alive for at least 30 Gyr. However, complex life forms require much energy to establish extended biospheres. The energy available at most of the potential habitats discussed in this section is orders of magnitudes less than at present Earth (Jakosky and Shock, 1998; Stevenson, 1999). Because, biosignatures of biological communities dwelling in a planets subsurface are hard to detect, planets with the potential to develop Earth-like extended biospheres on their surfaces are better candidates to search for life outside of our Solar System.

7 Conclusions

The evolution of biospheres and life on Earth-like exoplanets inside the region where life supporting planetary environments can exist, depends on the size and mass of the planet, greenhouse gases abundance such as H_2O, CO_2, its distance to the central star, the luminosity of the host star, etc. We show that the habitable zone is not a static or permanent region and the evolution of planetary atmospheres and water inventories is closely connected to the evolution of the X-ray and EUV activity of their host stars. Furthermore, Earth-like planets in orbits around M and K dwarfs are tidally locked after about 100 Myr, that results in weak magnetic moments, no plate tectonics, strong atmospheric erosion caused by CME's, and high energy particle exposure on the planets surface. These conditions can led to an enhancement of mutations in biological systems. Although, surface habitability and the evolution of Earth-like biospheres may not be favored at M star planets, subsurface life may evolve. Because low-mass M dwarfs constitute about 75 % of all main sequence stars in the solar neighborhood and the Galaxy, this result has important astrobiological implications, although more studies on surface habitability of Earth-like planets inside habitable zones of low-mass stars should be carried out.

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