Cosmological aspects of planetary habitability

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ABSTRACT

The habitable zone (HZ) is defined as the region around a star where a planet can support liquid water on its surface, which, together with an oxygen atmosphere, is presumed to be necessary (and sufficient) to develop and sustain life on the planet. Currently, about twenty potentially habitable planets are listed. The most intriguing question driving all these studies is whether planets within habitable zones host extraterrestrial life.

It is implicitly assumed that a planet in the habitable zone bears biota. However along with the two usual indicators of habitability, an oxygen atmosphere and liquid water on the surface, an additional one – the age — has to be taken into account when the question of the existence of life (or even a simple biota) on a planet is addressed. The importance of planetary age for the existence of life as we know it follows from the fact that the primary process, the photosynthesis, is endothermic with an activation energy higher than temperatures in habitable zones. Therefore on planets in habitable zones, due to variations in their albedo, orbits, diameters and other crucial parameters, the onset of photosynthesis may take much longer time than the planetary age.

Recently, several exoplanets orbiting Population II stars with ages of 12–13 Gyr were discovered. Even though these stars have low metallicity, they can still form protoplanetary clouds where the abundance of metals can be enhanced due to the action of physical fractionation. Masses of protoplanets in such conditions can, in principle, be within Earth to super-Earth range. These planets had enough time to develop necessary chains of chemical reactions and may thus carry life provided they are within a habitable zone.

Subject headings: planetary systems: formation - quasars: abundances - cosmology: early universe

1. Introduction

The habitability can be loosely defined as a measure of the ability of a planet to develop and sustain life in some form (Schulze-Makuch et al. 2011). Quantitatively, its maximum can be set as 1 for a planet where life as we know it has formed, thus it is 1 for the Earth. The requirement for a planet to be called habitable (or potentially habitable)[1] is that the planet is located within the HZ and has terrestrial characteristics: rocky, with a mass of 0.1–10 Earth masses and a radius of 0.5–2.5 Earth radii. Practically, a habitable zone around a star is commonly understood as a region where a planet can support liquid water on the surface. This requirement, along with the presence of an oxygen atmosphere, is presumed to be necessary (and sufficient) for a planet to develop and sustain complex life. In addition, Chyba & Hand (2005) argue that biogenic elements (such as C, H, N, O, P and S) are a crucially important complementary factor of the habitability. Note however that if water in any form is found, the presence of all these elements is implied, as they are produced in the same stars (Heger & Woosley 2002; Umeda & Nomoya 2006).

Outstanding efforts have been recently undertaken to find exosolar systems with planets in habitable zones, resulting in numerous discoveries. The *Kepler* space mission launched in 2009 (Koch et al. 2010) aimed to search for habitable planets around nearby (within $\sim 3,000$ light years down to a magnitude of about $V = 14.5$[2]) solar-like stars towards the Cygnus-Lyra region, therefore only probing stars from the thin stellar disk — the population I stars (Pop I). Currently, around twenty potentially habitable planets are listed[3]. The most intriguing question driving all these studies is whether planets within habitable zones host (or may host) life.

A common and intuitively obvious understanding is that habitable planets should only exist around metal-rich (and relatively young, see below) stars, which mostly implies stars from the thin Galactic disk, and this is supported by all observations to date. Most confirmed exoplanets detected so far are less than ~ 320 parsecs away and are predominantly found around stars abundant in heavy elements (Pop I stars). This could be though a result of an observational selection bias (Shchekinov, Safonova & Murthy 2013) — current instruments can robustly detect planetary photometric and spectral signatures of only nearby systems.

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[1] Both definitions *habitable* and *potentially habitable* are used in the literature, meaning essentially the same.

[2] http://kepler.nasa.gov/Mission/QuickGuide/

[3] See, for example, the online Habitable Exoplanets Catalog (HEC), maintained by the Planetary Habitability Laboratory at the University of Puerto Rico, Arecibo, `http://phl.upr.edu/projects/habitable-exoplanets-catalog`, but not exclusively.

It is generally expected that a planet in the HZ is habitable — can (or does) bear life. However, a more thorough consideration shows that the commonly understood attribute of an HZ, liquid water on the surface, is only a necessary, but not sufficient, condition for developing and sustaining life on a planet. An additional one — the age, has to be taken into account when the question of the existence of life (or even a simple biota) on a planet is addressed. The planetary age as a critical parameter has been initially stressed by Huang (1959), and then implicitly mentioned by Crick & Orgel (1973) in their concept of a Directed Panspermia.

The importance of planetary age for existence of life as we know it follows from the fact that the primary global process — the development of blue-green algae — involves (among others) endothermic reactions and requires sufficiently high temperatures to be activated. In general, the temperature dependence of the photosynthetic rate is rather complicated and conditionally sensitive, with the effective activation energy being of the order of tens of kJ mol^{-1} (Hikosaka et al. 2006), which is much higher than a typical equilibrium temperature on habitable planets. It implies that small variations in atmospheric and crust properties can considerably inhibit photosynthesis and increase the growth time of the mass of blue-green algae. In order to illustrate this conclusion, let us consider an elementary process of carboxylation of RuBP (ribulose-1,5-bisphosphate: $C_5H_{12}C_{11}P_2$) in the so-called dark (or Calvin) cycle of photosynthesis (Farquhar et al. 1980). These photosynthetic reactions, controlled by enzymes, are known to be very sensitive to ambient temperatures with an optimum rate at around 40°C, and a practically zero rate outside the temperature range of $0° < t < 60°$C (Toole & Toole 1997). Amongst other fundamental factors, RuBP carboxylation may be the most relevant factor determining the optimal temperature of photosynthesis, and is characterized by the activation energy $V_{\rm C} \simeq 30 - 60$ kJ mol^{-1} at the growth temperature (Hikosaka et al. 2006). One can thus roughly characterize the RuBP carboxylation by the Arrhenius law

$$k_{\rm C} = Ae^{-V_{\rm C}/T}, \tag{1}$$

where $k_{\rm C}$ is the rate constant, A the prefactor, and T is the absolute temperature. The characteristic time of RuBP carboxylation is $\tau_{\rm C} \propto k_{\rm C}^{-1} \propto \exp(V_{\rm C}/T)$. Since the RuBP carboxylation is one of the main processes optimizing photosynthetic reactions, $\tau_{\rm C}$ can roughly characterize the rate of photosynthesis on a planet. The range of variation in $\tau_{\rm C}$ on a habitable planet due to the uncertainty in the equilibrium temperature T_e is

$$\frac{|\delta\tau|}{\tau_e} = \frac{V_{\rm C}}{T_e}\frac{|\delta T|}{T_e}\,, \tag{2}$$

with τ_e being a characteristic time of photosynthesis at T_e, which in turn is calculated from the planetary parameters inferred from observations,

$$T_e = \left[\frac{L(1-a)}{16\pi\sigma\varepsilon r^2}\right]^{1/4} . \tag{3}$$

The uncertainties in the parameters determine the uncertainty in its estimate,

$$\frac{|\delta T|}{T_e} = \frac{1}{4}\left(\frac{|\delta L|}{L} + \frac{|\delta a|}{1-a} + |\delta\varepsilon| + 2\frac{|\delta r|}{r}\right), \tag{4}$$

here L is the luminosity of the central star, a and ε the planet's albedo and emissivity, r is the orbital radius, and σ the Stephan-Boltzmann constant. It is readily seen that the actual time of photosynthesis for a given habitable planet might differ significantly from the value calculated from largely uncertain parameters that themselves were derived from observables. Indeed, uncertainties in estimates of the equilibrium temperature $|\delta T|/T_e$ are heavily amplified for habitable planets with $V_{\rm C}/T_e \simeq 10-20$ for $V_{\rm C} \simeq 30-60$ kJ mol^{-1} and $T_e \sim 300$ K, such that even relatively low observational errors in deriving the parameters in Eq. (4), say 5% each, might result in 50–100 % error in the estimates of the overall photosynthesis rate. If one considers oxydation of the Earth atmosphere as a process tracing the developing photosynthesis, the characteristic time for biota to grow on early Earth can be estimated as the oxydation time $\tau_{\rm O_2} \sim 2$ Gyr. Therefore a 50% error in $\tau_{\rm C}$ might shift the possible onset of biological evolution on a planet by 1 Gyr, i.e. biogenesis might have started not earlier than at 3 Gyr. In general, however, the problem of photosynthetic process is much more complex, depending on many factors determined by thermal and non-thermal processes on a planet (Hikosaka et al. 2006; Shizgal & Arkos 1996), and might be even more sensitive to variations in physical conditions.

The most generic form of the habitability index was recently proposed by Schulze-Makuch et al. (2011)

$$\mathrm{PHI} = (S \cdot E \cdot C \cdot L)^{1/4}, \tag{5}$$

where S defines a stable substrate, E the necessary energy supply, C the polymeric chemistry and L the liquid medium; all the variables here are in general vectors, while the corresponding scalars represent the norms of these vectors. We propose to implement explicitly the age of the planet t into the habitability, such that the habitability approaches unity asymptotically when enough time for the development of the basic chemical and biochemical reactions has elapsed. Then the evolutionary behaviour can be broadly defined as

$$\mathrm{PHI}(t) = (S \cdot E \cdot C \cdot L)^{1/4} \prod_i (1 - e^{-t/t_i}), \tag{6}$$

where i denotes a chemical chain relevant for further biochemical evolution, and t_i is its characteristic time. It is obvious that the asymptotic behaviour – approaching the maximum habitability – is controlled by the slowest process with the longest t_i.

This issue is important not only for the correct classification of a given habitable planet as being able to carry biota, but for a more fundamental question of how numerous are the planets in the Milky Way that are able to develop and sustain life, and how such an ability depends on particular physical and chemical conditions on the planet. The latter is of a primary importance for developing the future strategy of looking for life on habitable planets. For example, in the list of targets of the Degenerate Objects around Degenerate Objects (DODO) direct imaging search for sub-solar mass objects around white dwarfs (Hogan et al. 2009), the average age of the hosts was rather low, around 2.25 Gyr. While considering candidate targets for future missions such as, for example, Exoplanet Characterization Observatory (EChO) mission (Drossart et al. 2013) or Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE) (Swain et al. 2010), it is important to take age into account: only those habitable planets orbiting stars of at least 2–3 Gyr old — a time interval which would be possibly marginally sufficient for developing the simplest prokaryote — are interesting, otherwise they hardly can reveal well-developed atmospheres abundant in products of photosynthetic processes, such as carbon dioxide and oxygen. Moreover, though atmospheric oxygen appeared up at the Earth at about 2.5 Ga (Gyr ago), Earth itself became visibly habitable only about 750–600 Ma (Myr ago), when the planet emerged from the one having a simple biota to a planet with diverse complex life (at about 540 Ma), capable of changing the environment enough to be noticed from space (for example, Mendéz et al. (2013)). It seems reasonable to fix the period of ~ 4 Gyr as the minimum necessary time for the formation of complex life at optimal conditions equivalent to ones established on the Earth.

From this point of view, most (if not all) known habitable planets can only potentially serve as places for developing biota but can hardly carry it currently. This conclusion follows from the fact that all habitable planets are found around relatively young Pop I stars in the very narrow vicinity of Sun. We discuss here how plausible is a discovery of a habitable planet with biota on it among the closest (within 600 pc) neighbours of the Sun. We argue that even for planets in habitable zones, due to variations in their albedos, orbits, diameters and other crucial parameters, the onset of photosynthetic processes which manifest in formation of oxygen atmosphere may take longer time than the current planetary age. We discuss recent observational exoplanetary data from this point of view and estimate the probability for a planetary system from the nearest Galactic environment to bear biota.

2. Candidate and Confirmed Planets

More than 1800 planets have been confirmed and more than 3800 are waiting for confirmation at time of writing[4]. Due to obvious reasons connected with the sensitivity thresholds for the detection, the majority of detected planets are in the close vicinity of the Sun. As a consequence, a considerable fraction of the hosts belongs to the youngest population I with expected ages of hundreds of Myrs. This expectation is confirmed in Figure 1, where the age distribution of the host stars is shown: 60% of the host stars have ages of 4.5 Gyr and less, and more than a third (43.5%) are younger than 3 Gyr. Actually, simple statistics shows that the mean age is 4.27 Gyr even if we include stars with such unrealistic age estimates as 13 to 15 Gyr. If we remove these unrealistic numbers, the average age comes down to 4.17 Gyr.

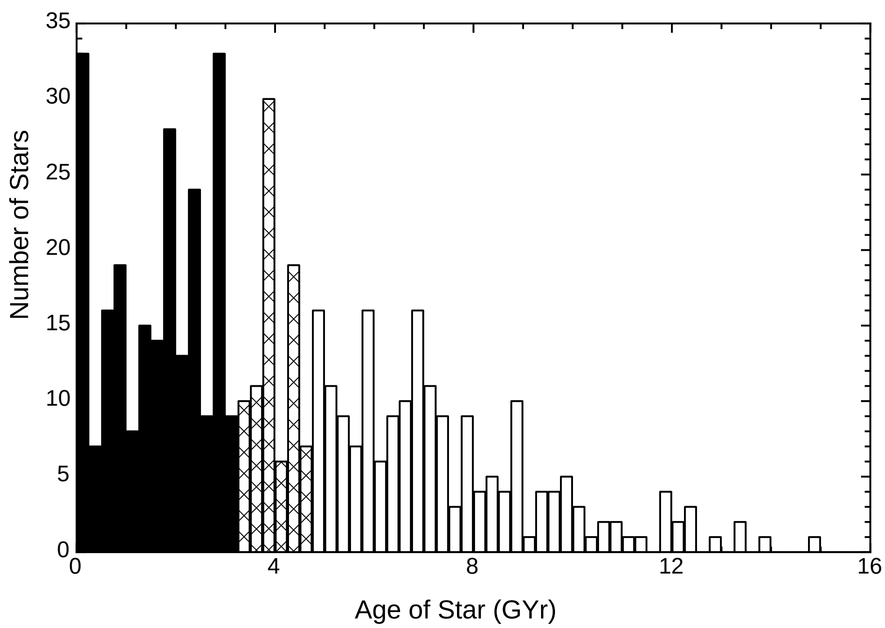

Fig. 1.— Age distribution of the stars hosting confirmed planets (total 504 hosts with measured ages at time of writing). With different shading we highlight the number of stars with ages below 3 Gyr in black and between 3 and 4.5 Gyr as hatched. The predominance of young host stars is clearly seen, which could be the effect of observational selection (Shchekinov, Safonova & Murthy 2013). This figure was made using the Extrasolar Planets Encyclopaedia data.

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[4]Extrasolar Planets Encyclopaedia, `http://http://exoplanet.eu/catalog/`, March 2014.

The fact that more than a third of the planetary systems in the solar vicinity, discovered by ongoing exoplanetary missions, is younger than 3 Gyr is not surprising, because the continuous star formation (SF) in the Galactic disk supplies young stars, and the fraction of hosts younger than 3 Gyr represents that very fraction of Pop I stars that would be born provided the star formation rate is nearly constant during the whole period of the thin disk formation. One of the biggest sources of the latest generation of stars in the Milky Way is the Orion nebula, where many substellar objects and planets (most likely, free-floating) with ages around 3 Myr were recently discovered (Lucas & Roche 2000; Bihain et al. 2009). Similar young substellar objects were recently reported by Scholz et al (2012) in another nearby young ($\sim$ 1 Myr) stellar cluster NGC 1333. These two examples indicate that all current planetary missions suffer from observational bias, detecting a considerable fraction of systems with ages below that at which life appeared on Earth[5] may have appeared.

In Table 1 we show the data for potentially habitable planets with the estimates of the host ages (as of March 2014). The fraction of young planetary systems is nearly consistent with the age distribution of Pop I stars: among the eleven confirmed habitable planets with known ages and the Earth Similarity Index[6] ESI ≥ 0.53, six are at ≤ 3 Gyr. This result does actually support the statement that the age is essential for a planetary system to turn from being a potentially habitable planet to an "active" (habitable) state. On the youngest planets in this list (≤ 2 Gyr) we may expect only primitive form of biogenesis. On $\sim$ 2–4 Gyr old planets the biogenesis could have started or even progressed to a more advanced stage with an oxidized atmosphere. In the former case one can expect that methane from metabolic reactions has already filled the atmosphere, while in the latter case, oxygen molecules will be abundant in the atmosphere. In both cases, traces of these gases may in principle be observed in sub-mm and micron wavelengths provided the planets are orbiting low-mass stars (0.5–0.8 $M_\odot$). Even if a third of low-mass stars host planets (Tutukov & Fedorova 2012), their number within a 10 pc vicinity may be as high as a thousand, with ages ranging from Myr to a few Gyr. Direct observations of planetary atmospheres in IR and sub-mm wavebands would be a promising method for tracing biogenesis. Planned future IR and sub-mm observatories could provide such observations (see discussion in Sec. 4 below.)

Fig. 1 clearly shows a deficit of stars with ages $t > 6$ Gyr. Assuming that the population

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[5]The earliest geological/fossilized evidence for the existence of biota on Earth dates to $\sim$ 3.8–3.5 Ga, see Brack et al. (2010) and references therein.

[6]ESI is a multiparameter index developed to indicate how similar is a planet compared to the Earth; planet with ESI = 1 is identical to Earth, while planet with ESI = 0 has no similarity at all. A planet with an ESI > 0.8 is considered an Earth twin: rocky, with an atmosphere suitable for complex life (Schulze-Makuch et al. 2011)

Table 1: The ages of stars hosting potentially habitable planets

Star	Planet(s)	Age Estimate (Gyr)	Metallicity [Fe/H]	Distance (pc)	Ref. to age
Gliese 667C	Gl 667c,e,f	< 2; 2–5; > 2	-0.55 $(-0.59)^{\text{Ref. 2}}$	7.24	1; 2; 3
Kepler 62	Kepler-62e,f	7 ± 4	-0.21	367.9	4
Gliese 581	Gl 581d,g*	7–11; 8^{+1}_{-1}	-0.135	6.2	1; 5
τ Ceti	τ Ceti e*	5.8	-0.55	3.65	6
Kepler 22	Kepler-22b	~ 4	-0.29	190	14
Gliese 163	Gl 163c	3^{+7}_{-2}; > 2; 6 ± 5	0.1 ± 0.1	15	1; 7; 8
Kepler 61	Kepler-61b	1	0.03	326	1
HD 40307	HD 40307g*	1.2 ± 0.2; 4.5; 6.1	-0.31	12.8	9; 10; 11
Kepler 69	Kepler-69c	0.4	-0.29	307–828	12
HD 85512	HD 85512b	5.61 ± 0.61	-0.33	11	13
Kepler 283	Kepler-283c	K dwarf	-0.26	534.4	*Note*
Gliese 180	Gl 180b,c	red dwarf M2V	0	11.7	
Gliese 422	Gl 422b	M3.5 V	0	12.7	
Gliese 682	Gl 682b	subdwarf M3.5-4.5 V-IV	-0.2	5.1	
Kepler 298	Kepler-298d	K dwarf	-0.121	474.3	
Kepler 296	Kepler-296f	K dwarf	0.168	518.7	
Kepler 174	Kepler-174b	K dwarf	-0.556	360	

* planet candidates. There are 30 more potentially habitable planets in the new release of 2740 Kepler candidates (Kepler Objects of Interest) in NASA Exoplanet Archive at `http://exoplanetarchive.ipac.caltech.edu`.

References to ages: 1. The Extrasolar Planet Encyclopaedia (`http://exoplanet.eu`); 2. Angala-Escudé et al. 2012; 3. Anglada-Escudé et al. 2013; 4. Borucki et al. 2013; 5. Selsis et al. 2007; 6. Mamajek & Hillenbrand 2008; 7. Tuomi & Anglada-Escudé 2013; 8. Open Exoplanet Catalogue (`http://www.openexoplanetcatalogue.com`); 9. Nordström et al. 2004; 10. Tuomi et al. 2013; 11. Barnes et al. 2009; 12. Kalteneggeret al. 2013; 13. Pepe et al. 2011; 14. Metcalfe 2013.

Note: The following planets were discovered only in March 2014 and their hosts do not yet have the age estimate.

I stars, i.e. the thin Galactic disk, have started forming at around 10 Ga (Chen et al. 2003; Carfraro et al. 2007), one can expect the presence of such old stars in our vicinity in the proportion corresponding to the SF history in the early Galaxy, i.e. when it has started forming the thin disk. The most conservative assumption implies a constant SF rate, in which case one should expect the number of planet-hosting stars with ages $t > 5$ Gyr of about 50%. It is, however, believed that the star formation was more active in the early epochs (Bouwens et al. 2008), therefore, the fraction of hosts older than 6 Gyr should be correspondingly higher. The reason for the decline in the number of the hosts in this age range is unclear, and might, in particular, indicate that planetary systems lose planets with age.

3. Other environmental factors in young planetary systems

Not only aspects connected with endothermicity of photosynthetic reactions restrict the age of habitability from below, but sporadic over-heating from planetary collisions might also delay the formation of biota and oxygen atmosphere as well. For instance, late heavy bombardment (LHB) episodes of the Earth and the Moon at 3.8 Ga are known from the ^{182}W isotope dating (Schoenberg et al. 2002; Moynier et al. 2009). In addition, the Martian cratering chronology confirms that heavy bombardment on Mars continued until around 4 Ga (Robbins & Hynek 2012). Moreover, the Martian primitive atmosphere is believed to have been lost through a giant impact catastrophic event 4 Ga; first proposed in 1998 (Hancock, Bauval and Grigsby, 1998), it was recently reconfirmed by data returned by the Curiosity rover (e.g., Webster et al. 2013).

Several evidences of an LHB in other systems are found recently from *Spitzer* data: Lisse et al. (2012) argue the presence of such an episode in η Corvi at ~ 1 Ga, where clear manifestations from warm water- and carbon-rich dust, as well as spectral features due to collision-produced silica and high-temperature carbonaceous phases, are seen. In general, however, the initial period of the planet build-up phase which includes early bombardment, late veneer and late bombardment stages, can last even longer. Raymond et al. (2013) conclude that it may take in total up to 700–800 Myr. Out of seven sun-like stars that have hot dust (Wyatt et al. 2007), resulting from recent frequent catastrophic collisions between asteroids, planetesimals or even planets (Song et al. 2005), only two are mature 2 to 5 Gyr old systems. The rest are young systems within their first Gyr of life.

Laboratory experiments on high-speed solid body collisions suggest that prebiotic molecules could have started forming during these initial stages of planetary systems (Managadze 2007, 2010). These suggest that the LHB might have brought organics to the Earth at the rate of 10^{14} kg yr^{-1} with a cumulative total several magnitudes greater than what might existed before (Goldman & Tamblin 2013). In addition, if the early atmosphere was very dense at 10 bar, for example, organics-rich small comets may have had reached the ground non-destructively (Whitett 1996). In fact, LHB impacts may have provided exactly the needed large chemical and thermal disequilibrium conditions for the biogenesis to (re)start.

It is also well-known that young Sun and solar-type stars remain very active in the first billion years of their life with conditions that are detrimental to the survival of the atmosphere and to the planetary habitability (Kulikov et al. 2007). G stars within the first 100 Myr of reaching ZAMS produce continuous flares of EUV radiation up to 100 times more intense than the present Sun and have much denser and faster stellar winds with an average wind density of up to 1000 times higher. Low-mass M and K stars remain X-ray and EUV-active longer than solar-type stars and with higher intensities; early K and M-type and may have EUV emission of around 3–4 times and 10–100 times higher, respectively, than G stars of the same age; and active M-type stars could keep stellar winds in the HZ that are at least be 10 times stronger than that of present Sun (France et al. 2013).

4. Old planetary systems

The so-called "metallicity" effect — the metallicity distribution function of host stars peaking at around solar value — is clearly an observational selection bias, merely reflecting the fact that in the solar vicinity Pop I stars are overrepresented: the percentage of old stars in the solar neighbourhood with metallicities of less than an order of magnitude of the solar value (Pop II) is only $\sim 1\%$, which is close to the percentage of planetary systems with low-metallicity hosts, $\sim 2\%$. In spite of a very strong observational selection connected with the fact that old Pop II stars are distant and faint, several very old ($t \simeq 13$ Gyr) stars hosting planets were recently discovered (e.g. Setiawan et al. 2010, 2012). Therefore, a considerable fraction of planetary systems, equal to the fraction of old Pop II stars in the Milky Way, can be under-abundant in metals. The arguments, based on an intuitive understanding that high mass of metals is necessary for planets to form, may not be applicable to the conditions in the early Universe. For instance, Shchekinov, Safonova & Murthy (2013) argued that due to the centrifugal selection of dust planets can form even at metallicities as low as $Z \sim 0.01\ Z_{\odot}$.

On the other side, it is well known that spatial distribution of metals in the Universe is highly inhomogeneous, and even in the early Universe, when it was as young as a few hundreds of Myr, one can find regions with metallicities at or even higher than solar values. There is a growing number of arguments that heavy elements, after being ejected into the ISM, may form pockets (Savaglio et al. 2000; Simcoe et al. 2007). It is the result of a non-perfect mixing in the early Universe and in young galaxies (Dedikov & Shchekinov 2004; Vasiliev et al. 2009). Therefore, there could be old Pop II stars with sufficient amount of metals able to form planets in a traditional way and our Galaxy may have a vast number of planets residing in the habitable zones of Pop. II hosts with ages up to 13 Gyr. Such planets would have a longer time to develop biogenesis, provided that biogenic chemical elements (e.g., C, H, N, O, P and S) are present.

The sources of heavy elements (often referred loosely as metals) in the Universe are mostly supernovae (SNe) explosions. The initial episode of metal enrichment of the Universe is believed to have occurred around 13 Ga when the Universe was about 500–700 Myr old — the absorption spectra of galaxies and quasars show significant amount of metals, in some cases up to 0.3 of the solar metallicity (e.g., Savaglio et al. 2000; Finkelstein et al. 2013). The nature of the very first stars in the Universe as progenitors of the first SNe is still widely debated. Recent high-resolution numerical simulations demonstrated that the first stars on the lower mass end could have masses in the range of 15–40 $M_\odot$ (Clark et al. 2011; Stacy et al. 2011), while on the upper mass end (for nonrotating stars), the masses could be as high as 140–260 $M_\odot$ (Bromm, Coppi & Larson 1999; Abel, Bryan & Norman 2000). Even though the abundance pattern of heavy elements in this initial enrichment is sensitive to the mass of SN progenitors it contain a copious amount of elements necessary for rocky planets to form within the whole range of masses.

Direct measurements of the metallicities and the abundance pattern in the early Universe have recently become possible with the discovery of extremely metal-poor (EMP) stars with an abundance of heavy elements as low as 10^{-5} of solar value — these objects are commonly thought to represent the population next after the Population III stars (Beers & Christlieb 2005). The relative abundances observed in the EMP stars are shown to stem from the explosions of Pop III intermediate-mass SNe with an enhanced explosion energy around 5×10^{51} erg (Umeda & Nomoya 2006). These stars are also often found to be overabundant in CNO elements, though their relative abundance (Aoki et al. 2006; Ito et al. 2013) is consistent with the abundance pattern of the Earth crust (Taylor & McLennan 1995; Yanagi 2011) and the chemical composition of the human body (see, e.g. Nielsen 1999). Though Earth is rich in chemistry, most living organisms use only a few of all the available elements: C, N, O, H, P and S, which make up proteins, lipids and DNA. Apart from hydrogen, the elements C, N, O, P and S are all produced by the very first massive pop III stars. Detection of substantial amount of CO and water in the spectrum of $z = 6.149$ quasar SDSS J1148+5251, for example, means that at ~ 800 Myr after the Big Bang, all the ingredients for our carbon-based life were already present. This may mean that planets formed in the early Universe, which are observed now as those planets orbiting very old ($\sim$ 10–13 Gyr) Pop II stars, may have developed and sustained life over the epochs when our Solar System had only started to form. In this way, the restricted use of only 6 'biogenic' elements may be considered as a fossil record of an ancient life — it is well known that at the molecular level, living organisms are strongly conservative. The general direction of the biological evolution is in the increase of complexity of species rather than (chemical) diversity (Mani 1991). For example, paradoxically, both oxygen and water are destructive to all forms of carbon-based life. Presence of water reduces the chance of constructing nucleic acids and most other macromolecules (Shluze-Makuch and Irwin, 2006). The toxic nature of oxygen necessitated the evolution of a complex respiratory metabolism, which again shows the strong chemical conservatism at the molecular level in that the living organisms developed the protection mechanisms to circumvent these problems rather than use other compounds.

All discovered (till now) old (with host ages of > 9 Gyr) planetary systems have giant planets with masses between 0.8 and 15 Jupiters and do not fall into the category of habitable planets. All these planets are discovered by the radial velocity (RV) method, which due to a limited sensitivity is biased to detect preferentially massive planets. However, because giant gaseous planets typically harbor multiple moons, these moons may lie in the domain of higher habitability. For example, Schulze-Makuch et al. (2011) estimate the PHI for Jupiter to be only 0.4, while for Titan it is around 0.65 (see their Fig. 2). There are 33 potentially habitable exomoons with habitable surfaces listed by HEC (excluding possibility of subsurface life), which have on average even higher ESI than potentially habitable planets. Even though Pop II stars are normally two order of magnitude less abundant in metals, they may harbor, in principle, up to 10 rocky Earth-size subsolar objects each (Shchekinov, Safonova & Murthy 2013), either as planets or as moons orbiting gaseous giants, which are potentially habitable.

5. Observational prospectives

Till recently, the planets orbiting old stars have been discovered serendipitously. Only in 2009 were targeted surveys of metal-poor stars initiated (Setiawan et al. 2010), resulting in discoveries of a few very old stars with planets. Recently, a 13.6 Gyr star was detected, placing it as the oldest star in the Universe (SMSS J031300.36670839.3, Keller et al. 2014); the age was estimated by its metallicity [Fe/H]≤ -7.41. This star, however, contains some carbon, metals like lithium, magnesium, calcium, and even methylidyne (CH). It was formed from the remnants of the first-generation SN. It is quite possible that such stars may have planets, which could be directly observable in micron wavelength. Such EMP stars are known to have low masses and as such the orbiting planets may be seen directly in the IR.

The number of EMP stars is estimated to be around 250,000 within 500 pc in SDSS database (Aoki et al. 2006), so the mean distance between them is about 10 pc. If each EMP star hosts an Earth-size planet, the flux from the planet at a distance d in the IR range ($\lambda \sim 10$ μm) can be

$$F_\nu^{\rm pl} \sim 0.73 \left(\frac{T_{\rm eq}}{300\ {\rm K}}\right)^3 \left(\frac{d}{10\ {\rm pc}}\right)^{-2} \left(\frac{R}{R_{\rm E}}\right)^2 \ {\rm mJy}\,, \qquad (7)$$

where $T_{\rm eq}$ is the equilibrium temperature of a planet and R is its radius. For the Sun/Earth system, the ratio of the fluxes at a distance of 10 pc at 10 μm is

$$\frac{F_\nu^{\rm pl}}{F_*} = \frac{T_{\rm E}}{T_\odot}\left(\frac{R_{\rm E}}{R_\odot}\right)^2 \sim 4\times 10^{-6}\,. \tag{8}$$

However, if we consider a super-Earth with $M\sim 5\,M_{\rm E}$, $R\sim 2R_{\rm E}$ and $T_{\rm eq}=300$ K, orbiting the star with $T=3000$ K and $R\sim 0.1\,R_\odot$ – an M dwarf, we get the ratio of

$$\frac{F_\nu^{\rm pl}}{F_*} = 3\times 10^{-3}\,, \tag{9}$$

at 10 pc and at 10 μm. Here we explicity assume the Rayleigh-Jeans regime for a star.

It seems obviously challenging to detect such a weak contribution to a total flux from a planet even in the IR observations. There is however a possibility to distinguish emission from the planet in IR molecular features, such as O_2 (e.g., the 10 μm feature) and CH_4 tracing initiated biogenesis and metabolism. Even at the low temperatures of EMP stars $T_*\sim 3000$ K, these molecules are unlikely to survive in sufficient amount in their atmospheres. Therefore, if such emission is observed from an EMP star, it should be considered as a direct indication of an orbiting rocky planet bearing metabolic processes on its surface having already entered the habitable epoch with growing H (Eq. 5). The possibility to detect a direct IR emission from O_2 in exoplanets going through the initial epoch of biogenesis, or which are already at a stage with developed biota, is discussed in Churchill (2000) and Rodler & López-Moralles (2013), respectively. Methane also has spectral features in the near-IR at $\simeq 8$ μm (see discussion in Kaltenegger et al. 2007). It was already tentatively identified in the atmospheres of Jovian planets HD189733b and HD209458b (Swain et al., 2008; 2009), which was, however, not confirmed later by the Keck Telescope for HD189733b (Mandell et al. 2011). Abiotic formation of O_2 and O_3 in atmospheres with high concentrations of CO_2 is also possible and could show as possible false positives in near-IR or mid-IR range (Segura et al. 2007). However, this would be important only if planets are frozen or devoid of water completely, because then O_2 and O_3, produced through the photolysis of CO_2, build up in the atmosphere in the absence of geochemical sink (Wordsworth & Pierrehumbert 2014). Therefore, the most promising way to identify (really) habitable planets seems to look for simultaneous presence of water, O_2, O_3 and methane in atmospheric spectra (e.g. Selsis et al. 2002). Molecular spectra from such tracers of developing habitability fall into a shorter wavelength range, and are expected to be negligibly weak for direct detection (Christensen et al. 1997). Even though such observations can, in principle, be used to detect direct emission from planets with highly developed habitability orbiting old EMP stars, the expected fluxes in the IR are still below current sensitivity limits and might be only possible in the future.

6. Summary

- The age of a planetary system is an essential attribute of habitability along with other factors, such as liquid water (or an equivalent solvent), rocky mantle, appropriate temperature, extended atmosphere, and so forth. The knowledge of the age of a "habitable" planet is an important factor in developing a strategy to search for exoplanets carrying complex (developed) life;
- more than a third of the confirmed habitable planets are too young (with the age less than 3 Gyr) and have not had enough time to develop and sustain life;
- planets do exist around old Pop. II stars, and some may have low masses and rocky mantles. In addition, gaseous giants may also have habitable worlds around them in the form of orbiting moons. In both cases, either the planets or the moons had sufficient time to develop life provided they are located within a habitable zone.
- recently discovered EMP stars (belonging presumably to an intermediate Pop II.5 stars) seem to be good candidates for direct detection of orbiting Earth-size rocky planets in the IR and sub-mm wavelengths. In general, IR and sub-mm observations of rocky planets orbiting subsolar-mass old stars seem a promising way to trace biogenetic evolution on exoplanets in the vicinity of the Sun.

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