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BIOSIGNATURES

Pathways to Earth-Like Atmospheres

Extreme Ultraviolet (EUV)-Powered Escape of Hydrogen-Rich Protoatmospheres

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Abstract We discuss the evolution of the atmosphere of early Earth and of terrestrial exoplanets which may be capable of sustaining liquid water oceans and continents where life may originate. The formation age of a terrestrial planet, its mass and size, as well as the lifetime in the EUV-saturated early phase of its host star play a significant role in its atmosphere evolution. We show that planets even in orbits within the habitable zone of their host stars might not lose nebular- or catastrophically outgassed initial protoatmospheres completely and could end up as water worlds with CO_2 and hydrogen- or oxygen-rich upper atmospheres. If an atmosphere of a terrestrial planet evolves to an N_2-rich atmosphere too early in its lifetime, the atmosphere may be lost. We show that the initial conditions set up by the formation of a terrestrial planet and by the evolution of the host star's EUV and plasma environment are very important factors owing to which a planet may evolve to a habitable world. Finally we present a method for studying the discussed atmosphere evolution hypotheses by future UV transit observations of terrestrial exoplanets.

Keywords Atmosphere formation · Young stars · Early Earth · Habitability

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Introduction

The Search for Exo-Earth

Since the discovery of several exoplanets within the so-called "super-Earth" domain such as Gliese 876d ($\sim 7 M_{\mathrm{Earth}}$) (Rivera et al. 2005), OGLE-2005-BLG-390Lb ($\sim 5 M_{\mathrm{Earth}}$) (Gould et al. 2006), HD 69830b ($\sim 10 M_{\mathrm{Earth}}$) (Lovis et al. 2006), Gliese 581c ($\sim 5.6 M_{\mathrm{Earth}}$) and Gliese 581d ($\sim 8 M_{\mathrm{Earth}}$) (Beust et al. 2008), CoRot-7b ($\sim 7.4 M_{\mathrm{Earth}}$) (Léger et al. 2009), GJ 1214b ($\sim 6.55 M_{\mathrm{Earth}}$) (Charbonneau et al. 2009), Kepler-10b ($\sim$3.3–5.7M_{Earth}) (Batalha et al. 2011) and planets within the Kepler-11 system such as Kepler-11b ($\sim 4.3 M_{\mathrm{Earth}}$) and Kepler-11f ($\sim 2.3 M_{\mathrm{Earth}}$) (Lissauer et al. 2011), the hunt for finding a second Earth-like planet within the habitable zone (HZ) of its host star was opened. The recent discovery of the first transiting "super-Earth" candidate, Kepler-22b, with a size of about $2.38 \pm 0.13 R_{\mathrm{Earth}}$ within the HZ at about 0.7 AU of the solar-type G5 star KIC 10593626, indicates that it is only a matter of time before the first Earth-size exoplanet inside the HZ is discovered (Borucki et al. 2011).

However, although Kepler-22b orbits within the HZ of its host star, without knowing the mass of the planet there is no evidence that it is really a rocky planet. This suggestion is supported by the observation of three "super-Earths" with known radii and masses, Kepler-11b and Kepler-11f, with masses of $\sim 4.3 M_{\mathrm{Earth}}$ and $\sim 2.3 M_{\mathrm{Earth}}$ and radii of $\sim 1.97 R_{\mathrm{Earth}}$ and $\sim 2.61 M_{\mathrm{Earth}}$, which result in mean densities of 3.1 and 0.7 g cm^{-3} (e.g. Borucki et al. 2011; Lissauer et al. 2011), and the "super-Earth" GJ 1214b, with a radius of $\sim 2.68 R_{\mathrm{Earth}}$ and a mass of $\sim 6.55 M_{\mathrm{Earth}}$, corresponding to a mean density of 1.87 g cm^{-3} (e.g. Charbonneau et al. 2009). These low densities indicate substantial envelopes of light gases such as H and He or H_2O and H. Could it be that these "super-Earths" could not lose their initial protoatmospheres? Interestingly, Kepler-11b and Kepler-11f have orbital locations which are >0.1 AU, while "super-Earths" with higher densities which indicate rocky bodies such as the "super-Earths" CoRoT-7b, Kepler-9b, Kepler-10b, or Kepler-20b have very close orbital locations of <0.05 AU.

The discovery of these low density "super-Earths" indicates that besides the orbit location and the host star's EUV and plasma environment evolution, also some initial protoatmosphere parameters such as the surface pressure, temperature, chemical composition, etc., which result from specific planetary and atmosphere formation pathways for a given planet, can be additional important factors which determine whether or not the planet might have evolved to an Earth-type habitable world.

In this work we investigate the young star/Sun EUV-radiation driven escape of dense hydrogen-rich gaseous envelopes and steam dominated protoatmosphere scenarios. We do not focus however on the possible build up of secondary atmospheres from outgassing by volcanos or similar processes (e.g. Rubey 1951; Schaefer and Fegley 2009; Grott et al. 2011), or study the modification of planetary atmospheres by life forms. It is very important for habitability research to understand under which initial conditions Earth-like planets and "super-Earths" may or may not lose their protoatmospheres.

Are planets like Kepler-11b, Kepler-11f or GJ 1214b common or rare? Before we focus on the escape and evolution of feasible hydrogen-rich gaseous envelopes, we discuss briefly the important connections between planet formation, impacts and protoatmosphere production.

Terrestrial Planet Formation, Giant Impacts and Their Influence on Early Atmospheres

The pathway to Earth-like atmospheres starts with the accretion of planetesimals (Kusaka et al. 1970; Nakagawa et al. 1981). Several Mars-sized planetary embryos can originate (e.g. Wetherill 1986; Kokubo and Ida 1998; Raymond et al. 2004). These bodies would have an impact-induced, a solar-type, or a mixed atmosphere (Zahnle et al. 1988; Halliday 2003) and collide with each other (Chambers and Wetherill 1998). In such simulations, planets with masses between twice that of Mars and "super-Earths" ($\sim 4 M_{\mathrm{Earth}}$) are usually formed. The composition of these planets can range from completely dry to "water worlds", where the initial H_2O content mainly depends on the configuration of the protoplanetary disk and the location of the snowline (e.g., Raymond et al. 2004; Leinhardt and Richardson 2005; Alibert et al. 2007; Lunine et al. 2011).

Terrestrial planets form during and after giant planet migration (e.g., Mandell et al. 2007). A giant planet accretes rapidly all bodies that cross its orbit. As a consequence, the probability that a short periodic comet would hit the Earth over its dynamical lifetime is $\sim 1{:}10^6$, but could be very different in planetary systems without gas giants. Comets, which are planetesimals formed beyond the snowline, carried $<10\%$ of the total amount of H_2O to the Earth (Morbidelli et al. 2000). This is consistent with the D/H isotope ratio of Earth's water which is more asteroidal than cometary (Genda and Ikoma 2008). The collision probability of comets with the Earth would be orders of magnitude higher if Jupiter and Saturn were replaced by lower mass planets, like Uranus or Neptune (Morbidelli et al. 2000). Hence, one can assume that in systems like ours, but without gas giants, comets could be a dominant source for additional delivery of water to terrestrial planets orbiting inside the HZ.

In the case of the Earth, a few Myr after the planet finished its accretion ($\sim$50 Myr after the formation of the Sun) (Allègre et al. 1995; Touboul et al. 2007), a giant impact occurred, most likely with a Mars-sized body which resulted in the formation of the Moon (e.g., Touboul et al. 2007). Because co-accretion (Taylor 1992) and capture (Urey 1966) cannot explain the angular momentum of the Earth-Moon system, and because of the difference in density and volatile depletion and similar oxygen isotope composition, it is expected that this giant collision ejected a cloud of fragments, which aggregated into a full or partial ring around Earth and then coalesced into a proto-Moon (Hartmann and Davis 1975). By investigating the escape fraction of an atmosphere by a Moon-forming giant impact, early studies estimated that Earth's primordial atmosphere was completely lost (Ahrens 1993; Chen and Ahrens 1997). However, modern impact studies indicate that only $\leq 30\%$ escaped and most of the atmosphere survived (Genda and Abe 2003).

Nebular Based and Catastrophically Outgassed Protoatmospheres

As long as there is nebular gas, large planetesimals and planetary embryos which form terrestrial planets should have been surrounded by large nebular atmospheres.

This hypothesis was considered by several researchers because it could explain why large amounts of nebular gases such as ^{3}He, solar-like Ne, or solar-like Ar can be found in Earth's plume basalts (e.g., Clarke et al. 1969; Mamyrin et al. 1969; Craig and Lupton 1976; Sasaki and Nakazawa 1988; Pepin 2000; Moreira et al. 2001). In case the proto-Earth was surrounded by a dense H/He, or H_2/He-type protonebular gas envelope, the thermal effects on the planet's surface would have been dramatic and the surface temperature T_s could have reached >4000 K (Hayashi et al. 1979; Matsui and Abe 1986). These atmospheric temperatures would have resulted in high temperatures in the outer mantle so that magma oceans could have originated and a significant amount of noble gases with the solar composition could have been incorporated in the planet's interior.

During recent years this nebular-based protoatmosphere hypothesis has been criticized because several researchers argue that the accumulated hydrogen envelopes would be lost by EUV-powered hydrodynamic escape before the protoplanet finished its accretion. It has also been argued that the lifetime of gas around stars in the process of planetary formation is most likely limited to a few Myr (e.g., Halliday 2003; Najita et al. 2007; Lunine et al. 2011). To attract such an amount of gas before the remains of the nebular gas are accreted into the Sun/star or other planetary bodies, the time scales should have been in the order of ~1–10 Myr and on average ~3 Myr (Halliday 2003). However, one cannot completely rule out an accumulation of hydrogen-rich nebular-based remnants of gaseous envelopes around early Earth and similar planets. Hayashi et al. (1979) and Mizuno et al. (1980) suggested that in stages earlier than the formation of Jupiter or other gas giants, rocky protoplanets grew in the gaseous disk and hydrogen-rich envelopes up to a few tens of an Earth-ocean equivalent amount could be accumulated during 1–3 Myr. Depending on the EUV flux, the active time of the system's host star and the efficiency of the expected EUV-powered hydrodynamic loss after the nebular gas was blown away, the protoplanets which formed the early Earth or other terrestrial planets may not completely lose these gaseous envelopes, so that the accreted planet could be surrounded by a hydrogen- and He-rich remnant of nebular gas.

A second protoatmosphere formation process is related to a catastrophically outgassed dense steam and CO_2-rich atmosphere from the magma ocean during its solidification (e.g., Elkins-Tanton 2008, 2011). Depending on the initial volatile inventories which can be accreted during impacts of planetesimals and embryos, and based on meteorite studies, a wide range of initial H_2O contents between 0.01–3 weight percent (wt%) in the bulk silicate of terrestrial planets can be expected (Jarosewich 1990; Elkins-Tanton 2011). The pressure gradient in the magma ocean of the accreted planet controls solidification and is related to its mass. Because the majority of the minerals that solidify from a bulk planetary magma composition are denser compared to the coexisting magma, the solidification process proceeds from the bottom upward to the surface, with increasing amounts of magma lying above solid silicate minerals (e.g., Solomatov 2000; Elkins-Tanton 2008, 2011). H_2O and CO_2 molecules can enter solidifying minerals only in small quantities (Elkins-Tanton 2008). As a result they will degas into early dense steam and CO_2-rich atmospheres (e.g., Liu 2004; Elkins-Tanton 2008).

If all the expected surface and upper mantle H_2O and CO_2 can be converted into a primitive atmosphere, a steam atmosphere with ~560 bar of H_2O and ~100 bar of CO_2 could build-up (Elkins-Tanton 2008). For higher initial volatile amounts, these models predict atmospheres with surface pressures from thousands up to several 10^4 bar which can result directly in supercritical H_2O. When the pressure reaches ~220 bar, the liquid and vapor densities are similar and become supercritical—an exotic environment where water exists in both liquid and gas form. For an Earth-like planet, surface temperatures near the supercritical point of H_2O can be reached during tens of Myr after the formation of a magma ocean. These timescales agree also with studies by several researchers who investigated the early stages of accretion and impacts and expect that thermal blanketing temperatures ≥1,500 K could keep the volatiles in vapour phase during several tens of Myr, or even up to 100 Myr (e.g., Hayashi et al. 1979; Mizuno et al. 1980; Matsui and Abe 1986; Zahnle et al. 1988; Abe 1997; Albarède and Blichert-Toft 2007). For "super-Earths" with dense steam atmospheres up to several 10^4 bar, this timescale may last hundreds of Myr (Elkins-Tanton 2008).

After the surface temperature of a young planet cools below a critical point of ~650 K, corresponding to a pressure of ~220 bar, the supercritical state steam atmosphere collapses into a liquid surface water ocean (Elkins-Tanton 2011). For Earth, initial magma ocean water inventories >>0.1 wt% were unlikely, because they would have implied initial atmosphere pressures of thousands of bars and times of cooling to clement surface conditions of hundreds of Myr (Elkins-Tanton 2008). Such long cooling times in combination with high surface pressures do not agree with the evidence for liquid H_2O on Earth's surface discovered in zircons ~4.4 Gyr ago (Valley et al. 2002). If Earth obtained slightly more material from water-rich planetesimals, its CO_2 content would have been much higher and the ocean would have been hundreds of kilometers deep. This would have resulted in a globally covered water world surrounded by a dense CO_2 atmosphere. The related greenhouse effect would have produced a hot evaporating upper ocean layer.

Thus, from the results of these studies we can conclude that a wide variety of initial atmospheres with different water and CO_2 contents could be possible. It can be crucial for the evolution of Earth-analogue habitats, even if these planets orbit within the HZs of their host stars, whether or not they lose their dense protoatmospheres. As a result they may end as water worlds with dense CO_2 atmospheres or hydrogen-rich sub-Uranus-type bodies such as Kepler-11b and Kepler-11f.

Outline and Study Aims

As discussed above, the aim of this work focuses on the early escape of nebular, or catastrophically outgassed hydrogen-rich, or steam and CO_2-rich atmospheres from Earth-type planets during the EUV-active phase of their host stars. In Section "The Role of the Radiation Environment of Young Stars on Atmospheric Evolution" we discuss briefly the role of the EUV radiation of young stars and its impact on hydrogen-dominated upper atmospheres. In Section "Hydrodynamic Escape of H Atoms from Primitive Atmospheres" we calculate the hydrogen loss from primitive atmospheres of Earth-like planets and estimate the possible dragging of O atoms by hydrodynamically outward flowing H atoms which can be produced from the dissociation of H_2O molecules. We discuss also stability problems for nitrogen atmospheres during the high EUV periods of the young stars. A method for testing atmospheric evolution hypotheses via future UV observations of transiting Earth-type exoplanets is presented in Section "Testing Atmospheric Evolution Scenarios by UV-Transit Follow-Up Observations".

The Role of the Radiation Environment of Young Stars on Atmospheric Evolution

The evolution of planetary atmospheres can only be studied together with the history of the host stars' activity (e.g., Lammer et al. 2008). The Xe isotope data provide evidence that Earth lost a huge amount of its early atmosphere during the first 100 Myr after the planet's origin (e.g., Pepin 1991; Ozima and Podosek 1999; Porcelli and Halliday 2001; Halliday 2003; Dauphas 2003). Due to the high EUV flux of the young Sun/star and frequent impacts, the H_2O molecules in the thermosphere are dissociated and H_2 and H atoms dominate the upper atmosphere as long as they are not lost due to a combination of thermal and nonthermal escape processes and giant impacts.

Depending on atmospheric composition and planetary mass, when the EUV flux in the wavelength range $\lambda \approx 2$–120 nm exceeds a critical value, the outward flow of the bulk upper thermosphere cools it due to adiabatic expansion (Tian et al. 2005, 2008). As it was shown by studies of Watson et al. (1981), Kasting and Pollack (1983) and Tian et al. (2005), for the EUV flux which is only a few times larger than that of the present Sun, the exobase of a hydrogen-rich upper atmosphere can expand several planetary radii above the planet's surface. Figure 1a shows the critical temperature T_c (e.g., Öpik 1963; Chamberlain 1963) for atomic hydrogen blow-off as a function of planetocentric distance, r, of the exobase

$$T_c = \frac{2m_H G M_{pl}}{3kr}, \tag{1}$$

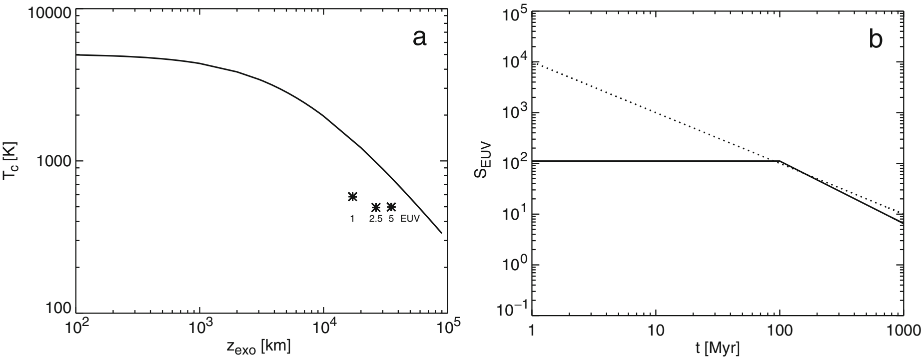

Fig. 1 **a** Critical temperature for hydrogen blow-off on Earth as a function of exobase distance. The symbols indicate the exobase levels for a hydrogen-rich thermosphere exposed to the present time solar EUV flux and enhanced fluxes which are 2.5 and 5 times larger (Tian et al. 2005). **b** *Solid line* shows the EUV-enhancement factor S_{EUV} as obtained from the detailed analysis of solar analogues with different ages (Güdel et al. 1997; Ribas et al. 2005). The *dotted line* shows the S_{EUV} factor as obtained by Zahnle and Walker (1982) from the scalings and extrapolations of solar and T-Tauri star's data

where m_H is the mass of a hydrogen atom, k is the Boltzmann constant, and M_{pl} is the planetary mass. The asterisk symbols mark the exobase levels for a hydrogen-rich thermosphere of Earth if it were exposed to a present, 2.5 and 5 times higher solar EUV flux. According to Tian et al. (2005), for a 5 times higher EUV flux than that of the present Sun, the exobase level which separates the collision dominated thermosphere from the collisionless exosphere moved up to $7R_{\mathrm{Earth}}$. Therefore, it can be expected that for EUV fluxes ~50–100 times (~4.3 Gyr ago) compared to today's Sun, blow-off of hydrogen could certainly occur. If a sufficiently high amount of IR-cooling molecules were absent from the thermosphere at such high EUV fluxes, even atomic oxygen would have reached, most likely the blow-off condition.

Observation-Based EUV-Enhancement Factors of Young Stars

In previous studies of the EUV-powered hydrodynamic escape of hydrogen from growing protoplanets and early steam atmospheres (e.g., Zahnle et al. 1988), an EUV flux enhancement approximation for the young Sun of $S_{\mathrm{EUV}} = 10^4/t_{\mathrm{Myr}}$ for $t_{\mathrm{Myr}} \geq 1$ Myr was applied for the time periods of 3–100 Myr after the Sun's origin. Their S_{EUV} enhancement factor was not based on observational data of solar analogue stars with different ages, but was a simple interpolation of the solar data and observations of a T-Tauri star (Zahnle and Walker 1982).

In the meantime, observations of solar analogue stars with different ages have revealed that the EUV flux is saturated at ~100 times of its mean present time value during the first 100 Myr (Güdel et al. 1997) and decreases after that period according to an empirical scaling law $S_{\mathrm{EUV}} = (t_{\mathrm{Gyr}}/t_{\mathrm{Sun[Gyr]}})^{-1.23}$ (Ribas et al. 2005; Güdel 2007). Figure 1b shows a comparison of the EUV-enhancement factor S_{EUV}, which was applied in the pioneering works of the EUV-powered hydrodynamic escape estimations by Zahnle et al. (1988), with that inferred from the detailed analysis of solar proxies (Ribas et al. 2005), by taking into account the EUV saturation phase during the first 100 Myr (Güdel et al. 1997). One can see that the S_{EUV} factor applied by Zahnle et al. (1988) overestimated the EUV flux of the young Sun during the first 100 Myr by up to two orders of magnitude. For time periods between present and 4.4 Gyr ago, both S_{EUV} factors have more or less similar values.

Hydrodynamic Escape of H Atoms from Primitive Atmospheres

Due to the high EUV flux of the young Sun or other stars, the H_2O molecules which populate the atmosphere of an early terrestrial planets are dissociated, and atomic and molecular hydrogen populate the upper atmosphere until they are lost to space. Photons in the EUV range are absorbed by the light hydrogen atoms and molecules which are uniquely suited to induce thermal escape. By applying the energy-limited[1] escape (ELE) formula (e.g., Hunten 1993), we can calculate the atmospheric loss rate

$$\frac{dM}{dt} = \frac{3\eta S_{\mathrm{EUV}} F_{\mathrm{EUV}}}{4G\rho_{\mathrm{pl}}}, \tag{2}$$

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[1] Energy limited means that the ratio of the net heating rate to the rate of stellar energy absorption is $\eta = 100\%$ that is all absorbed EUV energy is converted to heat.

with a heating efficiency η, the gravitational constant G, a mean planetary density ρ_{pl}, and the present time EUV flux F_{EUV} in the wavelength range ≈2–120 nm at 1 AU. Integrating Eq. 2 over time, we obtain the mass of atomic hydrogen lost from the atmosphere at time (t) due to hydrodynamic escape, which is shown in Fig. 2a. Zahnle et al. (1988) obtained an equivalent loss of hydrogen from early Earth during the protoplanetary stage up to the end of accretion, that is over ∼3–100 Myr, as ∼25 Earth oceans (EO). From atmospheric escape studies of hydrogen-rich "Hot Jupiters", it is known that the thermal mass loss rate, obtained from the energy-limited formula, underestimates atmospheric loss at a close orbital distance of the planet to its host star. This underestimation comes from the neglect of the stellar tidal loss at close orbital distances where the tidal effect is important. The accuracy of the loss calculations can be improved by using a realistic heating efficiency of ∼15% for the stellar EUV radiation and by including the effect of the stellar tidal force (the Roche lobe effect) in Eq. 2 (Erkaev et al. 2007; Penz et al. 2008; Lammer et al. 2009a, b; Leitzinger et al. 2011). Because the terrestrial planets considered here are located at larger orbital distances compared to "Hot Jupiters", we can neglect the Roche lobe effect, but have to introduce a realistic η. Lower values for η are also in agreement with previous studies, related to the loss of Venus' initial water inventory (Watson et al. 1981; Kasting and Pollack 1983; Chassefière 1996a), and a recent study by Murray-Clay et al. (2009) who modelled the EUV-driven mass loss from "Hot Jupiters" during the host star's early active phase and found that η changes with time. Murray-Clay et al. (2009) discovered that for high EUV fluxes, as expected during the first 100 Myr after the origin of a G-class host star, Lyman-α cooling of the thermosphere is important and η should be <20%. In this process Lyman-α radiation is emitted by atmospheric hydrogen atoms which are collisionally excited by electrons. Because we also need to know the escape efficiency of the EUV radiation during early periods of planets' evolution, we assume, in agreement with the before mentioned studies, that $\eta \sim 15\%$ and take the scaling EUV-enhancement factor, S_{EUV}, according to Ribas et al. (2005). As a result we obtain a much lower upper limit for the hydrogen loss which is equivalent to less than 7 EOs.

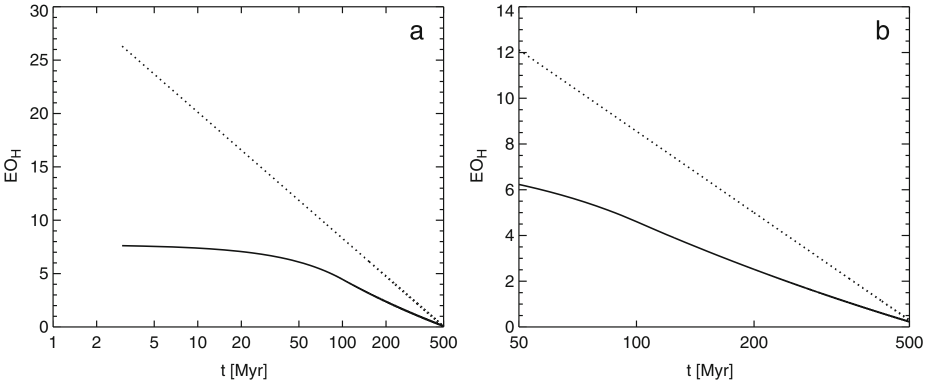

Fig. 2 Amount of atomic hydrogen in units of equivalent Earth Oceans (EOs) that can be lost **a** shortly after the origin of the Solar System, and **b** after the expected time period of ∼50 Myr when Earth finished its accretion, based on the two different EUV-enhancement factors (*dotted line*: Zahnle et al. (1988); *solid line*: Ribas et al. (2005))

From the much higher EUV flux, related to the S_{EUV} factor, and the energy-limited assumption of a heating efficiency of $\eta = 100\%$ applied by Zahnle et al. (1988), a considerably overestimated mass loss was obtained by those authors.

Moreover, the cooling effect of IR-radiating molecules such as H_3^+ and CO_2, as well as dragging of heavy species such as remaining oxygen atoms by the hydrogen outflow, would additionally reduce the escape rate of H (e.g., Zahnle et al. 1988; Kulikov et al. 2006).

Figure 2b shows the maximum amount of H atoms that could escape for a heating efficiency $\eta = 15\%$ in units of Earth's oceans (EOs), after the end of accretion of the Earth at ~50 Myr (Allègre et al. 1995; Touboul et al. 2007), during 450 Myr for both EUV-enhancement factors shown in Fig. 1. Here the solid line corresponds to the hydrogen content of ~6 EOs and the dotted line to ~12 EOs, based on the EUV-enhancement factors of Ribas et al. (2005) and Zahnle et al. (1988), respectively. From our loss estimates one can see that the S_{EUV} factor used by Zahnle et al. (1988) overestimates hydrogen loss by about ~6 EOs. It should be kept in mind that our loss estimates are very conservative, because the protoplanet started to lose its atmosphere before its accretion had finished. It is expected that about 80% of Earth's mass was accreted at ~20 Myr, and ~90% at ~30 Myr after the origin of the Sun (Zahnle et al. 1988). If a terrestrial planet had acquired a water dominated atmosphere after its accretion, more than 1,600 bar of its hydrogen fraction could not have escaped completely during the EUV-active phase of a solar-like G star and a dense hydrogen atmosphere might have remained after the active phase ended. Furthermore, if the EUV-powered hydrogen blow-off were efficient enough, so that the hydrogen content of several EOs could have escaped from the planet, then a huge amount of abiotic oxygen should have accumulated in the atmosphere.

Hydrodynamic Escape of Dragged O Atoms

The problem arising from large amounts of oxygen that could be accumulated during a strong escape of hydrogen from H_2O-rich primitive atmospheres, was first addressed by Kasting (1995). Stimulated by this argument, Chassefière (1996b) investigated the hydrodynamic loss of oxygen from primitive atmospheres of Venus and Mars in more detail. However, the study by Chassefière (1996b) is based on terrestrial planet formation models in which the time of the end of accretion for Earth and Venus was assumed to be ~100 Myr after the formation of the Sun (Wetherill 1986). At that time the EUV saturation phase of the young Sun ended and the S_{EUV} factor decreased according to the S_{EUV} power laws discussed before and shown in Fig. 1b. As discussed in Section "Terrestrial Planet Formation, Giant Impacts and Their Influence on Early Atmospheres", based on W isotope studies in lunar metals, it is now expected that the Earth, most likely, finished its accretion ~50 Myr after the Sun's origin and obtained ~80–90% of its present mass even ~30 Myr earlier (e.g., Quingzhu et al. 2002; Touboul et al. 2007). These data indicate that the Earth finished its formation several tens of Myr earlier than it was assumed in previous atmospheric escape studies.

Moreover, in the study by Chassefière (1996b), the cooling phase of the magma ocean was expected to last longer than 100 Myr, while more recent studies indicate that solidification of a magma ocean with a depth of ~2,000 km is a rapid processes and mantle solidification of ~98% can be completed in ≤5 Myr (e.g. Elkins-

Tanton 2008, 2011). The assumption of long formation timescales resulted in ages when the EUV flux of the young Sun was much lower than that during the EUV saturation phase. While Kasting and Pollack (1983) studied the hydrodynamic escape of hydrogen and water from early Venus assuming the EUV flux values which can be compared to that of the present Sun, Chassefière (1996b) applied a maximum S_{EUV} factor of ~25 times higher than that of the present Sun. However, as it follows from the detailed analysis of solar analogue stars (Güdel et al. 1997; Ribas et al. 2005), from the evidence for faster planetary formation (e.g., Quingzhu et al. 2002; Touboul et al. 2007) and shorter nebular evaporation times (e.g., Najita et al. 2007; Lunine et al. 2011), the accreted or nearly accreted terrestrial planets in the Solar System were, most likely, exposed during the first ~50–70 Myr to an EUV flux which was ~100 times than today. Because of the different initial parameter values which were assumed in the previous studies by Kasting and Pollack (1983) and Chassefière (1996b), and the complex links between various astrophysical, geophysical and aeronomic factors, it is difficult to comment on the overall accuracy of these early results. And it is certainly beyond the scope of this study to reinvestigate the pioneering works of Kasting and Pollack (1983), Zahnle and Kasting (1986), Zahnle et al. (1988) and Chassefière (1996a, b). However, it would be instructive to analyze roughly the expected evolution of an early outgassed steam atmosphere of Earth since the time when the planet ended its accretion, which should have probably occurred during the EUV-saturated phase of the young Sun.

In an atmosphere dominated by water vapour, the H_2O molecules should be dissociated by the EUV and X-rays, as well as by frequent meteorite impacts in the lower thermosphere (Chassefière 1996b). Therefore, it is likely that O atoms are a major form of oxygen which can be dragged to space by the outward flowing hydrogen flux F_{H}, according to the formula given by Hunten et al. (1987)

$$F_{\mathrm{O}} = \frac{X_{\mathrm{O}}}{X_{\mathrm{H}}} F_{\mathrm{H}} \left[\frac{\left(m_{\mathrm{H}} + \frac{kTF_{\mathrm{H}}}{bgX_{\mathrm{H}}} \right) - m_{\mathrm{O}}}{\left(m_{\mathrm{H}} + \frac{kTF_{\mathrm{H}}}{bgX_{\mathrm{H}}} \right) - m_{\mathrm{H}}} \right] = \frac{X_{\mathrm{O}}}{X_{\mathrm{H}}} F_{\mathrm{H}} f, \qquad (3)$$

with the escaping flux, F_{O}, of atomic oxygen; the mole mixing ratios, X_{H} and X_{O}; their masses, m_{H} and m_{O}; a molecular binary diffusion parameter, b for O atoms in hydrogen gas given by Zahnle and Kasting (1986); gravity acceleration, g; Boltzmann constant, k; and an average upper atmosphere temperature, T, which can be assumed for hydrogen under such conditions in the order of ~500 K (Zahnle and Kasting 1986; Chassefière 1996b). There are basically two conditions for Eq. 3 to be valid (Zahnle and Kasting 1986; Chassefière 1996b). The first condition requires that the mass of the dragged particle (O) is much larger compared to the mass of the main gas particle (H) that is evidently satisfied. The second condition is linked to the isothermal assumption of Hunten et al. (1987) that the fractionation factor, f is $> m_{\mathrm{H}}/m_{\mathrm{O}}$, which in our case is also valid (Chassefière 1996b). In our rough estimations we assume that dragging of O atoms becomes negligible when their number density reaches that of hydrogen.

Figure 3a shows the loss in time of an initial 500 bar (~2 EOs) steam atmosphere calculated by assuming a heating efficiency $\eta = 15\%$ and S_{EUV} of ~100 during the saturation phase of the young Sun. Here it is also assumed that the atmosphere near the surface and the surface itself have reached the critical temperature of ~650 K, at which the remaining amount of ~1EO of the H_2O-vapour has condensed and

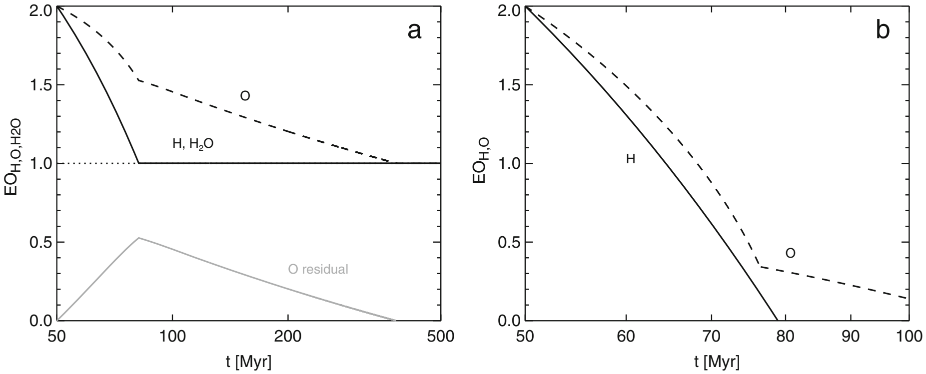

Fig. 3 **a** A likely loss scenario for an outgassed 500 bar (∼2 EOs) steam atmosphere from early Earth which ended its accretion at ∼50 Myr. The *solid line* shows the escape of hydrogen content from the initially outgassed H_2O atmosphere until the equivalent amount of 1EO is reached. The *dashed line* corresponds to the dragged O atoms which accumulate to a residual fraction of a corresponding amount of ∼0.5EO when the H blow-off stops ∼25 Myr after the atmosphere outgassing due to the formation of Earth's ocean. The remaining O atoms escape during the following ≥150 Myr of the high activity phase of the young Sun. **b** A similar loss scenario, but at Venus' orbit at 0.7 AU where thermal blanketing and higher and increasing bolometric luminosity of the young Sun inhibits formation of a liquid ocean due to higher surface temperature (Matsui and Abe 1986). In such an environment an upper limit of ∼2 EOs of H_2O vapour can be lost during the EUV saturation phase of the young Sun/star

collapsed into the liquid water ocean. One should note that this is a rough assumption and some additional amount of water could have been delivered by later impacts too. However, the bulk of early Earth's initial water inventory, most likely could have been produced by condensation of a fraction of the outgassed steam atmosphere. Under these assumptions, the hydrogen fraction would be lost during ∼25 Myr after the atmosphere's origin until the ocean was formed, but an equivalent amount of ∼0.5 EO of accumulated oxygen atmosphere would remain. If these accumulated oxygen atoms populated the upper atmosphere, they might also have experienced blow-off and strong nonthermal escape during the following ≥150 Myr, when the solar EUV flux was ∼50–100 times higher than today. It should be noted that a fraction of ≤30% of atmosphere could have also been lost during the Moon-forming impact (e.g., Genda and Abe 2003).

Thus, from our estimations, in agreement with Elkins-Tanton (2008, 2011), we can draw two interesting conclusions. First, it appears that the early Earth might not have acquired a dense steam atmosphere, with a surface pressure much more than ∼500 bar, because higher water vapour amounts would, most likely produce a large remaining oxygen atmosphere. And second, if the Earth's surface temperature and pressure reached the proper conditions for H_2O condensation (∼650 K, ∼250 bar) and atmospheric water collapsed into the Earth's ocean around ∼25–30 Myr after the atmosphere formation, the accumulated oxygen in an amount of ≤0.5 EOs could have been lost during the next hundreds of Myr. So, if the early Earth accumulated much higher amounts of oxygen, or formed its liquid ocean after the EUV saturation phase, then due to the decreased solar EUV flux there might have been a problem in losing its dense abiotic oxygen atmosphere.

Figure 3b shows the loss of ~500 bar of water from an Earth-like planet of a Sun-type star in Venus' orbit. One can see that in such a scenario, the Earth-like planet would have lost a hydrogen amount contained in 2 EOs during ~25 Myr, leaving behind an oxygen content of ~0.4 EOs. By assuming that the remaining O atoms also experienced blow-off during the high EUV activity phase of the young Sun, atomic oxygen would be lost ~30 Myr later. If due to high CO_2 density, the lower thermosphere was efficiently cooled down to a level, below which oxygen blow-off was inhibited, the remaining several tens of bar of O could have been lost by nonthermal escape processes (Kulikov et al. 2006).

If the outgassed steam atmosphere had a higher surface pressure than ~500 bar, the planet might have had a problem in losing its dense hydrogen and oxygen envelopes. Figure 4 shows the loss in time of hydrogen and oxygen from an initially outgassed 10^3 bar steam atmosphere during the EUV saturation phase of the young Sun, or a similar G-type star. In such a case, an Earth-mass planet would retain more than 2.3 EOs of hydrogen and more than 3.2 EOs of oxygen. It is very unlikely that such a huge amount of oxygen could have been lost due to solar wind produced O^+ ion erosion or another nonthermal atmospheric escape process. So, our rough estimates agree with the suggestion of Kasting (1995) and Chassefière (1996a, b) that there may be planets, depending on their size, mass, orbital distance, as well as their host star's EUV flux evolution, which could accumulate huge amount of abiotic oxygen. Thus, "super-Earths" which might have outgassed steam atmospheres of several 10^3 to several 10^4 bar surface pressure (Elkins-Tanton 2011) can be good candidates for worlds with dense abiotic oxygen atmospheres.

EUV-Driven Loss and a Stability Problem for Earth-Like N_2-Rich Atmospheres

Another problem related to the evolution of early Earth's atmosphere is that its nitrogen inventory should have been protected from atmospheric loss during the first hundreds of Myr after the Earth's formation. Similar to hydrogen-rich thermosheres, an N_2-dominated thermosphere of the early Earth would also experience a rapid transition to a hydrodynamic expansion regime if it were exposed to sufficiently high EUV radiation. When the EUV flux reaches ≥7 times the flux of the present Sun, the exobase temperature will exceed 7000–8000 K (Tian et al. 2008). In such a case,

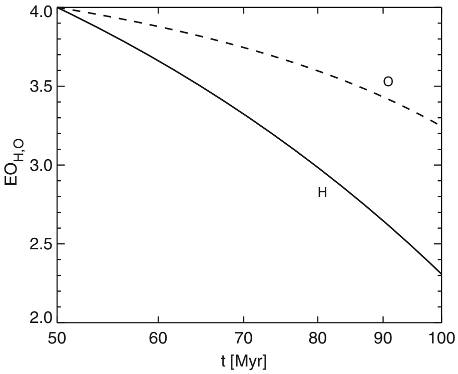

Fig. 4 Escape and accumulation of H and O atoms in EOs from a 10^3 bar (~4 EO) outgassed steam atmosphere at a 50 Myr old Earth-like planet during the EUV saturation phase of a solar-like G-type star

Table 1 Escape of a N_2-rich Earth-like atmosphere from a planet with the size and mass of the Earth in units of bar as a function of solar/stellar EUV flux and wind exposure time Δt, for a weak wind with corresponding values as at present Earth Δt^{w} in 1 AU and a wind Δt^{st} which is assumed to be ~30 times denser (Lichtenegger et al. 2010)

EUV	t_{Earth} [Myr]	$\Delta t^{w} = 10$ Myr	$\Delta t^{w} = 100$ Myr	$\Delta t^{st} = 10$ Myr	$\Delta t^{st} = 100$ Myr
20	350	1 bar	10 bar	5 bar	50 bar
10	650	0.4 bar	4 bar	3 bar	30 bar
7	850	0.2 bar	2 bar	1 bar	10 bar

the exobase will move above the present average subsolar magnetopause stand-off distance of ~10 R_{Earth}, so that the neutral constituents beyond the magnetopause can be ionized and picked up by the solar wind. This mechanism is capable to erode a 1 bar N_2 atmosphere during 10 Myr (see Table 1) (Lundin et al. 2007; Lichtenegger et al. 2010).

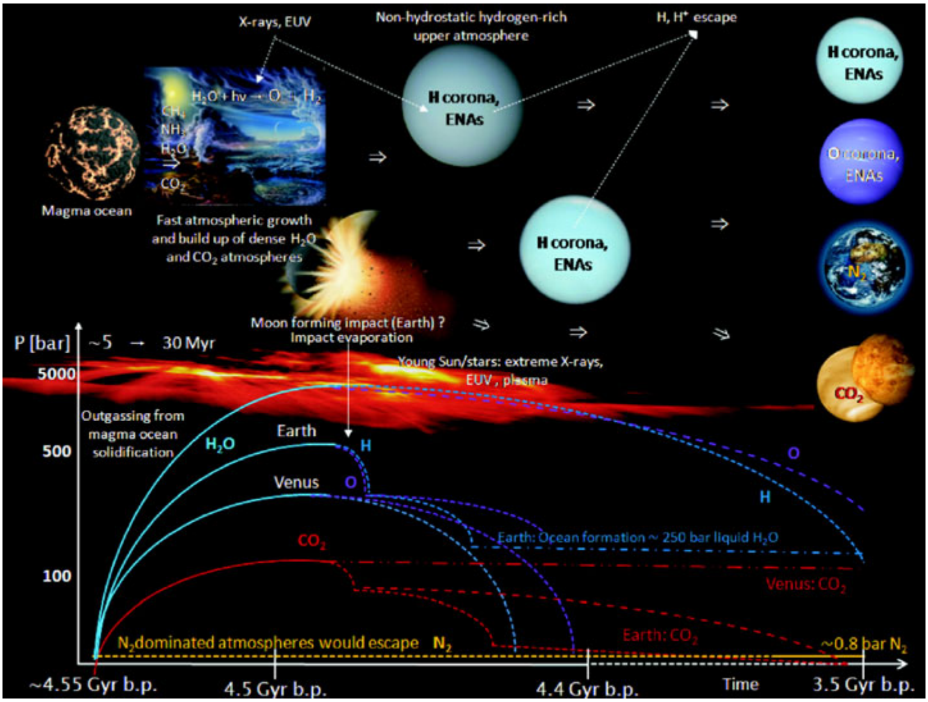

Fig. 5 Atmosphere evolution scenarios for Earth-type planets after outgassing of volatiles and fast growth of dense steam and CO_2-rich atmospheres (e.g., Elkins-Tanton 2008, 2011). A complex interplay between the young star's EUV activity, atmospheric escape processes, large impacts and weathering of CO_2 into carbonates during the first 500 Myr resulted in the formation of Earth's 0.8 bar N_2-rich atmosphere ~3.5–4 Gyr ago (Kempe and Degens 1985; Kasting et al. 1984). If the outgassed amount of water vapour was too large, the oxygen fraction of the H_2O might be lost only partially and an abiotic oxygen-rich atmosphere could accumulate (Chassefière 1996a, b). Earth-like N_2-dominated atmospheres on early terrestrial planets were not stable against EUV-induced atmospheric expansion and nonthermal escape when the EUV flux was ≥7 times that of the present solar value (Lichtenegger et al. 2010)

A higher amount of CO_2 if it were present in the atmosphere between ~3.8–4.3 Gyr ago, might have confined the upper atmosphere within the shielding magnetosphere and thus could have protected Earth's N_2 inventory from escape. However, model simulations show that an Earth-like planet, with even a 95% CO_2 atmosphere, should have experienced problems related to atmospheric escape during the first ~200–300 Myr after the Sun arrived at the ZAMS, when the EUV flux reached a value ≥30 times that of the present Sun (Tian 2009; Lichtenegger et al. 2010).

Moreover, depending on the alkalinity of the early ocean water, CO_2 might be weathered efficiently as $CaCO_3$, so that a substantial amount of CO_2 from the primitive atmosphere could have been removed within a short geological time period (Kempe and Degens 1985). In such a scenario the nitrogen inventory should have escaped to space efficiently (Lichtenegger et al. 2010), but as we know, nitrogen remained.

Because the Earth's atmosphere is not enriched in ^{15}N compared to the solar $^{15}N/^{14}N$ ratio, one can expect that its initial N_2 inventory has remained unchanged until today. Based on observed similarities of isotopic fractionation in Earth's and Titan's atmospheres, some researchers argue that the late heavy bombardment ~3.8 Gyr ago might have enriched Earth's volatile content, including the N_2 inventory (Trigo-Rodriguez and Martin-Torres 2012).

To overcome this problem we may assume that a dense and extended hydrogen, or accumulated oxygen envelope, which might be a remnant of the initially outgassed huge H_2O inventory and which could have survived, or was formed after the Moon-forming impact, could have also acted as a protecting shield against the loss of heavier atmospheric specie such as the Earth's initial N_2 inventory. However, if early Earth's N_2 inventory was indeed protected by such envelopes, such remnant gases should have been lost until today. Figure 5 summarizes in an illustration the expected atmosphere evolution scenarios for early Earth, Venus and other terrestrial planets.

Testing Atmospheric Evolution Scenarios by UV-Transit Follow-Up Observations

The detection of EUV heated, extended, non-hydrostatic upper atmospheres around terrestrial exoplanets would constrain the uncertainties related to the issues addressed in the previous sections. Since the discoveries of several "super-Earths", the search for terrestrial exoplanets within HZs of low mass M stars has become feasible. As discussed in the previous sections, we can expect that an upper planetary atmosphere will expand to several planetary radii if no effective cooling by IR-radiating molecules is available when a planet is exposed to a several times higher EUV flux than that of the present Sun. As illustrated in Fig. 6, in such a case, the upper atmosphere would expand beyond a magnetopause distance and energetic neutral atoms (ENAs) would be produced by charge exchange collisions between neutral atmospheric and charged particles of the planet's host star stellar wind.

If we could observe extended upper atmospheres and related ENA clouds around Earth-type exoplanets, then we would obtain information about the stellar wind plasma properties, the upper atmosphere structure, non-thermal ion escape, and planet's magnetic or non-magnetic obstacle. For the simulation of the ENA production, one can apply plasma flow models or particle flow models in combination with upper atmosphere and exosphere models (Holmström et al. 2008; Ekenbäck et al.

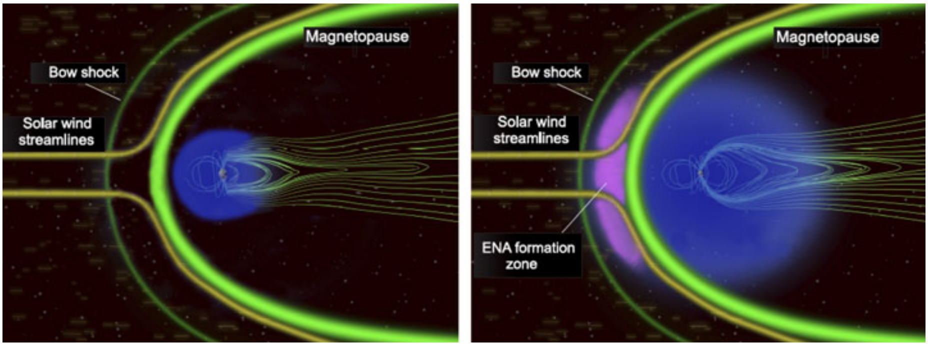

Fig. 6 *Left* A hydrostatic atmosphere like that of the present Earth which is protected by its magnetosphere. *Right* An illustration of an EUV heated upper atmosphere, which extends above the magnetopause, so that energetic neutral atoms (ENAs) can be produced in charge exchange collisions between stellar wind protons and the extended upper neutral atmosphere

2010; Lammer et al. 2011a). For illustrating expected stellar wind interaction with a hydrogen-rich upper atmosphere of an Earth-size exoplanet, which is exposed to a 5 times higher EUV flux compared to the modern Sun, we applied, as Ekenbäck et al.

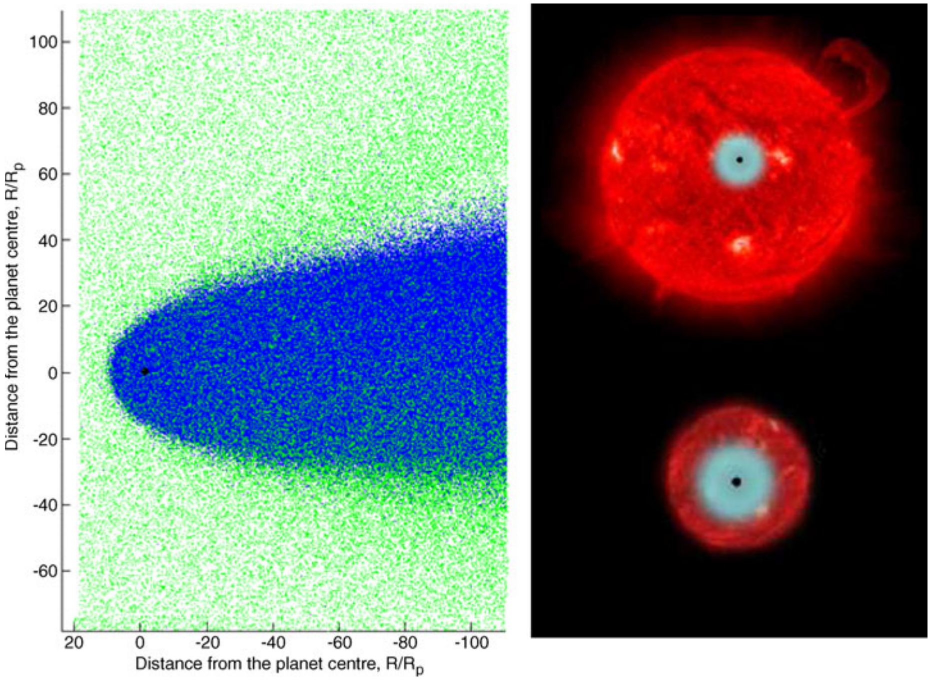

Fig. 7 Preliminary model simulation of an expanded hydrogen-rich thermosphere of $7R_{\mathrm{Earth}}$ and related hydrogen corona which contains outward flowing planetary hydrogen atoms and stellar wind produced hydrogen ENAs around an Earth-like planet, orbiting an M-star within its habitable zone at 0.16 AU . The *dark circle* corresponds to the size of the planet, x-axis points towards the star. *Right* Illustration of possible size relations of terrestrial exoplanets with extended hydrogen coronae around M-dwarfs (after Lammer et al. 2011b)

(2010) and Lammer et al. (2011a, b), a direct simulation Monte Carlo code, which is coupled with a stellar wind plasma flow model, and obtained the preliminary results shown in Fig. 7. In this case the exobase level expands to about $7R_{\text{Earth}}$. We exposed the huge planetary hydrogen corona to a stellar wind with a moderate density of ~500 cm^{-3} and a velocity of 300 km s^{-1}. Such plasma parameters can be expected within the HZs of active M-type stars. Terrestrial planets around M-stars can be promising candidates for such observations, because most of them remain active in the EUV range much longer than Sun-like G-stars and their HZs are located at closer orbital distances. Also, one can expect dense plasma environments comparable to the early solar wind (Lammer et al. 2011b).

After the discovery of a terrestrial exoplanet transit, follow-up observations within the Lyman-α range for the detection of emission/absorption caused by extended hydrogen and ENA clouds with the upcoming World Space Observatory-UV (WSO-UV) could be performed. The WSO-UV is a Russian-led international space telescope project, devoted to high resolution UV spectroscopy and imaging, which is included in the Federal Space Program of the Russian Federation with a foreseen launch date around 2014–2015 (Shustov et al. 2009). The confirmation of an observation of a hydrogen coronae and/or ENA clouds in Lyman-α during the transit of a rocky exoplanet would indicate that its upper atmosphere is in a non-hydrostatic regime. Such observations which can be expected to be performed in the not so distant future, will have an important impact on our understanding of the evolution of terrestrial planetary atmospheres, including those of early Venus, Earth and Mars.

Conclusion

Studies related to the origin of protoatmospheres of terrestrial planets indicate that a dense steam and CO_2-rich atmosphere, with a surface pressure from ~10^2 to 10^4 bars, equivalent to an amount of hydrogen contained in ~0.4–40 Earth oceans, can be outgassed during the magma ocean solidification process. This outgassed protoatmosphere would be added to a possibly accumulated nebular-based hydrogen envelope which might remain from the earlier stage of the planet formation. If the atmospheric escape processes or giant impacts cannot remove these initial hydrogen and water inventories, a terrestrial planet will accumulate a dense abiotic oxygen-rich atmosphere, or otherwise it will become a sub-Uranus type body, even within the habitable zone of its host star. On the other hand, if a terrestrial planet's atmosphere evolved during the high EUV phase of its young host star to a nitrogen-rich, Earth-like atmosphere too early, then all of its nitrogen inventory might have been lost. This indicates that the nitrogen-inventory of the Earth might have been protected from escape by a higher amount of IR-cooling CO_2 in the thermosphere, or by a dense hydrogen or oxygen envelope. If the initially outgassed water inventory of an early Earth were much larger than ~500 bar, and the Moon-forming impact did not remove a part of it, the Earth might have accumulated an abiotic oxygen-rich atmosphere or evolved to a "water world" with no continents and an H_2O and CO_2 atmosphere surrounded by an atomic hydrogen envelope. If the Earth originated dryer, the young Sun might have been active enough to remove the less dense initial atmosphere and the planet might have ended up with a present-day Venus- or Mars-like CO_2 atmosphere. Hence it follows that the Earth-like planets within

HZs of less active F-stars might have a problem to lose their initially dense outgassed protoatmospheres, while the planets orbiting more active, lower mass stars (K- and M-type) might have lost their atmospheres more easily during their lifetimes. More massive "super-Earths" which outgassed, most likely very dense steam and CO_2-rich atmospheres, may be good candidates for accumulating during their life times abiotic oxygen-rich upper atmospheres.

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