R. Dvorak and S. Ferraz-Mello (eds.), A Comparison of the Dynamical
Evolution of Planetary Systems (2005) 273–285
DOI 10.1007/s10569-005-0004-4

STELLAR-PLANETARY RELATIONS: ATMOSPHERIC STABILITY AS A PREREQUISITE FOR PLANETARY HABITABILITY

H. LAMMER[1], YU. N. KULIKOV[2], T. PENZ[1], M. LEITNER[1],
H. K. BIERNAT[1] and N. V. ERKAEV[3]

[1] *Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, A-8042 Graz, Austria, e-mails: {helmut.lammer, thomas.penz, helfried.biernat, martin.leitner}@oeaw.ac.at*

[2] *Polar Geophysical Institute, Russian Academy of Sciences, Khalturina Str. 15, Murmansk, 183010, Russian Federation, e-mail: kulikov@pgi.ru*

[3] *Institute for Computational Modelling, Russian Academy of Sciences, 660036 Krasnoyarsk 36, Russian Federation, e-mail: erkaev@icm.krasn.ru*

Abstract. The region around a star where a life-supporting biosphere can evolve is the so-called Habitable Zone (HZ). The current definition of the HZ is based only on the mass-luminosity relation of the star and climatological and meteorological considerations of Earth-like planets, but neglects atmospheric loss processes due to the interaction with the stellar radiation and particle environment. From the knowledge of the planets in the Solar System, we know that planets can only evolve into a habitable world if they have a stable orbit around its host star and if they keep the atmosphere and water inventory during: (i) the period of heavy bombardment by asteroids and comets and (ii) during the host stars' active X-ray and extreme ultraviolet (XUV) and stellar wind periods. Impacts play a minor role for planets with the size and mass like Earth, while high XUV fluxes and strong stellar winds during the active periods of the young host star can destroy the atmospheres and water inventories. We show that XUV produced temperatures in the upper atmospheres of Earth-like planets can lead to hydrodynamic "blow off", resulting in the total loss of the planets water inventory and atmosphere, even if their orbits lie inside the HZ. Further, our study indicates that Earth-like planets inside the HZ of low mass stars may not develop an atmosphere, because at orbital distances closer than 0.3 AU, their atmospheres are highly affected by strong stellar winds and coronal mass ejections (CME's). Our study suggests that planetary magnetospheres will not protect the atmosphere of such planets, because the strong stellar wind of the young star can compress the magnetopause to the atmospheric obstacle. Moreover, planets inside close-in HZ's are tidally locked, therefore, their magnetic moments are weaker than those of an Earth-like planet at 1 AU. Our results indicate that Earth-like planets in orbits of low mass stars may not develop stable biospheres. From this point of view, a HZ, where higher life forms like on Earth may evolve is possibly restricted to higher mass K stars and G stars.

Key words: Atmospheric erosion, Atmospheric XUV heating, Stellar radiation, Stellar wind, Water loss

1. Introduction

An important requirement for the evolution of a biosphere is the orbital long-term stability of a terrestrial planet moving in the Habitable Zone (HZ) of its host star (Dvorak et al., 2003; Menou and Tabachnik, 2003). The circumstellar HZ was defined and delimited by Kasting et al. (1993) based on the consideration of a planet with the size and mass comparable to Earth, containing large H_2O and CO_2 reservoirs, at an orbital distance where the atmospheric CO_2 is able to sustain stable liquid H_2O at the planetary surface. If the planet orbit is below a critical distance, the planet would experience a so-called *runaway greenhouse effect*: the vaporized H_2O starts to increase the surface warming and thus enhance the evaporation in a positive feedback (Kasting, 1988).

This results in a H_2O-rich atmosphere that keeps the surface temperature at high level, in which H_2O vapor reaches the high altitudes of the atmosphere, where it is photolyzed. Within a period of the order of 10–100 Myr, the planet loses the hydrogen to space and becomes dry. At the outer border of the HZ, an increase of the CO_2 pressure results in a surface cooling more than heating, due to enhanced Rayleigh back-scattering of the incoming stellar radiation to space. With this definition, the HZ only depends on the luminosity of the star and the surface temperature which is assumed to be stabilized above 0° Celsius through the carbon-silicate cycle.

The range of the HZ is slightly larger for planets that are larger than Earth and for exoplanets, which have higher N_2 partial pressures. The HZ moves to greater orbital distances with time because the star's luminosity increases as it ages. The HZ of F-type stars is larger and may reach orbital distances between 1 and 2.5 AU, while the HZ of K and M dwarf stars is smaller and occurs closer to the star.

Recently, Menou and Tabachnik (2003) investigated 85 detected exoplanetary systems concerning the possibility of harboring "hypothetical" terrestrial planets in the HZ of their host stars. For the global statistics they classified these systems according to the remaining habitable test bodies after an integration time of one Myr and found that about 25% of the investigated systems have a high probability of hosting terrestrial planets in their HZ. These systems are mostly those with relatively close giant planets moving on nearly circular orbits. Another 25% may allow additional terrestrial planets, but the probability is not very high. The remaining 50% are very unlikely for hosting additional planets, due to the strong perturbations of the giant planets in these systems.

The current simplified definition of the HZ and the estimation of its inner and outer boundaries (Kasting et al., 1993) are useful but several uncertainties still need to be discussed. Indeed, if a planet has a stable orbit within the HZ, this condition is far from being sufficient that an Earth-like biosphere may develop. The HZ of low mass K stars and M stars are in orbital distances, where the planets are tidally locked, which can result in hostile climate effects, where the whole atmosphere can snow out on the planets nightside (Joshi, 2003). Furthermore, due to the slow rotation tidally locked Earth-like planets shall have weak magnetic dynamos resulting in weak intrinsic magnetic moments and magnetospheres which can not protect the planet from atmospheric erosion processes by the stellar wind (Griessmeier et al., 2004). Because planets inside the HZ of M and the majority of K stars are tidally locked, plate tectonics may not develop and super-volcanoes like on Venus (big hot spot volcanoes) may frustrate life periodically or destroy the long-time habitability of the planet (Courtillot, 2002).

However, we will focus in this work only on problems related to aeronomy and long-time stability of planetary atmospheres, which can affect the atmospheres of terrestrial planets inside stable orbits of close-in HZ's of low mass stars. The HZ of low mass stars (late K and M: the large majority of stars) are exposed to strong X-ray and extreme ultraviolet (XUV) irradiation (λ: 1–1000 Å) and with a high probability, to strong stellar winds as well (e.g. Wood et al., 2002; Lammer et al., 2003a,b). We show that this radiation and particle exposure can make the atmosphere of an Earth-size planet unstable, can destroy the planets water inventory and may also limit the range of the currently defined HZ.

We review the latest results on observations of the evolution of the radiation environment of solar-like stars in Section 1. In Section 2, we present the effects of thermospheric heating on an Earth-like planet due to XUV radiation and discuss the implications for an evolving biosphere. In Section 3, we describe observational evidence of strong mass loss of young solar-like G and K-type stars and use empirical correlations of stellar mass loss rates with X-ray surface flux values to estimate the stellar winds of young stars. The obtained stellar wind fluxes are used in Section 4 for the estimation of atmospheric erosion on Earth-size exoplanets in orbits of close-in HZ's. Further, we discuss the effects of coronal mass ejection[1] (CME) from the host stars on the atmospheric environments of hypothetical Earth-like planets in orbital distances $\leqslant 0.1$ AU and discuss the implications for the search of habitable terrestrial exoplanets.

---

[1] Coronal mass ejections or CME's are huge bubbles of gas threaded with magnetic field lines that are ejected from the Sun over the course of several hours.

2. The XUV Radiation Environment of Solar-like Stars

Because the escape of atmospheric constituents in planetary atmospheres depends on the evolution of the stellar XUV radiation ($\lambda \leqslant 1000$ Å), which affects the thermosphere[2] and exosphere[3] temperature, the evolution of planetary atmospheres must be understood within the context of the evolving stellar energy and particle fluxes.

The relevant wavelengths for the heating of upper atmospheres of planets are the ionizing ones less than 1000 Å (e.g. Bauer and Lammer, 2004; Lammer et al., 2004), which contain only a small fraction of the stellar spectral power. The wavelength range with an energy flux of $\geqslant 2\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ represents the predominant XUV heat source for the upper atmosphere of an Earth-like planet.

Astrophysical observations, obtained with the ASCA, ROSAT, EUVE, FUSE and IUE satellites, show that coronal XUV emissions of young main-sequence G-type stars are about 100–1000 times stronger than those of the 4.5 Gyr old Sun. The resulting relative XUV fluxes yield an excellent correlation between the emitted flux and stellar age. In the 1000–1 Å interval, the fluxes follow a power-law (Lammer et al., 2003a,b; Ribas et al., 2005), which is valid for solar like G-type stars of ages between 0.1–7 Gyr. One finds fluxes of about six times the present XUV flux about 3.5 Gyr ago, and about 100 the present XUV flux 100 Myr after a G-type star arrived on the Zero-Age-Main-Sequence (ZAMS). The total X-ray flux of stars with different age and rotation period shows also a decreasing behavior with time (Guedel et al., 1997).

For an initial estimation of the evolution of XUV irradiances on stars with lower masses like K and M stars one can use as a proxy indicator, the ratio of the X-ray luminosity L_{X} to the bolometric luminosity L_{bol}. This ratio is highest for the more active stars with the shortest rotation periods and decrease monotonically with decreasing level of chromospheric activity (Pizzolato et al., 2003).

With the same underlying physical mechanism responsible for XUV emissions and a supposedly similar spectral energy distribution, it is reasonable to assume that stars with similar values of $\log(L_{\mathrm{X}}/L_{\mathrm{bol}})$ will also have similar $\log(L_{\mathrm{XUV}}/L_{\mathrm{bol}})$ (i.e., $1\,\text{Å} < \lambda < 1000$ Å).

---

[2] Thermosphere: the region in the upper atmosphere where the stellar XUV radiation is absorbed and in part used for atmospheric heating (Bauer and Lammer, 2004).

[3] Exosphere: the outermost atmospheric layer where no collisions between atmospheric particles take place and light atoms with energies higher than the escape energy can be lost thermally from the planet (Bauer and Lammer, 2004).

Recent studies of K type stars show that they stay at saturated emission levels of about 100 times the present solar XUV flux for a little longer time and then also decrease following a power–law relationship of a very similar slope. Interestingly, M0–M5 stars seem to have saturated emission levels up to 1 Gyr and possibly longer and then decrease in an analogous way to G and K stars (Ribas et al., 2005). These preliminary results indicate that early K stars and early M-type stars may have XUV irradiances that are about 3–4 times and about 10–100 times higher, respectively, than solar-type stars of the same age. More accurate investigations are currently being carried out with an extended sample and a large variety of observational data (Ribas et al., 2005).

3. Atmospheric Blow off Due to XUV Heating

The critical phase if a water-bearing terrestrial planet, at a dynamically stable orbit inside the HZ, can evolve a biosphere, is its survival during the early period of the high XUV flux of the young host star. As discussed before, the energy budget of the upper atmosphere of Earth-like planets is primarily governed by the heating of the gas due to the absorbtion of the XUV radiation by the atmospheric species, by heat transport due to conduction and convection and by heat loss due to emissions in the infrared (IR) (e.g. Bauer and Lammer, 2004).

One can summarize the important heating and cooling processes in the upper atmosphere of the Earth due to the N_2, O_2, and O photo-ionization, photo-dissociation of O_2 and O_3 molecules, chemical heating in exothermic reactions with O and O_3 and neutral gas heat conduction (e.g. Gordiets et al., 1982). Radiative loss by IR occurs when atmospheric constituents are present which have transition levels in the IR. This is the case for atomic oxygen in the terrestrial atmosphere and NO, CO, CO_2, OH, O_3, etc. in other planetary atmospheres.

The effective heat production Q_{XUV} in the upper atmosphere of an Earth-like planet is balanced by the divergence of a conductive heat flux in the thermosphere due to the incoming XUV radiation and the heat energy L_{IR} lost by emitted IR radiation per unit volume

$$\rho c_v \left[\frac{\partial T}{\partial t} + \vec{v}_n \cdot \vec{\nabla} T \right] + p \vec{\nabla} \cdot \vec{v}_n - \vec{\nabla} \cdot (K_n \vec{\nabla} T) = Q_{XUV} - L_{IR}, \tag{1}$$

where ρ is the atmospheric mass density, c_v the corresponding specific heat at constant volume, $\vec{v}_n$ the velocity and p the pressure of the neutral atmosphere and K_n is the thermal conductivity. A simplification in the one-dimensional case (vertical variability z only) can be applied in the following form

$$\rho c_p\left(\frac{\partial T}{\partial t}+v_{nz}\frac{\partial T}{\partial z}\right)-\frac{\partial}{\partial z}\left(K_n(T)\frac{\partial T}{\partial z}\right)=Q_{\mathrm{XUV}}-L_{\mathrm{IR}}. \tag{2}$$

For the calculation of temperature profiles as function of various stellar XUV radiation fluxes, we use the thermospheric model of Gordiets et al. (1982) and solve the time-dependent 1D equations of continuity, hydrostatic and heat balance simultaneously in the height region above the base of the thermosphere up to the exosphere level.

When a large amount of XUV energy is deposited at the top of an atmosphere, heated atoms can overcome the planetary gravity field and a planetary wind consisting of the heated atoms develops. By assuming a progressive increase of stellar XUV flux from present features (Sun = 1 XUV) to 10 or even 100 times the present XUV flux, the following conditions shown in Figure 1 occur:

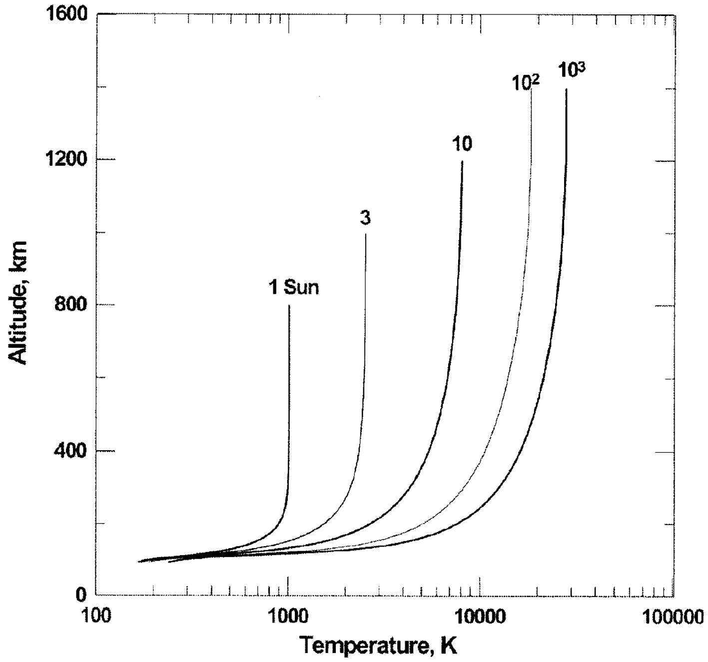

Figure 1. Illustration of the rise of exobase level and temperature in Earth's present thermosphere and exosphere for various XUV levels times the present Sun-value (1 Sun). If the exosphere temperature reaches about 5000 K (6 XUV: 3.5 Gyr ago), diffusive or even energy-limited escape for hydrogen atoms originates. 100 time higher XUV fluxes can even remove heavy gases like O, C and N atoms with a very high efficiency from an Earth-like planet.

First step: the upper atmospheric temperature increases, with a subsequent increase of the altitude of the exobase[4] (see Figure 1).

Second step: at a certain level of the XUV flux, there is no (quasi) static solution anymore and atmospheric blow off occurs.

If IR cooling of the thermosphere can not balance the incoming stellar XUV energy anymore, the excess thermal energy is directly converted into kinetic energy and hydrodynamic escape occurs. Jeans escape occurs when only a very small fraction of atoms, in the energetic wing of the velocity Maxwellian distribution, are lost to space (in quasi steady state), hydrodynamic diffusion-limited or energy-limited escape[5] results in a rapid depletion of the full distribution, which cannot be re-populated over sufficiently short time-scales. The critical temperature for H atoms on an Earth-mass planet is about 5000 K. One can see from Figure 1 that the temperature would have been overcome during the first Gyr, indicating that the early Earth had a different atmosphere than today. Our calculation indicates that only dense Venus-like CO_2 atmospheres can protect the atmospheres of young Earth-like exoplanets from atmospheric evaporation and survival of their water inventories during active XUV periods of their host stars because of strong IR cooling. However, long-time XUV radiation fluxes in the order of about 50–100 times the present value can dramatically affect the water inventory of a terrestrial exoplanet and possible even the stability of its whole atmosphere.

The latter problem may occur on a terrestrial H_2O-rich planet inside the HZ of a low mass M or K star, where there is observational evidence that their XUV energy fluxes stay active over longer time periods. First, the CO_2 may prevent extreme hydrodynamic escape conditions like on early Earth due to its heavy mass and good IR cooling capabilities, but after the CO_2 is removed from the atmosphere like on Earth due to chemical weathering in a humid wet environment (Franck et al., 2002), N_2 like on present Earth may become the dominant constituent in the atmosphere, so that the upper atmosphere is heated like in Figure 1 and large escape

---

[4] Exobase: atmospheric level where the mean free path of the main atmospheric species is similar to the scale height $H = (kT/mg)$ of the gas, with k the Boltzmann constant, T the exospheric temperature, g the gravitational acceleration and m is the mass of the atmospheric species.

[5] Hydrodynamic escape: diffusion-limited escape means that all atoms especially the light ones, which diffuse through the surrounding heavy gas up to the upper atmosphere can escape from the planet. Energy-limited escape occurs if only one species (i.e., hydrogen) is available in large amounts in the upper atmosphere so that it can escape as a planetary wind as observed at the giant hydrogen-rich exoplanet HD 209458 b (e.g. Lammer et al., 2003b).

rates develop, which evaporate the planets H_2O inventory (e.g. Chassefiere, 1997a; Lammer et al., 2003b; Bauer and Lammer, 2004).

Parallel to chemical weathering and removal of CO_2 from the planets atmosphere a CO_2 atmosphere can also be eroded by the interaction of the stellar wind plasma of the young star.

4. Stellar Wind Evolution of Solar-like Stars

The temporal evolution of the stellar wind velocity can be derived from lunar and meteorite fossil records (Newkirk, 1980). For the estimation of the early stellar wind density, one can use the mass loss estimations provided by Wood et al. (2002), which are IR from Hubble Space Telescope high–resolution spectroscopic observations of the H Lyman-α feature of several near–by main–sequence G and K stars.

Wood et al. (2002) found from their observations that the mass loss $\mathrm{d}M/\mathrm{d}t$ of solar-like G and K stars is proportional to their observed X-ray surface flux, which is correlated to the rotation periods P_{rot} of the stars. The product of the mass loss and the stellar wind velocity v_{sw} can be determined by (Griessmeier et al., 2004; Lammer et al., 2004)

$$\frac{\mathrm{d}M}{\mathrm{d}t} v_{\mathrm{sw}} \propto P_{\mathrm{rot}}^{-3.34\pm0.67}. \tag{3}$$

By using the temporal behavior of the stellar wind from Newkirk (1980) as $v_{\mathrm{sw}} = v_0(1 + t/t_c)^{-0.4}$, the time behavior of the stellar wind density can be found as $n_{\mathrm{sw}} = n_0(1 + t/t_c)^{-1.54\pm0.47}$. The time constant is $t_c = 2.56 \times 10^7$ year. The proportionality constants n_0 and v_0 can be derived for present–day conditions at 1 AU. For distances other than 1 AU, the constants can be evaluated with a r^{-2} dependence.

Nevertheless it should be noted that Newkirk (1980) pointed out that a lower initial rotation rate in this model would give slightly lower values for the early solar/stellar wind velocities and vice versa, which is not considered in this work. Therefore, more active young solar-like G and K stars with X-ray surface fluxes larger than $10^6\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ must be studied during the near future (Linsky and Wood, 2004).

5. Atmospheric Loss Induced by Stellar Wind and CME Events

The boundary between the stellar wind and the planetary magnetosphere, which protects an atmosphere from stellar wind erosion processes is called the magnetopause. The precise location and shape of the magnetopause are determined mainly by the stellar wind parameters, which depend on the orbital distance from the host star and the planetary magnetic field strength.

Planets in orbits close to their host star are subject to strong tidal dissipation, leading to tidal locking on a very short timescale. For tidally locked planets the rotation period is equal to the orbital period, therefore, a fast rotation of the planet is not possible. All common scaling laws for the planetary magnetic moment yield a magnetic moment rapidly decreasing with decreasing rotation rate (Griessmeier et al., 2004). Due to the reduced internal magnetic moment the pressure balance is shifted closer to the planet until the planetary atmosphere acts as an obstacle (Figure 2). In this case, the atmosphere is subject to various non-thermal loss processes. Moreover, the magnetic and flare activity of young stars is much higher than at a 4.5 Gyr old star like our Sun, therefore, it is reasonable to assume that more CME's occur at these stars. These CME's reach close-in exoplanets at orbital distances <0.1 and affect strongly their magnetospheres and atmospheres. Scaling laws from the observation of CME's for the spatial evolution of the maximum and minimum density $n_{\max} = 7.1 \times r^{-2.99}\,\mathrm{cm}^{-3}$

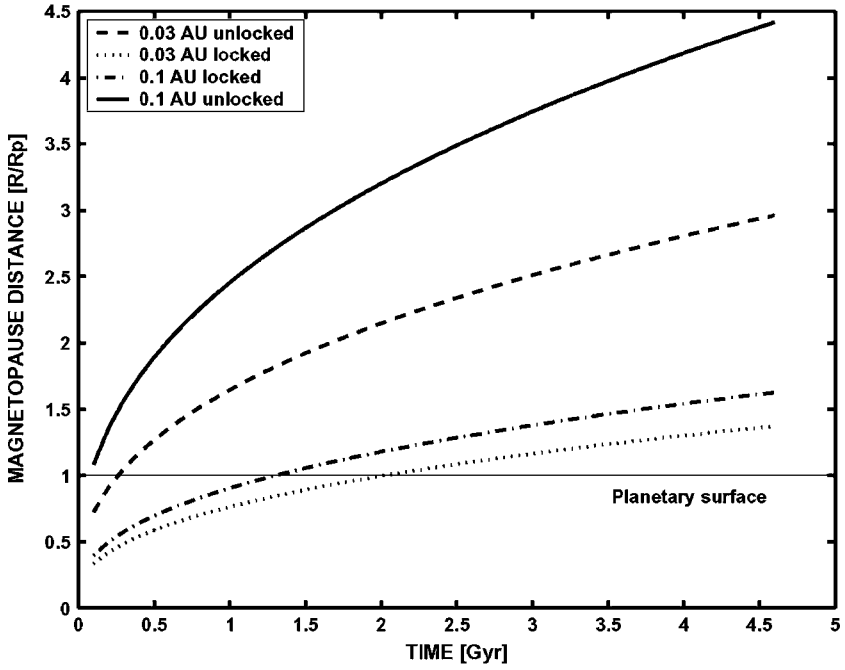

Figure 2. Compression of the magnetopause with and without tidal locking (Magnetic field strength is similar than on Earth) at orbital distances of 0.03 and 0.1 AU in units of the planetary radii R_p.

and $n_{\min} = 4.88 \times r^{-2.31}\,\mathrm{cm}^{-3}$, respectively, and the bulk velocity is about 500 km/s (Kodachenko et al., 2005). For example the planetary magnetic field compression of a Jupiter-class exoplanet due to the interaction with a CME is shown in Figure 3. We use a rough estimation for the calculation of the temporal evolution of an unprotected planetary atmosphere due to mass loss estimations caused by photo-ionization, electron impact ionization and charge exchange from the upper atmosphere into the stellar wind plasma flow around the planetary obstacle for the changing solar wind parameters (Michel, 1971; Bauer, 1983).

For preliminary mass loss estimations we use the model of Michel (1971) and Bauer (1983), which assumed that the solar wind interaction is confined to the scale height H of the atmospheric gas and the mass loss is produced by the ionization of the neutral gas above the planetary obstacle corresponding to the compressed magnetopause/ionopause distance. By applying momentum balance considerations between the stellar wind and

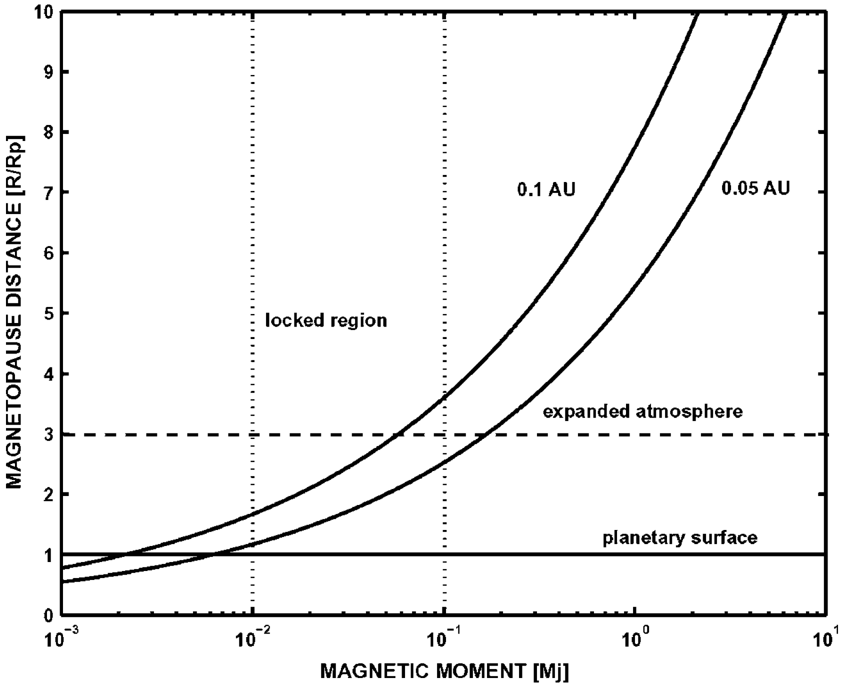

Figure 3. Compression of the magnetopause of a Jupiter-class exoplanet due to a CME for orbital distances of 0.05 and 0.1 AU. Note that the Earth magnetic moment is less than 10^{-4} times the Jupiter magnetic moment, and therefore the atmosphere of terrestrial planets, which are hit by a CME at this orbital distances will be eroded or destroyed.

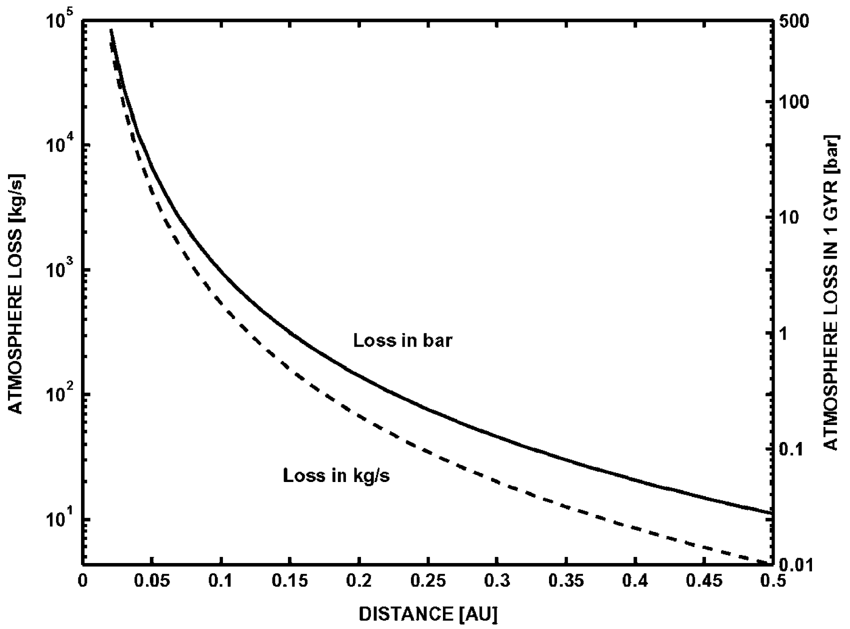

Figure 4. Atmospheric loss rates for Earth-like exoplanets with low magnetic moments due to tidal locking as a function of the orbital distance in bar during 1 Gyr (solid line, right axis) and in kg/s (dashed line, left axis).

the photo-ions and steady-state conditions (Bauer, 1983) the atmospheric mass loss rate $\mathrm{d}M_a/\mathrm{d}t$ due to the solar wind interaction is given as

$$\frac{\mathrm{d}M_a}{\mathrm{d}t} \approx -2\mathrm{K}\rho_{\mathrm{sw}} v_{\mathrm{sw}} R_{ip}^2, \tag{4}$$

where $K \approx 0.3$ is a so-called mass loading limit[6] (Michel, 1971; Bauer, 1983), and the subscript "sw" indicates stellar wind conditions. The estimated loss rates for Earth-like planets as function of orbital distance are shown in Figure 4 for low magnetic moments due to tidal locking. One can see that atmospheres of more than about 500 bar can be removed within 1 Gyr for close-in orbits of 0.03 AU. At orbits of 0.1 AU, the atmospheric loss is in the range of several bars during 1 Gyr. The loss rate per second is about 500 kg/s for planets orbiting at 0.1 AU, more than 5000 kg/s at 0.05 AU and less than 5 kg/s at 0.5 AU. For comparison, the present loss rate at Venus is about 1 kg/s (Bauer, 1983). A recent study by Lammer et al. (2005) applied a more complex numerical test particle model to

---

[6] Mass loading limit: Only a fraction of about 1/3 of the atmospheric species, which are affected by the stellar wind plasma flow will be ionized and picked up.

Earth-like exoplanets-CME interaction in close-in HZ's. They found that a combination of weak magnetic moments, high XUV fluxes and extended upper atmospheres can result in loss rates up to 100 of bars even at 0.2 AU, which is much higher than the estimates obtained from equation (4) and shown in Figure 4.

6. Conclusion

Our study suggests that exoplanets orbiting inside close-in HZ's of M and low mass K stars may not develop Earth-like biospheres, because these planets may lose their atmospheres and water inventories due to the long-time activity in high XUV radiation, strong stellar winds and CME's of their host stars. Moreover, exoplanets inside the HZ of these stars are tidally locked so that their magnetic dynamos and the resulting magnetospheres will be weaker than the magnetosphere of Earth at 1 AU. From this point of view we suggest that higher mass K and G stars should be considered as good primary stellar candidates for the search of "hypothetically" habitable planets in future terrestrial planet finding missions like Darwin (ESA) and TPF-C (NASA). Thus, dynamical stability with further restrictions on the orbit of a planet is the requirement of a stable atmosphere, the result of our investigation has also an impact on studies, which are underway to produce catalogues of hypothetical planetary systems where terrestrial exoplanets can have stable dynamical orbits but can also keep their atmospheres and surface water inventories.

Acknowledgements

H. Lammer, Yu. N. Kulikov, H. K. Biernat, and T. Penz thank the "Österreichischer Austauschdienst", which supported this work by the projects I.12/04 and I.2/08. The authors thank also the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" which supported this study under projects P17100-N08 and P17099-N08 and the support by the Austrian Academy of Sciences, "Verwaltungsstelle für Auslandsbeziehungen" and by the Russian Academy of Sciences. Yu. N. Kulikov also thanks the "Russian Fund for Basic Research" of the Russian Academy of Sciences which supported this study as the Russian-Austrian project RFBR No. 03-05-20003 BWTZ a. This study was supported by International Space Science Institute (ISSI) and benifited from the ISSI team "Evolution of Habitable Planets".

References

Bauer, S. J.: 1983, *Ann. Geophysics* **1**, 477.

Bauer, S. J. and Lammer, H.: 2004, *Planetary Aeronomy: Atmosphere Environments in Planetary Systems*, Springer-Verlag, New York.

Chassefiere, E.: 1997a, *Icarus* **124**, 537.

Chassefiere, E.: 1997b, *Icarus* **126**, 229.

Courtillot, V.: 2002, *Evolutionary Catastrophes: The Science of Mass Extinctions*, Cambridge University Press, Cambridge.

Dvorak, R., Pilat-Lohinger, E., Funk, B. and Freistetter, F.: 2003, *Astron. Astrophys.*, **398**, L1.

Franck, S., Kossacki, K. J., v. Bloh, W. and Bounama, C.: 2002, *Tellus* **54B**, 325.

Gordiets, B. F., Kulikov, Yu., Markov, N., Marov, M. N., Ya M.: 1982, *J. Geophys. Res.* **87**, 4504.

Griessmeier, J.-M., Stadelmann, A., Penz, T., Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Motschmann, U., Biernat, H. K. and Weiss, W. W.: 2004, *Astron. Astrophys.* **425**, 753.

Guedel, M., Guinan, E. F. and Skinner, S. L.:1997, *Astrophys. J.* **483**, 947.

Joshi, M. M.: 2003, *Astrobiology* **3**, 415.

Kasting, J. F.: 1988, *Icarus* **74**, 472.

Kasting, J. F., Whitmire, D. P. and Reynolds, R. T.: 1993, *Icarus* **101**, 108.

Kodachenko, M. L., Ribas, I., Lammer, H., Griessmeier, J.–M., Selsis, F., Leitner, M., Penz, T., Eirora, C., Hanslmeier, A., Biernat, H. K., Farrugia, C. J. and Rucker, H. O.: 2005, *Astrobiology*, submitted.

Lammer, H., Lichtenegger, H. I. M., Kolb, C., Ribas, I., Guinan, E. F. and Bauer, S. J.: 2003a, *Icarus* **165**, 9.

Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Bauer, S. J. and Weiss, W. W.: 2003b, *Astrophys J. Lett.* **598**, L121.

Lammer, H., Ribas, I., Griessmeier, J.-M., Penz, T., Hanslmeier, A. and Biernat, H. K.: 2004, *Hvar. Obs. Bull.* **28**, 139.

Lammer, H., Lichtenegger, H. I. M., Yu, N., Kulikov, Yu, N., Grießmeier, J.-M., Erkaev, N. V., Biernat, H. K., Khodachenko, M. L., Ribas, I., Penz, T. and Selsis, F.: 2005, *Astrobiol.* submitted.

Linsky, J. L. and Wood, B. E.: 2004, in *The Sun and the Heliosphere as an Integrated System*, Kluwer Academic Publ., lordrecht in press.

Menou K. and Tabachnik, S.: 2003, *Astrophys. J.* **583**, 473.

Michel, C. F.: 1971, *Planet. Space Sci.* **19**, 1580.

Newkirk, Jr., G.: 1980. *Geochi. Cosmochi. Acta Suppl.* **13**, 293.

Pizzolato, N., Maggio, A., Micela, G., Sciortino, S. and Ventura, P.: 2003, *Astron. Astrophys.* **397**, 147.

Ribas, I., Guinan, E. F., Güdel, M. and Audard M.: 2005, *Astrophys. J.* **622**, 680.

Stauffer, J. R., Caillault, J.-P., Gagne, M., Prosser, C. F. and Hartmann, L. W.: 1994, *Astrophys. J. Suppl.* **91**, 625.

Stelzer, B. and Neuhäuser, R.: 2001, *Astron. Astrophys.* **377**, 538.

Wood, B. E., Müller, H.-R., Zank, G. and Linsky, J. L.: 2002, *Astrophys. J.* **574**, 412.