

****FULL TITLE****

*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***

****NAMES OF EDITORS****

The loss of nitrogen-rich atmospheres from Earth-like exoplanets within M-star habitable zones

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Abstract. After the first discovery of massive Earth-like exoplanets around M-type dwarf stars, the search for exoplanets which resemble more an Earth analogue continues. The discoveries of super-Earth planets pose questions on habitability and the possible origin of life on such planets. Future exoplanet space projects designed to characterize the atmospheres of terrestrial exoplanets will also search for atmospheric species which are considered as bio-markers (e.g. O₃, H₂O, CH₄, etc.). By using the Earth with its atmosphere as a proxy and in agreement with the classical habitable zone concept, one should expect that Earth-like exoplanets suitable for life as we know it should have a nitrogen atmosphere and a very low CO₂ content. Whether a water bearing terrestrial planet within its habitable zone can evolve into a habitable world similar than the Earth, depends on the capability of its water-inventory and atmosphere to survive the period of high radiation of the young and/or active host star. Depending on their size and mass, lower mass stars remain at high X-ray and EUV (XUV) activity levels for hundreds of Ma's to Ga's. XUV flux values which are 10 or 20 times higher than that of the present Sun can heat the thermosphere and expand the exobase of N₂-rich Earth-like exoplanets to altitudes well above their expected magnetopause distances. This results in magnetically non-protected upper atmospheres and high non-thermal escape rates. We studied this plasma induced N⁺ ion pick up escape and applied a numerical test-particle stellar wind plasma - exosphere interaction model. Our results indicate that Earth-analogue exoplanets with atmosphere compositions similar to that of present Earth will lose their nitrogen inventories if they are exposed over a sufficient period of time to XUV fluxes ≥ 10 times that of the present Sun. Because most M-type stars are active in XUV radiation we suggest that these planets will undergo a dif-

ferent atmospheric evolution than the Earth so that life as we know it may not evolve on their surfaces.

1. Introduction

Atmospheric escape from a planet during the active period of its host star is an important factor which influences the evolution of atmospheres and planetary water inventories. Based on the energy source, escape processes can be separated into thermal escape and non-thermal escape.

Kulikov et al. (2006) and Lammer et al. (2007) found that high XUV radiation of the active young Sun or active dwarf stars results in considerable expansion of CO₂-rich thermospheres and exospheres of terrestrial planets. In case the upper atmosphere expands beyond a protecting magnetosphere (magnetopause), the atmosphere of an exoplanet which is exposed to high XUV fluxes and stellar plasma flows can be in a real danger of being stripped of its whole gaseous envelope even if the planet orbits its parent M star within the habitable zone (HZ). However, as shown in Lammer et al. (2007), a high CO₂ atmospheric mixing ratio will result in enhanced IR cooling in the thermosphere and inhibits its expansion and therefore leads to reduced non-thermal atmospheric erosion due to dense stellar winds or Coronal Mass Ejections (CME's).

Recently, Tian et al. (2008) developed a multi-component hydrodynamic thermosphere model where they could self consistently study the present time Earth thermosphere under extreme solar XUV conditions. Their model was validated against observations (MSIS-00) and models (e.g., Roble et al. 1987; Smithro and Sojka 2005a; Smithro and Sojka 2005b) of the Earth's present N₂-rich thermosphere. Tian et al. (2008) found that a thermosphere of an Earth-size and mass planet with the present time Earth gas composition can experience a hydrodynamic expansion, so that hydrostatic equilibrium can no longer be maintained. Their results indicate that hydrodynamic flow of the bulk atmosphere and the associated adiabatic cooling cannot be ignored when one studies the response of thermospheres to high stellar XUV radiation.

Furthermore, these authors show that the fast variation of the thermospheric bulk motion velocities under different XUV induced temperatures suggest that the adiabatic cooling effect could keep the exobase temperature ≤ 1000 K if light gases such as atomic hydrogen are the dominant species in an thermosphere.

From the model results of Tian et al. (2008) one can conclude that the upper atmosphere of an Earth-mass planet having the same atmospheric composition than present Earth and exposed to extreme XUV fluxes ≥ 10 times that of the present Sun would start to rapidly expand if thermospheric temperatures exceeded values of about 7000-8000 K, when atomic O and N dominate the upper thermosphere. Due to the heating, the atmosphere may even expand beyond the magnetopause stand-off distance as illustrated in Fig. 1. However, this process is limited due to the outflow of the dominant species which in turn results in adiabating cooling of the atmosphere.

The finding of Tian et al. (2008) is very relevant for Earth-like exoplanets within orbits of M star HZ's, because these low mass stars are active over long

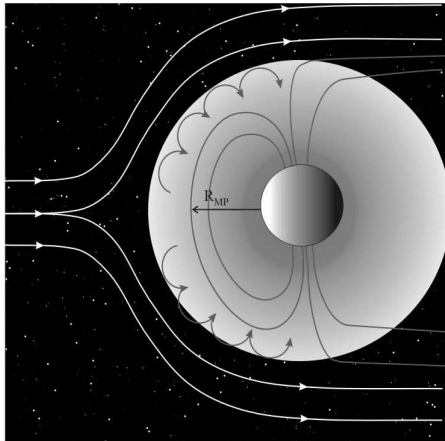


Figure 1. Illustration showing the expected stellar wind – atmosphere interaction in a case where the upper atmosphere expands above a compressed magnetosphere. Neutral species above the magnetopause can be ionized and picked up by the stellar wind plasma flow.

time periods in the XUV wavelength range due to strong magnetic fields, which are generated by their fully or partially convective interiors (e.g. Ayres 1997; Audard et al. 2004; Ribas et al. 2005; Scalo et al. 2007; and references therein).

Low mass dwarf stars are more numerous in the solar neighbourhood than solar-like G-stars, therefore, they are also considered as interesting candidates for planet finding projects and missions. Furthermore, due to a smaller size of these stars they are less luminous which results in a closer orbital distance of their HZ's (e.g., Khodachenko et al. 2007). Although one can not generalize dwarf stars because their mass-range spread is wider compared with Sun-like spectral type stars, it is certain that terrestrial-type exoplanets within HZs of M-type stars are more influenced by the stellar radiation and particle environment than a planet in a HZ of a solar-like star.

The focus of this study is to investigate if nitrogen-rich Earth-like exoplanets within M star HZs can keep their atmospheres or if they suffer strong stellar plasma wind induced atmospheric erosion. In Sect. 2 we briefly explain the input parameters and the numerical test particle model used for the ion pick up estimation and in Sect. 3 we discuss our results and the consequences for habitability.

2. N^+ pick up loss modeling

For studying the stellar plasma induced N^+ pick up escape rates we use for our model input the neutral atmosphere profiles, which were modeled by Tian et al. (2008). Their model treats the whole thermosphere as a single fluid with a varying mean molecular mass. For this moving atmosphere, the model iteratively solves the momentum and energy equations and includes neutral and ion species. Time independent diffusion equations are solved for the following long-lived species O, O_2 , N_2 , He, H, H_2 , CO_2 , CO, $N(^4S)$, NO, H_2O , O^+ , N^+ ,

I_{EUV}/I_{Sun}	z_{exo}	T_{exo} [K]	n_N [cm ⁻³]
7	2.5 r_{Earth}	8000	10^5
10	4.8 r_{Earth}	5700	4.8×10^4
20	12.7 r_{Earth}	2500	1.6×10^4

Table 1. Exobase distance, temperature and nitrogen number density as a function of stellar EUV flux normalized to 1 AU for present Sun (Tian et al. 2008).

and H^+ . Chemical equilibrium is applied to 18 short-lived species (Tian et al. 2008). They assume quasi-charge neutrality and the model includes 154 chemical reactions, collected from thermospheric models of the present Earth (Roble 1995; Smithtro and Sojka 2005a), Venus and Mars (Nagy et al. 1983; Barth et al. 1992; Fox and Delgado 1979), and extrasolar planets (Yelle 2004). The lower boundary is at the mesopause at about 95 km and the upper boundary is the exobase, which moves to higher distances with increasing stellar XUV flux. Hydrodynamics is valid in the collision dominated thermosphere below the exobase. Above the exobase the particles are treated kinetically.

In agreement with Smithtro and Sojka (2005b), the results of Tian et al. (2008) indicate that under extreme XUV conditions atomic nitrogen becomes a competing species with atomic oxygen at the exobase level. Table 1 shows the corresponding exobase distances, temperatures and atomic nitrogen densities for 7 times, 10 times and 20 times that of the present Sun at a distance of 1 AU (within the HZ). For estimating the number density in the collisionless exosphere above the exobase levels given in Table 1, we use Chamberlain’s approach (e.g., Chamberlain 1963; Lammer et al. 2007). This approach is based on Liouville’s equation, where the exospheric nitrogen number density as a function of the planetocentric distance can be written as the product of the barometric density and the sum of the partition functions that correspond to escaping, ballistic, and satellite particle trajectories (Chamberlain 1963).

Khodachenko et al. (2007) studied the influence of dense plasma flows (stellar winds and CME activity) on the expected planetary and magnetospheric environments of Earth-like exoplanets in orbital locations within close-in HZs and concluded that dense plasma flows could play a critical role in the definition of the habitability criterion for the evolution of terrestrial exoplanets orbiting dwarf stars.

Due to tidal locking and, hence, slow planetary rotation, Earth-like exoplanets within M star HZs are expected to have weaker magnetic dynamos compared to the faster rotating Earth at 1 AU (Grießmeier et al. 2005; Khodachenko et al. 2007). The dynamic pressure of denser and faster plasma winds acts against the planetary magnetic pressure, so that the magnetosphere is compressed and the resulting atmosphere protecting area is smaller. To investigate if smaller or more compressed magnetospheres of nitrogen-rich terrestrial exoplanets will result in little or no magnetospheric protection against the stellar plasma flow, we estimate the magnetopause stand off distance by assuming the plasma parameters shown in Table 2.

I_{XUV}/I_{Sun}	v_{sw} [km/s]	n_{sw} [cm ⁻³]	r_{mag}	r_{exo}
7	780	90	$6.0r_{Earth}$	$2.5r_{Earth}$
10	900	200	$5.2r_{Earth}$	$4.8r_{Earth}$
20	1010	270	$4.7r_{Earth}$	$12.7r_{Earth}$

Table 2. Stellar XUV flux normalized to present day Sun, stellar plasma parameters, magnetopause and exobase distances.

To make optimistic loss estimations, we assume a planet with the size and mass of the Earth and a faster rotation period of about 13 hours. The faster rotation assumed in our study will enhance the strength of the intrinsic magnetic moment of our Exo-Earth to about $1.5 \times \mathfrak{S}_{Earth}$, with $\mathfrak{S}_{Earth} = 6.6845 \times 10^{22}$ Am² being the magnetic moment of the Earth. Because HZs of M-stars are closer to the star compared with G-type stars, one can expect higher plasma densities(winds, CME's) (Khodachenko et al. 2007). The values shown in Table 2 correspond to orbital distances between 0.2 - 0.4 AU. M star planets within closer HZ's are exposed to denser stellar plasma flows. One can see from Table 2 that due to the higher plasma pressure the magnetopause boundaries of our test planets should be closer to the planetary surfaces than at Earth even if we assume a 1.5 times stronger magnetic moment. At Earth the average solar activity induced magnetopause stand-off distance in 1 AU is located at about 10 Earth-radii and corresponds to average solar wind plasma densities of about 8 cm⁻³ and velocities of about 450 km/s.

One can see from Table 2 that only the 7 XUV case in connection with a stellar wind plasma density which is about 10 times that of the present Earth builds up a pressure balance between the stellar wind plasma and the magnetosphere at a distance which is $\geq 2.5r_{Earth}$ above the exobase. Because we assume a denser stellar plasma flow for the 10 XUV case the dynamic pressure compresses the magnetosphere to a distance which is comparable to the expanded exobase level. For the 20 XUV case and the assumed stellar plasma flow parameters the magnetic moment is too weak for balancing the stellar wind dynamic pressure above or close to the exobase level. This result indicates that magnetospheres of nitrogen-rich Earth-like exoplanets which are exposed to XUV fluxes ≥ 10 XUV are not protecting the expanded upper atmosphere against stellar plasma erosion. In such a case one can expect that an ionopause will build up like at present day Venus or Mars around the exobase level (see also Yamauchi and Wahlund 2007).

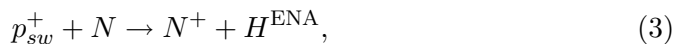
We consider now the production rate of planetary N⁺ ions as the sum of the rates of photo-ionization,



electron impact ionization,



and charge exchange



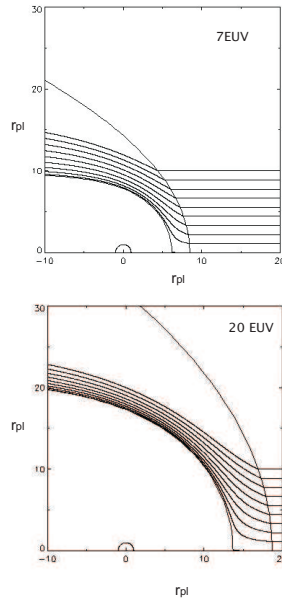


Figure 2. Flow lines, obstacle boundary and bow shock for two different XUV cases. Upper panel (7 XUV case): obstacle corresponds to the magnetopause and is well above the exobase. Lower panel (20 XUV case): obstacle is at the exobase level. The dimensions are given in planetary radii; the small half-circle about the origin represents the planet.

between the atomic nitrogen exosphere above the planetary obstacle (magnetopause or ionopause) and the stellar plasma flow.

The simulation of the particle escape is initialized by dividing the space around the planetary obstacle into a number of volume elements. Production rates of planetary N^+ ions are then obtained by calculating the ion production along streamlines around the planetary obstacle (shown in Fig. 2). Upon assuming that all newly created N^+ ions will be picked up by the stellar wind and carried away from the planet, the loss rate in each volume element can be determined. Finally, by summing over all elements the total N^+ pick up escape rate is obtained (e.g., Lammer et al. 2003; Erkaev et al. 2005; Lammer et al. 2007).

3. Results

For the input parameters shown in Tables 1 and 2, our test-particle model yields N^+ ion pick up loss rates of about $5 \times 10^{28} \text{ s}^{-1}$ (7 XUV), $5 \times 10^{29} \text{ s}^{-1}$ (10 XUV) and $2 \times 10^{30} \text{ s}^{-1}$ (20 XUV). Table 3 summarizes the integrated atmospheric loss in units of bar over 50 Ma, 100 Ma and 1 Ga. It shows that if the Earth-analogue test planet would be exposed longer to the various XUV fluxes, the loss accumulates to much higher values. Thus, the stability of the nitrogen reservoirs of Earth-like exoplanets is in greater danger if the nitrogen-rich thermosphere is exposed to higher XUV fluxes, denser stellar winds, or a combination of both.

Δt [Ma]	L_7 XUV [bar]	L_{10} XUV [bar]	L_{20} XUV [bar]
50	0.35	3	15
100	0.7	6	30
1000	7	60	300

Table 3. Time integrated nitrogen loss in units of bar for an Earth-analogue planet with a similar atmosphere as present Earth as function of stellar XUV and the parameters given in Tables 1 and 2.

Both stellar factors, high XUV fluxes and dense plasma winds are expected at the orbital locations of M star HZs, therefore our results indicate that the expansion of the upper atmospheres of Earth-analogue nitrogen-rich exoplanets would result in high non-thermal escape rates which most likely remove the initial nitrogen reservoirs from terrestrial planets. One should note that we estimated the N^+ ion pick up loss rates by assuming a fast rotating planet with a strong intrinsic magnetic moment (stronger than that of present Earth).

From these preliminary results we suggest that stable atmospheres of terrestrial exoplanets around XUV active host stars should contain a high mixing ratio of molecules like CO_2 , NO , or H_3^+ which can cool the thermospheres due to IR-cooling. Cooler thermospheres will result in less expanded upper atmospheres (see also Lammer et al. 2007) so that the atmosphere can be protected in case the planet remains geodynamically active and generates a strong enough intrinsic magnetic field.

Conclusion

High XUV radiation of active M-type stars result in considerable expansion of nitrogen-rich thermospheres of Earth-like exoplanets orbiting their HZ's. Our study shows that even intrinsic magnetic fields comparable or even larger than those of the present Earth can not effectively protect the expanding upper atmosphere against stellar winds or CME plasmas if the XUV flux is ≥ 10 times that of the present solar value. Furthermore, in absence of IR-cooling species like CO_2 , NO , or H_3^+ molecules in the thermospheres of such exoplanets, their initial nitrogen reservoirs are in great danger and can be lost via non-thermal atmospheric escape. Non-magnetized or weakly magnetized Earth-like exoplanets which are exposed to high XUV fluxes and stellar plasma flows within the HZ of dwarf stars can be much easier stripped of their whole atmospheres. Our results are in agreement with Lammer et al. (2007) that we do not expect that M-star Earth-like mass or size exoplanets evolve atmospheres and biospheres “analogous” to that of the present Earth even if they orbit within the HZ's.

Acknowledgments. H. Lammer, H. I. M. Lichtenegger, M. L. Khodachenko and Yu. N. Kulikov acknowledge the support of this study by the Helmholtz Association through the research alliance “Planetary Evolution and Life”. The authors also thank the International Space Science Institute (ISSI, Bern) because the study was carried out under the framework of the ISSI Team “Evolution of Exoplanet Atmospheres and their Characterization”. The authors also thank F.

Tian for providing the exobase parameter values from Tian et al. (2008) for the 7 XUV, 10 XUV and 20 XUV cases.

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