Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
Proceedings IAU Symposium No. 259, 2008
K.G. Strassmeier, A.G. Kosovichev & J.E. Beckman, eds.

doi:10.1017/S1743921309030622

The role of intrinsic magnetic fields in planetary evolution and habitability: the planetary protection aspect

Maxim L. Khodachenko[1], **H. Lammer**[1], **H. I. M. Lichtenegger**[1], **J.-M. Grießmeier**[2], **M. Holmström**[3] **and A. Ekenbäck**[3]

[1]Space Research Institute, Austrian Academy of Sciences, Graz, Austria
email: maxim.khodachenko@oeaw.ac.at

[2]ASTRON, Dwingeloo, The Netherlands
email: griessmeier@astron.nl

[3]Swedish Institute of Space Physics, Kiruna, Sweden
email: matsh@irf.se

Abstract. The widely used definition of a habitable zone (HZ) for planets as a circumstellar area, where the star's luminosity is sufficiently intense to maintain liquid water at the surface of a planet, is shown to be too simplified. The role of a host star's activity and the intrinsic magnetic field of a planet with respect to their influence on mass loss processes of close-in gas giants and a definition of a HZ for the terrestrial-type exoplanets are discussed. The stellar X-ray/EUV radiation and the stellar wind result in ionization, heating, chemical modification, and slow erosion of the planetary upper atmospheres throughout their lifetime. The closer the planet is to the star, the more efficient are these processes, and therefore, the more important becomes the magnetic protection of a planet as a potential habitat. Different ways for planetary magnetic dipole moment estimation, based on existing magnetic dynamo scaling laws as well as on the recent measurements of hot atomic hydrogen clouds around close-in 'Hot Jupiters' are considered, and the predictions of these estimations are compared to each other.

Keywords. Astrobiology – magnetic fields – plasmas – molecular processes – atmospheric effects – stars: planetary systems – stars: winds – stars: activity

---

1. Introduction

Although most of the discovered exoplanets (http://exoplanet.eu/catalog.php) have parameters more comparable to the gas giants of the Solar System rather than the Earth-like, rocky planets, nowadays, because of contemporary technical advances, observers begin to detect non-Jupiter type lower mass exoplanets. By this, the giant exoplanets family demonstrate a separation in to sub-groups: (*i*) rather short orbit Jupiter-type planets, called 'Hot Jupiters'; and (*ii*) more massive giant planets with orbits $\geqslant 1$ AU.

With the discovery of low mass exoplanets (Santos, *et al.* 2004; Rivera, *et al.* 2005), the question as to whether life could evolve on a planet outside our Solar System has taken on a new urgency. Answering this question requires a complex study of a variety of internal and external factors which may influence the conditions on a planet in order that life could evolve there. In that respect, a circumstellar area, where a planet could have the necessary conditions for development and maintaining any kind of life is called a Habitable Zone (HZ). The only criterion, used so far, for definition of boundaries of a HZ in the vicinity of a star is based on the possibility for a planet with an atmosphere to have climate and geophysical conditions which allow the existence on its surface of liquid water over geological time periods (Huang 1960; Kasting, *et al.* 1993; Kasting 1997). This approach supposes that the width and circumstellar distance of the HZ depend mainly on the stellar luminosity, which evolves during the life time of a star and influences the planetary surface temperature. It is widely accepted now, that such general definition of the HZ, based only on the "*stellar luminosity* and *on-surface liquid water*" criterion, is incomplete. It needs further specification that includes considerations of the whole complex of stellar-planetary relation factors, whereas potential habitats have to be better defined.

In this paper we discuss the potential role for a HZ definition of such factors as the activity of a host star, as well as the related to that stellar wind and plasma environment conditions around a planet. By this, the intrinsic planetary magnetic field and magnetospheric protection of a planet appear of exceptional importance in the context of possible habitability of a planet.

2. Stellar radiation and plasma environment

The stellar X-ray/EUV (XUV) radiation and the stellar wind constitute permanent forcing of upper planetary atmospheres. The effect of this forcing is ionization, heating, chemical modification, and slow erosion of the upper atmosphere throughout the lifetime of a planet. The closer a planet is to the star, the more efficient are these processes, which finally influence the whole complex of physical and climatologic conditions on a planet. At the same time, only stable and dense enough atmospheres allow water to be liquid over geological time periods and prevent the destructive action from hostile radiation on the planetary surface, increasing the chances for life to emerge there.

2.1. *Stellar activity*

The relevant physical phenomena of stellar activity on late-type stars (i.e., spectral classes G, K, M) and their observational manifestations include modulations of the stellar photospheric light due to stellar spots, intermittent and energetic flares, coronal mass ejections (CMEs), stellar cosmic rays, enhanced XUV emissions (see Scalo, *et al.* 2007 and references therein).

According to the currently accepted paradigm, the wide range of activity levels and related phenomena observed in different stars is directly connected with operation of the stellar magnetic dynamo. By this, two basic parameters: (*i*) stellar rotation rate and (*ii*) depth of the convective zone, are believed to control the stellar dynamo efficiency, which increases with increasing of any, or both of these quantities. Since the stellar convective envelope becomes thicker with decreasing stellar mass, it is straightforward to infer that, at a given rotation period (i.e. age), the low-mass M- and K- stars should be more active than a solar-type G- star. This fact has many observational confirmations. For example, a relatively old ($\sim$ 5.5 Gyr) dwarf M- star, Proxima Centauri, experiences measurable flares at a rate of about one flare per hour (Walker 1981).

Recently, Audard, *et al.* (2000) found that the energy of flares correlates with the stellar activity, characterized by L_X/L_{bol}, where L_X and L_{bol} are X-ray and bolometric luminosities of a star, respectively. The evolution of $log(L_X/L_{bol})$ with time for stars of various masses is shown in Figure 1, provided by Scalo, *et al.* (2007). According to this activity-age portrait, solar-type G- stars stay at saturated emission levels only until ages of $\sim$ 100 Myr, and then their XUV luminosities rapidly decrease with age: $\propto (t[Gyr])^{-1.72}$. On the other hand, M- stars have saturated emission periods up to 0.5–1 Gyr, and then their luminosity decreases in a way similar to the solar-type stars.

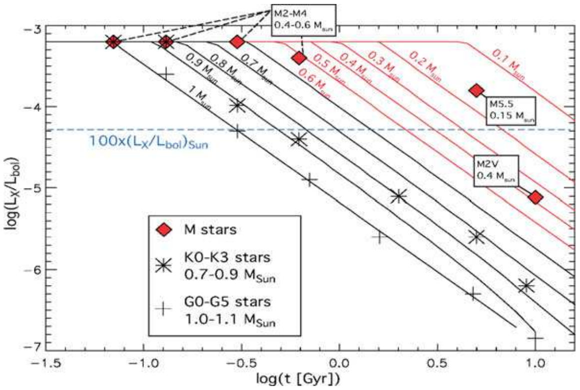


Figure 1. L_X/L_{bol} as a function of age for stars with masses $< M_{Sun}$. Symbols represent stars from the "Sun in Time" program (adopted from Scalo, *et al.* 2007).

Audard, *et al.* (2000), estimates the rate of high-energy ($E > 10^{32}$ erg) flares per day as $logN|_{E>10^{32}}$ erg $= -26.7 + 0.95logL_X$, which in the case of M- stars with a saturated activity level $L_X = 7 \times 10^{28}$ erg/s implies ∼ 6 strong flares per day. Altogether it has been found (Ribas, *et al.* 2005; Scalo, *et al.* 2007) that early K- stars and early M- stars may have XUV emissions level, and therefore flaring rates, of ∼(3–4) and ∼(10–100), respectively, times higher than solar-type G- stars of the same age.

2.2. *Stellar winds and CMEs*

Along with the high and long lasting stellar XUV emissions, another crucial factor of stellar activity, which may strongly affect the potential habitability of a planet, is the stellar wind plasma flow. Important parameters for characterization of the 'stellar plasma–planetary atmosphere/surface interaction' are the stellar wind density n_{sw} and velocity v_{sw}, which are highly variable with stellar age and depend also on the stellar spectral type, as well as on the orbital distance of the planet. We have currently a good knowledge of n_{sw} and v_{sw} for the Sun, whereas the amount of corresponding data related to other stars is much more limited.

While the dense stellar winds from hot stars, cool giants/supergiants and young T-Tauri stars produce detectable spectroscopic features from which the wind parameters can be derived, the tenuous winds from solar-type stars are a few orders of magnitude less massive, and cannot be detected spectroscopically. Different methods have been used to attempt direct measurements of mass loss rates in M- stars, most notably using *mm*-wavelength observations (van den Oord & Doyle 1997). Recently, there have been important developments towards indirect detections of stellar winds through their interactions with the surrounding interstellar medium. In particular, the stellar mass loss rates and related stellar winds were estimated for several nearby G- and K- stars using Hubble Space Telescope (HST) high-resolution measurements of the hydrogen Lyman-α absorption features, associated with the interaction between the stellar fully ionized coronal winds and the partially ionized local interstellar medium (Wood, *et al.* 2005). From these observations it was possible to conclude that younger solar-type G- stars have much denser and faster stellar winds as compared to the present Sun.

Furthermore, it is known from observations of our Sun that flaring activity of a star is accompanied by eruptions of coronal mass (e.g. CMEs), occurring sporadically and propagating in the stellar wind as large-scale plasma-magnetic structures. Traveling outward from the star at high speeds (up to thousands km/s), CMEs create major disturbances in the interplanetary medium and produce strong impacts on the planetary environments. Since CMEs can be directly observed only on the Sun, the current knowledge on them comes from the study of the Sun and the heliosphere by means of coronagraphs or by direct satellite measurements of particle velocities, densities and magnetic fields. On the Sun, CMEs are associated with flares and prominence eruptions and their sources are usually located in active regions and prominence sites. The likelihood of CME-events increases with the size and power of the related flare event. Based on the estimations of solar CME plasma density n_{CME}, using the in-situ spacecraft measurements (at distances > 0.4 AU) and the analysis of white-light coronagraph images (at distances $\leqslant 30R_{Sun} \approx 0.14$ AU), Khodachenko, *et al.* (2007a) provided general power-law interpolations of n_{CME} dependence on the distance to a star:

$$n_{CME}^{min}(d) = 4.88(d[\mathrm{AU}])^{-2.3}, \quad n_{CME}^{max}(d) = 7.10(d[\mathrm{AU}])^{-3.0}, \tag{2.1}$$

which identify a typical maximum-minimum range of n_{CME}. Besides of that, the average mass of solar CMEs was estimated as 10^{15} g, whereas their average duration at distances (6–10)R_{Sun} is close to 8 hours.

Until now, very few indications of CME activity on other stars come mainly from absorption features in the UV range during the impulsive phase of strong flare events, or from the blue-shifted components in time series spectra (Cully, *et al.* 1994; Houdebine, *et al.* 1990). In general, Cully, *et al.* (1994) concludes that CMEs on active stars might be much stronger than the solar events. Besides of that, the existing correlation between strong flares and CMEs on the Sun may be used, assuming a solar-stellar analogy, as an argument in favour of possible high CME activity on magnetically active, late-type stars.

Because of the relatively short range of propagation of majority of CMEs, they should impact most strongly the magnetospheres and atmospheres of close orbit (< 0.1 AU) planets. Khodachenko, *et al.* (2007a) have found that for a critical CME production rate $f_{CME}^{cr} \approx 36$CMEs per day (and higher) a close orbit exoplanet appears under continuous action of the stellar CMEs. This may have crucial outcomes for the climate evolution and habitability conditions on the terrestrial exoplanets in close-in HZs of the low mass active M- and K- stars (Khodachenko, *et al.* 2007a; Lammer, *et al.* 2007). Therefore, definition of a HZ for the case of low mass M- and K- stars, besides of their longer XUV activity periods, should take also into account the effects of "short range" (in astrophysical scales) planetary impacting factors of the stellar activity such as relatively dense stellar winds, interplanetary shocks, magnetic clouds (MCs) and CMEs propagating in the stellar winds.

3. Impact of stellar radiation and plasma flows on planetary atmospheres

The action of intensive stellar radiation and stellar winds on planetary environments consists of the following effects.

1) XUV radiation of the host star affects the the planetary thermospheric heat budget, resulting in the heating and expansion of the upper atmosphere (see Figure 2), which under certain conditions could be so large that the majority of light atmospheric constituents overcome the gravitational binding and escape from the planet in the form of a hydrodynamic wind, i.e. hydrodynamic escape (Yelle 2004; Tian, *et al.* 2008; Penz, *et al.* 2008). High upper atmospheric temperatures and the resulting hydrodynamic escape have a strong impact on the atmospheric stability of terrestrial-type planets (Kulikov, *et al.* 2007; Lammer, *et al.* 2008) and the evolution of the planet's water inventory.

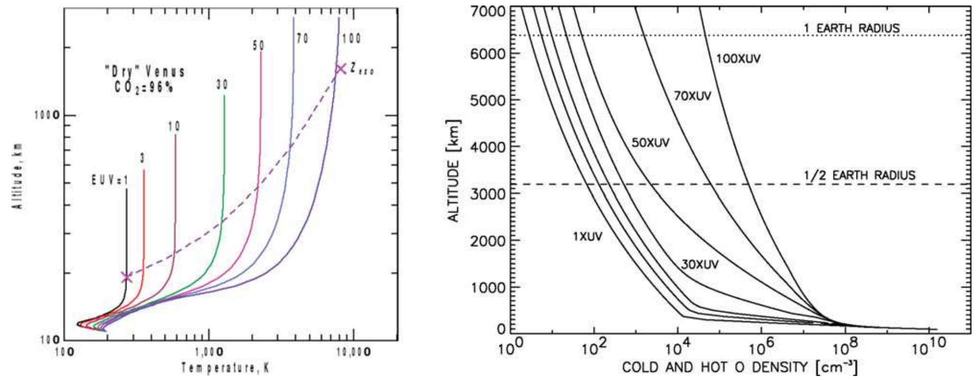


Figure 2. Temperature (a) and hot atomic oxigen (b) profiles of a CO_2-rich Venus-type atmosphere for different stellar EUV fluxes (in units of the present Sun EUV flux). The dashed line in (a) corresponds to the exobase distance at which the particle mean free path equals the scale height (adopted from Lammer, *et al.* 2007, 2008)

2) Simultaneously with the direct radiational heating of the upper atmosphere, the processes of ionization with the consequent production of energetic neutral atoms (ENAs) by various photo-chemical and charge exchange (for example $O_2^+ + e^- \rightarrow O^* + O^* + \Delta E$) reactions take place (Lammer, *et al.* 2008; Lichenegger, *et al.* 2008). Such processes result in the formation around planets of extended (in some cases) coronas, filled with hot neutral atoms.

The extended, because of the heating, upper planetary atmosphere and/or hot neutral corona may reach, and even exceed, the heights of the planetary magnetosphere. In this case they will be directly exposed to the plasmas of the stellar wind and CMEs. In this case the non-thermal atmospheric loss processes connected with ion pick-up, sputtering, and different kinds of photo-chemical energizing and escape will take place (Lichtenegger, *et al.* 2008). This makes the planetary magnetic field and connected with it, the size of the magnetosphere, as well as the parameters of the stellar wind (mainly n_{sw} and speed v_{sw}) to be important for the processes of atmospheric erosion and mass loss of a planet, affecting finally its possible habitability.

4. Exoplanet magnetic fields

Magnetic field of a planet is generated by the planetary magnetic dynamo, which is connected with the specific internal structure of a planet. Limitations of the existing observational techniques make direct measurements of the magnetic fields of exoplanets impossible. We can only judge on the strengths of extrasolar planetary magnetic fields and the sizes of exoplanetary magnetospheres, based on the sensitive to that, measurable phenomena, which may serve as their proxies. Among such indirect ways for detection of exoplanetary magnetic fields are:

1) measurement of extended ENA coronas of 'Hot Jupiters' and fit of the experimental data with the existing models, dependent on the parameters of stellar wind and planetary magnetosphere size;

2) Consideration of the detected exoplanets in the context of known planetary evolution trends, including the effects of atmospheric erosion and planetary mass loss, which are also controlled by the planetary magnetic field, and judging about possible values of the last;

3) Search for exoplanetary radioemission signatures.

Besides of that, exoplanetary magnetic fields can be also estimated using the existing scaling laws for planetary magnetic dynamos, developed for the known magnetized planets of the solar system. Below we consider briefly all these approaches, except exoplanetary radioemissions, addressed in details in Grießmeier, *et al.* (2007) with the conclusion about the strength of an exoplanet radio signal, as received on Earth, being at the limit of sensitivity of the existing radio telescopes.

4.1. *Planetary magnetic moments and magnetosphere sizes predicted by scaling laws*

The planetary magnetic dipole moment can be estimated from different scaling laws, which were derived from simple theoretical models and summarized by Grießmeier, *et al.* (2004):

$$\begin{array}{ll} \mathcal{M} \propto \rho_c^{1/2} \omega r_c^4 & \text{(Busse 1976),} \\ \mathcal{M} \propto \rho_c^{1/2} \omega^{1/2} r_c^3 \sigma^{-1/2} & \text{(Stevenson 1983),} \\ \mathcal{M} \propto \rho_c^{1/2} \omega^{3/4} r_c^{7/2} \sigma^{-1/4} & \text{(Mizutani, \textit{et al.} 1992),} \\ \mathcal{M} \propto \rho_c^{1/2} \omega r_c^{7/2} & \text{(Sano 1993).} \end{array} \tag{4.1}$$

Here $\mathcal{M}$ is the planetary magnetic dipole moment, r_c is the radius of the dynamo region, and ω is the angular velocity of the planet rotation around its axis. The internal properties of a planet, such as mass density and conductivity in the dynamo region are denoted by ρ_c and σ, respectively. The equations (4.1) provide a $\mathcal{M}_{min} \div \mathcal{M}_{max}$ range of reasonable planetary magnetic moment values.

It is important that all the models (4.1) yield an increase of $\mathcal{M}$ with an increasing planetary rotation rate, and vice versa. In that respect it is necessary to take into account that the close-orbit planets, such as terrestrial-type planets in the close-in HZs of the low mass stars and 'Hot Jupiters', are very likely to be tidally locked to their host stars. The angular rotation of a tidally locked planet is synchronized with its orbital motion so, that ω is equal to the orbital angular velocity, determined by Kepler's law: $\omega = \sqrt{M^* G/d^3}$, where G is gravitational constant, M^* is the mass of the star, and d is the semi-major axis of the planet. The time scale for tidal locking τ_{sync} depends on the planetary structure, orbital distance to the host star, and the stellar mass. By this, the planets for which $\tau_{sync} \leqslant 0.1$ Gyr, usually are assumed as tidally locked ones, since such planet's age is at least an order of magnitude longer. On the other hand, the planets with $\tau_{sync} \geqslant 10$ Gyr are almost certainly tidally unlocked. Based on (4.1), Grießmeier, *et al.* (2004, 2005) have shown that the magnetic moment $\mathcal{M}$ of a slowly rotating tidally locked planet is much smaller than it would be for a freely rotating tidally unlocked one (see Figure 3a).

A general view of an exoplanetary magnetosphere can be built on the basis of a phenomenological (non self-consistent) model which approximates the magnetosphere by a semi-infinite cylinder on the nightside and by a half-sphere on the dayside (Grießmeier, *et al.* 2004). Both have the same radius R_m. The planet is located within the half-sphere at $R_s < R_m$. Here R_s is a planetocentric standoff distance of magnetopause, which can be estimated from the pressure balance condition at the substellar point (Grießmeier, *et al.* 2004; Khodachenko, *et al.* 2007a):

$$R_s = \left[\frac{\mu_0 f_0^2 \mathcal{M}^2}{8\pi^2 \rho v^2} \right]^{1/6}, \tag{4.2}$$

where $f_0 = 1.16$ is a form-factor of the magnetosphere (Voigt 1995); $\rho = nm$ and v are the density and speed of the stellar wind, respectively. Note that for a planet with a weak magnetic moment (e.g. a tidally locked planet at a close-in orbit) exposed to a dense and/or fast stellar wind or CME plasma flow, (4.2) may yield R_s shorter then the

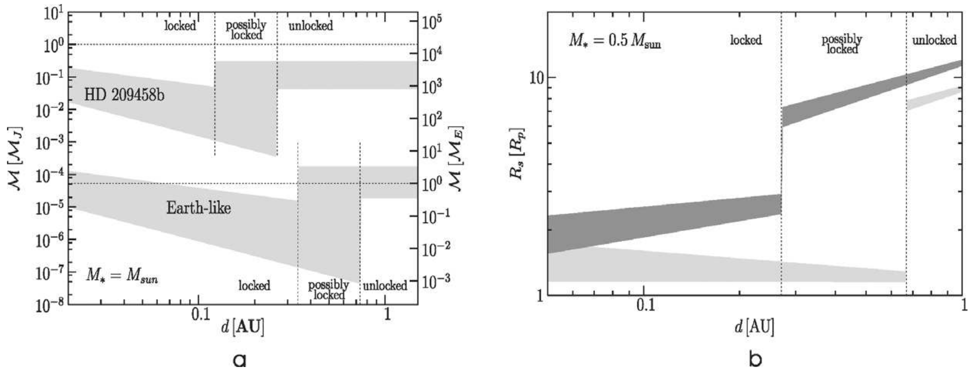


Figure 3. (a): Range of possible magnetic moments defined by (4.1) for a terrestrial-type and 'Hot Jupiter' exoplanets orbiting a solar-type star; (b): Range of the magnetopause standoff distances R_s compressed by CME plasma flow. The dark and light gray area correspond to the cases of a strongly (i.e. $\mathcal{M}_{max}$) and weakly magnetized (i.e. $\mathcal{M}_{min}$) terrestrial-type exoplanets, respectively. The size of the gray areas is determined by the difference between dense and sparse CMEs as described by (2.1). (adopted from Khodachenko, *et al.* 2007a)

planetary radius R_p. In such extreme cases R_s is usually set to $\sim R_p$, supposing that deep in the atmosphere the dense neutral gas layers deflect the plasma flow at somewhat higher altitudes above the planetary surface. Figure 3b shows the range of expected R_s, given by (4.2) with (4.1) taken into account, as a function of orbital distance for a terrestrial-type exoplanet orbiting a star with $M^* = 0.5M_{Sun}$ and affected by the flow of stellar CME plasmas. For these calculations the range of stellar CME densities, given by (2.1) as a function of orbital distance, and an average velocity of CMEs $\sim$ 500 km/s have been used. The mass of the host star also plays a certain role in these estimations because it influences the tidal locking of a planet and therefore determines its rotation rate. As can be seen from the Figure 3b, the magnetopause standoff distances of weakly magnetized terrestrial exoplanets at close orbits, which may correspond to the traditionally defined HZs, can be shrunk, under the action of CMEs, towards the planetary surface so, that the planetary atmospheres are directly exposed to the stellar CME plasma flows.

4.2. *'Hot Jupiters' magnetic moments estimations by observations of ENA coronas*

Observations of multiple transits of the 'Hot Jupiter' exoplanet HD 209458b in front of its parent star, performed with Hubble Space Telescope (HST), have shown absorption in the stellar Lyman-α line (at $1215.67\mathring{A}$) during transit, revealing the presence of high-velocity atomic hydrogen (i.e. ENA corona) at great distances around the planet (Vidal-Madjar, *et al.* 2003). HD 209458b is a Jupiter-type gas giant with a mass of $M_p \sim 0.69 M_{Jup}$ and a size of $R_p \sim 1.32 R_{Jup}$ that orbits at 0.045 AU around its host star HD 209458, which is a solar-type G- star with an age of about 4 Gyr. The activity of the star is comparable to that of the present Sun during a moderately quiet phase.

There are several features of the transit Lyman-α absorption spectrum that any proposed source of the observed hydrogen atoms needs to account for: 1) the indication of presence of hydrogen atoms with velocities $\geqslant 130$ km/s moving *away* from the star; 2) a fairly uniform absorption over the whole, outward from the star, velocity range 45–130 km/s; 3) the indication of presence of hydrogen atoms with velocities 30 - 105 km/s moving *towards* the star. The originally proposed explanation of the observed around HD 209458b ENA corona is that hydrogen atoms in the exosphere are undergoing hydrodynamic escape, and are further accelerated by the stellar radiation pressure (Vidal-Madjar, *et al.* 2003). However, there are difficulties in explaining the above mentioned three

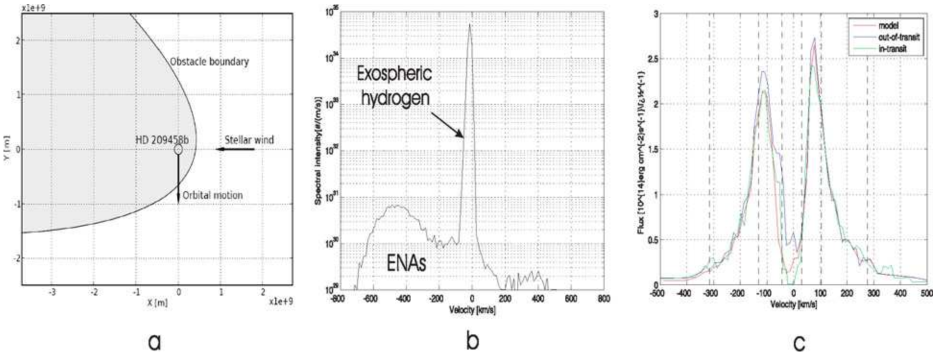


Figure 4. (a): Planetary magnetospheric obstacle in the simulation box for ENA production; (b): Hydrogen atoms velocity spectrum (high velocity population are ENAs, low-velocity narrow peak corresponds to the exospheric hydrogen); (c): Lyman-α profiles observed before and during the transit, and the modelled attenuation profile (adopted from Holmström, *et al.* 2008 and Ekenbäck, *et al.* 2008)

features of the atomic hydrogen velocity distribution. In particular, rather large radiation pressure is needed to accelerate the hydrogen atoms up to 130 km/s before they are photoionized, whereas uniform absorption in the velocity range 45 - 130 km/s, as well as the presence of atoms moving towards the star with speeds up to 105 km/s, cannot be at all reproduced within a model of an exosphere driven by radiation pressure.

In view of these difficulties, an alternative interpretation of observations was suggested by Holmström, *et al.* (2008), showing that the measured Lyman-α absorption spectrum can be explained via ENAs, produced by charge exchange between the stellar wind protons around HD 209458b and its exospheric neutrals. This mechanism is quite similar to the known formation of ENAs around Earth, Mars and Venus. In the model, proposed by Holmström, *et al.* (2008), it is assumed that charge exchange reactions take place outside a quasi-conic obstacle which represents the magnetosphere of the planet (Figure 4a), i.e. the exosphere has to be extended enough to reach the stellar wind above the planet's magnetopause. The shape of the magnetospheric obstacle is modelled phenomenologically as a surface: $X = r^2/(20R_p) + R_s$, where r is the distance to the planet−star line, aberrated by an angle of $arctan(v_p/v_{sw})$ to account for the finite stellar wind speed v_{sw} relative to the planets orbital speed v_p. Simulation of interaction between the stellar wind and planetary exosphere, extended above magnetopause, yields an exospheric cloud, along with the produced ENAs, shaped like a comet tail. In the resulting hydrogen velocity spectrum along the planet−star line (Figure 4b), the population of atoms with high velocity are the stellar wind protons that have charge-exchanged, becoming ENAs, whereas the narrower peak, centered in the low-velocity region, is due to the exospheric hydrogen atoms.

The next step is to estimate how the ENA corona affects the Lyman-α absorption spectrum of HD 209458b and to fit the estimated spectra to observations. The Lyman-α line profiles were observed outside and during the transit, and the difference between these two profiles corresponds to the attenuation by hydrogen atoms (Figure 4c). By this, the details of the neutral hydrogen distribution near HD 209458b, and the resulting attenuation spectrum, depend on the parameters of the stellar wind, geometrical characteristics of the magnetospheric obstacle and the exospheric parameters (e.g. temperature and density distributions). Taking the exospheric conditions on HD 209458b from the known models (Yelle 2004; Penz, *et al.* 2008) and assuming the stellar wind parameters similar to those of the present Sun, Ekenbäck, *et al.* (2008) determined an upper bound of the magnetospheric obstacle standoff distance $R_s^{fit} \simeq$ (4-10)$\times 10^8$ m, for which the modelled attenuation spectra provide the best fit to the observed spectra during the HD 209458b transit (Figure 4c). This value of the R_s^{fit}, according to (4.2), yields an estimation for the magnetic moment $\mathcal{M}_{HD\ 209458b} \approx 0.4\mathcal{M}_{Jup}$, where $\mathcal{M}_{Jup} = 1.56 \times 10^{27}$ Am^2 is the magnetic dipole moment of Jupiter.

Note, that the scaling laws (4.1), in view of the fact of likely tidal locking of the HD 209458b, provide for possible $\mathcal{M}_{HD\ 209458b}$ a bit smaller values: $(0.005...0.1)\mathcal{M}_{Jup}$. Thus, it may be concluded that the planetary rotation is an important factor for magnetic moment generation, however the true magnetic moment is bigger then the maximum value predicted by the scaling laws, which means that planetary rotation is not as important as previously was thought.

4.3. *Magnetospheric protection of 'Hot Jupiters'*

When considering the evolutional history of the 'Hot Jupiter' HD 209458b, it is necessary to keep in mind that close orbital location of this exoplanet to the host star may result in a strong erosion of its atmosphere by the ion pick-up mechanism caused by stellar CMEs, colliding with the planet (Khodachenko, *et al.* 2007b). Because of the sporadic character of the CME-planetary collisions, in the case of a moderately active host star of HD 209458b, these effects have not been taken into account in the considered in Section 4.2 study of ENA production on HD 209458b (Holmström, *et al.* 2008; Ekenbäck, *et al.* 2008). However, as it has been shown in Khodachenko, *et al.* (2007b), the integral action of the stellar CME impacts over the exoplanet's lifetime can produce significant effect on the planetary mass loss.

To study the interaction between the hydrodynamically driven neutral hydrogen wind in HD 209458b and the CME plasma flow, Khodachenko, *et al.* (2007b) applied the hydrodynamic numerical model described in Penz, *et al.* (2008). Distribution of the upper atmospheric neutral hydrogen, predicted by the model, was superimposed with estimations of the planetary magnetopause stand-off distance. The last was calculated for the typical maximum and minimum values of n_{CME}, given by (2.1) at the orbital distance of HD 209458b, within the assumption of the tidal locking of the planet, which according to (4.1) limits the values of possible magnetic dipole moment of the planet to the range $(0.005...0.1)\mathcal{M}_{Jup}$. It has been found that encountering CMEs plasma pushes the magnetopause stand-off distance of HD 209458b down to the heights at which the ionization and pick-up of the upper planetary neutral atmosphere by the CME plasma flow takes place. The hydrogen ion pick-up loss rates, caused by the CMEs, acting on the the extended above the magnetopause upper atmosphere of HD 209458b were calculated by Khodachenko, *et al.* (2007b) using a numerical test particle model (Lichtenegger, *et al.* 2002), which includes the effects of photo-ionization, as well as the ionization by the CME plasma flow (i.e. charge exchange and electron impact). Finally, assuming for the host star of HD 209458b the same CME occurrence rate as that on the Sun, Khodachenko, *et al.* (2007b) estimated that over its lifetime HD 209458b may have lost the mass from $\sim$0.2 (for $\mathcal{M}_{HD\ 209458b} = \mathcal{M}_{max} \equiv 0.1\mathcal{M}_{Jup}$ and dense CME flow) up to several tens (for $\mathcal{M}_{HD\ 209458b} = \mathcal{M}_{min} \equiv 0.005\mathcal{M}_{Jup}$ and sparse CME flow) of its present mass. Under certain conditions it could even be evaporated down to the core. On the other hand, the existence of rather large population of known 'Hot Jupiter' exoplanets at close orbital distances from their host stars indicates that such tremendous planetary mass losses are probably not typical. This means that the 'Hot Jupiter' exoplanets should have strong enough intrinsic magnetic fields and extended magnetospheres, which are able to protect the planetary atmospheres against of stellar winds and CME plasma flows. In view of that, the relatively small ($\sim 0.2M_p$) total mass loss of HD 209458b, caused by CMEs in the case of the predicted by the scaling laws (4.1) maximal possible value $\mathcal{M}_{HD\ 209458b} \approx 0.1\mathcal{M}_{Jup}$, may be considered as an additional indication of the consistency of even a bit higher ($0.4\mathcal{M}_{Jup}$) value for $\mathcal{M}_{HD209458b}$, estimated from the planetary hydrogen ENA corona observations.

5. Conclusions

To summarize this review we would like to emphasize that stellar XUV radiation and stellar wind plasmas exposure strongly impact the environments of close-orbit exoplanets, such as terrestrial-type exoplanets in the HZs of low mass stars and 'Hot Jupiters'. By this, complete or partial tidal locking of such exoplanets should lead to relatively weak intrinsic planetary magnetic moments. This may result in a situation when a stellar wind and encountering stellar CMEs will compress a planetary magnetosphere down to the heights at which the ionization and pick-up of the planetary neutral atmosphere by the CMEs plasma flow takes place. All this makes the stellar activity and planetary magnetospheric protection factors to play a crucial role for the whole complex of planetary evolution processes, including atmospheric erosion, mass loss and, finally, for the definition of HZ zone parameters for the terrestrial-type planets near a star. The last may significantly limit an actual HZ range, as compared to that followed from the traditional HZ definition, based on the pure climatological approach.

Acknowledgements

This work was supported by the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" (project P21197-N16) and the ÖAD Scientific and Technical Collaboration Program. The authors acknowledge the International Space Science Institute (ISSI; Bern, Switzerland) and the ISSI team "Evolution of Exoplanet Atmospheres and their Characterization". H.L., H.I.M.L. and M.K. thank Helmholtz Association and its research alliance project "Planetary Evolution and Life".

References

Audard, M., Güdel, M., Drake, J. J., & Kashyap, V. L. 2000, *ApJ* 541, 396

Busse, F. H. 1976, *Phys. Earth Planet. Int.* 12(4), 350

Cully, S. L., Fisher, G. H., Abbott, M. J., & Siegmund, O. H. W. 1994, *ApJ* 435, 449

Ekenbäck, A., Holmström, M., Wurz, P., Grießmeier, J.-M., Lammer, H., Selsis, F., & Penz, T. 2008, *ApJ*, submitted

Grießmeier, J.-M., Stadelmann, A., Penz, T., Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Motschmann, U., Biernat, H. K., & Weiss, W. W. 2004, *A&A* 425, 753

Grießmeier, J.-M., Stadelmann, A., Motschmann, U., Belisheva, N. K., Lammer, H., & Biernat, H. 2005, *Astrobiology* 5, 587

Grießmeier, J.-M., Preusse, S., Khodachenko, M. L., Motschmann, U., Mann, G., & Rucker, H. O. 2007, *Planet. & Space Sci.* 55, 618

Holmström, M., Ekenbäck, A., Selsis, F., Penz, T., Lammer, H., & Wurz, P. 2008, *Nature* 451, 970

Houdebine, E. R., Foing, B. H., & Rodonó, M. 1990, *A&A* 238, 249

Huang, S. S. 1960, *PASP* 72, 489

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

Kasting, J. F. 1997, *Orig. Life Evol. Biosph.* 27(1/3), 291

Khodachenko, M. L., Ribas, I., Lammer, H., Grießmeier, J.-M., Leitner, M., Selsis, F., Eiroa, C., Hanslmeier, A., Biernat, H., Farrugia, C. J., & Rucker, H. 2007a, *Astrobiology* 7, 167

Khodachenko, M. L., Lammer, H., Lichtenegger, H. I. M., Langmayr, D., Erkaev, N. V., Grießmeier, J.-M., Leitner, M., Penz, T., Biernat, H. K., Motschmann, U., & Rucker, H. O. 2007b, *Planet. & Space Sci.* 55, 631

Kulikov, Yu. N., Lammer, H., Lichtenegger, H. I. M., Penz, T., Breuer, D., Spohn, T., Lundin, R., & Biernat, H. K. 2007, *Space Sci Rev.* 129, 207

Lammer, H., Lichtenegger, H., Kulikov, Yu., Grießmeier, J.-M., Terada, N., Erkaev, N., Biernat, H., Khodachenko, M. L., Ribas, I., Penz, T., & Selsis, F. 2007, *Astrobiology* 7, 185

Lammer, H., Kasting, J. F., Chassefière, E., Johnson, R. E., Kulikov, Yu. N., & Tian, F. 2008, *Space Sci Rev.* 139, 399

Lichtenegger, H. I. M., Lammer, H., & Stumptner, W. 2002, *JGR* 107 (A10), doi:10.1029/2001JA000322

Lichtenegger, H. I. M., Gröller, H., Lammer, H., Kulikov, Yu. N., & Shematovich, V. 2008, *Geophys. Res. Lett.* submitted

Mizutani, H., Yamamoto, T., & Fujimura, A. 1992, *Adv. Space Res.* 12(8), 265

Penz, T., Erkaev, N. V., Kulikov, Yu. N., Langmayr, D., Lammer, H., Micela, G., Cecchi-Pestellini, C., Biernat, H. K., Selsis, F., Barge, P., Deleuil, M., & Leger, A. 2008, *Planet. & Space Sci.* 56, 1260

Ribas, I., Guinan, E. F., Güdel, M., & Audard, M. 2005, *ApJ* 622, 680

Rivera, E. J., Lissauer, J. J., Butler, R. P., Marcy, G. W., Vogt, S. S., Fischer, D. A., Brown, T. M., Laughlin, G., & Henry, G. W. 2005, *ApJ* 634, 625

Sano, Y. 1993, *J. Geomag. Geoelectr.* 45, 65

Santos, N. C., Bouchy, F., Mayor, M., Pepe, F., Queloz, D., Udry, S., Lovis, C., Bazot, M., Benz, W., Bertaux, J.-L., Curto, G. L., Delfosse, X., Mordasini, C., Naef, D., Sivan, J.-P., & Vauclair, S. 2004, *A&A* 426, L19

Scalo. J., Kaltenegger. L., Segura, A. G., Fridlund, M., Ribas, I., Kulikov, Yu. N., Grenfell, J. L., Rauer, H., Odert, P., Leitzinger, M., Selsis, F., Khodachenko, M. L., Eiroa, C., Kasting, J., & Lammer, H. 2007, *Astrobiology* 7, 85

Stevenson, D. J. 1983, *Rep. Prog. Phys.* 46, 555

Tian, F., Kasting, J. F., Liu, H., & Roble, R. G. 2008, *JGR* 113, Issue E5, CiteID E05008 (DOI: 10.1029/2007JE002946)

van den Oord, G. H. J. & Doyle, J. G. 1997, *A & A* 319, 578

Vidal-Madjar, A., des Etangs, A. L., Désert, J.-M., Ballester, G. E., Ferlet, R., Hébrard, G., & Mayor, M. 2003, *Nature* 422, 143

Voigt, G.-H. 1995, in: H. Volland (ed.), *Handbook of atmospheric electrodynamics*, vol. II (CRC Press), p. 333

Walker, A. R. 1981, *MNRAS* 195, 1029

Wood, B. E., Müller, H.-R., Zank, G. P., Linsky, J. L., & Redfield, S. 2005, *ApJ* 628, L143

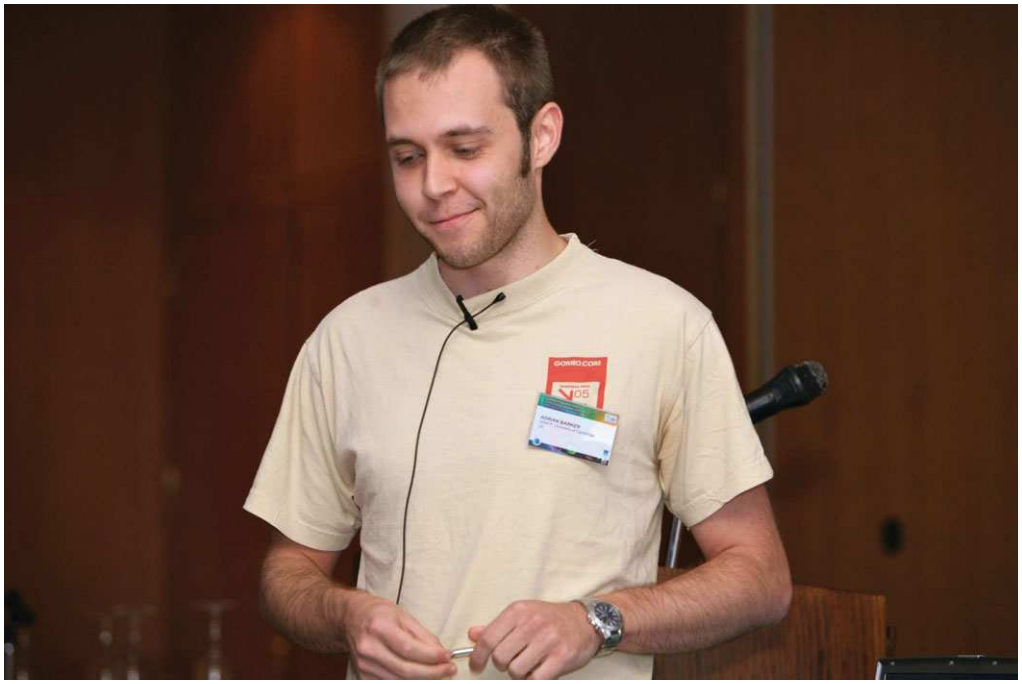
Yelle, R. V. 2004, *Icarus* 170, 167

Discussion

KOUTCHMY: Regarding 'Hot Jupiters', is not clear that they are not habitable just because they are too hot (no water), and also probably because gravity effects are too big at their surface?

KHODACHENKO: 'Hot Jupiters' cannot be considered as potential habitats by many reasons, including also those, you just have mentioned. It is unlikely that such planets may have liquid water on their surfaces. However, similarly to the known giant planets in the solar system, 'extra-solar Jupiters' may have moons (like Europa, Ganimed, Titan, Enceladus, etc.). These smaller planets, under certain circumstances, may evolve into worlds, much more suitable for life, and keep liquid water on their surfaces or in the interiors.

Serge Koutchmy (with microphone)



Adrian Barker