Influence of the interaction between stellar wind plasma and upper atmospheres on the evolution of the exoplanet

K.G. Kislyakova[1], H. Lammer[1], N.V. Erkaev[2], M. Holmstöm[3], P. Odert[1,4], M.L. Khodachnko[1], Yu.N. Kulikov[5], and M. Güdel[6]

(1) Space Research Institute (IWF), Graz, Austria; (2) Institute of Computational Modelling, Krasnoyarsk, Russia; (3) Swedish Institute of Space Physics, Kiruna, Sweden; (4) Institute for Physics, University of Graz, Austria; (5) Polar Geophysical Institute (PGI), Murmansk, Russia; (6) Institute for Astrophysics, University of Vienna, Austria;

ABSTRACT

Interaction between stellar wind plasma and the upper atmosphere of the exoplanets plays a significant role in their evolution. Together with the present or absent planetary dynamo, evolving stellar radiation and wind conditions influence the intensity of the interaction processes. The most intensive interaction is expected in systems of non- or weakly magnetized planets which are located close to an active host star. The influence of the star can be divided in two main aspects: high radiation level in the XUV branch (extreme ultraviolet and soft X-ray) causes the expansion and heating of the upper atmosphere leading in some cases even to the blow-off state. During blow-off the atmosphere is not hydrostatic anymore and expands upwards, undergoing extremely strong thermal escape. The second aspect consists in non-thermal erosion processes: even if the atmosphere is still hydrostatic, fast and dense stellar wind of a young active star may erode it effectively leading to ionization and subsequent ion escape, especially strong if the planet's magnetic field is weak or the exosphere expands above the magnetopause. In the presented investigation both, thermal escape and non-thermal ion pickup together with attendant processes are studied. Escape rates, their dependence on various conditions and change during the system's history are determined. As an example we consider a hypothetical Earth-like planet and a "Super-Earth" both located in the habitable zone of an M dwarf (Gliese 436 is taken as a proxy).

AIMS OF THE STUDY

Recent discoveries of so-called low density "super-Earths" (SE) by various ground- and space-based exoplanet-transit surveys indicate large populations of volatile-rich big rocky planets. From the radius-mass relation and the resulting density of discovered SE, one finds that these bodies probably have rocky cores but are surrounded by significant H/He and/or H_2O envelopes. In the present study we try to estimate, how quick these planets may lose their dence hydrogen envelopes if it is still present after the most active stage of the host star's activity. We study the thermal escape (Jeans and blow-off, see [2]) as well as non-thermal ion pickup [3]. Thermal profiles obtained in this part of the study are used as inputs for the second non-thermal part.

In the current study the plasma interaction between the stellar wind and the upper atmosphere of the planets is modeled applying a Direct Simulation Monte Carlo (DSMC) upper atmosphere-exosphere particle model which is coupled with a stellar wind particle interaction code. The 3D model is described in detail in [4] and includes stellar wind protons and planetary hydrogen atoms. The model takes into account evolution of the host star according to the present-day knowledge.

Thermal escape

Based on following equation system [2,3]:

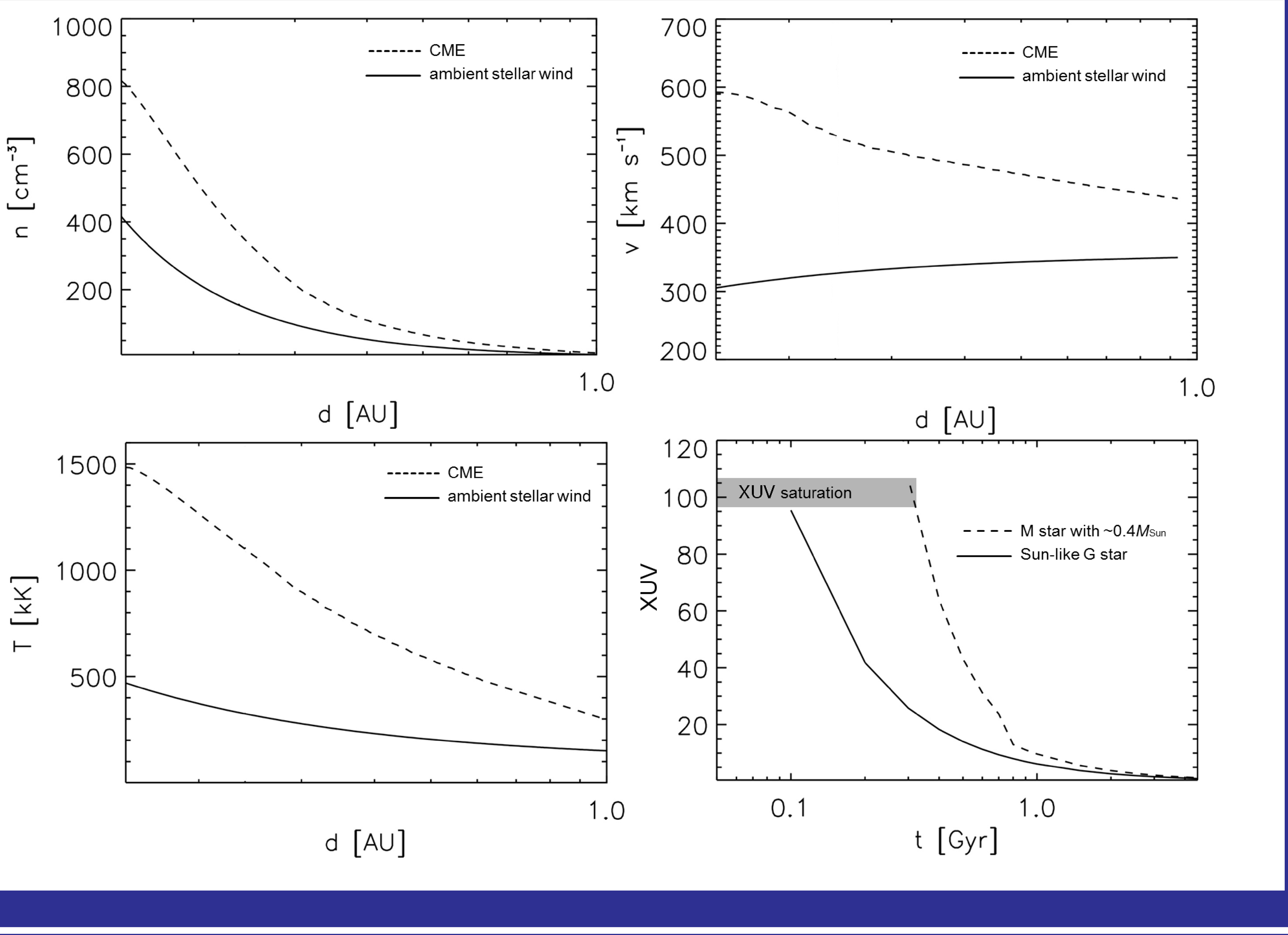
$$\frac{\partial n}{\partial t} + \frac{1}{r^2}\frac{\partial n v r^2}{\partial r} = 0$$
$$n\frac{\partial n}{\partial t} + nv\frac{\partial v}{\partial r} + \frac{1}{m}\frac{\partial p}{\partial r} = nF_{grav}$$
$$nm\left(\frac{\partial E}{\partial t} + v\frac{\partial E}{\partial r}\right) = q - p\frac{1}{r^2}\frac{\partial r^2 v}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \chi \frac{\partial T}{\partial r}\right)$$

where
$p = nkT, E = \frac{1}{\gamma - 1}\frac{p}{nm}$
- the set of the hydrodynamic fluid equations for mass, momentum and energy conservation in spherical coordinate system

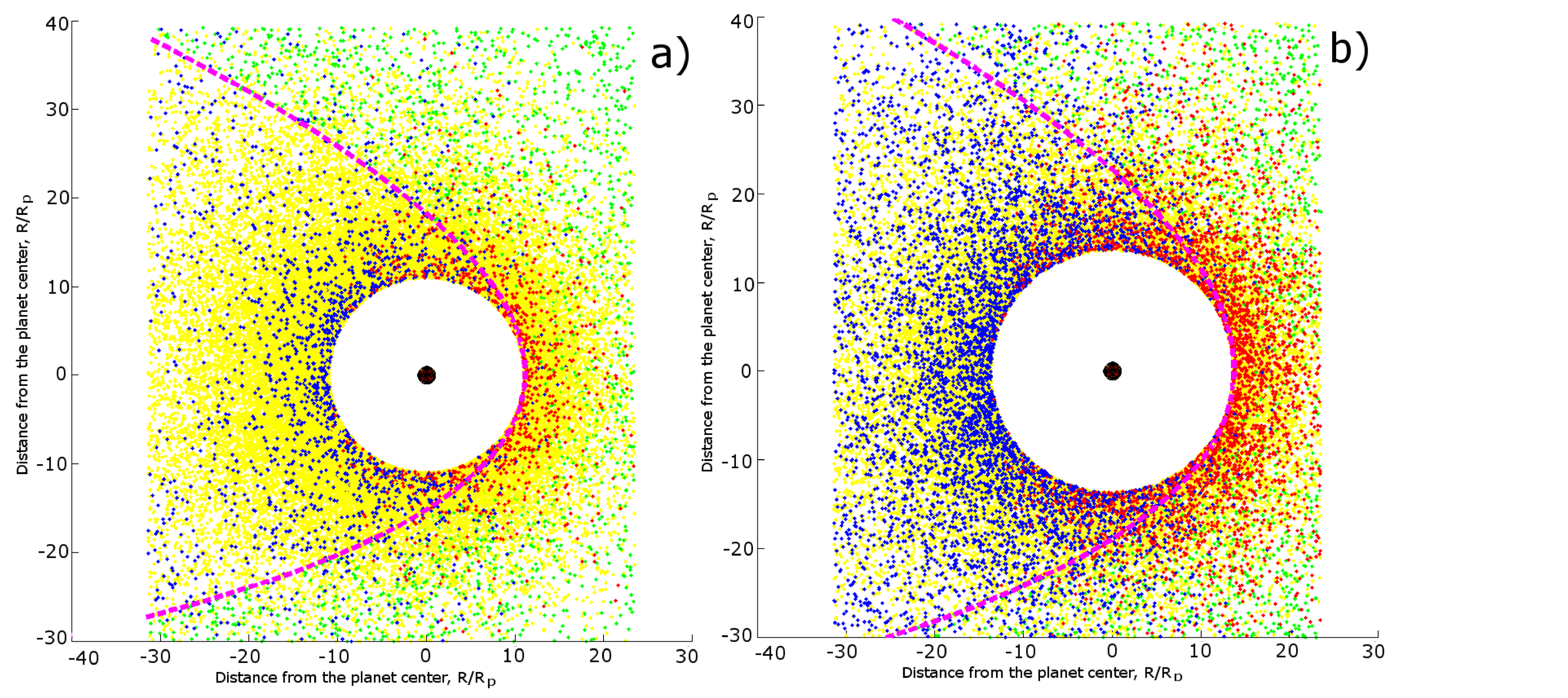
Ion pickup: included processes for an exospheric atom

- Charge-exchange with stellar proton: $H^+_{sw} + H_{pl} \rightarrow H^{ENA}_{sw} + H^+_{pl}$
- Ionization (photoionization, electron impact ionization)
- Scattering of an UV photon (radiation pressure)
- Elastic collision with another hydrogen atom
- Gravitational effects (besides gravity - tidal, coriolis, centrifugal forces)

The radiation environment of Gliese 436



Modeling of non-thermal ion pickup



Modeled atomic hydrogen coronae and stellar wind plasma interaction around a "super-Earth" hydrogen-rich planet inside an M star HZ at 0.24 AU (green: protons, yellow: H atoms, blue ENAs flying away from the star, red ENAs flying towards the star; dotted line: magnetopause/planetary obstacle). a): the XUV flux is 50 times higher than that of the present Sun, heating efficiency $\eta = 15$%, the planet is exposed to a moderate stellar wind (Case I). b): similar conditions except for heating efficiency of $\eta = 40$% [1].

Thermal escape and ion pickup during the planet's lifetime

H loss: $\Delta t = 4.5$Gyr	H-rich Earth [EO_h]	H-rich "SE" [EO_h]
Γ_{th}:$\eta = 15$%	≈6.5	≈3.5
Γ_{th}:$\eta = 40$%	≈14.5	≈11.5

H loss: $\Delta t = 4.5$Gyr	H-rich Earth [EO_h]	H-rich "SE" [EO_h]
Γ_{ion}:$\eta = 15$%, SW I	≈0.6	≈0.41
Γ_{ion}:$\eta = 40$%, SW II	≈0.93	≈0.7
Γ_{ion}:$\eta = 15$%, SW I	≈1.13	≈0.64
Γ_{ion}:$\eta = 40$%, SW II	≈1.63	≈1.44

References

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Mail: kristina.kislyakova@oeaw.ac.at