Characterizing stellar and exoplanetary environments via Ly-α transit observations of exoplanets

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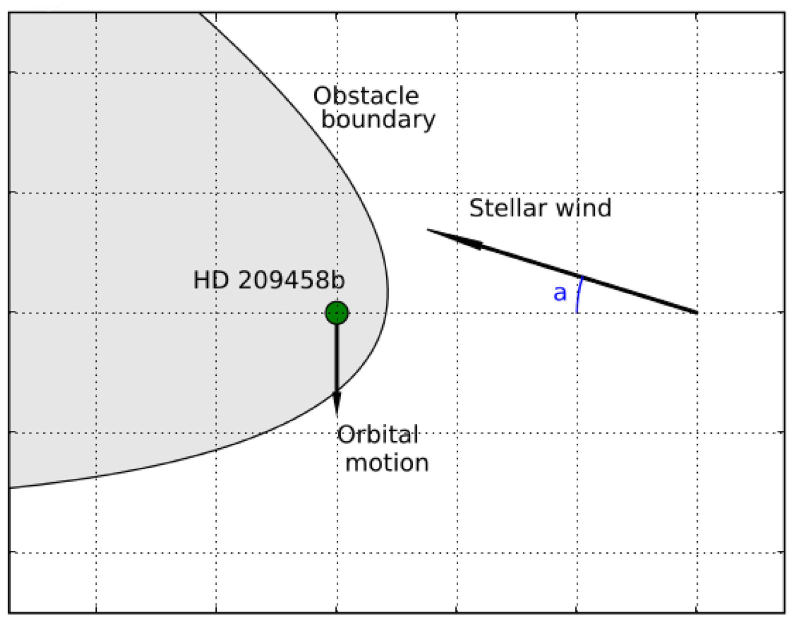
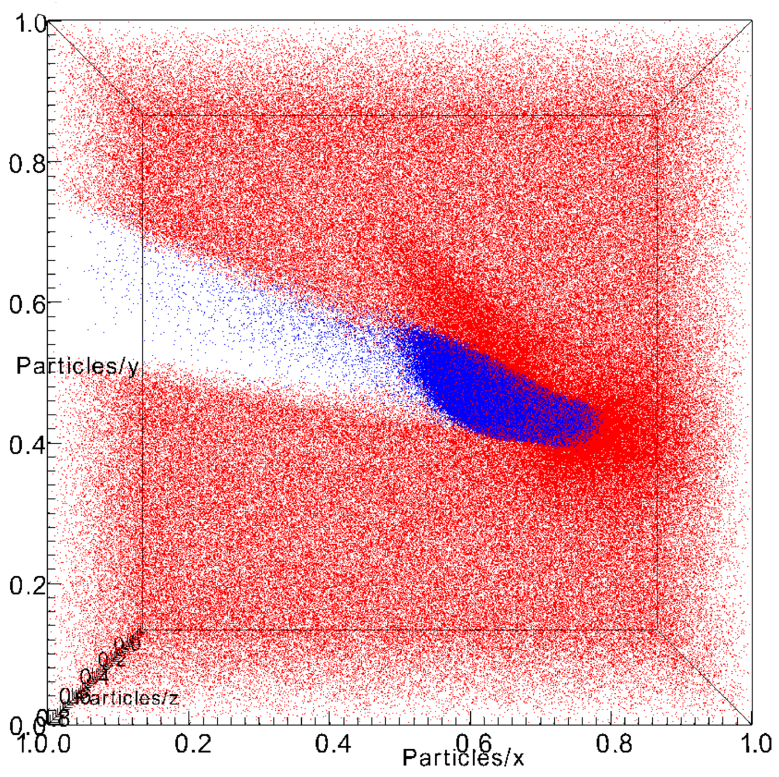
ABSTRACT

Transit observations of the Hubble Space Telescope of the hot gas giants HD 209458b and HD 189733b revealed an absorption in the Ly-α line during transits suggesting that a huge hot neutral hydrogen corona exists permanently or in the case of HD 189733b sporadically around these exoplanets. There were several attempts to explain the observed phenomena, i.e. the absorption in the wings of the Ly-α line, by taking into account such factors as atmospheric Doppler broadening, acceleration of the initially slow planetary hydrogen atoms by the stellar radiation pressure, and the production of energetic neutral atoms (ENAs). ENAs arise due to charge-exchange between a stellar wind proton and a planetary atom resulting in a hot neutral hydrogen atom moving with the velocity of the former proton and an initially cold planetary ion. Nevertheless all these models have some difficulties in the explanations if they are applied separate. The present study includes all three factors as well as the gravitational and rotational effects (Coriolis, centrifugal, tidal forces). The plasma interaction between stellar wind and the upper atmosphere of a planet is modeled by applying a Direct Simulation Monte Carlo (DSMC) upper atmosphere-exosphere particle model which is coupled with a stellar wind particle interaction code. It allows calculating the appearance, density and form of the hydrogen corona around the planet. We developed also post-processing code which reconstructs the Ly-alpha in-transit spectrum based on the modeled corona. With PLATO more transiting exoplanets around bright stars would be available; our approach allows one to obtain knowledge about the upper atmosphere structure, plasma environment in the vicinity of the exoplanet and indirectly about the strength of the planetary magnetic field.

Simulation domain geometry





Processes included 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)

Computation of L-α transmissivity and natural broadening

Relation between observed and the source intensity and the transmissivity [1]:

$$I(f) = I_0(f)e^{-\tau(f)}; \qquad T = I/I_0 = e^{-\tau(f)} = e^{-\sigma(f)Q}$$

Here $\tau = \sigma(f)Q$ is the frequency dependent optical depth, $\sigma(f)$ is the cross section and Q is the column numer density of hydrogen atoms.

Frequency dependent cross section:

$$\sigma(f) = \int_{-\infty}^{+\infty} \breve{u}(v)\, \sigma_N((1 + v/c)f)dv\ [m^2],$$

where $\breve{u}(v)$ is the normalized velocity spectrum, so that $\int_{-\infty}^{+\infty} \breve{u}(v)dv = 1$, c - the speed of light.

The natural absorption cross section in the rest frame of the scattered hydrogen atom is $\sigma_N(f) = \frac{3\lambda_\alpha^2 A_{21}^2}{8\pi} \frac{(f/f_\alpha)^4}{4\pi^2(f-f_\alpha)^2+(A_{21}/4)(f/f_\alpha)^6}$ $[m^2]$

Here $f_\alpha = c/\lambda_\alpha$ with $\lambda_\alpha = 1.21576 \times 10^{-7}$ m the L-α resonant wavelength and $A_{21} = 6.265 \times 10^8$ s^{-1} the rate of radiative decay from the $2p$ to the $1s$ energy level

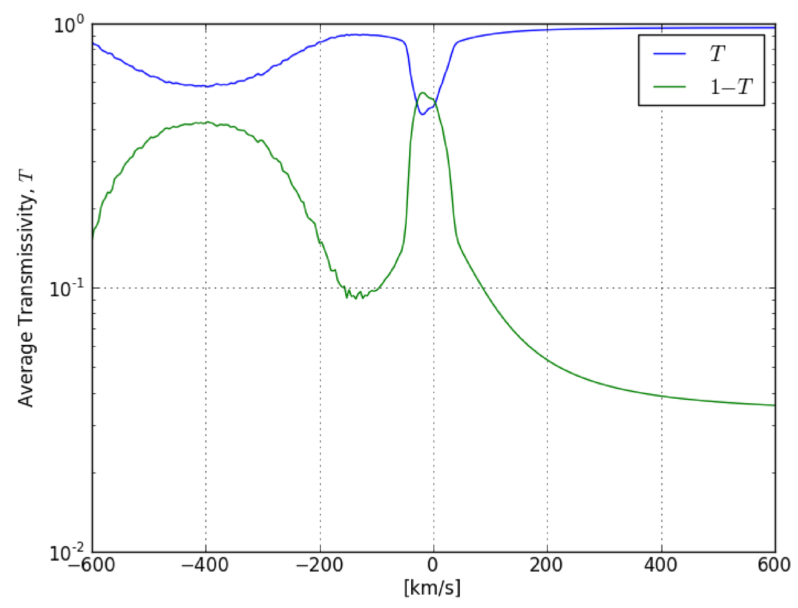
Multiplying $\sigma(f)$ with Q the optical depth can be computed directly without normalizing the velocity spectrum:

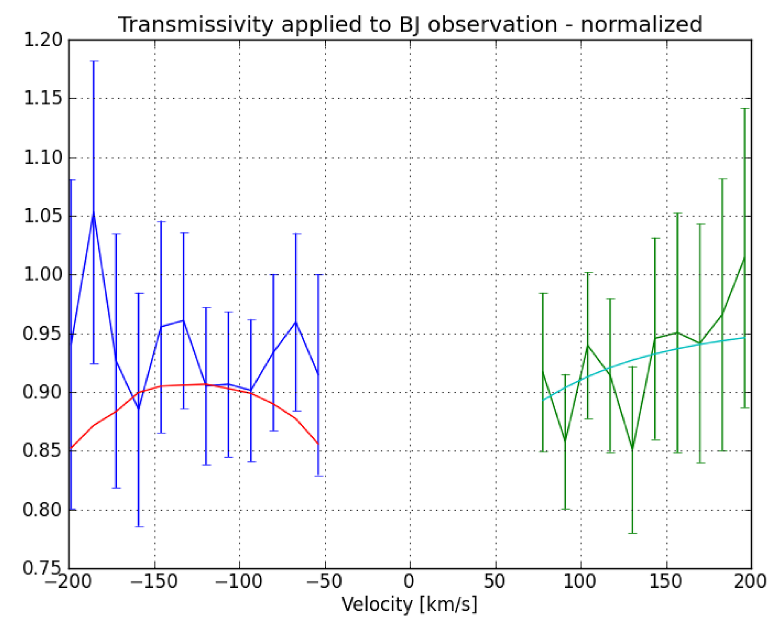
$$\tau(f) = \int_{-\infty}^{+\infty} u(v)\, \sigma_N((1 + v/c)f)dv.$$

References

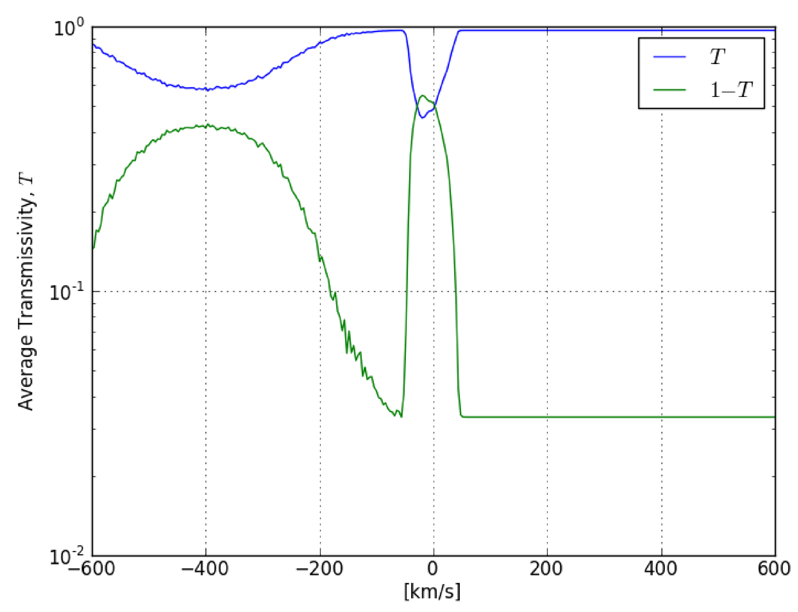
1. Kislyakova et al., 2013 (in preparation)
2. Holmström et al., Nature, vol. 451, 2008
3. Ekenbäck et al., ApJ, 709, 2010
4. Lecavelier et al., A&A, 2012

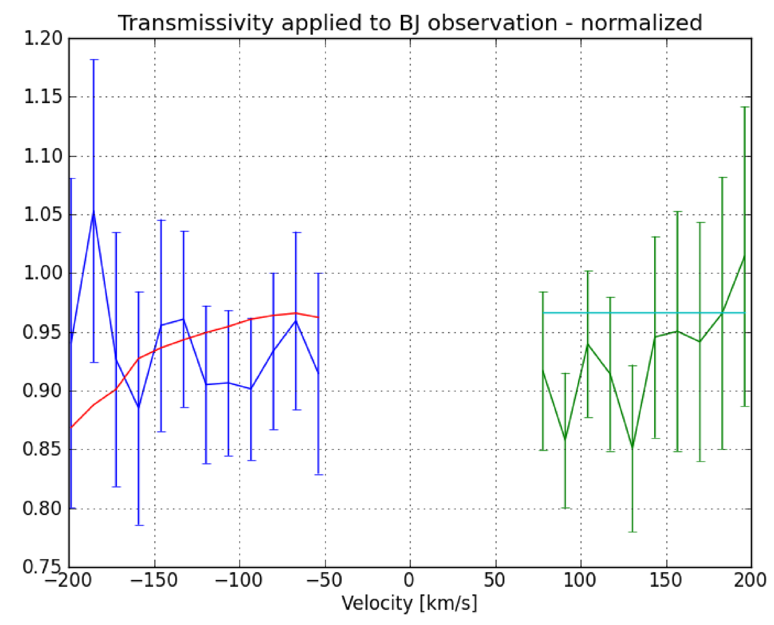
Hydrogen corona around HD 209458b, broadening included





Hydrogen corona around HD 209458b, no broadening





301 velocity bins, 10x10 spacial bins, upsampling 600

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Simulation input parameters, HD 209458(b)

Stellar parameters:

- Star mass = **2.283** $\times$ **10^{30}** kg $\approx$ 1.1 $M_\odot$
- Orbital distance = **7.1** $\times$ **10^{9}** m = 0.047 a.u.
- Stellar wind density = **1.0** $\times$ **10^{10}** m^{-3}
- Stellar wind velocity = 400 km/s
- Stellar wind temperature = **1.1** $\times$ **10^{6}** K

Planetary parameters:

- Planet mass = **1.21** $\times$ **10^{27}** kg $\approx$ 0.71 M_{Jup}
- Planet radius = **9.54** $\times$ **10^{7}** m $\approx$ 1.38 R_{Jup}
- Exobase distance (inner boundary) = **2.7** $\times$ **10^{8}** m
- Exobase temperature = 8000 K
- Exobase density = **4.0** $\times$ **10^{13}** m^{-3}
- Magnetopause distance = **3.8** $\times$ **10^{8}** m = 4.0 R_{Pl}
- Magnetopause width = **5.7** $\times$ **10^{8}** m = 6 R_{Pl}

Some numerical parameters play a role as well: velocity and spacial cell size, number of so-called "metaparticles" each representing a certain number of "real" particles

Conclusions and future outlook

- Natural broadening plays significant role in the observable L-α absorption of the "Hot Jupiters" with high atmospheric densities
- ENAs can contribute in the cases with decreased density (for example, HD 189733b)
- L-α observations may be very helpful in detemining the stellar wind parameters in the vicinity of the hot giants
- Electron impact ionization (i.e. stellar wind) plays a role in shaping of the observable L-α spectrum.
- Numerical parameters should be taken into account as well
- Future outlook: applying the method to HD 189733b [4]

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