

# Energetic Neutral Atoms Around the Extrasolar Planet HD 209458b

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## Abstract

Absorption in the stellar Lyman- $\alpha$  (Ly- $\alpha$ ) line observed during the transit of the extrasolar planet HD 209458b reveals high velocity atomic hydrogen at great distances from the planet[1, 2]. This has been interpreted as hydrogen atoms escaping from the exosphere of the planet[1, 3], possibly undergoing hydrodynamic blow-off[4], being accelerated by stellar radiation pressure. However, around solar system planets the production of energetic neutral atoms from charge exchange between solar wind protons and neutral hydrogen from the exospheres has been observed[5, 6, 7], and should also occur at extrasolar planets. Here we show that the measured transit-associated Ly- $\alpha$  absorption can be explained by the interaction between the exosphere of HD 209458b and the stellar wind, and that radiation pressure alone cannot explain the observation. This is the first observation of energetic neutral atoms outside the solar system. Since the stellar wind protons are the source of the observed energetic neutral atoms, this provides a completely new method of probing stellar wind conditions, and our model suggests a slow and hot stellar wind near HD 209458b at the time of the observation.

## Energetic neutral atoms (ENAs)

Energetic neutral atoms (ENAs) are produced wherever energetic ions meet a neutral atmosphere, and solar wind ENAs have been observed at every planet in the solar system where ENA instrumentation has been available — at Earth[5], at Mars[6], and at Venus[7].

This mechanism, well-known in the solar system, has however not been considered as a possible origin of the atomic hydrogen corona revealed by HST observations of HD 209458b. Here we investigate whether the observed Ly- $\alpha$  signature could be due to such ENAs.

## A Model of ENA production at HD 209458b

For a first estimate of the ENA production near HD 209458b, we assume that the charge exchange takes place in an undisturbed stellar wind that is flowing radially away from the star. Here we model the ENA production by a particle model that includes stellar wind protons and atomic hydrogen. Charge exchange between stellar wind protons and exospheric hydrogen takes place outside a conic obstacle that represents the magnetosphere of the planet (Fig. 1). The resulting exospheric cloud, along with the produced ENAs, is shown in Fig. 2, where we see the great extent of the hydrogen cloud, covering a region larger than the stellar disc, as seen from Earth. The cloud is shaped like a comet tail due to the stellar radiation pressure, curved by the Coriolis force, as predicted[8] and as seen in earlier numerical simulations[1, 3]. The velocity spectrum along the  $x$ -axis (the planet–star line) is shown in Fig. 3. The ENAs are clearly visible as a distribution that is separate from the main exospheric hydrogen component, due to the different bulk velocities and temperatures.

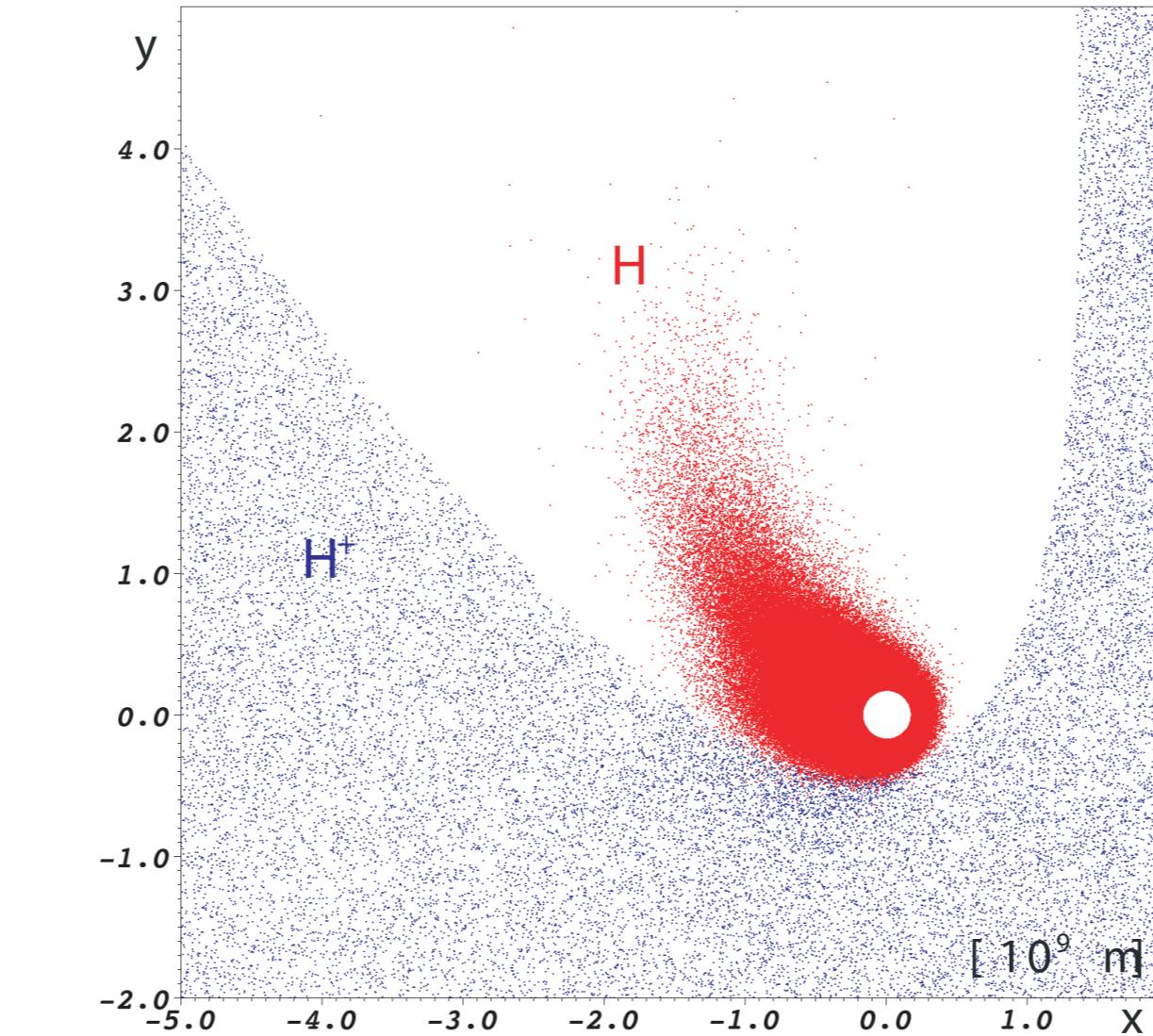


Figure 1: The flow of solar wind protons and the hydrogen exosphere cloud seen from above in the direction of the negative  $z$ -axis (perpendicular to the orbital plane). Each point corresponds to a neutral hydrogen (red), or a proton (blue) meta-particle in the slice  $-10^8 \leq z \leq 10^8$  m. The circle without particles correspond to the inner boundary of the simulation, and the large area without protons corresponds to the assumed obstacle to the stellar wind, that is emptied of protons after each time step.

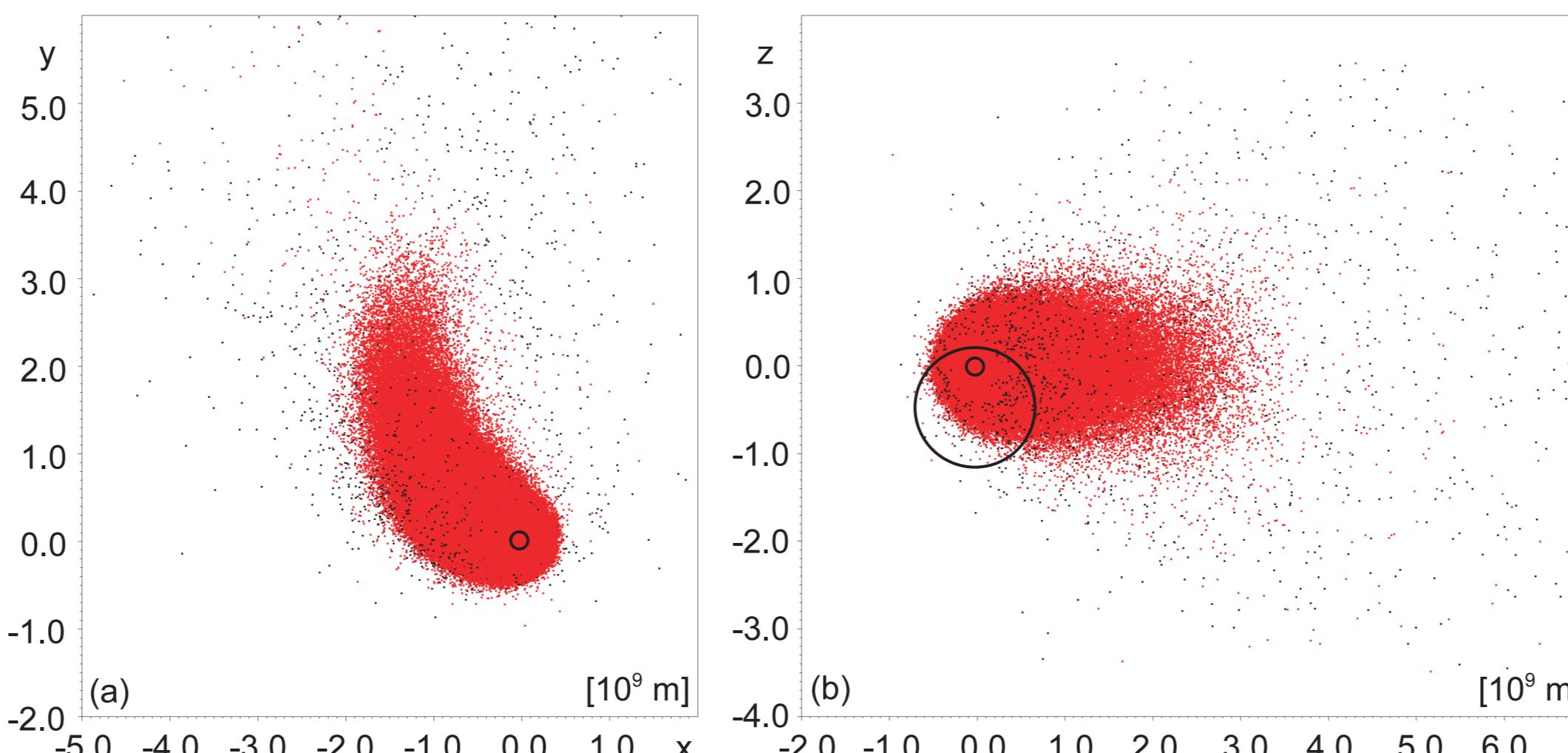


Figure 2: The hydrogen cloud from two different view points. (a) above, perpendicular to the planet's orbital plane, and (b) from Earth, along the  $x$ -axis direction. Each point corresponds to an hydrogen meta-particle. The color of the points show the velocity of the particles along the  $x$ -axis. Particles with velocity magnitude smaller than 50 km/s are red, and those with higher velocity are black. The small circles show the planet size. The large circle in (b) shows the star's position at mid transit. During transit the star moves from left to right in (b). The coordinate system used is centered at the planet with its  $x$ -axis toward the star, and the  $y$ -axis opposite to the planet's velocity.

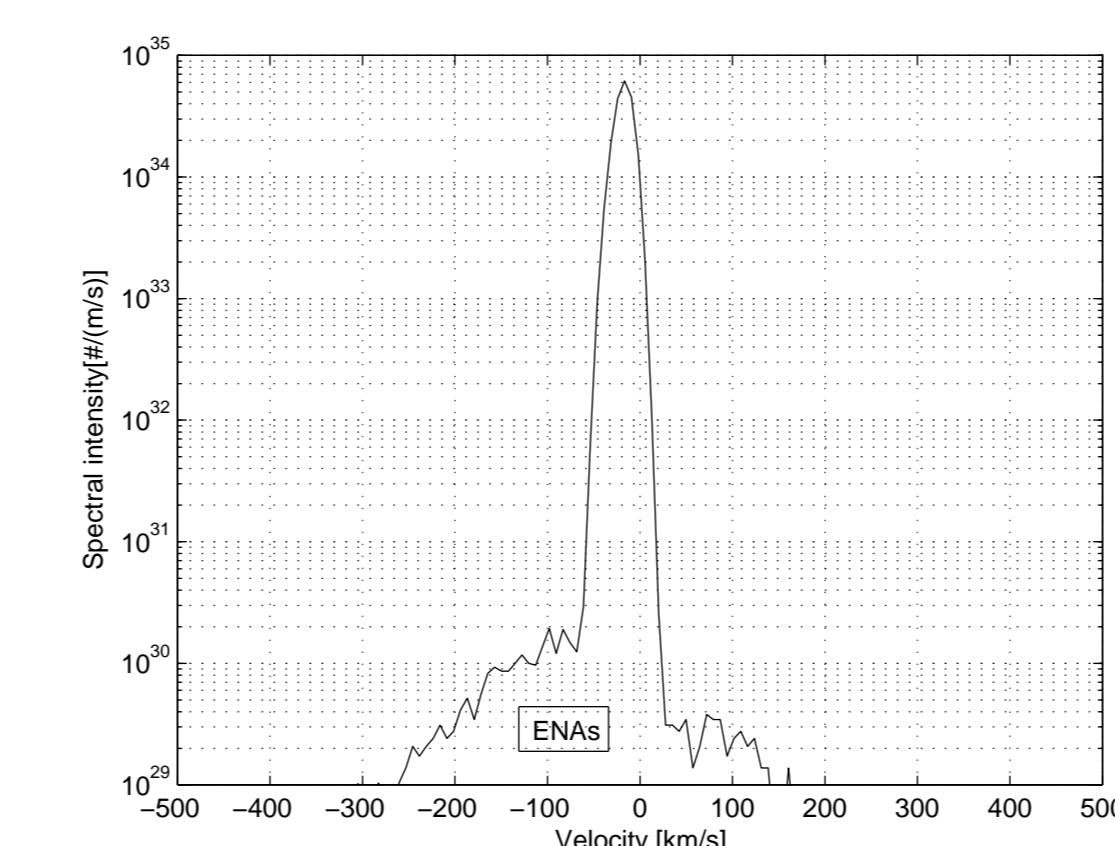


Figure 3: The modeled  $x$ -axis (planet–star) velocity spectrum of hydrogen atoms in front of the star. The width of the ENA part of the distribution is proportional to the temperature of the stellar wind and the center of the distribution follows the stellar wind velocity.

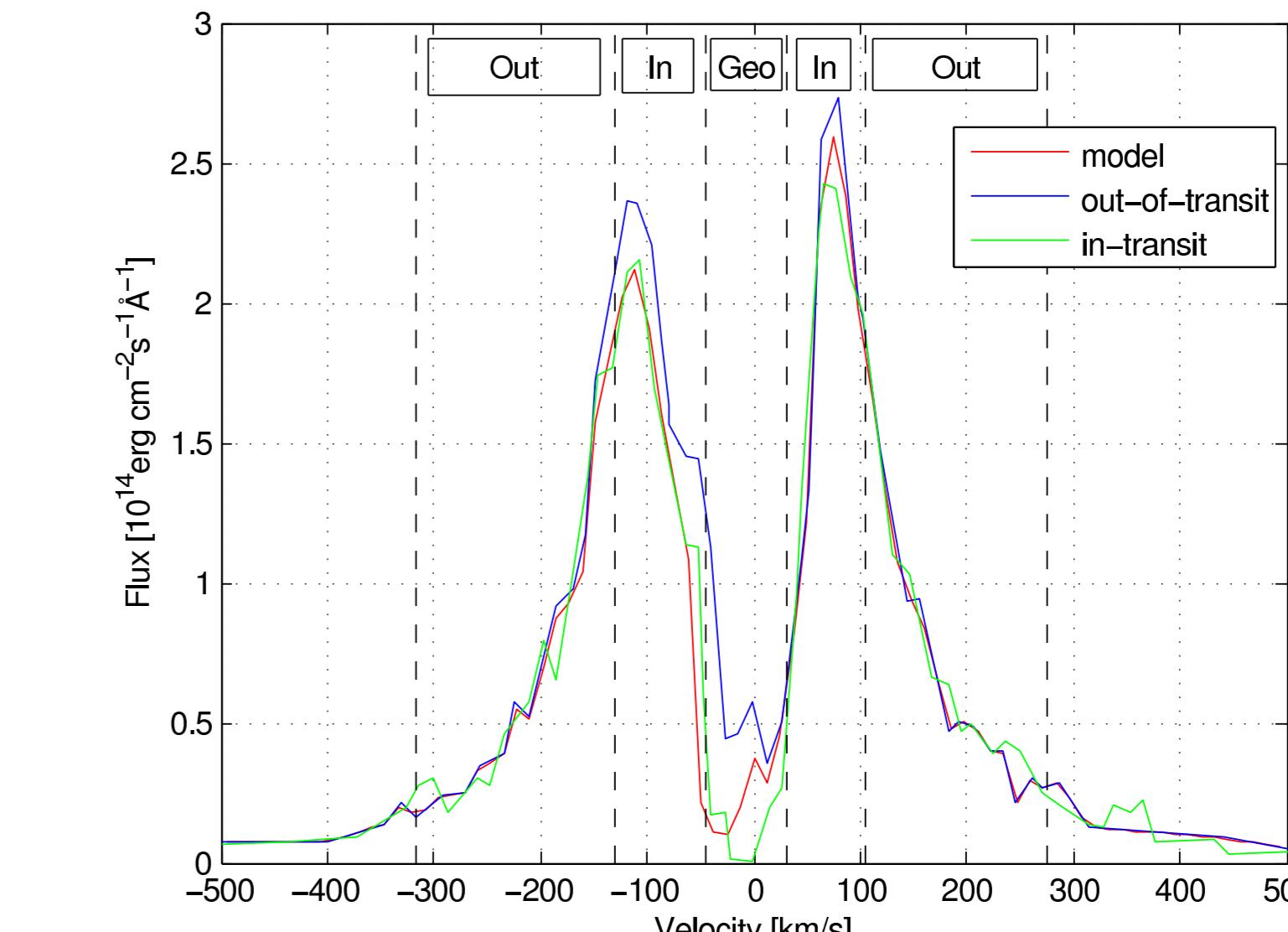


Figure 4: Comparison of the modeled Ly- $\alpha$  profile with the observed ones. In blue is the observed profile before transit. In green is the observed profile during transit. In red is the modeled profile, constructed by applying the attenuations computed from the simulations to the observed profile before transit. The abscissa is the hydrogen velocity along the  $x$ -axis (away from Earth — toward the star). The regions where there is a significant difference between the profiles are denoted 'In' and 'Geo', the latter being the region of geocoronal emission at low velocities that should be excluded.

## Conclusions

- All observed absorptions features are explained by our model
- The absorption features are only explained by ENA production Without ENA production in the model, none of the features are present
- Attenuation in modeled spectrum from -130 to -45 km/s, in agreement with observations
- Attenuation in red part of the spectrum, in agreement with observations
- A completely new technique for observing stellar wind properties at extrasolar planets
- By varying the stellar wind temperature, the stellar wind velocity and the radiation pressure in the model, we find a best fit of the modeled Ly- $\alpha$  absorption to the observation for a stellar wind velocity of 50 km/s, and a temperature of  $10^6$  K, as shown in Fig. 4.

## References

- [1] Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., Ballester, G. E., Ferlet, R., Hébrard, G. & Mayor, M., An extended upper atmosphere around the extrasolar planet HD209458b, *Nature*, 422, 143–146 (2003)
- [2] Ben-Jaffel, L., Exoplanet HD 209458b: Inflated hydrogen atmosphere but no sign of evaporation, *The Astrophysical Journal*, 671, L61-L64 (2007)
- [3] Vidal-Madjar, A. & Lecavelier des Etangs, A., "Osiris"(HD209458b), an evaporating planet, in *Extrasolar Planets: Today and Tomorrow*, ASP Conference Proceedings, Vol. 321. Edited by J.-P. Beaulieu, A. Lecavelier des Etangs, & C. Terquem, 152– (2004). ISBN: 1-58381-183-4
- [4] Vidal-Madjar, A., Désert, J.-M., Lecavelier des Etangs, A., Hébrard, G., Ballester, G. E., Ehrenreich, D., Ferlet, R., McConnell, J. C., Mayor, M., & Parkinson, C. D., Detection of Oxygen and Carbon in the Hydrodynamically Escaping Atmosphere of the Extrasolar Planet HD 209458b, *The Astrophysical Journal*, 604(1), L69-L72 (2004)
- [5] Collier, M. R., et al., Observations of neutral atoms from the solar wind, *Journal of Geophysical Research*, 106(A11), 24906 (2001)
- [6] Futaana, Y., et al., First ENA observations at Mars: Subsolar ENA jet, *Icarus*, 182(2), 413–423 (2006)
- [7] Galli, A., et al., First observation of energetic neutral atoms in the Venus environment, *Planetary and Space Science*, in press (2007)
- [8] Schneider, J., Rauer, H., Lasota, J. P., Bonazzola, S., & Chassefière, E., Brown Dwarfs and Extrasolar Planets, *ASP Conference Series* 134, 241-244 (1998)