Observational constraints on the exospheres and stellar wind interactions of transiting exoplanets

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Overview

- Exospheres of transiting exoplanets
  - Nature paper 2008
  - ApJ paper 2010
- Some technical details
  - Comparison with Wood method
  - Attenuation computations
- Review of recent publications
  - Reanalysis
  - New observations

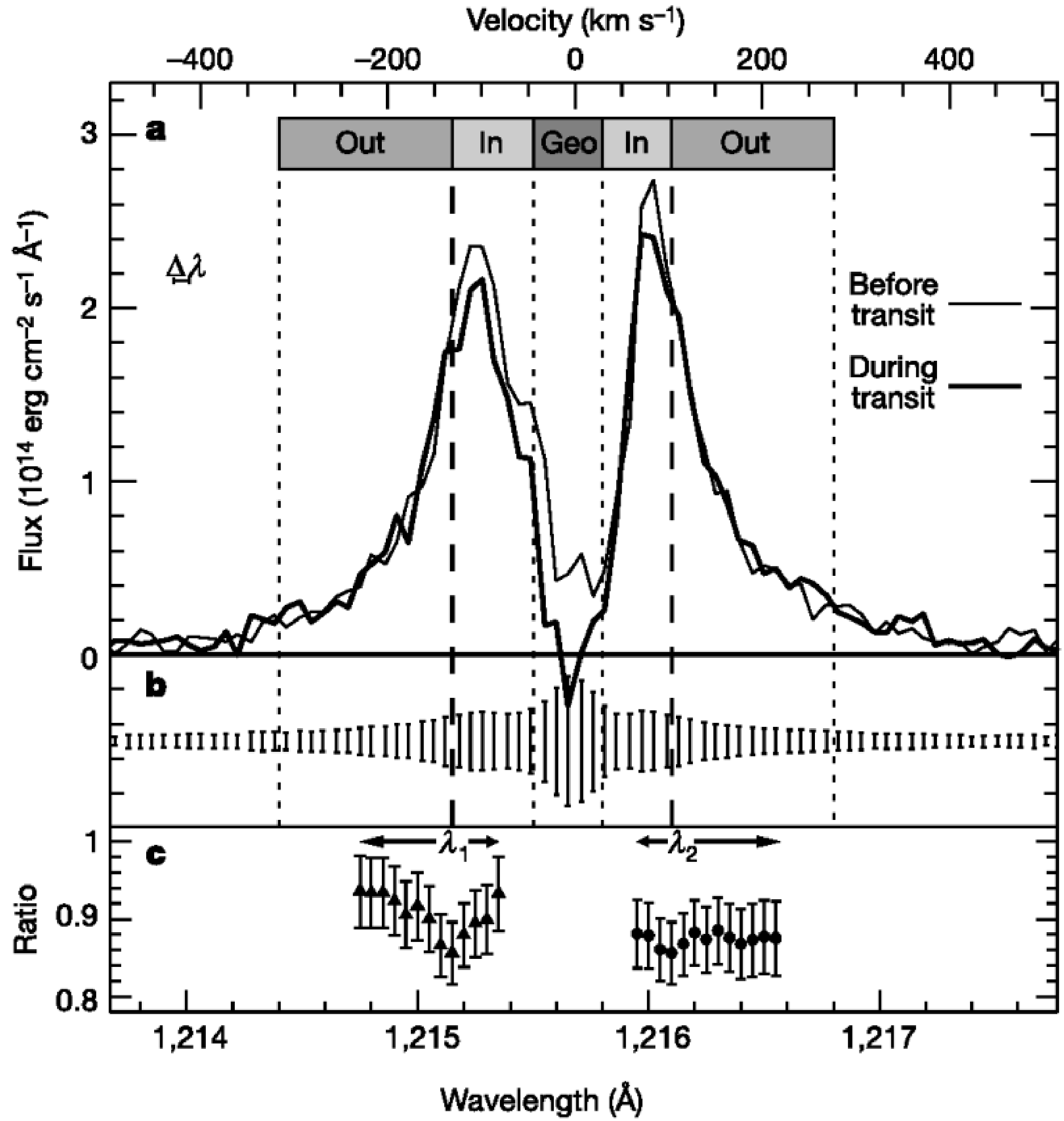
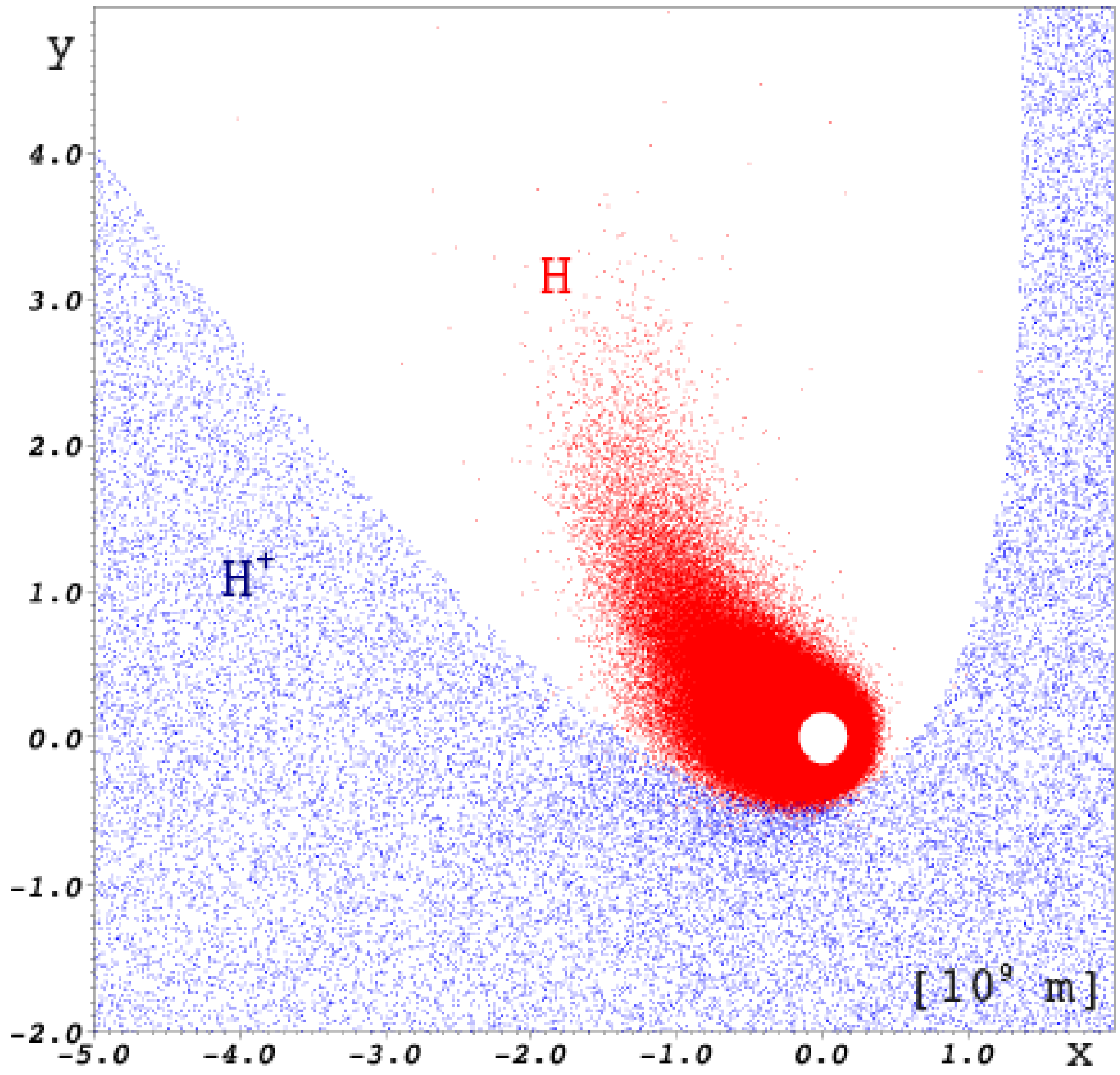


Figure 2 The HD209458 Lyman α profile observed with the G140M grating.

Vidal-Madjar, Nature, 422, 2003


y
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H
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[10⁹ m]
4.0
3.0
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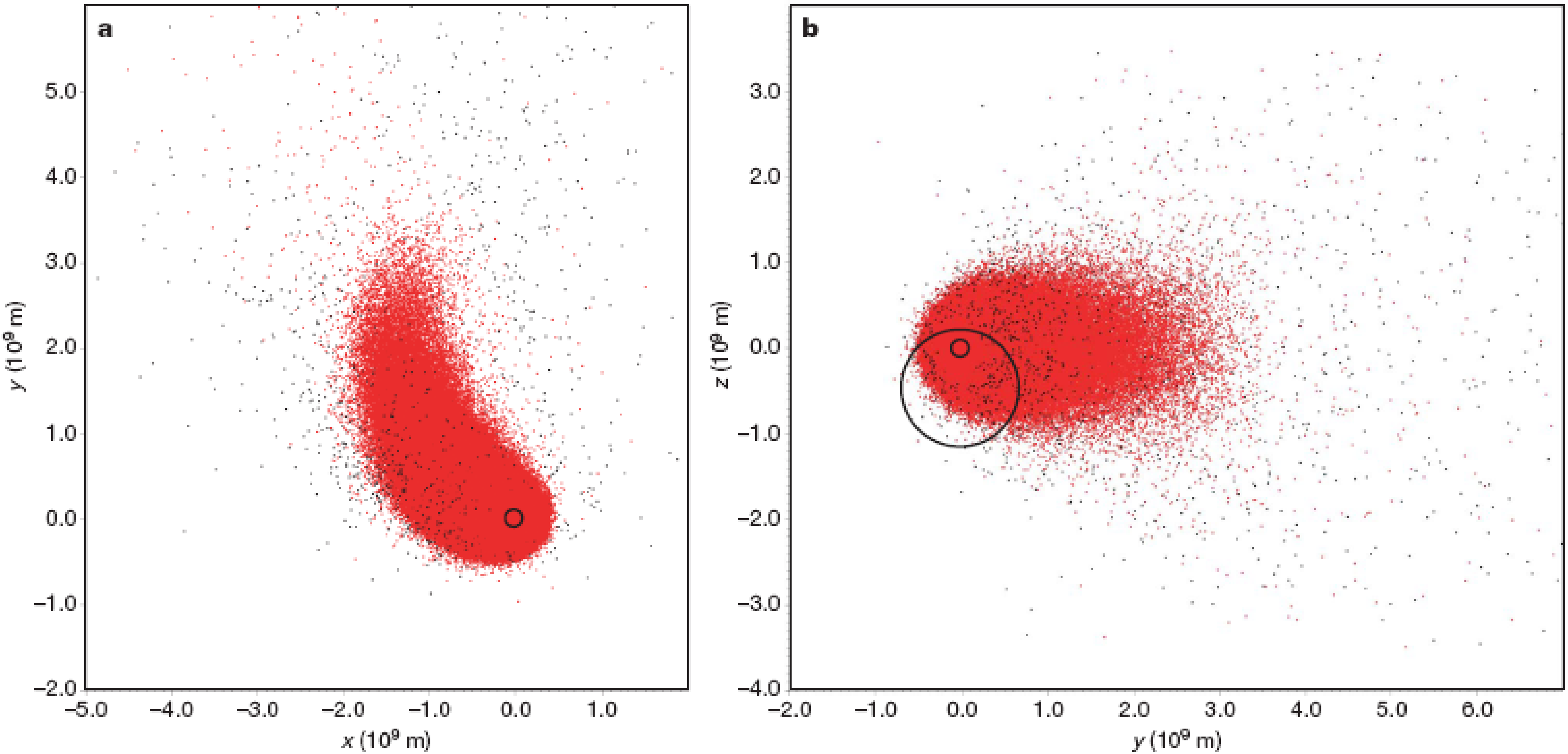

a
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4.0
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y (10^9 m)
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0.0
1.0
x (10^9 m)
b
3.0
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z (10^9 m)
−2.0
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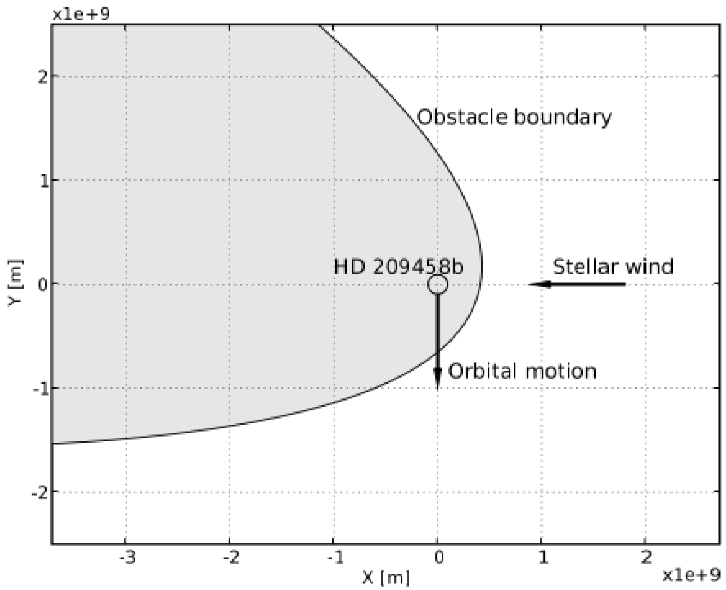
y (10^9 m)

Improved flow model



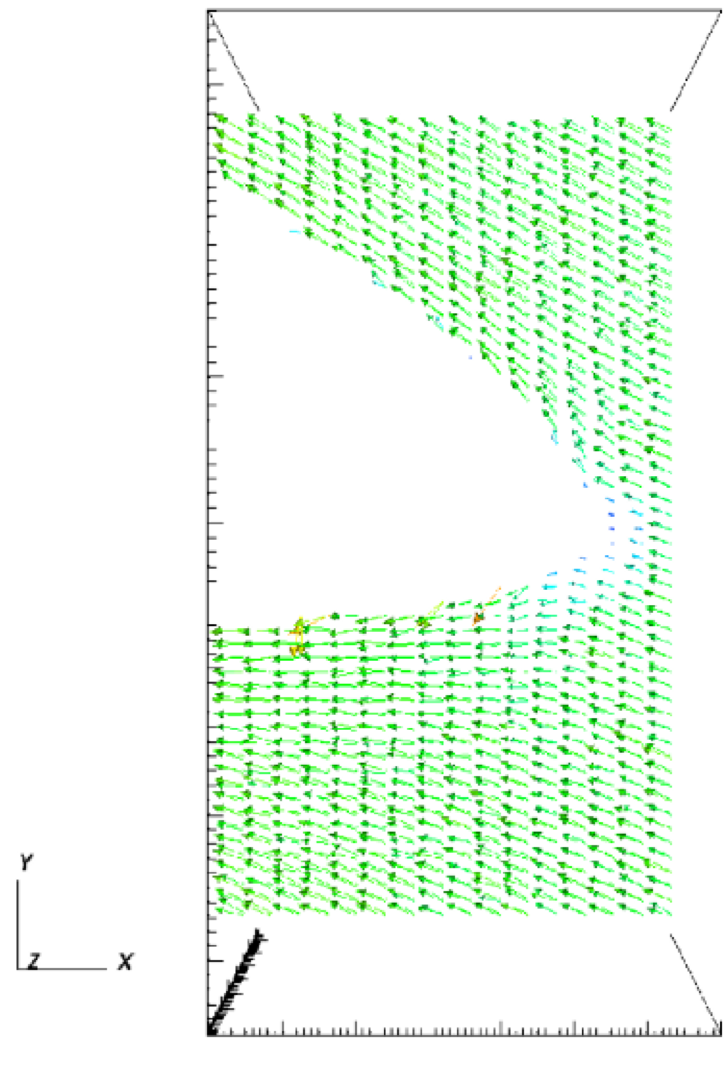


Fig. 3.— Velocity vectors of stellar wind protons in the orbital plane.

=> 350 km/s stellar wind

Ekenbäck et al., ApJ 2010

Three problems for radiation pressure

- A large radiation pressure on the hydrogen atoms is needed to accelerate them to a velocity of 130 km/s before they are photoionized. The acceleration must occur before they move out from the region in front of the star, owing to the orbital motion of the planet.
- If hydrogen atoms were driven to speeds of up to 130 km/s, we would expect the velocity spectrum to have an exponential decay for higher velocities, because photoionization gives the hydrogen atoms a finite lifetime (four hours on average). This drop-off for high velocities is independent of the details of the model, for example the values of radiation pressure and photoionization lifetime used. This would lead to a decay in the absorption spectrum, inconsistent with the observed fairly uniform absorption over the whole velocity range -130 to -45 km/s.
- An exosphere driven by radiation pressure cannot explain hydrogen atoms moving towards the star with speeds between 30 and 105 km/s. However, this feature is not completely certain, and more observations may be needed to clarify whether an absorption is present in the red part of the line (towards the star).

No charge exchange

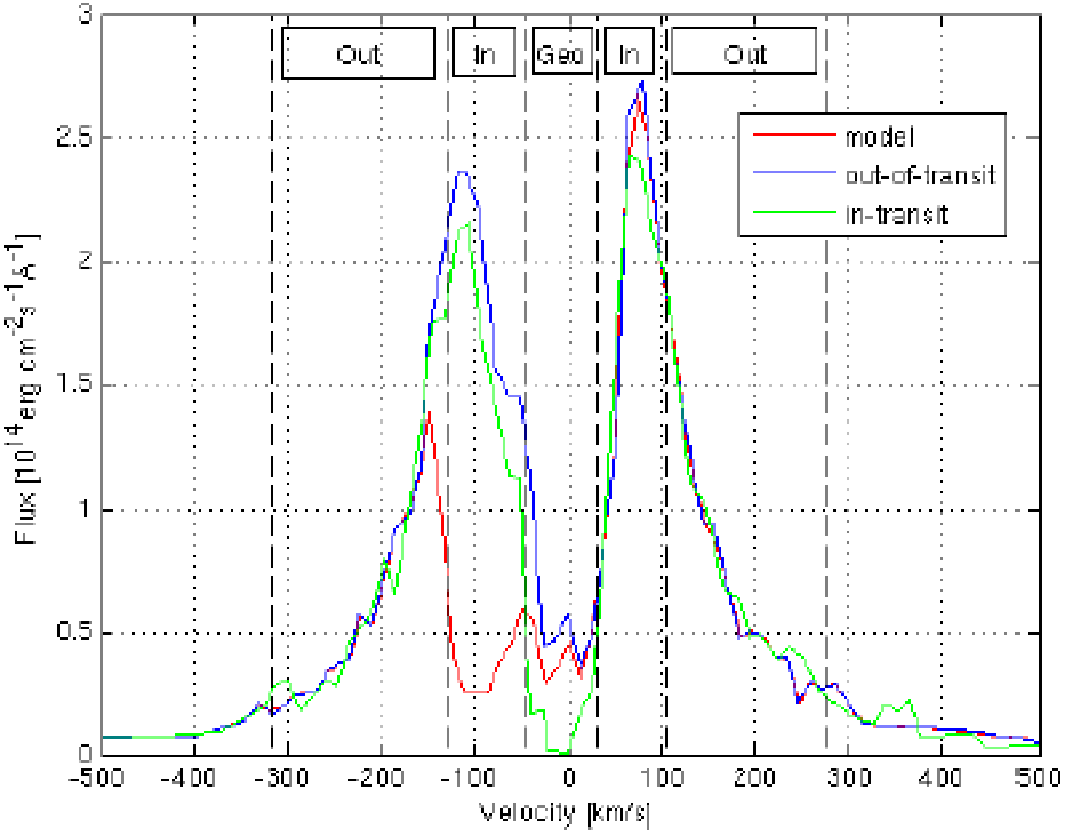
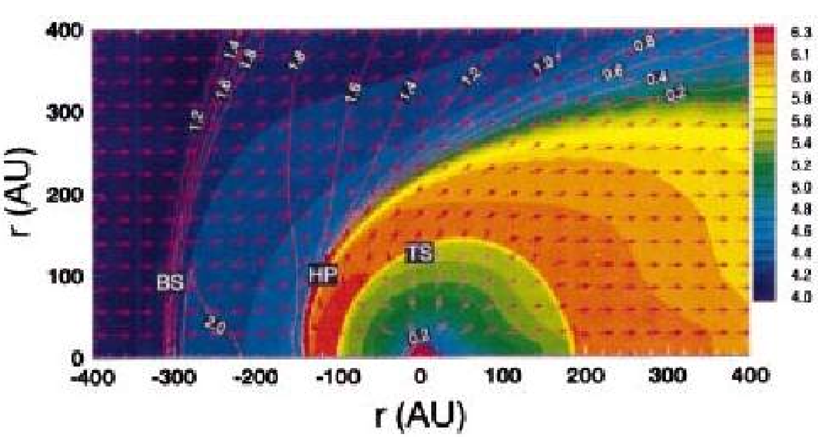


Figure 3: The attenuation spectrum with no ENA production and a larger radiation pressure corresponding to a photon collision rate of 1.4 s^{-1}.

Wood et al., ApJ, 2002

- Assume Ly-a emission spectrum
- Know ISM flow direction
- Use astrosphere flow model



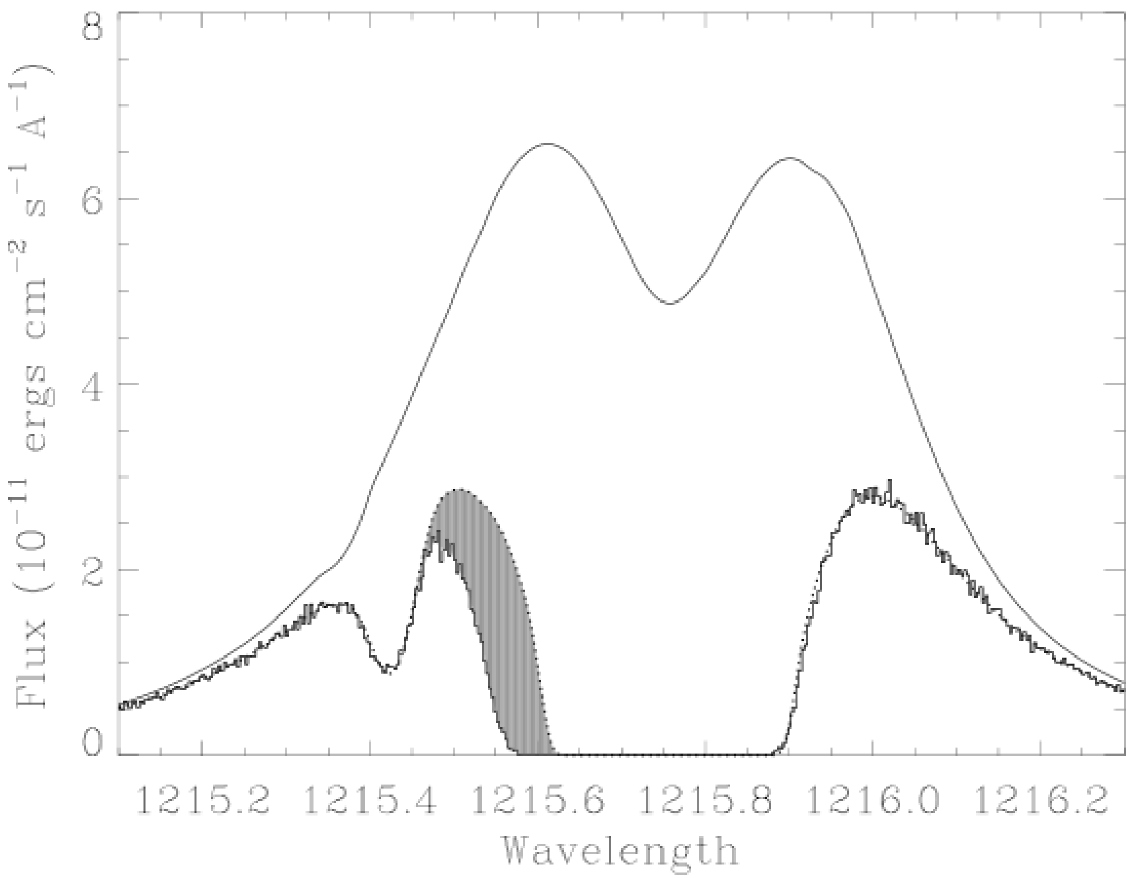


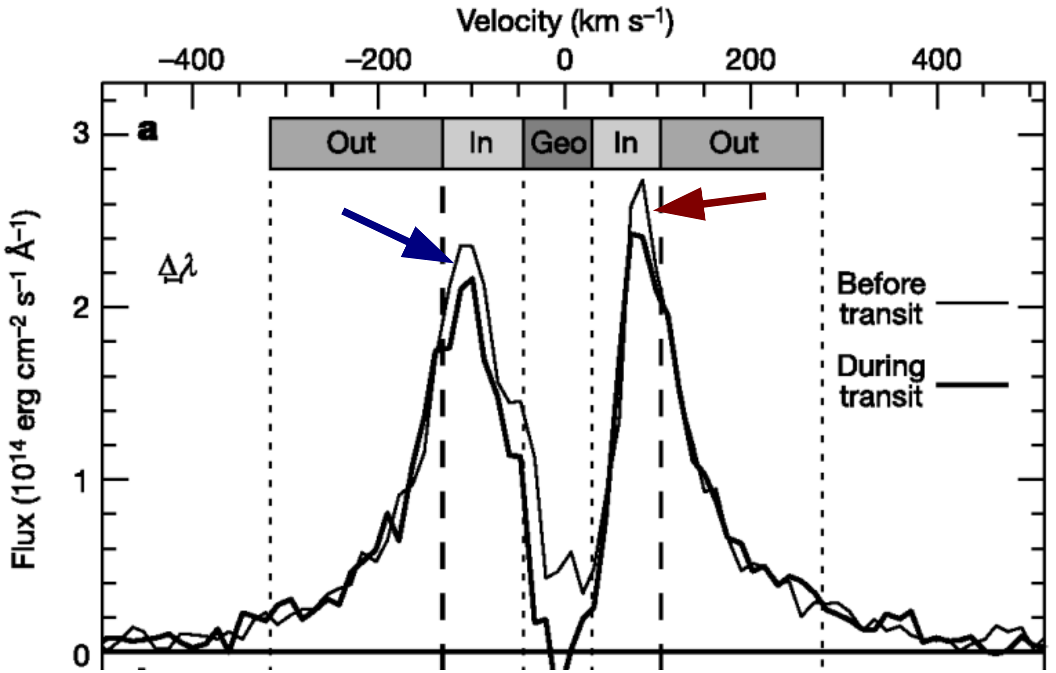
FIG. 1.—*HST*/GHRS Lyα spectrum of ϵ Eri, showing broad H I absorption at 1215.7 Å and narrow D I absorption at 1215.4 Å. The upper solid line is the assumed intrinsic stellar emission line, and the dotted line is the profile after ISM absorption alone, derived by forcing consistency between the ISM H I and D I absorption. The excess H I absorption on the blue side of the line (*shaded region*) is astrospheric absorption.

Transit Ly-a observations

- Direct observation of hot hydrogen

- Important features
  - Red-blue asymmetry?
    - Hydrogen flow toward-away from star (or natural broadening)
  - Time dependence
    - => shape of the hydrogen cloud

Three processes



- Radiation pressure
  - VM. Blue
- Natural broadening
  - BJ. Red and blue, symmetric
- Energetic neutral atoms (ENAs)
  - Blue. Red possible

Time evolution of the Ly-α flux

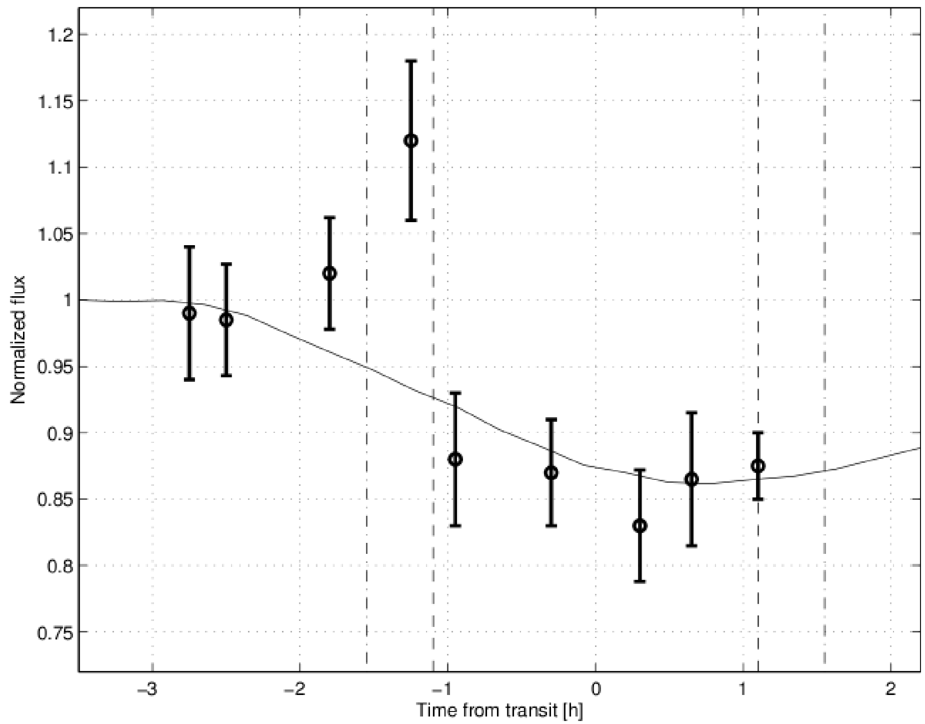
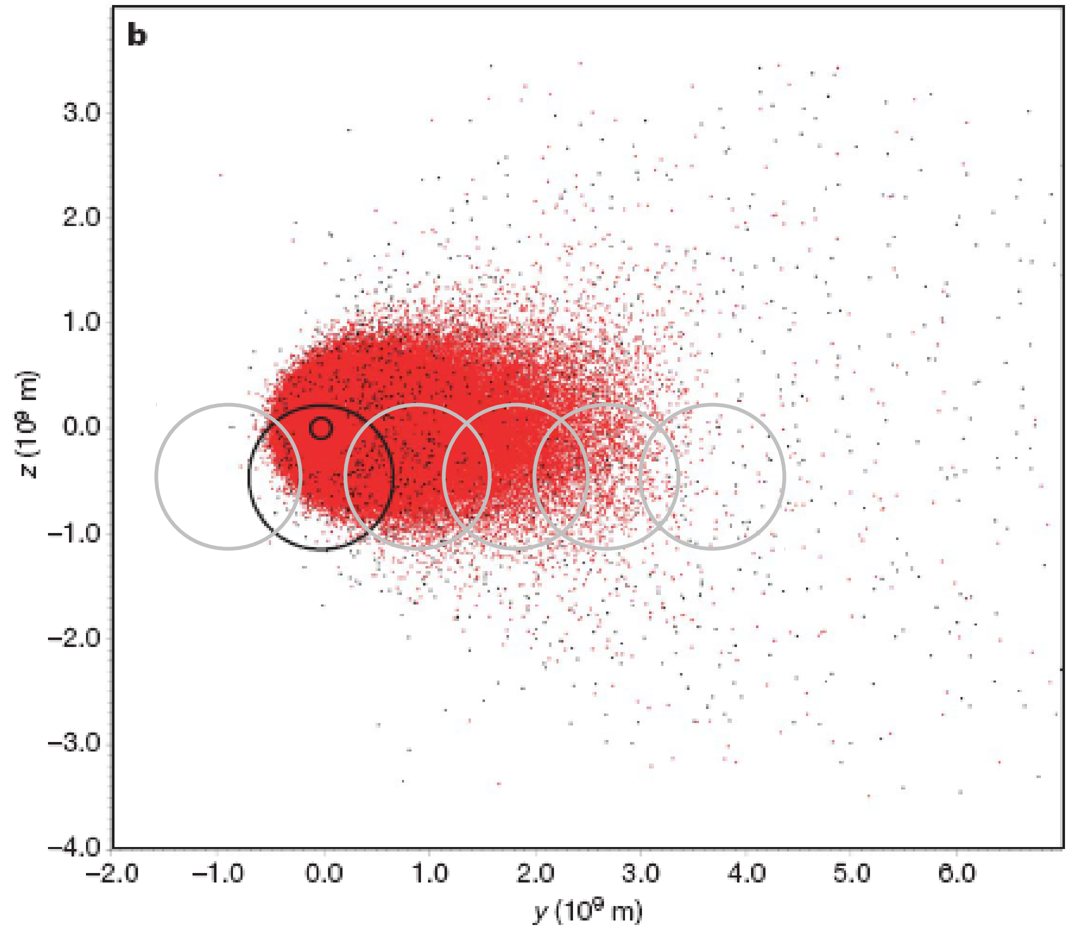
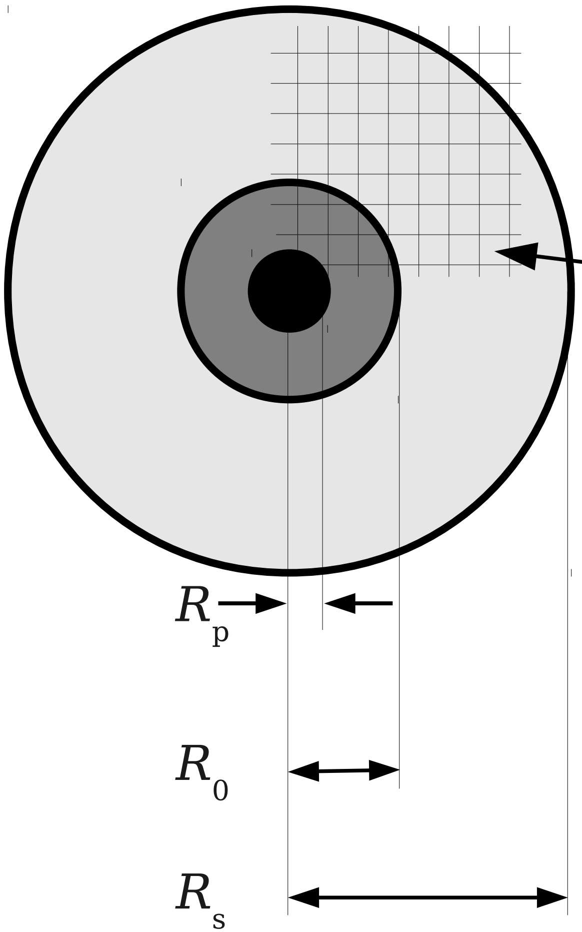


Fig. 7.— Relative flux of Lyman α as a function of HD 209458's system phase. Time is centered around mid-transit. The curve is the attenuation as obtained by our model, and circles with error bars are observational data as reported by Vidal-Madjar et al. (2003). The dashed lines mark the first and second contact at the beginning and end of the transit.



Note: Time evolution is a way around the one pixel problem

An explanation of how the attenuation is computed
in the paper *Energetic neutral atoms around HD 209458b: Estimations of magnetospheric properties*, Ekenbäck et al.



For each "pixel" the attenuation as function of velocity (wavelength) is computed. Then the attenuation is averaged over all pixels. This average attenuation is then applied to the undisturbed star spectrum (the out of transit spectrum) to produce the model spectrum.

The attenuation = 1 for pixels covering the planet

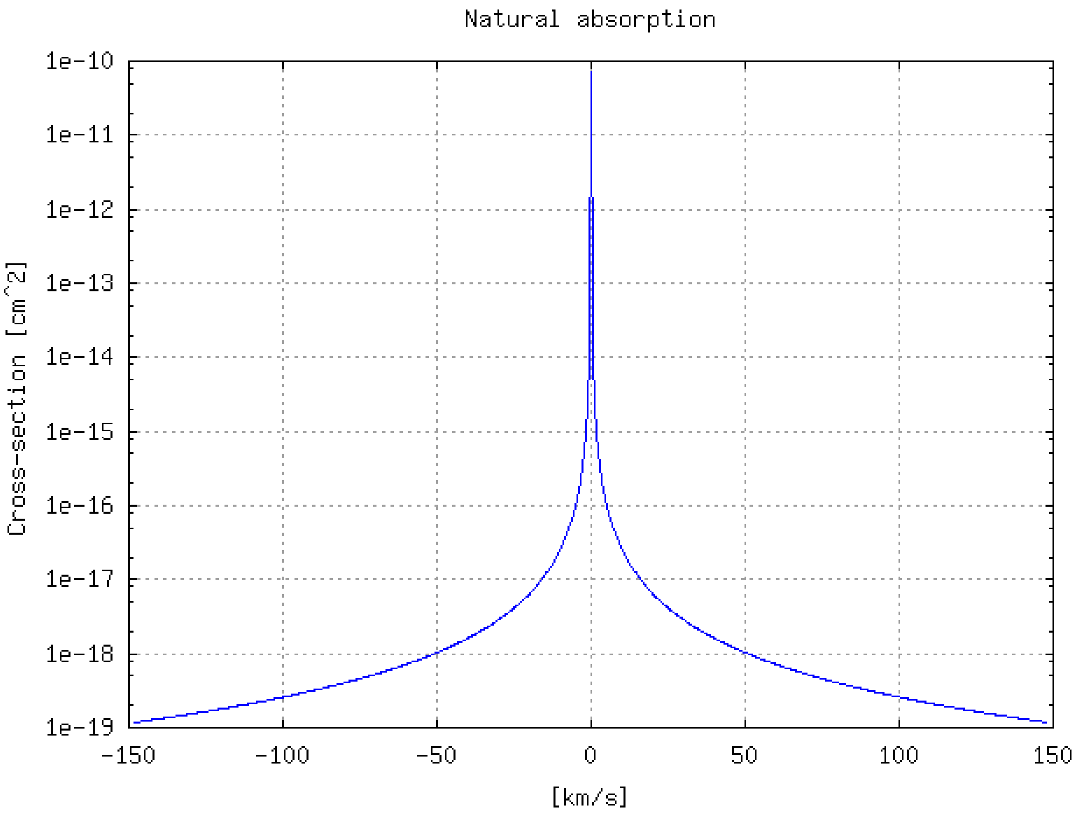
To account for Doppler broadening by the atmosphere we add to all pixels inside the inner boundary at R_0 a Maxwellian velocity spectrum corresponding to a hydrogen gas with a specified column density, *n,* and a temperature of 10^4 K.

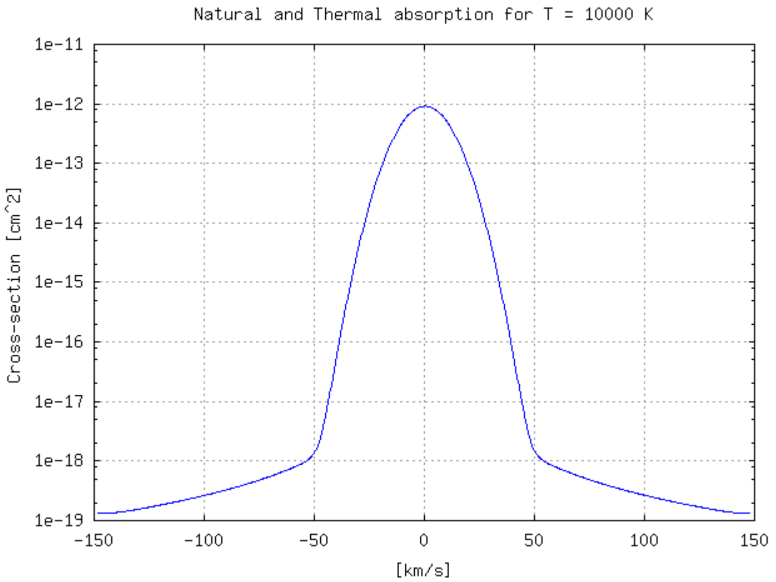
The attenuation in each pixel is computed from the velocity spectrum of all hydrogen atoms in the simulation model. To account for natural broadening, the velocity spectrum is then convolved with a Lorentz function [1, 2].

R_p: Planet radius
R_0: Inner boundary radius
R_s: Star radius

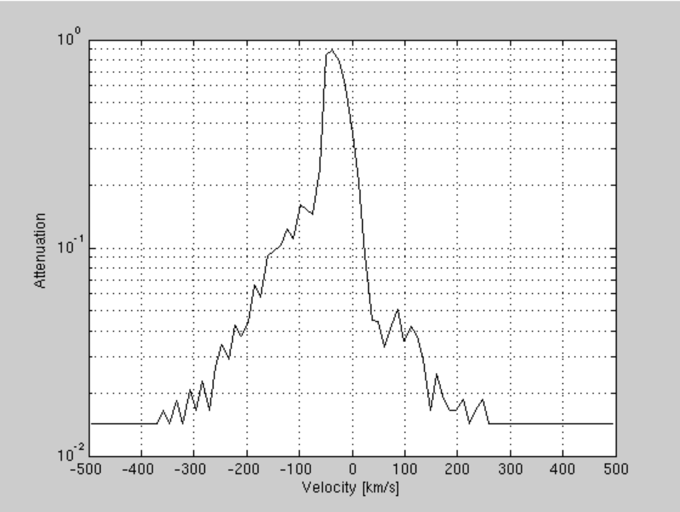
[1] Principles of Physical Cosmology, P.J.E. Peebles, Princeton University Press, 1993. p. 573.
[2] Michael R. Santos, Probing reionization with Lyman-alpha emission lines, Mon.Not.Roy.Astron.Soc.349:1137,2004

Natural broadening

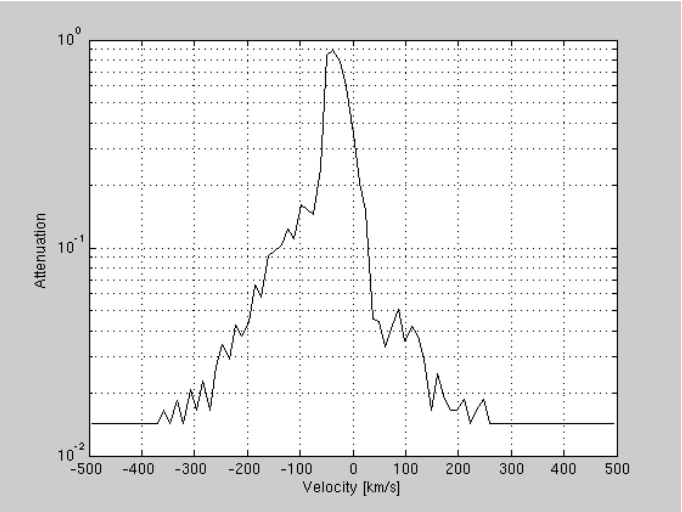




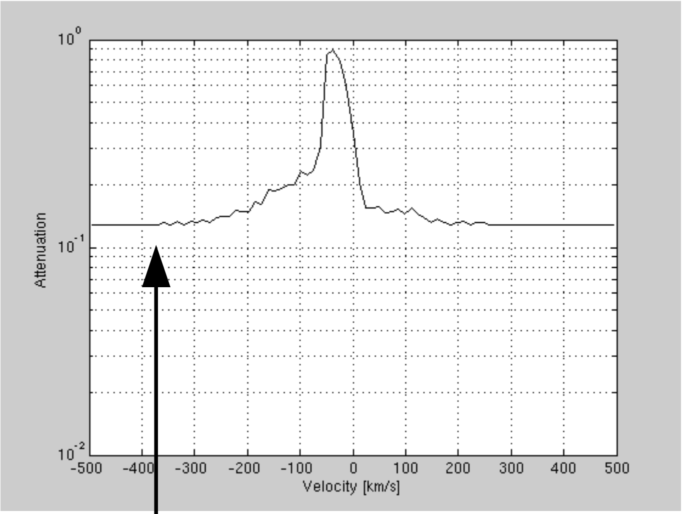
Different column densities in the atmosphere,
now including natural broadening



n = 0 cm^{-2}



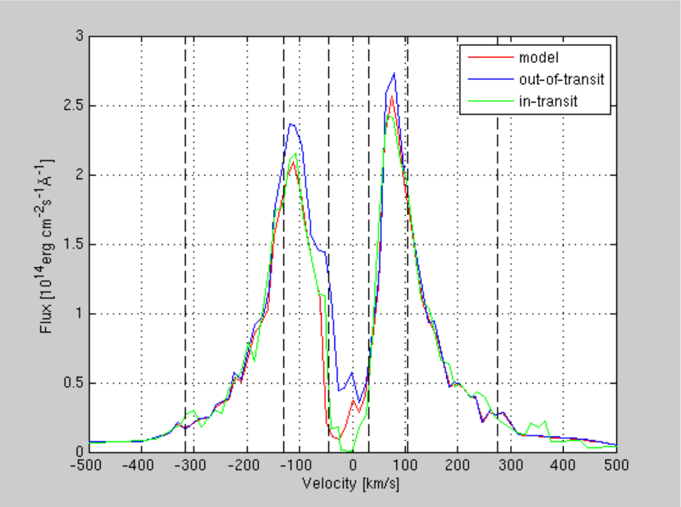
n = 1e17 cm^{-2}



n = 1e27 cm^{-2}

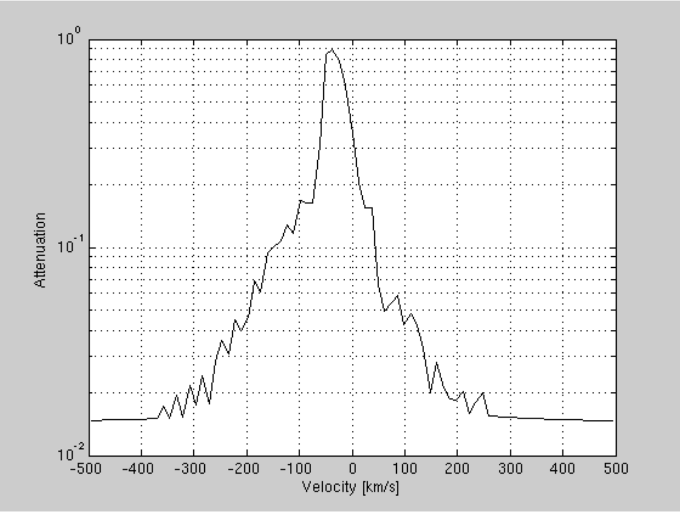
At very large column densities the Lorentz wings becomes noticable

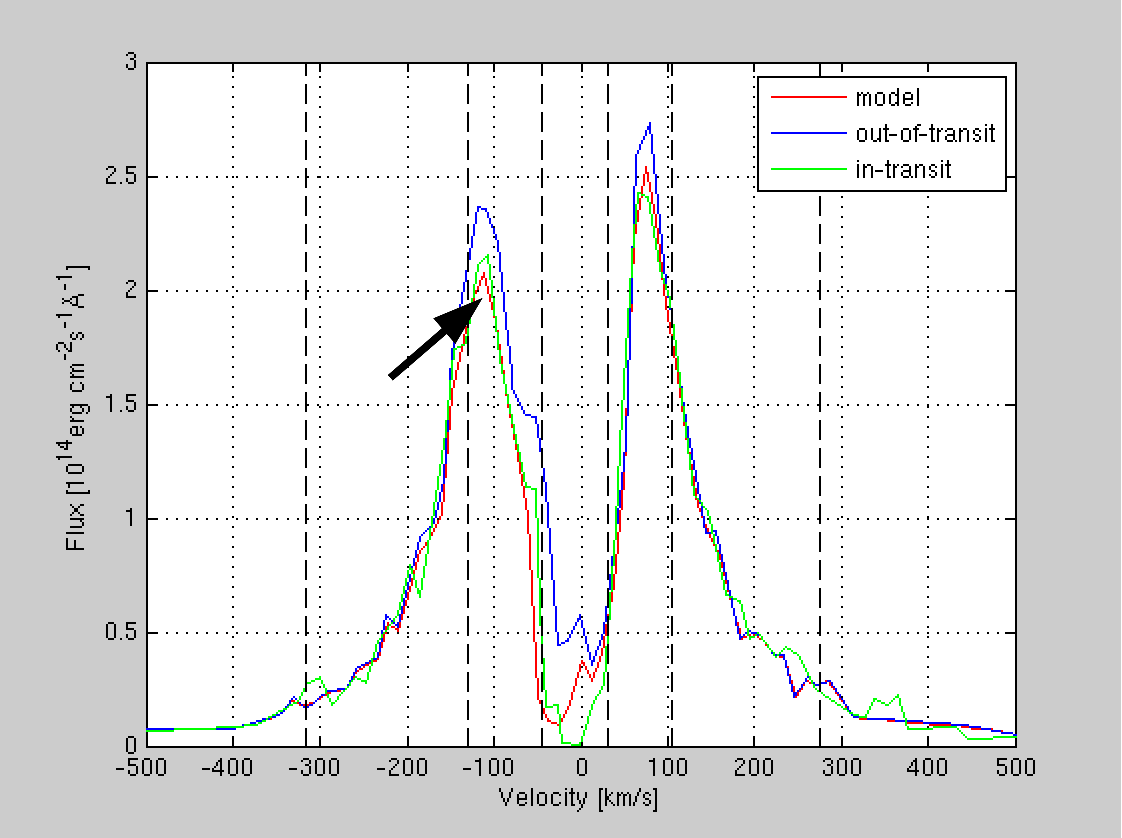
There is no visible effect on the final spectrum for n = 1e17 cm^{-2}



At what column density is an effect seen?

At about 1e20 cm^{2} we see an effect (slight reduction)

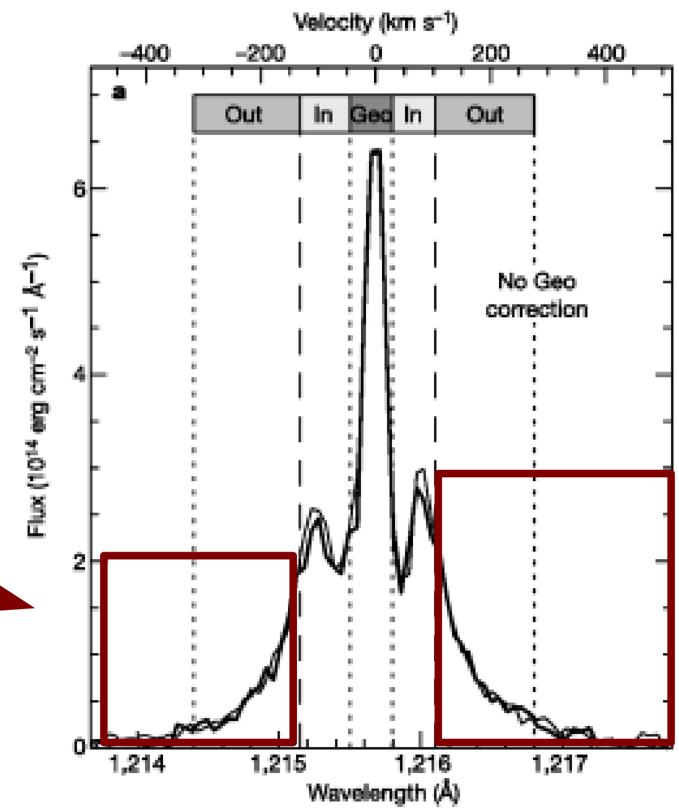




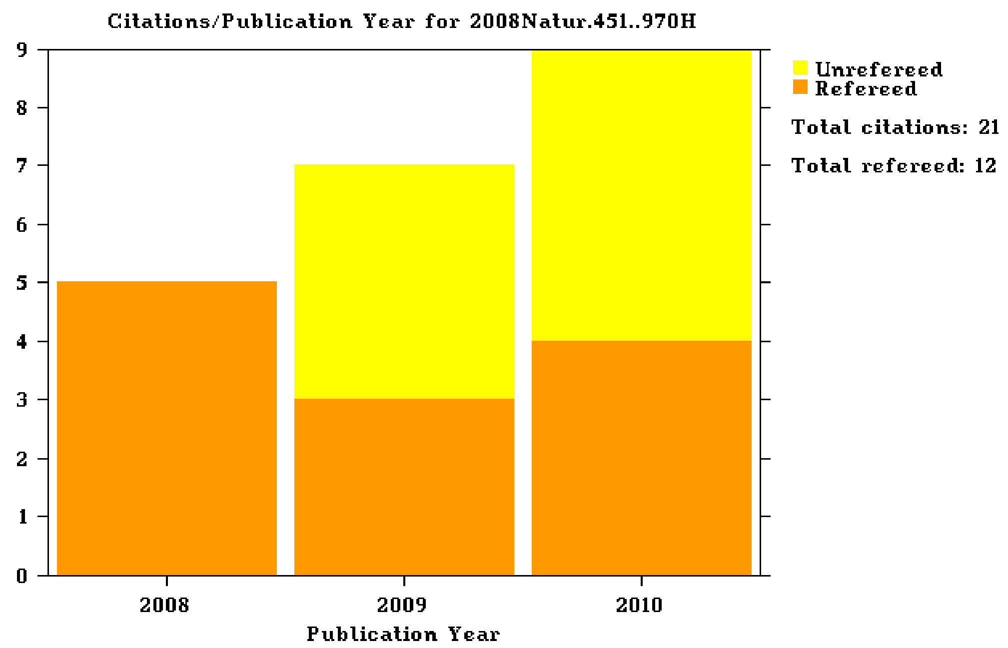
Natural broadening **not** important

- No transit effect on highest velocities puts an upper limit on the effect of natural broadening

- If broadening was important, the out regions would be affected



Citations of Holmström et al., Nature, 2008



http://adsabs.harvard.edu/abs/2008Natur.451..970H

Jackson	2010	ArXiv	The Roles of Tidal Evolution and Evaporative Mass Loss in the Origin of CoRoT-7 b
Lai	**2010**	**ArXiv**	**Mass transfer, transiting stream and magnetopause in close-in exoplanetary systems with appl**
Linsky	**2010**	**ArXiv**	**Observations of Mass Loss from the Transiting Exoplanet HD 209458b**
Fossati	**2010**	**ApJ**	**Metals in the Exosphere of the Highly Irradiated Planet WASP-12b**
Shematovich	2010	SSR	Suprathermal hydrogen produced by the dissociation of molecular hydrogen in the extended atm
Koskinen	2010	ArXiv	Characterizing the thermosphere of HD209458b with UV transit observations
Lecavelier des Etangs	**2010**	**ArXiv**	**Evaporation of the planet HD189733b observed in HI Lyman-alpha**
Ribas	2010	IAU	The Sun and stars as the primary energy input in planetary atmospheres
Ben-Jaffel	**2010**	**ApJ**	**On the Existence of Energetic Atoms in the Upper Atmosphere of Exoplanet HD209458b**
Ekenbäck	2010	ApJ	Energetic Neutral Atoms Around HD 209458b: Estimations of Magnetospheric Properties
Fortney	2009	ArXiv	Giant Planet Interior Structure and Thermal Evolution
Campanella	2009	ArXiv	The search for exomoons and the characterization of exoplanet atmospheres
Khodachenko	2009	IAU	The role of intrinsic magnetic fields in planetary evolution and habitability: the planetary
Murray-Clay	2009	ApJ	Atmospheric Escape From Hot Jupiters
Johansson	2009	A&A	Consequences of expanding exoplanetary atmospheres for magnetospheres
Cecchi-Pestellini	2009	A&A	The relative role of EUV radiation and X-rays in the heating of hydrogen-rich exoplanet atmo
Tinetti	2009	IAU	The extrasolar planet atmosphere and exosphere: Emission and transmission spectroscopy
Ben-Jaffel	2008	ApJ	Spectral, Spatial, and Time Properties of the Hydrogen Nebula around Exoplanet HD 209458b
Lecavelier Des Etangs	2008	Nature	The origin of hydrogen around HD 209458b
Holmström	2008	Nature	Holmström et al. reply
Sengupta	2008	ApJ	Cloudy Atmosphere of the Extrasolar Planet HD 189733b: A Possible Explanation of the Detecte
Ehrenreich	2008	A&A	New observations of the extended hydrogen exosphere of the extrasolar planet HD 209458b

Linsky et al., 2010

- HD 209458b
- Using new COS on Hubble (HST)
- Observed velocity structure for C and Si
  - advantage to Ly-a: low velocities can be observed
- 8% transit depth (1.5% optical)
- Observation of Ly-a (or O) not possible (geocorona)

Absorption of Lyman-α photons during transit over the velocity range –130 to +100 km s^{-1} raises the question of the origin of the high-velocity hydrogen that is difficult to explain by a thermal plasma at moderate temperature. Holmström et al. (2008) proposed that the high-velocity neutral hydrogen can be produced by charge exchange between stellar wind protons and neutral hydrogen in the planet's outflow. Such energetic neutral atoms (ENAs) are seen in the solar system and likely occur where the stellar and planetary winds interact between HD 209458b and its host star. If this were the only possible explanation, then the Lyman-α profile during transit provides useful information on the stellar wind but ambiguous information on mass loss from the planet (Holmström et al. 2008; Murray-Clay et al. 2009). However, Lecavelier des Etangs et al. (2008) argued that the observed Lyman-α profile and the high-velocity hydrogen atoms can be simply explained by stellar radiation pressure and the ENA explanation required a peculiar stellar wind model.

Non-thermal velocity structure

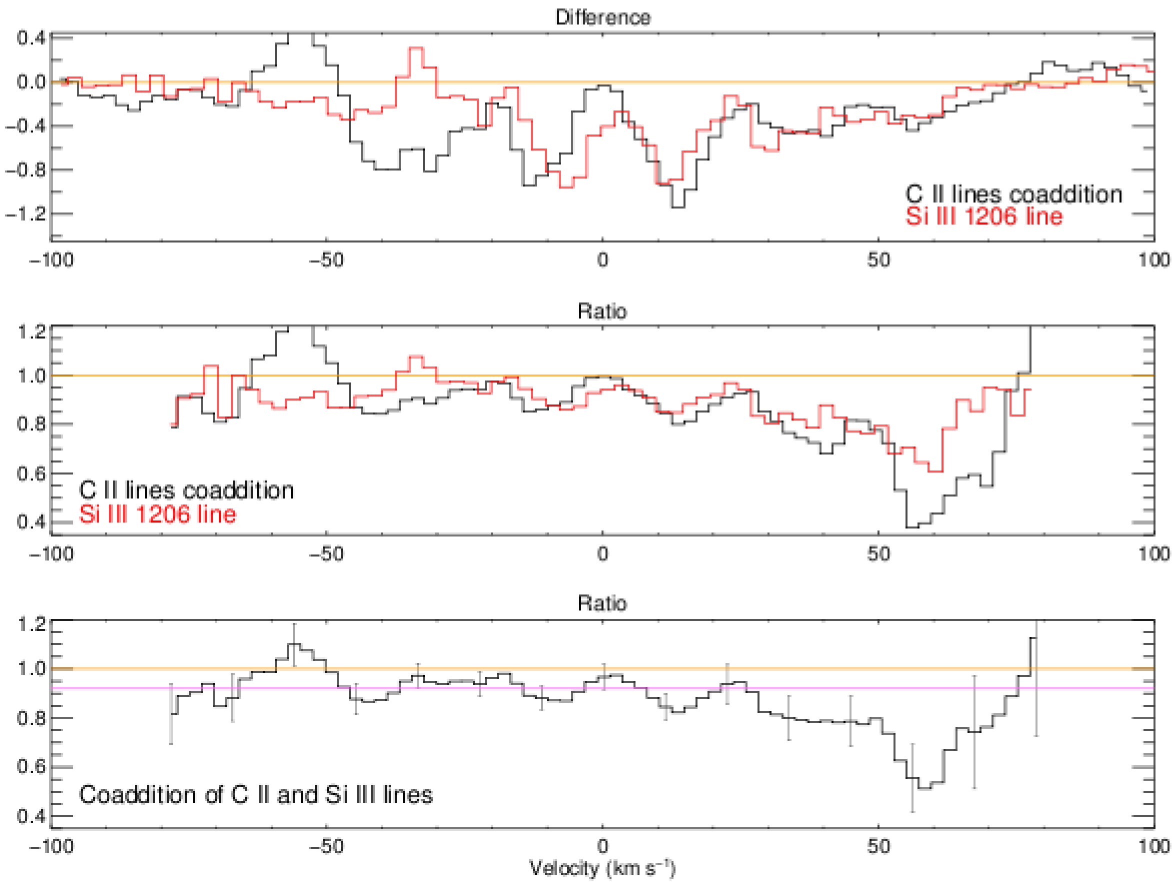


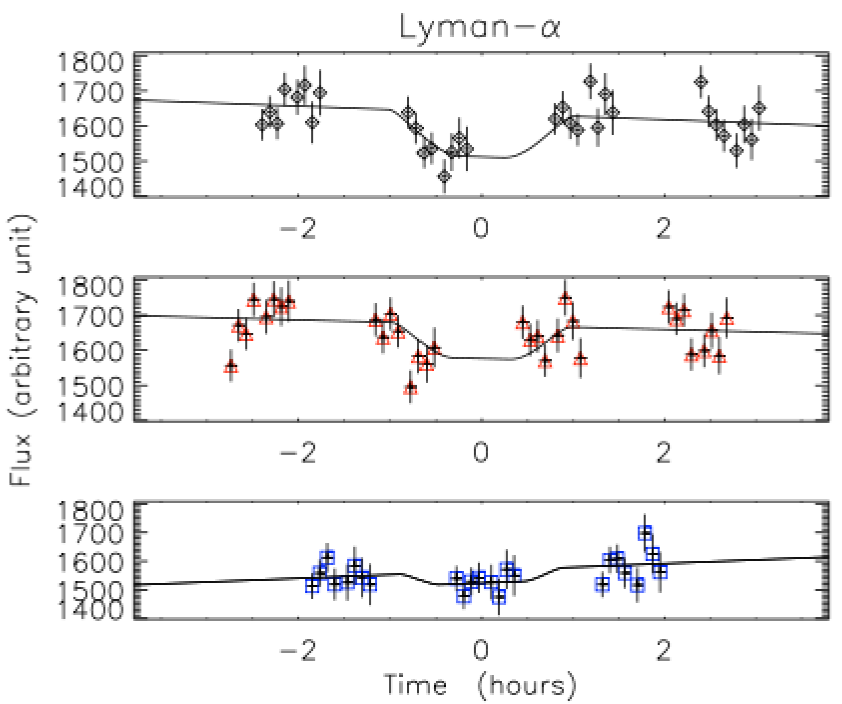
Fig. 4.— Upper and middle panels: Comparison of the difference spectra (transit minus non-transit) and ratio spectra (transit/non-transit) for the co-addition of the C II Lines (black) and the Si III line (red). Lower panel: Co-addition of the C II and Si III ratio spectra with typical errors per spectral resolution element (about 17 km s^{-1}). The horizontal line at 0.92 is the mean ratio for the velocity interval –50 to +50 km s^{-1}. The dips near –10 and +15 km s^{-1} are each more than 2σ and likely real. The low ratio features near –40 and +30–70 km s^{-1} occur where the line fluxes are low and are thus less certain.

Note: Away from Star

Lecavelier des Etangs et al., A&A, 2010

- Very hot Jupiter HD 189733b
- Non-resolved observation using HST/ACS
- Three transits
- 5% Ly-a transit depth (2.5% optical)

Variability



1 wk

1 yr

Fig. 4. Lyman-α flux as a function of time during three transits of HD 189733b. Different colors and symbols are for different epochs. The measurements in black diamonds, red triangles, and blue squares are for the 1st, 2nd, and 3rd transits, respectively. The curve shows the best fit to the data assuming a linear baseline and an optically-thick disk transiting the star. The transit depth (defined by the size of the occulting disk) is free to vary from one transit to another.

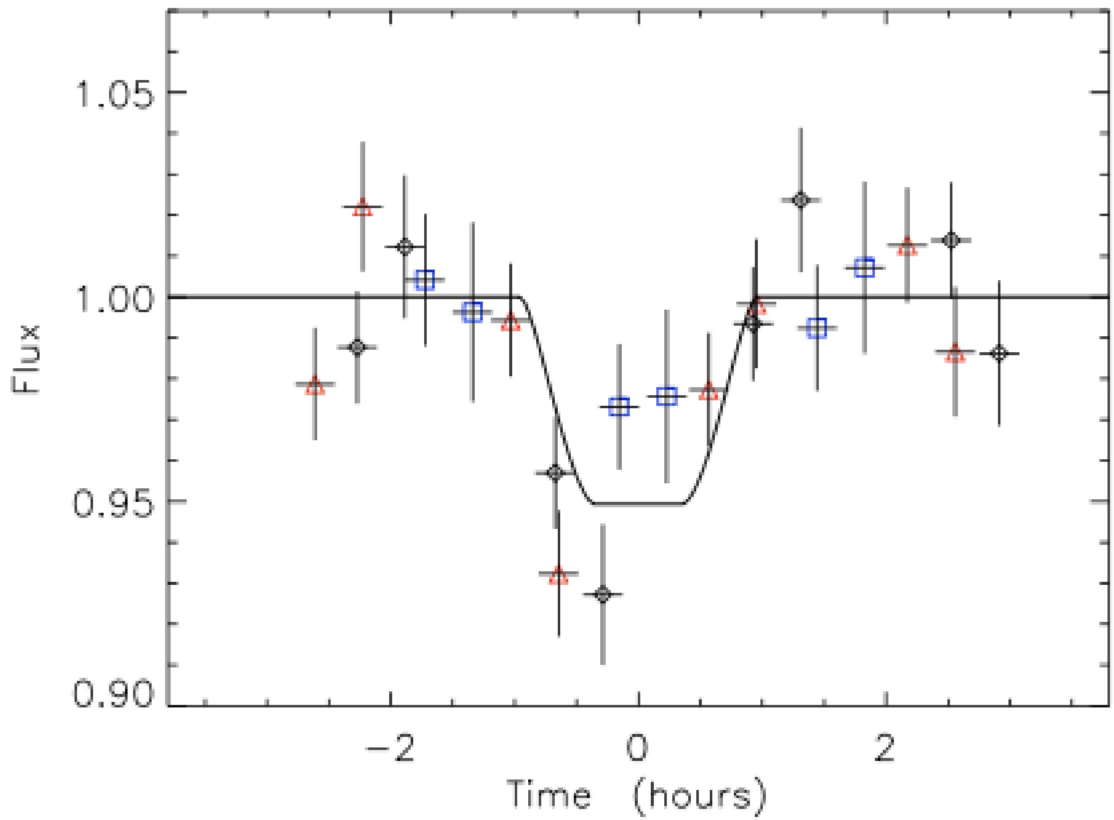


Fig. 6. Same as previous plot in which the data have been rebinned by four. The possible difference of transit depth between different epochs are visible here.

Model

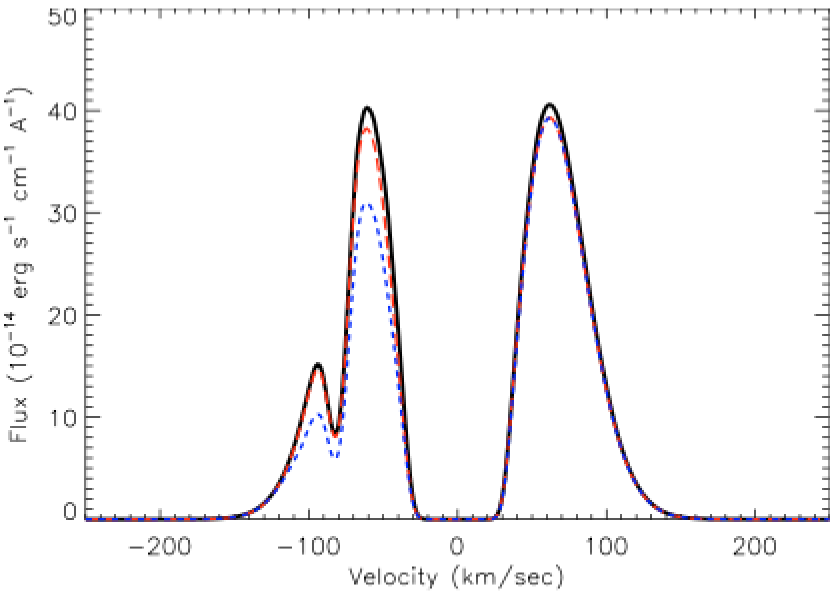


Fig. 10. Plot of the theoretical spectrum of the Lyman-α line of HD 189733. The line shape takes the absorption by the interstellar medium hydrogen and deuterium into account (black thick line). Two different spectra, including absorption by the planetary exophere when it passes in front of the star, are superimposed (dashed lines). The blue short-dashed line shows the resulting spectrum when the escape rate is 3×10^{8} g s^{-1} and the ionizing EUV flux is 0.1 times the solar value. With these values, in particular the low EUV flux, the blue side of the line is absorbed by about 25%, resulting in a decrease of about 13% in the total Lyman-α flux. The red long-dashed line shows the theoretical spectrum of the Lyman-α line during transit for an escape rate of 10^{10} g s^{-1} and an ionizing EUV flux 20 times the solar value. In this last case, the total Lyman-α flux decreases by about 5% when the exosphere passes in front of the star.

Comment and *Reply*

- Radiation pressure can explain the spectrum
  - *Not in our model. Unresolved model difference*
- ENA production requires significant escape
  - *No, ENA production will occur independently of a large or small thermal escape rate*

Nature, Vol 456, 13 November 2008

The origin of hydrogen around HD 209458b

Arising from: M. Holmström *et al. Nature* **451**, 970–972 (2008)

Using numerical simulation, Holmström *et al.*[1] proposed a plausible alternative explanation of the observed Lyman-α absorption that was seen during the transit of HD 209458b (ref. 2). They conclude that radiation pressure alone cannot explain the observations and that a peculiar stellar wind is needed. Here we show that radiation pressure alone can in fact produce the observed high-velocity hydrogen atoms. We also emphasize that even if the stellar wind is responsible for the observed hydrogen, to have a sufficient number of atoms for charge exchange with stellar wind, the energetic neutral atom (ENA) model also needs a significant escape from the planet atmosphere of similar amplitude as quoted in ref. 2.

The simulation of ref. 1 is aimed at reproducing the observed absorption spectrum in Lyman-α with 15 ± 4% absorption between −130 and 100 km s^{-1} (refs 2, 3). A mechanism is needed to produce hydrogen atoms at these high velocities exceeding the planet escape velocity. We previously proposed that hydrogen atoms in the exosphere are naturally accelerated by the stellar radiation pressure[2,4]; however, Holmström *et al.*[1] concluded that radiation pressure alone cannot explain the observation. Nonetheless, in their work, the strength of the radiation pressure has been artificially reduced to a value 2 to 5 times lower than the solar value, whereas the observed Lyman-α line strength and profile shows that it is significantly larger than the solar value. The low radiation pressure assumed by Holmström *et al.*[1] is valid only at high radial velocity. However, if low radiation pressure is assumed, high velocities are not reached, which therefore explains the different conclusion reached by Holmström *et al.*[1]. We believe that the treatment of the link between the radiation pressure and radial velocity needs to be corrected.

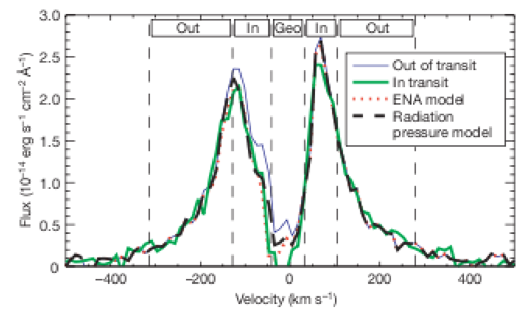


Figure 1 | Comparison of modelled with observed Lyman-α profiles as in Fig. 3 of ref. 1. The thin blue line and the thick green line are for the observed profile before and during the transit, respectively. The red dotted line is for the modelled profile from the ENA model with reduced radiation pressure. The black dashed line is for the modelled profile computed using a model with radiation pressure. This last profile fits the data well with a χ^2 of 45 for 40 degrees of freedom. As the profile for the radiation pressure model is similar to the one for the ENA model, neither possible model can be favoured. Radiation pressure cannot be excluded as an explanation for the observed spectrum. Geo, the wavelength domain contaminated by the geocoronal airglow.

To show that the radiation pressure can explain the observed spectrum, we calculated the modelled Lyman-α profile with radiation pressure alone, in the same way as done in Fig. 3 of ref. 1 for the ENA model. This calculation is done taking into account the strength and profile of the Lyman-α line, and the corresponding variation of radiation pressure as a function of radial velocity. Planetary and stellar gravities are also included. These differences explain the different results obtained with radiation pressure alone in the two models. The result plotted in Fig. 1 shows that the resulting profiles are similar in the two models (radiation pressure alone and ENA with reduced radiation pressure), and neither possible model can be favoured. Radiation pressure cannot be excluded as an explanation of the observed spectrum.

Although we agree that the ENA model is a plausible scenario, we do not believe that ENAs can explain the observations better than a classical scenario with radiation pressure. The ENA model requires extraordinary conditions for the wind parameters (high temperature and low velocity) which are not constrained by any other observations, whereas the radiation pressure as measured in the Lyman-α spectrum can self-consistently explain the observations.

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1. Holmström, M. *et al.* Energetic neutral atoms as the explanation for the high-velocity hydrogen around HD 209458b. *Nature* **451**, 970–972 (2008).
2. Vidal-Madjar, A. *et al.* An extended upper atmosphere around the extrasolar planet HD209458b. *Nature* **422**, 143–146 (2003).
3. Vidal-Madjar, A. *et al.* Exoplanet HD 209458b (Osiris). Evaporation strengthened. *Astrophys. J.* **676**, L57–L60 (2008).
4. Vidal-Madjar, A. & Lecavelier des Etangs, A. "Osiris" (HD209458b), an Evaporating Planet. *ASP Conf. Series* **321**, 152–159 (2004).

doi:10.1038/nature07402

Holmström et al. *reply*

Replying to: A. Lecavelier des Etangs, A. Vidal-Madjar & J.-M. Désert *Nature* **456,** doi:10.1038/nature07402 (2008)

Lecavelier des Etangs *et al.*[1] object to the conclusion by Holmström *et al.*[2] that radiation pressure alone cannot explain the Lyman-α absorption observed[3] during transits of HD 209458b. We agree that hydrogen atoms can be accelerated to large velocities by radiation pressure. However, with our model we cannot reproduce the observed spectrum, as shown in the Supplementary Information and Fig. 3 of ref. 2.

To support the hypothesis that radiation pressure alone can explain the observation, Lecavelier des Etangs *et al.* show a modelled spectrum that fits well with the observed spectrum[1]. Thus, there is a

What do the observations tell us?

- Previous approaches have been to use complex parametric models to fit the observations
- Maybe a better approach is to see what can be learnt without (too many) a priori assumptions

Ben-Jaffel, ApJ, 2010

- Re-interpretation of HD 209458b
- Few parameter model
- Hot OI and CII
  - O and C transits as strong as H, but they are [from models] several orders of magnitude less abundant
- For HI
  - Hot population at a distance from the planet

In that frame, we show that OI and CII are preferentially heated compared to the background gas with effective temperatures as large as $T_{OI}/T_B \sim 10$ for OI and $T_{CII}/T_B \sim 5$ for CII. By contrast, the situation is much less clear for HI because several models could fit the Ly-α observations including either thermal HI in an atmosphere that has a dayside vertical column $[HI] \sim 1.05 \times 10^{21}\mathrm{cm}^{-2}$, or a less extended thermal atmosphere but with hot HI atoms populating the upper layers of the nebula. If the energetic HI atoms are either of stellar origin or populations lost from the planet and energized in the outer layers of the nebula, our finding is that most models should converge toward one hot population that has an HI vertical column in the range $[HI]_{hot} \sim (2-4) \times 10^{13}\mathrm{cm}^{-2}$ and an effective temperature in the range $T_{HI} \sim (1-1.3) \times 10^6$K, but with a bulk velocity that should be rather slow.

Problem for radiation pressure (and natural broadening?)

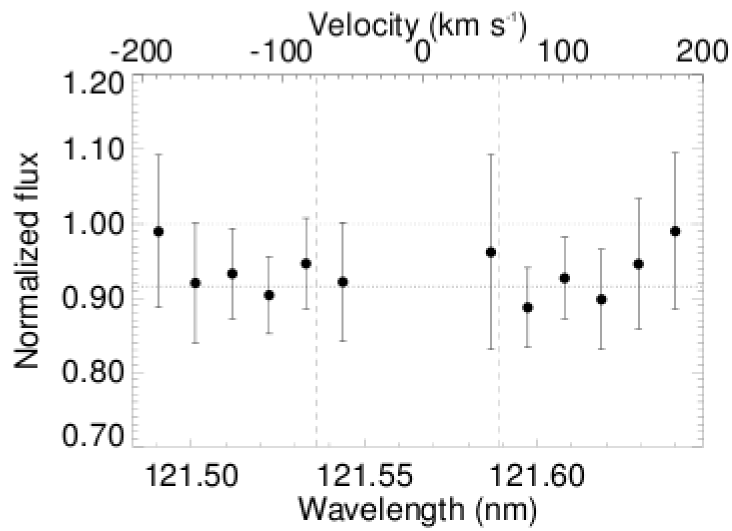
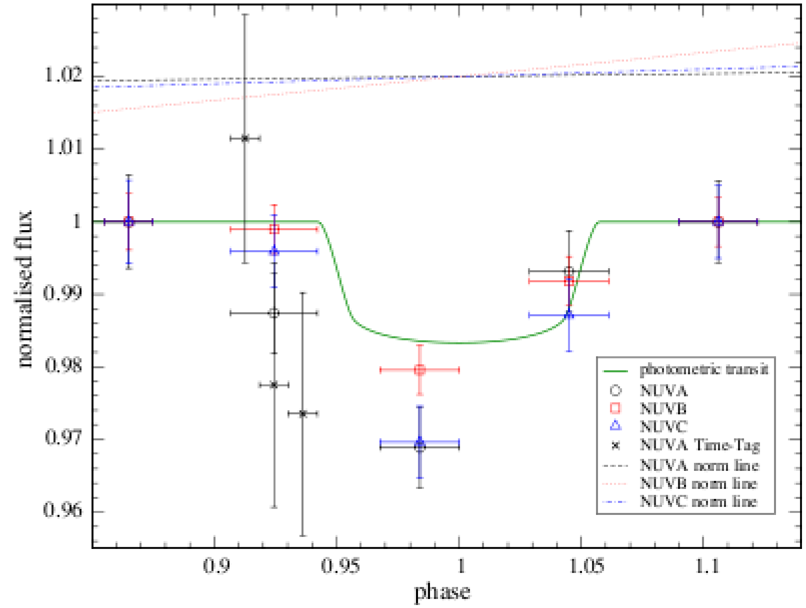


FIG. 1.— Absorption line profile (filled circles) during transit of HD209458b obtained as a ratio between Ly-α line profiles in-transit and unperturbed. The sky background spectral domain as defined here is indicated by two vertical dashed lines. The spectral window was restricted to $\sim \pm 200 \mathrm{km\,s^{-1}}$ from line center because the signal becomes much too noisy beyond. A flat absorption rate of $\sim 8.4\%$ fits rather well with the obtained absorption profile (dashed line). In BJ08, we used the DIV1 atmospheric model of Garcia Munoz, (2007) to propose a Lorentzian-like line profile model with extended wings that also fits quite well with these observations.

This is the spectrum that should be fitted by models

Fossati et al., ApJL, 2010

- Using repaired COS on HST
- WASP-12b
- Metals
- Early ingress?



We do not have any detailed explanation for the observed early ingress in NUVA, but we speculate the effect could be produced if material is lost from the planet exosphere and forms a diffuse ring or torus around the star enveloping the planet's orbital path, as models suggest (Li et al. 2010). The orbital motion of the planet through this medium might compress the material in front of it. This could increase the opacity of the medium through which the star is viewed immediately before first contact. A void in the medium might be expected to form behind the planet, and consequently the egress is relatively unaffected by the diffuse ring.

Lai et al., 2010

- Interprets the WASP-12b observation
- Early ingress by stream to a disc?
- Or by compressed gas inside the magnetopause?

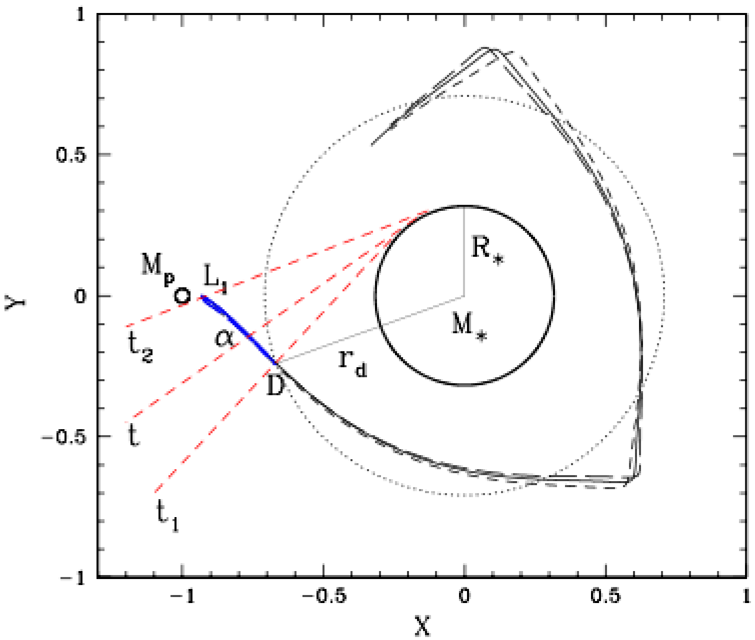


FIG. 1.— Stream trajectory and disk formation in the orbital plane for the case of planet-star mass ratio $q = M_p/M_\star = 10^{-3}$ (WASP-12b parameter). The planet is located at $(X, Y) = (-1, 0)$ (in units of a), and rotates counter-clockwise around the star. Three stream lines leaving L1 are shown, corresponding to the initial velocity (in units of the orbital velocity of the planet, $\sqrt{GM_\star/a} = 228$ km s^{-1}) of $(u_x, u_y) = (0, 0)$ (solid line), $(0.02, 0)$ (dashed line) and $(0.02, -0.02)$ (long-dashed line). The disk outer radius is at $r_d = 0.71$. The stream strikes the disk at point D, beyond which the stream does not exist. The dashed straight line labeled t_1 indicates the line of sight when the star light is first blocked by the stream (the ingress of the "stream transit"), and the line labeled t_2 indicates the ingress of the "normal" planet transit. A general line of sight is labeled t, with the angle between the symmetry axis of the stream and the line of sight denoted by α.

Summary

- No new Ly-a spectrum observations
- However, reanalysis and new unresolved observations contains information
  - Time dependence?
- Other species than H at lower velocities complicates the picture
  - Large abundances
  - Early ingress

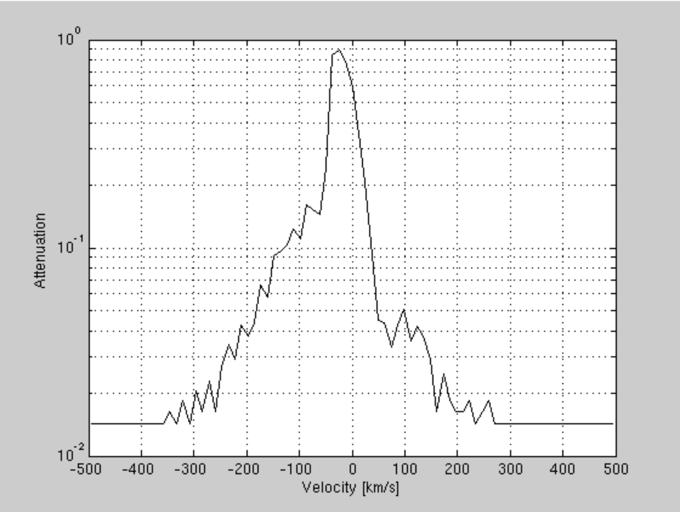
References

- Look at exonsw-log.odp, EPSC10 abstract
- Attenuation computation
- Literature review. We, BJ, VM, ...
  - Koskinen ArXiv 2010
  - Andreas ApJ 2010
  - Lecavelier AA 2010
  - Ben Jafell ApJ 2010
  - Wood ApJ 2002
    - Zank SSR 1999
  - Wasp-12
    - Fosatti, ApJL, 2010
    - Lai, 2010
  - Linsky, 2010 and BJ reply (See Helmut email May 14)

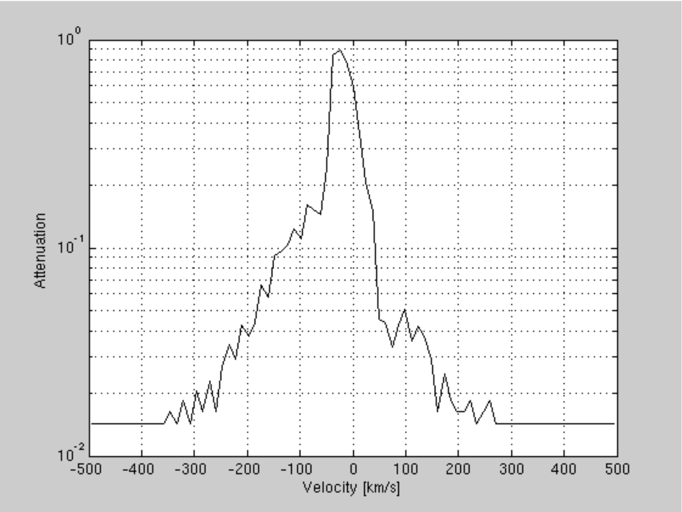
Ly-a

- Limb brightening(?)
- Neutral stellar wind

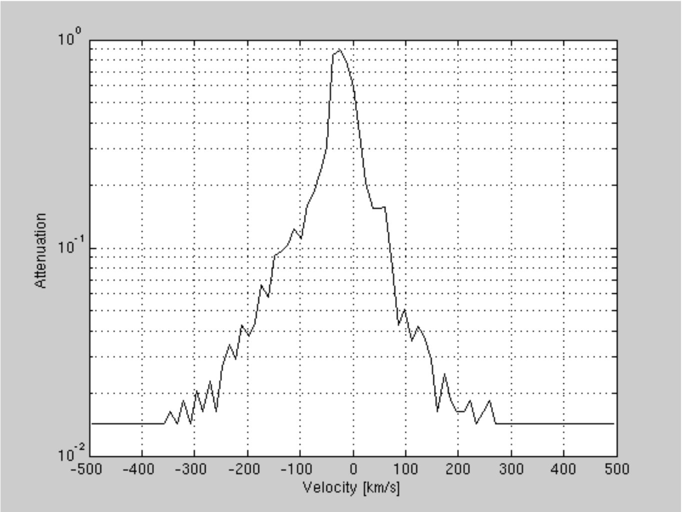
Different column densities in the atmosphere



n = 0 cm^{-2}



n = 1e17 cm^{-2}

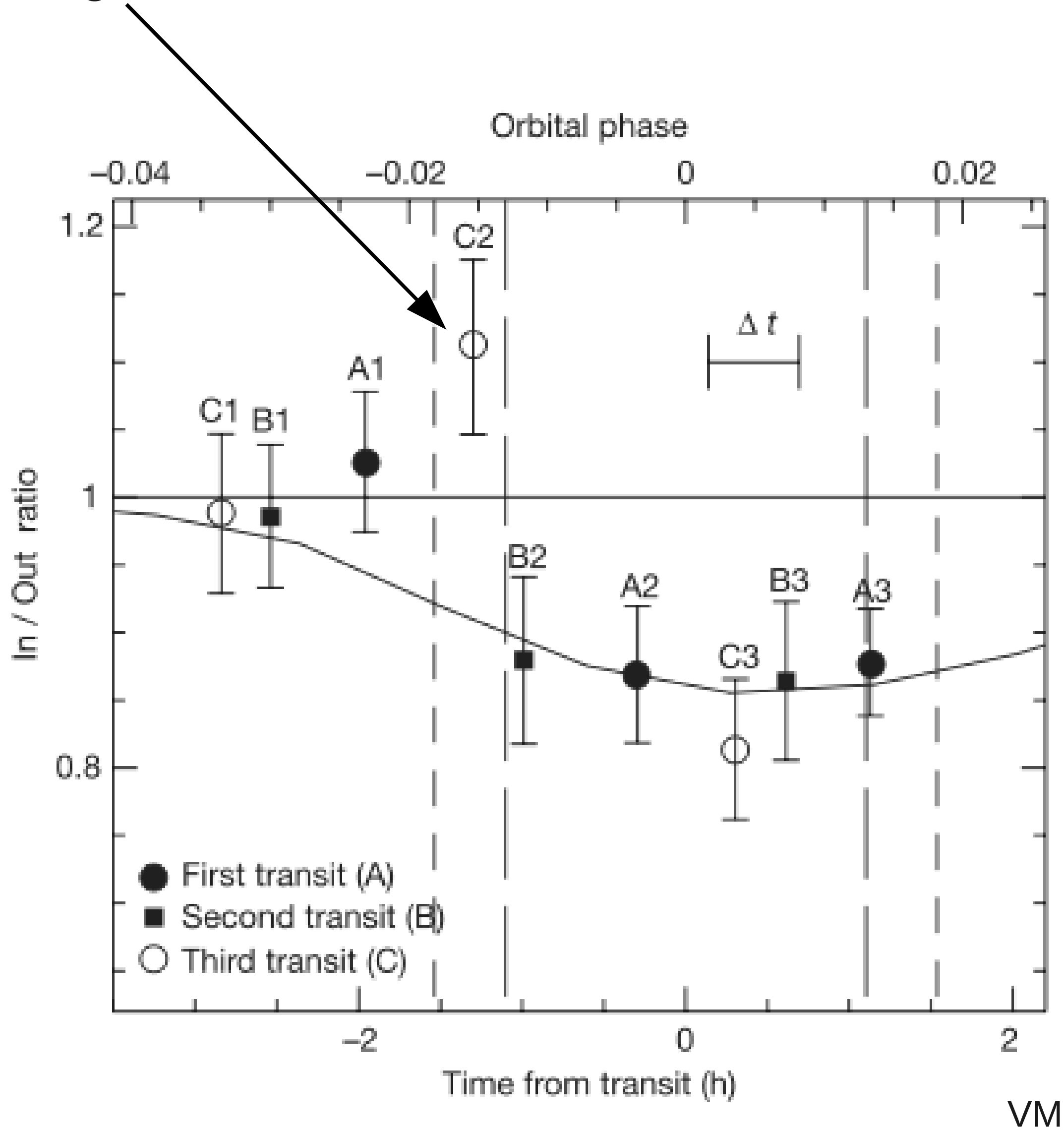


n = 1e27 cm^{-2}

The effects of the atmosphere is small, especially at high velocities, all the way up to very large assumed column densities.

A puzzle

How can the flux be higher in transit?



VM, Nature, 2003, Fig. 3