Characterisation of exoplanet atmospheres, magnetospheres and stellar winds from energetic neutral atom observations

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Overview

- Energetic neutral atoms (ENAs)
- Extrasolar planets
- The Hubble observation of H around HD 209458b
- Model of ENA production at HD 209458b
- Comparison of model results and observations
- Stellar wind and magnetosphere estimates
Energetic Neutral Atoms (ENAs)

The Solar Wind

Magnetized Planets

ENA Production by Charge-Exchange

Non-Magnetized Planets

[Kivelson and Russel]
ENA Observations in the Solar System

ENAs from charge-exchange between solar wind protons and exospheric hydrogen has been observed at all planets where suitable ENA detectors were present:

- At Earth by IMAGE
- At Mars by Mars Express
- At Venus by Venus Express
Doppler Velocity Curve for HD 209458

HD209458 velocity curve with the Keplerian orbital fit for a period $P = 3.52$ days. Error bars are shown. The derived companion mass is: $M \sin i = 0.63$ Jupiter Masses. The transit ensures that the orbital inclination, $i$, is nearly 90 deg. So the companion mass is 0.63 Jupiter masses. The odd behavior in the velocities near phase=0.5 is due to the rotation of the star, as the planet blocks of the approaching and receding limbs of the star.
Photometric observations of HD 209458 from the night of 1999 Nov. 7 UT taken with the T8 0.80m APT at Fairborn Observatory showing ingress of the planetary transit. The measured transit depth is 0.017 mag or 1.58%. The error bar shows the predicted time of mid transit and its uncertainty computed from the Keck radial velocities.
Figure 2 The HD209458 Lyman $\alpha$ profile observed with the G140M grating.
Figure 3. A numerical simulation of hydrogen atoms sensitive to radiation pressure (0.7 times the stellar gravitation) above an altitude of 0.5 times the Roche radius where the density is assumed to be $2 \times 10^5 \text{ cm}^{-3}$ is presented here. It corresponds to an escape flux of $\sim 10^{10} \text{ g s}^{-1}$. The mean ionization lifetime of escaping hydrogen atoms is 4 hours. The model yields an atom population in a curved cometary like tail.
Aeronomy of extra-solar giant planets at small orbital distances

Roger V. Yelle

... There is a qualitative agreement between the hot thermospheres calculated here and the H Lyα absorption measurements of Vidal-Madjar et al. (2003). The observed absorption signature has a magnitude of \( \sim 15\% \). In the visible, the planet occults about 1% of the star light, so an absorption of 15% implies that H is optically thick to about 4\( R_P \). The reference model has an H density of \( 4.1 \times 10^5 \text{ cm}^{-3} \) at 3\( R_P \) and a temperature of 10,909 K, implying a tangential column abundance of \( 1.7 \times 10^{16} \text{ cm}^{-2} \). Assuming a Maxwell–Boltzmann distribution for the H cloud and using the temperature quoted above implies an absorption cross section at Lyα line center of \( 5.6 \times 10^{-14} \text{ cm}^2 \) and an optical depth of \( \sim 1000 \). Thus, the H distribution calculated here is opaque out to several planetary radii, in rough agreement with the measurements. Vidal-Madjar et al. (2003) also show that the absorption extends roughly 0.5 Å from the center of the Lyα line. This only occurs if the H distribution is characterized by a high temperature. Assuming a Maxwell–Boltzmann distribution and a temperature of 10,000 K implies a Doppler broadened absorption line with a width of 0.055 Å. An optical depth at line center of 1000 implies that optical depth unity is reached roughly 3 Doppler widths from line center or at 0.16 Å. This is of the same order but somewhat smaller than measured by Vidal-Madjar et al. (2003).

A more quantitative comparison requires improvements to the models. As mentioned earlier, the assumptions contained in these aeronomical models become questionable at a distance of 3\( R_P \) from the planet. The gravitation field of the central star and radiation pressure can no longer be neglected and a 1D calculation is no longer possible. Instead it is preferable to construct kinetic models that calculate the H distribution by integrating along trajectories in the exosphere. ...
Can Energetic Neutral Atoms (ENAs) Explain the Observation?
Illustration of the geometry

Planet centered coordinate system. $x$-axis is planet-star line
Fig. 7. Alfvén Mach number (solid line) and plasma-$\beta$ (dashed line) of the stellar wind model in dependence of the distance in AU from the star. The locations of the simulated planets are marked with dotted lines.

Preusse et al., PSS, 2006
A model of the ENA production at HD 209458b

- Hydrogen atoms launched from an inner boundary
- Stellar wind protons inflowing
- Charge-exchange outside an obstacle
- Forces on an H atom:
  - gravity (planet), coriolis force (stellar)
- Events for an H atom:
  - charge exchange with a proton (ENA production)
  - elastic collision with another H atom
  - photon collision (radiation pressure)
  - photoionization
### Table 1: Default values of physical parameters, and values of constants used in the simulations, unless otherwise noted.

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<td>Solar wind temperature</td>
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Stellar wind velocity and temperature

$u_{sw} = 50 \text{ km/s}$

$T_{sw} = 10^6 \text{ K}$
Average H Velocity Spectrum (along x-axis)
Attenuation

- Columns along x-axis in a grid in front of the star
- Attenuation spectrum computed for each column
- Average attenuation for each velocity is computed
- This attenuation can then be applied to the out-of-transit observed spectrum, and compared to the in-transit spectrum
Comparison with the observation
Three problems with existing models

- 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}.
Figure 4: The attenuation spectrum (a) and velocity spectrum (b) for a 100 km/s stellar wind, and the attenuation spectrum (c) and velocity spectrum (d) for a 0 km/s stellar wind.
Figure 5: The velocity spectrum for a lower stellar wind temperature of $0.5 \cdot 10^6$. 
Figure 7: The attenuation spectrum for an increased obstacle distance of $6 \cdot 10^8$ m.
Computational Details

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**Speed-up**
Energetic neutral atoms as the explanation for the high-velocity hydrogen around HD 209458b

M. Holmström, A. Ekenbäck, F. Selsis, T. Penz, H. Lammer & P. Warz

Absorption in the stellar Lyman-α (Lyα) line observed during the transit of the extrasolar planet HD 209458b in front of its host star reveals high-velocity atomic hydrogen at great distances from the planet1. This has been interpreted as hydrogen atoms escaping from the planet's exosphere2, possibly undergoing hydrodynamic blow-off1, and being accelerated by stellar radiation pressure. Energetic neutral atoms around Solar System planets have been observed to form from charge exchange between solar wind protons and neutral hydrogen from the planetary exosphere2,3, however, and this process also should occur around extrasolar planets. Here we show that the measured transit-associated Lyα 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 observations. As the stellar wind protons are the source of the observed energetic neutral atoms, this provides a way of probing stellar wind conditions, and our model suggests a show of the stellar wind near HD 209458b at the time of the observations.

Energetic neutral atoms (ENA) 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—for Earth4, Mars5 and Venus6.

By energetic we mean that the ions have a much greater velocity than the thermal velocities of the exospheric neutrals. During the charge exchange process, an electron is transferred from the neutral to the ion, resulting in a neutral atom and an ionized neutral. Because of the large relative velocities of the ions and the exospheric neutrals, the momenta of the individual atoms are preserved to a good approximation. Thus, the produced ENA will have the same velocity distribution as the source population of ions.

When first observed (also by their Lyα signature7), the extended hydrogen corona of Mars and Venus were assumed to constitute the uppermost layers of an escaping exosphere. The observed densities were used to infer exospheric scale heights and temperatures, which proved to be extremely high compared with theoretical predictions (up to 700 K). In situ spacecraft observations8 later found exospheric temperatures of ~210 and ~230 K. The discrepancy was eventually explained by photochemistry-produced energetic particles, and by ENAs produced by charge exchange between energetic solar wind protons and the planetary exosphere. Although this mechanism is well known in the Solar System, it has not been considered as a possible origin of the atomic hydrogen corona revealed by Hubble Space Telescope observations of HD 209458b.

HD 209458b is a Jupiter-type gas giant with a mass of ~0.65 M_Jup and a size of ~1.32 R_Jup that orbits ~0.045 AU (ref. 11) around its host star HD 209458, which is a sole-like G-type star with an age of about 4 Gyr. The activity of the star can be estimated from its X-ray luminosity measured by the XMM-Newton space observatory, and is comparable to that of the present Sun during a moderately quiet phase12. Because of its Sun-like stellar type and average activity, it is reasonable to use the energy environment observed at the Sun as inputs for our model.

For a first estimate of the ENA production near HD 209458, we assume that the charge exchange takes place in an undisturbed stellar wind that is flowing radially away from the star. Assuming a Model atmosphere from HD 209458, the stellar wind is most likely subsonic13 and does not produce a planetary bow shock. Simulations indicate a subsonic magneto-terrestrial distance of about 4 planetary radii if the planet is magnetized14. If the planet is not magnetized, we would expect the undisturbed stellar wind to get even closer to the planet. 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 atoms takes place outside a dense obstacle that represents the magnetosphere of the planet (Supplementary Fig. 1). The resulting exospheric cloud, along with the produced ENAs, covers a region larger than the stellar disk, as seen from Earth (Fig. 1). The cloud is shaped like a comet tail owing to the stellar radiation pressure, curved by the Coriolis force, as predicted15 and seen in earlier numerical simulations16. There is a population of atoms with high velocity—these are the stellar wind protons that have charge-exchanged, becoming ENAs. In the velocity spectrum along the x-axis (the planet-star line), the ENAs are clearly visible as a distribution that is separate from the main exospheric hydrogen component, because of the different bulk velocities and temperatures (Fig. 2).

Now we estimate how the ENA cloud would affect the observed Lyα absorption spectrum of HD 209458b. The line profile was observed outside and during transit, and the difference between the two profiles corresponds to the attenuation by hydrogen atoms (Fig. 3).

There are several features of the transit spectrum that any proposed source of the observed hydrogen atoms needs to account for. First, there are hydrogen atoms with velocities of up to ~130 km s⁻¹ (away from the star). Second, there is a uniform absorption over the whole velocity range ~130 to ~45 km s⁻¹. Third, there is absorption in the velocity range between 160 and ~165 km s⁻¹ (towards the star).

The current explanation of the observation is that hydrogen atoms in the exosphere are undergoing hydrodynamic escape, and are further accelerated by the stellar radiation pressure16. But there are difficulties in explaining the observations by this process, as can be seen by examining the three features listed above.

First, a large radiation pressure on the hydrogen atoms is needed to accelerate them to a velocity of 130 km s⁻¹ before they are...
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


The origin of hydrogen around HD 209458b


Using numerical simulation, Holmström et al. 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 35 ± 4% absorption between ∼130 and 160 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 and, however, Holmström et al. 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 3 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. is valid only at high radial velocity. However, if low radiation pressure is assumed, high velocities are not reached, which would therefore explain the different conclusion reached by Holmström et al. We believe that the treatment of the link between the radiation pressure and radial velocity needs to be corrected.

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 various combination of radial velocity 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 our model. The results 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 for the observed spectrum.

Although we agree that the ENA model is a plausible scenario, we do not believe that ENAs can explain the observed line under 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 other observations, whereas the radiation pressure as measured in the Lyman-α spectrum can self-consistently explain the observations.

Levacher des Etangs et al. reply


Levacher des Etangs et al. object to the conclusion by Holmström et al. that radiation pressure alone cannot explain the Lyman-α absorption observed 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, Levacher des Etangs et al. show a modelled spectrum that fits well with the observed spectrum. Thus, there is a
Improved flow model

=> 350 km/s stellar wind

Submitted to ApJ
Figure 3 Relative flux of Lyman $\alpha$ as a function of the HD209458’s system phase. The averaged ratio of the flux is measured in the In (1,215.15–1,215.50 Å and 1,215.80–1,216.10 Å) and the Out (1,214.40–1,215.15 Å and 1,216.10–1,216.80 Å) domains in individual exposures of the three observed transits of HD209458b.
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.
Estimations of magnetospheric properties

Table 3. Obtained upper bounds for obstacle stand-off distance as a function of exosphere density and temperature. The lengths are given in $10^8$ m.

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Table 4. Estimated obstacle stand-off distance for each exospheric scenario. The lengths are given in $10^8$ m.

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$^a$An entry of $\leq 3$ means that a better fit could probably be found by decreasing the obstacle standoff below $3 \cdot 10^8$ m. Such simulations would not be accurate with the current model since we have used an inner boundary of $2.7 \cdot 10^8$ m.

With our default parameters we estimate the magnetic moment of HD 209458b to be approximately 40 per cent of Jupiter’s magnetic moment.
Conclusions

- Energetic Neutral Atoms (ENAs) can explain the observed Lyman α absorption
- Stellar wind, atmospheric, and magnetospheric properties can be inferred from Lyman α observations through ENAs
- Plasma processes should be considered in exoplanet investigations