Energetic neutral atoms as the explanation for the high velocity hydrogen around HD 209458b

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Absorption in the stellar Lyman-α (Ly-α) line observed during the transit of the extrasolar planet HD 209458b reveals high velocity atomic hydrogen at great distances from the planet. This has been interpreted as hydrogen atoms escaping from the exosphere of the planet, possibly undergoing hydrodynamic blow-off, 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, and should also occur at extrasolar planets. Here we show that the measured transit-associated Ly-α 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) 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, Mars, and at Venus.

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. Due to 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 ENAs will have the same velocity distribution as the source population of ions.

When first observed (also by their Ly-α signature), the extended hydrogen coronae 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 to theoretical predictions (up to 700 K). In situ spacecraft observations later found exospheric temperatures of ~210 and ~270 K. The discrepancy was eventually explained by photochemically-produced energetic particles, and by ENAs, produced by charge exchange between energetic solar wind protons and the planetary exosphere. 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.

HD 209458b is a Jupiter-type gas giant with a mass of ~0.65 M$_{\text{Jup}}$ and a size of ~1.32 R$_{\text{Jup}}$ that orbits around its host star HD 209458 at ~0.045 AU, which is a solar-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 phase. Because of its Sun-like stellar type and average activity, it is justified to use the energy environment observed at the Sun as inputs for our model.

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. At 0.045 AU from HD 209458, the stellar wind is most likely subsonic and does not produce a planetary bow shock. Simulations indicate a subsolar magnetopause distance of about four planetary radii if the planet is magnetized. 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 conic 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 disc, as seen from Earth (Fig. 1). The cloud is shaped like a comet tail due to the stellar radiation pressure, curved by the Coriolis force, as predicted and seen in earlier numerical simulations. 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, due to the different bulk velocities and temperatures (Fig. 2).

Now we estimate how the ENA cloud would affect the observed Ly-α absorption spectrum of HD 209458b. The line profile was observed outside and during transit, and the difference between the two profiles correspond 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 need to account for. First, hydrogen atoms with velocities of up to -130 km/s (away from the star). Second, a fairly uniform absorption over the whole velocity range -130 to -45 km/s. Third, absorption
in the velocity range between 30 and 105 km/s (toward the star).

The current explanation of the observation is that hydrogen atoms in the exosphere are undergoing hydrodynamic escape, and are then further accelerated by the stellar radiation pressure\cite{1,2}. There are however some difficulties in explaining the observations by this process, as can be seen by examining the three features listed above.

First of all, 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 also has to occur before they move out from the region in front of the star, due to the orbital motion of the planet. The second feature is difficult to explain, since 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, due to the finite lifetime of hydrogen atoms because of photoionization (four hours on average). This drop-off for high velocities is independent of the details of the model, e.g., 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. Finally, an exosphere driven by radiation pressure cannot explain hydrogen atoms moving toward the star with speeds between 30 and 105 km/s. However, this feature of the observation is not completely certain, and it has been stated\cite{1} that more observations are needed to clarify whether an absorption is present in the red part of the line (toward the star).

Our model shows that all observed features listed above can be explained by ENAs. If we turn off the ENA production in the model, none of these features are explained. When we compare the modeled Ly-\(\alpha\) profile with the observed ones, we find that the modeled spectrum leads to attenuation over the whole velocity range from -130 to -45 km/s, as is seen in the observation. The model also shows some absorption in the red part of the velocity spectrum, i.e. hydrogen atoms moving at high velocities toward the star, since for this stellar wind (50 km/s and 10^6 K), some part of the proton velocity distribution will have positive velocities along the \(x\)-axis (toward the star), resulting in an ENA flux toward the star. This slow and hot stellar wind is not unrealistic at such small orbital distances\cite{3}.

If ENAs from charge exchange are responsible for the observed attenuation, we have on one hand, much less information on the main exospheric component than suggested by previous explanations. Since what we observe are mainly ENAs, a range of exospheric conditions and atmospheric loss rates can be consistent with the observation. Thus, the observation only constrains the radiation pressure driven atmospheric escape insofar that the exosphere has to be extended enough to reach the stellar wind outside the magnetopause of the planet. The atmospheric escape through ENA production is small. For the model parameters used here, the loss is 7 \(\cdot\) 10^5 kg/s, which is more than an order of magnitude smaller than the estimated thermal loss of about 10^7 kg/s for similar exospheric conditions\cite{16,17,18}.

On the other hand, we gain information on the underlying plasma flows, and if it is the undisturbed stellar wind, we have a way of observing stellar wind properties such as temperature and velocity around other stars, at the location of 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-α absorption to the observation for a stellar wind velocity of 50 km/s, and a temperature of 10^6 K (Fig. 3).

Although, for HD 209458b, the available Ly-α data are affected by large uncertainties, more accurate observations would improve the derived stellar wind estimates. Also, the depletion of the stellar wind proton flow by charge exchange will change the character of the planet–stellar wind interaction. Present models of the stellar wind interaction with HD 209458b have not taken this process into account. More observations of the Ly-α absorption by HD 209458b, and its variation over time, could be used to confirm the origin of the extended hot hydrogen cloud. The variability of the Ly-α by ENAs should be larger on short time scales than for other explanations, e.g., hydrodynamic escape, since the solar wind parameters can change significantly on a timescale of hours, as seen near Earth.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature

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Author Contributions
A.E. wrote an initial version of the simulation code. F.S. helped in modeling the observation. T.P. provided knowledge on the atmospheres of extrasolar planets. H.L. and F.S. suggested that the HST observation could be due to ENAs. P.W. contributed with expertise in ENA processes.

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Figure 1: The hydrogen cloud around the planet. Shown from (a) above, perpendicular to the planet’s orbital plane, and (b) from Earth, along the x-axis direction. Each point corresponds to a hydrogen meta particle. The color of the points shows 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). At the outer boundaries of the simulation domain, stellar wind protons are injected with a $2 \cdot 10^3$ cm$^{-3}$ number density, 50 km/s velocity, and $10^6$ K temperature. The planet’s interaction with the stellar wind is modeled by removing all stellar wind protons inside a conic obstacle at a sub-stellar distance of about $4.2 R_p$ (where the radius of the planet $R_p = 9.4 \cdot 10^7$ m). Hydrogen atoms are launched from an inner boundary (a sphere of radius $2.1 R_p$) assuming a number density of $10^8$ cm$^{-3}$ and a temperature of 7000 K, consistent with atmospheric models. The trajectory of each proton and hydrogen atom is followed in time. The forces on a hydrogen atom are the gravity of the planet, the Coriolis force due to the rotating coordinate system, and radiation pressure. After each time step a hydrogen atom can undergo photoionization, elastic collision with another hydrogen atom or charge exchange with a proton. The photoionization time assumed is 4 hours which is a scaled Earth value. The radiation pressure corresponds to a photon-hydrogen collision rate of 0.35 s$^{-1}$ and is chosen to improve the model fit. It is lower than a scaled Earth value of $0.6 \cdot 1.6$ s$^{-1}$ over a solar cycle. 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. Further details of the simulations can be found in the SI.

Figure 2: Velocities of the hydrogen atoms. The modeled x-axis (planet–star) velocity spectrum of hydrogen atoms in front of the star at the moment of mid transit, not including atoms in front or behind the planet. The part of the distribution that is due to ENAs is shaded. Varying the stellar wind temperature and velocity in the model confirms that the width of this part of the distribution is proportional to the temperature of the stellar wind, with a larger width for larger temperatures, and the center of the distribution follows the stellar wind velocity. The un-shaded part of the spectrum is due to the exospheric hydrogen atoms.
Figure 3: Comparison of the modeled Ly-α 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. The modeled profile is computed at the instant of mid-transit. The details of computing the Ly-α attenuation from the hydrogen cloud are given in the SI. The modeled Ly-α absorption shown here is for a stellar wind velocity of 50 km/s and a temperature of $10^6$ K. The fit is worse for stellar wind velocities of 0 or 100 km/s, or stellar wind temperatures of $2 \cdot 10^6$ K or $0.5 \cdot 10^6$ K as shown in the SI.
Figure 1
Figure 2
Figure 3

![Graph showing velocity and flux with in-transit and out-of-transit models]

- Velocity [km/s]
- Flux [10^{14} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}]
- Modelled out-of-transit and in-transit.