ENAs around HD 209458b: Estimations of magnetospheric properties

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An observation of high velocity Hydrogen near a transiting exoplanet

H atoms at velocities of >100 km/s

Figure 2 The HD209458 Lyman $\alpha$ profile observed with the G140M grating.

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

Energetic neutral atoms (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

ENAs should be produced also at exoplanets. ENAs could explain the observed high velocity H
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
Illustration of the geometry

Planet centered coordinate system. $x$-axis is planet-star line

0.045 AU
View from above the orbital plane

assumed obstacle (magnetopause)

H
Exosphere
Stellar wind

H^+

star
The hydrogen exosphere of the planet (red), with ENAs as black dots
Average H Velocity Spectrum (along x-axis)
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].

Comparison with the observation

In the "In" region model absorption is very close to the observation
=> The model can explain 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

To get absorption at high velocities we get too much absorption at lower velocities => Without ENAs, our model cannot explain the observation.

**Figure 3:** The attenuation spectrum with no ENA production and a larger radiation pressure corresponding to a photon collision rate of 1.4 \( \text{s}^{-1} \).
Improved flow model

The stellar wind flows around the obstacle (not just disappear)

=> best estimate now is a more realistic 350 km/s stellar wind

Paper submitted to ApJ
Estimations of magnetospheric properties

With our default parameters we estimate the magnetic moment of HD 209458b to be 40% 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.