EXOPLANET MAGNETIC FIELD ESTIMATION VIA ENERGETIC NEUTRAL ATOMS (ENAS) AND HYDROGEN CLOUD OBSERVATIONS AND MODELLING

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Abstract

The discovery of more than 500 exoplanets during the past 15 years has enabled us to characterize the upper atmosphere structure of some exosolar gas giants and to compare observational and modelling results to the known planets in the Solar System. It is of great interest to understand if these exosolar "Hot Jupiters" share similar physical processes compared to the giant planets (Jupiter and Saturn) in the Solar System with regard to their magnetic dynamos and the corresponding expected magnetic field strengths. In this work we discuss how observations of stellar Lyman-α absorption by so-called Energetic Neutral Atoms (ENAs) around transiting exoplanets together with theoretical modelling efforts can be used as a tool for estimating magnetic obstacle sizes and the corresponding magnetic field strength. For demonstrating this method we model the production of stellar wind related planetary hydrogen and ENA populations around the exosolar gas giant HD 209458b and show how a detailed analysis of attenuation spectra obtained during transits can be used for the estimation of the planet's magnetic obstacle size and hence its dynamo field strength. Our study indicates that the magnetic field strength of HD 209458b which is able to balance the stellar wind plasma flow by a magnetic obstacle around the planet which can explain the observed Lyman-α line profiles observed before and during the transits by HST corresponds to a magnetic dipole moment which is ~40 % of Jupiters value.

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1 Introduction

By applying an analogy between giant exoplanets and magnetized planets in the Solar System such as Jupiter and Saturn, radio-emissions resulting from the interaction of their magnetospheres with the solar/stellar wind are probably generated by electrons which are accelerated to several keV. These accelerated electrons emit radio waves at the local cyclotron frequency [e.g., Farrell et al., 1999; Zarka, 1992; 2007]. As Farrell et al. [1999] and shown in Fig. 1 from Zarka [2007], radio-emissions emitted from exoplanets could outshine the radio emission from a quiet host star, and would give us a possibility to infer information on their magnetic field and dynamo.

Usually it is assumed that exoplanetary radio-emissions can be generated in the same way as they are generated at Jupiter or Saturn. Recent estimates of radio fluxes from known exoplanets were presented by Farrell et al. [1999], Lazio [2004], Grießmeier et al. [2007], and Jardine and Cameron [2008]. One of the large uncertainties in the prediction of radio emission is the magnetic moment of extrasolar planets. Different magnetic dynamo scaling laws which can be applied to estimate the magnetic dynamo at exoplanets are discussed in Farrell et al. [1999] and Grießmeier et al. [2004]. Most scaling laws depend on the rotation of the exoplanet. Due to tidal locking of close-in exoplanets, these scaling laws yield lower magnetic moments compared to a recent hypothesis which does not depend on rotational effects, favored by Reiners and Christensen [2010]. Their magnetic dynamo model is based on scaling properties of convection-driven dynamos [Reiners and Christensen 2010]. These authors estimated the evolution of average magnetic fields of "Hot Jupiter"-type exoplanets and found that young exosolar gas giants may have intrinsic magnetic dynamo moments with ~ 100 G with a field which weakens steadily down to about ≤ 10 G after 10 Gyr.

However, both magnetic dynamo hypotheses could not be tested so far because the magnetic fields of "Hot Jupiters" are currently unconstrained by observation. Although, huge efforts in the discovery of radio-emissions from exoplanets were carried out during the past decade, until now, none of these searches could present a positive detection. One reason for the non-detection of radio-emissions may be related to the fact that the largest available ground-based radio telescope facilities are not sensitive enough or only close to the threshold to observe the expected weak radio flux. Due to the relatively faint signal, large antenna arrays are required. For this reason, this kind of observations can only be performed by radio telescopes such as the UTR-2 in the Ukraine or the future Low Frequency Array (LOFAR). The frequency and the total radio flux depend critically on the planetary magnetic field strength which controls together with the stellar plasma flow properties the cross section of the magnetosphere. The energy flux of the stellar wind plays also an important role for the emitted total radio flux.

Therefore, obtaining knowledge from the stellar wind plasma properties and the magnetic obstacle around an exoplanet will help to constrain the estimations of the total emitted radio flux. Additionally future observations of the radio spectrum of exoplanets can constrain the magnetic field strength and should shed some light on the magnetic dynamo hypotheses currently discussed within the scientific community. The aim of this work is to present a method, which can be used to estimate magnetic obstacle positions and hence size, which balance the stellar wind plasma flow around the upper atmosphere of "Hot Jupiters" by studying the absorption of the stellar Lyman$-\alpha$ flux during transits.

2 Expanding Thermospheres of "Hot Jupiters"

The first physically plausible hypothesis for the upper atmospheric structure of "Hot Jupiters" such as HD 209458b was presented by Lammer et al. [2003] whose results indicated that the thermospheres of hydrogen-rich exosolar gas giants in orbits close to their host stars are heated by the large stellar EUV flux to temperatures up to 10,000 K, which results in an expansion of the exobase level up to the Roche lobe or even beyond. In the same year a huge neutral hydrogen corona around HD 209458b was observed by Vidal-Madjar et al. [2003] with the Hubble Space Telescope (HST) Imaging Spectrograph (STIS). From the absorption the stellar Lyman-α line during three transits these authors suggested in agreement with Lammer et al. [2003] that the hydrogen-rich upper atmosphere of HD 209458b is expanded up to the Roche lobe or even beyond. After initial scepticism regarding the data analysis and interpretation of Vidal-Madjar et al. [2003] by Ben-Jaffel [2007], two recent observations with low spectral resolution by the HST STIS/ACS instruments [Ehrenreich et al., 2008] confirmed that the depth of Lyman-α in-transit is significantly greater compared to the out-of-transit situation [Ben-Jaffel and Sona Hosseini, 2010]. That HD 209458b and similar "Hot Jupiters" experience dynamic expansion of its thermosphere and hydrogen outflow up to the Roche lobe is also supported by other HST observations which were carried out recently with the Cosmic Origins Spectrograph where carbon, oxygen and silicon were observed up to the Roche lobe distance [Linsky et al., 2010]. Wherever a solar- or stellar plasma interacts with an extended neutral atmosphere charge-exchange reactions take place, transforming the solar/stellar protons into Energetic Neutral Atoms (ENAs) which are unaffected by magnetic and electric fields so that Lyman-α absorption by these particles provide an opportunity for global imaging of stellar-plasma interactions with planetary bodies.

3 Stellar Wind Interaction with HD 209458b and Production of Hydrogen and ENA-Clouds

Holmström et al. [2008] and Ekenbäck et al. [2010] applied for the first time a plasma flow model which was developed for the study of ENA production around Mars, Venus and comets to HD 209458b and discovered that the majority of the "observed" hydrogen atoms correspond to ENAs which are produced by the stellar wind protons H_{sw}^{+} due to the charge exchange reaction with outward flowing planetary hydrogen atoms H_p $H_{sw}^{+} + H_p \rightarrow H_{sw}^{ENA} + H_p^{+}$. After the charge exchange process the neutralized solar/stellar wind proton H_{sw}^{ENA} atom will travel along its way with the proton (stellar wind) velocity.

Thus, the observation of hydrogen ENAs can provide a global distribution of the stellar wind plasma flow around an exoplanet if its magnetic obstacle does not prevent the production of these fast neutral hydrogen atoms by deviating the stellar wind flow. ENA observations combined with modelling provides, therefore, information about: the stellar wind plasma properties, non-thermal ion escape from the planet's exosphere, and the planets magnetic or non-magnetic obstacle. ENAs are involved in the Lyman-α absorbtion observed during the transits of HD 209458b. This is also in agreement with the recent data analysis by Ben-Jaffel and Sona Hosseini [2010], who analyzed the impact of external sources of energetic neutral atoms to the sensitivity of HD 209458b's transit absorbtion. By analyzing the velocity spectra these authors found that the derived external H source compares nicely with the energetic neutral atom hypothesis proposed by Holmström et al. [2008] and Ekenbäck et al. [2010]. Similar as in Holmström et al. [2008] and Ekenbäck et al. [2010] we apply the so-called FLASH-code which was developed at the University of Chicago for the study of astrophysical thermonuclear flashes which originate from X-ray bursts and super novae explosions [Fryxell et al., 2000]. The FLASH-code provides adaptive grids and is parallelized and extended for a planetary exosphere Direct Simulation Monte Carlo (DSMC) model [Ekenbäck and Holmström 2006; Ekenbäck et al., 2008] which is run by us via the High Performance Computing Center North (HPC2N), Umeå University, in Sweden.

For modelling ENAs around an assumed obstacle of HD 209458b we define a simulation domain box in a right handed coordinate system x, y and z, where the x-axis points towards the star, the y-axis directs opposite to the planet's velocity, and the z-axis is perpendicular to the planet's velocity. In this configuration HD 209458b is located in the center. The inner boundary R_0 of the simulation domain has a spherical shape, which is located at about $2.8R_p$ close to the Roche lobe distance. The planetary H atoms are launched as meta-particles, according to their atmospheric temperature T_p, density n_p and velocity v_p distributions from the inner boundary R_0 where the initial gas parameters T_p and n_p are taken from results of the theoretical [Yelle 2004, García Muñoz et al., 2007, Penz et al., 2008] and quasi-empirical models [Koskinen et al., 2010]. One should note that all these models converge to an atmospheric density and temperatures at our lower boundary location of about 3×10^{13} m^{-3} and 6000–10,000 K, respectively.

Each meta-particle corresponds to $N_m = 3.44 \times 10^{32}$ particles. After launching an atmospheric meta-particle from the inner boundary, its trajectory is numerically integrated and it is checked, within the volume elements along the particle trajectories, if charge exchange reactions take place. Collision with an UV photon and charge exchange with a stellar wind proton as well as photo-ionization or electron impact ionization or elastic collisions with another hydrogen atom on an outward flowing exospheric atom can occur. Because the host star of the studied exoplanet is comparable with the Sun, it is justified to estimate the stellar wind properties by using the solar values at HD 209458b's orbital distance at 0.045 AU as a proxy. Table 1 summarizes the planetary and stellar wind input parameters used in the simulations discussed below. After a hydrogen atoms and ENAs cloud is calculated and by knowing the positions of all the hydrogen meta-particles at a certain time we compute how these atoms attenuate the stellar Lyman-α radiation during a transit. For this task the yz-plane is discretized by applying a grid where we compute for each "pixel" the attenuation as function of velocity and wavelength. For pixels which cover the planet the attenuation is "1". Then the attenuation is averaged over all pixels and is then applied to the out of transit spectrum so that we produce a model spectrum.

Table 1: Planetary and stellar wind parameters for HD 209458b according to Ekenbäck et al. [2010].

Parameter	unit	value
Planetary radius: R_p	$[R_{Jup}]$	1.35
Planetary mass: M_p	$[M_{Jup}]$	0.69
Inner boundary distance: R_0	$[R_p]$	2.8
Inner boundary atmospheric density: n_p	$[\mathrm{m}^{-3}]$	4×10^{13}
Inner boundary atmospheric temperature: T_p	[K]	6000
Orbital location: d	[AU]	0.045
Stellar wind velocity: v_{sw}	$[\mathrm{m\ s}^{-1}]$	4.5×10^{5}
Stellar wind density: n_{sw}	$[\mathrm{m}^{-3}]$	3.5×10^{9}
Stellar wind temperature: T_{sw}	[K]	10^{6}

Because the magnetic field of HD 209458b is unknown we assume various obstacle stand-off distances from $3.5R_p$ to $10R_p$, where each of them corresponds to a magnetic field strength related to a value of a magnetic dynamo. The collision processes outside the assumed magnetic obstacle are modelled by a DSMC-method. After many runs we compare the best fit of our model results to the observed attenuation spectrum in and out of transit. The best fit enables us to estimate the corresponding magnetic field strength which can balance the incoming stellar plasma flow at the sub-stellar point.

Figure 1 shows the modelling results of hydrogen clouds around HD 209458b for ENAs, which are produced around magnetic obstacles by assuming sub-stellar magnetopause stand-off distances at $4.3R_p$ (Figure 1a,b) and $6.3R_p$ (Figure 1c,d). A planetary obstacle at the sub-stellar point of about $6.3R_p$ corresponds to a magnetic dipole field strength of Jupiter and that at $4.3R_p$ to a weaker one which is about 40% of Jupiters. The bright area/dots correspond to the stellar wind protons. The dark dots shown in Figure 1a and 1c show a mixture between the slow moving (<10 km s^{-1}) planetary neutral hydrogen atoms and fast moving stellar wind produced ENAs ($>$10-100 km s^{-1}). Figures 1b, and 1d show only ENAs which are produced outside the magnetic obstacle and correspond to hydrogen atoms with velocities > 50 km s^{-1}. One can also see that the interaction between the stellar wind and the planetary H atoms is more effective if the assumed magnetopause obstacle is closer to the planet. In such a case the stellar wind protons can interact with more outward flowing planetary hydrogen atoms so that more ENAs can be generated via the charge exchange process. On the other hand one can see that less ENAs are produced around the exoplanet in case the magnetopause obstacles are located at further distances as for example in Figure 1d. This is because the density of the outward flowing planetary hydrogen atoms is much lower at magnetopause stand-off distances $\geq 4.3R_p$, such as in the $6.3R_p$ case, resulting in less planetary atoms available for the charge exchange reactions.

Figures 2 shows the observed and modelled attenuation (2b velocity) spectra of HD 209458b when the exoplanet was out-of-transit (upper solid lines) and in-transit (lower solid lines). Figure 2a shows the modelled in-transit case for a magnetopause stand-off

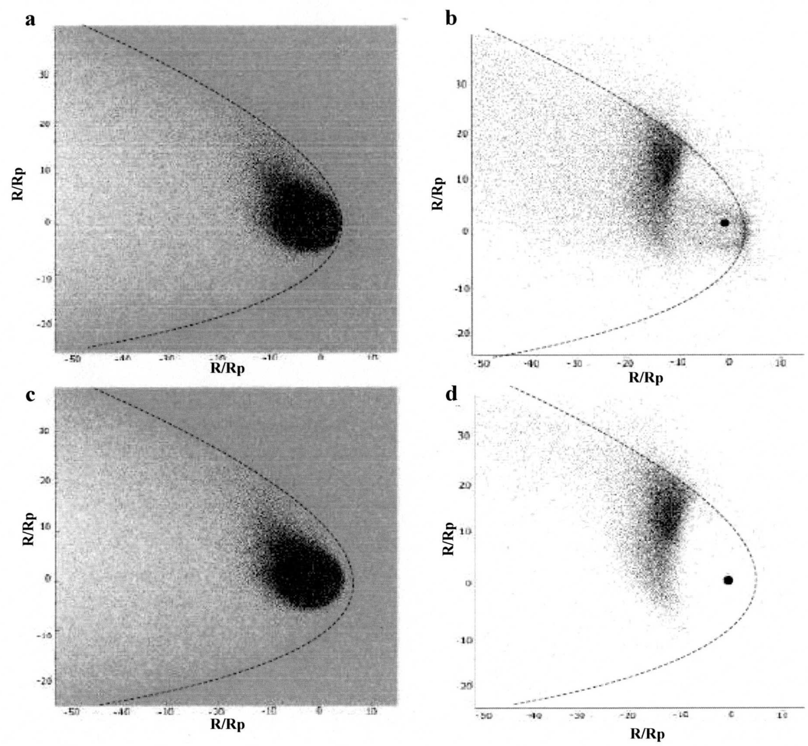

Figure 1: (a) Modelled stellar wind protons (bright gray area/dots), planetary and hydrogen ENAs (dark dots) around HD 209458b with an assumed sub-stellar magnetopause obstacle at 4.3R_p. (b) Only hydrogen atoms with velocities > 50 km s^{-1} around HD 209458b for the same stellar wind parameters and planetary obstacle. (c) and (d) correspond to similar model runs but with a magnetopause stand-off distance at 6.3R_p.

distance at $4.3R_p$ (dashed line). One can see that a relative good fit of the HST Lyman-α in-transit observation can be obtained if the magnetic field corresponding to a planetary magnetic dipole moment in units Jupiter's magnetic moment ($M_{Jup} = 1.56 \times 10^{27}$ Am^2) of about 40% of Jupiter's (see also, Ekenbäck et al. 2010). Figure 2b shows the corresponding velocity spectra. As one can see in Figure 2c larger magnetic dipole moments yield magnetic obstacles which balance the stellar wind at further distances such as $6.3R_p$ that can not reproduce the observed Lyman-α absorption because the resulting absorption is to weak and may therefore be ruled out for that particular exoplanet. Figure 2d shows a result where we moved the sub-stellar magnetopause obstacle closer to the inner boundary $\sim 3.2R_p$. One can see that if the obstacle is to close to the planet, the ENA-produced Lyman-α absorption is too strong and does also not fit the in-transit HST observation. If the stellar wind density is higher and the obstacle is compressed closer to the planet so that more ENAs can be produced, this result in to strong absorption too. If we assume a slower stellar wind velocity the obstacle moves outwards and we obtain less ENA absorption. Thus, due to possible uncertainties in the stellar wind and thermosphere parameters one may find good fits to the Lyman-α in-transit observations around $4.3 \pm 0.2R_p$.

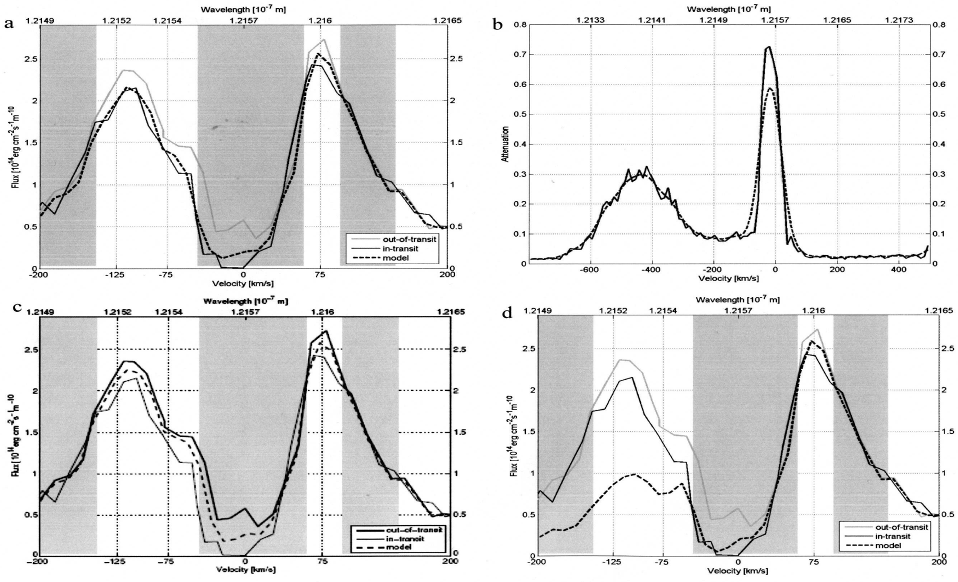

Figure 2: Observed and modelled Lyman-α attenuation spectra for HD 209458b. Out-of-transit (upper solid lines), in-transit (lower solid lines) and ENA-modelled attenuation spectra (dashed lines). a) the best fit of the observations yield a sub-stellar magnetopause stand-off distance of about 4.3R_p, b) shows the corresponding velocity spectrum; c) shows the modelled attenuation spectra (dashed lines) for a sub-stellar magnetopause stand-off distance of 6.3R_p or a lower exobase temperature; d) shows the modelled attenuation for a denser stellar wind ($9 \times 10^9 m^{-3}$) and the sub-stellar magnetopause stand-off distance at about 3.2R_p.

4 Conclusion

We have shown that observations of stellar Lyman-α absorbtion and modelling of hydrogen clouds around hot exosolar gas giants such as HD 209458b is a good tool for the investigation of the magnetic properties around exoplanets which are exposed to extreme stellar radiation fields. By analyzing the hydrogen ENA-cloud topology one can obtain information on the sub-stellar planetary obstacle location, which is related to the exoplanets magnetic environment and the upper atmosphere structure as well as the stellar wind plasma flow. From our preliminary studies we estimate a planetary magnetic dipole moment in units Jupiter's magnetic moment DM_{Jup} for HD 209458b which corresponds to about 40 % DM_{Jup}. Interestingly the field strength which is needed for the explanation of the observed Lyman-α absorbtion spectra correspond to a dipole moment which is stronger than that estimated by the tidal-locking hypothesis ($DM=$ 0.03-10% DM_{Jup}) but weaker as that proposed by the convection-driven dynamo hypothesis of Reiners and Christensen [2010] ($DM \geq DM_{Jup}$). High resolution UV observations of more "Hot Jupiters" in the near future by space observatories such as the World Space Observatory-Ultra Violet (WSO-UV) [Shustov et al., 2009] together with the expected detection of radio-emissions from exoplanets can be used for testing the discussed magnetic dynamo hypotheses in the future.

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