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Magnetic moment and plasma environment of exoplanets as determined from Lyα observations

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Abstract

We present an indirect method for estimate of exoplanetary magnetic moment based on Lyα observations in combination with the consequent numerical modelling and analysis [1, 2].

1. Introduction

Transit observations of HD 209458b in the stellar Lyman-α (Lyα) line revealed strong absorption in both blue and red wings of the line interpreted as hydrogen atoms escaping from the planet's exosphere at high velocities. The following sources for the absorption were suggested: acceleration by the stellar radiation pressure, natural spectral line broadening, charge exchange with stellar wind. We reproduce the observation by means of modelling that includes all aforementioned processes. Our results support a stellar wind with a velocity of $\approx$ 400 km$\times$s^{-1} at the time of the observation and a planetary magnetic moment of $\approx 1.6 \times 10^{26}$ A$\times$m^2.

2. Method

The particle code is based on Direct Simulation Monte Carlo (DSMC) method and includes stellar wind protons and atmospheric neutrals presented by metaparticles. We include also radiation pressure, gravitational effects (gravity, Coriolis, centrifugal, tidal forces), charge-exchange between protons and neutrals and elastic collisions between neutrals. The code allows to study the interaction processes in the exosphere under different conditions for magnetized and non-magnetized bodies. As a result the distribution of neutrals and ions around the planet and the location of the magnetospheric obstacle is obtained. Afterwards we apply post-processing programs developed to estimate the Lyα attenuation produced by neutral cloud around an exoplanet and observed in-transit.

3. Results

As an example of the simulation result we shown a slice of a 3D hydrogen cloud around HD 209458b (Fig. 1). The star is on the right. The red and blue dots correspond to H^+ ions and neutral hydrogen atoms, respectively. The black dot represents the planet. The white empty area around the planet is the lower atmosphere which is not considered in this study.

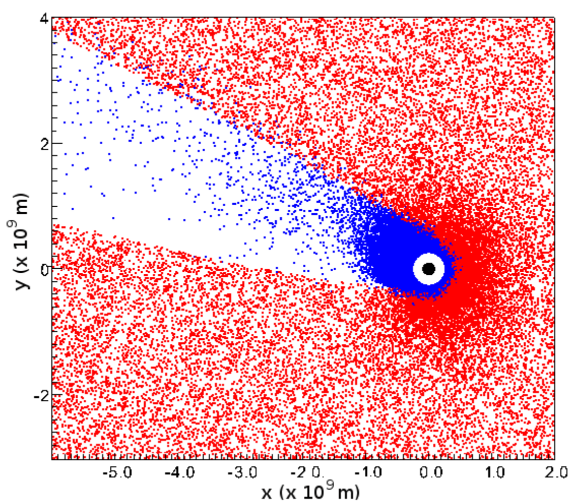

Figure 1: An example of modelled neutral hydrogen cloud around HD 209458b [1].

After a hydrogen corona is modelled, we apply the post-processing software to calculate the Lyα absorption caused by the cloud during the planetary transit, which is then compared to the observations [1, 2, 3]. When the observations are reproduced with a good precision (Fig. 2), we assume the obtained magnetic obstacle to estimate the planetary magnetic moment in a dipole approximation using the formula [4]

$$\mathcal{M} = \left(\frac{8\pi^2 R_s^6 \rho_{sw} v_{rel}^2}{\mu_0 f_0^2} \right)^{1/2} . \quad (1)$$

Here, R_s is the magnetospheric stand-off distance, μ_0 is the diamagnetic permeability of free space, $f_0 \approx 1.22$ is a form factor of the magnetosphere, ρ_{sw} is the mass density of the stellar wind, and v_{rel} is the relative velocity of the stellar wind plasma, including the planetary orbital velocity. The parameters R_s, ρ_{sw}, and v_{rel} are obtained from the modelling.

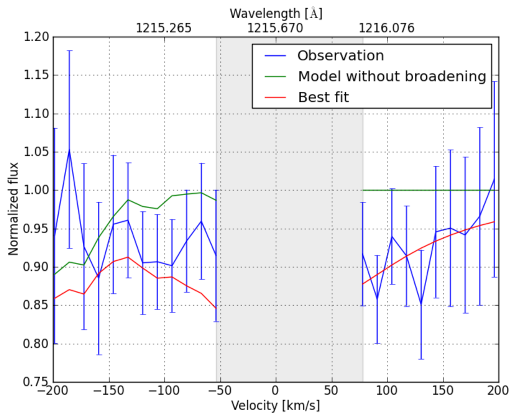

Figure 2: Comparison of modelled and observed (according to Ben-Jaffel and Hosseini[3]) Lyα spectra at mid-transit [1]. The blue lines show the observation, the red and green lines - best-fit modelling with and without Doppler line broadening, respectively. The region in the center contaminated by the geocoronal emission is excluded.

In the case of a close-in obstacle, the exosphere interacts directly with the stellar wind. This diminishes the number of H neutrals, first by charge exchange and second by stellar wind electron impact ionization. A stronger intrinsic field shifts the magnetic boundary away from the planet and effectively protects the atmosphere from these processes. This increases the number of neutrals undergoing acceleration by radiation pressure and leads to overabsorption in comparison to the in-transit observation. The stellar wind speed influences the speed of the newly produces energetic neutral atoms and can be defined from the spectral signatures in the Lyα line as well.

4. Summary and Conclusions

We presented an indirect method, which can be used to estimate the total magnetic moment of exoplanets, as well as restrict the stellar wind parameters at the time of observation. The methodology is of a particular interest considering the lack of the direct measurements of exoplanetary magnetic moments at present. The method was successively applied to the Hot Jupiter HD 209458b [1] and predicted the magnetic moment of the planet of $\approx 10\%$ of the one of Jupiter. Also, the model predicted a fast stellar wind at the time of observation (≈ 400 km/s).

The method can be applied to every exoplanet for which the Lyα observations are available.

Acknowledgements

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