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The thermospheres of extrasolar giant planets

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Abstract

The hot and extended thermospheres of close-in transiting planets make them highly amenable to study by transit observations at UV wavelengths. We discuss the characteristics of the thermospheres of hydrogen-rich close-in extrasolar giant planets (EGPs) in light of recent observations and theoretical modeling. Results from both global and one-dimensional (1D) models demonstrate that the thermal state and photochemistry of the upper atmosphere depends on the orbital distance a of the planet and the EUV flux of the host star. At close-in orbits ($a < 0.2$ AU for a Sun-like star) the atmosphere is composed of atoms and atomic ions at $p < 1$ μbar and the temperature of the thermosphere is $T \sim 10{,}000$ K. Under these circumstances, the neutral atmosphere extends to $z \sim 3$ R_p and the atmosphere evaporates with a mass loss rate that depends on the heating efficiency.

1. Introduction

Transit observations in the FUV have led to the detection of hydrogen (H I), oxygen (O I), ionized carbon (C II) and silicon (Si III) on HD209458b [7, 1, 6], and the possible detections of H I on HD189733b. The large transit depths of 5–10 % indicate that these observations probe extended thermospheres that extend to several planetary radii and may escape hydrodynamically. The HLy α transits are particularly interesting because they probe the dominant species of the neutral thermosphere. Here we discuss models that can be used to explain the H I transit observations and clarify such fundamental properties as optical depth, the base of the outflow, temperature, composition, and ionization of the EGP thermospheres.

2. Methods

We have used a global hydrostatic model [2] and 1D outflow models ([8],Koskinen and Harris, in prep.) to characterize the thermospheres of EGPs at different orbital distances. These models are based on solving either the horizontal or vertical components of the Navier-Stokes equations and they include realistic heating, ionization, and photochemical calculations. Guided by the results, we also constructed an empirical model for the atmosphere of HD209458b with a few free parameters that can be varied to fit the observations. Figure 1 illustrates the model atmosphere and the important transition altitudes and parameters that affect the appearance of the thermosphere during transit.

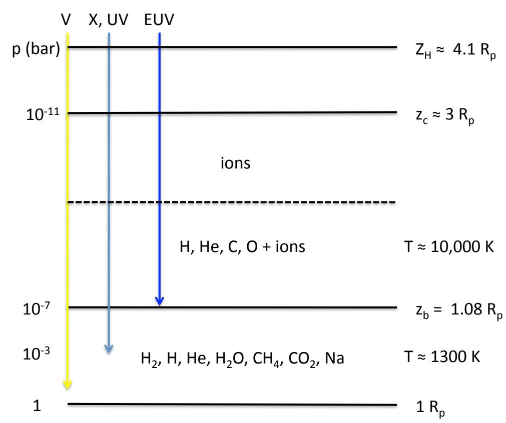

Figure 1: Empirical model for the thermosphere of HD209458b [3]. The lower boundary at 1.08 R_p coincides with the H_2/H dissociation front and the above the upper boundary of ~ 3 R_p most of the atmosphere is ionized.

3. Results

We used the empirical model to fit the H Ly α transmission curve for HD209458b [1] (see Figure 2). We found that the H_2/H dissociation front is located at $p \sim 0.1$ μbar or deeper and the temperature above this level is T =8000–10,000 K. At $z \sim 2.9$ R_p the atmosphere becomes predominantly ionized. By introducing a solar proportion of oxygen, the model OI 1304 transit depth is 4.3 %, which lies within 1.4σ of the observed low S/N transit depth of 10.5 $\pm$ 4.4 %. A larger

O I transit depth is possible if the atmosphere escapes hydrodynamically, the O/H ratio is supersolar, or significant quantities of O I are present outside the Roche lobe. Preliminary results indicate that a similar model can explain the observed H I transit depth of ∼5 % for HD189733b.

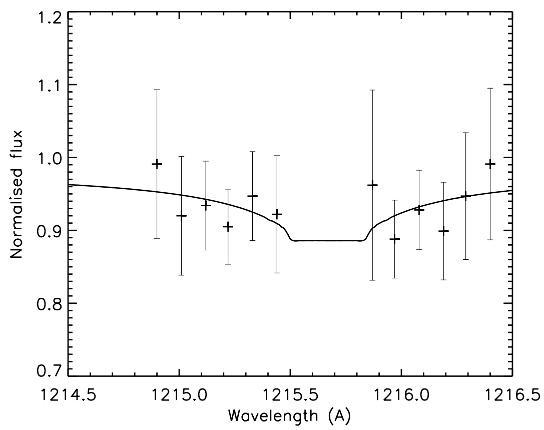

Figure 2: Transmission as a function of wavelength at HLy α during the transit of HD209458b. The data points are from [1] and the solid line shows our model transmission [3]. The line-integrated transit depth is 6.6 %.

More complex models support the above results. In our global and 1D models, almost all of the stellar EUV radiation is absorbed at $p < 1$ μbar. This leads to the dissociation of molecules, ionization, and heating of the thermosphere. The optical depth to EUV radiation $\tau = 1$ in the EUV ionization peak (EIP) layer at p =1–10 nbar [4]. Above this level, the atmosphere may escape hydrodynamically at close-in ($a < 0.2$ AU) orbits. The density profile deviates significantly from hydrostatic equilibrium above the critical level at $z > 3$ R_p. We note that the thermospheres are significantly ionized. In the EIP layer, the electron-neutral mixing ratio $x_e = 10^{-2}$–10^{-5} between $a = 0.047$–1 AU, and at close-in orbits the escaping atmosphere is predominantly ionized. The coupling of the plasma to the neutral atmosphere must therefore be considered properly in future modeling.

The density, temperature, and velocity profiles depend on the heating efficiency, which in turn depends on the composition. Depending on the heating efficiency, we obtain different escape velocities and mass loss rates between $dM/dt = 10^{10}$–10^{11} g s^{-1} for HD209458b. In future modeling, the heating efficiency for different planets should be calculated consistently from detailed energy deposition rates. At larger orbital distances ($a > 0.2$ AU), the dominant species below the exobase is H_2 because the EUV flux is lower than at close-in orbits. Thus the thermospheres are significantly cooler and the density in the exosphere may not be high enough for hydrodynamic escape to take place [2].

4. Summary and Conclusions

We have constructed an empirical model for the thermospheres of close-in EGPs and used it to interpret the detections of neutral hydrogen and oxygen atoms around HD209458b. Our results are supported by several first principles models that can be used to estimate important transition altitudes and parameters that affect the observable properties of the thermospheres of EGPs.

References

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