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Stellar activity effects on the atmospheric escape of hot Jupiters

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Abstract. Transit observations have revealed the existence of atmospheric escape in several hot Jupiters. High energy photons from the host star heat the upper atmosphere and drive the hydrodynamic escape. The escaping atmosphere can interact with the stellar wind from the host star. We run radiation hydrodynamics simulations with non-equilibrium chemistry to investigate the wind effects on the escape and the transit signature. Our simulations follow the planetary outflow driven by the photoionization heating and the wind interaction in a dynamically coupled, self-consistent manner. We show that the planetary mass-loss rate is almost independent of the wind strength, which however affects the Ly-α transit depth considerably. But the Hα transit depth is almost independent of the wind strength because it is largely caused by the lower hot layer. We argue that observations of both lines can solve the degeneracy between the EUV flux from the host and the wind strength.

Keywords. hydrodynamics – methods: numerical – planets and satellites: atmospheres – planets and satellites: physical evolution

1. Introduction

For close-in exoplanets, the extreme irradiation from the host star can drive the atmospheric escape. Such escape process can be important in planetary evolution and can even shape the statistical properties of observed close-in exoplanets (sub-Jovian desert; Szabó and Kiss (2011), sub-Neptune desert; Fulton et al. (2017)). Transit observations have revealed the extended atmosphere for close-in exoplanets (Vidal-Madjar et al. 2003; Ehrenreich et al. 2015).

Extreme-Ultraviolet (EUV$>$ 13.6 eV) photons ionize the hydrogen atoms and heat the atmospheric gas through thermalization of the photoelectrons. The photoionization heating contributes to atmospheric escape. Radiation hydrodynamics simulations identified the important physical processes and allowed detailed studies of the atmospheric structure (Murray-Clay et al. 2009). Interaction with the stellar wind is also investigated in several studies (Bisikalo et al. 2013, 2018; Cherenkov et al. 2018; Vidotto and Cleary 2020; Carolan et al. 2021). Often the Ly-α transit depth is considered because of its large absorption. Ly-α photons from the host star can be easily absorbed by the interstellar medium between the star-plane system and the earth, which makes it difficult to observe directly. Recent observations by ground-based telescopes use other lines (e.g. Helium triplet line, Hα line) which are more useful to detect the extended atmosphere.

Recent observations have also detected hot Jupiters around young active stars. Vigorous activities of such young stars can cause a strong influence on the planetary atmosphere, especially on the close-in planets. Strong winds can confine the upper atmosphere and reduce both the mass loss and the transit depth. The wind effect is expected to be important particularly in young systems with strong activities.

Numerical simulations so far that have used to investigate the wind confinement and Ly-α and Hα transits do not treat photoionization heating and the launched outflow in a self-consistent manner. To study the wind effect on the planetary atmosphere, self-consistent radiation hydrodynamics simulations are necessary to follow the launching of the outflow because Hα absorption may be significant in the lower atmospheric layers. We run simulations with varying the strength of the stellar wind and calculate the Ly-α and Hα transit depths. We discuss the possibility that the strong stellar activity changes the absorption signatures.

2. Methods

We first introduce our simulations. We use the hydrodynamics simulation code PLUTO (Mignone et al. 2007) with the EUV radiation transfer module (Nakatani et al. 2018). Detailed implementation is described in (Nakatani et al. 2018; Mitani et al. 2021). Our simulations solve the following 2D axisymmetric hydrodynamic equations and non-equilibrium chemistry:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0 \tag{2.1}$$

$$\frac{\partial \rho v_R}{\partial t} + \nabla \cdot (\rho v_R \vec{v}) = -\frac{\partial P}{\partial R} - \rho \frac{\partial \Psi}{\partial R} \tag{2.2}$$

$$\frac{\partial \rho v_z}{\partial t} + \nabla \cdot (\rho v_z \vec{v}) = -\frac{\partial P}{\partial z} - \rho \frac{\partial \Psi}{\partial z} \tag{2.3}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho H \vec{v}) = -\rho \vec{v} \cdot \nabla \Psi + \rho(\Gamma - \Lambda) \tag{2.4}$$

$$\frac{\partial n_H y_i}{\partial t} + \nabla \cdot (n_H y_i \vec{v}) = n_H R_i \tag{2.5}$$

where $\rho, \vec{v}, P$ are density, velocity, pressure of the gas. The potential Ψ includes contributions of the star and the planet and also incorporates the centrifugal force due to the orbital motion. We also follow the non-equilibrium chemistry including photoionization of the hydrogen atoms which can be important in the hydrogen absorption signatures. $y_i = n_i/n_H$ and R_i represent the abundance and the reaction rate, respectively. The incorporated chemical species are H, H^+, H_2, e−.

The heating and cooling rates are denoted as Γ, Λ, respectively. We calculate the EUV photoionization heating rate by ray-tracing:

$$F_\nu = \frac{\Phi_\nu}{4\pi a^2} \exp[-\sigma_\nu N_{\mathrm{HI}}] \tag{2.6}$$

$$\Gamma_{\mathrm{ph}} = \frac{1}{\rho} n_{\mathrm{HI}} \int_{\nu_0}^{\infty} \mathrm{d}\nu \, \sigma_\nu h(\nu - \nu_0) F_\nu \tag{2.7}$$

where σ_ν is the absorption cross section as a function of ν (Osterbrock and Ferland 2006) and N_{HI} is the column density of hydrogen atoms and $h\nu_0 = 13.6\,\mathrm{eV}$. We implement Ly-$\alpha$ cooling and hydrogen recombination cooling (Spitzer 1978; Anninos et al. 1997).

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Table 1. Model parameters in the fiducial run.

Stellar parameters	
Stellar Mass M_*	$1\,M_\odot$
Stellar Radius R_*	$1\,R_\odot$
Stellar EUV photon emission rate Φ_ν	$1.4 \times 10^{38}\ \mathrm{s}^{-1}$
Stellar wind velocity	$540\,\mathrm{km/s}$
Stellar wind temperature	$2 \times 10^6\ \mathrm{K}$
Stellar wind density	$2.5 \times 10^3\ \mathrm{g/cm}^3$
Planetary parameters	
Planet Mass M_p	$0.3\,M_\mathrm{J}$
Planet Radius R_p	$1\,R_\mathrm{J}$
Semi-major axis a	0.045 AU

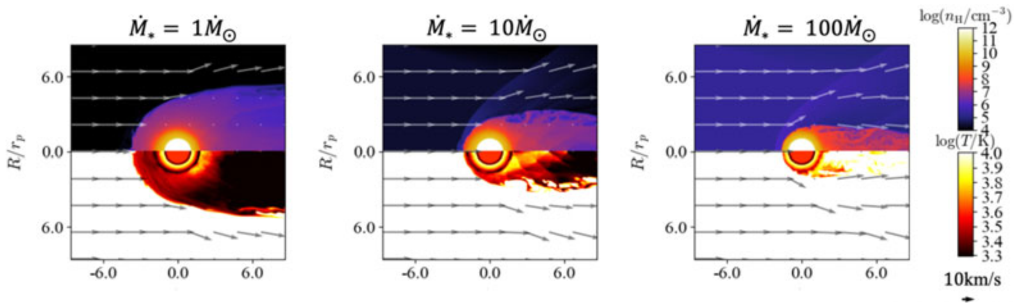

Figure 1. The atmospheric structure of our simulations. The EUV photons and the wind from the host star are injected from the left side of the figure. The stellar mass loss rates are $\dot{M}_* = 1\dot{M}_\odot(left), 10\dot{M}_\odot(middle), 100\dot{M}_\odot(right)$. In each figure, the upper panel shows the density and lower panel shows the temperature.

In our simulations, Ly-α cooling is a major radiative cooling process, and the adiabatic cooling dominates the overall cooling processes.

Table 1 shows the stellar and planetary parameters of our fiducial simulation.

We also run simulations with various stellar wind strength by varying the stellar wind density.

3. Results and Implications

Figure 1 shows the atmospheric structure of our simulations. The strong wind confines the outflow. The wind-outflow structure is shaped by the balance between the ram pressure of the wind and the thermal pressure of the outflow. The balanced point can be estimated as

$$k_\mathrm{B}\rho_\mathrm{p}(r)\,T_\mathrm{p}(r)/\mu m_H = \rho_*(r)\,v_*^2(r) \tag{3.1}$$

where $\rho_\mathrm{p}(r), T_\mathrm{p}(r)$ are the density and temperature of the planetary atmosphere at the contact point, μ is the mean molecular weight, m_H is the hydrogen atomic mass, and $\rho_*(r), v_*(r)$ are the density and velocity of the wind. The balanced point depends on both the velocity and density of the wind because the ram pressure determines the structure, implying that the mass-loss rate of the star does not uniquely determine the structure of the atmosphere and the observational signatures.

Table 2 shows that the mass-loss rates of the planet are almost independent of the wind strength and that the value is approximately 10^{10} g/s because the wind can suppress the outflow only when it strongly affects the atmosphere around the launching point. This is achieved for $\dot{M}_* > 1000\,\dot{M}_\odot$.

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Table 2. Planetary Mass-loss rates with different stellar winds.

Stellar Wind strength	Mass-loss rate (g/s)
1 $\dot{M}_\odot$	2.9×10^{10}
10 $\dot{M}_\odot$	2.2×10^{10}
100 $\dot{M}_\odot$	2.3×10^{10}

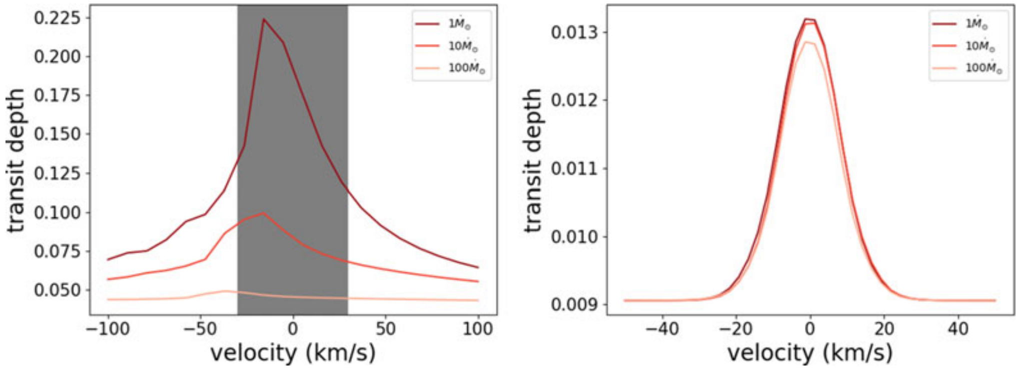

Figure 2. *left panel*: Ly-α transit depth at mid-transit. The shaded region is the line center region where the local interstellar medium can absorb. *right panel*: Hα transit depth.

Figure 2 shows the Ly-α and Hα transit of our outputs. The peak of the Ly-α transit is blue-shifted due to the wind. This is consistent with the previous studies (McCann et al. 2019). To calculate Hα absorption, we assume the $n=2$ level population using the $2p$, $2s$ population of Christie et al. (2013):

$$\frac{n_2}{n_1} = \frac{n_{2p}+n_{2s}}{n_1 s} \simeq 10^{-9}\left(\frac{5R_*}{a}\right)^2 e^{16.9-(10.2\,\mathrm{eV}/k_B T_{\mathrm{Ly}\alpha,*})} + 1.627\times 10^{-8}\left(\frac{T}{10^4\,\mathrm{K}}\right)^{0.045} e^{11.84-118400\,\mathrm{K}/T} \times \frac{8.633}{\log(T/T_0)-\gamma} \tag{3.2}$$

where $T_{Ly\alpha,*} \sim 7000\,\mathrm{K}$ is the excitation temperature for the solar Lyman-α, $T_0 = 1.02\,\mathrm{K}$ and $\gamma = 0.57721\ldots$ is the Euler-Mascheroni constant. In our simulations, the strong wind can reduce the Ly-α transit depth while the Hα signature is almost independent of the strength. The Hα absorption by the atmosphere is significant in lower hot region because the $n=2$ level population is larger there ($n_2/n_1 \sim 10^{-9}$).

The transit signatures due to the extended atmosphere are also dependent on the EUV flux from the host star. The Ly-α transit depth depends on the EUV flux and the wind strength, whereas the Hα transit signature does not sensitively depend on the wind strength unless the wind is extremely strong with $\dot{M}_* > 1000\dot{M}_\odot$. Our simulations are 2D axisymmetric and neglect the tail contribution to the transit signatures. The tail contribution should be significant in Ly-α blue-wing but is likely unimportant in Hα absorption because the lower hot atmospheric layer matters. The difference between the wind effects on Ly-α and Hα would be essentially the same even if we consider the tail contribution to the signature. We argue that observations of both signatures can solve the degeneracy of the stellar EUV luminosity and the wind properties in close-in gas giants.

The stellar activities have a significant impact on the planetary atmosphere and the observational signatures (Zhilkin et al. 2020). The rate of the flare activities is well

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known for the Sun (Maehara et al. 2017). Strong flares are accompanied by coronal mass ejections (CMEs) in many cases, and thus we can estimate the rate of the strong mass-loss $\dot{M}_* > 10\,\dot{M}_\odot$ due to the activities.

$$\int_{10^{32}\,\mathrm{erg}}^{\infty} f(E_{\mathrm{flare}})\,\mathrm{d}E_{\mathrm{flare}} \sim 1 - 100\,\mathrm{year}^{-1} \tag{3.3}$$

For solar type stars, the possibility that the strong CME changes the observational Ly-α is expected to be small.

For young stars, stellar activities should be stronger than that of the sun. Also the rate becomes higher. In the case of a very young host star ($< 50\,\mathrm{Myr}$), the probability becomes an order of magnitude larger (Feinstein et al. 2020). We note that, in many cases, the age of the host star in the observed exoplanets is older than 50 Myr and the effect can be small. Interestingly, the activities are also stronger (Maehara et al. 2014) for cooler stars. The spectral type dependence of the stellar activity is also investigated. The flare frequency in M dwarfs is a few orders of magnitude larger than in G-type stars. The strong CME frequency becomes larger in late-type stars, and the CME happens almost always in every transit around M dwarfs.

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Discussion

HANAWA: I am wondering whether your simulation resolved the bow shock and contact discontinuity.

HIROTO: We talked about the force balance which describes the shock front. Our simulations resolve the shock front and contact discontinuity.

BISIKALO: Do you take into account orbital motion of planets? Because I cannot see the influence of the Coriolis force.

HIROTO: Our simulations are 2D axisymmetric and we consider the centrifugal force but neglect the Coriolis force. The Ly-α transit signature can be affected by the 3D effect because of the tail contribution. That can be important. Hα transit absorption can be independent of the existence of the tail because the absorption is significant around a relatively lower region in which the gas temperature is high. The difference of the stellar wind strength dependence between Ly-α and H α may be qualitatively similar to the 3D.

RONY: In the case of Jupiter, the strong magnetic field plays a role of having magnetic (ram) pressure, setting the size of the planetary interaction with the solar wind, will you eventually do MHD simulations as well? And what is your boundary condition at the planet: you just give a radial subsonic (or supersonic) outflow?

HIROTO: Magnetic pressure can indeed be important. I would run MHD simulations eventually but do not have an immediate plan currently. In our simulations, the EUV-driven outflow is excited from the hydrostatic, stratified gas, and the outflow base is well above the planet boundary. We use the boundary condition where the gas is hydrostatic across the boundary.