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The estimate of hot Jupiter mass loss rate in the interaction with CME from a solar type star

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Abstract. We consider the influence of a coronal mass ejection (CME) of a solar type star on the mass loss rate of a hot Jupiter exoplanet. We have conducted 3D numerical gas-dynamic simulations of the planet's atmosphere that interacts with CME. Using the results of these simulations we have estimated the specific parameters that influence the mass loss rate. Based on the assumption that CME totally sweeps away part of the planet's gaseous envelope located outside the Roche lobe we estimated the maximum mass loss rate. Finally, we have considered the dependence of mass loss rate on the frequency of CMEs in course of star's evolution.

1. Introduction

Hot Jupiter exoplanets have masses comparable with the mass of Jupiter and orbit their host stars at quite short distances, not longer than 0.1 A.U. According to (Bisikalo *et al.* (2013a), Bisikalo *et al.* (2014)), all gaseous envelopes surrounding hot Jupiters can be divided into three groups. Closed envelopes are those where the head-on collision point, located at the minimum distance between the contact discontinuity and the planet, is inside the Roche lobe. Depending on the degree of Roche lobe filling, the shape of these envelopes may deviate from sphere, but their mass loss rates are low ($\dot{M} < 10^9$ g/s, Cherenkov *et al.* (2014)). If the head-on collision point and, hence, part of the atmosphere are located outside the planet's Roche lobe, a noticeable outflow occurs in the vicinity of L_1 and L_2 points, which results in a significantly asymmetric shape of the envelope. Some of these envelopes may be quasi-closed if the dynamic pressure of the wind is strong enough to stop the outflow. In this case the envelope has a complex shape (Bisikalo *et al.* (2013b)) and a mass loss rate $\dot{M} \sim 3 \times 10^9$ g/s (Cherenkov *et al.* (2014), Bisikalo *et al.* (2015a)). If the wind cannot stop the outflow from the L_1 an open (non-spherical) envelope forms in the system.

For the study of planet's mass loss rate, quasi-closed envelopes are of the main interest. Indeed, if the envelope is bigger than the Roche lobe, the material, formally belonging to the atmosphere, actually, has a weak gravitational binding with this atmosphere. In this case, even an weak impact (for example, a coronal mass ejection) can sweep the outer part of the atmosphere away and significantly increase the mass loss rate. Formally, the same effect takes place in open envelopes. However, they are not stationary and evolve toward quasi-closed envelopes within a short time (see, e.g., Bisikalo *et al.* (2015b)). According to (Bisikalo *et al.* (2015c)), one third of hot Jupiters should have extended envelopes exceeding their Roche lobes.

The interaction between hot Jupiter extended gaseous envelopes and coronal mass ejections first has been considered by (Bisikalo *et al.* (2015b)). In this work the authors have shown that CME can destroy the outer part of a hot Jupiter envelope and increase the mass loss rate by more than an order of magnitude. However, these results have been obtained only for a single typical coronal mass ejection, i.e. they allow determining only the average mass loss rate for a single event.

Determining the total atmospheric mass loss of an exoplanet is a more complicated problem, since the frequency of CMEs and their power are functions of time and significantly grow for younger stars (Vidotto *et al.* (2010)). In this paper we consider the mass loss rate as a function of only CME frequency, assuming that their power is low and sufficient only to sweep away the outer part of the atmosphere located beyond the Roche lobe. The paper has the following structure: in Section 2 we describe the problem setup; Section 3 is focused on the analysis of the mass loss rate as a function of CME frequency; in Section 4 we summarize the main conclusions of the work.

2. Problem setup

We consider the HD 209458b exoplanet as a typical hot Jupiter. This is a transiting exoplanet with the radius $R_{pl} \sim 1.38\,R_{jup}$ and mass $\sim 0.69\,M_{jup}$, orbiting a G0V main sequence star at a distance of 0.04747 A.U. with the orbital period of 3.52472 d. (Southworth *et al.* (2010)). The parameters of the planet's upper atmosphere has been found in (Koskinen *et al.* (2013)). We consider a purely gas-dynamical solution, since one may neglect the magnetic field of the planet when considering envelopes that exceed the planet's Roche lobe. Indeed, even at maximum estimated magnetic fields (up to 1/10 of Jupiter's field, Kislyakova *et al.* (2014)) the radius of the magnetosphere is smaller than the size of the Roche lobe and, hence, the magnetic field does not influence the outer parts of the envelope.

In this work we analyze a solution with a quasi-closed envelope from (Cherenkov *et al.* (2014)). It is characterized by the temperature $T = 7.5 \cdot 10^3$ K and concentration on photometric radius $n = 10^{11}$ cm^{-3}. In Fig. 1 we show the main flow elements in the quasi-closed envelope. One can see that in the solution two streams are formed; the major, from the vicinity of the L_1 point, directed to the star, and a minor, weak, but still noticeable from the L_2 point, directed from the star. The stellar wind stops the outflow from the L_1 at a distance of several R_{pl} from L_1. Due to the supersonic motion of the planet in the gas of the stellar wind a system of two bow-shocks forms in the flow. The head-on collision point of the first bow-shock is located ahead of the stream from L_1. The head-on collision point of the second wave is located ahead of the spherical part of the atmosphere. At the accepted parameters of the stelar wind, equal to those of the Sun, the total mass loss rate is lower than $3 \cdot 10^9$ g/s. Analyzing this solution we have determined the mass M_{env} of the quasi-closed envelope located beyond the Roche lobe. This envelope mass is $\sim 6 \cdot 10^{-16} M_{jup}$.

In (Bisikalo *et al.* (2015b)) we have modeled the interaction between CME and a hot Jupiter envelope. In these simulations we used the parameters of the solar wind measured by (Farrell *et al.* (2012)) during a typical coronal mass ejection. In (Bisikalo *et al.* (2015b)) it was assumed that the relative variations of the wind parameters in the orbit of the modeled hot Jupiter are the same as in Earth's orbit. The CME phases proposed by (Farrell *et al.* (2012)) are separated by vertical gray lines in Fig. 2. The mass loss rate measured during the propagation of CME through the quasi-closed envelope is shown in Fig. 2. One can see that most of the time the mass loss rate is significantly higher than that in the equilibrium state, except short time periods in the beginning of phases 2

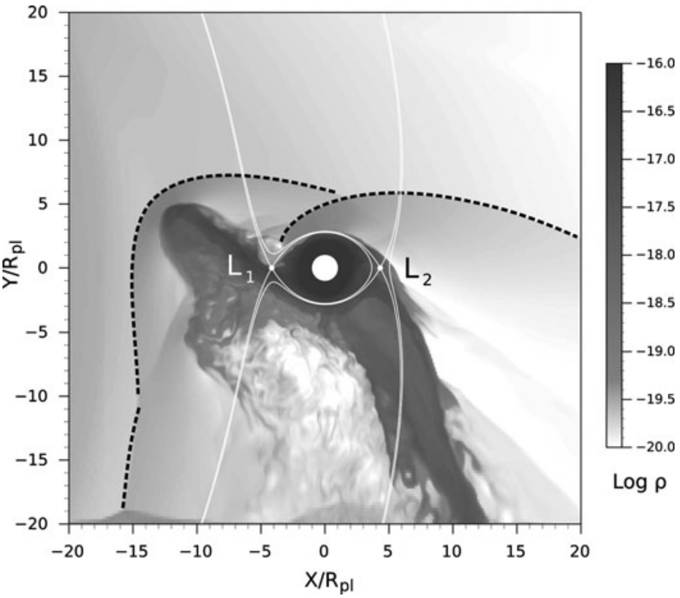

Figure 1. Density distribution in a quasi-closed envelope of an exoplanet. We show the cross–section in the equatorial plane of the system. The star is on the left. A white circle in the center is the planet. White solid lines depict the isolines of the Roche lobe. We also show the positions of the L_1 and L_2. Dashed black lines show positions of bow-shocks.

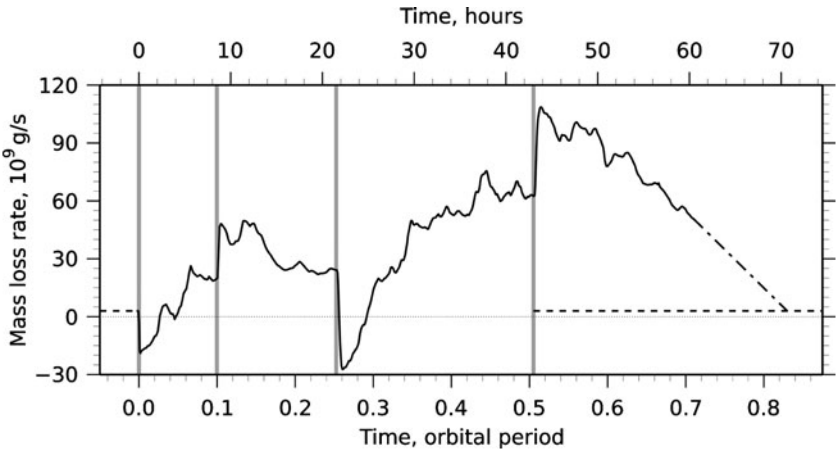

Figure 2. Mass loss rate during the propagation of CME through a quasi-closed envelope. CME phases are separated by vertical gray lines. This figure is taken from the paper by (Bisikalo *et al.* (2015b))

and 4 when the dense stellar wind approaches the envelope. The equilibrium value of the mass loss rate is $3 \cdot 10^9$ g/s and is shown in Fig. 2 by a dashed line at phases 1 and 5. The total mass the planet loses in the interaction with CME is 10^{16} g, which is approximately 14 times higher than the mass the planet loses in the stationary solution within the same period of time $\Delta t \sim 0.83 \cdot P_{orb}$. The characteristic time t_{loss}, during which the planet loses the envelop with the mass M_{env}, may be determined as a ratio between the total mass loss during CME and the CME duration. This approach enables one to take into account the complex behavior of CME in time and to obtain an appropriate estimate that allows describing an average solar CME. From (Bisikalo *et al.* (2015b)) the value of t_{loss} can be estimated as ≈ 7.4 hours.

Another important parameter that governs the total mass loss rate in the interaction with CME is the time of formation of the quasi-closed envelope t_{form}. The results of the simulations show that for HD 209458b this parameter is $t_{form} \approx 24$ hours, which is approximately twice as longer than the time needed to form the stream of the same size in the ballistic approach.

All the estimates we show here have been obtained for only one configuration of the gaseous envelope of HD 209458b that corresponds to model 3, described in (Bisikalo *et al.* (2015b)). According to our results the size of the envelope L (distance between the L_1 point and the head-on collision point) is $\sim 10\,\mathrm{R_{pl}}$. However, in (Bisikalo *et al.* (2015a)) by analyzing the results of HST observations of the WASP-12b exoplanet (Johnstone *et al.* (2015)) have shown that the envelope may be significantly bigger, up to $L > 21\,\mathrm{R_{pl}}$. It is obvious that at bigger envelope sizes the parameters M_{env}, t_{loss}, and t_{form} should be different. According to our estimates the maximum possible size of the envelope of HD 209458b should be $\sim 52\,R_{pl}$. In this case its mass is $\sim 10^{-15}\,\mathrm{M_{jup}}$; t_{loss} and t_{form} are ~ 15 and ~ 39 hours, respectively.

The combination of M_{env}, t_{loss}, and t_{form}, in principle, allows determining the mass loss rate as a function of CME frequency. However, one also should take account of CME duration t_{CME} in comparison with t_{loss}. Indeed, if $t_{CME} > t_{loss}$, mass loss efficiency decreases, since the entire envelope disappears within t_{loss} and during the rest period t_{CME}-t_{loss} no mass loss occurs. If $t_{CME} > t_{loss}$ the efficiency also decreases, since during t_{CME} the envelope loses a mass $M_{env} \cdot (t_{CME}/t_{loss})$. It is obvious that optimal CME (in the sense of efficiency) should have duration t_{CME}=t_{loss}. Hereafter, we consider these CMEs.

CME frequency significantly varies during star's lifetime. Using observational data, including those from the Kepler space telescope, (Vidotto *et al.* (2010)) have derived an empirical dependence of superflare's frequency on star's age for flares, whose energy exceeds the energy of solar flares by up to 1000 times: $f \sim t^{-1.4}$. According to (Shibayama *et al.* (2013)), the dependence of flare frequency on their energy has a unified form $dN/dE \sim E^{-2}$, which allows us to assume that the frequency of flares of any types varies in course of stellar evolution in the same way as that of superflares.

3. Mass loss rate as a function of CME frequency

Let us consider the influence of CME frequency on the mass loss rate. We show above that the optimal duration of CME is $t_{CME} = t_{loss}$. In addition, CMEs take the maximum mass away if the envelope fully forms by the next flare, i.e. the time between CMEs should be equal to t_{form}. This means that the most efficient mass outflow takes place if the specific time between flares is $(t_{loss} + t_{form})$ and mass loss rate is $\dot{M} = M_{env}/(t_{loss} + t_{form})$. For a quasi-closed envelope with the size $L \sim 10\,\mathrm{R_{pl}}$ the optimal flare recurrence time is 31.4 hours and the total mass loss rate is $\sim 10^{10}$ g/s or $\approx 1.64 \cdot 10^{-13}\mathrm{M_{Jup}}$/year. For an envelope of the maximum size ($L \sim 52\,\mathrm{R_{pl}}$) the optimal mass loss rate is more or less the same, but at a specific inter-flare time of ~ 54 hours.

The obtained estimates are the highest possible for flares having enough power to sweep the outer envelope, but weak to significantly affect the material inside the Roche lobe. We should note that these estimates $\dot{M}$ are in a good agreement with the value of mass loss rate $\dot{M}_{L_1} = 2 \cdot 10^{10} g/s$ that takes place at free outflow through the vicinity of the L_1 point. This allows us to use the theoretical value $\dot{M}_{L_1}$ when analyzing the total mass loss of exoplanets.

If the flare frequency grows or decreases (at a constant flare duration) the mass loss decreases, since either the flares overlap and prevent the outflow through the Roche lobe or the envelope retains in a quasi-stationary state between the flares when the mass loss rate is low. If the power of flares grows above some level CME should be able to sweep even those parts of the atmosphere that are located within the Roche lobe, which significantly increases $\dot{M}$. This mechanism requires additional study, so in this work we consider only sufficiently weak flares, whose parameters are close to those of the Sun.

If one knows the flare frequency as a function of star's age (Vidotto *et al.* (2010)) and uses the observed frequency of Solar flares (approximately two flares a month detected in Earth's orbit, Farrell *et al.* (2012)), he can estimate the age at which the exoplanet analogous to HD 209458b undergoes the maximum mass loss: the most efficient frequency occurs at an age of ~ 0.8 billion years.

4. Conclusions

We have considered how a coronal mass ejection (CME) from a solar type star influences the mass loss rate of a hot Jupiter exoplanet. Using the results of 3D gas-dynamical simulations (described in Bisikalo *et al.* (2015b)) of the typical hot Jupiter planet HD 209458b we have estimated the maximum possible mass loss rate due to planet's interaction with CME. It has been shown that the maximum mass loss rate of $\approx 1.64 \cdot 10^{-13} \mathrm{M_{Jup}}$/year takes place at the flare recurrence time of ≈ 31 hours, which corresponds to the star's age of ≈ 0.8 billion years. This estimate has been made under the assumption that the size of the planet's envelope is $\sim 10\, R_{pl}$. However, its maximum size, in the case of low velocity stellar wind, may be $\sim 52\, R_{pl}$ for HD 209458b. In this case the mass loss rate should be the same, but at the flare recurrece time of 54 hours, which corresponds to the star's age of 1.2 billion years.

In this paper we consider only one parameter, the frequency of flares. We assumed that the power of a CME is sufficient to sweep away the outer envelope and insufficient to affect the material within the Roche lobe. Analyzing the light curves, obtained with the Kepler space telescope, (Vidotto *et al.* (2010)) have shown that solar type stars may demonstrate super flares, whose energy may exceed that of the Sun by three orders of magnitude. These flares may move the atmosphere/wind head-on collision point deep inside the Roche lobe and push part of material from the lobe. The mass loss in these flares may be by 2-3 orders of magnitude higher than in those we consider here. However, this mechanism requires additional study.

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