Gas dynamic modeling of the CME propagation through the envelope of a hot Jupiter-type exoplanet

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Abstract. We propose a 3D gasdynamic numerical model for the study of the interaction between the extended envelopes of hot Jupiters, overfilling their Roche lobes, and non-stationary stellar wind. In the model we use a Roe-Osher numerical scheme with Eindfeldt entropy fix. To test the model we have simulated a flow structure, forming due to the interaction between the extended quasi-stationary envelope of the hot Jupiter planet HD 209458b and the bow shock formed ahead of a propagating coronal mass ejection (CME). We have adopted the solar CME parameters in our computations and taken into account the fact that the planet is located close to its host star. The simulation results show that the bow shock of the CME partially destroys the stream, starting from the L_1 point of the quasi-closed planet's envelope. A bow shock, existing ahead of the planet in its orbital motion when the stellar wind is undisturbed, almost disappears when the CME shock passes through the system.

1. Introduction

The Hubble Space Telescope observations of hot Jupiter HD 209458b [1, 4] have shown that within the transit the absorption in the Ly-α reaches 9%–15% while the planet's is able to absorb only 1.8% of the star's light. Later the same effect have been observed in the C, O and Si lines [5–7]. The results of these observations have driven the scientists to suppose that the planet is surrounded by an extended gaseous envelope. Similar results have been obtained for the HD 189733b and WASP-12b planets. In addition, the observations of WASP-12b, taken in 2009, showed that the transit onset occurs at different time moments in different wavelength ranges, which means that a bulk of relatively dense gas exists ahead of the planet at a distance of 4-5 planet's radii [8].

Hot Jupiters have a number of outstanding features, caused by the proximity to the host star. For example, the proximity of the planet to the host star may result in the effect of gas outflowing from the planet's atmosphere to the star, which is well known in the physics of close binary stars. Besides, the short distance between the planet and the star gives a high value of the planet's orbital velocity. If the planet's orbital velocity exceeds the local sound speed a bow-shock forms ahead of the planet. These effects substantially change the form of interaction of the planet and the stellar wind.

A system consisting of a star and a hot Jupiter may be regarded as a close binary system with extremely low mass ratio. We can consider the force field in a binary system with the components that are a star and a hot Jupiter. We can also assume that the orbits of the components are circular and their proper rotations are synchronized with the orbital motion of

the planet. Under these assumptions we can use the Roche approximation, as it described in the Model section below. The Roche potential has five libration points, called Lagrangian points, where its gradient is equal to zero. The equipotential, going through the inner Lagrangian point L_1, encloses two contiguous volumes, known as critical surfaces or Roche lobes. For the Hot Jupiters the L_1 point locates close enough to the planet to allow significant mass transfer in the system [3].

In the papers [9, 10] the authors proposed a gasdynamic model for the study of interaction between exoplanet's atmospheres and stellar wind. The reported computation results have shown that for typical hot Jupiters, orbiting their host stars with supersonic velocities, a bow shock, forming ahead of the planet, strongly influences the final solution. In particular, in [9] it has been shown that the type of the exoplanet's envelope depends on the position of the head-on collision point (a point where the wind's dynamic pressure is equal to the pressure of the planet's atmosphere). The envelopes of planets, where head-on collision points are located inside the Roche lobe, are almost spherical, only slightly distorted by the gravitational influence of the star and stellar wind. If the head-on collision point is located outside the Roche lobe, the planet's atmosphere starts to outflow through the vicinity of the L_1 and L_2 points, which results in the formation of an extended asymmetric envelope. The latter envelopes may be related to two different types. If the dynamic pressure of the stellar wind is strong enough to stop the outflow through the inner Lagrangian point L_1, a quasi-closed stationary envelope can form around the planet (see [10]). If the wind cannot stop the outflow from L_1, an open envelope forms in the system. The estimates of mass-loss rates made in [11] have shown that a quasi-closed envelope loses have mass loss rate comparable to that of a "classical" closed envelope, which means that quasi-closed envelopes may be stationary.

Previously, we simulated the dynamics of hot Jupiter atmospheres under an assumption that the stellar wind is stationary. Nonetheless, it is known that solar-type stars demonstrate flare activity, including coronal mass ejections (CME), which may drastically change the parameters of stellar wind. The first attempts to simulate the interaction between a hot Jupiter envelope and non-stationary stellar wind has been described in [12] where the main attention has been payed to the physical aspects of the problem. In this paper we give a detailed description of the proposed numerical model that allows one to study all the stages of CME development. In particular, we study the propagation of a shock wave, induced by CME, through hot Jupiter envelopes.

2. The model

Hot Jupiters are located close to their host stars. Therefore, when modeling these objects, one should take into account all the forces acting in the binary star/planet system. In our paper we use the Roche approach, within which the star and planet are represented by point masses, moving in circular orbits around the system's center of mass. This approach is fairly appropriate, since the mass of the gaseous envelopes under study is much less than the planet's mass.

The flow is described by a system of 3D gasdynamic equations that take into account the gravitational field of the binary system. The system of equations is closed by the equation of state of ideal monatomic gas. In this model we neglect non-adiabatic processes of radiative heating and cooling, and radiative transfer processes. The resulting equation system is following:

$$
\begin{cases}
\dfrac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{v}) = 0 \\[2mm]
\dfrac{\partial \rho \mathbf{v}}{\partial t} + \operatorname{div}(\rho \mathbf{v} \otimes \mathbf{v}) + \operatorname{grad} P = -\rho \operatorname{grad} \Phi - 2\left[\boldsymbol{\Omega} \times \mathbf{v}\right]\rho \\[2mm]
\dfrac{\partial \rho(\varepsilon + |\mathbf{v}|^2/2)}{\partial t} + \operatorname{div} \rho \mathbf{v}(\varepsilon + P/\rho + |\mathbf{v}|^2/2) = -\rho \mathbf{v} \operatorname{grad} \Phi \\[2mm]
P = (\gamma - 1)\rho\varepsilon \\[2mm]
\Phi = -\left(\dfrac{GM_*}{\sqrt{x^2 + y^2 + z^2}} + \dfrac{GM_{pl}}{\sqrt{(x-A)^2 + y^2 + z^2}} \right) - \\[2mm]
\qquad - \dfrac{1}{2}\,\Omega^2 \left[\left(x - A\dfrac{M_{pl}}{M_* + M_{pl}} \right)^2 + y^2 \right]
\end{cases}
\tag{1}
$$

where ρ is the density, $\mathbf{v} = (u, v, w)$ is the velocity vector, P is the pressure, ε is the specific internal energy, Φ is the Roche potential, $\gamma = 5/3$ is the adiabatic index, Ω is the angular velocity of the star-planet system's rotation, G is the gravitational constant, M_* and M_{pl} are the masses of the star and planet respectively, A is the orbital radius of the planet.

In our computations we neglected the magnetic field of the planet, since the estimates, made in [13] for the typical hot Jupiter HD 209458b, show that its magnetic moment is only ~ 0.1 of the Jupiter's magnetic moment, which is in agreement with theoretical estimates made for magnetic fields of tidaly-locked hot Jupiters. A field of this intensity may stop the plasma of stellar wind at a distance of only ~ 3 planet radii, which means that one should take it into account only when studying an envelope, whose size is smaller than the size of the Roche lobe. However, the observed parameters of the atmosphere reported in [9] show that the planet may have a much bigger envelope, and one may neglect magnetic field when modeling this envelope. Assuming that ratio between magnetic pressure and dynamical pressure in the wind is the same as on the Earth orbit (less then 0.1 during the CME propogation, [15]) we can neglect effects caused by magnetic fields in our study.

We solved the system of gasdynamic equations in the Cartesian coordinate frame (X, Y, Z) with the origin in the star's center. The coordinate frame rotates along with the star/planet system with the angular velocity Ω. The planet coordinates in this frame are $(A, 0, 0)$.

All the physical quantities are associated with cell centers of a Cartesian grid that has the dimension of $(468 \times 468 \times 178)$ in X, Y and Z dimensions, respectively. The physical size of the computational domain is $(40 \times 40 \times 10)\,R_{pl}$, where R_{pl} is the photometric radius of the planet. The computational grid was locally refined near the exoplanet. Hence, the size of the cells at the photometric radius of the planet $(\Delta x, \Delta y \simeq 0.04\,R_{pl})$ is smaller than the smallest scale height of the simulated atmosphere. The scales of the major flow elements, located near the boundaries of the computational domain (at a distance of $r \simeq 20\,R_{pl}$ from the planet's center) is significantly larger than the size of the cells in this region $(\Delta x, \Delta y \leq 0.25\,R_{pl})$.

In this work we investigate the dynamics of the outer atmosphere located far beyond the planet's photometric radius. Therefore, we excluded the inner region of the planet from the computations and set the solid wall boundary conditions at the distance of $r = 0.5\,R_{pl}$ from the planet's center. In this way, we avoid the region with the high gradients of gasdynamic quantities. In the boundary cells we set the normal component of the velocity equal to zero.

To damp waves that may propagate inside the planet due to the interaction between the atmosphere and supersonic stellar wind and cause undesired oscillations of the solution we added artificial viscosity in the cells located below the photometric radius $(r < R_{pl})$. At each step within this region we reduced the gas velocities and maintained the constant temperature. Thus the sphere with the radius of $r < R_{pl}$ may be considered as a "soft" boundary that

Phase	1	2	3	4
Phase duration (hours)	-	8.5	13	21.5
(P_{orb})	-	0.1	0.15	0.25
N (cm^{-3})	10^4	$4 \cdot 10^4$	$6 \cdot 10^3$	10^5
T (K)	$7.3 \cdot 10^5$	$3.65 \cdot 10^6$	$5.84 \cdot 10^5$	$2.19 \cdot 10^5$
V (km/sec)	100	133	144	111

Table 1. Average parameters of the stellar wind at a moment, when an exoplanet with the orbital parameters of HD 209458b passes through CME

effectively absorbs waves.

We adapted the solution with a quasi-stationary envelope reported in [9] as the initial conditions. This solution includes a stream starting from the vicinity of the L_1 point. At a certain distance from the L_1 point the dynamical pressure of the wind becomes equal to that of the stream, which stops the stream. As a result, a portion of the stream material returns toward the planet and form a quasi-stationary circulating envelope. In [9] we studied the interaction of the atmosphere of a hot Jupiter planet with the stellar wind having constant parameters that correspond to the parameters of the solar wind at the distance equal to the radius of the planet's orbit. The wind was set as the boundary conditions at the outer boundary of the computational domain.

In [9, 10] the authors assumed that the parameters of the stellar wind are constant in time. However, real stellar winds are not stationary. This can be observed, for instance, in the Sun that demonstrates solar wind disturbances caused, in particular, by powerful coronal mass ejections (CME). In accordance with [14], solar CMEs are characterized by the following average quantities: the mass ejected into the interplanetary medium is $\sim 10^{16}$ g, the ejection energy is $\sim 10^{31}$ erg, the velocity of the ejected gas varies from 400 to 1000 km/s, which means that it moves with supersonic velocities and a shock wave should form in the medium. In addition, in a CME the abundance of He ions is usually $10 - 15\%$ higher than in the undisturbed solar wind. It is important to note that the frequency of CMEs is very high even for the Sun. It varies from 0.5 to 5 CMEs per day, depending on the stage of the solar activity cycle [14]. This means that an exoplanet orbiting a relatively quiescent star experiences CMEs fairly often (not less than 2 CMEs per month for Earth). These CMEs should significantly change the flow structure in the planet's gaseous envelope.

During a CME propogation the parameters of stellar wind may significantly vary on short timescales. If a host star of a hot Jupiter is similar to the Sun, one may assume the parameters of its CMEs to similar to those of the Sun. In [15] the authors report the parameters of the solar wind in the vicinity of Earth, measured by ACE, WIND, and SOHO on May 1-4, 1998, when Earth passed through a CME. In this work the reported structure of the CME is complicated and consists of three major elements: a shock wave, an early CME, and a late CME. In the shock wave the density and temperature jump by approximately 2 times, and the velocity grows from ~ 450 to ~ 600 km/s. The early CME has a lower density and temperature, and its parameters do not differ much from those of the undisturbed solar wind, except the gas velocity that is equal to the velocity behind the shock. In the late CME the temperature is almost equal to that of the undisturbed wind, the velocity monotonously decreases, and the density grows by up to 5 times. It reaches the maximum in approximately the middle of the late CME and demonstrates strong variations, which means a significantly non-uniform structure of the CME.

The parameters of CME in an orbit of a hot Jupiter should significantly differ from those observed in Earth's orbit. If the stellar wind density is inversely proportional to the squared distance from the star, and the velocity and temperature dependence on the distance is described

by Parker's model [16], then the average values at four CME stages (undisturbed wind, shock wave, early and late CMEs) should correspond to those given in Table 1. We should note that the duration of the CME phases in the orbit of the hot Jupiter should also differ from the respective phases in Earth's orbit, since the size of CME gasdynamic elements grows while the CME propagates. Unfortunately, we cannot take this effect into account, since we should have conducted a detailed MHD simulation, which is beyond the scope of this work.

In our simulations we use a TVD Roe-Osher numerical scheme with the Einfeldt entropy fix. This explicit scheme of a higher-order of approximation possesses low numerical viscosity in the regions of smooth solution and does not smear out shock waves. This scheme is considered in detail in [17]. It is based on the Roe scheme designed to solve the equations of gasdynamics. To increase the order of spatial approximation the Osher TVD correction is applied [18]. To avoid unphysical discontinuities, occurring in the unmodified Roe scheme, we apply the Einfeldt entropy fix [19].

We use a parallel gasdynamical code, parallelized using MPI library. The computations have been performed with 324 processors of the Kurchatov Institute Supercomputer.

3. Modeling results

To test the proposed model we adapted the simulation results described in [9]. These results have been obtained for the quasi-closed envelope of the hot Jupiter HD 209458b. In the top-left panel of Fig. 1 the density distribution that existed in 30 minutes since the CME shock wave started propagating through the system is shown. As one can see, at this moment the flow structure is still almost undisturbed, though the CME shock has already started to sweep out the rarified material and interact with the bow shock located ahead of the stream issuing from the L_1 point. In the top-right panel of Fig. 1 one can see a more developed stage of the process (one hour since the start). By this moment a new more powerful bow shock has formed ahead of the stream, and the density jump in this wave is noticeably stronger. A part of the CME shock, located below the stream in Fig. 1 starts to dissolve after having met a turbulent stream forming behind the stream. We also should mention the noticeable regions of the interaction between the shock waves, where the density is significantly increased. One also can see secondary shock waves propagating from these regions. The middle-left panel demonstrates the flow structure that occurs in 1.5 hours since the CME shock have started propagating. In addition to the previously found features one also can see that the stream structure has changed. This change is caused by with the compression of the stream by the shock wave. In fact the stream now has a pipe-like structure with dense walls and rarified interiors. In the middle-right panel one can clearly see the pipe-like shape of the stream. By this moment new shock waves has formed ahead of the planet and stream. In addition, a weaker attached shock wave has formed. It starts near the head-on collision point. Behind this wave, in the rarifaction wave, one can see the "walls" of the pipe-like decay, which results in the formation of gas filaments. In the bottom-left panel one can see the time moment of 2.5 hours since the process started. By this moment the stream has totally collapsed and its rarified core has disappeared. It continues to decay, though remains visible as a whole and still starts near the L_1 point. The CME shock is well seen in the upper part of the figure (ahead of the planet in its orbital motion), but is almost absent in the bottom part, since it has decayed while propagating through the nonuniform and strongly turbulent trail behind the planet. The outflow from the vicinity of the L_2 still exists, though becoming pipe-like and also starting to decay. Finally, in the bottom-right panel we show the moment when the planet has passed through the CME shock (8 hours after onset). By this moment the stream debris are still at the same place, but they have no connection to the L_1 point. The wind pressure is high enough to prevent the Roche lobe overflow. The outflow from the L_2 point has a shape of separate filaments swept out by the wind. The planet's envelope has a ragged shape where shock waves dissipated. As a result we see only weak secondary attached shock waves in

different parts of the solution, while the bow shock ahead of the planet is absent. The shock wave, located ahead of the whole envelope still exists, but it is out of the region, shown in Fig. 1.

4. Conclusions

We have developed a numerical model that allows studying the influence of non-stationary stellar wind on the gaseous envelopes of hot Jupiter exoplanets. In the model we use the Roe-Osher numerical scheme with the Einfeldt entropy fix. This scheme belongs to the TVD family, possesses low numerical viscosity and does not smear shock waves. This allows us to consider the interaction between the shock waves, induced by CMEs, and the flow structure of the planet's gaseous envelope.

To test the model we simulated the process of CME shock wave propagation through an extended quasi-stationary envelope of the hot Jupiter HD 209458b, forming due to the gas outflow through the vicinity of L_1 and L_2 points. The simulation result confirms the efficiency of the proposed model. The results show that the CME shock, propagating through an extended quasi-stationary envelope, prevents the formation of the stream in the vicinity of the L_1. The previously existing stream decays and losses most of its material by the moment when the planet will have passed through the CME shock. The material issuing from the L_2 point is almost totally swept out by the CME shock. The CME shock wave also destroys the bow shock, forming ahead of the planet.

Acknowledgements

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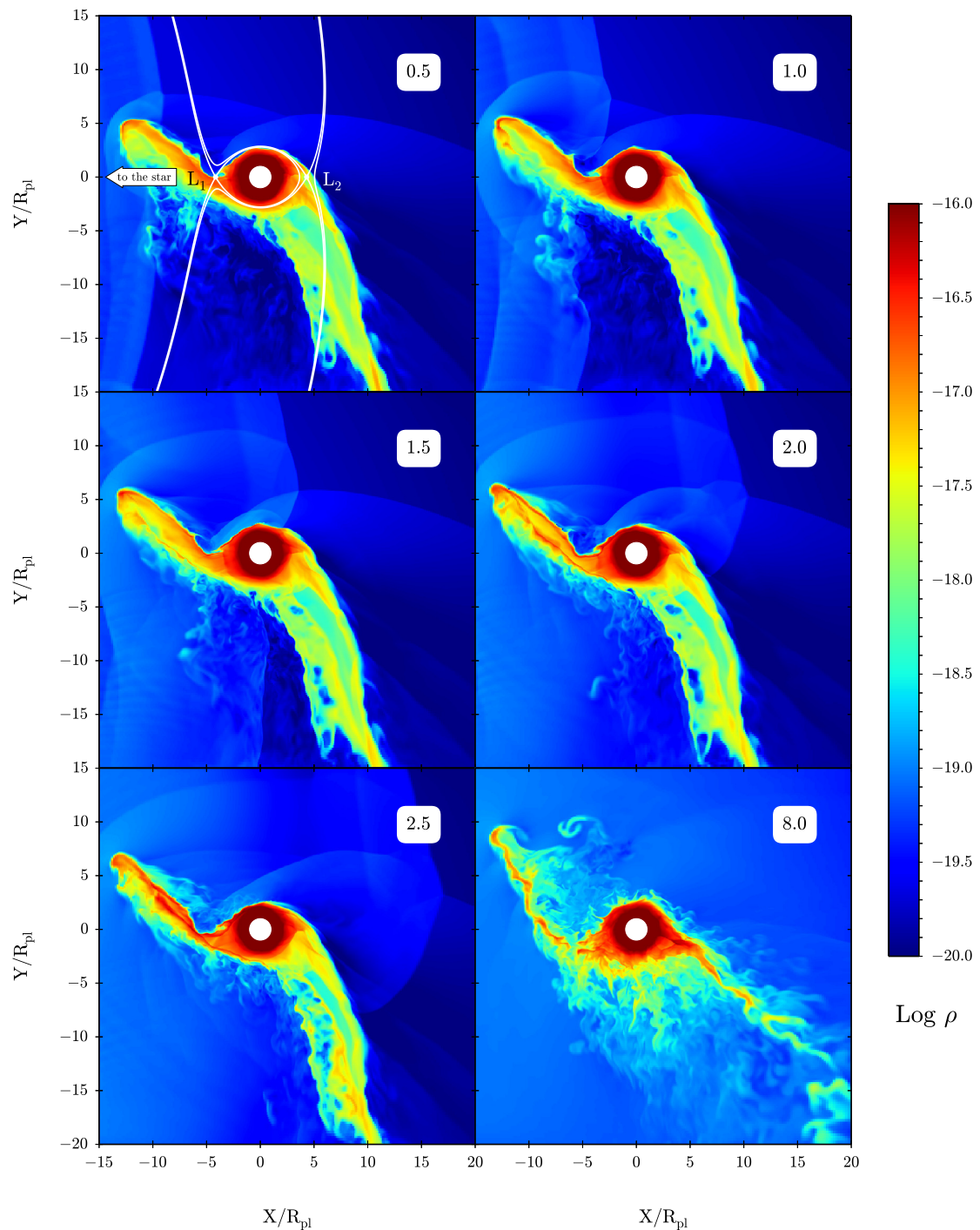
Figure 1. The density logarithm distribution in the equatorial plane of the system for 6 moments during the propagation of the shock wave of CME. The parameters of the atmosphere and the initial state correspond to the model with the temperature of 7500 K described in [9]. On the first diagram white solid lines depict the isolines of the Roche lobe. We also show the positions of the L_1 and L_2 points. White arrow[8] shows direction to the star.