On Possible Types of Magnetospheres of Hot Jupiters

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Abstract—As a rule, the orbits of “hot Jupiter” exoplanets are located close to the Alfvén point of the stellar wind of the host star. Many hot Jupiters could be in the sub-Alfvén zone, where the magnetic pressure of the stellar wind exceeds the dynamical pressure. Therefore, the magnetic field in the wind should play an extremely important role in the process of stellar wind flowing around the atmosphere of a hot Jupiter. This must be taken into account when constructing theoretical models and interpreting observational data. Analyses show that many typical hot Jupiters should have shockless induced magnetospheres, which have no analogs in the solar system. Such magnetospheres are characterized first and foremost by the fact that there is no bow shock, and the magnetic barrier (ionopause) is formed by induced currents in upper layers of the ionosphere. This conclusion is confirmed here using three-dimensional numerical simulations of the flow of the stellar wind from the host star around the hot Jupiter HD 209458b, taking into account both the intrinsic magnetic field of the planet and the magnetic field in the wind.

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1. INTRODUCTION

A celestial body possessing its own magnetic field creates a cavity around itself when it interacts with ambient ionized matter, called a magnetosphere. In particular, magnetospheres are possessed by planets in the solar system past which plasma in the solar wind flows [1]. A magnetosphere can have a complex structure and can vary with time, due to inhomogeneity and non-stationarity of the solar wind. The planetary magnetic field hinders the direct penetration of the wind plasma into the atmosphere. The boundary of the magnetosphere is a relatively thin current sheet called the (magnetopause), which separates the intrinsic magnetic field of the planet from the magnetic field of the solar wind. The position of the magnetopause is determined by the balance between the total pressures (the sum of the dynamical, gas, and magnetic pressures) on either side of this structure. However, in most cases, the total pressure exerted from the outside is equal to the dynamical pressure, while the total pressure exerted from the inside is magnetic. This situation is realized, for example, in the magnetosphere of the Earth [2]. A bow shock forms in front of the magnetopause, due to the supersonic regime of the material flowing past. A transition region is located between this shock and the magnetopause, where the wind plasma is heated, compressed, and decelerated as the direction of its motion changes. An extended magnetospheric tail forms on the night side.

Exoplanets, of which several thousand have now been found, should also possess magnetospheres, which should have characteristic properties. We focus in our current study on the structures of the magnetospheres of hot Jupiters—exoplanets with masses of the order of a Jupiter mass located in the immediate vicinity of their host star [3]. The first hot Jupiter was discovered in 1995 [4]. Due to its proximity to its host star and the relatively large size of its gaseous envelope, a hot Jupiter can fill its Roche lobe, leading to the formation of an outflow from the vicinities of the Lagrange points $L_1$ and $L_2$ [5, 6]. Such outflows have been indirectly indicated by excess absorption in the near-UV that has been observed for some such exoplanets [7–12]. These conclusions are also supported theoretically in the framework of one-dimensional aeronomical models [3, 13–16].

In the series of studies [17–23], three-dimensional numerical simulations have shown that, depending on their parameters, three types of gaseous envelopes can form around hot Jupiters [18]. The first type is closed envelopes, when the planetary atmosphere lies inside the Roche lobe. The second type is open envelopes, formed in the presence of outflows from the nearest Lagrange points. Finally, we can have the intermediate case of quasi-closed envelopes, when the dynamical pressure of the stellar wind stops the outflow beyond the boundary of the Roche lobe. Computations show that the mass-loss rates of hot Jupiters are appreciably lower in the closed and quasi-closed cases than in the open case. Numerical simulations of the flow structure...
in the vicinity of the hot Jupiter WASP 12b taking into account the influence of the planet’s magnetic field were presented in [24]. It was shown that the presence of even a relatively weak planetary magnetic field (with a magnetic moment comprising 10% of the magnetic moment of Jupiter) could appreciably reduce the mass-loss rate, compared to the purely gas-dynamical case. Moreover, the magnetic field can give rise to fluctuations in the outer parts of the envelope [25].

In the studies cited above, there remained an important factor that was not taken into consideration, namely, the magnetic field of the stellar wind. The analysis we have carried out in our current study shows that this factor is very important. The reason for this is apparently that many hot Jupiters are located in the sub-Alfvén zones of their stellar winds, where the magnetic pressure exceeds the dynamical pressure. Therefore, inclusion of the wind magnetic field formally leads to a change in the regime for the wind flowing around the hot Jupiter from supersonic to subsonic. As a result, no bow shock should form in front of the atmosphere in the subsonic regime [26]; i.e., the wind flowing around the planet should have a shockless character. This conclusion follows from the assumption that the wind magnetic field is comparable to the mean magnetic field at the surface of the Sun, about 1 G. However, the magnetic fields of solar-type stars can lie in the range from 0.1 to several Gauss [27, 28]. Moreover, the host stars of hot Jupiters, whose spectral types range from F to M, may not be solar-type stars. The azimuthal component of the magnetic field of the stellar wind is determined by the angular velocity of the stellar rotation, which, in turn, also depends on the spectral type [28]. As a result of taking these additional factors into consideration, some hot Jupiters may lie in the transition region separating the sub-Alfvénic and super-Alfvénic zones, or even in the super-Alfvénic zone. This appreciably expands the set of possible scenarios for the magnetospheres of hot Jupiters.

Note that a simple means of approximately taking into account the wind magnetic field in purely gas-dynamical computations is known: using the total pressure \( P_T = P + B^2/(8\pi) \) in place of the gas pressure \( P \). It is not difficult to see that this is equivalent to taking the following temperature in place of the wind temperature \( T \):

\[
\tilde{T} = T \left( 1 + \frac{u_A^2}{2c_T} \right),
\]

where \( c_T \) is the isothermal sound speed and \( u_A \) the Alfvén speed. In this case, the spatial distribution of the magnetic field \( B \), and consequently the temperature \( \tilde{T} \), must be determined using some magnetohydrodynamical (MHD) model for the wind. This correction can effectively increase the wind temperature and move the process of the wind flow around the planet into the subsonic regime.

In this study, we analyzed possible types of magnetospheres of hot Jupiters taking into account various outflows resulting from overflow of the Roche lobe. The results of our numerical computations carried out using a three-dimensional MHD model support the conclusions implied by simple theoretical arguments.

The paper is organized as follows. Section 2 describes the model for the magnetic field of the stellar wind that we used. Section 3 presents an analysis of possible types of magnetospheres of hot Jupiters. Section 4 describes our numerical model. Section 5 presents the results of our numerical computations. Finally, Section 6 summarizes our main results.

## 2. MODEL FOR THE MAGNETIC FIELD OF THE STELLAR WIND

In our numerical model, we draw on well studied properties of the solar wind. Numerous ground- and space-based studies (see, e.g., the recent review [29]) have shown that the magnetic field of the solar wind has a fairly complex structure, shown schematically in Fig. 1. The magnetic field in the vicinity of the corona is appreciably non-radial, since it is mainly determined by the intrinsic magnetic field of the Sun. At the boundary of the corona, which is located at a distance of several solar radii, the field becomes purely radial with high accuracy. Further, we encounter the heliospheric region, where the magnetic field is substantially determined by the properties of the solar wind. In the heliospheric region, the field lines gradually twist in the form of a spiral with distance from the center as a consequence of the solar rotation, so that the wind magnetic field can with good accuracy be described with a simple Parker model [30], especially at large distances.

However, the observed magnetic field in the solar wind is not axially symmetric, and it has a well defined sector structure. This is due to the fact that the fields at different points of the spherical surface of the corona can have different polarities (different directions of the field lines relative to the normal vector), for example, due to the inclination of the solar magnetic axis to the solar rotation axis. As a result, in the plane of the ecliptic, two well defined sectors with different magnetic-field directions form in the solar wind. In one sector, the magnetic-field lines are directed toward the Sun, while, in the other sector, they are directed away from the Sun. These two sectors are separated by a heliospheric current sheet, shown by the gray region in Fig. 1. The current sheet itself is shown by the two twisted dashed lines extending from
Fig. 1. Schematic of the structure of the solar wind in the plane of the ecliptic. The Sun corresponds to the small circle at the center, and the arrow shows the direction of the solar rotation. The middle circle indicates the region of the corona at the surface where the magnetic field is purely radial. The gray region corresponds to zones of the heliospheric current sheet (shown by the dashed curves extending from the corona to the periphery) separating the magnetic field of the solar wind and the magnetic field of the planet (shown by the dotted circle) located in the vicinity of the heliosphere.

the boundary of the corona to the periphery of the heliosphere. This heliospheric current sheet rotates together with the Sun, so that the Earth intersects it multiple times in its motion around the Sun, moving from a sector of the solar wind with one magnetic-field polarity to a neighboring sector with the opposite magnetic-field polarity.

In this study, we take into account the sector structure of the wind magnetic field, focusing on the influence of its global parameters. We plan to carry out a more detailed treatment taking into account certain undoubtedly important effects related to the passage of the planet through the current sheet and the change in polarity of the magnetic field in future studies. In our model, we assumed that the orbit of the hot Jupiter is located in the heliospheric region beyond the boundary of the corona. The orbit of the planet is shown in Fig. 1 by the large dotted circle.

The wind magnetic field $\mathbf{B}$ in the heliospheric region can be described in a first approximation using the simple axially symmetric model described by Baranov and Krasnobaev [31]. In an inertial frame in spherical coordinates $(r, \theta, \varphi)$, the magnetic field and velocity of the stellar wind can be written

$$
\mathbf{B} = B_r(r) \mathbf{n}_r + B_\varphi(r, \theta) \mathbf{n}_\varphi,
$$

$$
\mathbf{v} = v_r \mathbf{n}_r + v_\varphi(r, \theta) \mathbf{n}_\varphi.
$$

In contrast to [31], the dependence of $B_\varphi$ and $v_\varphi$ on the angle $\theta$ is taken into account here, since ours is a three-dimensional model. For simplicity, we took the radial component of the wind velocity $v_r$ in the vicinity of the planet to be constant and equal to $v_w$.

In this approximation, the structure of the stellar wind can be described by a system of equations consisting of the continuity equation,

$$
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \rho v_r \right) = 0,
$$

the Maxwell equation $\nabla \cdot \mathbf{B} = 0$,

$$
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 B_r \right) = 0,
$$

$$
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 B_\varphi \right) = 0.
$$
the equation for the angular momentum
\[
\rho v_r \left( \frac{\partial}{\partial r} (rv_\varphi) \right) = \frac{B_r}{4\pi r} \frac{\partial}{\partial r} (rB_\varphi), \tag{5}
\]
and the induction equation
\[
\frac{1}{r} \frac{\partial}{\partial r} (rv_r B_\varphi - rv_\varphi B_r) = 0. \tag{6}
\]

We find from the continuity equation (3)
\[
\rho = \rho_w \left( \frac{A}{r} \right)^2, \tag{7}
\]
where \( A \) is the semi-major axis of the planet’s orbit and \( \rho_w \) the density of the stellar wind at the planet’s orbit. We obtain from (4)
\[
B_r = B_0 \left( \frac{R_s}{r} \right)^2 = B_w \left( \frac{A}{r} \right)^2, \tag{8}
\]
where \( R_s \) is the stellar radius, \( B_0 \) the magnetic field at the surface of the star, and \( B_w \) the radial component of the field at the planet’s orbit.

It follows from (2) and (3) that
\[
\frac{B_r}{\rho v_r} = \frac{r^2 B_r}{4\pi r^2 \rho v_r} = \text{const}. \tag{9}
\]

This can be used together with (5) and (6) to obtain the two integrals of the motion
\[
rv_\varphi = \frac{B_r}{4\pi \rho v_r} r B_\varphi = L(\theta), \tag{10}
\]
\[
rv_r B_\varphi - rv_\varphi B_r = F(\theta). \tag{11}
\]

The function \( F(\theta) \) can be found from the boundary conditions at the surface of the star \((r = R_s)\):
\[
B_\varphi = 0, \quad B_r = B_0, \quad v_\varphi = \Omega_s R_s \sin \theta, \tag{12}
\]
where \( \Omega_s \) is the angular velocity of the stellar rotation. Therefore,
\[
F(\theta) = -\Omega_s R_s^2 \sin \theta B_0 = -\Omega_s r^2 \sin \theta B_r. \tag{13}
\]

Taking this into account, the solution of (5) and (6) can be written
\[
v_\varphi = \frac{\Omega_s \sin \theta r - \lambda^2 L(\theta)/r}{1 - \lambda^2}, \tag{14}
\]
\[
B_\varphi = \frac{B_r}{v_r} \lambda^2 \Omega_s \sin \theta r - L(\theta)/r \frac{1 - \lambda^2}{1 - \lambda^2}. \tag{15}
\]

Here, \( \lambda \) denotes the Alfvén Mach number for the radial components of the velocity and magnetic field,
\[
\lambda^2 = \frac{4\pi \rho v_r^2}{B_r^2}. \tag{16}
\]

Near the stellar surface, the radial velocity of the wind \( v_r \) should be less than the Alfvén velocity \( u_\lambda = |B_r|/\sqrt{4\pi \rho} \), with \( \lambda < 1 \). At large distances, on the contrary, the radial velocity \( v_r \) exceeds the Alfvén velocity \( u_\lambda \) \((\lambda > 1)\). This means that, at some distance from the center of the star \( r = a \) (the Alfvén point), \( \lambda = 1 \). The region \( r < a \) can be considered the sub-Alfvén zone of the stellar wind, and the region \( r > a \) the super-Alfvén zone.

The quantities \( v_\varphi \) and \( B_\varphi \) in (14) and (15) must remain continuous at the Alfvén point \( r = a \). Therefore, we must have
\[
L(\theta) = \Omega_s \sin \theta a^2. \tag{17}
\]

This yields the final solution
\[
v_\varphi = \Omega_s \sin \theta r \frac{1 - \lambda^2 a^2/r^2}{1 - \lambda^2}, \tag{18}
\]
\[
B_\varphi = \frac{B_r}{v_r} \Omega_s \sin \theta r \frac{1 - a^2/r^2}{1 - \lambda^2}. \tag{19}
\]

These relations were used in our numerical model to describe the structure of the stellar wind.

Figures 2 and 3 show the initial (without including outflow from the envelope) structure of the magnetic field in the vicinity of the hot Jupiter HD 209458b, for which we carried out the numerical simulations considered here. The parameters of the planetary magnetic field (its strength and the orientation of the magnetic axis) correspond to those specified in the computations (see Section 5). Figure 2 depicts the distribution of the magnetic-field lines for the case \( B_0 = 10^{-3} \) G, which corresponds to a weak wind field. The star is located to the left and the planet to the right. The star is shown by the shaded circles, with the inner circle corresponding to the star’s surface and the outer circle to the surface of the corona. The radius of the corona is about three times the radius of the star. The bold solid curve denotes the boundary of the Roche lobe. The magnetic-field lines are shown by the solid curves with arrows. It is easy to see that the magnetic field can be divided into four magnetic zones, marked by the corresponding numbers. Zone 1 is determined by open field lines, where the magnetic field lines begin on the stellar surface and go to infinity. Zone 2 contains the corresponding open magnetic-field lines of the planet. In Zone 3, the magnetic-field lines are common for the star and planet, and begin on the stellar surface and end on the planetary surface. Finally, Zone 4 contains the closed field lines of the planet. The direction of the magnetic field is not defined at the neutral points in the equatorial plane, denoted \( N_1 \) and \( N_2 \). The set of such points forms a neutral line in space, which is close to a circle, whose shape is determined by the parameters of the orientation of the magnetic axis of the planet.
Fig. 2. Initial distribution of the magnetic field in the equatorial plane for the case $B_0 = 10^{-3}$ G. The solid bold line shows the Roche lobe. The star is shown by the concentric shaded circles, where the inner circle corresponds to the radius of the star, and the outer circle to the radius of the corona. The figures 1–4 denote four magnetic zones. The neutral points are denoted $N_1$ and $N_2$.

Fig. 3. Initial distribution of the magnetic field in the equatorial plane for the case $B_0 = 1$ G (a). An enlargement of the region near the planet is shown (b). The notation is the same as in Fig. 2.
3. THE MAGNETOSPHERES OF HOT JUPITERS

Assuming that the radial velocity of the stellar wind is constant, \( v_r = v_w \), we can obtain the simple expression for the Alfvén Mach number

\[
\lambda^2 = \frac{4\pi \rho_w v_w^2}{B_w^2} \left( \frac{r}{A} \right)^4 = \lambda_w^4 \left( \frac{r}{A} \right)^4, \tag{20}
\]

where

\[
\lambda_w = \frac{4\pi \rho_w v_w}{B_w} \tag{21}
\]
denotes the value of \( \lambda \) at the orbit of the planet. The Alfvén point is given by

\[
a = \frac{A}{\lambda_w}. \tag{22}
\]

The Alfvén radius in the solar wind is [31]

\[
a = 0.1 \text{ AU} = 22 R_\oplus. \tag{23}
\]

Since the semi-major axis of the orbit of Mercury is 0.38 AU = 82 \( R_\oplus \), all the planets in the solar system are located in the super-Alfvén zone of the solar wind. The acoustic point in the solar wind, where the wind velocity is comparable to the sound speed, is located still closer to the Sun, at a distance of roughly 0.05 AU = 11 \( R_\oplus \). It follows that the magnetospheres of all planets in the solar system (when present) have complex structures similar to the structure of the Earth’s magnetosphere. They are characterized by the following set of main elements: a bow shock, transition region, magnetopause, radiation belts, and a magneto-tail.

Due to the proximity of hot Jupiters to their host stars, the structure of their magnetospheres can be somewhat different. Let us consider the two typical hot Jupiters HD 209458b and WASP 12b as examples. For HD 209458b, \( A = 10.2 R_\oplus, B_w = 0.0125 \text{ G}, \lambda_w = 0.37, \) and \( a = 16.8 R_\oplus \). At the orbit of the planet, \( B_\varphi/B_r = 0.12 \). For WASP 12b, \( A = 4.9 R_\oplus, B_w = 0.1 \text{ G}, \lambda_w = 0.045, a = 23.2 R_\oplus, \) and \( B_\varphi/B_r = 0.01 \) at the orbit of the planet. Thus, these hot Jupiters are located in the sub-Alfvén zones of their stellar winds. Taking into account the orbital motion of the planet can change this situation somewhat. The total speed of the wind relative to the planet is

\[
v = \sqrt{v_r^2 + v_\varphi^2}, \quad \text{where} \quad v_\varphi = \Omega A, \quad \Omega = \sqrt{GM/A^3}
\]
is the orbital angular velocity of the planet, \( G \) the gravitational constant, \( M \) the total mass of the system, \( M_p \) the mass of the planet, and \( M_s \) the mass of the star. Substituting the values of the corresponding parameters at the planetary orbits, we find \( v/u_A = 0.65 \) for HD 209458b and \( v/u_A = 0.11 \) for WASP 12b. In the former case, the total velocity of the wind is fairly close to the Alfvén velocity. Therefore, HD 209458b is located in the boundary region between the sub-Alfvén and super-Alfvén zones of the wind, since even modest fluctuations of the magnetic field (by a factor of 1.5–2) will be enough to change the flow regime.

Since the Alfvén Mach numbers for these hot Jupiters \( \lambda = v_r/u_A \) are less than unity, the ratio \( v_\varphi/u_F \) will also be less than unity, where \( u_F = \sqrt{c_s^2 + u_A^2} \) and \( c_s \) is the sound speed; the reason for this is that, obviously, \( u_F > u_A \), and consequently \( v_\varphi/u_p < v_r/u_A \). In other words, the stellar-wind speed in the vicinity of the hot Jupiters is less than the fast magneto-acoustic speed. In ordinary gas dynamics, this corresponds to subsonic flow around a body, without formation of a bow shock. Thus, we conclude that the flow of the stellar wind around such a hot Jupiter should be shockless. There should be no bow shock in the structure of the magnetosphere of such a hot Jupiter.

This conclusion is based on an analysis of parameters of the two typical hot Jupiters HD 209458b and WASP 12b. However, it probably remains valid for many other exoplanets of this type as well. To verify this, we reduced data for a sample of 210 hot Jupiters taken from the database at the site www.exoplanet.eu. This sample contains planets with masses \( M_p > 0.5M_\text{Jup} \), where \( M_\text{Jup} \) is the mass of Jupiter, orbital periods \( P_{\text{orb}} < 10 \text{ days}, \) and semi-major orbital axes \( A < 10 R_\oplus \). The sample excludes any planets for which not all the required data are available.

We used the results of the computations carried out in [32] as a model for the stellar wind in the immediate vicinity of the Sun, at distances of \( 1 R_\oplus < r < 10 R_\oplus \). The resulting profiles of the density \( \rho(r) \) and radial velocity \( v_r(r) \) for each hot Jupiter in the sample were used to calculate the dynamical pressure of the wind at the planet’s orbit,

\[
P_{\text{dyn}} = \rho(A) \left[ v_r^2(A) + \frac{G(M_s + M_p)}{A} \right]. \tag{24}
\]
and the magnetic pressure,

\[ P_{\text{mag}} = \frac{B_r^2(A)}{8\pi}, \]

where the radial field was calculated using the formula \( B_r(A) = B_0(R_0/A)^2 \) with \( B_0 = 1 \) G. The resulting distribution of the hot Jupiters in the \( P_{\text{mag}}-P_{\text{dyn}} \) diagram is presented in Fig. 4. The Alfvén Mach numbers used in the left-hand diagram were calculated taking into account only the radial speed of the wind. The right-hand diagram presents the distribution of the planets taking into account their orbital velocities. The positions of the planets coincide with the centers of the hollow circles, whose sizes on the logarithmic scale correspond to the mass of the planet. The line shows the positions of the Alfvén points. The letters indicate the super-Alfvén zone (A) and sub-Alfvén zone (B).

As can be seen from these distributions, many hot Jupiters from this sample are in the sub-Alfvén zone of the stellar wind. Taking into account the orbital velocity appreciably shifts the entire sequence of points upward toward the super-Alfvén zone of the wind. Most of the planets in this diagram form a sort of regular sequence (lower left corner of the diagrams). These planets are located fairly far from their stars, where the dependences of the density and wind speed on the radius are described well by power laws. Closer to the stars, the planets are scattered somewhat chaotically in the diagram. For these planets, the dynamical pressure of the wind is determined mainly by their orbital speeds. Note that the orbital speed of a planet depends not only on the radius of the orbit, but also (although fairly weakly) on the mass of the planet.

We must bear in mind that this distribution was obtained for the solar wind in a model for the quiescent Sun, assuming that the mean magnetic field at the surface of the Sun is 1 G. Even for the Sun, the positions of the hot Jupiters in Fig. 4 relative to the Alfvén point could vary to one side or the other in the course of the solar activity cycle. In reality, the matter flowing around each planet from the sample is the stellar wind from its host star, whose parameters can differ appreciably from those of the solar wind. This means that the regime for the stellar wind flowing around the planet’s atmosphere must be studied separately in each specific case, taking into account individual properties of the planet and its host star. In particular, in our numerical model, we can vary the mean field at the stellar surface \( B_0 \) (i.e., at \( r = R_\star \)), not at the surface of the Sun, at \( r = R_\odot \). The mean magnetic fields of solar-type stars can range from roughly 0.1 G to approximately 5 G [27]. Moreover, the radii of the stars can be both less than and greater than the solar radius. For example, the radius of the star WASP 12 is a factor of 1.57 larger than the radius of the Sun. Therefore, if we take the mean field to be \( B_0 = 1 \) G, the magnetic field in the vicinity of WASP 12b is roughly a factor of 2.5 higher than the magnetic field in the solar wind at the same distance from the Sun. This simple approach can be used to model the formation of all the main types of magnetospheres of hot Jupiters in our computations.

We characterized a magnetosphere using three parameters: the size of the ionospheric envelope \( R_{\text{env}} \), the radius of the magnetopause \( R_{\text{mp}} \), and the radius of the bow shock \( R_{\text{bs}} \). The ionospheric envelope refers to the upper layers of the atmosphere of the hot
Jupiter, which consist of nearly fully ionized gas [22]. In our terminology, a closed ionospheric envelope corresponds to the case when the atmosphere of the hot Jupiter lies fully inside its Roche lobe. An open ionospheric envelope corresponds to the case when the hot Jupiter overflows its Roche lobe, forming a planetary outflow from the vicinity of the Lagrange points $L_1$ and $L_2$. For the magnetopause and the bow shock, we can take the distance from the center of the planet to the corresponding point of the collision. We can propose the following simple classification of possible types of hot-Jupiter magnetospheres, depending on the relationship between these parameters.

Type A. The parameter $\lambda_w > 1$, and a bow shock is established in front of the magnetosphere, $R_{\text{bs}} < \infty$. Taking into account the relationship between the remaining parameters, we can obtain two special cases.

Subtype A1 (shocked, intrinsic magnetosphere): $R_{\text{env}} < R_{\text{mp}}$. In this case, the magnetic field of the planet is fairly strong, and the magnetopause is located outside the ionospheric envelope. The structure of such a magnetosphere for the cases of closed and open ionospheric envelopes is shown in Fig. 5. In the solar system, this situation with a closed ionospheric envelope corresponds, for example, to the magnetospheres of the Earth and Jupiter.

Subtype A2 (shocked, induced magnetosphere): $R_{\text{env}} > R_{\text{mp}}$. In this case, the magnetic field of the planet is weak, and the magnetopause is located inside the ionospheric envelope. The structure of such a magnetosphere for the cases of closed and open ionospheric envelopes is shown in Fig. 6. In the solar system, this situation with a closed ionospheric envelope corresponds, for example, to the magnetospheres of Venus (and in some sense Mars).

A driven, or induced, magnetosphere [33] is formed by currents excited in upper layers of the ionosphere. The mechanism for the excitation of these currents is related to unipolar induction [34] that arises during the motion of conducting material perpendicular to a magnetic field. The currents driven in the ionosphere partially screen the magnetic field of the wind. As a result, the resulting magnetic-field lines enshroud the planetary ionosphere, forming a magnetic barrier (the ionopause). The bow shock is stopped just before this barrier. A magnetospheric tail forms on the night side, which can partially fill with plasma from the ionosphere. In contrast to an intrinsic magnetosphere, the orientation of the magnetic field in an induced magnetosphere is determined fully by the field of the wind. As a result, all the structure of the magnetosphere traces the direction toward the star as the planet moves in its orbit.

Type B. Here, $\lambda_w < 1$ and no bow shock forms. Therefore, we can formally take $R_{\text{bs}} = \infty$. Again, we can distinguish two special cases.

Subtype B1 (shockless, intrinsic magnetosphere): $R_{\text{env}} < R_{\text{mp}}$. This situation arises when the intrinsic magnetic field of the planet is fairly strong, so that the boundary of the magnetopause is located outside the ionospheric envelope. A schematic of the structure of this type of magnetosphere for the cases of closed and open ionospheric envelopes is shown in Fig. 7. This case appears to be fairly exotic, since the intrinsic magnetic fields of hot Jupiters should be relatively weak.

Subtype B2 (shockless, induced magnetosphere): $R_{\text{env}} > R_{\text{mp}}$. This may be the most common case for hot Jupiters. Here, the magnetopause is formally located inside the ionospheric envelope, and outflows from the envelope interact directly with the magnetic field of the stellar wind. Figure 8 shows a schematic of the structure of this type of magnetosphere for the cases of closed and open ionospheric envelopes. Taking into account the possible types of gaseous envelopes of hot Jupiters [18], we can distinguish here additional subtypes corresponding, for example, to closed, quasi-closed, and open envelopes.

Type C. Here, $\lambda_w \approx 1$. This intermediate type of magnetosphere corresponds to a “gray zone”. In particular, in this case, the planet itself can be located in either the sub- or super-Alfvén zone of the wind, while, due to its large extent, the outflowing ionospheric envelope may intersect the Alfvén point and partially overlo\v{y} the other wind zone. This unusual situation may be fairly common for hot Jupiters, since their orbits are usually located near the Alfvén point (see the distribution of hot Jupiters in Fig. 4). This case must be analyzed separately.

4. DESCRIPTION OF THE MODEL

4.1. Main Equations

We described the flow structure in the vicinity of a hot Jupiter using a system of equations for ideal, one-fluid, MHD with a background field [24, 35, 36]. In this approach, the total magnetic field $B$ is represented as a superposition of a background magnetic field $H$ and the magnetic field induced by currents in the plasma itself $b$, $B = H + b$. Since we are taking the background field to be created by sources located outside the computational domain, this field should satisfy the condition $\nabla \times H = 0$ in the computational domain. Precisely this property of the external field can be used to partially exclude it from the MHD equations [37, 38]. Furthermore, our model assumes that the background magnetic field is stationary, $\partial H / \partial t = 0$, corresponding to the
Fig. 5. Schematic depiction of the structure of a magnetosphere of subtype $A1$ in the case of a closed (left) and open (right) ionospheric envelope of a hot Jupiter. The lines with arrows show the magnetic-field lines. The dotted curve shows the boundary of the Roche lobe. The shaded region corresponds to the gaseous envelope of the planet. The positions of the bow shock (outer solid curve) and magnetopause (inner solid curve) are shown.

Fig. 6. Schematic depiction of the structure of a magnetosphere of subtype $A2$ in the case of a closed (left) and open (right) ionospheric envelope of a hot Jupiter. Notation is the same as in Fig. 5.

case when the axial rotation of the hot Jupiter is synchronized with its orbital motion.

Taking into account the relation $\nabla \times \mathbf{H} = 0$, the ideal MHD equations can be written in the form

$$
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (26)
$$

$$
\rho \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = -\nabla P - \mathbf{b} \times \nabla \times \mathbf{b} - \mathbf{H} \times \nabla \times \mathbf{b} - \rho \mathbf{f}, \quad (27)
$$

$$
\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{b} + \mathbf{v} \times \mathbf{H}), \quad (28)
$$

$$
\rho \left[ \frac{\partial \varepsilon}{\partial t} + (\mathbf{v} \cdot \nabla) \varepsilon \right] + P \nabla \cdot \mathbf{v} = 0. \quad (29)
$$

Here, $\rho$ is the density, $\mathbf{v}$ the velocity, $P$ the pressure, and $\varepsilon$ the specific internal energy. For convenience in the numerical modeling, we used a system of units in these equations in which a factor of $4\pi$ does not arise. We assumed that the matter can be treated like
an ideal gas with the equation of state

\[ P = (\gamma - 1)\rho \varepsilon, \quad \text{(30)} \]

where \( \gamma = 5/3 \) is the adiabatic index.

The computations were carried out in a rotating coordinate frame in which the centers of the star and planet were fixed. In this case, the angular-velocity vector for the rotation of the frame \( \Omega \) coincides with the orbital angular velocity of the star–planet system. In this rotating frame, the specific external force is given by

\[ \mathbf{f} = -\nabla \Phi - 2(\Omega \times \mathbf{v}). \quad \text{(31)} \]

Here, the first term on the right-hand side describes the force due to the gradient of the Roche potential

\[ \Phi = -\frac{GM_s}{|\mathbf{r} - \mathbf{r}_s|} - \frac{GM_p}{|\mathbf{r} - \mathbf{r}_p|} - \frac{1}{2} \left[ \Omega \times (\mathbf{r} - \mathbf{r}_c) \right]^2, \quad \text{(32)} \]

where \( M_s \) is the mass of the star, \( M_p \) the mass of the planet, \( \mathbf{r}_s \) the radius vector of the center of the star, \( \mathbf{r}_p \) the radius vector of the center of the planet, and \( \mathbf{r}_c \) the radius vector of the center of mass of the system. The second term describes the Coriolis force.

The background magnetic field was specified in...
the form \( \mathbf{H} = \mathbf{H}_p + \mathbf{H}_s \). The first term, \( \mathbf{H}_p \), describes the intrinsic magnetic field of the planet. Our model assumed that the magnetic field of the hot Jupiter was dipolar, 

\[
\mathbf{H}_p = \frac{\mu}{|r - r_p|^3} [3(\mathbf{d} \cdot \mathbf{n}_p)\mathbf{n}_p - \mathbf{d}],
\]

(33)

where \( \mu \) is the magnetic moment, \( \mathbf{n}_p = (r - r_p)/|r - r_p| \), \( \mathbf{d} \) is a unit vector directed along the magnetic axis, and the vector magnetic moment is \( \mu = \mu \mathbf{d} \). The second term, \( \mathbf{H}_s \), describes the radial magnetic field of the stellar wind,

\[
\mathbf{H}_s = \frac{B_0 R_s^2}{|r - r_s|^2} \mathbf{n}_s,
\]

(34)

where \( R_s \) is the stellar radius and the vector \( \mathbf{n}_s = (r - r_s)/|r - r_s| \). It is not difficult to demonstrate that this background magnetic field satisfies the condition \( \nabla \times \mathbf{H} = 0 \). Thus, in our model at the initial time, the intrinsic magnetic field of the plasma \( \mathbf{b} \) is determined purely by the azimuthal component of the magnetic field of the stellar wind (19).

### 4.2. Numerical Method

We numerically solved the MHD equations described in the previous section using a combination of the difference schemes of Roe [39], Lax–Friedrichs [40, 41]. The solution algorithm consisted of several successive steps arising due to the application of separation according to physical processes. Suppose we know the distribution of all quantities in a computational cell at time \( t^n \). To obtain the corresponding values at the next time step \( t^{n+1} = t^n + \Delta t \), we expand the full system of equations (26)–(29) into two subsystems.

The first of these corresponds to ideal MHD with the intrinsic magnetic field of the plasma \( \mathbf{b} \), without allowance for the background field \( \mathbf{H} \):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]

(35)

\[
\rho \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right] = -\nabla P - \mathbf{b} \times \nabla \times \mathbf{b} - \rho \mathbf{f},
\]

(36)

\[
\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{b}),
\]

(37)

\[
\rho \left[ \frac{\partial \varepsilon}{\partial t} + (\mathbf{v} \cdot \nabla)\varepsilon \right] + P \nabla \cdot \mathbf{v} = 0.
\]

(38)

We solved this system in our numerical model using the scheme of Roe [42, 43] (see also [35]) for the MHD equations, with the enhancing correction of Osher [44]. An MHD version of the scheme of Roe was written into the code in such a way that, in the absence of a magnetic field (\( \mathbf{b} = 0 \)), the scheme became exactly equivalent to the scheme of Roe–Einfeldt–Osher used in our purely gas-dynamical computations [18].

The second subsystem allows for the influence of the background field:

\[
\rho \frac{\partial \mathbf{v}}{\partial t} = -\mathbf{H} \times \nabla \times \mathbf{b},
\]

(39)

\[
\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{H}).
\]

(40)

The first equation in this subsystem describes the influence of the electromagnetic force due to the background field, and the second describes the generation of the magnetic field. We took the density \( \rho \) and specific internal energy \( \varepsilon \) to be constant in this stage. To solve the second subsystem, we used a Lax–Friedrichs scheme with enhanced total variation diminishing (TVD) corrections [35].

We used the generalized Lagrange multiplier method [45] to clean the divergence of the magnetic field \( \mathbf{b} \). The choice of this method was motivated by the fact that the flow in the vicinity of the hot Jupiter is appreciably non-stationary, especially in the wake formed by the magnetospheric tail.

### 5. RESULTS OF THE SIMULATIONS

As examples demonstrating the ideas presented here, we numerically simulated the flow structures in the vicinity of the hot Jupiter HD 209458b. This was the first known transiting hot Jupiter, discovered in 1999 [46]. The main parameters of the model corresponded to the values used in our previous studies (see, e.g., [18]). The host star has spectral type G0, mass \( M_\odot = 1.15 M_\odot \), and radius \( R_\odot = 1.2 R_\odot \). The period of the stellar rotation is \( P_{\text{rot}} = 14.4 \text{d} \), which corresponds to an angular velocity of \( \Omega_\odot = 5.05 \times 10^{-6} \text{ rad/s} \), or a linear velocity at the equator of \( v_{\text{rot}} = 4.2 \text{ km/s} \). The planet has a mass of \( M_p = 0.71 M_{\text{Jup}} \) and a photometric radius of \( R_p = 1.38 R_{\text{Jup}} \), where \( M_{\text{Jup}} \) and \( R_{\text{Jup}} \) are the mass and radius of Jupiter. The semi-major axis of the planet’s orbit is \( A = 10.2 R_\odot \), which corresponds to a period of revolution about the star \( P_{\text{orb}} = 84.6 \text{ h} \).

At the initial time, a spherically symmetrical, isothermal atmosphere was specified around the planet, in which the density distribution was determined by the expression

\[
\rho = \rho_{\text{atm}} \exp \left( -\frac{GM_p}{R_{\text{gas}} T_{\text{atm}}} \left( \frac{1}{R_p} - \frac{1}{|r - r_p|} \right) \right),
\]

(41)
The magnetic dipole was inclined by the condition of pressure equilibrium with the matter in the stellar wind. The computations were carried out using the formulas presented in the description of our numerical model.

As parameters of the stellar wind, we used the corresponding values for the solar wind at a distance of 10.2 R⊙ from the center of the Sun [32]: \( T_w = 7.3 \times 10^5 \) K, \( v_w = 100 \) km/s, \( n_w = 10^4 \) cm\(^{-3}\). The wind magnetic field was specified using the formulas presented in the description of our numerical model.

It was found from observational data in [47] that the magnetic moment \( \mu \) of the hot Jupiter HD 209458b cannot exceed 0.1\( \mu_{\text{Jup}} \), where \( \mu_{\text{Jup}} = 1.53 \times 10^{30} \) G cm\(^3\) is the magnetic moment of Jupiter. Estimates according to [48] for the case of HD 209458b yield a magnetic moment of approximately 0.08\( \mu_{\text{Jup}} \). In our computations, we took the magnetic moment of HD 209458b to be \( \mu = 0.1 \mu_{\text{Jup}} \). The magnetic dipole was inclined by 30° to the rotational axis of the planet, in the direction away from the star. We took the rotation of the planet to be synchronized with its orbital motion, and the rotational axis to be aligned with the axis for the orbital motion.

The computations were carried out in a Cartesian coordinate system with its origin at the center of the planet. The \( x \) axis connected the centers of the star and planet and was directed away from the star. The \( y \) axis was oriented in the direction of the orbital motion of the planet, and the \( z \) axis in the direction of the rotational angular velocity vector. The size of our computational domain was \(-30 \leq x/R_p \leq 30, -30 \leq y/R_p \leq 30, -15 \leq z/R_p \leq 15\), with the number of cells in each direction being \( N = 480 \times 480 \times 240 \). We enhanced the spatial resolution in the region of the planet’s atmosphere by using a grid that condensed exponentially toward the center of the planet. The characteristic cell size at the photometric radius of the planet was 0.02\( R_p \), while the cell size at the outer edge of the computational domain was roughly 0.4\( R_p \). The boundary conditions were specified in the same was as in our earlier study [24].

We conducted two sets of computations, which differed only in the value of \( B_0 \), which specifies the mean magnetic field at the stellar surface. In the first set of computations (Model 1), \( B_0 = 10^{-4} \) G, which corresponds to the weak magnetic field of the stellar wind. In the second set (Model 2), \( B_0 = 1 \) G (a strong field), which corresponds to the mean magnetic field of the quiescent Sun. The results of the computations are presented in Figs. 9 and 10, which show the distribution of the density (color scale and contours), velocity (arrows in left-hand panels), and magnetic field (lines with arrows in right-hand panels) in the orbital plane of the hot Jupiter. The density was normalized to the density of the wind at the planet’s orbit \( \rho_w \). The numerical solutions presented correspond to a time of 0.23\( P_{\text{orb}} \) from the start of the simulations. The boundary of the Roche lobe is shown by a dotted line. The planet is located at the center of the computational domain and is depicted...
by a hollow circle whose radius corresponds to the photometric radius.

In both models, two powerful flows emerge from the vicinity of the Lagrange points \( L_1 \) and \( L_2 \). The first flow forms on the day-time side of the planet and is directed toward the star, so that it moves opposite to the wind under the action of gravity. The second flow begins on the night-time side and forms a broad, turbulent plume behind the planet.

An outgoing shock, clearly visible in Fig. 9, forms in Model 1 as a result of the interaction of the stellar wind and the planetary envelope. This can be taken to consist of two separate shocks, one arising around the planetary atmosphere and the other around the stream from the inner Lagrange point \( L_1 \). The right-hand panel of Fig. 9 shows that the magnetic field remains close to dipolar inside the planet’s Roche lobe. However, the magnetic-field lines in the outflows are stretched along the direction of the plasma flow. The magnetic field of the stellar wind in this model is so weak that it does not play a significant dynamical role. Essentially, it is manifest as a sort of passive admixture in the wind plasma. Such a magnetosphere clearly corresponds to subtype \( A1 \) for the case of an open ionospheric envelope of the hot Jupiter, whose structure is shown schematically in the right-hand panel of Fig. 5.

In Model 2, the interaction of the stellar wind with the planetary envelope has a shockless character. The left panel of Fig. 10 shows that no outgoing shock forms either around the planet’s atmosphere or around the stream from \( L_1 \). The strong magnetic field of the wind hinders the free movement of matter perpendicular to the field lines. Therefore, the flow in this model differs appreciably from the flow in Model 1, since, in addition to the star’s gravity, the centrifugal force, and the Coriolis force, an important role is also played by the electromagnetic force due to the wind magnetic field. The plume behind the planet is also oriented at a different angle, since the flow there adjusts itself to lie along the magnetic-field lines. The wind magnetic field is slightly distorted by the flows from the planet (see the right-hand panel in Fig. 10), but overall preserves its initial structure. The magnetosphere in Model 2 corresponds to subtype \( B2 \) for an open ionospheric envelope of the hot Jupiter, whose structure is shown schematically in the right-hand panel of Fig. 8.

A comparison of the computational results for the two models leads to the following conclusions. The magnetic field of the stellar wind has an important effect, influencing the outflow of the ionospheric envelope from the Roche lobe of the hot Jupiter. In the case of a weak wind magnetic field, the main factor is the dynamical pressure of the wind. With growth in the magnetic field strength, the total wind pressure increases. As a result, all other parameters being equal, the size of the quasi-closed ionospheric envelope decreases. In the direction toward the star (the direction of the \( x \) axis), the size of the envelope in Model 2 is about two-thirds the corresponding size for a weak magnetic field (Model 1). In the direction of the planet’s orbital motion (the \( y \) axis), the envelope extends from the planet to a distance of about ten photometric radii in Model 1, while it extends to about five photometric radii in Model 2. Note that precisely these characteristics of the envelope (in the direction of the orbital motion) determine the observational behavior during transits of the planet related to the early onset of the eclipse in the near-UV [7]. Consequently, the observed properties of the early onset of the eclipse...
during a transit also depend on the strength of the wind magnetic field.

6. CONCLUSION

The analyses we have presented here lead to the conclusion that many hot Jupiters could be located in the sub-Alfvén zones of the stellar winds of their host stars. This means that the wind magnetic field is a very important factor in studies of stellar winds flowing around the atmospheres of hot Jupiters, which it is essential to take into account both when constructing theoretical models and in interpreting observational data. The reason is that the magnetic pressure of the stellar wind exceeds the wind’s dynamical pressure in the sub-Alfvén zone, even when the orbital motion of the planet is taken into account.

We have proposed a classification for the possible magnetospheres possessed by hot Jupiters based on fairly simple model reasoning and a generalization of the results of numerical experiments. In particular, the well studied magnetospheres of the Earth and Jupiter correspond to subtype $A1$ in our classification (a shocked, intrinsic magnetosphere) with a closed envelope. Analyses of observational data have shown that the magnetospheres of many hot Jupiters may correspond to subtype $B2$ (shockless, induced magnetospheres). In this case, the wind magnetic field is fairly strong, so that the flow of the stellar wind around the planetary atmosphere is shockless. No outgoing shocks form around the atmosphere and the flow from the Lagrange point $L_1$ in this case. The structure of such a magnetosphere is fundamentally different from a magnetosphere such as the Earth’s.

However, since the characteristics of the stellar wind can vary fairly strongly with time (by about a factor of 1.5–2), some hot Jupiters fall in the range of parameters that we have called a “gray zone”, where the character of the wind flow around the planet is intermediate between being shocked and shockless. The structures of this type of magnetosphere are deserving of a separate study.

We have developed a three-dimensional MHD numerical model that we have used to investigate the flow of matter in the stellar wind around a hot Jupiter, taking into account both the intrinsic magnetic field of the planet and the wind magnetic field. This numerical model is based on a Roe–Einfeldt–Osher difference scheme with an enhanced order of approximation for the ideal MHD equations. In this model, the total magnetic field is represented as a superposition of an external magnetic field and the magnetic field induced by electric currents in the plasma. We took the external field to be a superposition of the dipolar magnetic field of the planet and the radial component of the wind magnetic field. In the numerical algorithm, factors related to the presence of the external magnetic field were taken into account separately using a corresponding Godunov-type difference scheme.

We conducted two sets of computations that differ only in the mean magnetic field at the stellar surface. In the first model, the wind magnetic field was weak and the pattern of the flow corresponded well to both the purely gas-dynamical computations [18] and computations taking into account only the planetary magnetic field [24]. These models yield a similar pattern for the supersonic flow around the planet, since the intrinsic magnetic field of the hot Jupiter is fairly weak. This type of magnetosphere corresponds to subtype $A1$ in our classification (a shocked, intrinsic magnetosphere), with an open ionospheric envelope. With such parameters, the planet ends up in the super-Alfvén zone of the wind, and an outgoing shock forms during the interaction between the planet and the wind. In our second model, the wind magnetic field corresponded to the magnetic field in the solar wind, which is determined by the mean magnetic field of the quiescent Sun. In this case, the hot Jupiter falls in the sub-Alfvén zone of the wind, and no outgoing shock forms, as we observed in our computations. Such a magnetosphere corresponds to subtype $B2$ in our classification (a shockless, induced magnetosphere), with an open ionospheric envelope.

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