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ON THE STAR-MAGNETOSPHERE INTERACTION OF CLOSE-IN EXOPLANETS

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ABSTRACT

Numerical simulations using a resistive MHD code are performed in order to investigate the interaction of the magnetospheres of hot Jupiters (or close-in extrasolar giant planets) with the central host stars. Because of the sub-Alfvénic nature of the stellar wind outflow at the orbital positions of these close-in exoplanets, no bow shock would form. When the orientation of the stellar coronal magnetic field is favorable to strong coupling with magnetic reconnection, the power ($\sim 10^{27}$ ergs s^{-1}) generated could reach the level of a typical solar flare. As a particular type of star-planet atmospheric interaction, as investigated by Cuntz, Saar, & Musielak, magnetospheric interaction as studied in this Letter could lead to extensive energy injection into the auroral zones of the exoplanets, producing massive atmospheric escape process as recently detected.

Subject headings: magnetic fields — planetary systems — stars: atmospheres — stars: chromospheres — stars: flare

1. INTRODUCTION

From high-resolution spectroscopic measurements employing Doppler and timing techniques (Mayor & Queloz 1995; Marcy & Butler 1998), more than 100 extrasolar planets have been found.[3] Because of observational selection effects, most of these exoplanets are a few Jovian masses (M_J). Of this sample, about 20% of them have orbital distances (a) closer than 0.1 AU (or orbital periods <11 days). HD 209458b with $a = 0.05$ AU orbiting around a G0 solar-type dwarf star is an outstanding representative of this group of close-in exoplanets. The light curves obtained during planetary transits of its host star have provided unique information on the orbital parameters, size, and average density of this hot Jupiter or close-in extrasolar giant planet (CEGP; Charbonneau et al. 2000; Henry et al. 2000).

There are several recent developments that might also shed further light on the physical properties and interaction of HD 209458b with its central star. First, Rubenstein & Schaefer (2000) and Cuntz, Saar, & Musielak (2000) have suggested that stellar interaction of the CEGPs could lead to observable magnetic effects such as stellar flares or chromospheric heating events. Their ideas have received support by the important observations of Cuntz & Shkolnik (2002) of temporal variations of the spectral line shape of the Ca II K line of a few close-in exoplanets, including HD 179949, HD 209458, and Tau Boo. HD 179949, in particular, has been found to show the clearest signature of CEGPS-induced chromospheric activity (Shkolnik, Walker, & Bohlender 2003). This chromospheric emission feature usually displays absorption minimum. But according to these authors, its line shape could change to a local maximum, thus suggesting external heating effect when these CEGPs are positioned between the host stars and the Earth with the phase angle ~0°. Second, Vidal-Madjar et al. (2003) reported the *Hubble Space Telescope* detection of an extended atomic hydrogen coma or tail of HD 209458b. A minimum escape flux of 10^{10} g s^{-1} or 5.9×10^{33} H atoms s^{-1} of hydrogen gas has been derived to account for the observed absorption feature in the Lyα emission profile. Third, time series photometric measurements by the Optical Graviational Lensing Experiment (OGLE) team have led to the discovery of 59 exoplanet candidates as revealed by the transit effects in their light curves (Udalski et al. 2002a, 2002b). Two of these candidates, namely, OGLE-TR-3b and OGLE-TR-56b, have been identified as exoplanets by follow-up spectroscopic observations (Konacki et al. 2003; Dreizler et al. 2003). Both of them have very small orbital distances ($a \sim 0.023$ AU or 5 $R_\odot$), making them the closest EGPs in orbit around main-sequence star ever detected. Taking these interesting results all together, we might ask the following questions: How would these CEGPs interact with the central stars? What would their magnetospheres look like if they had intrinsic magnetic fields of the same magnitude as that of Jupiter? By the same token, what would be the consequence of such magnetospheric interaction on the atmospheres and ionospheres of these close-in exoplanets? Building on the work of Rubenstein & Schaefer (2000), Cuntz et al. (2000), and Cuntz & Shkolnik (2002), we use a computational method in magnetohydrodynamics (MHD) to produce a set of magnetospheric models of the hot Jupiters. This allows us to study their possible configurations and exospheric and ionospheric effects that might be relevant to the magnetic coupling between the central stars and the CEGPs, as well as the massive atmospheric loss process. The numerical method is briefly described in § 2. The results are given in § 3, and the summary and discussion are given in § 4.

2. NUMERICAL METHOD

In this work we use a numerical simulation method in the framework of resistive MHD. This code was originally developed for simulations of planetary magnetospheres (Otto 1990; Kopp 1996; Ip & Kopp 2002). The numerical code integrates the basic equations of resistive MHD (with resistivity η) in a Cartesian coordinate system with the y-axis pointing along the stellar wind flow direction and the x-axis along the direction of motion of the CEGP on the orbital plane:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}), \quad (1)$$

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[3] See the Extrasolar Planet Encyclopedia, maintained by J. Schneider, at http://www.obspm.fr/encycl/encycl.html.

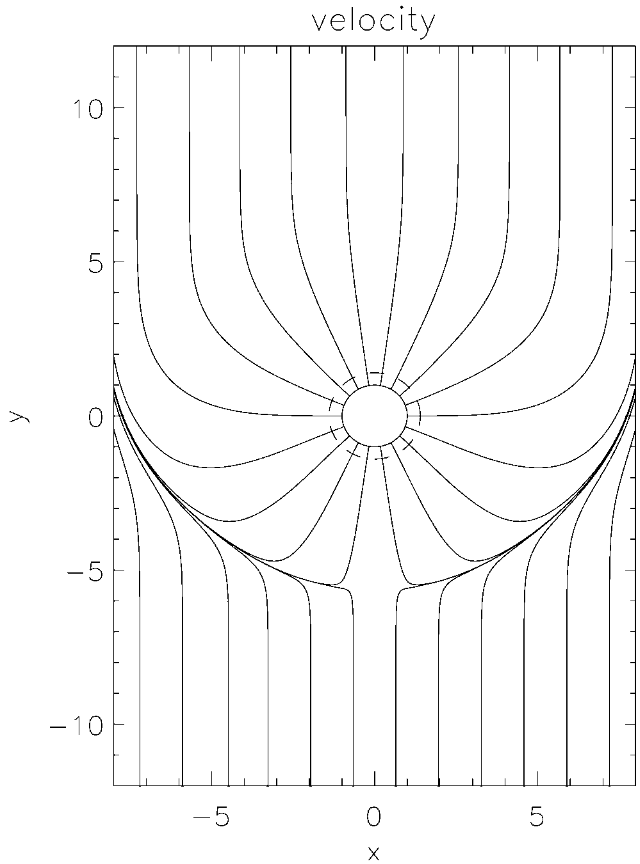

FIG. 1.—Plasma flow pattern on the equatorial plane resulting from the interaction of the expanding stellar corona and the dipolar magnetic field of a CEGP. The external coronal flow and the internal magnetospheric plasma flow are divided by a contact surface. Because the stellar outflow is highly sub-magnetosonic, no bow shock forms in the upstream region. Both of the vertical and horizontal coordinates are in units of planetary radii.

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} = -\nabla\cdot(\rho \boldsymbol{v}\boldsymbol{v}) - \frac{1}{2}\nabla P + \boldsymbol{j}\times\boldsymbol{B}, \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}) - \frac{1}{S}\nabla\eta\times\boldsymbol{j} + \frac{\eta}{S}\Delta\boldsymbol{B}, \tag{3}$$

$$\frac{\partial P}{\partial t} = -\nabla\cdot(P\boldsymbol{v}) + (\gamma-1)\left(P\nabla\cdot\boldsymbol{v} + \frac{\eta}{S}\boldsymbol{j}^2\right). \tag{4}$$

Here we used the following symbols: ρ is the plasma density, $\boldsymbol{v}$ is the flow velocity, t is the time, $\boldsymbol{B}$ is the magnetic field, and P is the gas pressure. The plasma is assumed to be an ideal gas with adiabatic index $\gamma = 5/3$. Moreover, $\boldsymbol{j}$ denotes the electric current density, and η is the resistivity. The latter is allowed to be a function of space. The factor 1/2 in front of the pressure gradient and the Lundquist number S are consequences of the normalization (e.g., Kopp 1996), where the gas pressure is normalized to the magnetic pressure $P_B = B^2/2\mu_0$.

Note that we have very little knowledge (if any) of the stellar corona and magnetic fields of the CEGPs (assumed to be OGLE-TR-56b, since it has the smallest orbital distance of $a = 0.023$ AU) except for the observational evidence reported by Cuntz & Shkolnik (2002) that the chromosphere of HD 209458 is subjected to magnetic coupling (heating) effect. Under this condition, we assume that the model EGP—with a mass of $m_p \sim 0.9M_J$ and a radius of $R_p \sim 1.3R_J$ (Jovian radius)—has a dipole field with an equatorial surface field of B_p. In the present model, the dipole moment of the planetary field is perpendicular to the orbital plane of the CEGP. The stellar coronal structure is further assumed to be similar to that of the Sun. Therefore, for the stellar wind (assumed to be in spherically symmetric expansion) at the orbital position of the CEGP, we have the following parameters (see Kohl et al. 1998): radial flow speed $V_{sw} \sim 200$ km s^{-1} and the thermal temperature $T \sim 2 \times 10^6$ K. The corresponding magnitude of the coronal magnetic field (which is another free parameter in this computation) is taken to be $B^* \sim$ 1–10 G at the stellar surface and ∼0.016–0.16 G at the CEGP.

Because the orbital velocity of OGLE-TR-56b is $V_k \sim 207$ km s^{-1}, the relative speed between the CEGP and the stellar wind would be $V_r \sim 280$ km s^{-1}. For a number density of $n_{sw} \sim 1.9 \times 10^4$ protons cm^{-3}, local thermal speed $V_{th} \sim 180$ km s^{-1}, and Alfvén speed $V_A = B^*/(4\pi\rho)^{1/2} \sim (2\text{–}6) \times 10^3$ km s^{-1}, the electrodynamical interaction would be highly sub-Alfvénic with the magnetosonic Mach number $M_A = V_r/V_A \sim$ 0.05–0.14. This means that, unlike the solar wind interaction with the Jovian magnetosphere, which is highly super-Alfvénic with $M_A > 10$, no bow shock will form in the upstream region of the CEGP.

3. RESULTS

In the numerical computations, the MHD interaction evolves from the initial conditions. The plasma is homogeneous streaming with constant velocity, which is assumed to be locally in y-direction; the magnetic field is the superposition of the magnetic fields of the star (homogeneous or dipole) and that of the planet (dipole). The steady state solutions are obtained when the simulation time is 80 times the Alfvén time (t_A) (which is the characteristic timescale of the crossing of the planetary radius [R_p] by the Alfvén wave). In the present calculation, $R_p \sim 1.3R_J$ and $V_A \sim 2 \times 10^3$ km s^{-1}, $t_A \sim 35$ s. Figure 1 shows the flow patterns of the stellar wind and the magnetosphere in the vicinity of the CEGP when the equatorial surface magnetic field of the hot Jupiter is taken to be $B_p = 0.3$ G. Instead of being subjected to a velocity transition at the position of the bow shock, the stellar flow is shielded from the planetary magnetosphere at a thin boundary called contact surface or magnetopause. The upstream distance of the magnetopause is located at about $5R_J$. (CEGPs with larger magnetic fields will possess magnetospheres of larger sizes.) As shown in Figure 1, ionized gas of planetary origin will move along diverging streamlines. The material injected on the dayside will first flow toward the magnetopause before being diverted in the opposite direction. The ionized gas injected on the nightside will be guided in the same direction as the radial stellar wind outflow. This means that if the atmospheric outflow is massive and that a significant fraction of the escaping gas is ionized by the strong stellar UV radiation, an ion tail similar to the cometary plasma tail will form.

In our idealized situation, the magnetic dipole axis of the CEGP is placed at the center of the exoplanet and that its direction is parallel to the rotational axis, which is, in turn, pointing perpendicular to the orbital plane. In the case of the Sun, the coronal magnetic fields are known to exhibit large

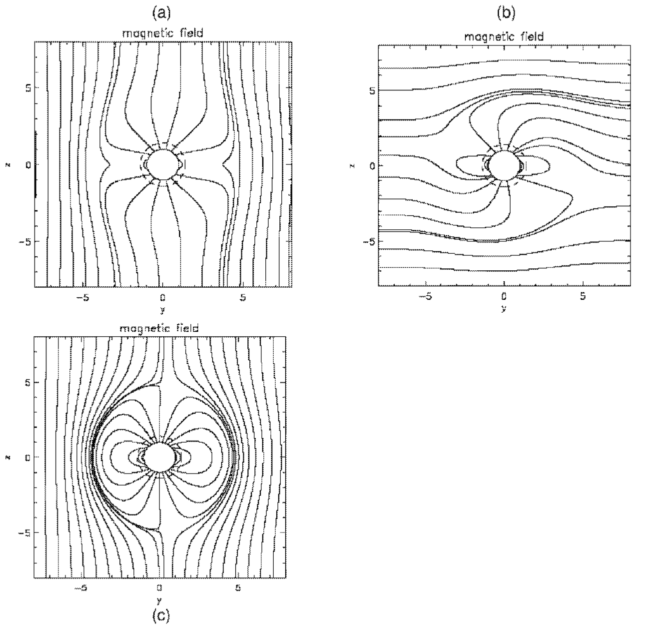

FIG. 2.—Magnetospheric configurations of the exoplanet with different orientations of the coronal magnetic field. (*a*) Open case, in which the pointing direction of the coronal magnetic field is opposite to the planetary field at the equatorial region. (*b*) Intermediate case, in which the coronal magnetic field is pointing radially. (*c*) Closed case, in which the direction of the coronal magnetic field is parallel to the equatorial planetary field. As in Fig. 1, the coordinates are in units of planetary radii.

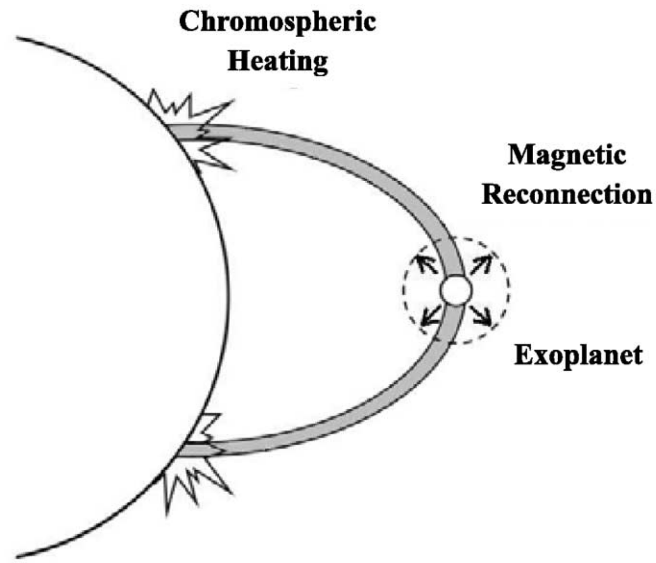

FIG. 3.—Illustration of how a strong electrodynamical interaction could lead to both chromospheric heating of the host star and massive atmospheric escape of the close-in exoplanet by solar flare–like process driven by magnetic reconnection.

temporal and spatial variations with the polarity of the interplanetary magnetic field changing from one direction to another at different timescales. It is therefore possible that the magnetosphere of the CEGP will interact with the stellar magnetic field pointing in different directions from one interval to another as it rotates around the host star. How would the CEGP magnetosphere look under these circumstances? To simulate these situations, we consider three cases, which are shown in Figure 2.

The first case (Fig. 2*a*) is referred to as the "open" magnetosphere, in which the direction of the coronal magnetic field is parallel to the orientation of the planetary dipole axis. We see that the dipole magnetic field lines in the polar regions down to a latitude of 30° are connected to the coronal magnetic field lines in the interplanetary space. A switch of the coronal magnetic field direction by 90° leads to a reduction of the "open" polar cap in one hemisphere (see Fig. 2*b*). But a more dramatic change happens when the coronal field swings by another 90°. For this so-called closed magnetosphere, most of the planetary surface field lines are interconnected from one hemisphere to the other, thus forming a cocoon shielding the CEGP from the interplanetary medium (see Fig. 2*c*).

From the study of the terrestrial magnetosphere we have learned that the open case as depicted in Figure 2*a* is most favorable to the tapping of the magnetic field energy into plasma kinetic energy. The merging (also called magnetic reconnection) of the opposite-pointing magnetic fields on the two sides of the magnetopause is generally considered to be the basic driving mechanism of solar flares, stellar flares, and large magnetospheric and auroral disturbances (Parker 1994). If the stellar wind-magnetosphere interaction is presumed to constitute a dynamo, its power can be approximated to be $P = V_r B^2 L^2$ ergs s^{-1}, where B is the magnetic field strength at the magnetopause and L is the size of the interaction area (Akasofu 1982). For $V_r \sim 280$ km s^{-1}, $B \sim 0.1$ G, and $L \sim 5R_J$, we have $P \sim 3.4 \times 10^{26}$ ergs s^{-1}, which is of the same magnitude of a typical solar flare (Cox 1999, pp. 373-374). Such magneto spheric analog therefore indicates that—as suggested by Rubenstein & Schaefer (2000) and Cuntz et al. (2000) before—solar flare–like activity triggered by interaction of the EGP-magnetosphere with the host star could be an important energy source.

X-ray observations of the *Yohkoh* solar telescope have shown that, during a solar flare event, energy release at the reconnection site at the loop top will create a burst of X-ray–emitting gas; the funneling of the hot plasma, along the magnetic field lines down to the footpoints, in turn produces anomalous heating at the chromospheric layer (Tsuneta 1997; Masuda, Kosugi, & Hudson 2001; Yokoyama & Shibata 2001). Such an effect is possibly what was observed at HD 179949, HD 209458, and Tau Boo by Cuntz & Shkolnik (2002). Since the reconnection process affected by the star-magnetosphere coupling is quasi-continuous, the energy input to the stellar atmosphere must be quite significant. What we want to add to this picture is that a part of this energy must be injected into the upper atmosphere of the CEGP, as illustrated in Figure 3. Because the auroral energy output of Jupiter is only about 10^{21} ergs s^{-1} (Hill, Dessler, & Goertz 1983), it is reasonable to infer that the upper atmosphere and ionosphere of HD 179949 and the like must be subjected to a very high level of heating by charged particle irradiation. This additional heating mechanism will likely raise the temperature of the thermosphere and the exosphere, in particular, to a value above the equilibrium temperature of about 1000 K usually assumed in the literature (Guillot et al. 1996; Barman, Hauschildt, & Allard 2001), thus contributing to the massive atmospheric loss as observed by Vidal-Madjar et al. (2003).

4. DISCUSSION

In this Letter, we have used a MHD numerical code to simulate the possible scenarios of the magnetospheric interaction of CEGPs (hot Jupiters) with their central host stars. We found that for close-in EGPs like HD 209458, OGLE-TR-56b and OGLE-

TR-3b with semimajor axes ∼ 0.05 AU, the electrodynamic coupling via magnetic reconnection could be effective in generating a powerful solar flare–like process (Rubenstein & Schaefer 2000; Cuntz et al. 2000; Cuntz & Shkolnik 2002). At the same time, substantial heating should also occur in the upper atmosphere and ionosphere of the CEGPs in the auroral zones. While the emission feature of the Ca II K line serves as an indicator of the chromospheric heating effect, the enhanced auroral activity of the CEGPs might lead to strong emission in H_3^+ from $H_2^+ + H_2 \rightarrow H_3^+ + H$, as observed in the Jovian aurora (Drossart et al. 1989; Maillard et al. 1990; Satoh & Connerney 1999). One possible difference is that the H_3^+ emission might cover a large part of the surfaces of the close-in EGPs for the case of an open magnetosphere. Although we could not be sure that similar H_3^+ production mechanism should take place at CEGPs, search of its possible signature at near-infrared wavelengths could set important constraints on the structure of the upper atmospheres and stellar interaction of the CEGPs.

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