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MAGNETODISK-DOMINATED MAGNETOSPHERES OF CLOSE ORBIT GIANT EXOPLANETS

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Abstract. A more complete view of a magnetosphere of a close orbit giant exoplanet, so called "Hot Jupiter", based on the Paraboloid Magnetospheric Model (PMM), is proposed. The key element of the considered model consists in taking into account the effects of an expanding upper atmosphere of a Hot Jupiter heated and ionized by the stellar XUV radiation. As a result, an extended magnetodisk is built around the planet. The magnetic field produced by magnetodisk ring currents, dominates above the contribution of intrinsic magnetic dipole of a Hot Jupiter and finally determines the size and shape of the whole magnetosphere.

1 Introduction

The constantly growing number of discovered exoplanets and accumulation of data regarding their physical and orbital characteristics provide an empirical platform for a more detailed study of general principles and major trends of the planetary evolution (including the planetary potential habitability aspect). Investigation of exoplanetary magnetic fields and their role in evolution of planetary systems forms a new and fast developing branch. This topic is closely connected with the study of the whole complex of stellar – planetary interactions, including consideration of influences of stellar radiation and stellar wind plasma flows on the planetary near-by plasma and atmosphere environments. Magnetic fields, those connected with the planetary intrinsic magnetic dipole, as well as the magnetic fields associated with the electric current systems induced in the close planetary plasma surroundings, form the planetary magnetosphere. Magnetosphere acts as an obstacle (magnetospheric obstacle), which interacts with the stellar wind, declining it and protecting planetary ionosphere and upper atmosphere against the direct impact of stellar plasmas and energetic particles (*e.g.*, cosmic rays).

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More than a half of known exoplanets have orbits around their host stars shorter than 0.6 AU. By this, a clear maximum in the orbital distribution of exoplanets takes place in the vicinity of 0.05 AU. A close location of planets to their host stars means that they are exposed to intensive stellar radiations and plasma flows, which are stronger near a star. Such significant stellar impact on planetary environments comprises the major specifics of the most of known exoplanets. The stellar X-ray/EUV (XUV) radiation and the stellar wind result in ionization, heating, chemical modification, and slow erosion of the planetary upper atmospheres throughout their lifetime (Lammer *et al.* 2003; Lammer *et al.* 2007). The closer the planet is to the star, the more efficient are these processes, and the more important becomes magnetospheric protection of a planet (Khodachenko *et al.* 2007a,b).

2 The problem of magnetospheric protection of exoplanets

For an efficient magnetospheric protection of a planet, the size of its magnetosphere characterized by the magnetopause stand-off distance R_s should be much larger than the height of the exobase. By this, the value of R_s is determined from the balance between the stellar wind ram pressure and the planetary magnetic field pressure at the substellar point (Grießmeier *et al.* 2004; Khodachenko *et al.* 2007a). So far, the study of an exoplanetary magnetospheric protection has been performed within a highly simplifying assumption of a planetary dipole-dominated magnetosphere. This means that only the intrinsic magnetic dipole moment of an exoplanet $\mathcal{M}$ and the corresponding magnetopause electric currents (*i.e.*, "screened magnetic dipole" case) were considered as the major magnetosphere forming factors. This approach resulted in the commonly accepted conclusion, that in order to have an efficient magnetic shield a planet needs a strong intrinsic magnetic dipole $\mathcal{M}$. The weak intrinsic magnetic dipole moments of the here considered tidally locked close-orbit giant exoplanets, so called "Hot Jupiters", have been shown in previous studies to be unable to provide an efficient magnetospheric protection of their expanding upper atmospheres against the stellar plasma flow, leading to significant non-thermal mass loss of the planets (Khodachenko *et al.* 2007b). On the other hand, the detection of a large number of "Hot Jupiters" indicates that they nevertheless survive in the extreme conditions of their close-in orbits and are probably better protected, than the present-day theories predict. Additional factors and processes have to be taken into consideration in order to explain the protection of close-in exoplanets against of destructive non-thermal mass loss. This stimulates further investigations of the magnetic and plasma environments of "Hot Jupiters" aimed at resolving the planetary survival paradox at close orbits.

3 Magnetodisk – a key element of a "Hot Jupiter" magnetosphere

A key element of the proposed view at the magnetosphere of a "Hot Jupiter" consists in taking into account the effects of expanding upper atmosphere of a close-orbit exoplanet, heated and ionized by the stellar XUV radiation. This leads to the formation of an extended, essentially dynamical planetary ionosphere/plasmasphere (Koskinen *et al.* 2010; Khodachenko *et al.* 2012). Of crucial importance in that respect appears the development of current-carrying plasma magnetodisk around the exoplanet resulting from the planetary rotation and thermal escape of the partially ionized upper atmospheric material (Khodachenko *et al.* 2012). The magnetodisk is formed outside of the Alfvénic surface ($r = R_A$), at which the equality of energy of the planetary magnetic dipole field and of the co-rotating plasma kinetic energy is achieved. Beyond this surface, the rotating magnetic field of a planet can not drive equatorial plasma in rigid co-rotation, and a centrifugal inertial outflow of material begins. Besides of that, thermal expansion of the partially ionized upper atmospheric material it-self, even without the centrifugal acceleration in the co-rotation region, under certain conditions may provide the escaping hydrodynamic flow and lead to the build-up of a current-carrying magnetodisk. For all the mechanisms of the magnetodisk formation, it is typical that the outflowing plasma, moving along the field lines inside the Alfvénic surface, is concentrated near the equatorial plane and provides the material source for creation of the magnetodisk. The plasma, escaping along the field lines, penetrating beyond the Alfvénic surface, deforms the original planetary magnetic dipole field, resulting in the radial stretching of the field lines and the creation of a thin disk-type current sheet in the equatorial region (see Fig. 1).

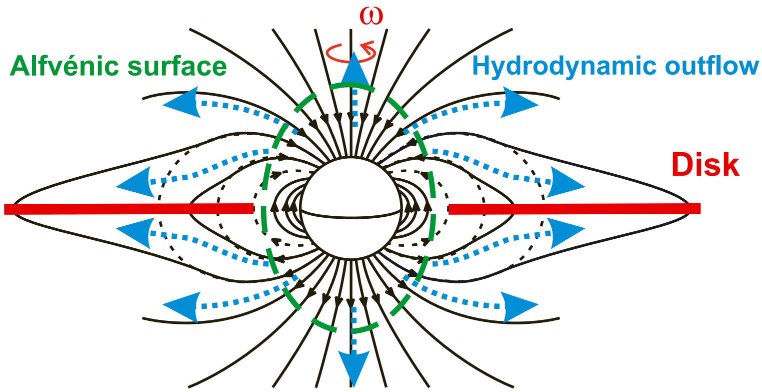

Fig. 1. Schematic view of magnetodisk formation.

4 Magnetosphere model

A more complete view of the “Hot Jupiter” magnetosphere structure is based on the Paraboloid Magnetospheric Model (PMM). PMM is a semi-analytical approach to the modeling of planetary magnetosphere structure (Alexeev *et al.* 2003; Alexeev & Belenkaya 2005; Alexeev *et al.* 2006; Khodachenko *et al.* 2012). The name of the model is derived from its key simplifying assumption that the magnetopause of a planet may be represented by a paraboloid surface co-axial with the direction of the ambient stellar wind plasma. The PMM calculates the magnetic field generated by a variety of current systems located on the boundaries and within the boundaries of a planetary magnetosphere. Besides of the intrinsic planetary magnetic dipole and magnetopause currents, the PMM has, among the main sources of magnetic field, also the electric current system of the magnetotail, and the induced ring currents of the magnetodisk. The model works without any restrictions imposed on the values of interplanetary medium parameters, enabling therefore the description of the whole variety of possible magnetosphere configurations caused by different intrinsic magnetic fields of exoplanets and various stellar wind conditions. As applied to the "Hot Jupiters" PMM reveals that the electric currents induced in the plasma disk produce an essential effect on the overall magnetic field structure around the planet, resulting in the formation of a magnetodisk-dominated magnetosphere of a Hot Jupiter.

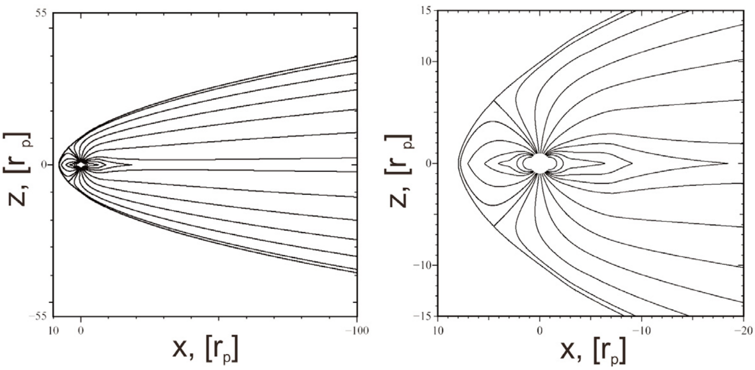

Fig. 2. Typical view of a magnetodisk dominated magnetosphere.

Table 1 summarizes the values for a "Hot Jupiter" magnetopause stand-off distance at different orbits around a Sun full analogue star and gives for the comparison the stand-off distance values, obtained in the case when the contribution of magnetodisk is ignored (*e.g.*, a pure dipole case).

A typical example of the magnetic field structure in the in the magnetosphere of a "Hot Jupiter", obtained with PMM, is shown in Figure 2.

5 Conclusions

Due to certain extension of the plasma disks around close-in exoplanets, the sizes of their magnetodisk-dominated magnetospheres (see Fig. 2) are usually larger than those, followed from the traditional estimates based on the account of only the screened planetary magnetic dipoles (Grießmeier *et al.* 2004; Khodachenko *et al.* 2007a). In general the role of magnetodisk may be formulated as an expansion of a part of the dipole magnetic flux from the inner magnetosphere regions outwards and a resulting increase of the magnetosphere size. The magnetic field

Table 1. "Hot Jupiter" Alfvénic radius, R_A, and magnetopause stand-off distance for only a dipole controlled magnetosphere, $R_s^{(dip)}$, and a magnetosphere with magnetodisk, $R_s^{(MD)}$, given by PMM. Full analog of the solar system Jupiter orbiting the Sun analog star at different orbits is considered. [1] Tidally locked. [2] Not tidally locked. [3] Jupiter.

d [AU]	$R_s^{(MD)}$ [$r_{\rm p}$]	$R_s^{(dip)}$ [$r_{\rm p}$]	R_A [$r_{\rm p}$]
0.045[1]	8.0	5.76	3.30
0.1[1]	8.27	6.16	4.66
0.3[2]	24.2	15.0	7.30
5.2[3]	71.9	41.8	19.8

produced by magnetodisk ring currents, dominates above the contribution of intrinsic magnetic dipole of a "Hot Jupiter" and finally determines the size and shape of the whole magnetosphere. A slower, than the dipole-type decrease of magnetic field with the distance comprises the essential specifics of magnetodisk-dominated magnetospheres of "Hot Jupiters". This results in their 40–70% larger scales, as compared to those traditionally estimated with taking into account of only the planetary dipole. Such larger magnetospheres, extending well beyond the planetary exosphere height, provide better protection of close-in planets against of the erosive action of extreme stellar winds (Khodachenko *et al.* 2007a).

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References

Alexeev, I.I., Belenkaya, E.S., Bobrovnikov, S.Yu., & Kalegaev, V.V., 2003, Space Sci. Rev., 107, 7

Alexeev, I.I., & Belenkaya, E.S., 2005, Ann. Geophys., 23, 809

Alexeev, I.I., Kalegaev, V.V., Belenkaya, E.S., *et al.*, 2006, Geophys. Res. Lett., 33, L08101

Grießmeier, J.-M., Stadelmann, A., Penz, T., *et al.*, 2004, A&A, 425, 753

Khodachenko, M.L., Ribas, I., Lammer, H., *et al.*, 2007a, Astrobiology, 7, 167

Khodachenko, M.L., Lammer, H., Lichtenegger, H.I.M., *et al.*, 2007b, Planet & Space Sci., 55, 631

Khodachenko, M.L., Alexeev, I.I., Belenkaya, E., *et al.*, 2012, ApJ, 744, 70

Koskinen, T.T., Yelle, R.V., Lavvas, P., & Lewis, N.K., 2010, ApJ, 723, 116

Lammer, H., Selsis, F., Ribas, I., *et al.*, 2003, ApJ, 598, L121

Lammer, H., Lichtenegger, H., Kulikov, Yu., *et al.*, 2007, Astrobiology, 7, 185