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# PLASMA AND MAGNETIC FIELD PARAMETERS AT BOW SHOCKS OF SHORT PERIOD EXTRASOLAR GAS GIANTS

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**Abstract.** During the last years, many short period extrasolar gas giants were discovered. Since their orbit distance from their host star is very close, they are embedded in a dense stellar wind. Additionally, recent astrophysical observations indicate that the stellar wind of young stars is much denser and faster than in the case of older stars like the present Sun. Therefore, we model both cases of the stellar evolution, namely an early stage of 0.7 Gyr and a present Sun scenario of 4.6 Gyr, respectively. We calculate the Alfven Mach number as well as a magnetosonic Mach number to analyse the different interaction regimes, which appear for different stellar wind parameters. We compare the results achieved for close-in exoplanets with the exoplanet HD 28185 b, which has an orbital distance of about 1 AU. Additionally, we discuss the influence of high eccentricities of exoplanets like HD 108147 b and HD 162020 b on the interaction regime.

## 1. Introduction

The solar wind interaction of exoplanets plays a crucial role with regard to loss processes of atmospheric particles. These processes are strongly dependent on the regime of interaction which is determined by the solar wind parameters, magnetosonic and Alfven Mach numbers. For magnetosonic Mach numbers more than unity, the solar wind interaction with a planetary obstacle results in the appearance of a bow shock separating the shocked, thermalized solar wind plasma from the undisturbed one. If the Mach number decreases to a value less than 1, the bow shock becomes weaker and finally disappears. In such a case a solar wind plasma flowing around the planet is not compressed much and its temperature is not high compared with the shocked case. Besides the magnetosonic Mach number, the Alfven Mach number itself is a key parameter for a so called magnetic barrier which is a layer of a enhanced magnetic field ahead of the obstacle. This magnetic barrier region is a result of stretching of the frozen-in interplanetary magnetic field by the solar wind flow streaming around the obstacle. This magnetic barrier plays a very important role for processes of mass, momentum and energy transfer into the ionosphere of a planet (Erkaev et al., 2003). In particular, the magnetic barrier is a background for instabilities occurring at the boundary of the obstacle (Arshukova et al., 2004; Penz et al., 2004). The thickness of the magnetic barrier is in the order of the curvature radius of the obstacle to the Alfven Mach number squared.

The aim of this work is to analyze the behaviour of the magnetosonic and Alfven Mach numbers for young and older stars, and to predict qualitatively corresponding regimes of solar wind interaction with exoplanets.

## 2. Temporal evolution of the stellar wind parameters

We use recent indirect mass loss estimations by Wood et al. (2002) to derive a scaling law for the time evolution of the stellar wind density of G and K stars (Grießmeier et al., 2004). Additionally, the scaling law developed by Newkirk (1980) for the stellar wind velocity evolution is taken into account. For cool main sequence stars, the mass loss rates depend on the rotation rate of the stars, which is a function of the stellar age. Since we are interested to find scaling laws for both, the density and velocity, we modify the scaling from Wood et al. (2002) and find the mass loss for a star with mass $M$ as

$$\frac{dM}{dt} v \propto P_{rot}^{-3.3} , \tag{1}$$

where $v$ is the stellar wind velocity, and $P_{rot}$ is the rotation period. To obtain the time-dependence of the rotation period, where we use the scaling of Newkirk (1980)

$$P_{rot} \propto \left(1 + \frac{t}{\tau}\right)^{0.7} , \qquad (2)$$

where *t* is the time elapsed since the formation of the stellar system and *t* = 2.56 x $10^7$ yr. Inserting eqn. (2) into eqn. (1), we find the time-dependence of the stellar mass loss as

$$\frac{dM}{dt}\, v \propto \left(1 + \frac{t}{\tau}\right)^{-2.3} , \qquad (3)$$

Since the stellar mass loss depends linearly on the density and velocity, we are able to derive scalings for both, the stellar wind velocity and density (Grießmeier et al., 2004) as

$$v = v_0 \left(1 + \frac{t}{\tau}\right)^{-0.4} ,$$
$$n = n_0 \left(1 + \frac{t}{\tau}\right)^{-1.5} , \qquad (4)$$

The proportionality constants can be derived from present conditions. By taking *v*= 400 km/s and *n*=$10^7$ $m^{-3}$ for *t* = 4.6 Gyr at 1 AU, the constants are obtained as $v_0$ = 3200 km/s and $n_0$ = 2.4 x $10^{10}$ $m^{-3}$ (Grießmeier et al., 2004). To get the particle density at distances other than 1 AU, we use a $r^{-2}$ dependence. The stellar wind density and velocity evolution for the past 4.6 Gyr at the orbits of OGLE-TR-56 b (0.023 AU), HD 209456 b (0.043 AU), and HD 28185 b (1 AU) is shown in Figure 1. Recent observations of Wood (priv. comm.) indicate that there possibly exists a high-activity cutoff regarding the mass loss/activity relation derived by Wood et al. (2002), but more observations of young solar-like G and K stars with ages less than 0.7 Gyr are needed (Lammer et al., 2004).

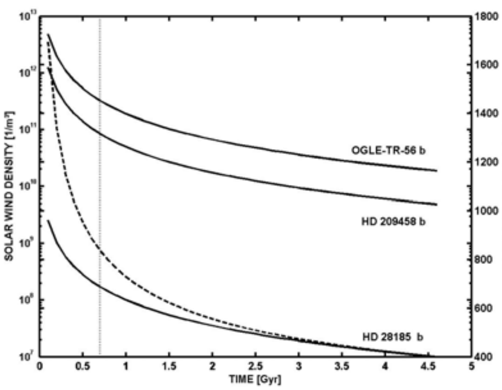


Fig. 1: The solar wind density (solid lines) for OGLE-TR-56 b, HD 209458 b, and HD 28185 b, respectively, and the solar wind velocity (dashed line). The dotted line marks the region of young stars, where the mass loss/activity relation may be modified.

## 3. Stellar wind parameters and Mach numbers at different orbits and times

In order to define if there will occur bow shocks due to the interaction with the stellar wind, it is necessary to calculate the Alfven Mach number $M_A$

$$M_A = \frac{v}{v_A} = \frac{v\,\sqrt{\mu_0\,\rho}}{B} , \qquad (5)$$

and the magnetosonic Mach number $M_{SL}$

$$M_{SL} = \frac{M_A}{\sqrt{1 + \frac{\gamma\beta}{2}}} . \qquad (6)$$

Here, $v_A$ is the Alfven velocity, $\mu_0$ is the magnetic permeability, $\gamma$ is the adiabatic coefficient, and $\rho$ is the particle mass. The plasma $\beta$ is given as the ratio of the thermal and the magnetic pressure.

We determine the solar wind density and velocity as described in the previous section. The magnetic field is scaled from present value at 1 AU of 4 nT with a $r^{-2}$ dependence. In this study, we assume the magnetic field to be constant over the last 4.6 Gyr. The plasma temperature needed to calculate the plasma $\beta$ is also assumed to be constant over the time. For the spatial variations we use $T \sim r^{-0.75}$ (Schwenn and Marsch, 1991). The corresponding values for all parameters at the orbits of the three exoplanets can be found in Table 1.

From Table 1 it can be seen that for an early stage of the host star, the close-in exoplanets as well as HD 28185 b establish bow shocks, since the Mach numbers are larger than unity. For the present Sun scenario, the situation is different. At the orbit of HD 28185 b, the solar wind parameters lead to an interaction which establishes a bow shock, while the short period exoplanets OGLE-TR-56 b and HD 209458 b are located in the regime where no bow shocks appear. In Figure 2 we plot the Mach numbers for this scenario as a function of the radial distance in order to find the transition region between the two interaction regimes. If we assume a magnetic field strength of 4 nT at the orbit of HD 28185 b, which corresponds to the situation in our solar system, the transition region lies at about 0.08 AU. Taking a strong magnetic field of 10 nT at 1 AU (corresponding to 5000 nT at the orbit of HD 209458 b), the transition region is shifted to an orbital distance of about 0.2 AU, meaning that more than 30 known exoplanets would establish no bow shocks in this case. If we consider a denser stellar wind, the transition region is shifted to closer orbital distances, which is also the case by assuming a faster stellar wind

| Object | t [Gyr] | r [AU] | v [km/s] | n [$m^{-3}$] | T [K] | B [nT] | $M_A$ | $M_{SL}$ |
|---|---|---|---|---|---|---|---|---|
| OGLE–TR–56 b | 0.7 | 0.023 | 840 | 3.3 x $10^{11}$ | 2.05 x $10^6$ | 7560 | 2.9 | 2.5 |
| HD 209458 b | 0.7 | 0.045 | 840 | 8.5 x $10^{10}$ | 1.19 x $10^6$ | 1970 | 5.6 | 3.77 |
| HD 28185 b | 0.7 | 1 | 840 | 1.7 x $10^8$ | $10^5$ | 4 | 125 | 22 |
| OGLE–TR–56 b | 4.6 | 0.023 | 400 | 1.9 x $10^{10}$ | 2.05 x $10^6$ | 7560 | 0.3 | 0.3 |
| HD 209458 b | 4.6 | 0.045 | 400 | 4.9 x $10^9$ | 1.19 x $10^6$ | 1970 | 0.6 | 0.6 |
| HD 28185 b | 4.6 | 1 | 400 | $10^7$ | $10^5$ | 4 | 14.5 | 8.6 |

Table 1: Parameters used to determine the Mach numbers at the orbits of OGLE-TR-56 b, HD 209458 b, and HD 28185 b for a early stage of the host star evolution (0.7 Gyr) and present Sun conditions.

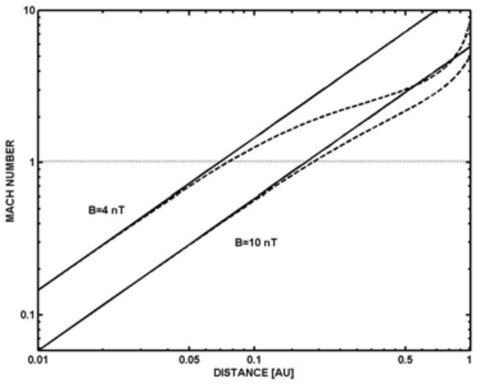


Fig. 2: The Alfven Mach number (solid line) and the magnetosonic Mach number (dashed line) as a function of the orbital distance. The dotted line indicates the transition region. In the plot, the Mach numbers for two magnetic field strength (4 and 10 nT) at the orbit of HD 28185 b are shown.

## 4. Regime change for exoplanets with high eccentricity

In our solar system, all planets except Pluto have a very small eccentricity $\varepsilon$ of their orbits, but many exoplanets with rather large eccentricities are found. The reason therefore is not well understood until now, but most proposed mechanisms invoke gravitationally scattering (Weidenschilling and Marzari, 1996) or perturbations of planets by other planets (Chiang, 2003), perhaps in resonances, or by interactions with the protoplanetary disk (Goldreich and Sari, 2003). Due to this high eccentricities of their orbits, some exoplanets cross the transition region between the two interaction regimes during their orbit around the host star. The eccentricity is given as $\varepsilon=c/a$, where $a$ is the semi-mayor axis, and $c$ gives the distance of the focus from the center of the elliptical orbit. We consider only present Sun conditions, because for young stars, the Mach numbers are more than unity also for the closes known exoplanets. In this case the transition region lies at an orbital distance of about 0.08 AU.

The most prominent close-in gas giant with a high eccentricity is HD 108147 b, which has an semi-mayor axis of $a=0.104$ AU and an eccentricity $\varepsilon=0.498$. Therefore, the perihelion is at 0.155 AU and the aphelion is at 0.052 AU, meaning that this exoplanet exhibits a bow shock during about ¾ of its orbital period, but has no bow shock during ¼ of its orbit. Another candidate for crossing the transition region is HD 162020 b with an semi-mayor axis $a=0.072$ AU and an eccentricity of $\varepsilon=0.277$, which gives a perihelion distance of 0.092 AU and an aphelion distance of 0.052 AU. More than half of its orbit, this exoplanet establishes no bow shock, but during the perihelion a bow shock appears. The orbital distance and the eccentricity of both exoplanets is shown in Figure 3.

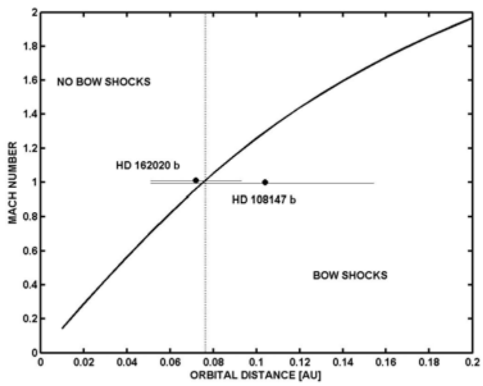


Fig. 3: The eccenticity of the orbits of HD 108147 b and HD 162020 b and the magnetosonic Mach number. The dotted line separates the region where bow shocks occur from the region without bow shocks.

## 5. Conclusions

For Mach numbers less than unity, the case of a slow shock is given. Therefore, the interaction of the close-in gas giants for present Sun conditions can not be considered as planetary bow shocks. Assuming that these planets have very weak magnetic fields due to tidal locking (Grießmeier, 2004), the close distance to the star leads to a hydrodynamically driven expanded upper atmosphere, giving rise to a Venus-like stellar wind interaction. This expansion/loss might be considered as an additional source term of particles getting involved in the stellar wind / exoplanet interaction.

This scenario might be similar to the Io--Jupiter interaction taking into account a pressure disturbance in the vicinity of Io (Erkaev et al., 2001). This pressure pulse generates two slow mode waves propagating along the Io flux tube into the northern and southern hemisphere of Jupiter. These slow waves evolve rather quickly into nonlinear waves due to a steepening mechanism with a supersonic plasma flow just behind the shock (Langmayr et al., 2003). The solution of the development of the pressure normalized to the initial strength of the amplitude is shown in Figure 4 for various values of the plasma beta. Naturally, at the initial time *t*=0 all profiles are equal to unity due to the chosen normalization. After this the amplitude decreases rather quickly to half its value as the pressure pulse decays into two slow mode waves propagating in opposite directions. If the slow mode wave would propagate strictly parallel to the magnetic field the amplitude stays constant at the half of its original value. This is the case for small values of beta, say β=0.05. On the other hand, for increasing values of beta, we obtain that the amplitude along the magnetic field decreases with time as the perpendicular propagation becomes more effective.

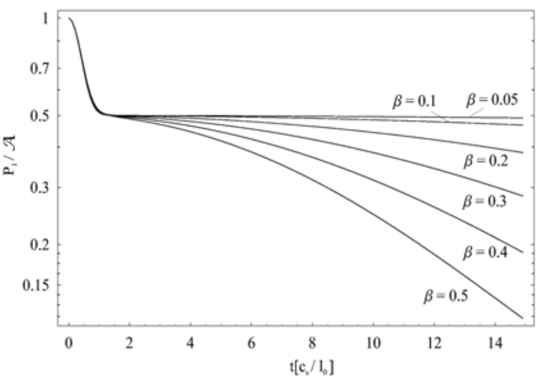


Fig. 4: Development of the amplitude of the pressure disturbance of the MHD slow wave for different values of β.

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