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Aurora on pulsar planets

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ABSTRACT
Exoplanets were long anticipated, but the discovery of the first such planet in an orbit around a pulsar came as a surprise. The only method for the detection of such planets is the precise timing method, relying on pulsars being precise clocks. In analogy with auroral emission from planets in our solar system, we suggest that planets around pulsars could also exhibit auroras. This would provide an additional method for observation of pulsar planets and conditions in the pulsar wind through emissions in visible wavelength (aurora) and cyclotron radiation in radio wavelengths. We present the first setup for magnetohydrodynamic (MHD) simulations of star-planet magnetospheric interaction for pulsar planets and the preliminary results.

Keywords: Magnetohydrodynamics – reconnection – energy dissipation – resistivity – numerical simulations – PLUTO – KORAL

1 INTRODUCTION

The first ever discovered exoplanets were found serendipitously, around the millisecond pulsar PSR 1257+12 (Wolszczan and Frail, 1992): one with $0.02M_\oplus$ and other two super-Earth planets with $4M_\oplus$ (Wolszczan, 1994). Only a 0.5% of known pulsars have a planetary companion, which could be formed around a main sequence star and later captured by a pulsar, or formed in the disk around the pulsar.

Because of their extremely stable rotation, the millisecond pulsars provide a very accurate timing method, of the order of $10^{-18}\ \mathrm{s}^{-1}$ (Lorimer, 2008) in the arrival time of the pulses to the observer. Irregularities in the pulsar time profile are a measure of (one or more) planet masses orbiting the pulsar.

Using our setup developed for star-planet magnetospheric interaction, which was used for Solar system planets and exoplanets, we perform simulations for pulsar-planet systems.

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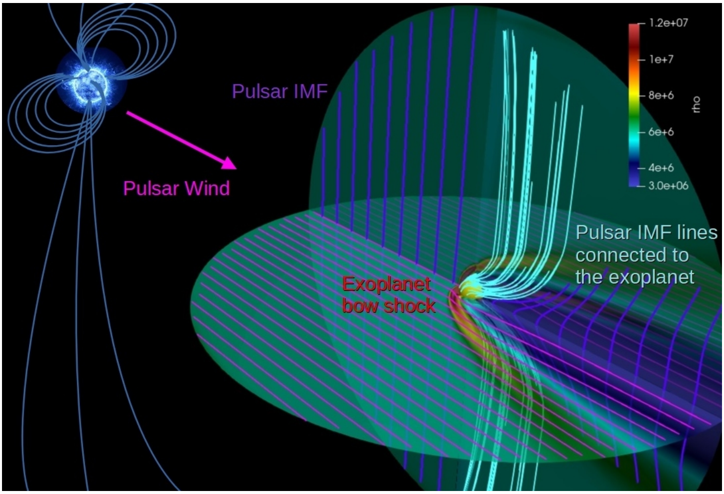

Figure 1. Pulsar-planet system in our simulation with conducting planet surface. The density is shown in a color scale and interplanetary magnetic field (IMF) with blue lines. Induced magnetic field lines at the planet dayside, which form during the piling-up of the IMF lines, are shown with cyan lines. The pulsar wind is shown with the violet lines, and its direction is indicated with an arrow. The pulsar itself is not a part of the simulation. It is assumed beyond the outer boundary of the simulation domain, which is inside the two intersecting bright circles.

Since the planetary magnetic field could be nonexistent or overwhelmed by the large pulsar field, we investigate the cases of non-magnetic planets.

2 NUMERICAL SETUP

For our simulations, we use the PLUTO code (Mignone et al., 2007). Our setup, which is almost identical to the setup presented in Varela et al. (2018), is presented in Fig. 1. The only difference stems from the assumption of non-magnetic planets, as the conducting or ferromagnetic planetary surface is set with the inner boundary specified in a slightly different, simpler way: we do not set a soft coupling region previously used atop the planet's surface to facilitate the flow towards the planet surface. The radial component of the magnetic field is set to zero, and the polar and azimuthal components are set to be smoothly absorbed by copying the values from the last active zone to the boundary ghost zone. Also, in the ferromagnetic case, the azimuthal component of the magnetic field changes the sign at the inner boundary. We neglect the anticipated relativistic nature of the pulsar wind, relegating it to future work.

We use a three-dimensional uniform spherical grid, with 128 radial cells, 48 cells in the polar angle $\theta \in [0, \pi]$ and 96 cells in the azimuthal angle $\phi \in [0, 2\pi]$. Our computational domain is between two spherical shells around the planet, representing the inner $R_{\rm in} = 1$ and outer boundary $R_{\rm out} = 20$ of the computational domain, expressed in the units of the planetary radius. We do not introduce physical resistivity so that the reconnection of the

Table 1. Parameters used in PLUTO setup file `pluto.ini` in our simulations. The pulsar wind (PW) (Speed, MagField, Dens and Temp) are setting the related initial values.

PWSpeed ($\mathrm{cm\ s^{-1}}$)	PWMagField (G)	PWDens ($\mathrm{g\ cm^{-3}}$)	PWTemp (K))
1.0×10^{9}	3.0	1.0×10^{-17}	2.0×10^{5}

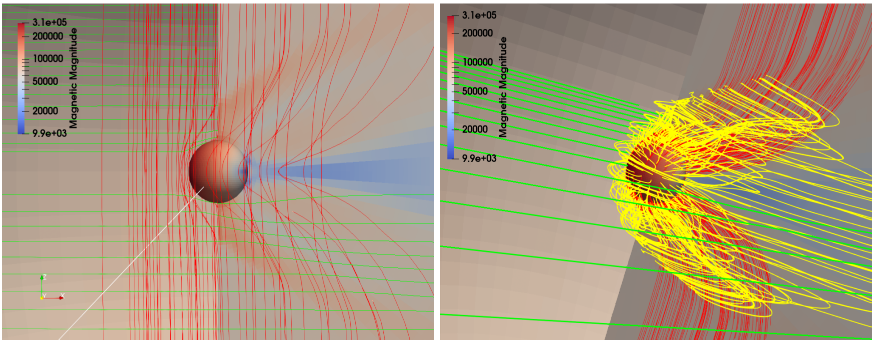

Figure 2. The results with the conductive planetary surface. *Left panel*: magnetic field strength is shown in the color grading, red solid lines represent the magnetic field lines, and green horizontal lines represent the velocity. *Right panel*: Yellow lines show the electric currents, red lines are the magnetic field lines connected to the planet, and green lines show the velocity streamlines of pulsar wind. Magnetic field magnitude is shown in color grading.

magnetic field is driven by the numerical magnetic diffusivity, evaluated from numerical experiments with the same grid resolution in a simpler setup. In Varela et al. (2018) it was estimated to $\eta \sim 10^{12}\ \mathrm{cm^2\ s^{-1}}$. Parameters used in our simulations are given in the Table 1, with $R_{NS} \sim 10$ km. The `PW(Speed, MagField, Dens, Temp)` are our best estimates for the largely unknown millisecond pulsar environment. The minimal density is set to `dens_min`=0.01. The inner boundary of the system R_{inb} is set to unity.

3 RESULTS OF NUMERICAL SIMULATIONS

We present results in our simulations with pulsar planets without intrinsic planetary magnetic field. In Fig. 2, we show the result for the conducting, and in Fig. 3 for the ferromagnetic planetary surface.

In the case of conducting planetary surface, the pulsar magnetic field lines are connected with the planet surface, while in the ferromagnetic case, they envelop the planet, producing a wider spread of the strong field region atop the planet. The results are shown in the left panels of the Figs. 2 and 3.

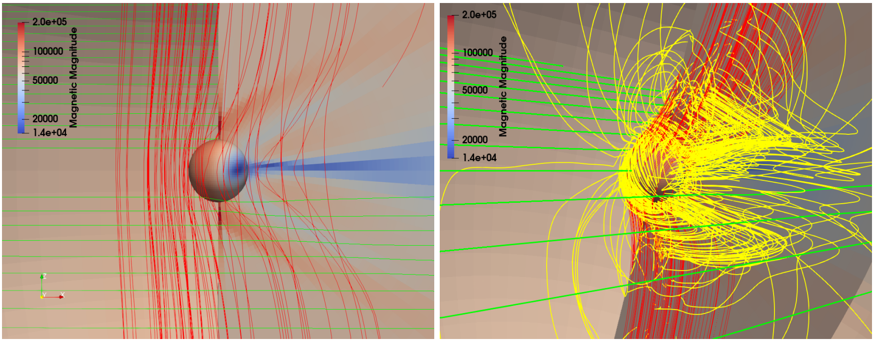

Figure 3. The results with the ferromagnetic planetary surface. The meaning of colors and lines is the same as in Fig. 2.

For the conducting planet's surface, electric current loops remain close to the planet's surface, while for the ferromagnetic planet's surface, the currents show an extended dipolar electric field structure, as shown in the right panels in the corresponding figures.

Anticipating the more violent environment, we set the magnetic field in the wind flow meeting the planet's surface to a much larger value than it would be in the Sun-like stars, and the flow velocity is also much larger.

In the previous work by Varela et al., simulations were conducted with intrinsic planetary magnetic field, so here we present the first attempt into the non-magnetic planets. Nevertheless, the magnetospheric interaction with the planetary surface occurs, as it is the obstacle in the magnetised flow with its induced field. The magnetotail is formed, but more narrow than in the cases with planetary field.

4 CONCLUSIONS

In our numerical simulations, we obtain the first results for the magnetospheric interaction of a millisecond pulsar and non-magnetized planets orbiting it. We find that in the cases of conductive and ferromagnetic planetary surface interacting with the pulsar magnetic field, the resulting flow near the planets shows different geometry of the induced electric field and currents. The strength of the induced magnetic field is different in the two cases, so the resulting radio emission from such objects would be different.

Here, we presented the concept of auroral emission from the vicinity of the millisecond pulsar planets. The plasma outflowing from the vicinity of a millisecond pulsar is expected to be lighter (electron-positron pairs instead of protons) and much faster than in the stellar wind from the Sun-like stars. In future work, we will compute the emerging radio-emission in the special-relativistic regime and assess the needed sensitivity for its observation from Earth. Such measurements would provide a new window to pulsar wind and planets in such extreme environments. It would be the first direct probe into the pulsar wind.

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