Simulation of a planet in highly relativistic pulsar wind

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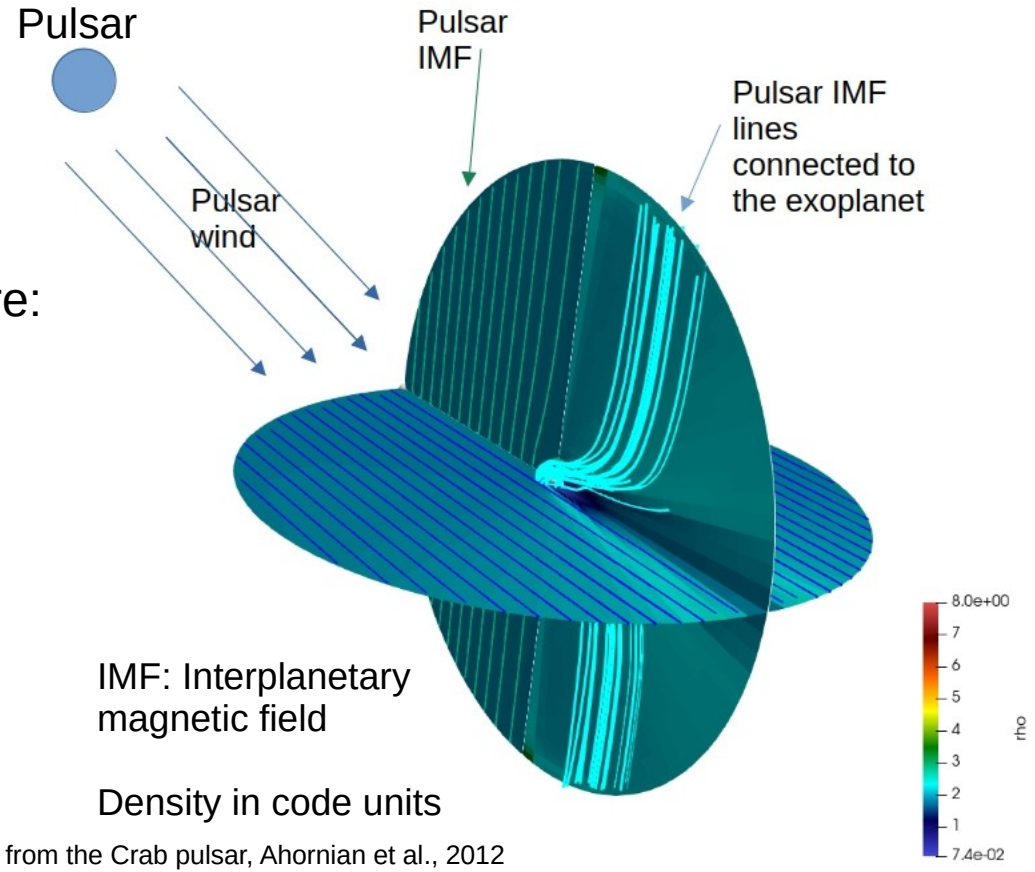
Motivation

- First exoplanets were discovered around a pulsar
- Only 7 confirmed pulsar planets (NASA exoplanet archive)
  - All found with the pulsar timing method
  - Only tells where the planet is, nothing about the conditions
- Close to pulsar means high local magnetic field
- Synchrotron emission in interplanetary magnetic field near planet
- Determine whether current radioemission detectors are sensitive enough

Setup of the simulation

- PLUTO RMHD code
- Simulation centered on planet,
  distant pulsar sets boundary conditions
- Model terrestrial planet without atmosphere:
  - Planet is a perfect conductor
  - Planet is a ferromagnet
- For realistic pulsar wind [1]: $\gamma \approx 10^4 - 10^6$
- Simulation: optimal $\gamma = 10$
- Conductive: $\gamma = 5.8$
- Ferro: $\gamma = 3.2$



[1] Abrupt acceleration of a 'cold' ultrarelativistic wind from the Crab pulsar, Ahornian et al., 2012

List of simulation parameters (conductive case)

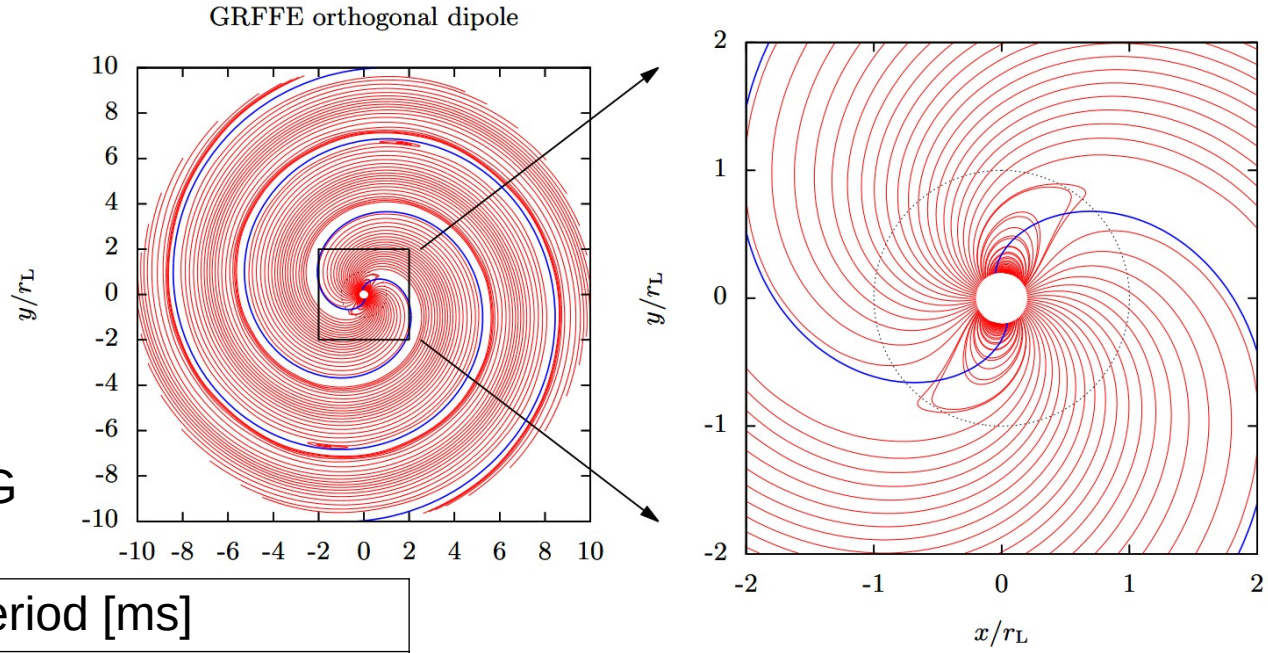
Planet	SWDens [g/cm^3]	SWSpeed [cm/s]	SWTemp [K]	SWMagField [G]	PlanetRad [cm]
Real terrestrial planets (Wolszczan's planets)					
PSR B1257+12 b	3.1×10^{-24}	2.953×10^{10}	5.0×10^{8}	4.1×10^{-2}	2.0×10^{8}
PSR B1257+12 c	3.1×10^{-24}	2.953×10^{10}	5.0×10^{8}	2.1×10^{-2}	1.0×10^{9}
PSR B1257+12 d	3.1×10^{-24}	2.953×10^{10}	5.0×10^{8}	1.6×10^{-2}	7.5×10^{8}
Theoretical terrestrial planet					
	3.1×10^{-17}	2.953×10^{10}	5.0×10^{8}	3.6	5.0×10^{8}
Diamond planet					
PSR J0636+5129 b	3.1×10^{-18}	2.953×10^{10}	5.0×10^{8}	9.9	5.0×10^{9}

Diamond planets

- Mass of order M_J
- High density
- Suspected origin:
  - Stripped core of gas giant
  - Brown dwarf

Pulsar magnetic field structure

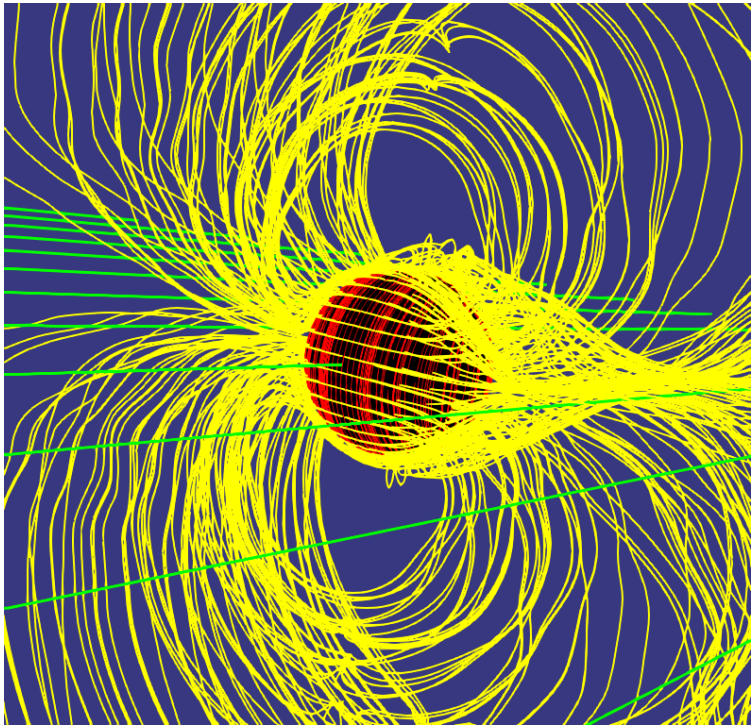
- Dipole field up to light cylinder radius r_L
- Spiral structure outside r_L
- Local magnetic field is determined by location *and* pulsar rotation speed
- Example: 2 ways to reach 3.6G



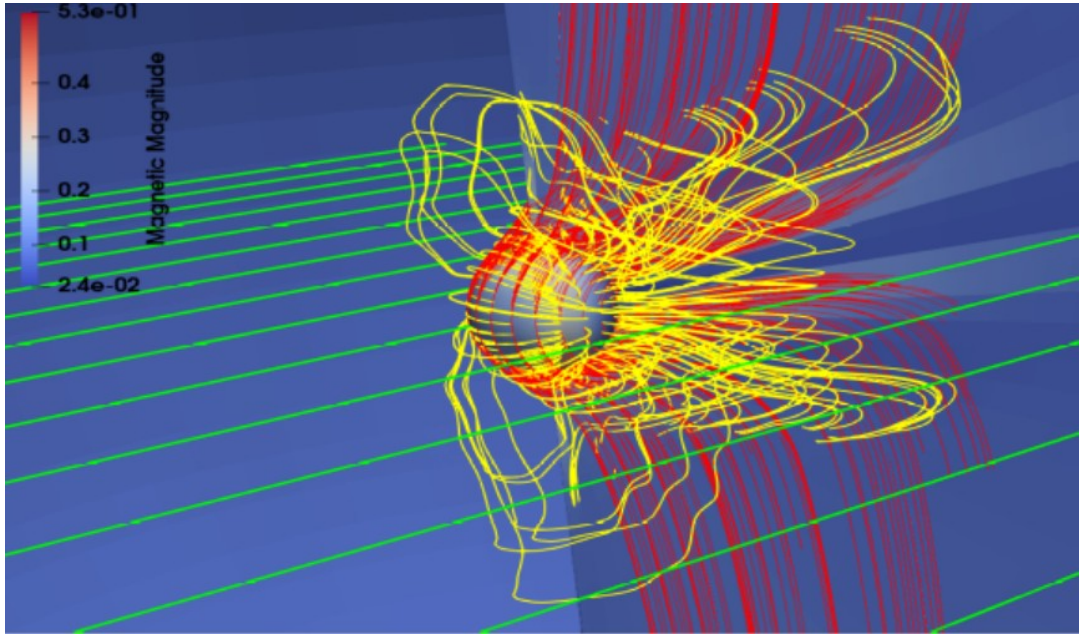
Orbital Radius [cm]	NSPeriod [ms]
1.2×10^{12}	1.0
3.4×10^{10}	6.0

[2] Theory of pulsar magnetosphere and wind, Pétri, 2016

Planetary magnetic field and currents – conductive case



$\gamma = 5.8$, this work



$\gamma = 2.0$, Mishra et al (2023)

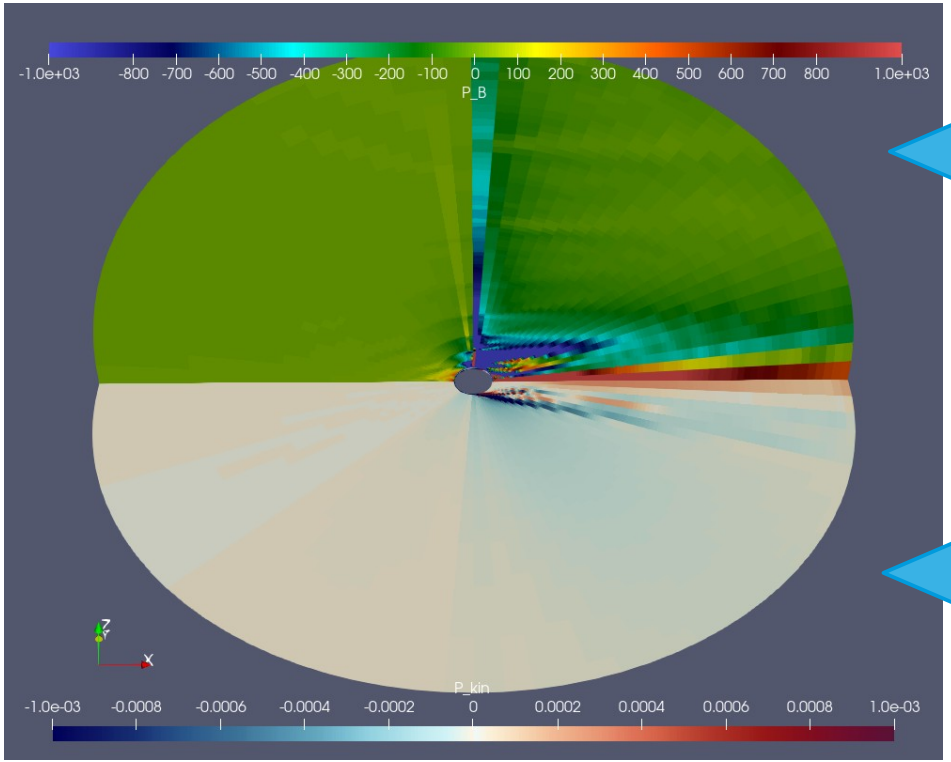
Red: magnetic field line

Yellow: current

[3] Auroras on Planets around Pulsars, Mishra et al., 2023

Radioemission sources – conductive case

Scale [W]: $-1.0\times10^{3}-1.0\times10^{3}$



Scale [W]: $-1.0\times10^{-3}-1.0\times10^{-3}$

Radiomission from dissipation of the magnetic field

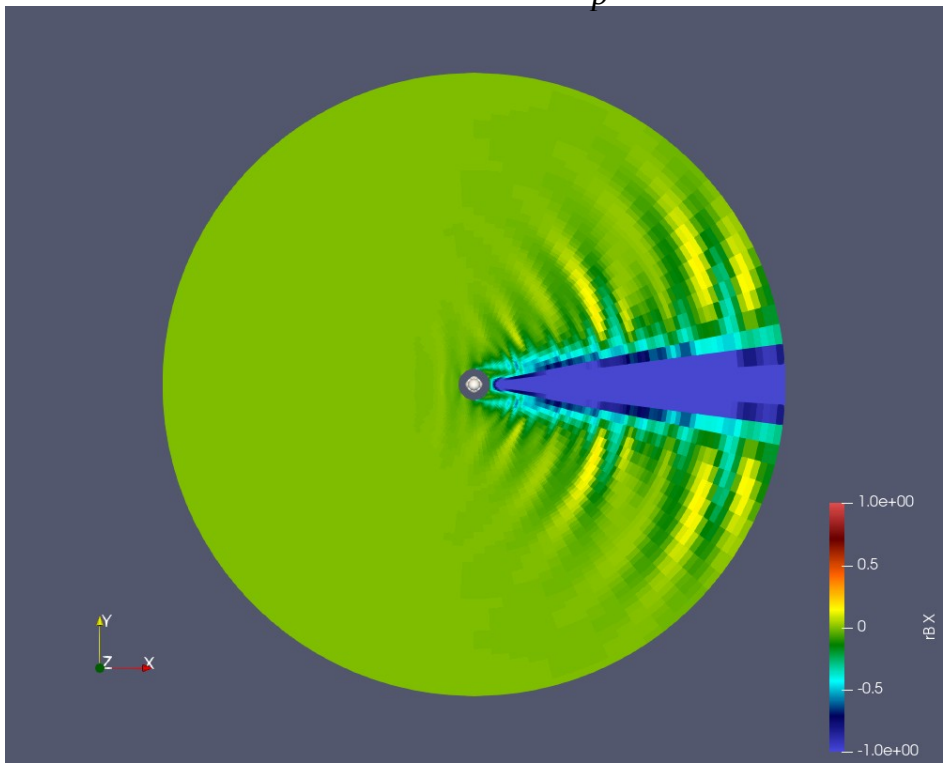
Simulation domain: $20.0\,R_p$

Radiomission from dissipation of kinetic energy

Pulsar
(far outside simulation domain)

Conductive diamond planet magnetic field wave

Simulation domain: $20.0\,R_p$



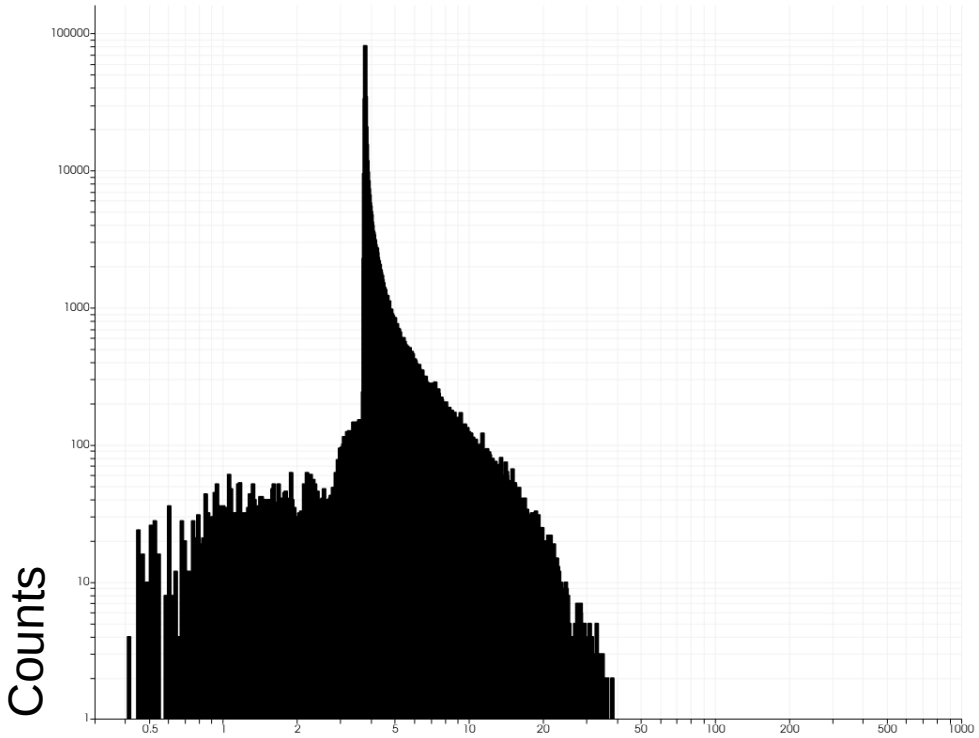
Scale [G]: $-1.0 - 1.0$

Pulsar
(far outside simulation domain)

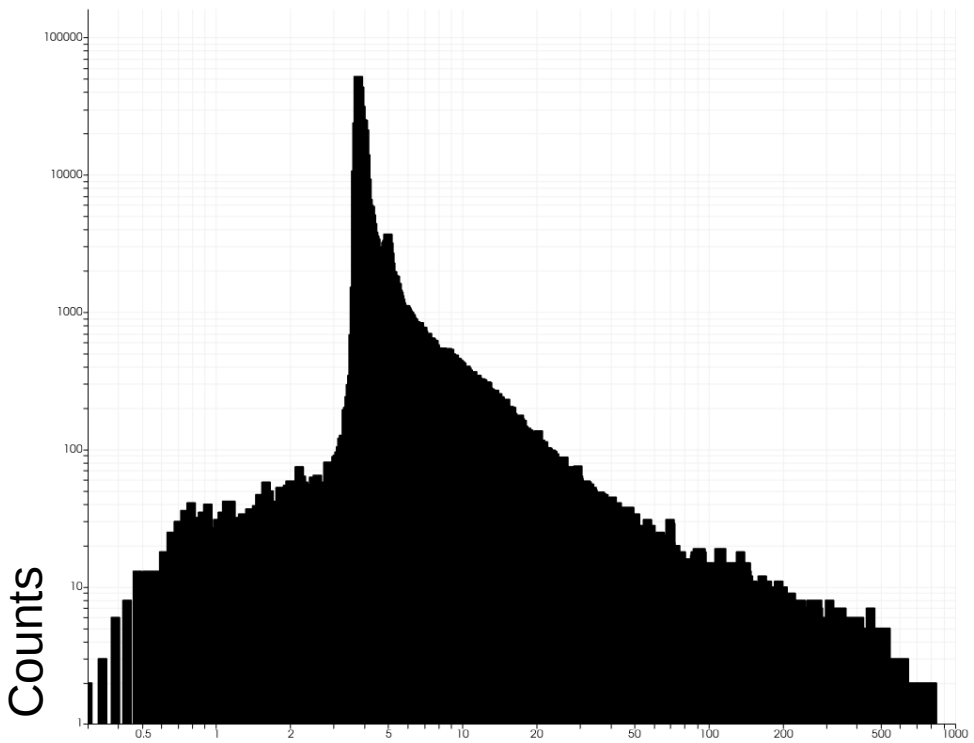
- Shown: X-component of magnetic field
- Transversal wave with phase velocity

  $v_p = 2.5 \times 10^6$ m/s
- Only appears for diamond planet

Emission bandwidth

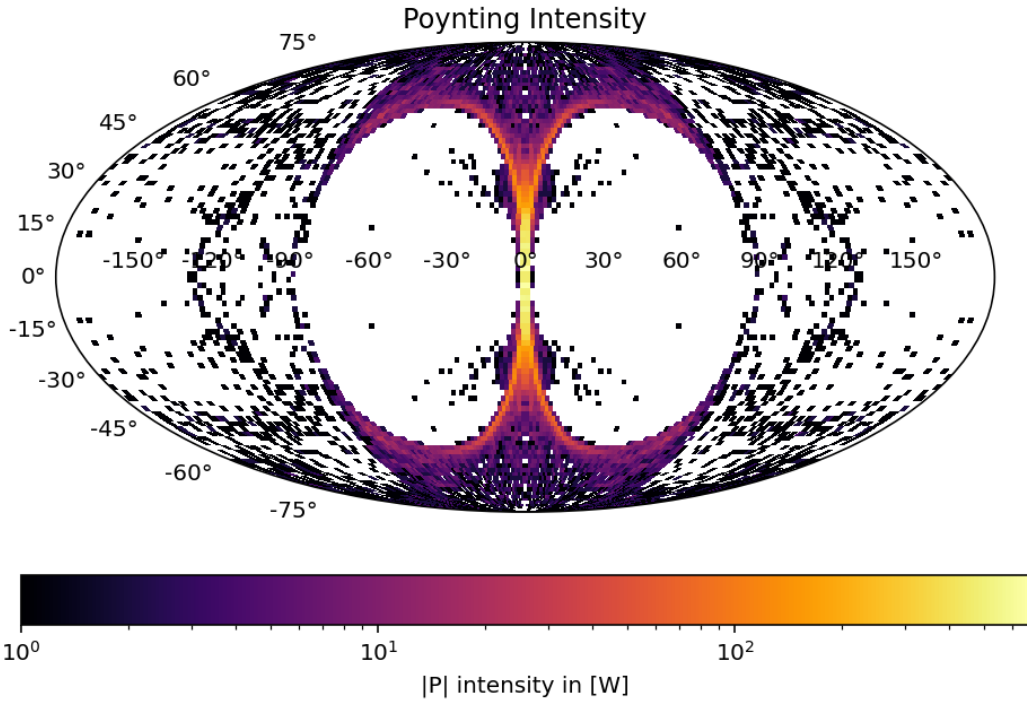


Emission Frequency in MHz
Conductive

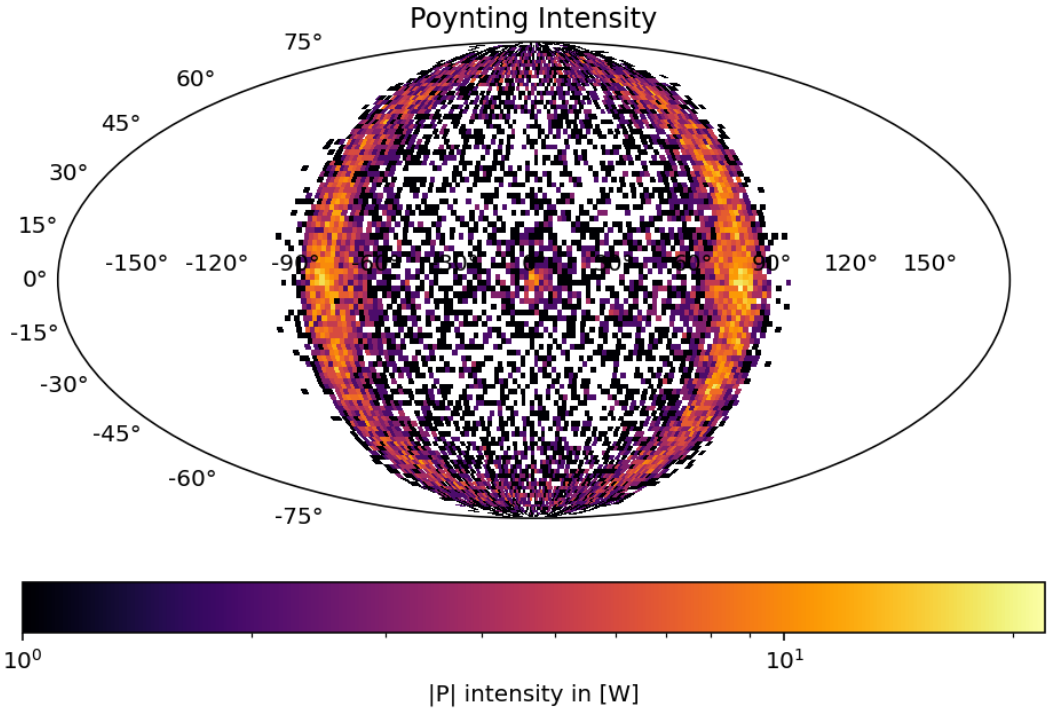


Emission Frequency in MHz
Ferromagnetic

Emission distribution



Conductive



Ferromagnetic

(Preliminary result)

Detection of emission on earth

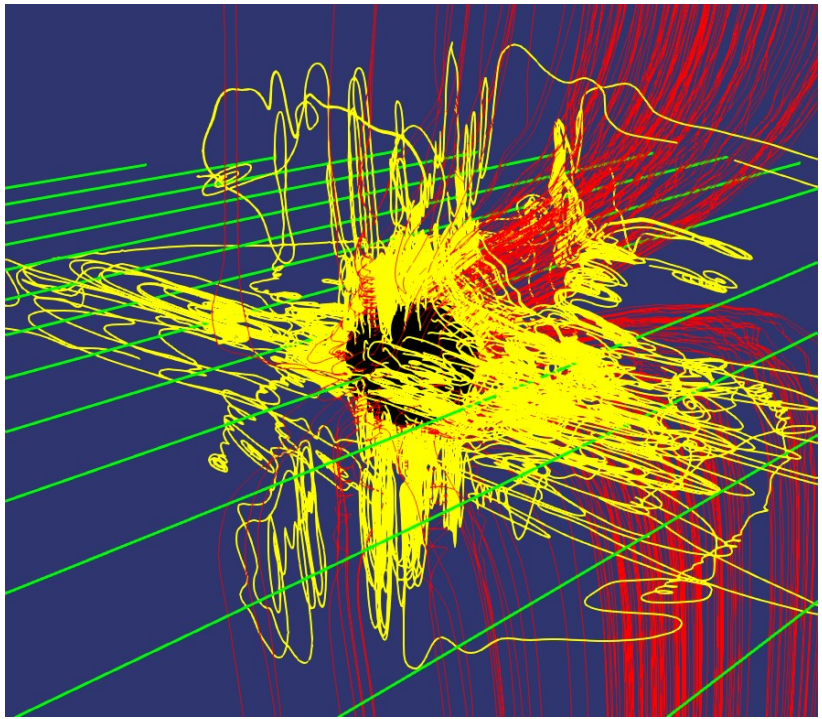
Planet	Fake Planet	Mishra	PSR B1257+12 b	PSR B1257+12 c	PSR B1257+12 d	PSR J0636+5129 b
$\Phi_a(750)$ [mJy]	4.45×10^{2}	4.64×10^{-1}	7.82×10^{-2}	2.32×10^{-1}	1.21×10^{-1}	3.81×10^{3}
$\Phi_b(250)$ [mJy]	4.01×10^{3}	4.18	7.04×10^{-1}	2.09	1.09	3.43×10^{4}
$\Phi_c(100)$ [mJy]	2.51×10^{4}	2.61×10^{1}	4.40	1.31×10^{1}	6.79	2.14×10^{5}
γ	5.798	2.0	5.798	5.798	5.798	5.798
P_{radio} [W]	1.04×10^{20}	3.53×10^{13}	4.08×10^{13}	7.74×10^{13}	3.01×10^{13}	4.01×10^{20}
$\Delta\omega(80\%)$ [MHz]	4.367	0.001	0.006	0.004	0.003	1.247
Ω	4.011	5.705	6.527	6.249	6.235	6.335
$\omega_{max,obs}$[MHz]	116.751	0.115	0.176	0.093	0.073	43.694
LOFAR (750)	YES	NO	NO	NO	NO	YES
MeerKAT (750)	YES	NO	NO	NO	NO	YES
SKA (750)	YES	NO	NO	NO	NO	YES

- Minimum sensitivities of LOFAR and MeerKAT and SKA are of the order of 0.1, 0.01, and 0.001 mJy
- Earth's ionosphere absorbs fequencies below 10MHz
- Flux at a distance is calculated with a formula from reference [4]

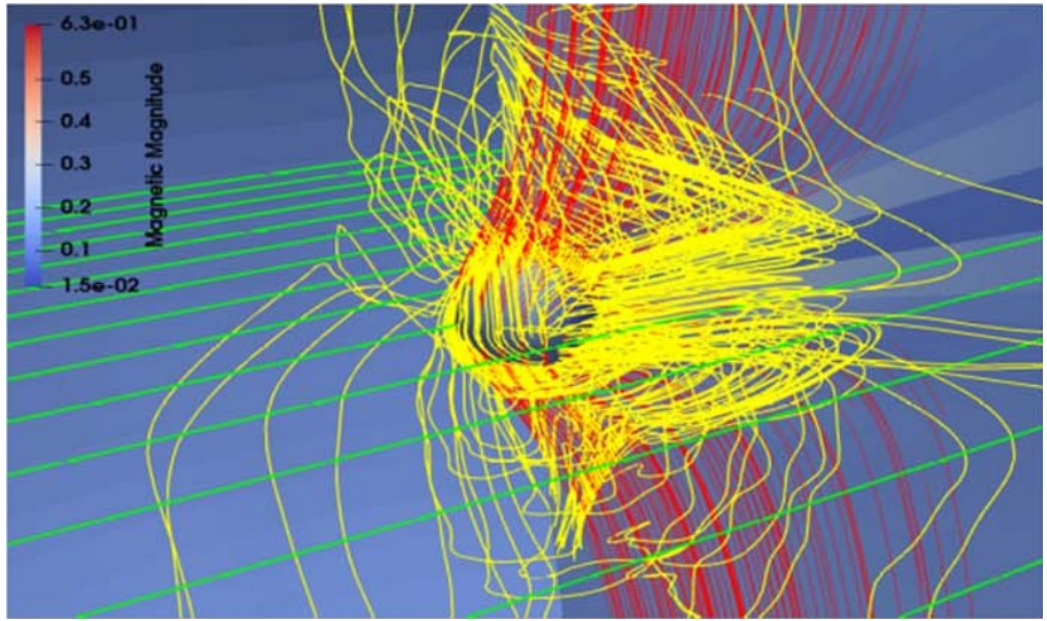
[3] Auroras on Planets around Pulsars, Mishra et al., 2023

[4] Pulsar-Planet Interaction, Mendez, 2025

Magnetic field and currents – ferromagnetic case



$\gamma = 3.2$, this work



$\gamma = 2.0$, Mishra et al (2023)

Red: magnetic field line

Yellow: current

[3] Auroras on Planets around Pulsars, Mishra et al., 2023

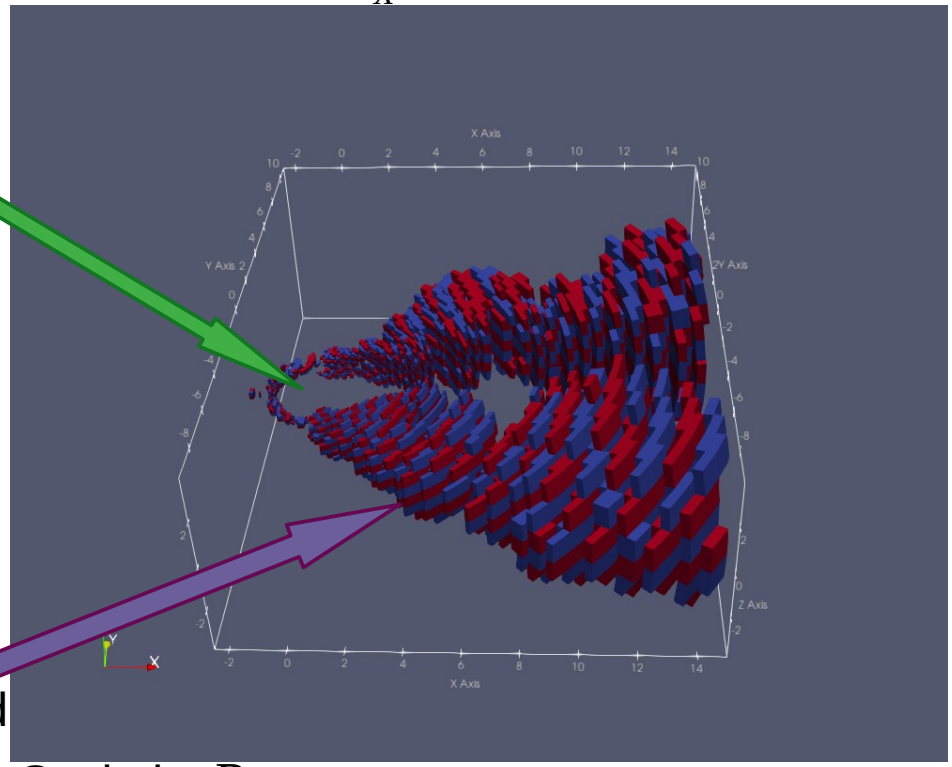
Magnetic wave – ferromagnetic case

Red: positive B_X Blue: negative B_X

Planet is here

Pulsar

Wave patten downwind of planet



Scale in R_p

- Transversal magnetic field wave for all planets
- Phase velocities:
  - PSR J0636+5129 b $v_p = 2.0 \times 10^6$ m/s
  - PSR B1257+12 b $v_p = 1.6 \times 10^6$ m/s
  - PSR B1257+12 c $v_p = 1.8 \times 10^6$ m/s
  - PSR B1257+12 d $v_p = 1.7 \times 10^6$ m/s
  - Theoretical planet $v_p = 1.7 \times 10^6$ m/s
- Group velocity is 0
- Not Alfvén
- Most probable numerical causes [5] could be ruled out

[5] Hyperbolic Divergence Cleaning for the MHD Equations, Dedner et al, 2002

Conclusion

- Conductive simulation more trustworthy than ferromagnetic
- Diamond planet visible according to simulation
  - Need observational data
- Method suitable to probe pulsar wind
  - Need high surrounding magnetic fields
    - Close in planets
    - Planets around fast-rotating pulsars
- Method independent of planet size
- Origin of magnetic field wave unclear