Art preceding science: auroras on pulsar planets

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- Aurora in Solar System and exoplanets
- Planets around pulsars
- Simulations of star-planet magnetosphere interaction
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Introduction-Art preceding science

In some striking cases, art is preceding sciences. Most renowned artist of astronomical art was Chesley Bonestell (1888-1986), whose paintings inspired-and as we see, still inspires American space program:

He also did many of the paintings of views from other worlds: “View of Saturn from Titan” (1944), his first artwork for “Life” magazine

Imaged by Heritage Auctions, HA.com

Today we can see many of such views in real imaging from the scientific missions.

Introduction-Art preceding science

The scientific discovery I will present today has its own well documented scientific predecessor. Ms Lynette Cook made this painting, “Pulsar Planets 1”, back in the year **2000**. Our recent publication, which is the first scientific description of such possibility, is from **2023**. More on this later.

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Auroras on Planets around Pulsars

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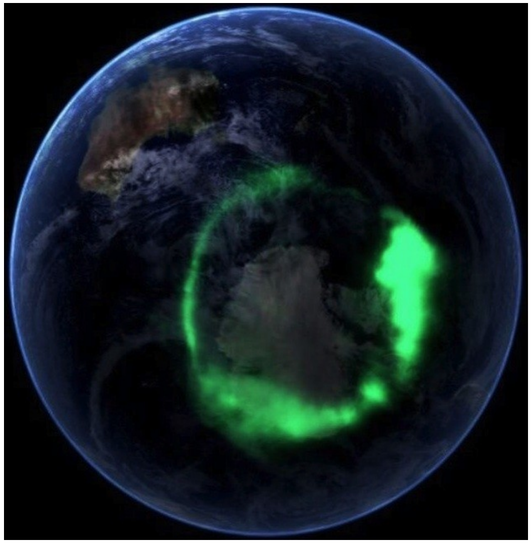
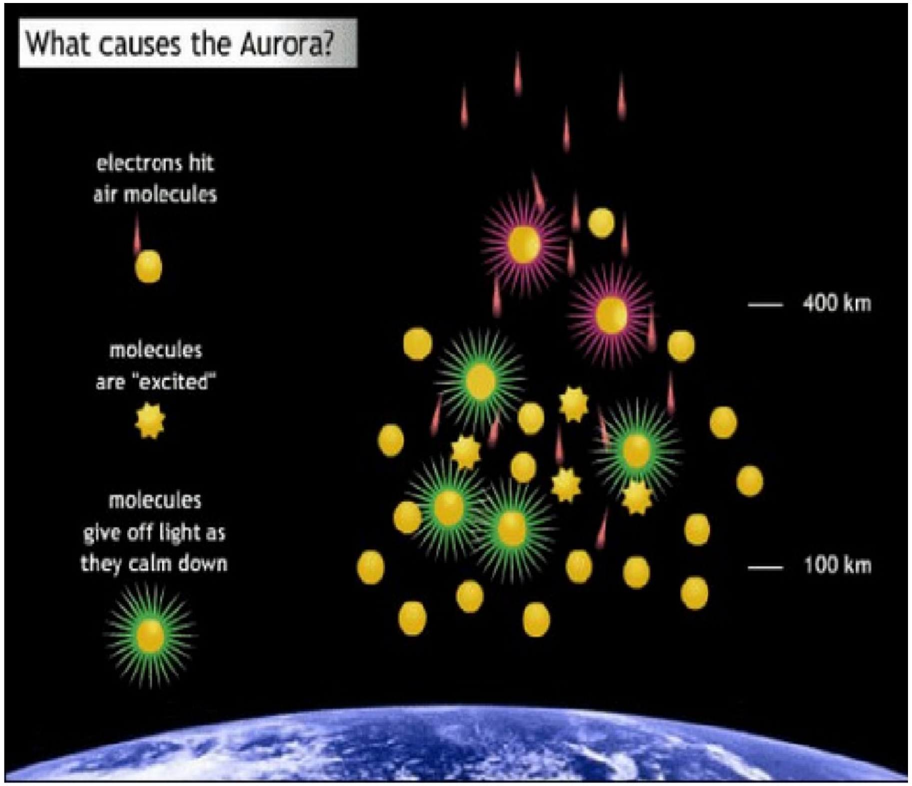
Aurora on Earth





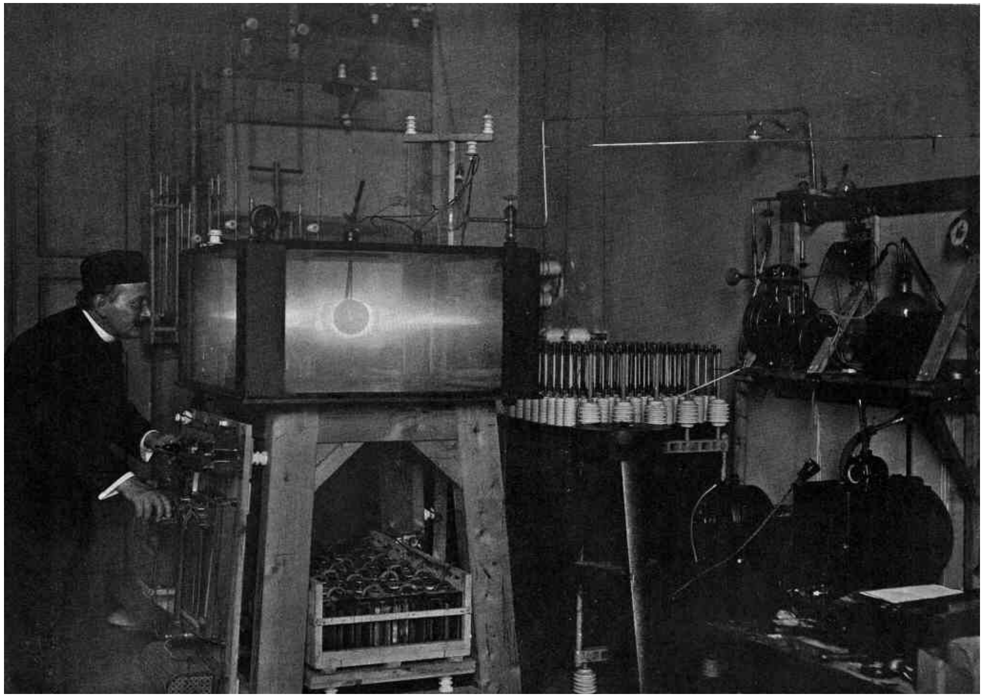
High-speed particles from the Sun, mostly electrons, strike oxygen and nitrogen atoms in Earth's upper atmosphere. Credit: NASA

Aurora, named **aurora borealis** (the Greek goddess of dawn, Aurora, + Greek name for northern wind, Boreas) was scientifically discussed by Pierre Gassendi in 1621.

It is an outcome of star-planet magnetospheric interaction. On Earth, aurora is visible close to the geographic poles, since they are also currently close to the magnetic poles of Earth. Aurora appears at >100-500 km, well above the von Karman line at 80-100 km, where airplanes are not supported by the air pressure any more, while ionosphere is from 50-1000 km.

Colors in aurora come from different gases in the upper layers of the atmosphere emitting light of different colors in collision with particles from the solar wind (mostly electrons in this case). Oxygen emits greenish or brown-red, and nitrogen blue or red light.

Aurora on Earth-Kristian Birkeland



Kristian Birkeland (1867 Oslo-1917 Tokyo) made electric models of **terrella** and measured magnetic fields and currents on continental scale. He funded his experiments by finding the use of powerful electric arcs in the fertilizer and aluminum production industry-it was the first enrichment of the whole Norway!

At the beginning of XX ct. he correctly explained the mechanism of aurora, but his results were for long time ridiculed (e.g. by Sydney Chapman, 1888-1970, later a leading researcher on geomagnetism)-they were accepted only after **1963.** when confirmed by cosmic probes.

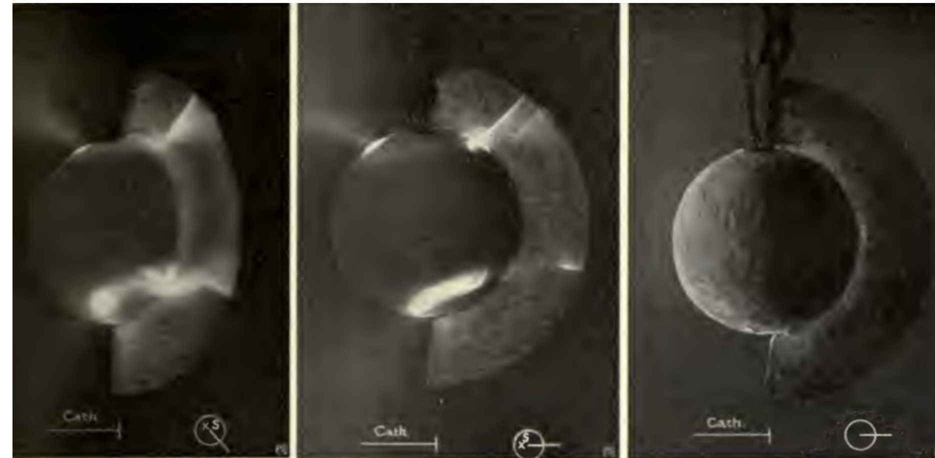


Fig. 46.

a horizontal current for a long distance between Dyrafjord and Axeløen. This would satisfactorily explain the constant direction that the perturbation in this and other similar cases shows.

In order to obtain a clear conception of the conditions, we will once more have recourse to my experiments with the terrella. The experiments shown in fig. 46, *a*, *b* and *c*, follow directly on to those in fig. 38, *a*, *b* and *c*. In fig. 46 *a*, the terrella is so turned that the screen forms an angle of 135° with its first position (fig. 38 *a*). In the next experiment (fig. 46 *b*), the angle is 180°. The angles are here measured from west to east. Fig. 46 *c* shows how the cathode rays strike the terrella; when the latter is not magnetic, but is in the same position as in the experiment given in fig. 46 *b*, only the half that is turned towards the cathode becomes luminous with phosphorescence.

It will be seen from figs. 46 *a* & *b* how the cathode rays behave when the terrella is very powerfully magnetised.

We will here especially direct our attention to the luminous wedge that is thrown upon the screen at about the 70th parallel

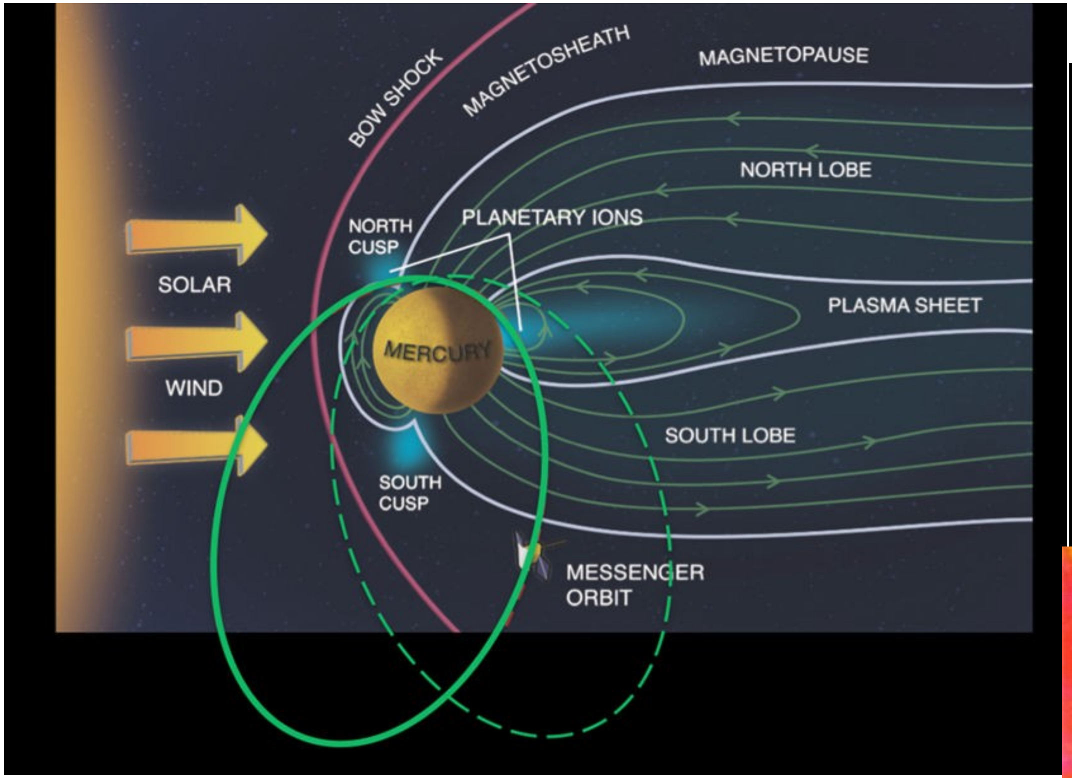
He might be the first to predict a plasma-filled space in 1913, writing: "It seems to be a natural consequence of our points of view to assume that the whole of space is filled with electrons and flying electric ions of all kinds..."

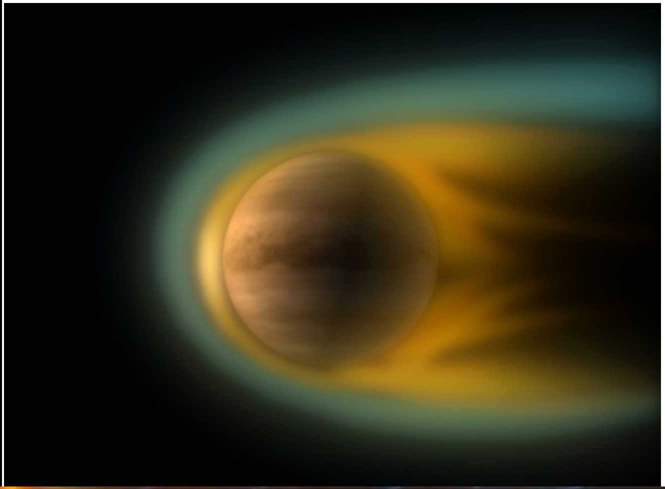
Aurora on Mercury & Venus

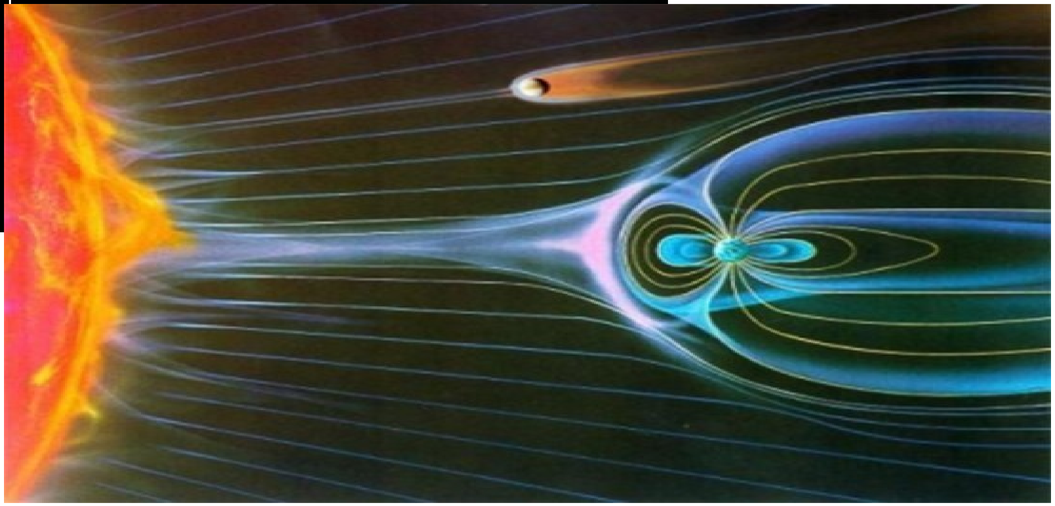
Auroras are found on most of the planets in the Solar system, magnetized or not.

Mercury (Mariner, Messenger probes)

Venus



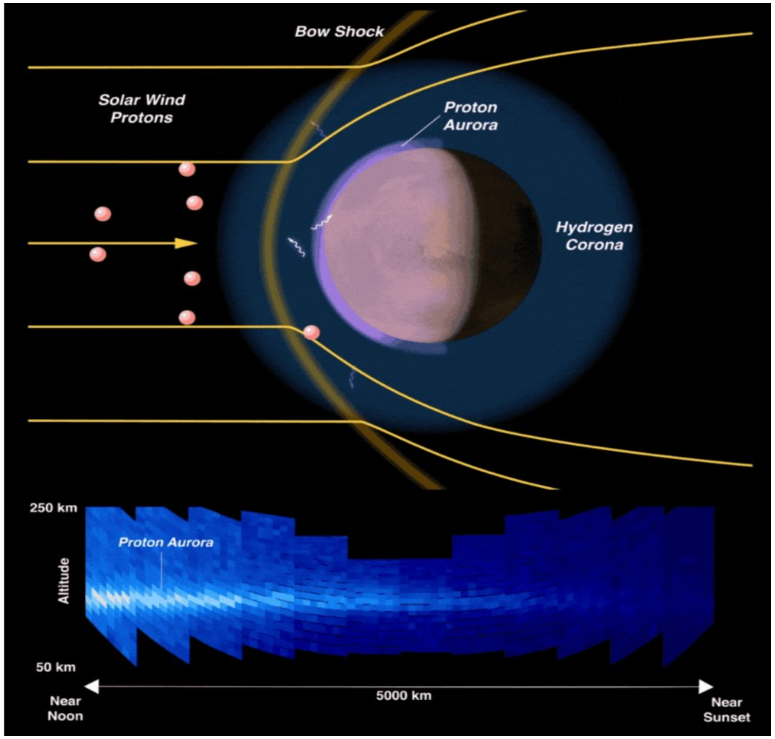




Venus has smaller aurora towards Sun than Earth.

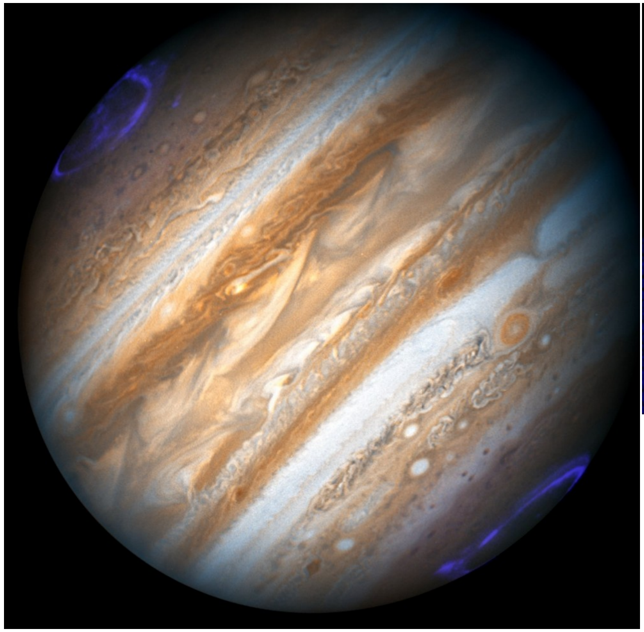
Mars aurora

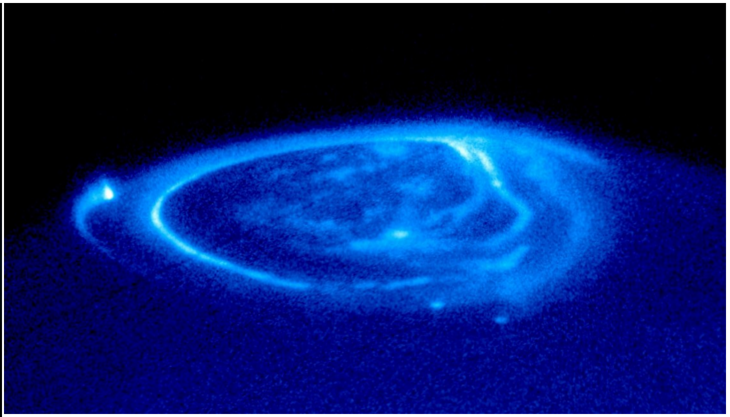
Even in the planets likeVenus or Mars, which do not have significant magnetic field, we observe aurora, formed as a result of interaction of particles-here mostly protons- from the solar wind shock where the planet moves through the wind. It is most visible at the sunny side of the planet.



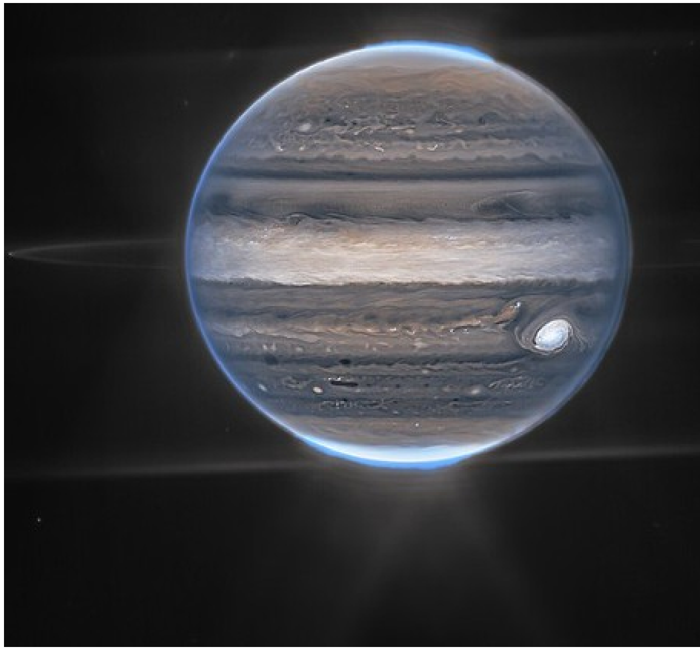
Auroras on large gaseous planets

Aurora is observed also on Jupiter and Saturn. On the gas planets aurora is visible mostly in ultra-violet, so we can observe it from outside our atmosphere.

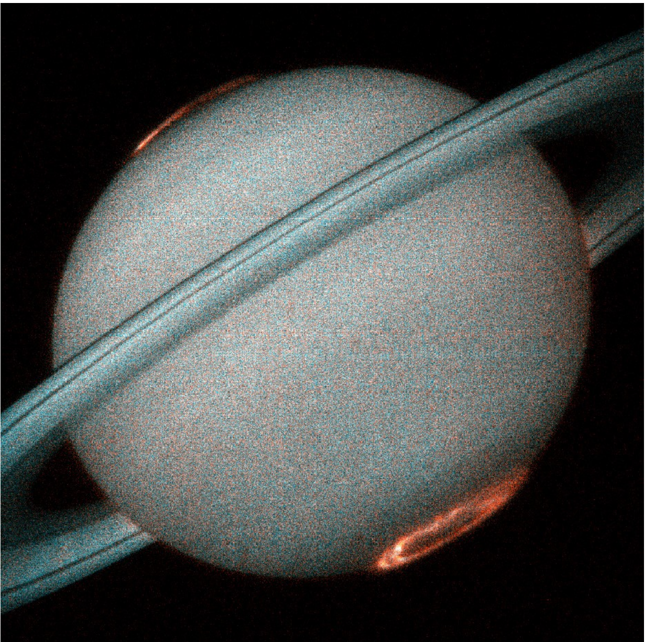




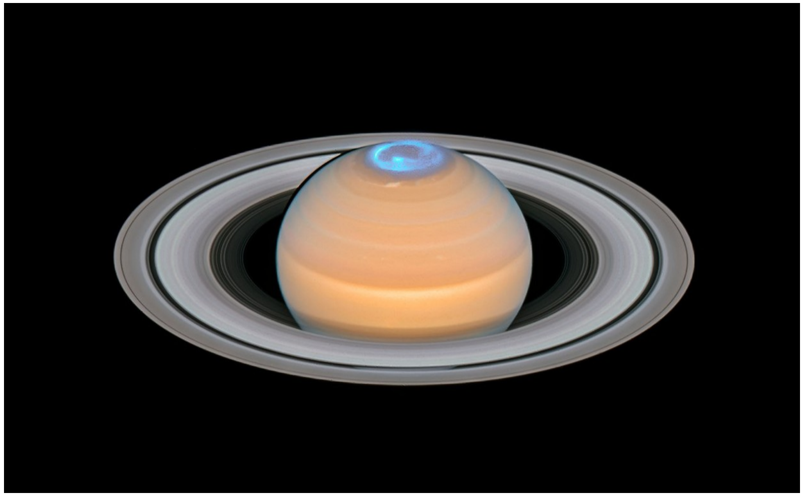
Spots in aurora on Jupiter are magnetically connected with its satellites: the spot on the left side is connected with Io, bottom two with Ganymede and Europe.

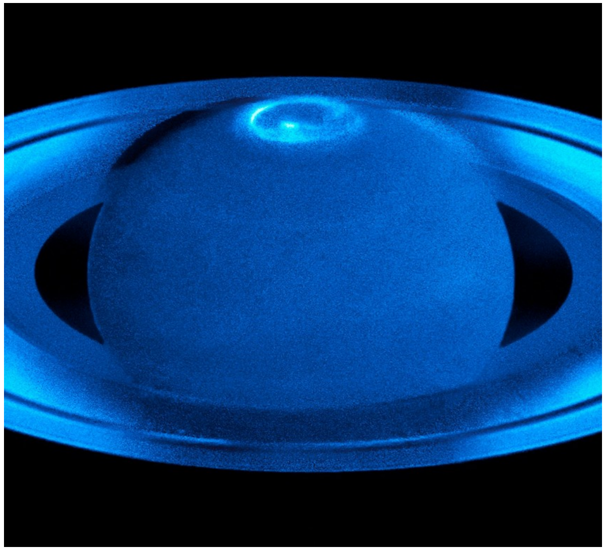


JWST’s capture of aurora on Jupiter



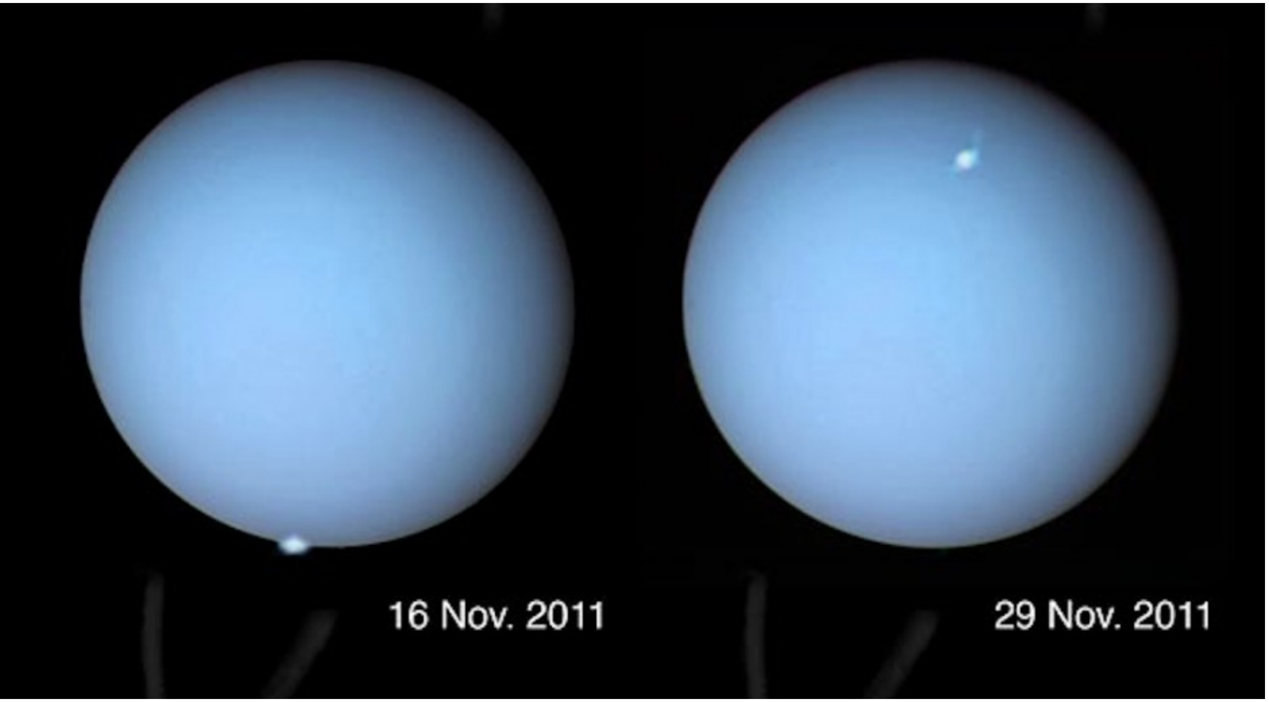
Saturn also features polar aurora:

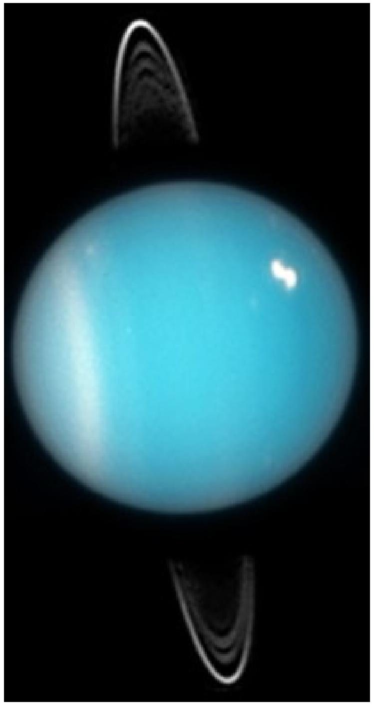




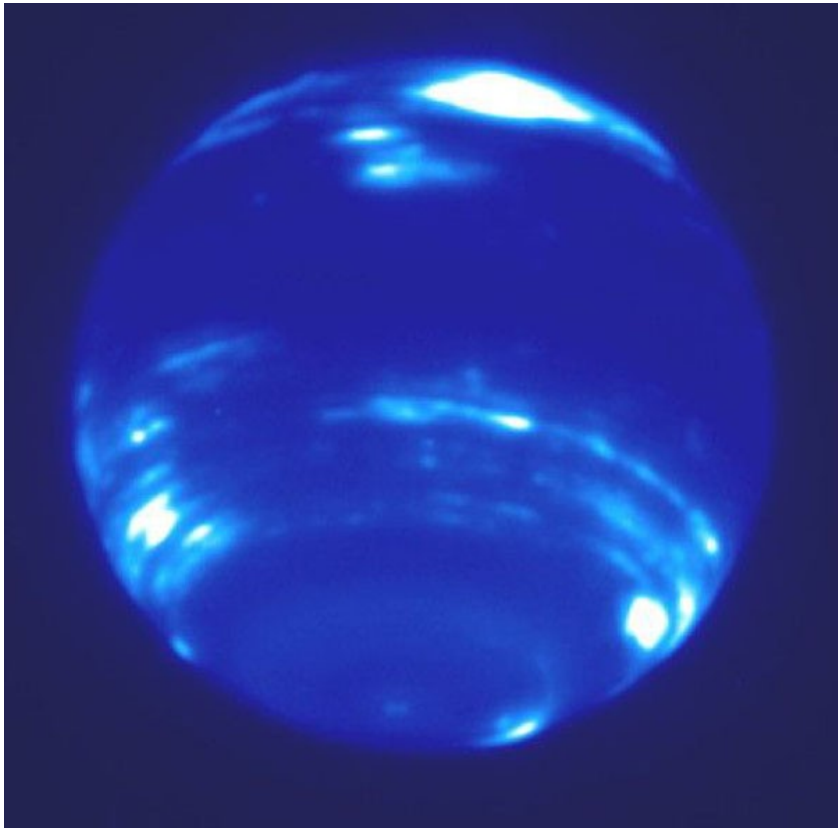
Aurora on Uranus

HST observed auroras on Uranus:





Keck observed it on Neptune:

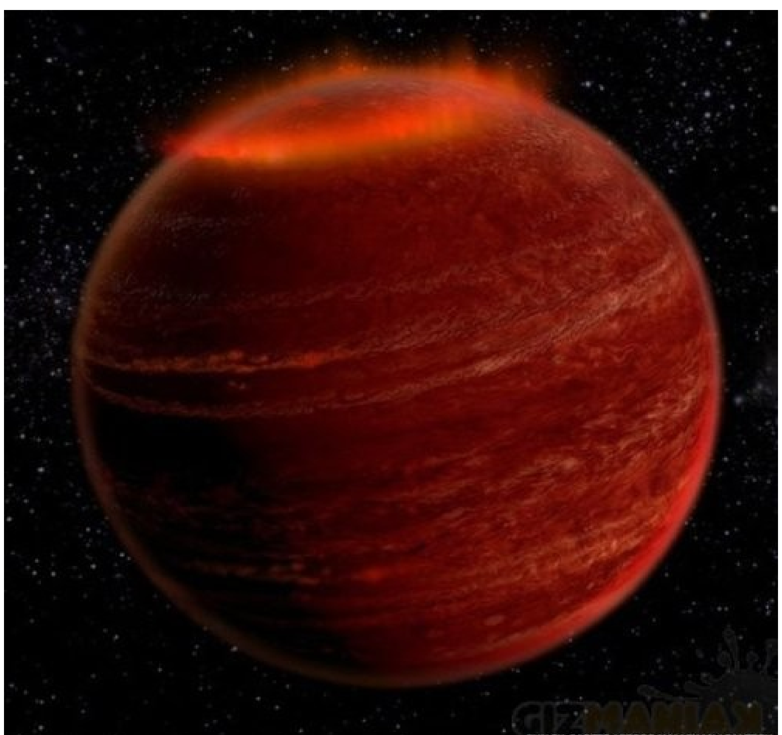


Extrasolar and exoplanet auroras

•On exoplanets we also can expect auroras, but **there is yet no confirmed extrasolar aurora observation**. We have a tentative observation, on a brown dwarf LSR J1835+3259, 18 lyrs from us, in Lyra (artist impression shown below, of a reddish aurora, from more hydrogen in the atmosphere, and about million times more intense than on Earth, because of larger magnetic field). There are more of similar objects which show characteristic spectral features which point to aurora.

•Such an aurora should also be of different nature, because there is no other star for producing the stellar wind.

•A model for aurora requires a continuously adding plasma within the magnetosphere. This mass-loading can be achieved in multiple ways, including interaction with the interstellar medium, a volcanic activity on the orbiting planet embedded within the magnetosphere, or magnetic reconnection at the photosphere, or particles from the stellar wind producing the emanations from the planetary surface like on Mercury.



In the cases of **planets around pulsars**, which were actually the first observed exoplanets, we can expect similar effects. Because of much larger pulsar magnetic field, and difference in pulsar wind ver. stellar wind, they could behave different from usual planet aurora.

We made the first such model, by introducing necessary modifications in our star-planet interaction setup.

First I show the usual simulations setup for Sun-like stars.

Numerical simulations of star-planet interaction

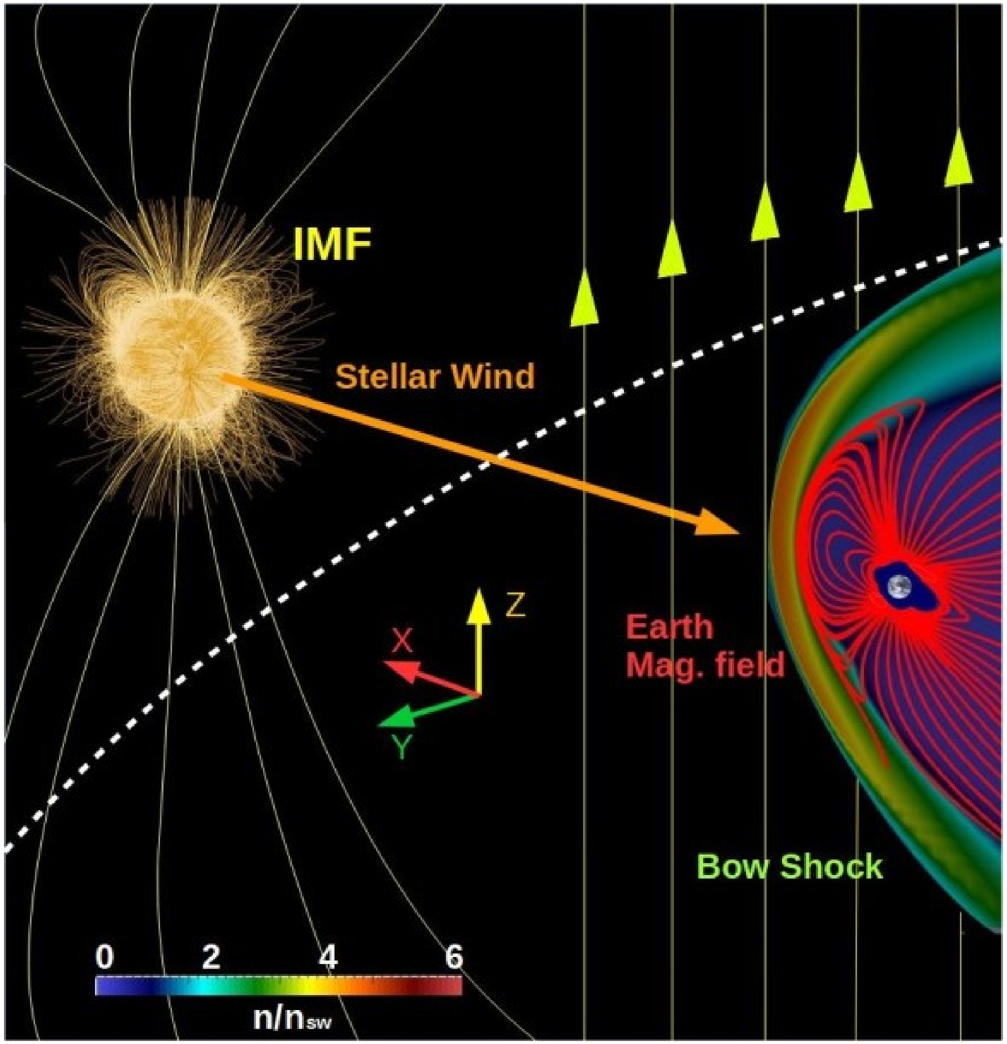


Fig. 1. 3D view of a typical simulation setup. We show the density distribution (color scale), Earth magnetic field lines (red lines), and IMF (yellow lines). The yellow arrows indicate the orientation of the IMF (northward orientation). The dashed white line shows the beginning of the simulation domain (the star is not included in the model).

- In a series of works by Varela et al. (e.g. A&A, 616, A182, 2018; A&A 659, A10, 2022) are given numerical simulations of planetary magnetospheric response in extreme solar wind conditions, using the PLUTO code.
- Such simulations are **valid for Earth and exoplanets**.
- We use this setup as a template for the much larger magnetic field of pulsar.

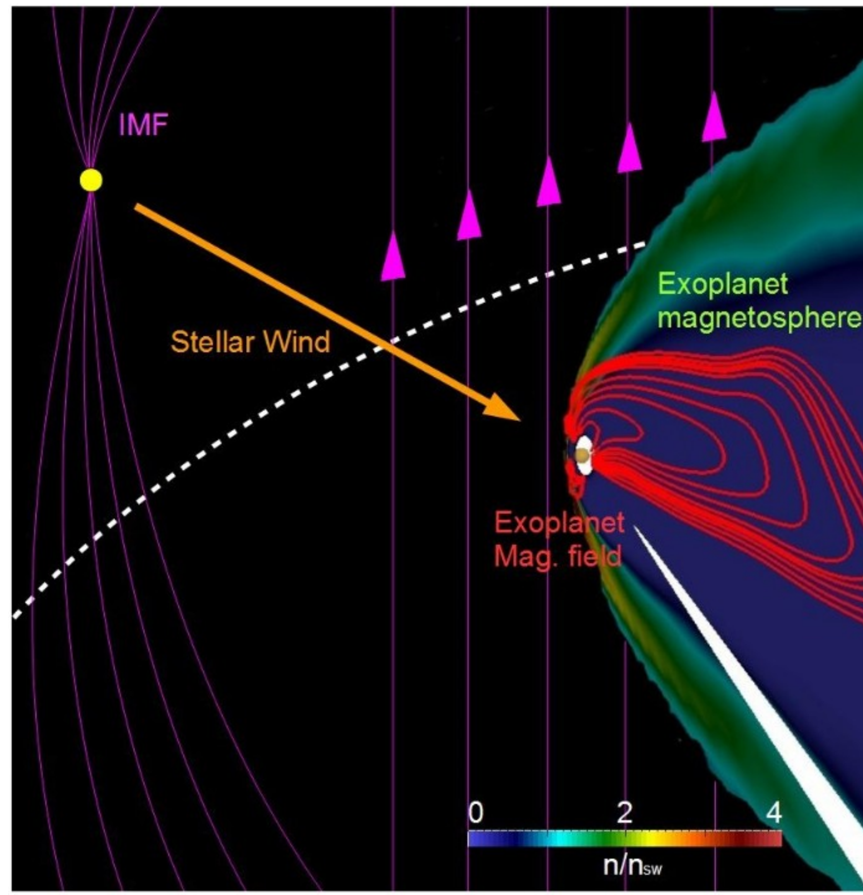
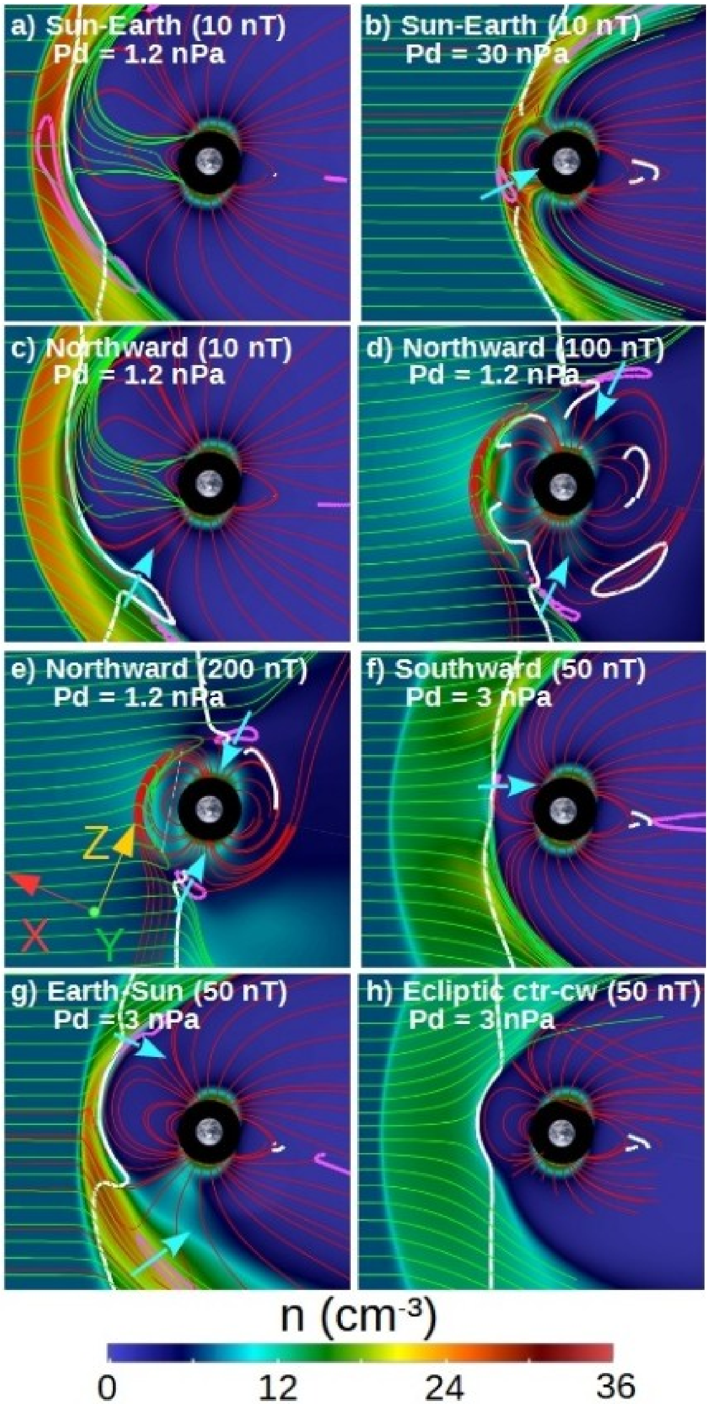


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the exoplanet magnetic field (red lines) and IMF (pink lines). The arrows indicate the orientation of the IMF (Northward orientation). Dashed white line shows the beginning of the simulation domain.

Numerical simulations of Sun-Earth magnetospheric interaction



Some results in the Sun-Earth simulations, where we can directly compare with measurements of the fields from orbiters.

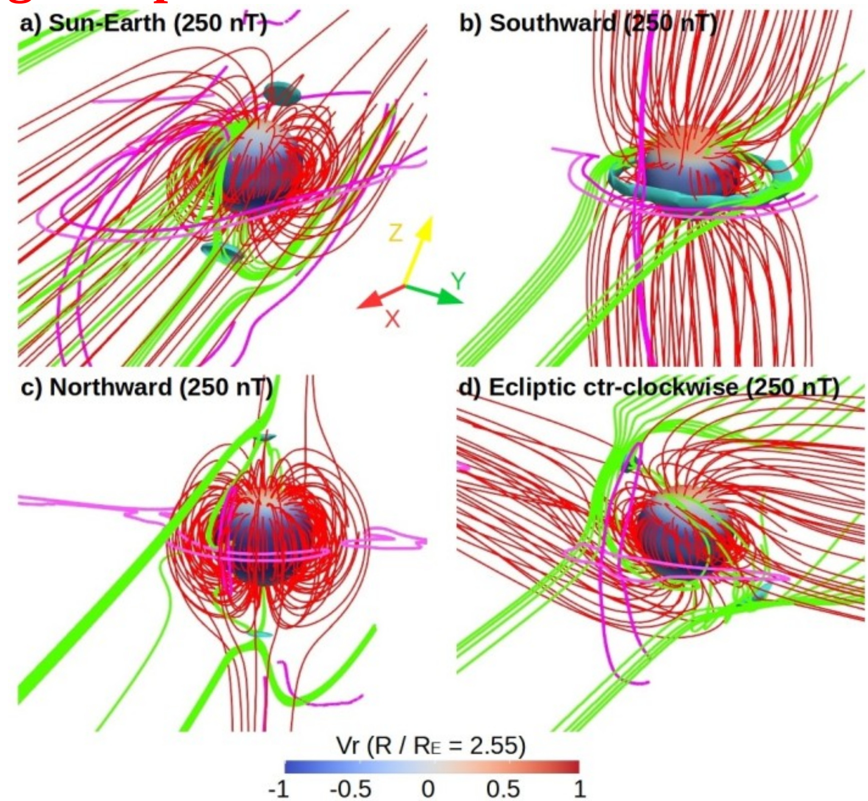
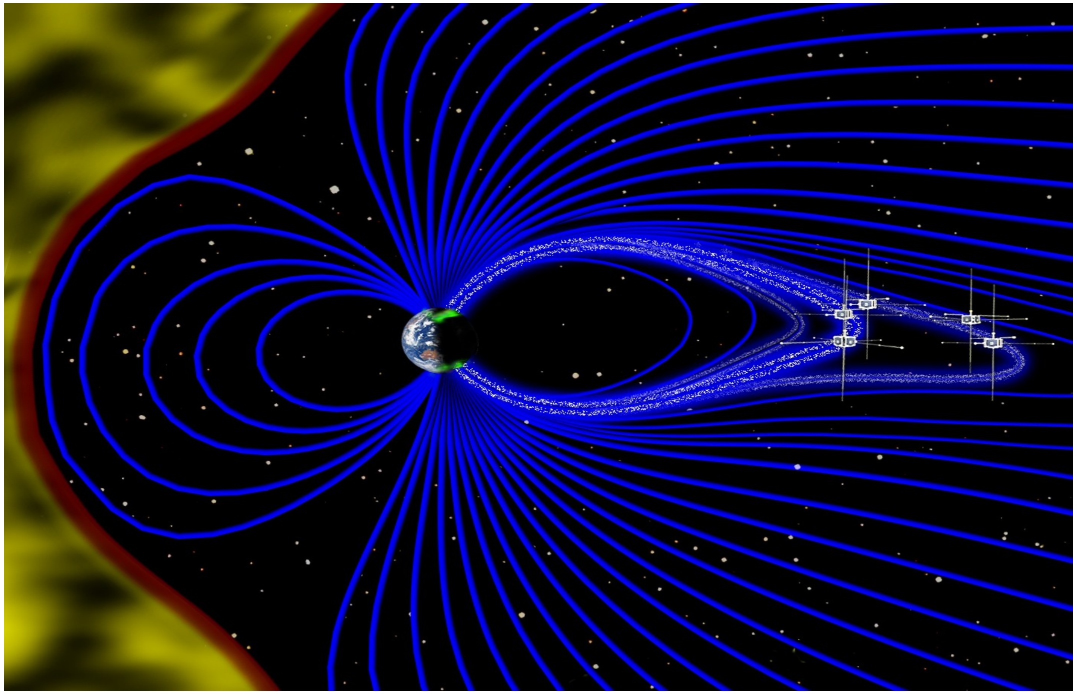
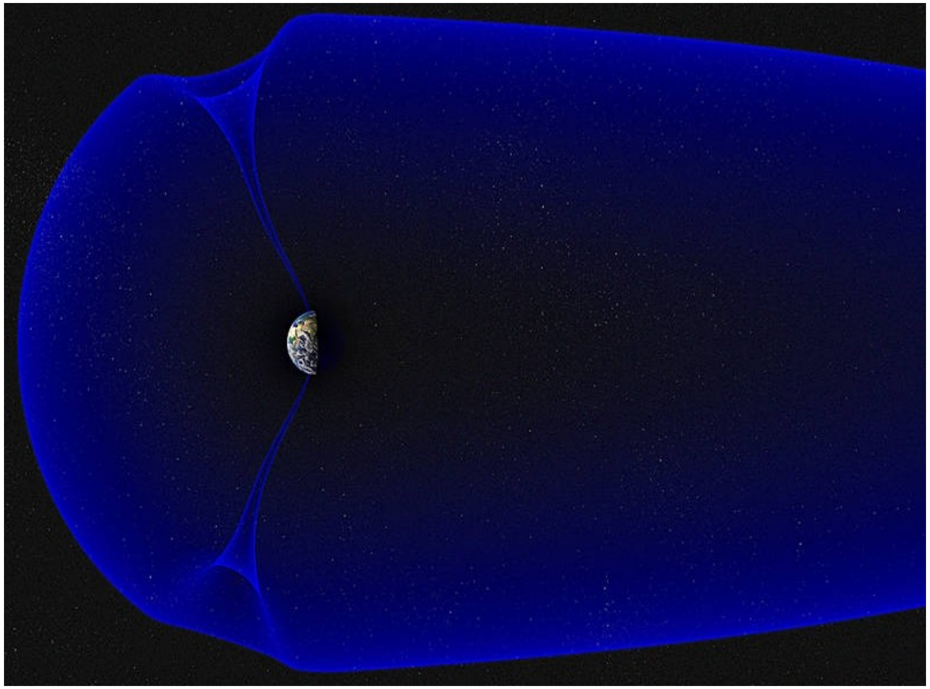


Fig. 3. 3D view of the Earth magnetosphere topology if $|B|_{\mathrm{IMF}} = 250\,\mathrm{nT}$ for (*a*) a Sun–Earth, (*b*) southward, (*c*) northward, and (*d*) ecliptic ctr-clockwise IMF orientations. We show the Earth magnetic field (red lines), SW stream functions (green lines), and isocontours of the plasma density for 6–9 cm^{-3}, indicating the location of the BS (pink lines). The cyan isocontours indicate the reconnection regions ($|B| = 60\,\mathrm{nT}$).

Fig. 2. Polar cut (*XY* plane) of the plasma density in simulations with (*a*) Sun–Earth IMF orientation $|B_{\mathrm{IMF}}| = 10\,\mathrm{nT}$ $P_{\mathrm{d}} = 1.2\,\mathrm{nPa}$, (*b*) Sun–Earth IMF orientation $|B_{\mathrm{IMF}}| = 10\,\mathrm{nT}$ $P_{\mathrm{d}} = 30\,\mathrm{nPa}$, (*c*) northward IMF orientation $|B_{\mathrm{IMF}}| = 10\,\mathrm{nT}$ $P_{\mathrm{d}} = 1.2\,\mathrm{nPa}$, (*d*) northward IMF orientation $|B_{\mathrm{IMF}}| = 100\,\mathrm{nT}$ $P_{\mathrm{d}} = 1.2\,\mathrm{nPa}$, (*e*) northward IMF orientation $|B_{\mathrm{IMF}}| = 200\,\mathrm{nT}$ $P_{\mathrm{d}} = 1.2\,\mathrm{nPa}$, (*f*) southward IMF orientation $|B_{\mathrm{IMF}}| = 50\,\mathrm{nT}$ $P_{\mathrm{d}} = 3\,\mathrm{nPa}$, (*g*) Earth–Sun IMF orientation $|B_{\mathrm{IMF}}| = 50\,\mathrm{nT}$ $P_{\mathrm{d}} = 3\,\mathrm{nPa}$, and (*h*) ecliptic ctr-cw IMF orientation $|B_{\mathrm{IMF}}| = 50\,\mathrm{nT}$ $P_{\mathrm{d}} = 3\,\mathrm{nPa}$. Earth magnetic field (red lines), SW stream functions (green lines), $|B| = 10\,\mathrm{nT}$ isocontour of the magnetic field (pink lines), and $v_{\mathrm{r}} = 0$ isocontours (white lines). The bold cyan arrows show the regions in which the plasma is injected into the inner magnetosphere.

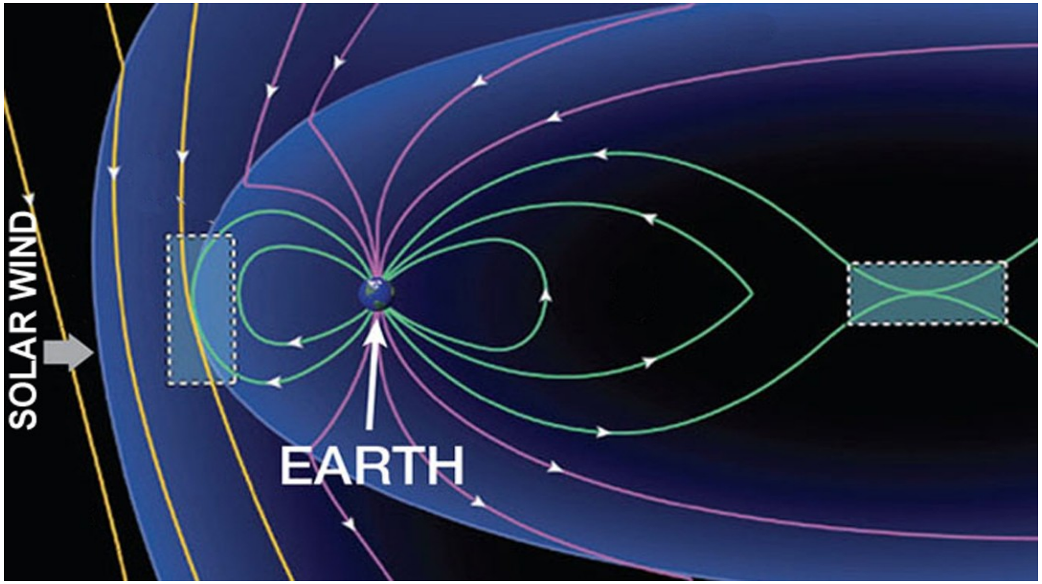
Cosmic probes of Earth magnetosphere



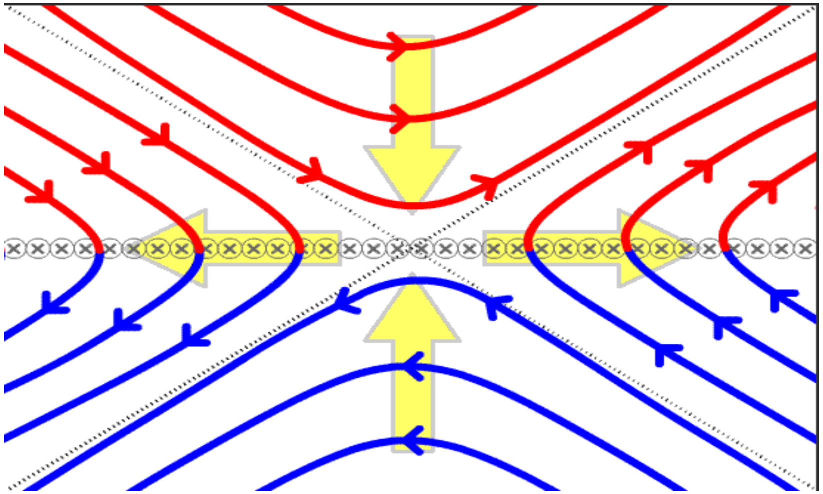


Magnetospheric regions from which gases from magnetosphere can escape.

Credits: Andøya Space Center/Trond Abrahamsen.



Location of THEMIS probes, for measuring mechanism of reconnection in Earth magnetosphere.



Numerical simulations of Sun-Mercury interaction

Similar study was also done for Mercury, where we have a wealth of **data from Mariner 10** mission, which measured the dipole moment, and later **Messenger** mission, which provided more precise measurements for the multipolar representation.

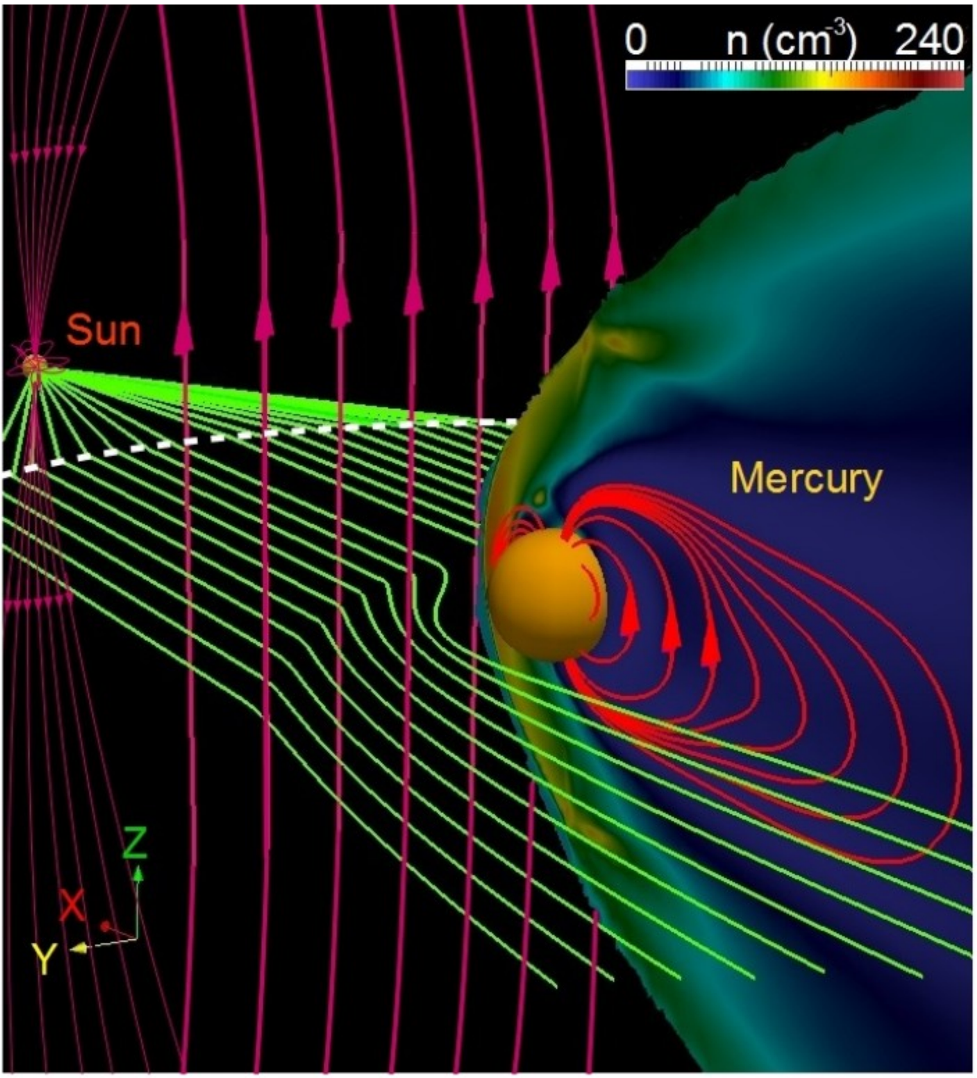
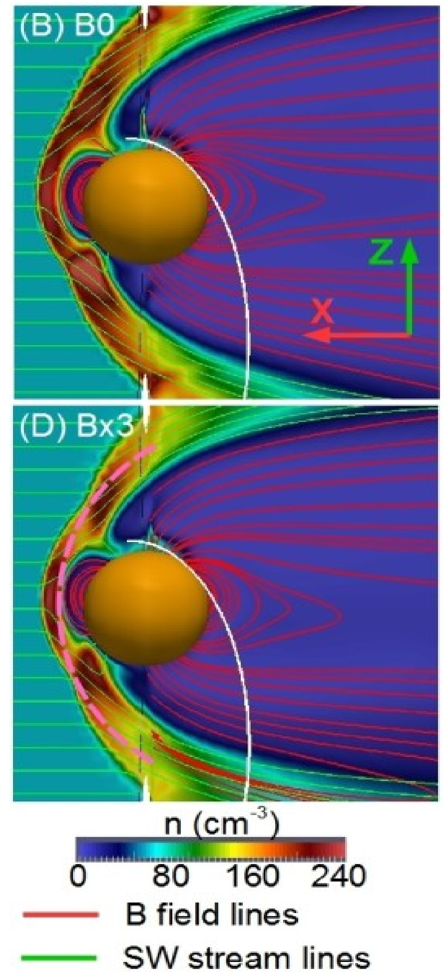
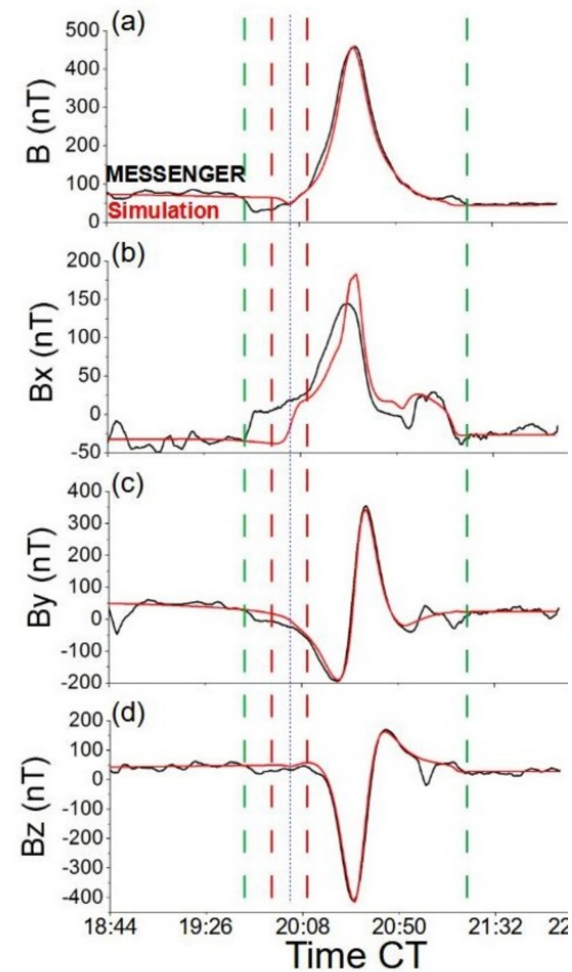


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the Hermean magnetic field (red lines), IMF (pink lines) and solar wind stream lines (green lines). The arrows indicate the orientation of the Hermean and interplanetary magnetic fields (case Bz). Dashed white line shows the beginning of the simulation domain.





Excellent matching of the MESSENGER magnetometer data vs. simulation magnetic field along satellite trajectory.

Planets around pulsars

•Exoplanets were long anticipated, but nobody expected it around a pulsar! **The first exoplanets** were found in orbit around a Galactic disk 6.2-ms pulsar PSR1257+12 (**Wolszczan & Frail, 1992**). *Actually, probably it is not so unexpected that a Polish scientist found it: In Demianski & Proszynski (1979) was discussed such a possibility for a planet around PSR B0329+54, 3 460 ly away in Camelopardalis, period 0.71452 s, 5 million yrs old. Because of non-detection by others it was rejected, but as of today the possibility of a long period planet is still not refuted. (PSR=*"Pulsating Source of Radio")

• The first planet around a "normal" star was found only in 1995, in a decades long search by Mayor & Queloz (not a chance discovery as Wolszczan's) and was awarded with a Nobel prize in 2019. It was the first "hot Jupiter", a large gaseous planet (named in NameExoWorlds as Dimidium="half" in Latin, because of half Jupiter mass) with a surprising period of 4.2 days, orbiting very closely the star 51 Pegasi.

•The precise timing is essential: this pulsar rotates about 161 times per second, period $P = 6.219 \times 10^{-3}$ s and a period derivative of $\dot{P} = 1.2 \times 10^{-19}$. In a standard magnetic dipole spindown model $B = 3 \times 10^{19} (P\dot{P})^{1/2}$ G $\approx 8.8 \times 10^{8}$ G and a characteristic age $\tau = P/(2\dot{P}) = 8 \times 10^{8}$ yrs. It is the fastest moving pulsar, with transverse velocity 326km/s and its surface is hot, 29 000 K, 2300 ly (710 pc) from us, in the constellation Virgo. Planets A,B,C masses 0.02 (2 M_{Moon}), 4.3 and 3.9 Earth masses, at 0.19, 0.36 and 0.46 AU from pulsar, in almost circular orbits at inclinations 50, 53, 47 degrees, periods of 25.3, 66.6 and 98 days. *Interesting implication: Scherer et al. (1997) pointed out that A planet's orbital period is close to the solar rotation period at the 17deg solar latitude of PSR 1257+12, and suggested it could be due to the electron density modulation of the solar wind in that direction. But, such an effect was not observed in other millisecond pulsars, and also the oscillation amplitude does not depend on the radio frequency as expected for a plasma effect (Wolszczan et al. 2000b), so it is rather still a planet.* The fourth possible planet in this system (Wolszczan 1996) was later dismissed (Wolszczan et al. **2000**a). **Remember the dates of publications for the artistic part of the story!**

•In 2015, in NameExoWorlds campaign, pulsar, which is an undead star, got the name of a Lich, undead character from fantasy fiction, known for controlling other undead creatures with magic. Planets are named Draugr, Poltergeist and Phobetor for planets A, B and C, respectively, by Norse mythology undead, noisy ghosts of supernatural world, and a character from Ovid's Metamorphoses (one of the thousand sons of Somnus=Sleep who appears in dreams in the form of beasts).

Formation of planets around pulsars

Pulsars are formed when an old star uses all the fuel. It first implodes, then explodes, and finally settles into the neutron star. Very violent processes, not only for star, but also its environment. This was the reason nobody really expected planets around pulsars.

• The formation mechanisms of planets around pulsars can be divided into presupernova and postsupernova scenarios:

-**Presupernova** scenario includes formation of planets around an ordinary star and either surviving the evolution (and a series of catastrophic events along it) or being captured by a NS.

• In **postsupernova** cases, planets are either formed from the material around newly formed NS (the **second generation planets**), or they are the last stage in the formation of some binary millisecond pulsars.

•For the rocky planets at circular orbits, a good possibility are mergers like WD+WD or WD+NS, or the remnant disk of the material from a Be star forming a binary with a NS. The first planets of Wolszczan best match the WD-WD merger scenario, so that planets are formed out of the debris of a merged companion star that used to orbit the pulsar when it was a white dwarf.

•Planets around pulsars seem to be rare, there are only few cases in about 3000 pulsars, all found by pulsar timing variations. Of more than 5000 currently known exoplanets, less than 10 around pulsars are confirmed

Almost complete list of planets around pulsars

-(1993) PSR B1620−26 A + WD with one exoplanet (2.5+/- 1 M_Jupiter, orbiting them at 23 AU, period 36500 days~10 yrs, found from Doppler shifts it induced on the orbits of stars). It is in Scorpius, at a distance 12.4ly away, just outside the core of the globular cluster M4 which is 12.2 bln years old. Stars are hot: <30 000 K and <25 200 K. It is most probably a captured planet.

-(2006) 4U 0142+61, a magnetar (supernova about 100 000 yrs ago, 0.63 solar luminosities, rotates with 8.7s period) in Cassiopeia, at 13 000 ly from us, debris disk detected, at 1.6 mln km from the star, contains about 10 Earth masses of material, mostly heavier metals.

-(2011) The "diamond-planet" system PSR J1719–1438 is a millisecond pulsar surrounded by a Jupiter-mass companion ay least 23 times denser than water, thought to have formed via ablation (evaporation) of its donor star. It is a 27 000km radius 10^31 carats diamond crystal core remaining from the evaporated white dwarf, at 600 000 km from the star, has 2hr10' rotation period. – of the similar kind is a Black Widow pulsar PSR B1957+20 (1988) in Sagitta constellation, with a period of 1.6ms and large mass, 1.6-2.4 M_Sun. It has a ~M_Jupiter companion, probably a brown dwarf, orbiting it with a period of 9.2hrs, making a 20min eclipses, through which the object was found.

-(1968 pulsar, 2013 asteroid?) PSR J0738−4042, encounter with an asteroid or in-falling debris from a disk. It is a bright, radio-emitting neutron star at a distance 37 000 ly in constellation Puppis, with rotational properties similar to the main population of middle aged, isolated, radio pulsars, P and Pdot 0.267 1/s (375ms) and -1/15e^-14 1/s^2, collected 24 yrs of data, so one can check the timing in detail.

-(1968 Puschino pulsar, 2014 planets) PSR B0943+10 is an 5mln years old pulsar in Leo, 2 000 ly away, with period 1.1s. Two gas giant planets,masses 2.8 and 2.6M_Jup with 730 and 1460 days orbital period, 1/8 and 2.9 AU radius orbits, respectively. There are more tentative objects with planets of Jupiter mass, like low luminosity (2017) PSR J2322−2650, with planet of 0.8M_Jup in the orbit with 0.32d at 0.01 AU; (2022) PSR J2007-3120 with a 0.008 M_J planet with 723d period; (2020, FAST) confirmed in globular cluster M13, PSR J1641+3627F, 3ms pulsar with a 0.16M_Sun mass companion, probably a WD, not a planet; the binary millisecond pulsar (2021, FAST) PSR J1641+3627E (also M13E) is a black widow with a companion mass around 19.42 M_J, 0.11d period; (2013) PSR J1544+493 eclipsing black widow 2.16 ms pulsar with a close companion of 18M_Jup at 2.19h orbit; (2016) PSR J0636+5129 with a 8M_J companion in 96min orbit; (1996, 2001?) PSR J2051−0827, 28.3M_Jup at 0.1d period orbit, (2000) PSR J1807-2459, 9.4M_J, 0.07days period.

Our initial work emerged from a direct analogy. We worked in a non-relativistic regime, Newtonian mechanics, using the PLUTO code:

6.2 The MHD Module

The MHD module is suitable for the solution of ideal or resistive (non-relativistic) magnetohydrodynamical equations. Source and definition files are located inside the Src/MHD directory.

With the MHD module, **PLUTO** solves the following system of conservation laws:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} &+ \nabla \cdot (\rho \boldsymbol{v}) &= 0 \\
\frac{\partial \boldsymbol{m}}{\partial t} &+ \nabla \cdot \left[\boldsymbol{m}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{I}\left(p + \frac{\boldsymbol{B}^2}{2}\right)\right]^T &= -\rho\nabla\Phi + \rho\boldsymbol{g} \\
\frac{\partial \boldsymbol{B}}{\partial t} &+ \nabla \times (c\boldsymbol{E}) &= 0 \\
\frac{\partial (E_t + \rho\Phi)}{\partial t} &+ \nabla \cdot \left[\left(\frac{\rho \boldsymbol{v}^2}{2} + \rho e + p + \rho\Phi\right)\boldsymbol{v} + c\boldsymbol{E} \times \boldsymbol{B}\right] &= \boldsymbol{m} \cdot \boldsymbol{g}
\end{aligned} \tag{6.4}$$

where ρ is the mass density, $\boldsymbol{m} = \rho\boldsymbol{v}$ is the momentum density, $\boldsymbol{v}$ is the velocity, p is the gas (thermal) pressure, $\boldsymbol{B}$ is the magnetic field[2] and E_t is the total energy density:

$$E_t = \rho e + \frac{\boldsymbol{m}^2}{2\rho} + \frac{\boldsymbol{B}^2}{2} \, . \tag{6.5}$$

where an additional equation of state provides the closure $\rho e = \rho e(p, \rho)$ (see Chapter 7). The source term on the right includes contributions from body forces and is written in terms of the (time-independent) gravitational potential Φ and and the acceleration vector $\boldsymbol{g}$ (see §5.4).

In the third of Eq. (6.4), $\boldsymbol{E}$ is the electric field defined by the expression

$$c\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \frac{\eta}{c} \cdot \boldsymbol{J} + \frac{\boldsymbol{J}}{ne} \times \boldsymbol{B} \qquad \left(\boldsymbol{J} = c\nabla \times \boldsymbol{B}\right) \tag{6.6}$$

where the first term is the convective term, the second term is the resistive term (η denotes the resistivity tensor, see §8.2) while the third term is the Hall term (§8.1). Note that the speed of light c never enters

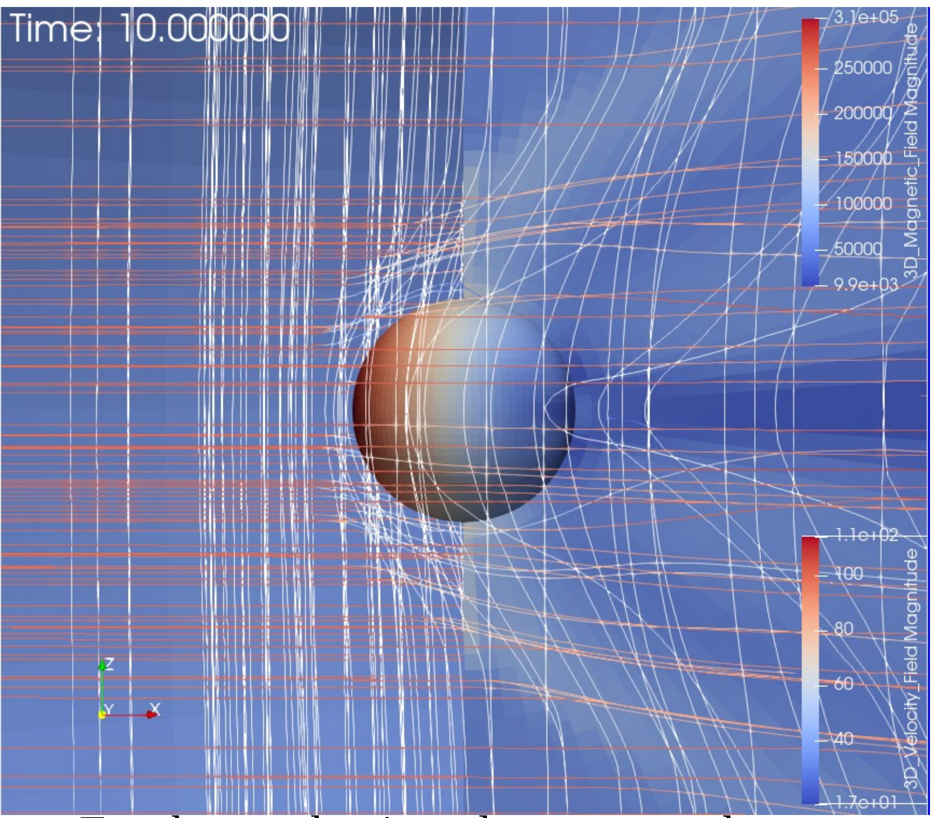
Numerical simulations – conducting planet

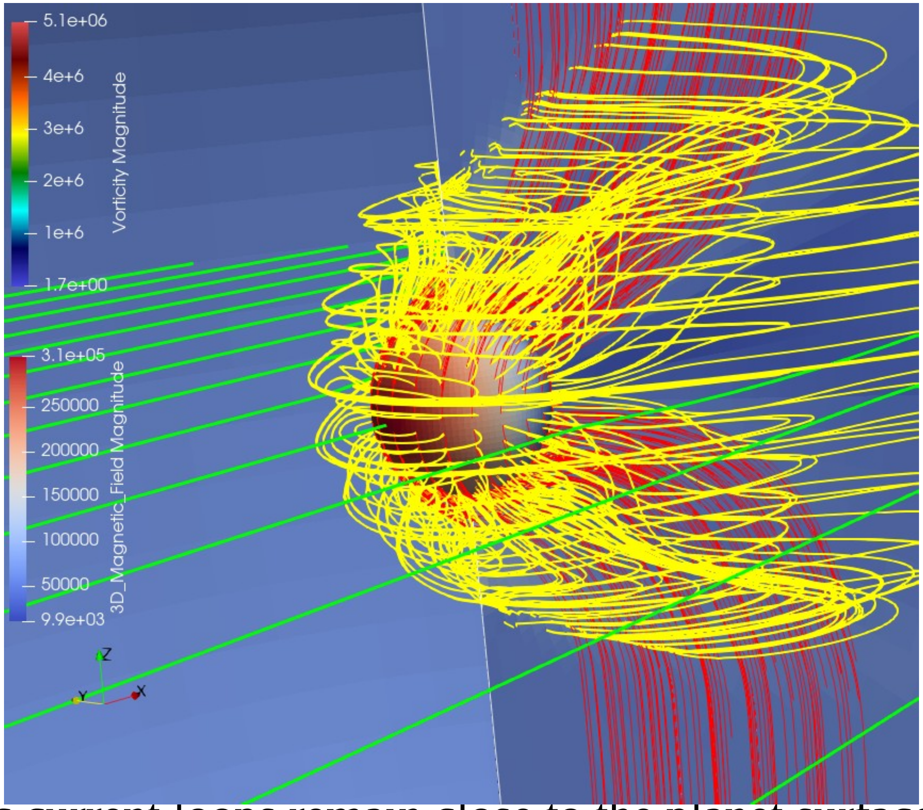
In the pulsar planet case, we considered rocky planets, as in Wolszczan's system, and assumed that they are not magnetized, or are negligibly magnetized, in comparison to the large magnetic field induced by the field carried in by the pulsar wind. Two simplest cases of the planetary surfaces are conductive and ferromagnetic. Simulations setups are different only in a conditions for magnetic field components at the planetary surface.

Conducting planet surface:

Bsw=3.0, Vsw=1.e9

Currents (yellow), Vsw(green), mag.field (red)



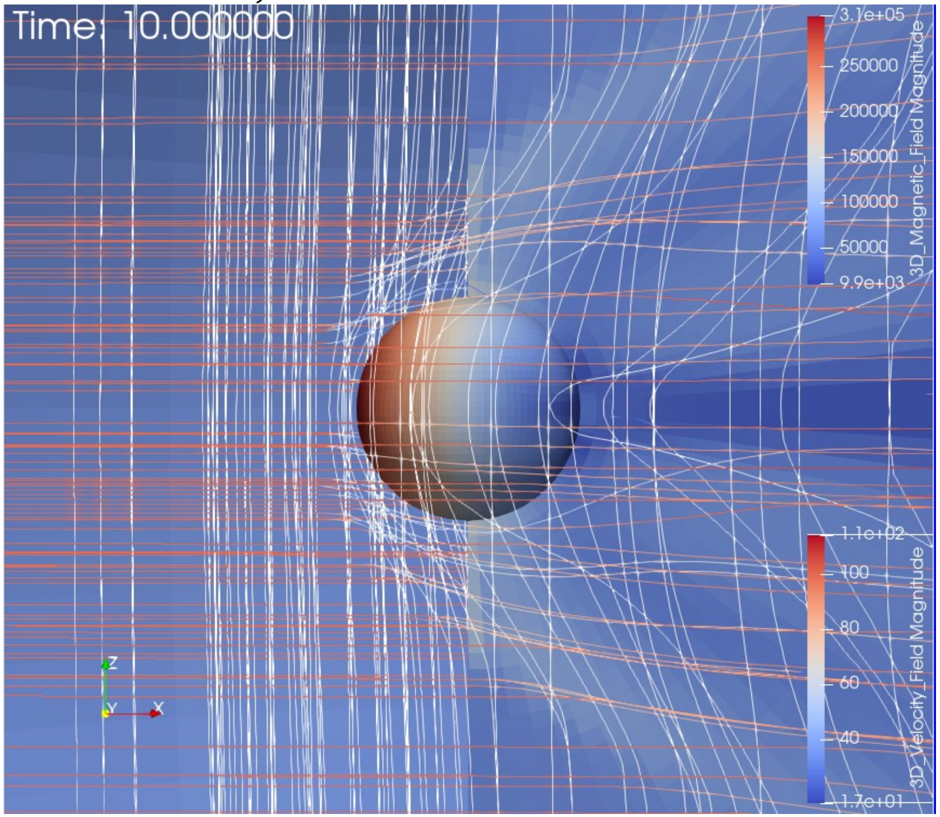


For the conducting planet atmosphere case, electric current loops remain close to the planet surface.

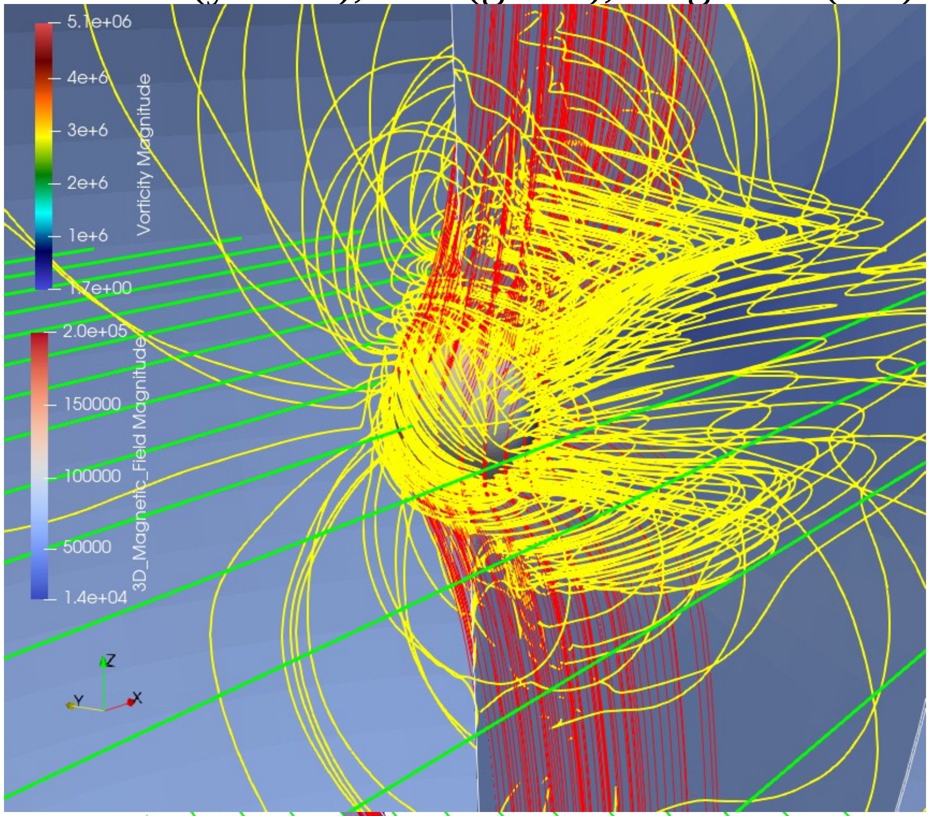
Numerical simulations – ferromagnetic planet

In the case of feromagnetic planet surface, results are different, currents point to an extended dipolar *electric field* structure.

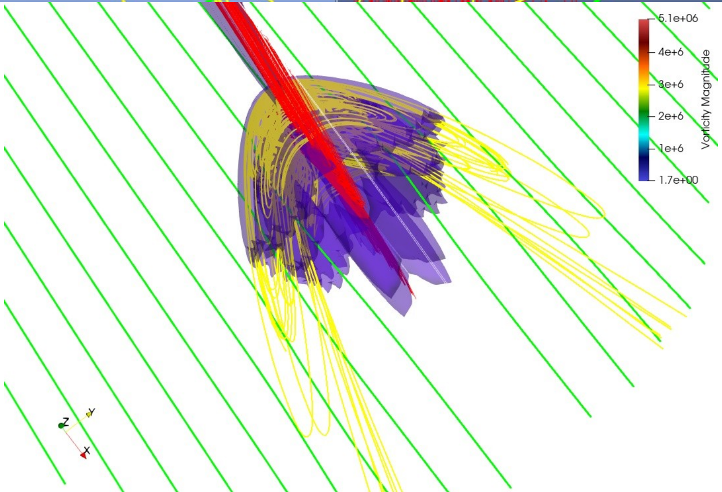
Bsw=3.0, Vsw=1.e9



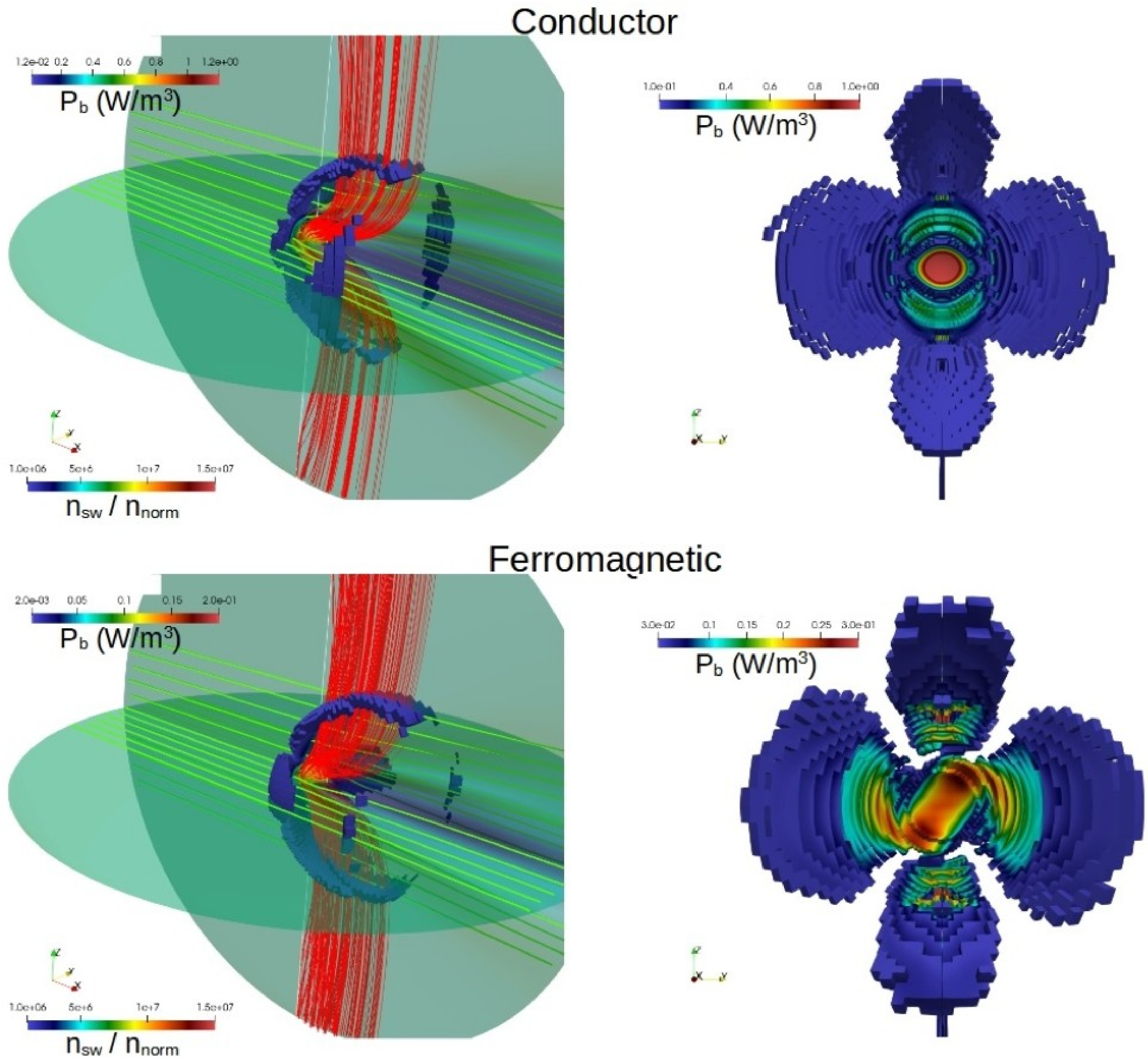
Currents (yellow), Vsw(green), mag.field (red)



Equatorial view-Alfven “wings”:



Radio emission patterns from non-magnetic planets



Left panels: Iso-volume of Poynting flux divergence in cases with non-magnetic planet. Red lines are the magnetic field lines and green lines are the velocity streamlines of stellar wind. *Right panels:* Mag. power in the same cases. A surface with the maximum radiated power is located in the nose of the bow shock, because of bending and compression of inter-planetary magnetic field.

- El.mag. emission is 100 million times more intense than in the Sun-Earth case.
- We suggest that it could be observable even with the current instruments.

Table 1. Parameters used in PLUTO setup file `pluto.ini` in our simulations for pulsar-planet setups with conductive and ferromagnetic planetary surfaces in comparison to Sun-Earth (CME) and Sun-Earth and Sun-Mercury (quiet) conditions. SW (Speed, MagField, Dens, and Temp) are setting the related initial values–in the Pulsar-planet case, SW corresponds to pulsar wind. PlanTemp sets the planetary temperature, and the Alfvén speed is limited by the AlfSpeedLimit. The radii R_{in} and $R_{sw,cut}$ set the inner boundary of the system and the radial position of the nose of the bow shock at the beginning of the simulation, respectively. The density floor is controlled by `dens_min`=0.01× `SWDens`.

Set-up	SWSpeed (cm s^{-1})	SWMagField (G)	SWDens (g cm^{-3})	SWTemp (K)	PlanTemp (K)	AlfSpeedLimit (cm s^{-1})	R_{in} (R_{NS})	$R_{sw,cut}$ (R_{NS})
Pulsar-planet	1.0×10^9	3	1.0×10^{-17}	2.0×10^5	1.0×10^4	1.0×10^9	1.0	1.0
Sun-Earth (CME)	1.0×10^8	1.0×10^{-3}	3.0×10^{-23}	1.0×10^5	1.0×10^3	5.0×10^8	3.0	6.0
Sun-Earth (quiet)	3.5×10^7	5.0×10^{-5}	6.0×10^{-24}	4.0×10^4	1.0×10^3	5.0×10^8	3.0	6.0
Sun-Mercury (quiet)	5.0×10^7	1.5×10^{-4}	2.0×10^{-23}	8.0×10^4	2.0×10^3	1.0×10^8	1.0	3.0

We increase the stellar magnetic field in the simulations-to accommodate for the large field we increase the density of the interplanetary medium, local magnetic field strength near the planet and stellar wind velocity. We probe for the different planetary surface boundary conditions (conducting or ferromagnetic) - this is potentially interesting for the planetary study: planets around NS could have some extreme physical properties, especially the second-generation planets, which could form around pulsars.

Intensity of radio emission

LOFAR was able to detect low-frequency radio waves that were predicted from a M-type dwarf GJ 1151 (or a planet around it) which is located 25 light-years from Earth (Vedantham et al. 2020). This was, tentatively, the first signal detected from an extrasolar aurora.

What are the numbers for Wolszczan's pulsar? The only case of star-planet interaction without non-thermal radio emission arises when both the planet and stellar wind are non-magnetized. In all the other cases, even without intrinsic planetary magnetic field, there can arise intense radio emission. Based on the observations of magnetized planets in the Solar system, the empirical Radiometric Bode's law (RBL) is employed to estimate the intensity of radio emission, with the emission roughly proportional to the power from the stellar wind:

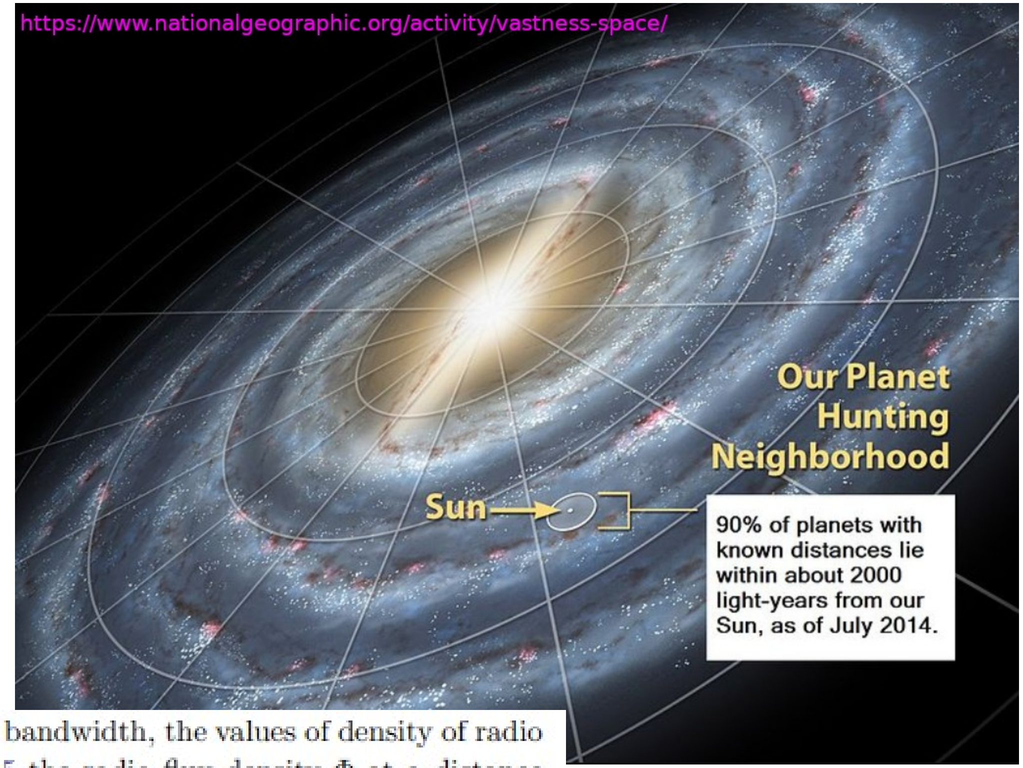
$$\nu_{min} = \sqrt{\frac{ne^2}{\pi m_e}} \sim 8.98 \text{ kHz}\sqrt{n}, \ \nu_{max} = \frac{eB_{sw}}{2\pi m_e} \sim 2.8 \text{ MHz} B_{sw},$$

$$\Phi = \frac{P_{rad}}{\Omega d^2 \Delta\nu},$$

Observational challenge

Most of the exoplanets we found until now are less than 2000 ly from us. Wolszczan's pulsar is about 750pc away, about 2300 ly from us, and there are many pulsars at about 250pc from us, among which some could have planets.

We computed the radio emission from such planets, what is the amount of it reaching us, could we observe it? LOFAR, MeerKAT, and the future SKA have minimal sensitivities of the order of 0.1, 0.01 and 0.001 mJy, respectively. Our preliminary results:



For the given integrated radio emission, distance of the planet and emission bandwidth, the values of density of radio flux for the pulsar-planet in the case with conductive planet, from the Eq. 5 the radio flux density Φ at a distance 700 pc, is given by

$$\Phi = \frac{1.9 \times 10^{18}}{1.6 \times (700 \times 3.1 \times 10^{16})^2 \times 5 \times 10^8} \times 10^{26} Jy = 0.5\ mJy, \tag{7}$$

and similarly, for the pulsar-planet in a ferromagnetic case $\Phi = 1.1$ mJy.

Set-up	$\Phi(700)$ (mJy)	$\Phi(250)$ (mJy)	P_{radio} (W)	$B_{p,max}$ (G)
Pulsar-planet (conductive)	0.5	4	1.9×10^{18}	3
Pulsar-planet (ferromagnetic)	1.1	9	4.3×10^{18}	3

Previous works on the topic

-Referee informed us that Mottez & Heyvaerts (2011a,b) worked on planets around pulsars in the context of theory of electromagnetic interaction of stars and planets or small bodies. They extended the theory of Alfven wings to relativistic winds. Mostly-in fact all 15-citations from FRB community. There will probably be a larger following in the second generation planets formation framework, which is still building-up.

-In the Abstract of that A&A paper they wrote:” For an Earth-like planet around a “standard” second pulsar, the associated current can reach the same magnitude as the Goldreich-Julian current that powers the pulsar’s magnetosphere.” The energy which is released in the vicinity of the smaller body affects its orbit-for the objects of 100km diameter and below, the orbit could change significantly on the timescale of millions of years to 10 000 years, respectively.

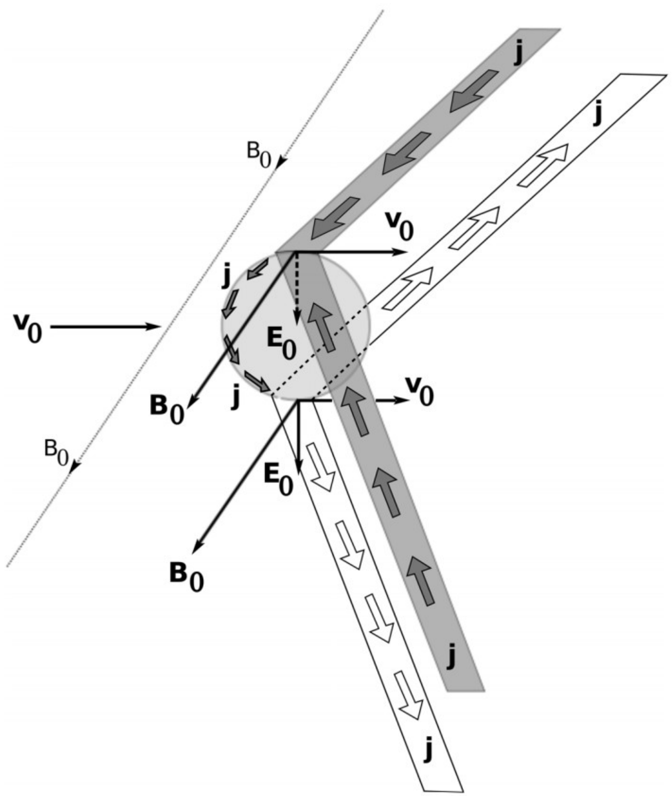


Fig. 1. Schematic view of a unipolar inductor.

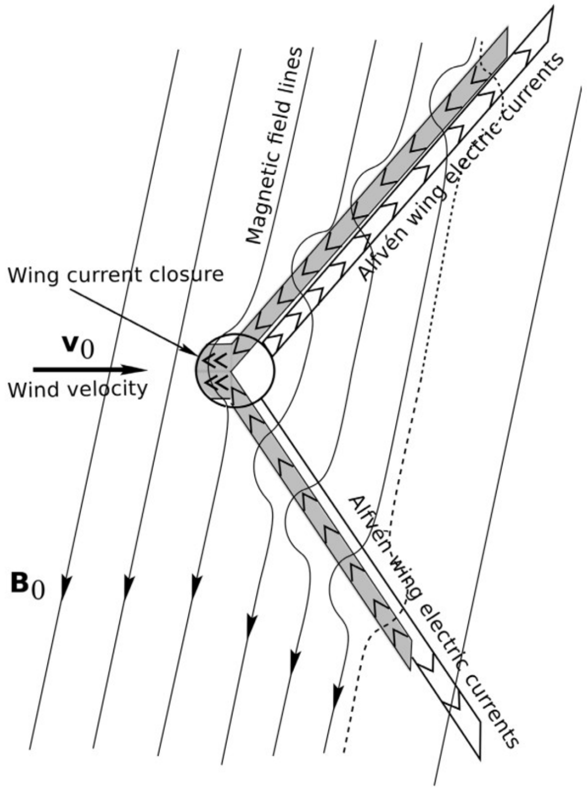


Fig. 2. Alfvénic wake of the planet seen from above the equatorial plane.

Previous works on the topic

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Feasibility and benefits of pulsar planet characterization

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Abstract

Planet orbiting neutron stars seem to be rare, but all the more interesting for science due to their origins. Characterizing the composition of pulsar planets could elucidate processes involved in supernova fallback disks, accretion of companion star material, potential survival of planetary cores in the post-MS phase of their stars, and more. However, the small size and unusual spectral distribution of neutron stars (NS) make any spectroscopic measurements very difficult if not impossible in the near future. In this work, we set to estimate the feasibility of spectroscopy of planets orbiting specifically pulsars, and to review other possible methods of characterization of the planets, such as emissions caused by aurorae.

circumstellar disk of the magnetar 4U 0142+61 [9], and a tentative asteroid belt around the millisecond pulsar B1937+21 [7]. PSR B1620-26 b is a circumbinary planet orbiting a pulsar and a white dwarf, and likely formed around the white dwarf precursor, with its system later captured by the pulsar, giving rise to a binary, while the pulsar's original stellar companion was ejected [8]. In a globular cluster with high star density, where this system is present, such an event is more likely than in the galactic disk. Finally, the PSR J1719-1438 system contains most likely a remnant of a disrupted WD companion that narrowly avoided its complete destruction, based on its minimum density [1].

These three known systems represent three of the possible means of origin of pulsar planets. Formation in disks from WD-NS mergers as opposed to

PLUTO (Special) Relativistic MHD equations

For more than the initial study, we need to include the fact that the pulsar wind is relativistic-so we used the relativistic module of the PLUTO code:

6.4 The RMHD Module

The RMHD module implements the equations of (ideal) special relativistic magnetohydrodynamics in 1, 2 or 3 dimensions. Velocities are always assumed to be expressed in units of the speed of light. Source and definition files are located inside the Src/RMHD directory.

The RMHD module solves the following system of conservation laws:

$$\frac{\partial}{\partial t}\left(\begin{array}{c} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{array}\right) + \nabla\cdot\left(\begin{array}{c} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{v}\boldsymbol{v} - \boldsymbol{b}\boldsymbol{b} + \mathsf{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{array}\right)^T = \left(\begin{array}{c} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \\ \boldsymbol{0} \end{array}\right) \tag{6.13}$$

where D is the laboratory density, $\boldsymbol{m}$ is the momentum density, E is the total energy (including contribution from the rest mass) while $\boldsymbol{f}_g$ is an acceleration term (see $\boxed{6.3}$).

Primitive variables are similar to the RHD module but they also contain the magnetic field, $\boldsymbol{V} = (\rho, \boldsymbol{v}, p, \boldsymbol{B})$. The relation between $\boldsymbol{V}$ and $\boldsymbol{U}$ is

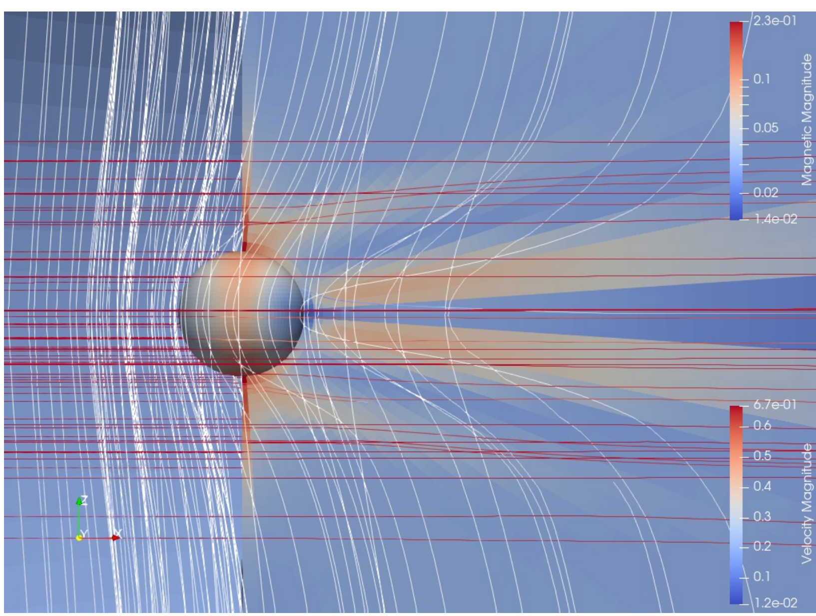
$$\begin{array}{rcl} D &=& \gamma\rho \\ \boldsymbol{m} &=& w_t\gamma^2\boldsymbol{v} - b^0\boldsymbol{b} \\ E_t &=& w_t\gamma^2 - b^0b^0 - p_t \end{array} \quad , \quad \left\{\begin{array}{rcl} b^0 &=& \gamma\boldsymbol{v}\cdot\boldsymbol{B} \\ \boldsymbol{b} &=& \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v} \\ w_t &=& \rho h + \boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2 \\ p_t &=& p + \dfrac{\boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2}{2} \end{array}\right.$$

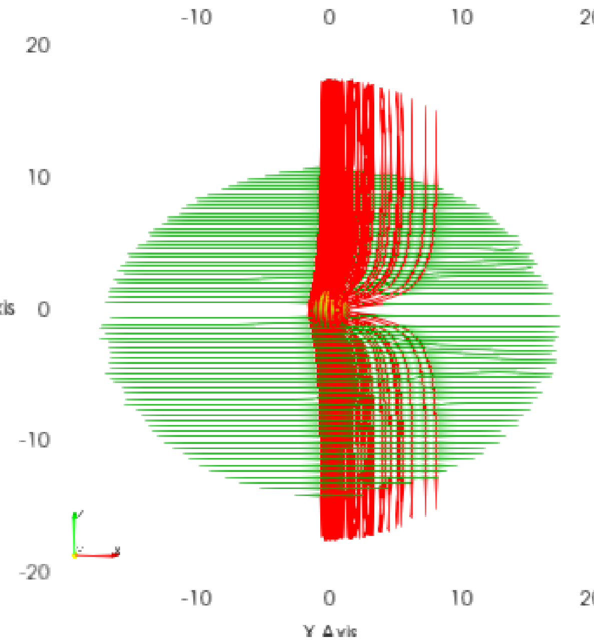
Results with the (Special) Relativistic PLUTO

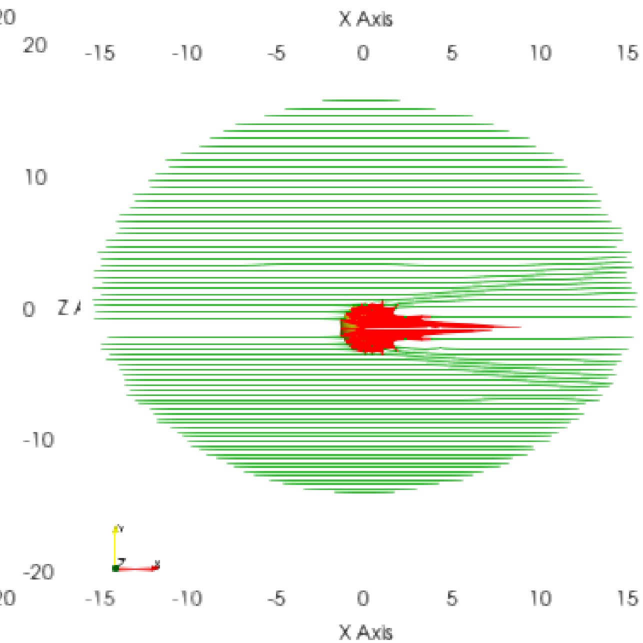
While the numbers change, results appear similar. In the case with a main sequence star case, the flow carried protons, and in the pulsar wind, the flow is electron-positron plasma. Both the Alfven speed and pulsar wind are close to the speed of light, which defines the time scales.

Table 1. Parameters used in PLUTO setup file `pluto.ini` in our simulations for pulsar-planet setups with conductive and ferromagnetic planetary surfaces in comparison to Sun-Earth (CME) and Sun-Earth and Sun-Mercury (quiet) conditions. SW (Speed, MagField, Dens, and Temp) are setting the related initial values–in the Pulsar-planet case, SW corresponds to stellar or pulsar wind. PlanTemp sets the planetary temperature, and the Alfvén speed is limited by the AlfSpeedLimit. The radii R_{in} and $R_{sw,cut}$ set the inner boundary of the system and the radial position of the nose of the bow shock at the beginning of the simulation, respectively. The density floor is controlled by `dens_min`$=0.01\times$ `SWDens`.

Set-up	SWSpeed (cm s^{-1})	SWMagField (G)	SWDens (g cm^{-3})	SWTemp (K)	PlanTemp (K)	AlfSpeedLimit (cm s^{-1})	R_{in} (R_{NS})	$R_{sw,cut}$ (R_{NS})
Pulsar-planet (cond.)	2.6×10^{10}	2.5×10^{-3}	5.0×10^{-26}	5.0×10^{8}	-	-	1.0	-
Pulsar-planet (ferro)	2.6×10^{10}	1.0×10^{-2}	1.0×10^{-24}	5.0×10^{8}	-	-	1.0	-
Sun-Earth (CME)	1.0×10^{8}	1.0×10^{-3}	3.0×10^{-23}	1.0×10^{5}	1.0×10^{3}	5.0×10^{8}	3.0	6.0
Sun-Earth (quiet)	3.5×10^{7}	5.0×10^{-5}	6.0×10^{-24}	4.0×10^{4}	1.0×10^{3}	5.0×10^{8}	3.0	6.0
Sun-Mercury (quiet)	5.0×10^{7}	1.5×10^{-4}	2.0×10^{-23}	8.0×10^{4}	2.0×10^{3}	1.0×10^{8}	1.0	3.0



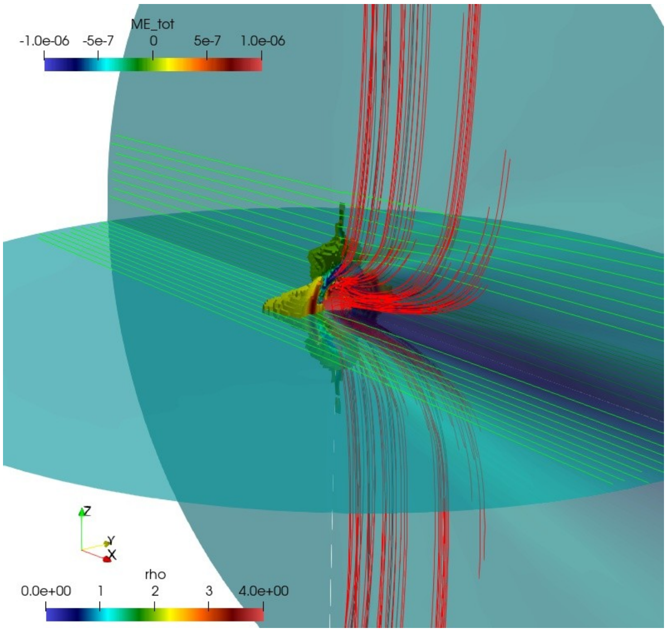


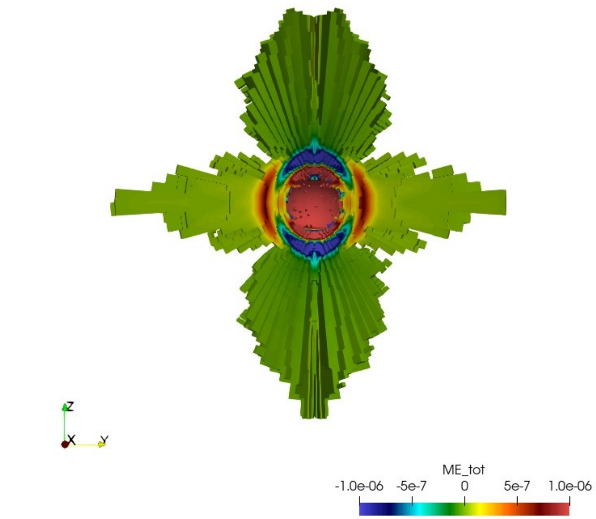


Results with the (Special) Relativistic PLUTO

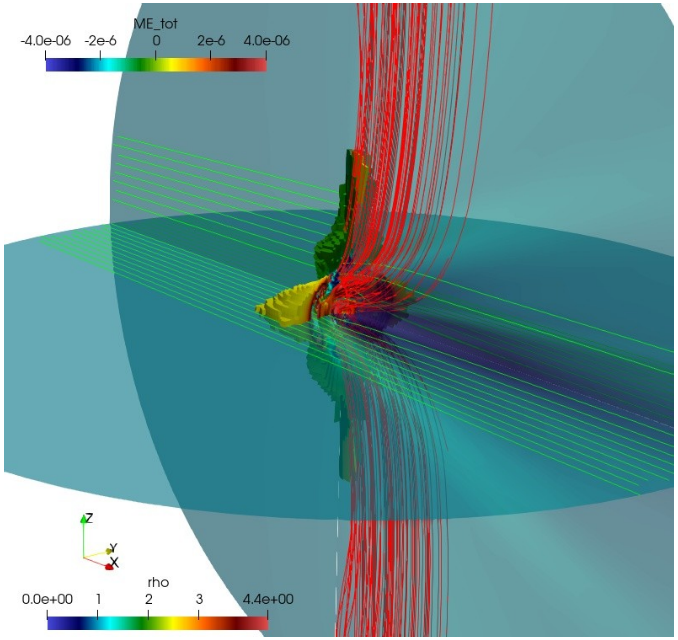
With the field as in the strong CME case in the IMF at the Earth distance, we obtain the emission powers 4.64e12 W and 5.37e13 W in the conductive and ferromagnetic cases, respectively. For a pulsar wind, the field should be probably for a few orders of magnitude stronger-the wind is faster but its density is smaller, and the normalization of the stellar wind field is ~V ρ½ .

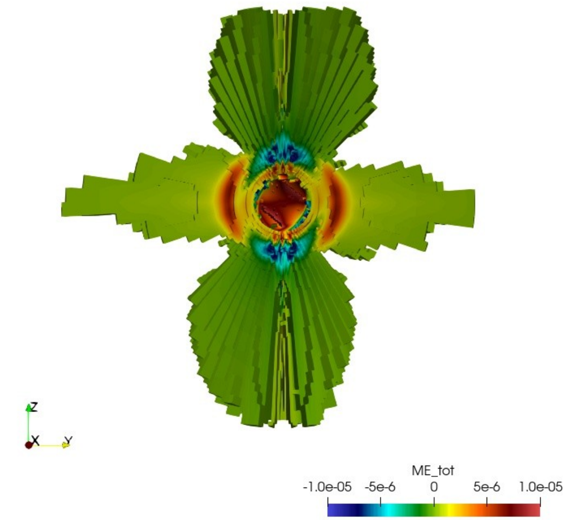
Conductive case:





Ferromagnetic case:





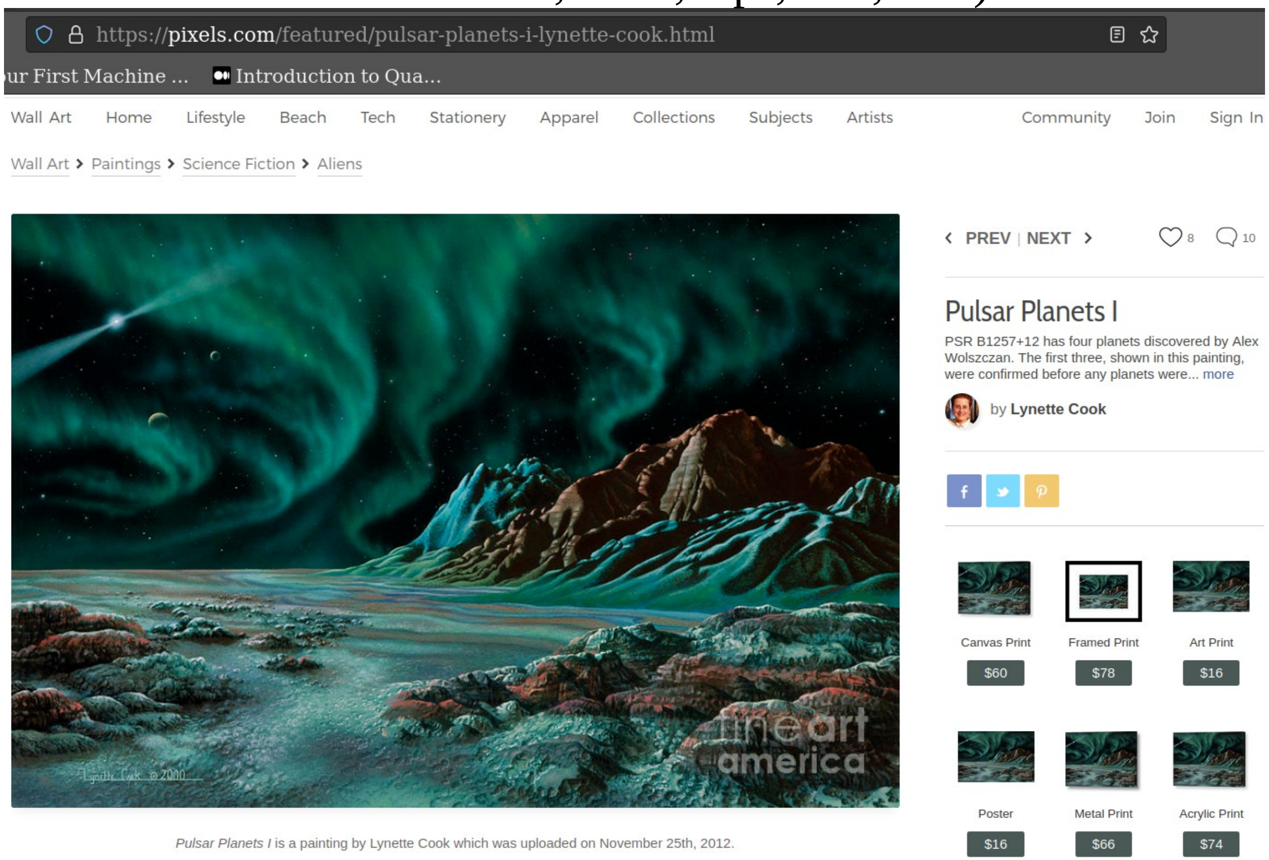
Results with the (Special) Relativistic PLUTO

Table 2. Predicted and tentative intensity of the radio emission flux Φ for an observer on Earth in our two simulations with non-magnetized pulsar planet with conducting and ferromagnetic planetary surfaces, at different distances (in parsecs) from us. In the last three columns we check if the predicted values are above the frequency limit *AND* sensitivity of the currently most sensitive instruments, LOFAR and MeerKAT, and the future SKA. We also estimate the tentative realistic results in each of the cases, which indicate that such objects could be observable today.

Set-up	$\Phi_a(750)$ (mJy)	$\Phi_b(250)$ (mJy)	$\Phi_c(100)$ (mJy)	P_{radio} (Wm^{-2})	B_{sw} (G)	$\Delta\nu$ MHz	LOFAR	MeerKAT	SKA
Pulsar-planet (cond.)	0.60	5.4	33.75	3.65×10^{12}	0.0025	0.007	NO	NO	NO
Tentative	>	>	>	>	7.4	20.1	YES	YES	YES
Pulsar-planet (ferrom.)	0.47	4.23	26.43	1.14×10^{13}	0.01	0.028	NO	NO	NO
Tentative	>	>	>	>	13	36.4	YES	YES	YES

Art preceding science

In the EAS 2023 meeting in Cracow in July 2023, where Ruchi Mishra, who worked with us on the article, had a poster with our results, I met Alex Wolszczan and asked him what he thinks of our idea. He listened carefully and commented: “I did not come to such an idea. Give numbers!” Exactly this is what we did in the paper, making a challenge to the observers. But there was an interesting twist to the story. Browsing for “pulsar planets aurora” for a content related to our already published paper (Mishra et al., “Auroras on Planets Around Pulsars”, 2023, ApJ, 959, L13) I was stunned to find the following picture:



What astonished me was not only the beautiful picture, but the posting date 2012. And, on closer inspection, an even earlier date on the picture, 2000! I already told you the timeline of the idea of such auroras, and this artist pictured it in 2000, with even the number of planets correct, 3, not 4!? I could not leave it like this, and contacted the artist, asking if she just made it by analogy with Earth? She answered that no, she asked Alex Wolszczan back in 1999 about the scientific plausibility of the painting, and he suggested her to add an aurora! So, it seems he did have an artistic idea of it, but it did not pass into the scientific work. Ours is the first where it is computed...almost a quarter of century after the painting!

Summary

- Auroras are present in almost all planets in the Solar system.
- We have a tool to simulate the star-planet magnetospheric interaction.
- Planets around pulsars are not very often, < 0.5%, with a variety of possible kinds of evolution. I give an overview for a better idea of current status.
- “Usual” rocky planets were the 1st to be observed. Their evolution could be quite normal.
- We try our tool for aurora on the pulsar planets… plus relativistic module of PLUTO.
- Radio emission from pulsar planets could be visible even with current instruments. Measuring the radio emission from pulsar planets would give us an additional window to study the pulsar wind.
- Artistic version of the results was public almost 25 years before the scientific discussion.