Aurore na planetima oko pulsara

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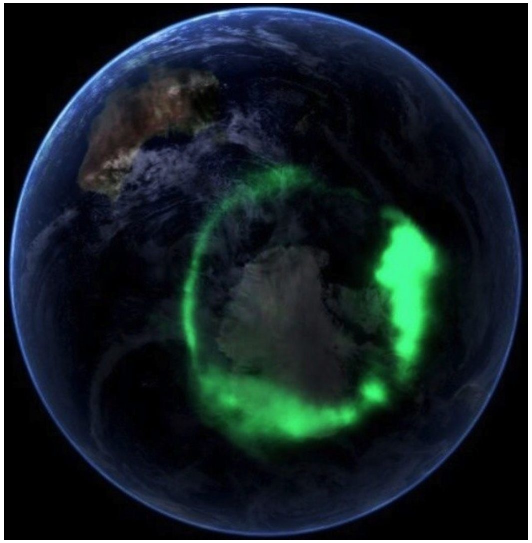
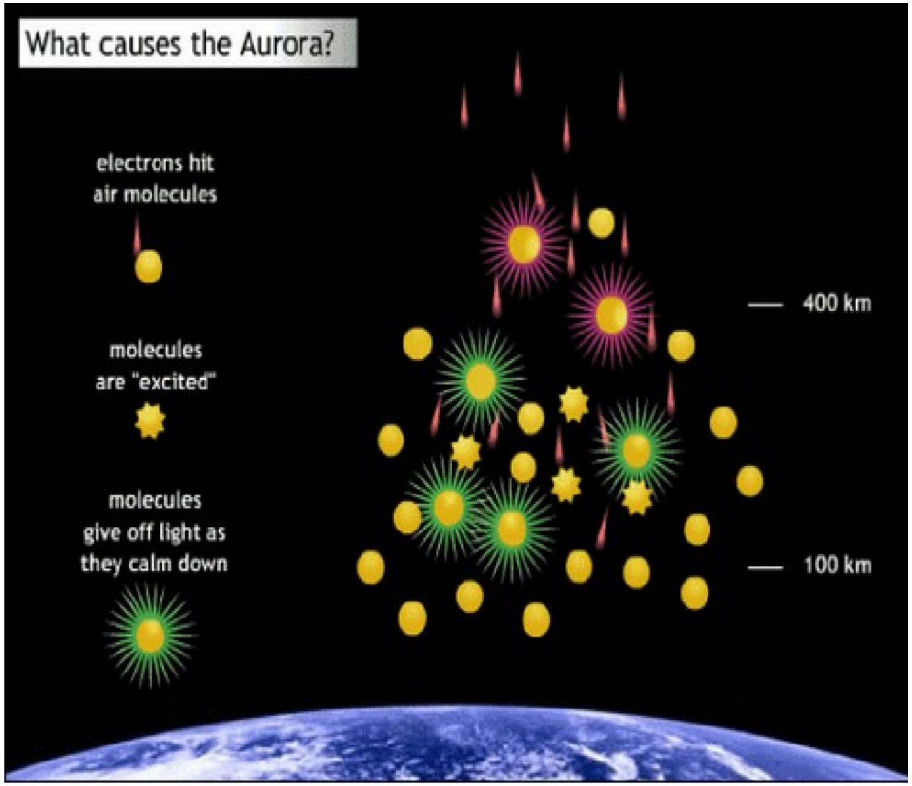
Sadržaj

- Uvod, polarna svjetlost u Sunčevom sustavu
- Simulacije magnetosferičkog međudjelovanja zvijezde i planeta
- Rezultati za auroru na planetima oko Sunca i egzoplanetima
- Planeti oko pulsara, lista (mogućih) objekata
- Preliminarni rezultati u našim simulacijama s parametrima pulsarskog vjetra
- Sažetak

Uvod-Aurora na Zemlji





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

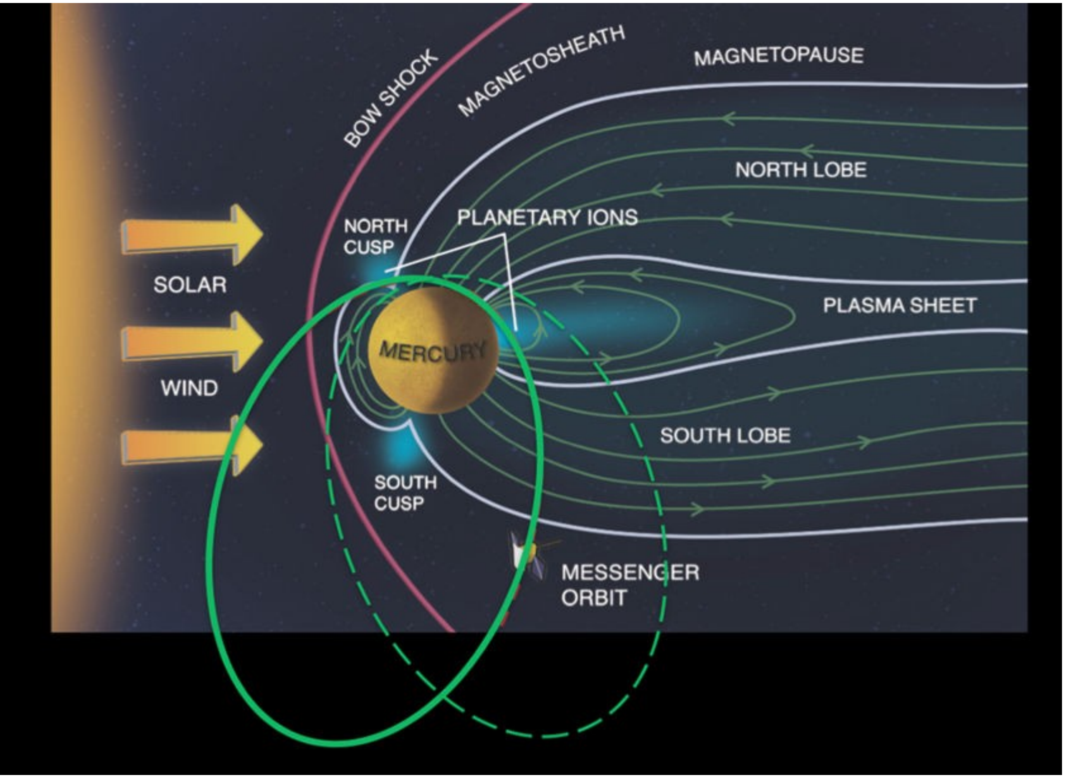
Aurora, koju je Pierre Gassendi 1621. nazvao aurora borealis (po grčkoj božici zore, Aurori, i grčkom nazivu za sjeverni vjetar, Boreas), nastaje kao rezultat interakcije magnetskog polja matične zvijezde s planetarnim poljem. Na Zemlji je polarna svjetlost vidljiva u blizini geografskih polova, budući da su trenutno blizu i magnetskih polova Zemlje.

Različiti plinovi u gornjim slojevima atmosfere emitiraju svjetlost različitih boja u sudaru s česticama Sunčevog vjetra (u ovom slučaju uglavnom elektronima). Kisik emitira zelenkastu ili smeđecrvenu, a dušik plavu ili crvenu svjetlost.

Aurora na Merkuru i Veneri

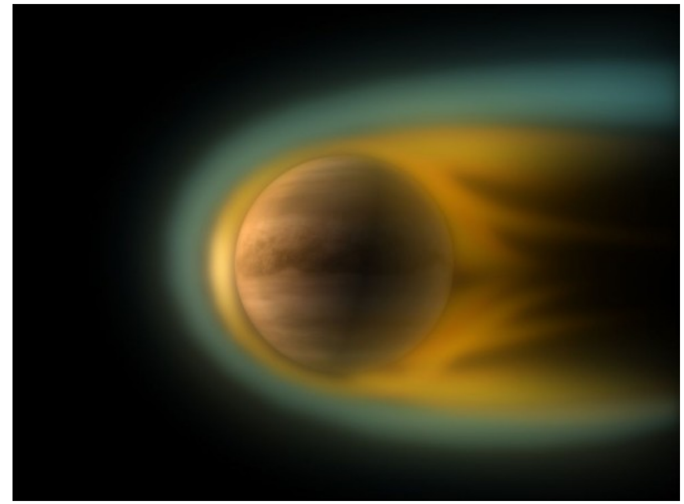
Osim na Zemlji, aurore se nalaze na većini planeta Sunčevog sustava.

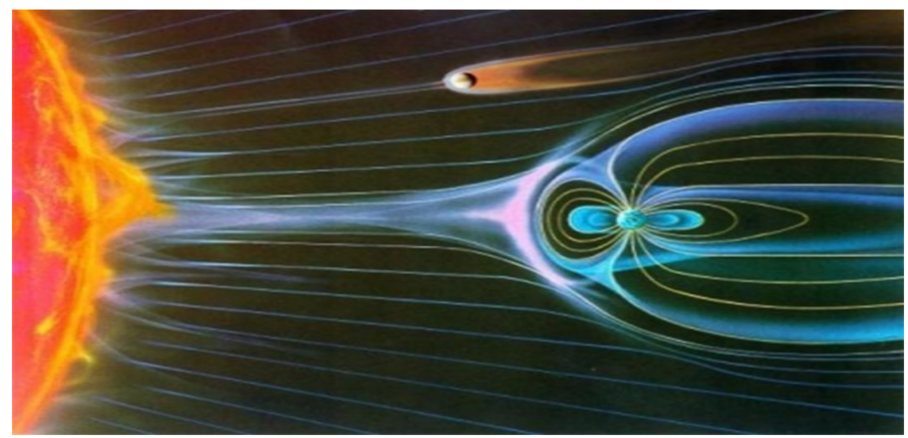
Merkur



Merkurovo magnetsko polje je dobro istraženo zahvaljujući sondi Messenger. Njegova aurora je slična Zemljinoj.

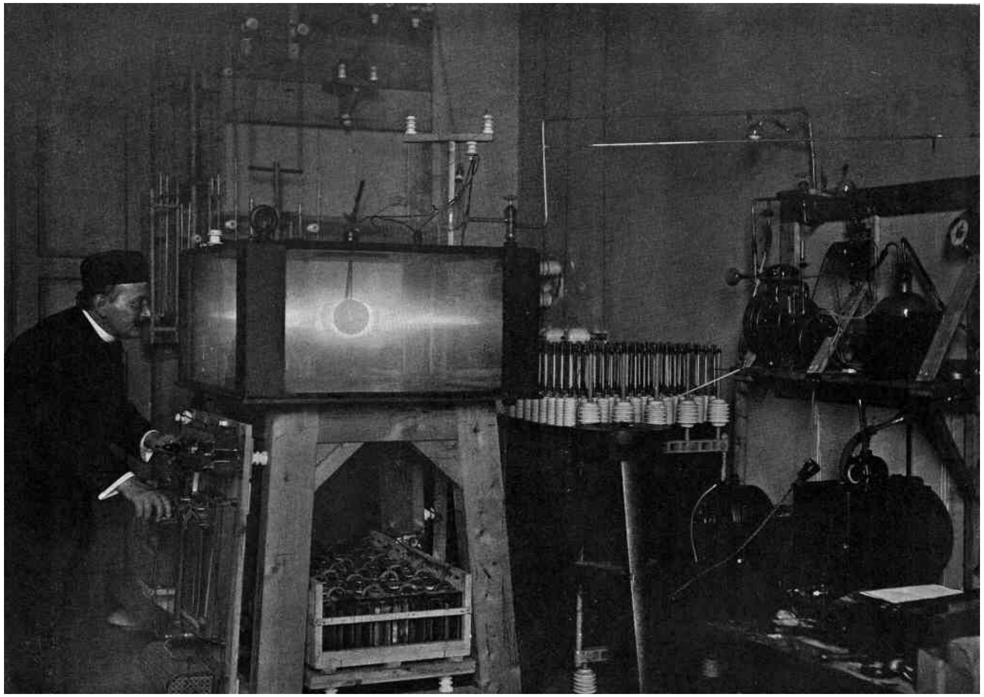
Venera





Venera ima manju auroru prema Suncu nego Zemlja, pokazana je usporedba.

Aurora na Zemlji-Birkeland



a. b. c.

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.

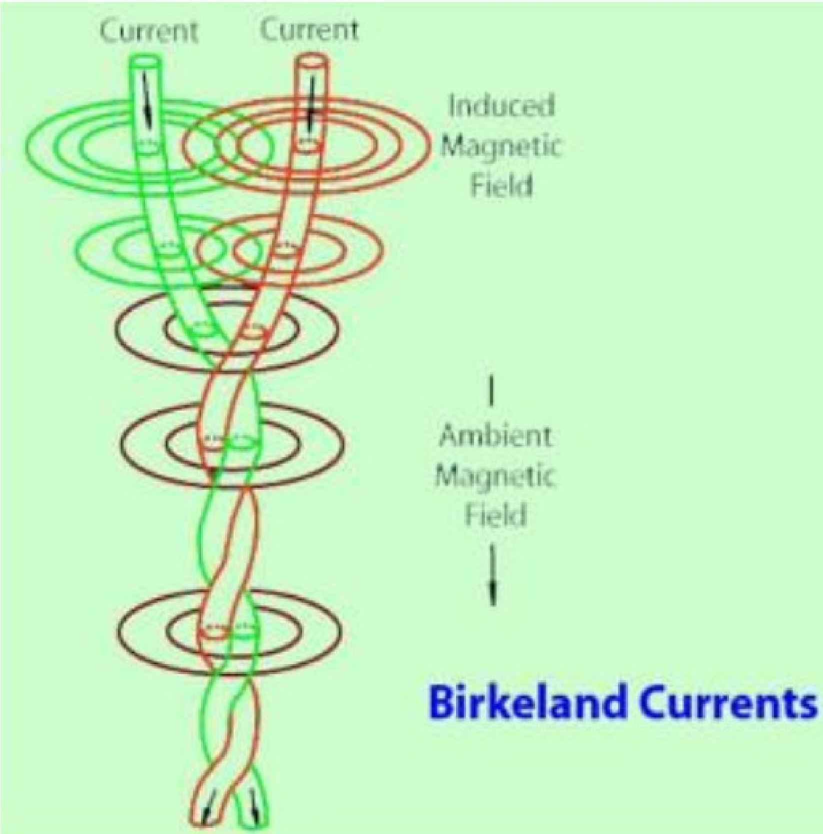
In order to obtain a clear conception of the conditions, we will once more have recourse to my experiments with the terrella. The experiments shown in fig. 46, *a*, *b* and *c*, follow directly on to ... 46 *a*, the terrella is so turned that the screen forms an angle of ... *a*). In ... angle ... d from ... the ca- ... the lat- ... same position as in the experiment given in ... towards ... h phos- ... *b* how ... rrella is ...

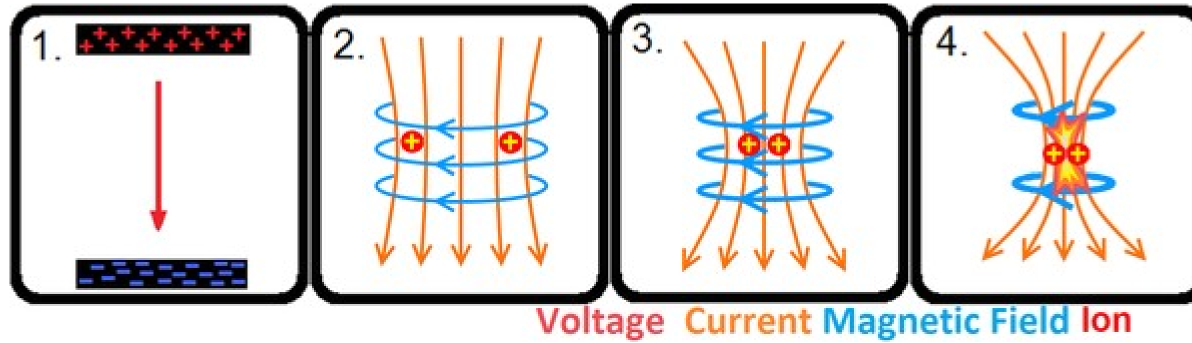
We will here especially direct our attention to the luminous wedge that is thrown upon the screen at about the 70th parallel

Kristian Birkeland izradio je električne modele (terrele) i mjerio magnetska polja i struje na kontinentalnoj razini, u ekspedicijama na Arktik.

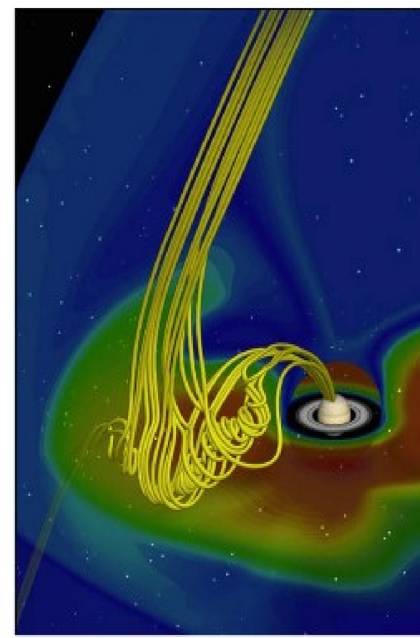
Početkom XX.st. točno je objasnio mehanizam aurore, ali su njegovi rezultati dugo bili ismijavani (npr. Chapman) - prihvaćeni su tek nakon 1963. godine kada su potvrđeni kozmičkim sondama.

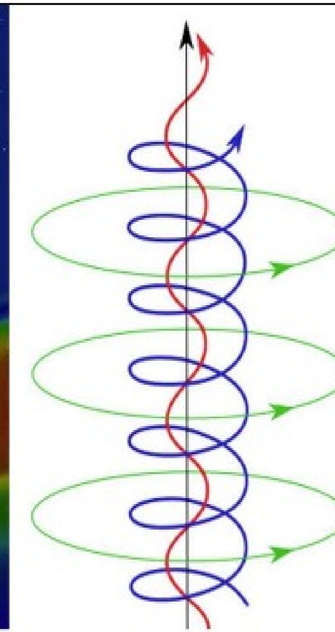
Birkelandove struje i Zemljino magnetsko polje

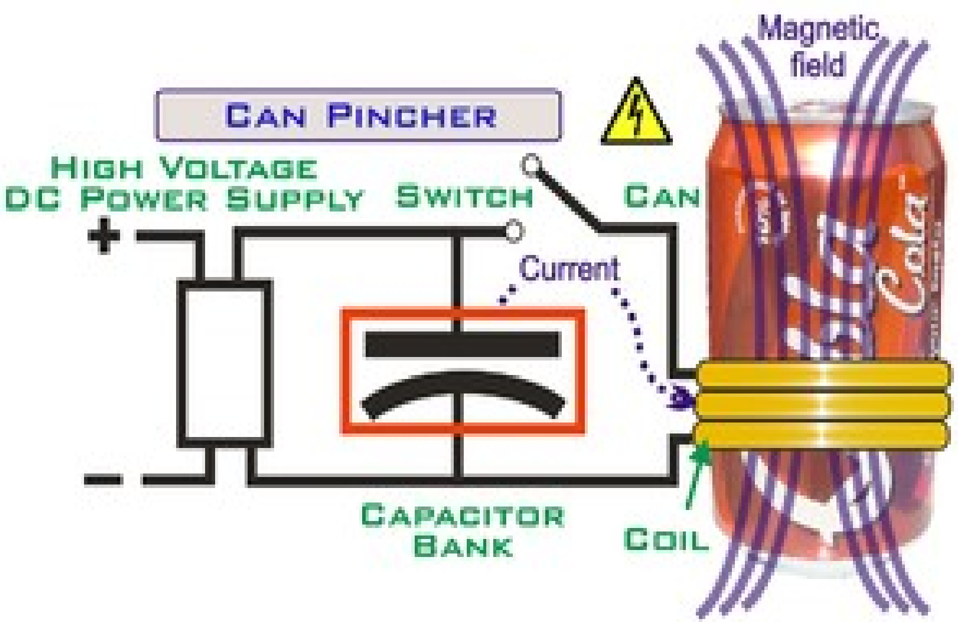




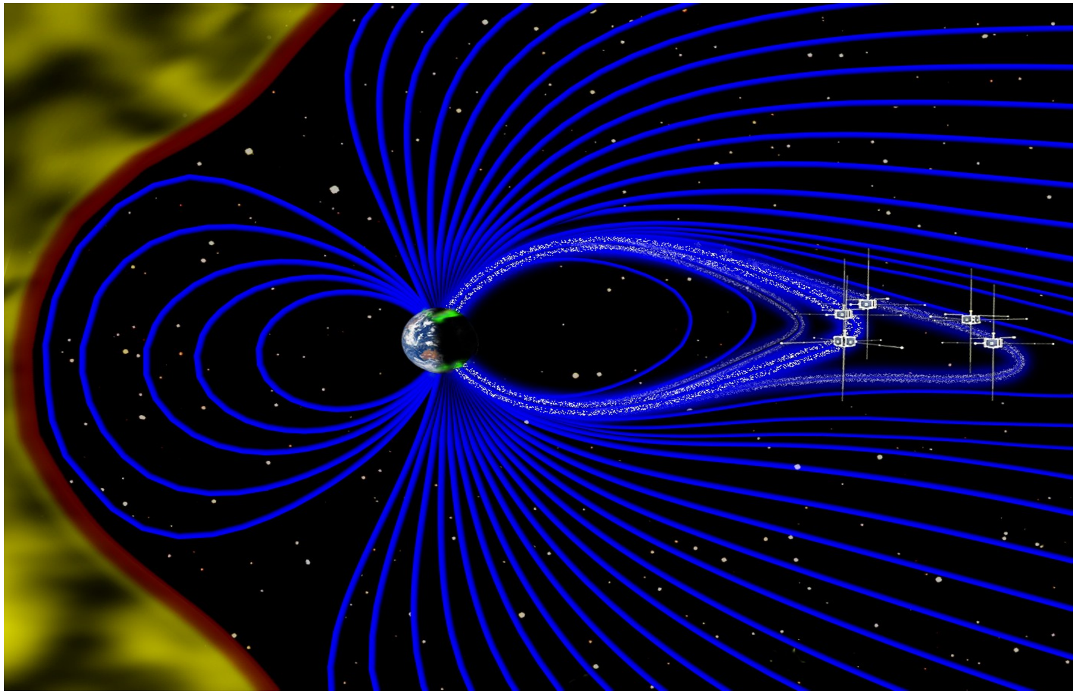
Birkeland je 1908. pokazao da struje mogu preživjeti međuplanetarne udaljenosti zahvaljujući zapetljavanju. Stvaraju se jake sile-mogu stisnuti limenke!

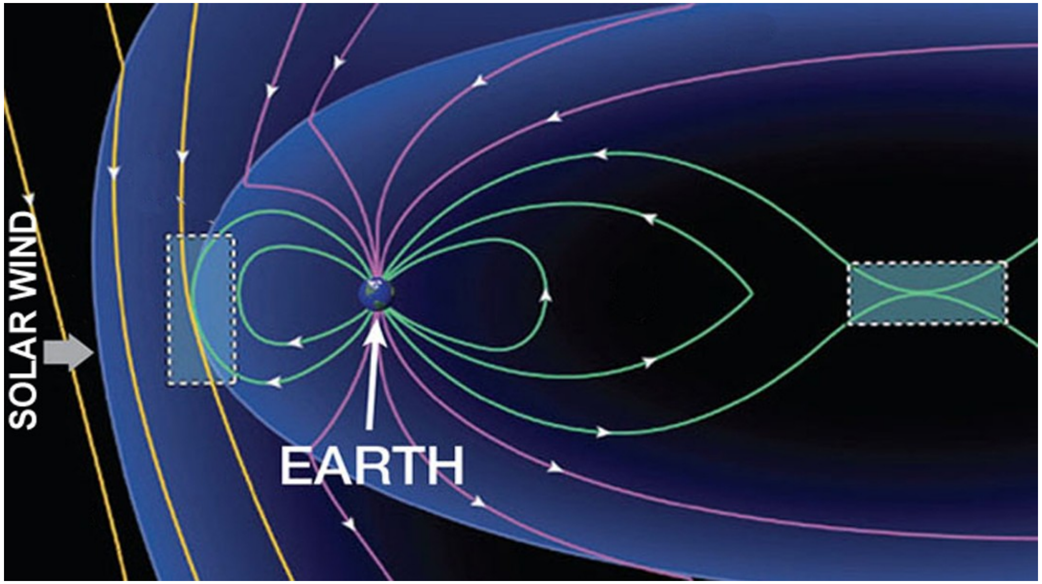




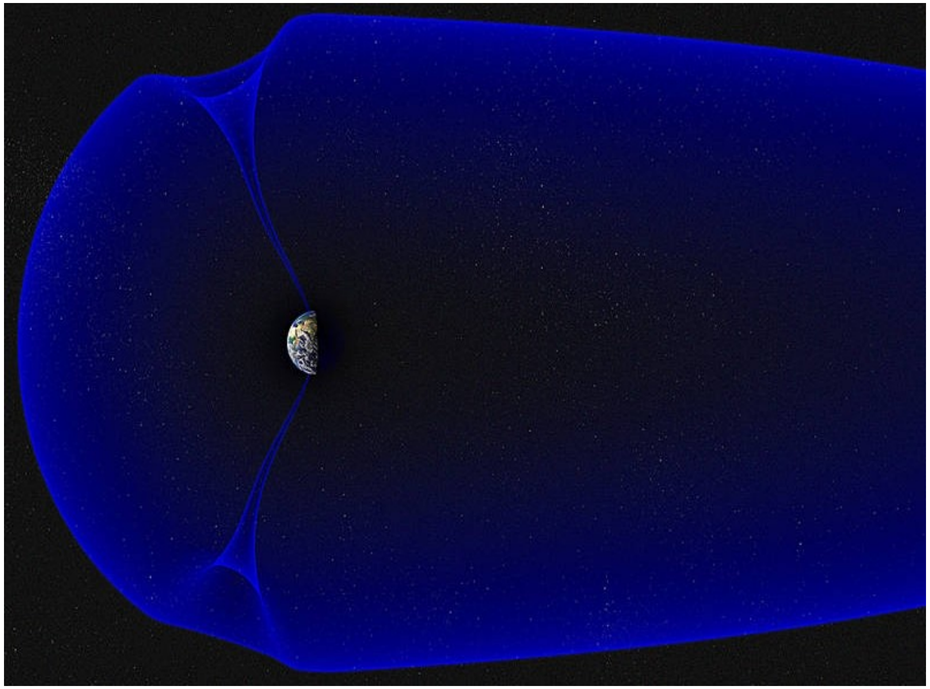


Mjerenje Zemljine magnetosfere



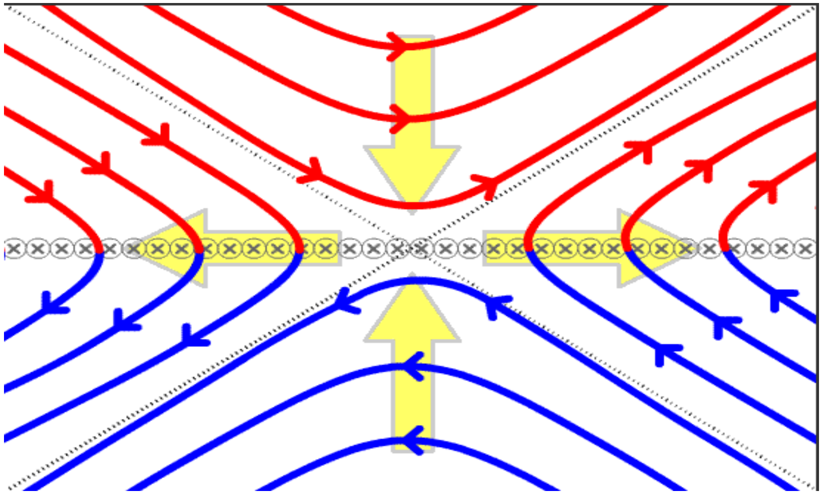


Položaj THEMIS sondi za mjerenje mehanizma rekonekcije u Zemljinoj magnetosferi.



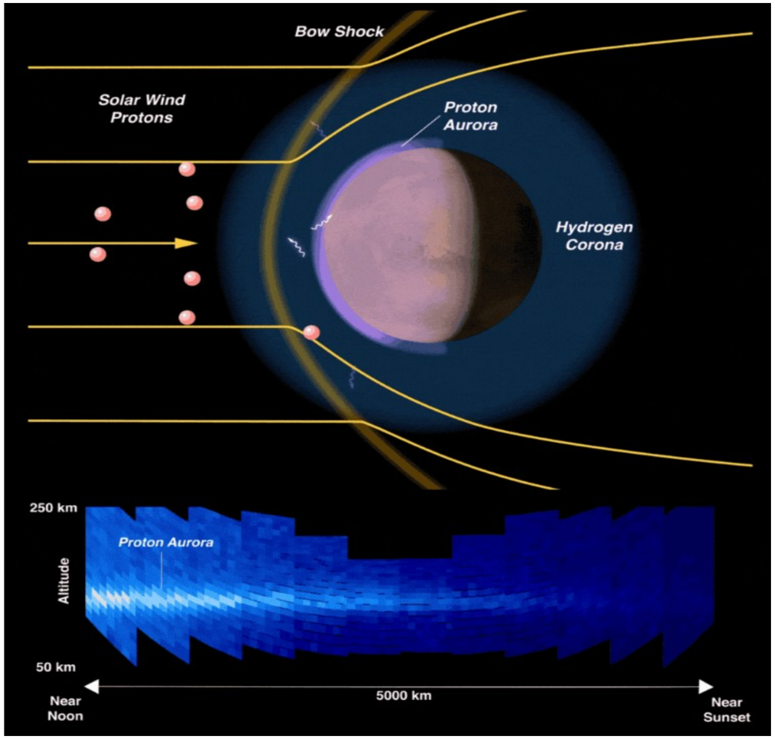
Magnetosferska područja iz kojih mogu izlaziti plinovi iz magnetosfere.

Credits: Andøya Space Center/Trond Abrahamsen.



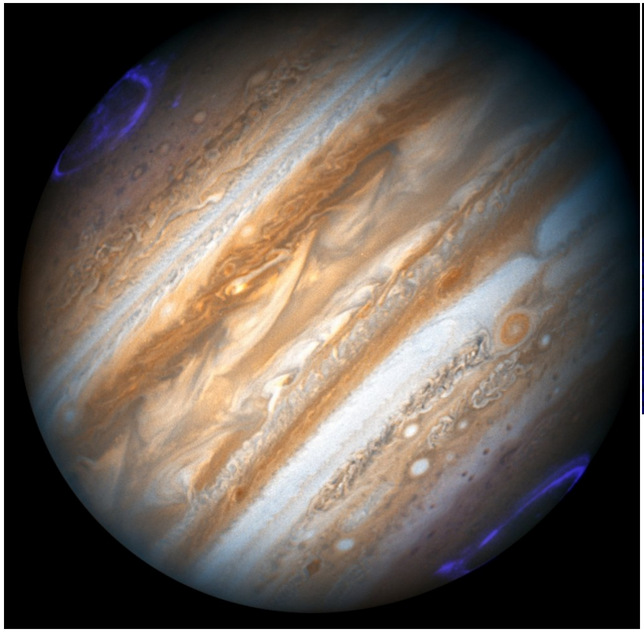
Aurora Marsa

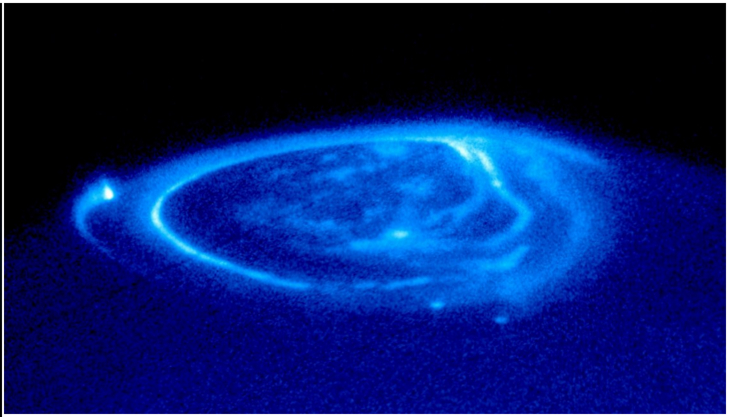
Čak i na planetima poput Marsa, koji nemaju značajno magnetsko polje, opažamo polarnu svjetlost koja nastaje kao rezultat interakcije čestica - ovdje uglavnom protona - od udara sunčevog vjetra gdje se planet kreće kroz vjetar. Najvidljiviji je na sunčanoj strani planete.



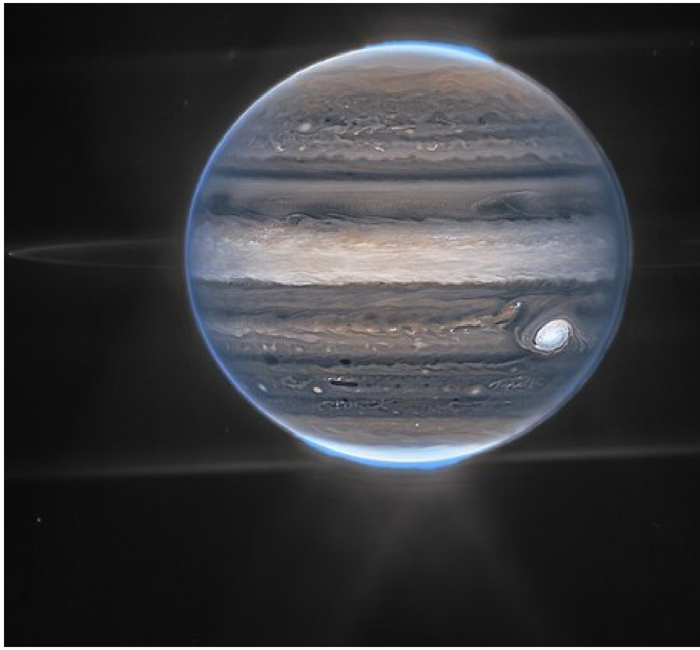
Aurore na velikim plinovitim planetima

Aurora se opaža i na Jupiteru i Saturnu. Na plinovitim planetima polarna svjetlost je vidljiva uglavnom u ultraljubičastom, tako da je možemo promatrati izvan atmosfere.

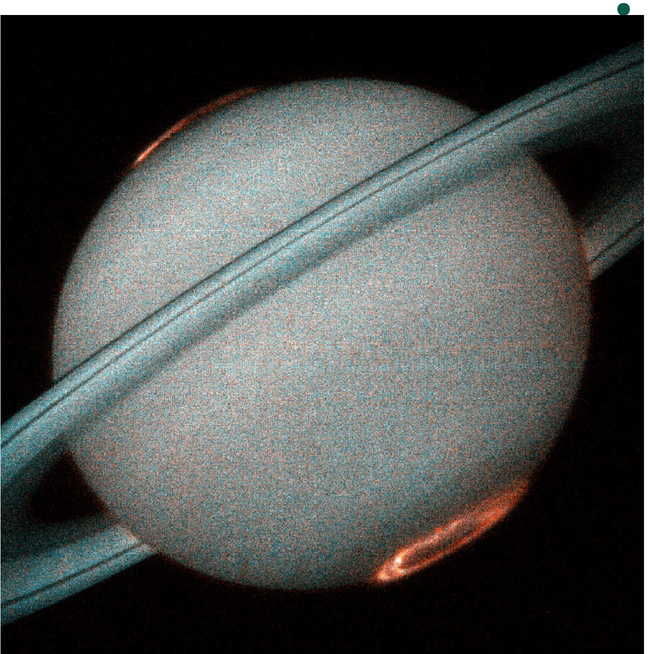


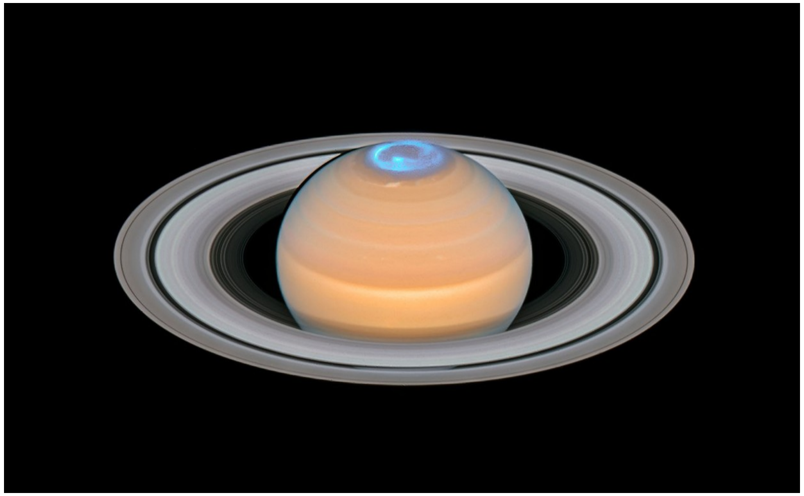


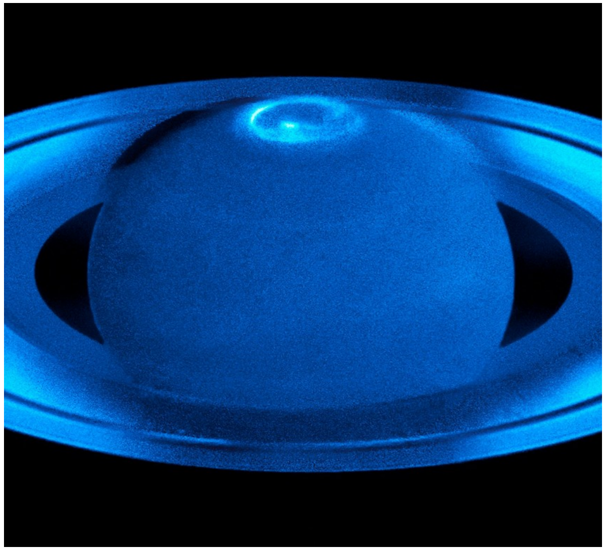
Pjege u aurori na Jupiteru magnetski su povezane s njegovim satelitima: pjega s lijeve strane povezana je s Iom, donja dva s Ganimedom i Europom.



JWST-ovo snimanje aurore na Jupiteru

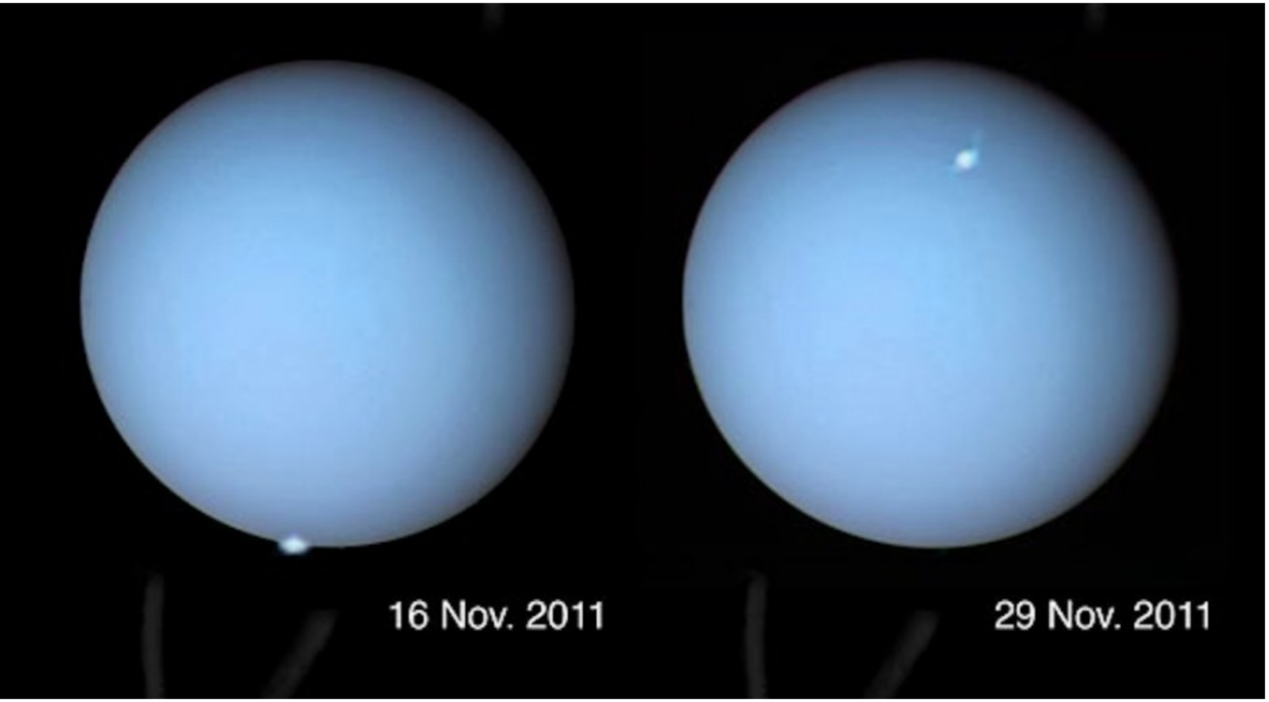


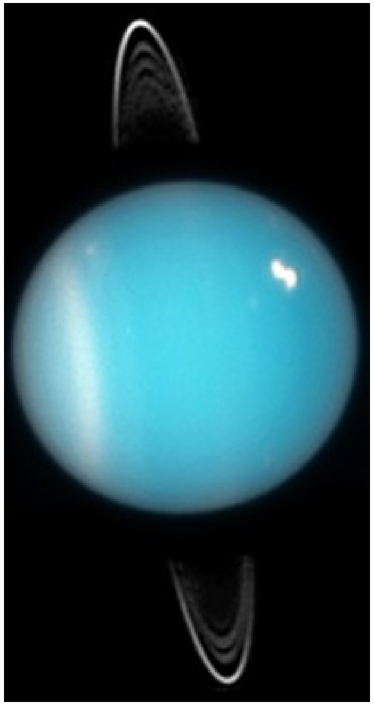




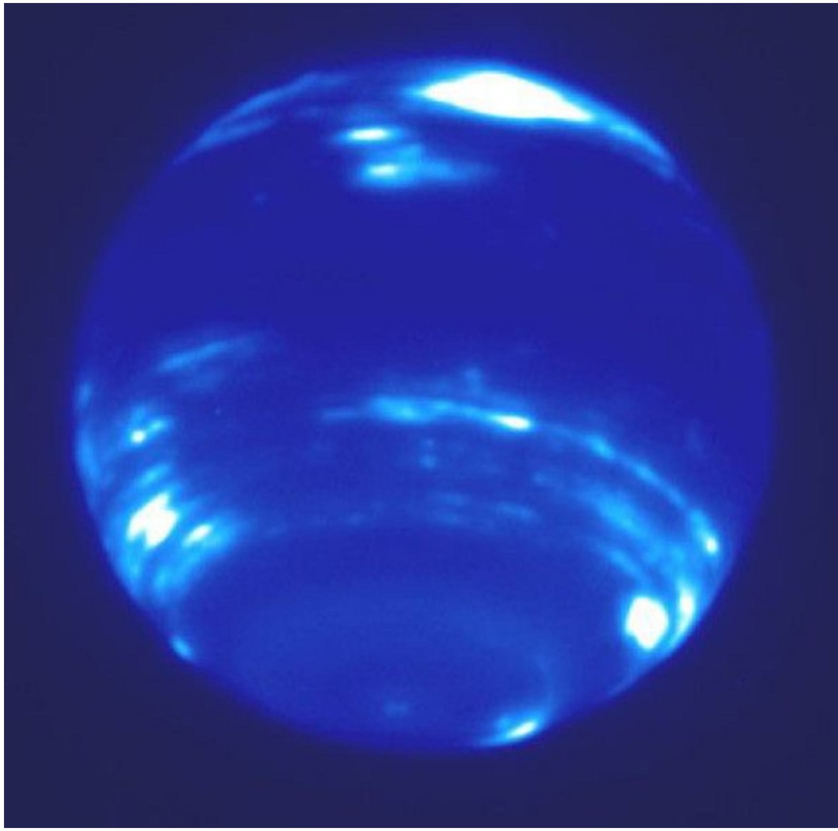
Aurora na Uranu

HST je snimio auroru na Uranu:





I Keck na Neptunu:

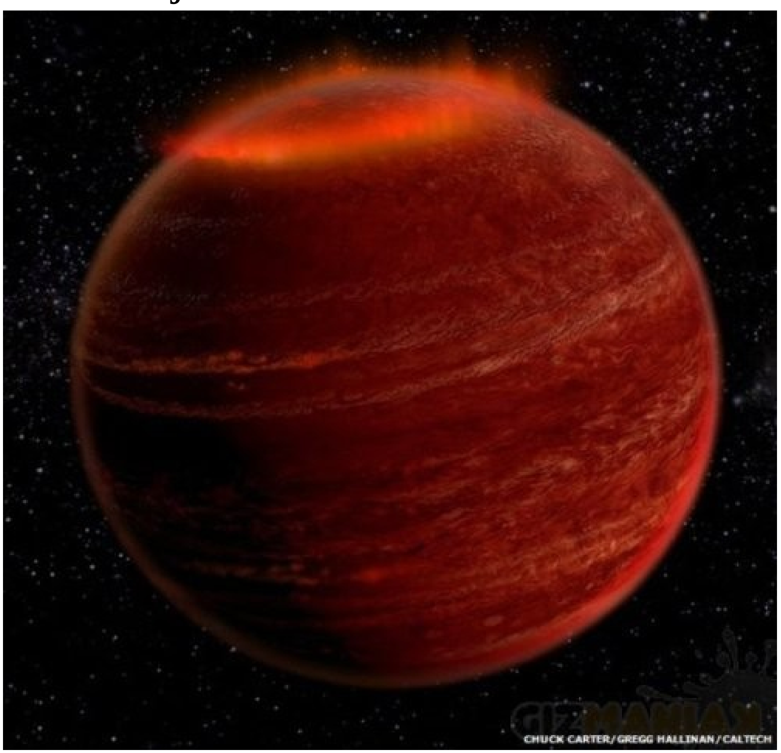


Ekstrasolarne i egzoplanetne aurore

•Za sada imamo opažanje ekstrasolarne aurore na smeđem patuljku LSR J1835+3259, 18 svj.god od nas, u Liri. Postoji više sličnih objekata koji pokazuju karakteristične spektralne značajke koje upućuju na polarnu svjetlost. Dolje je prikazan umjetnički prikaz, a ne stvarno opažanje. To je crvenkasta aurora, od više vodika u atmosferi, i oko milijun puta intenzivnija, zbog većeg magnetskog polja.

•Takva bi aurora također trebala biti drugačije prirode, jer ne postoji druga zvijezda za stvaranje zvijezdanog vjetra.

•Model aurore zahtijeva kontinuirano nadopunjavanje plazme unutar magnetosfere. To može uključivati interakciju s međuzvjezdanim medijem, vulkanski aktivan planet u orbiti ili magnetsku rekonekciju na fotosferi. Alternativno, kruženje planetarnog tijela kroz magnetosferu moglo bi osigurati magnetosfersku interakciju.



U slučaju egzoplaneta također očekujemo polarnu svjetlost, a možemo koristiti iste simulacije i napraviti predviđanja za različite vrste planeta.

U slučaju planeta oko pulsara, koji su zapravo bili prvi promatrani egzoplaneti, možemo očekivati slične učinke. Zbog mnogo većeg uključenog polja, mogli bi se ponašati drugačije od uobičajene planetarne aurore.

Ovdje pokušavamo napraviti prvi takav model, uvođenjem potrebnih izmjena u naše simulacije.

Numeričke simulacije međudjelovanja planeta i zvijezda

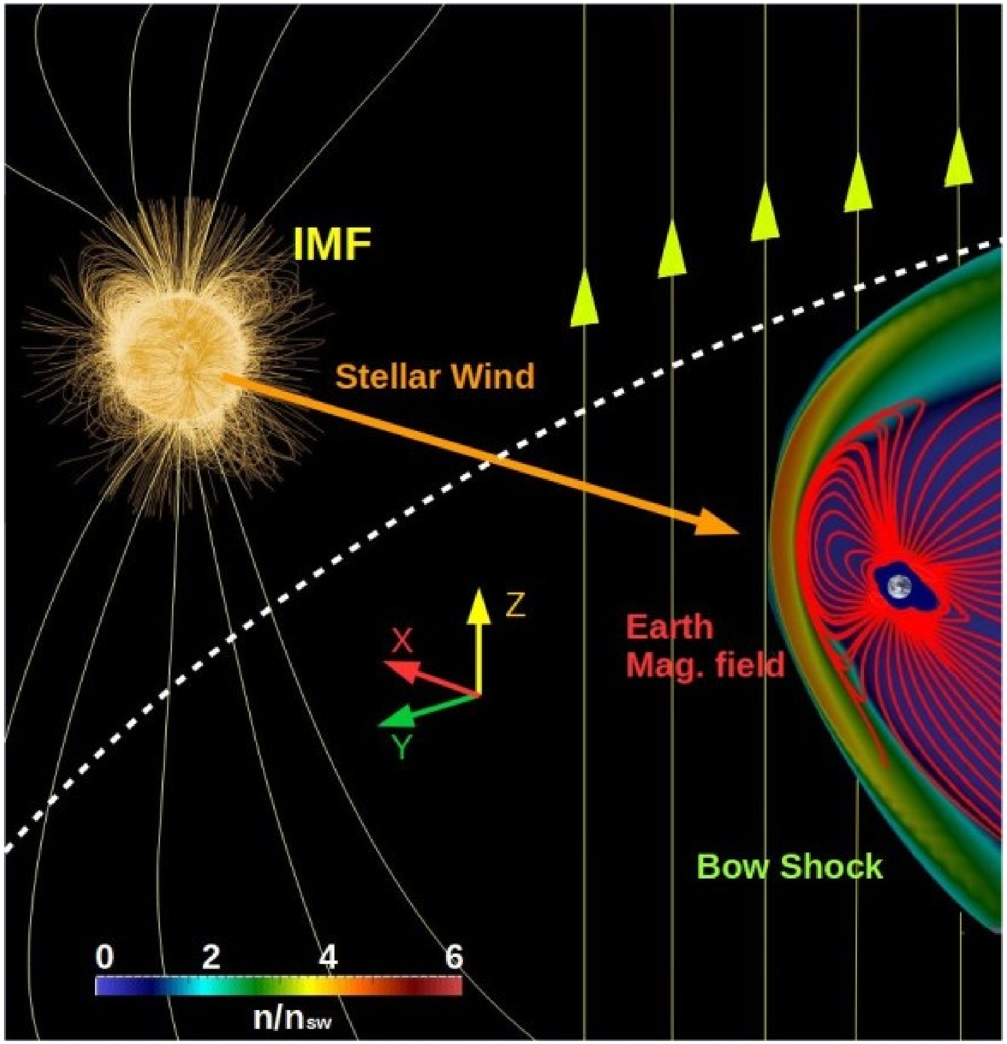


Fig. 1. 3D view of a typical simulation setup. We show the density distribution (color scale), Earth magnetic field lines (red lines), and IMF (yellow lines). The yellow arrows indicate the orientation of the IMF (northward orientation). The dashed white line shows the beginning of the simulation domain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

- U seriji radova Varela et al. (e.g. A&A, 616, A182, 2018; A&A 659, A10, 2022) dane su numeričke simulacije odgovora planetarne magnetosfere na ekstremne uvjete u Sunčevom vjetru, pomoću PLUTO koda.
- Takve simulacije su napravljene za Zemlju i egzoplanete.
- Iskoristili smo taj setup za mnogo redova veličine (milijardu puta) jače polje pulsara.

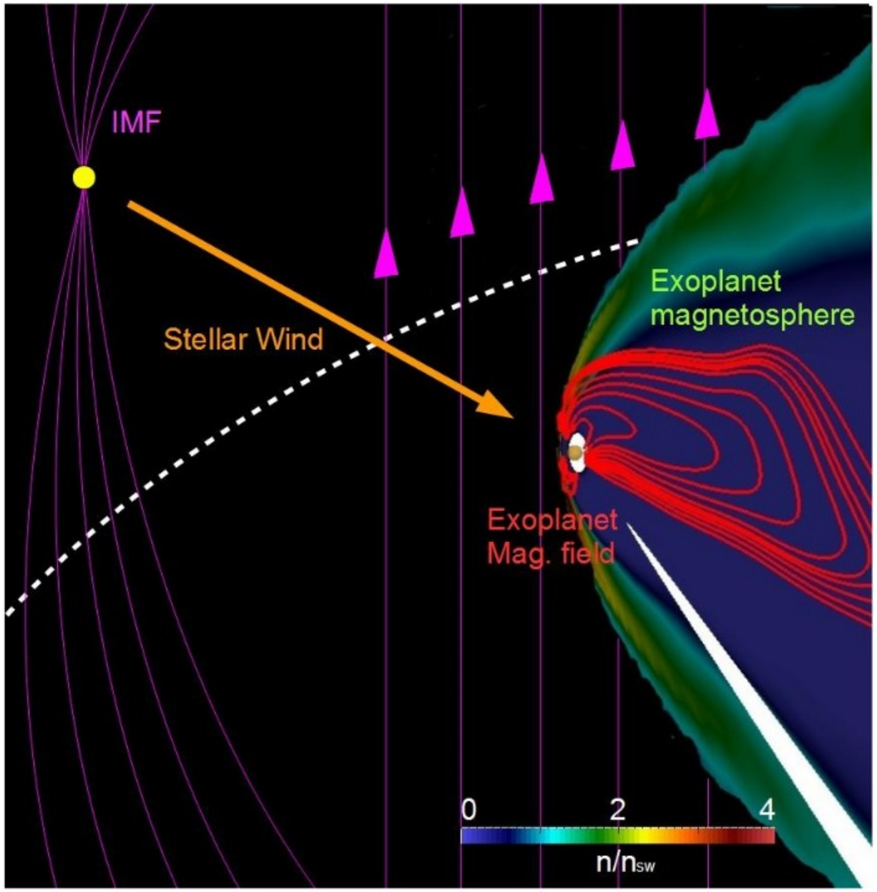


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the exoplanet magnetic field (red lines) and IMF (pink lines). The arrows indicate the orientation of the IMF (Northward orientation). Dashed white line shows the beginning of the simulation domain.

Neki rezultati za Zemlju, gdje možemo usporediti sa promatranjima sa uređaja u orbiti.

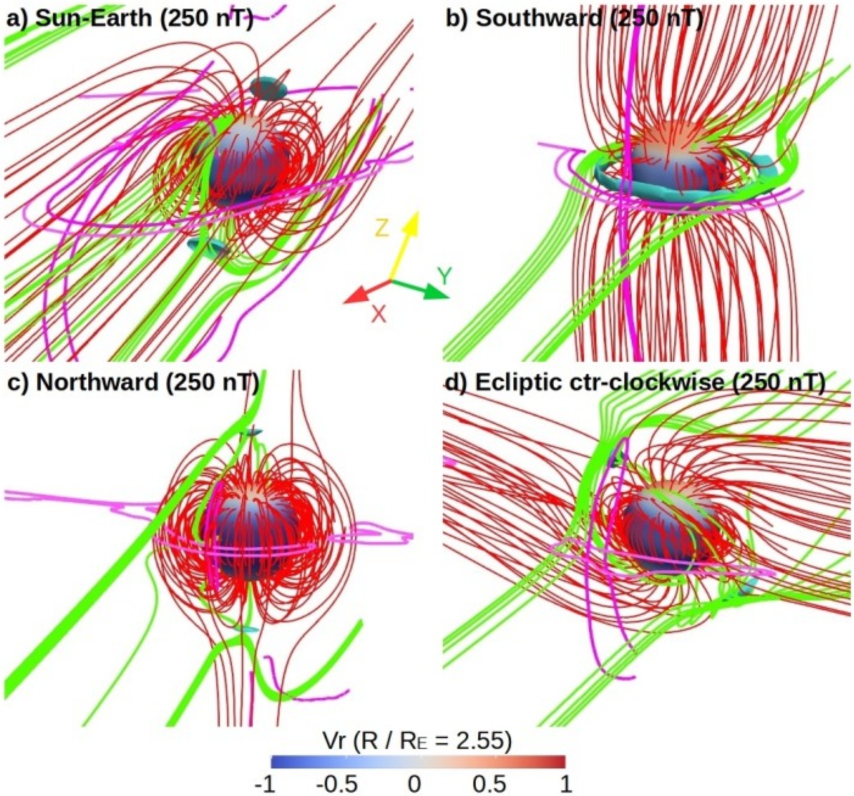


Fig. 3. 3D view of the Earth magnetosphere topology if $|B|_{\mathrm{IMF}} = 250$ nT for (*a*) a Sun–Earth, (*b*) southward, (*c*) northward, and (*d*) ecliptic ctr-clockwise IMF orientations. We show the Earth magnetic field (red lines), SW stream functions (green lines), and isocontours of the plasma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

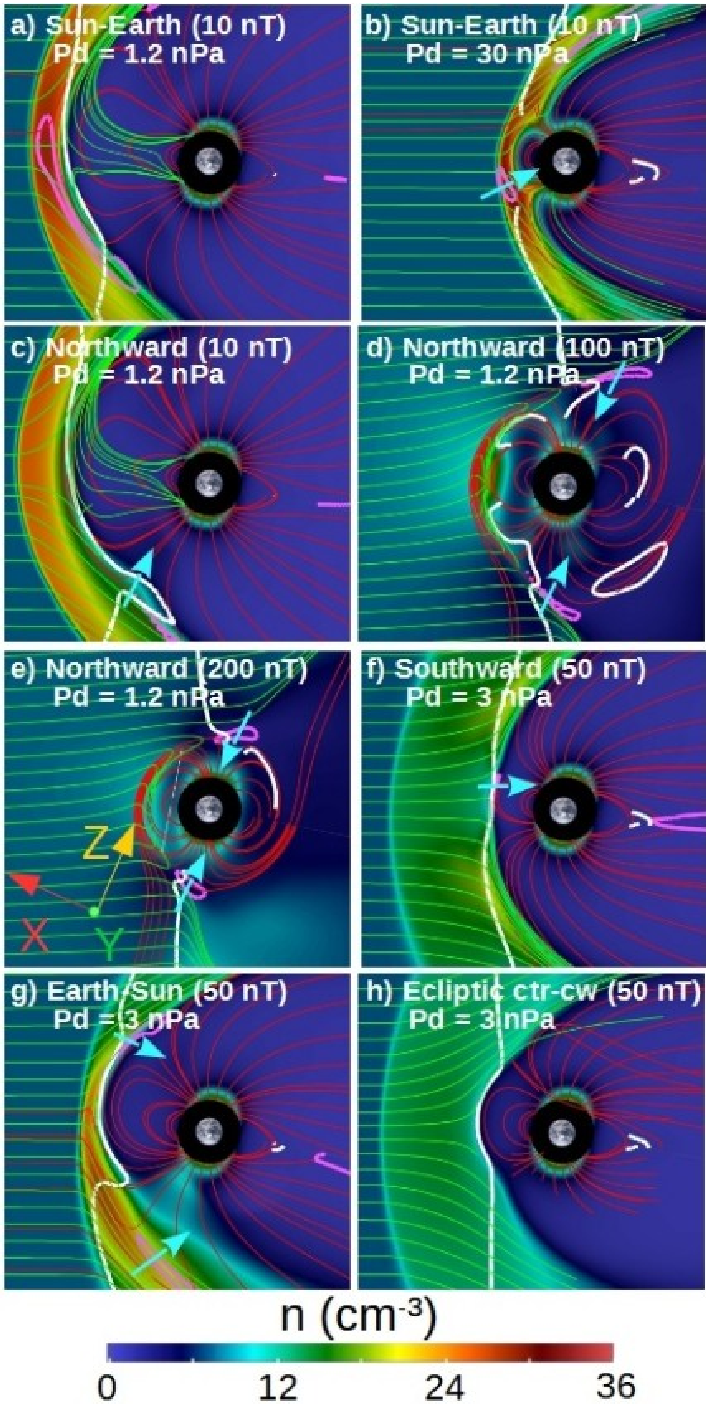


Fig. 2. Polar cut (*XY* plane) of the plasma density in simulations with (*a*) Sun–Earth IMF orientation $|B_{\mathrm{IMF}}| = 10$ nT $P_d = 1.2$ nPa, (*b*) Sun–Earth IMF orientation $|B_{\mathrm{IMF}}| = 10$ nT $P_d = 30$ nPa, (*c*) northward IMF orientation $|B_{\mathrm{IMF}}| = 10$ nT $P_d = 1.2$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

Simulacije međudjelovanja Sunca i Merkura

Slična studija također je napravljena za Merkur, gdje imamo mnoštvo podataka iz misije Mariner 10, koja je mjerila dipolni moment, i kasnije misije Messenger, koja je pružila preciznija mjerenja za multipolarni prikaz.

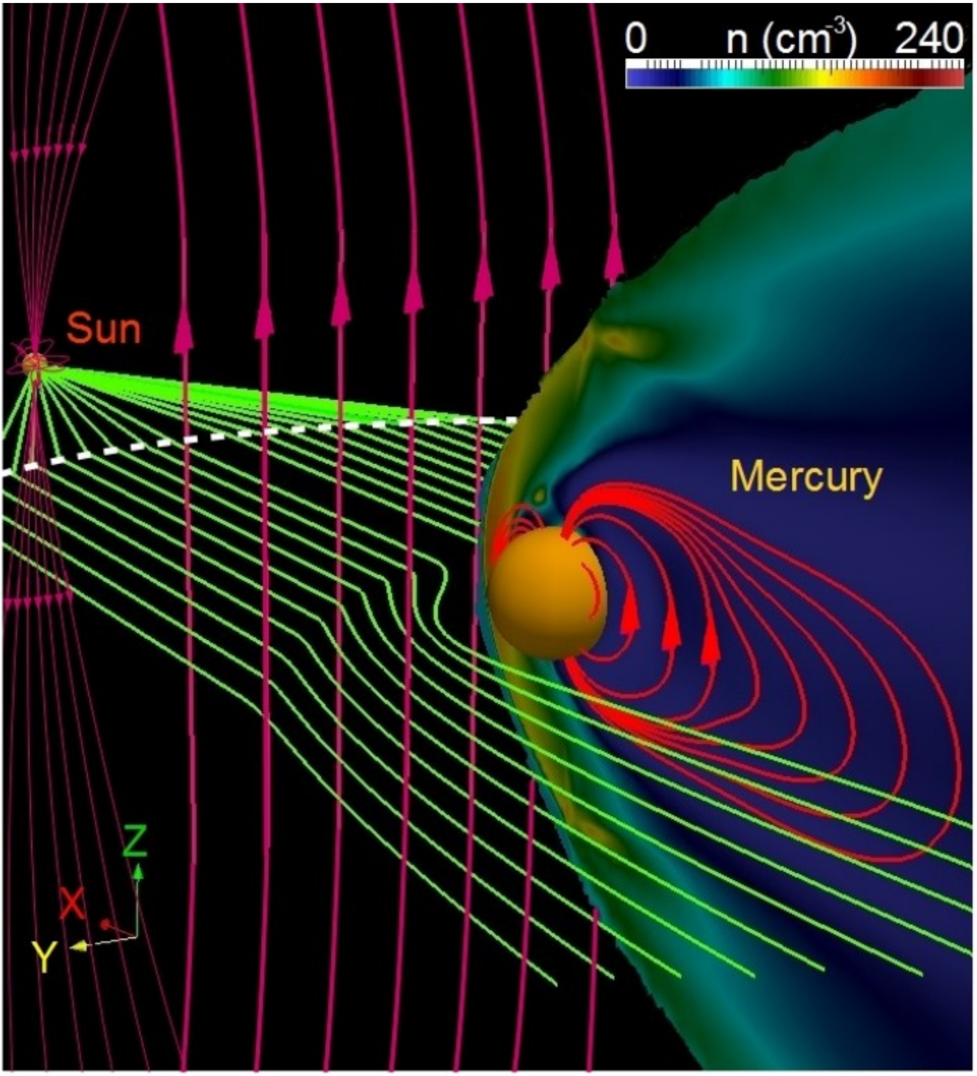


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the Hermean magnetic field (red lines), IMF (pink lines) and solar wind stream lines (green lines). The arrows indicate the orientation of the Hermean and interplanetary magnetic fields (case Bz). Dashed white line shows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

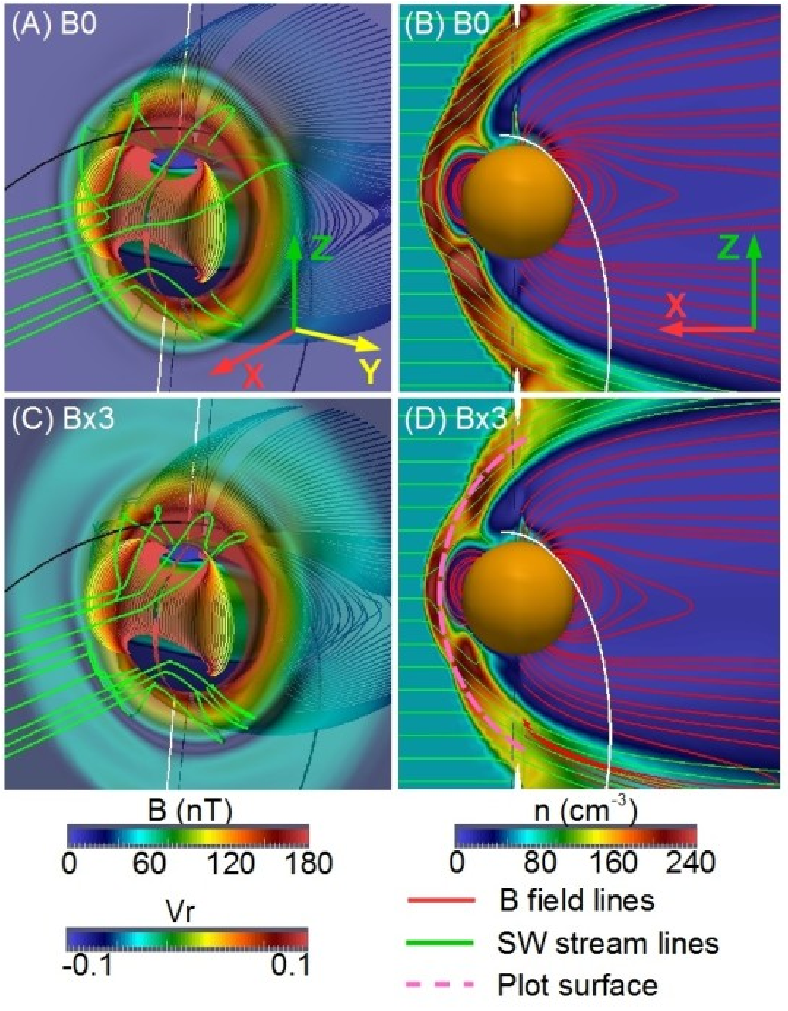


Fig. 2. Hermean magnetic field lines with the intensity imprinted on the field lines by a color scale for the reference case (A) and simulation Bx3 (C). Magnetic field intensity at the frontal plane $X = 0.3R_M$. SW stream lines (green). Inflow/outflow regions on the planet surface (blue/red). Polar plot of the density distribution (displaced $0.1R_M$ in Y direction) for the reference case (B) and simulation Bx3 (D). Dashed pink curve indicates the surface plotted in figures 3 and 4.

Postanak planeta oko pulsara

•Prve egzoplanete pronađene su u orbiti oko 6.2-ms pulsara PSR1257+12 (Wolszczan & Frail, 1992).

•Mehanizmi formiranja planeta oko pulsara mogu se podijeliti na pred-supernove i post-supernove scenarije.

•Scenarij predsupernove uključuje formiranje planeta oko obične zvijezde i/ili preživljavanje eksplozije (i niz katastrofalnih događaja uz nju) ili zarobljavanje od strane neutronske zvijezde

• U slučajevima postsupernove, planeti su ili formirani iz materijala oko novonastalih neutronskih zvijezda (druga generacija planeta), ili su posljednja faza u formiranju nekih binarnih milisekundnih pulsara.

•Za stjenovite planete u kružnim orbitama, dobra mogućnost su spajanja kao što su WD+WD ili WD+NS, ili ostatak diska materijala iz Be zvijezde koji formira binarni sistem s NS. Prvi planeti Wolszczana najbolje odgovaraju scenariju WD-WD spajanja, tako da se planeti formiraju iz ostataka prateće zvijezde koja je kružila oko pulsara dok je bio bijeli patuljak.

•Čini se da su planeti oko pulsara rijetki, postoji samo nekoliko slučajeva u oko 3000 pulsara, a svi su pronađeni varijacijama u vremenu signala pulsara. Od više od 5000 trenutno poznatih egzoplaneta, manje od 10 oko pulsara je potvrđeno da ima planete

•Poseban slučaj, koji je oživio istraživanja: (1982, 1994?) PSR B1937+21 blizu (nekoliko stupnjeva) od 1. otkrivenog pulsara PSR B1919+21 (od Jocelyn Bell), ovo je 1. otkriveni ms pulsar , 1,5 ms (624 rotacije u sekundi!), pratilac 0,001 M_Zemlje, poput Cerere, na 2,7 AJ, asteroidni pojas? Potrebno je više promatranja. Također ukazuje na veliku preciznost metode, kada su dostupna duga promatranja.

Our work here emerged from a direct analogy: I was searching for a good learning topic for PLUTO simulations for CAMK summer students, apart from my usual thin accretion disc simulations. I remembered the work of Jacobo Varela with PLUTO, a collaboration started, and it was not a far shot from discussing millisecond pulsars with the Warsaw group to remembering that pulsars also have planets. Didactic result: Summer students in CAMK in 2022 and 2023 were learning PLUTO on star-planet magnetospheric interaction project. We worked in non-relativistic regime, using

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:

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

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 of pulsar-planet interaction

In the pulsar planet case, we considered rocky planets, as in Wolszczan's system, and assumed that thy 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 surface are conductive and ferromagnetic.

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**$=0.01\times$ **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	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

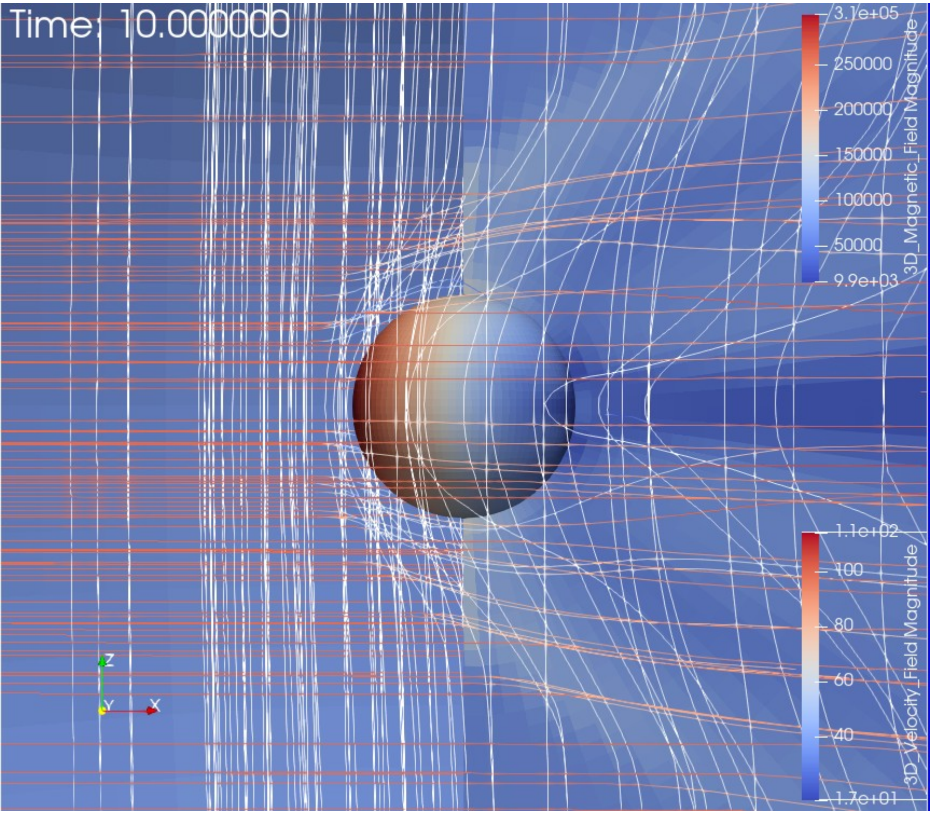
We increase the stellar magnetic field in the simulations-to accommodate for the large field we increase the density of the interplanetary medium, local magnetic field strength near the planet and stellar wind velocity. We probe for the different planetary surface boundary conditions (conducting or ferromagnetic) - 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.

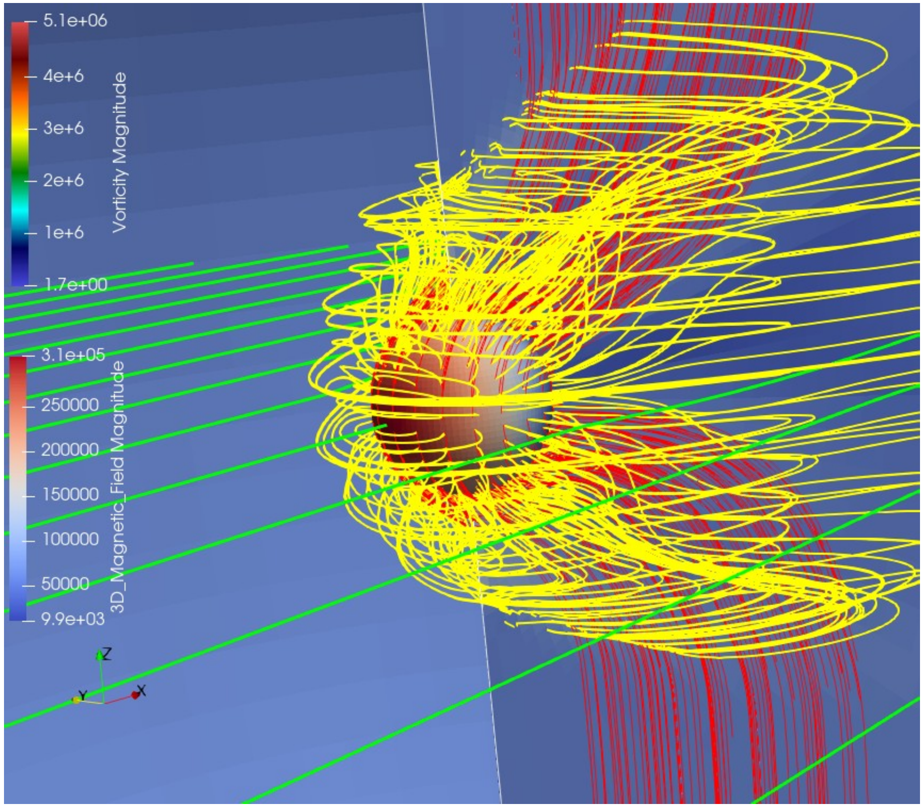
Numeričke simulacije – vodljivi planeti

Vodljiva površina planeta:

Bsw=3.0, Vsw=1.e9

Struje (žute linije), Vsw(zeleno), mag.polje (crveno)



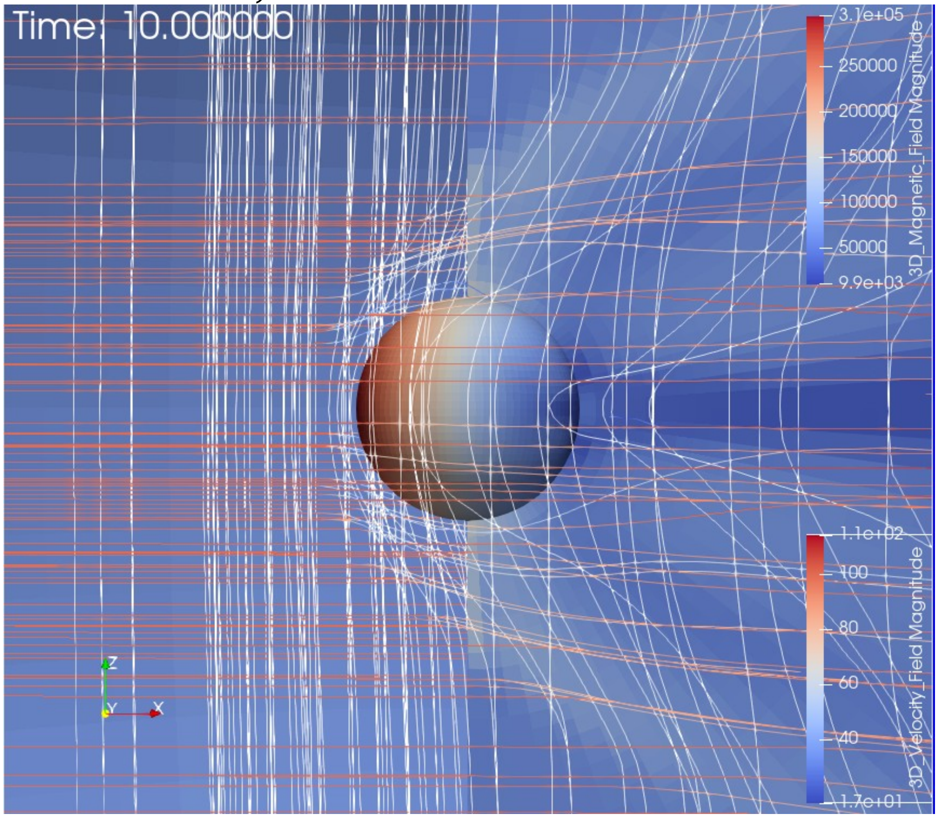


U slučaju vodljivog planeta, električne struje ostaju blizu površine planeta.

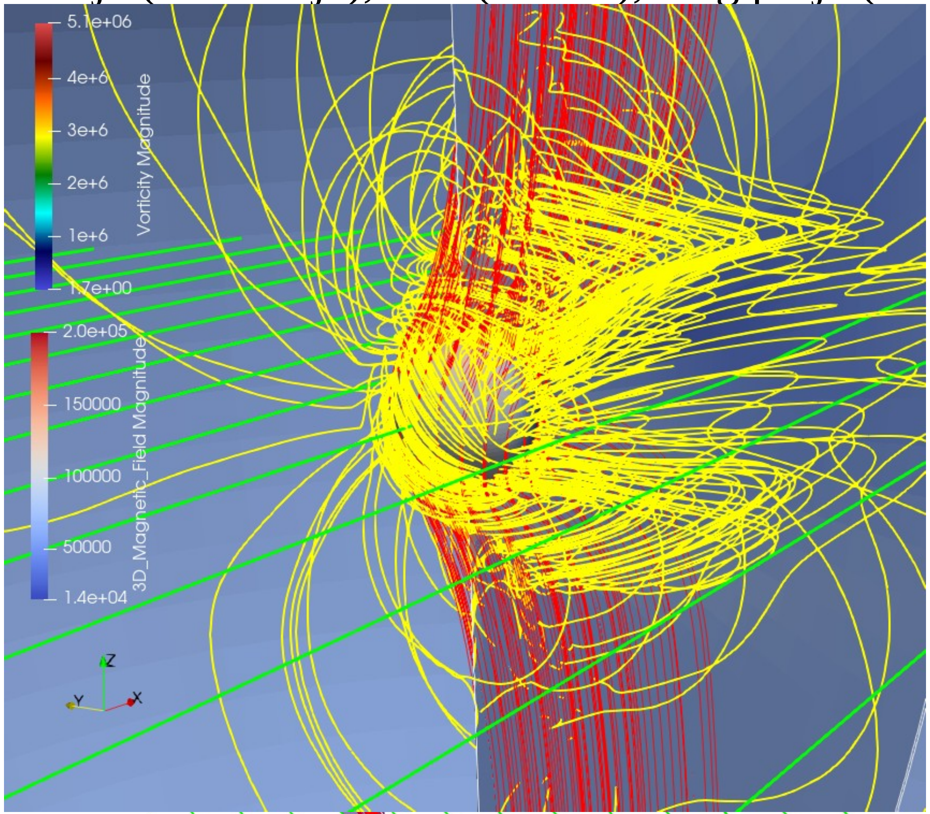
Numeričke simulacije – feromagnetski planeti

U slučaju feromagnetske površine planeta, rezultati su drugačiji, struje ukazuju na proširenu dipolarnu strukturu električnog polja.

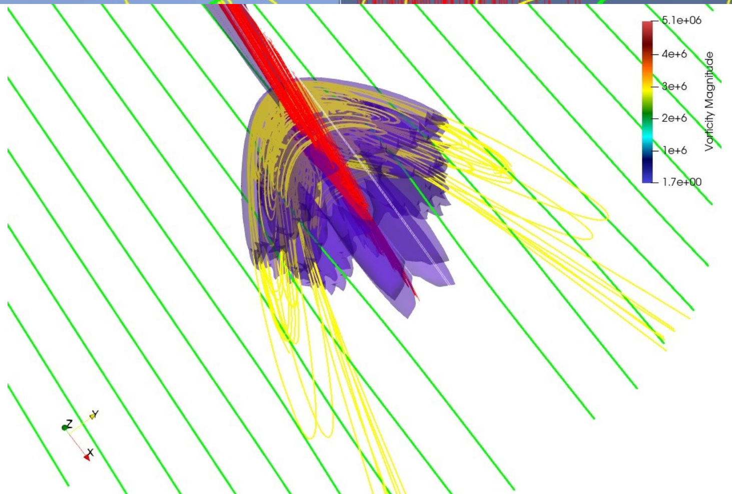
Bsw=3.0, Vsw=1.e9



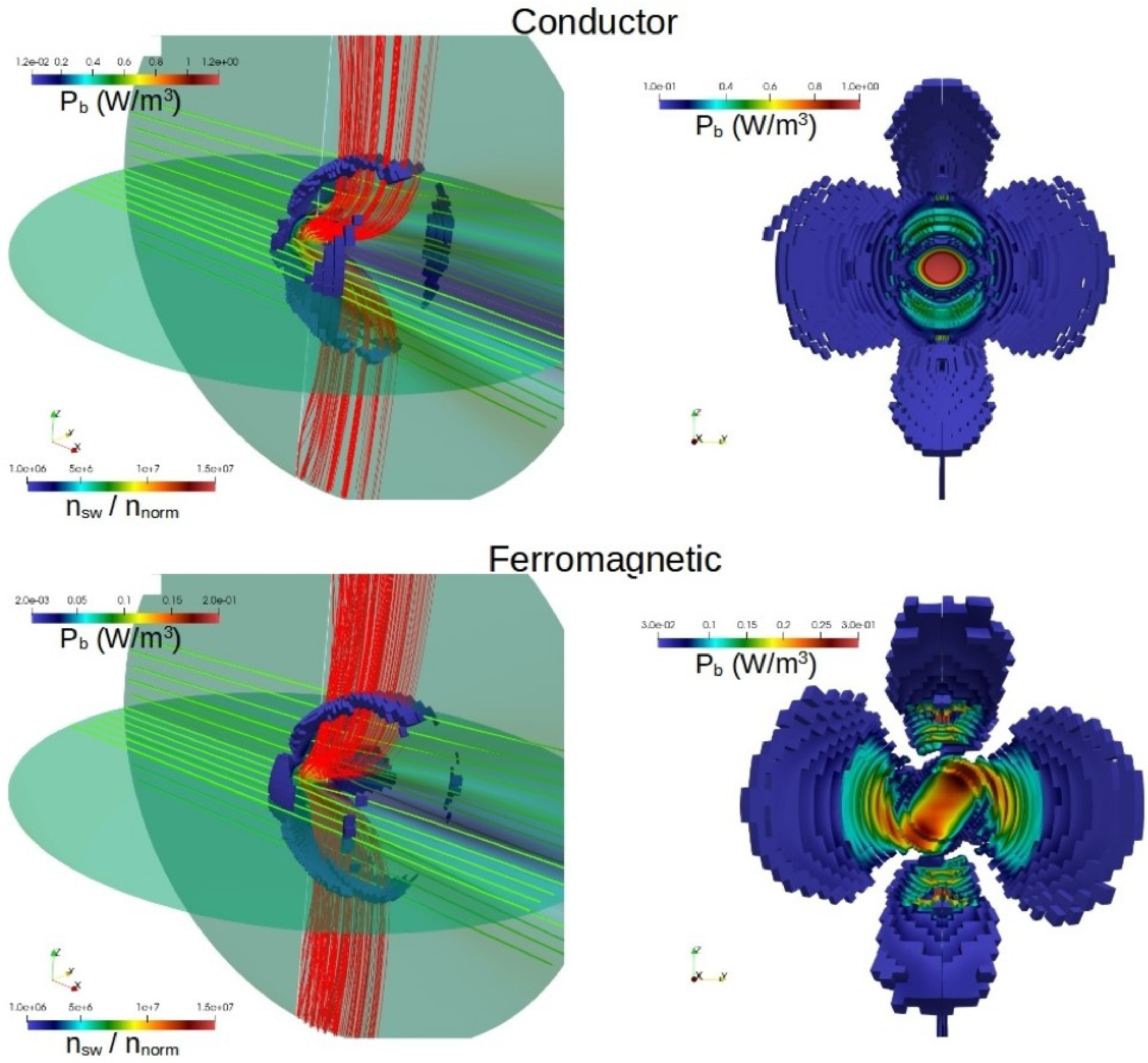
Struje (žute linije), Vsw(zeleno), mag.polje (crveno)



Egvatorijalni pogled-Alfvenova "krila":



Izgled radio emisije sa nemagnetičkih planeta



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.

Intenzitet radio emisije

LOFAR je uspio detektirati niskofrekventne radio valove koji su bili predviđeni sa patuljastog GJ 1151 tipa M (ili planeta oko njega) koji se nalazi 25 svjetlosnih godina od Zemlje (Vedantham et al. 2020). To je bio, uvjetno, prvi signal otkriven sa izvansolarne aurore.

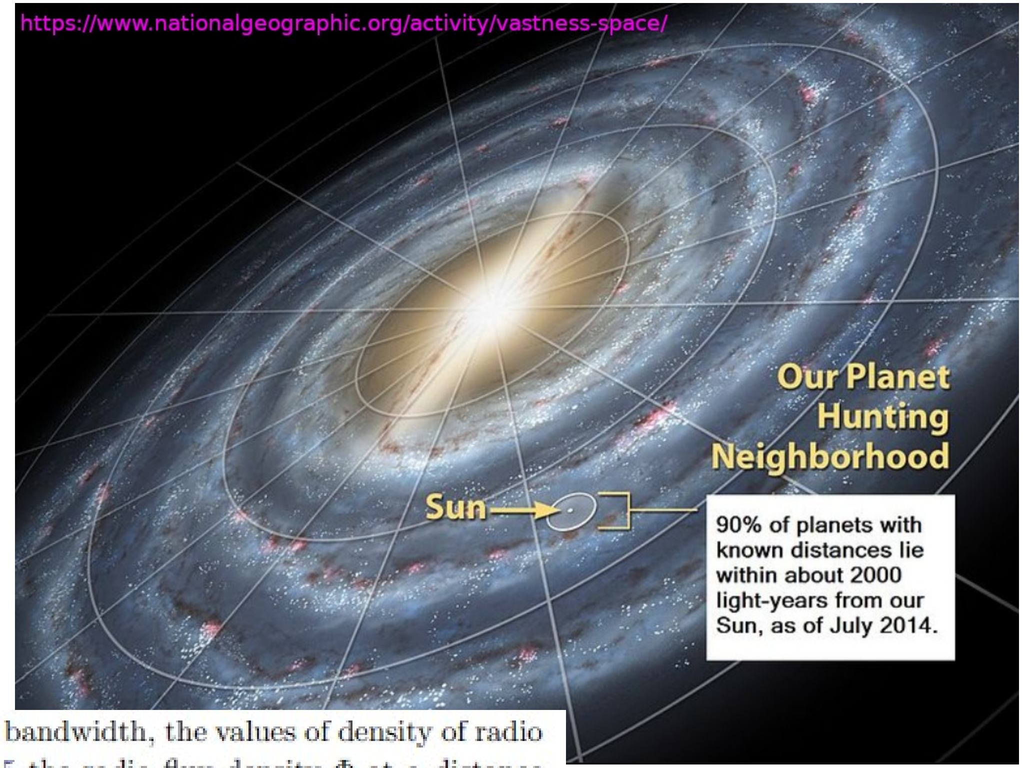
Koji su brojevi za Wolszczanov pulsar? Jedini slučaj interakcije zvijezda-planet bez netermalne radio emisije javlja se kada su i planet i zvjezdani vjetar nemagnetizirani. U svim ostalim slučajevima, čak i bez planetarnog magnetskog polja, može doći do intenzivnog radio zračenja. Na temelju opažanja magnetiziranih planeta u Sunčevom sustavu, empirijski radiometrijski Bodeov zakon (RBL) koristi se za procjenu intenziteta radioemisije, pri čemu je emisija otprilike proporcionalna snazi mag.polja zvjezdanog vjetra. Bitne jednadžbe su (Prad dobijemo iz simulacija):

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

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

Izazov promatračima

Većina egzoplaneta koje smo do sada pronašli udaljeni su manje od 2000 sg od nas. Wolszczanov pulsar udaljen je oko 750pc, oko 2300 sg od nas, a ima mnogo pulsara na oko 250pc od nas, među kojima bi neki mogli imati planete. Izračunali smo radio emisiju s takvih planeta, kolika je količina te emisije do nas, možemo li je promatrati?



LOFAR, MeerKAT i
budući SKA imaju minimalnu osjetljivost
reda 0,1, 0,01 i 0,001 mJy, respektivno.
Naši preliminarni rezultati:

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

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

and similarly, for the pulsar-planet in a ferromagnetic case Φ = 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

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 need to use 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:

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

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 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

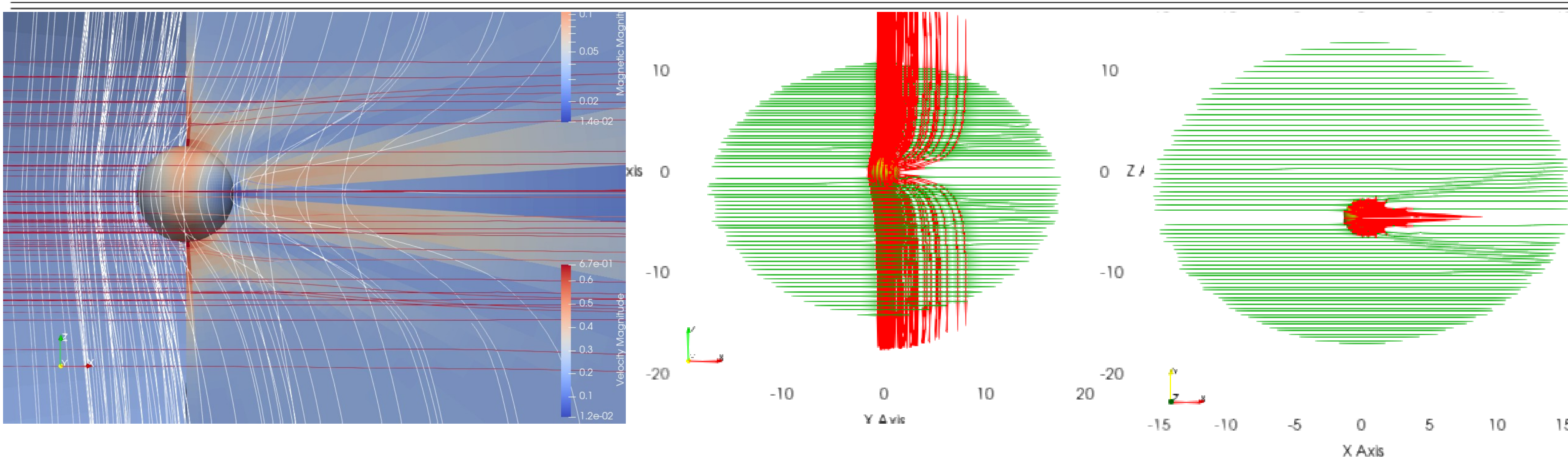
$$\begin{aligned} D &= \gamma\rho \\ \boldsymbol{m} &= w_t\gamma^2\boldsymbol{v} - b^0\boldsymbol{b} \\ E_t &= w_t\gamma^2 - b^0b^0 - p_t \end{aligned} \quad , \quad \left\{ \begin{aligned} b^0 &= \gamma\boldsymbol{v}\cdot\boldsymbol{B} \\ \boldsymbol{b} &= \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v}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

Rezultati simulacija u specijalnoj relativnosti sa PLUTO

Iako se brojke mijenjaju, rezultati se čine sličnima. U solarnom slučaju tok je nosio protone, u pulsarskom vjetru tok je elektronsko-pozitronska plazma. I Alfvenova brzina i pulsarni vjetar bliski su brzini svjetlosti, što definira vremenske skale.

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



Rezultati simulacija u specijalnoj relativnosti sa PLUTO

I brzina pulsarskog vjetra i jakost magnetskog polja koje smo mogli postići u našim simulacijama su ispod očekivanih vrijednosti za planetarni sustav oko milisekundnog pulsara. Na temelju dobivenih rezultata, ipak možemo osmisliti mogući scenarij za uspješno promatranje takvih planeta.

Dobivena frekvencija elektromagnetskog zračenja u našim simulacijama je ispod minimalne frekvencije frekvencije od 10 MHz, za koju bi emisiju apsorbirala plazma u Zemljinoj ionosferi,sprječavanje promatranja sa zemlje. Ipak, za planete na udaljenostima reda veličine 0,01 AJ od pulsara, naše simulacije pokazuju da bi se s realnom snagom magnetskog polja pulsarskog vjetra, takve planete moglo mjeriti.

Na udaljenosti reda veličine 750 pc, kao kod prvih otkrivenih egzoplaneta oko PSR B1257+12, signali su preslabi da bi se emisija mogla otkriti trenutnim instrumentima.

Ali za analogne planetarne sustave na 250 ili 100 parseka, emitirana radio snaga bila bi u dosegu sadašnjih instrumenata poput MeerKAT-a ili budućeg SKA, čija je minimalna osjetljivost reda 0,01 i 0,001 mJy.

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.)	2.1×10^{-4}	0.002	0.012	3.65×10^{12}	0.0025	0.007	NO	NO	NO
Tentative					7.4	20.1	NO	YES(b,c)	YES(b,c)
Pulsar-planet (ferrom.)	6.6×10^{-4}	0.006	0.037	1.14×10^{13}	0.01	0.028	NO	NO	NO
Tentative					13	36.4	NO	YES(b,c)	YES(b,c)

Sažetak

- Aurore su prisutne na gotovo svim planetima u Sunčevom sustavu.

- Imamo alate za simulaciju magnetosferske interakcije zvijezda-planet.

- Planeti oko pulsara nisu baš česti, <0,5%

- Iskušavamo naš alat za polarnu svjetlost na pulsarskim planetima… plus relativistički modul PLUTO koda.

- **Radioemisija s pulsarskih planeta mogla bi biti vidljiva čak i sa sadašnjim instrumentima.**