Aurora on planet around pulsar

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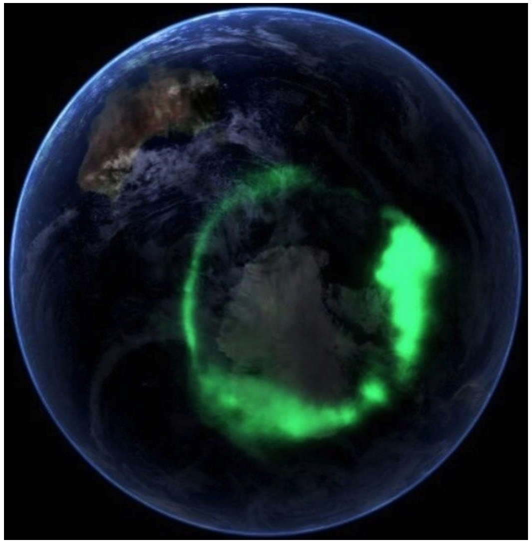
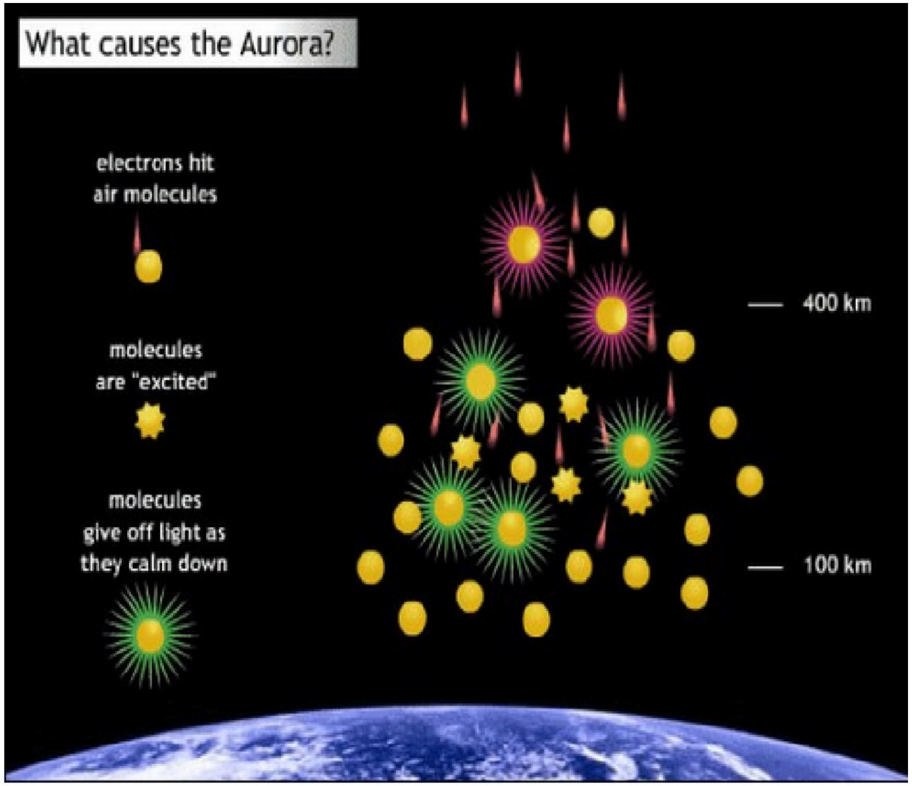
Outline

- Introduction, aurora in Solar System
- Numerical simulations of star-planet magnetosphere interaction
- Results for aurora on planets around Sun and exoplanets
- Planets around pulsars, list of (possible) objects
- Preliminary results in our simulations with pulsar parameters
- Summary

Introduction-Earth aurora





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

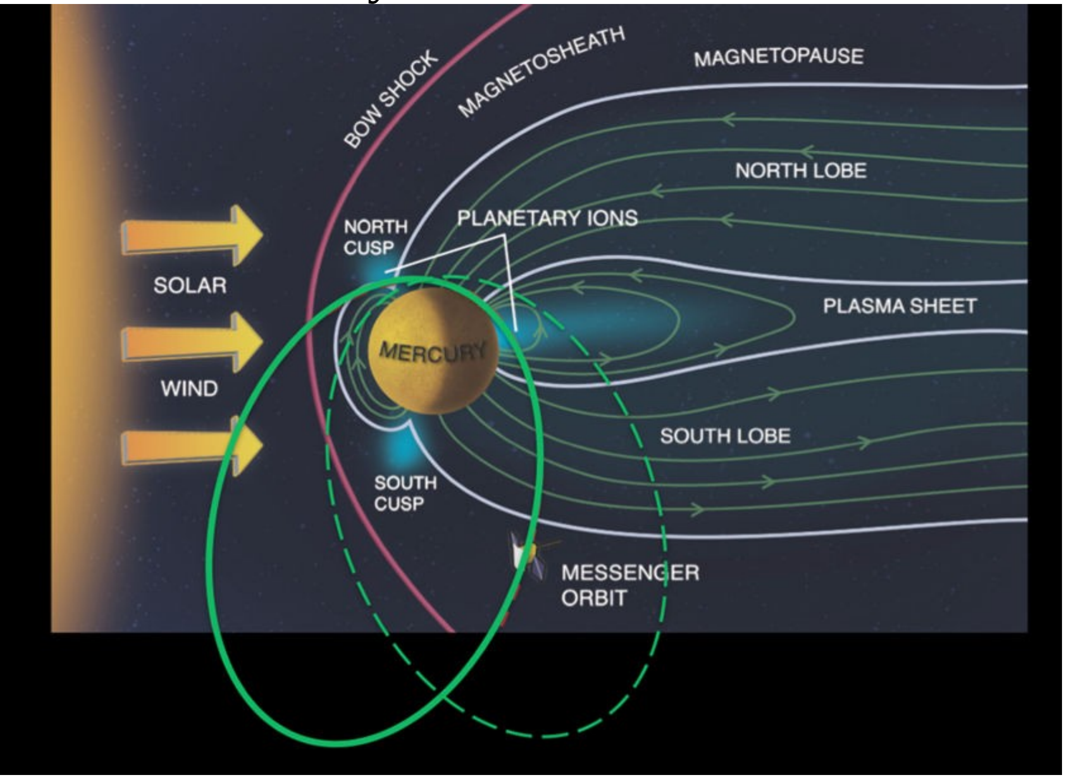
Aurora, named **aurora borealis** (by the Greek goddess of dawn, Aurora, and Greek name for northern wind, Boreas) by Pierre Gassendi in 1621, forms as an outcome of the interaction of a parent star magnetic field with the planetary field. On Earth, aurora is visible close to the geographic poles, since they are also currently close to the magnetic poles of Earth.

Different gases in the upper layers of the atmosphere are 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 Mercury, Venus

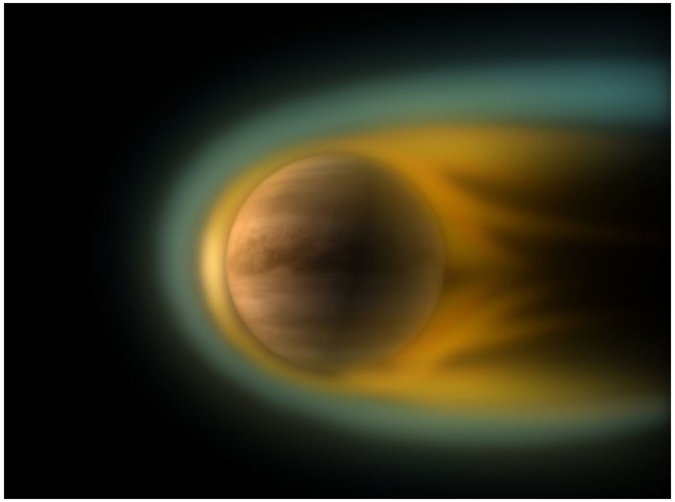
Except on Earth, auroras are found on most of the planets in the Solar system.

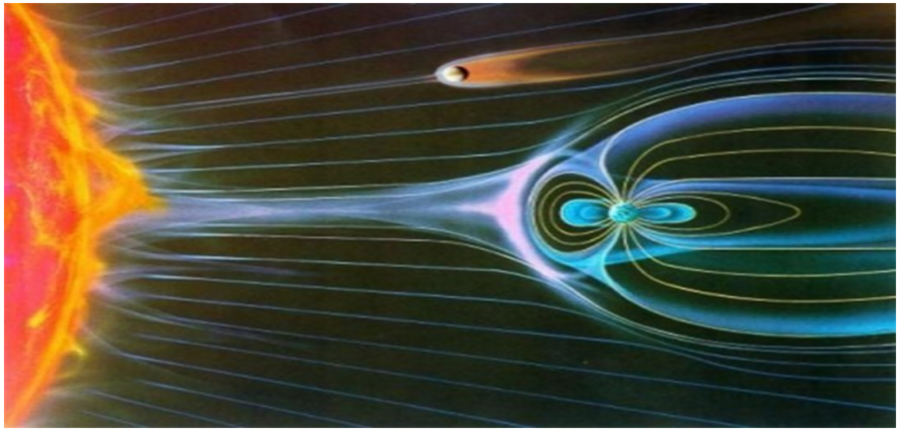
Mercury



Mercury magnetic field is well measured thanks to Messenger probe. Its aurora is similar to Earth's.

Venus

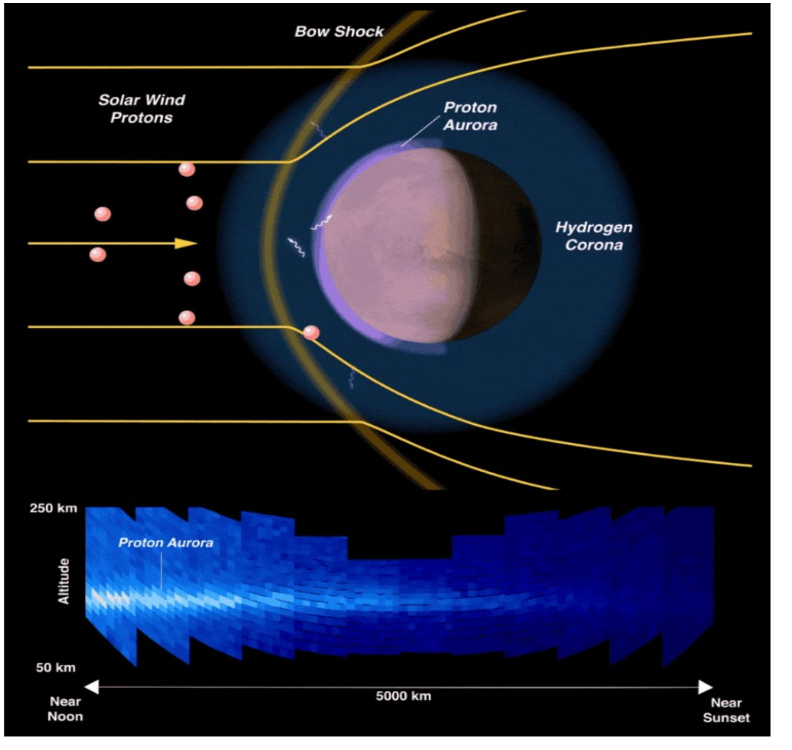




Venus has smaller aurora towards Sun than Earth, here a comparison is shown.

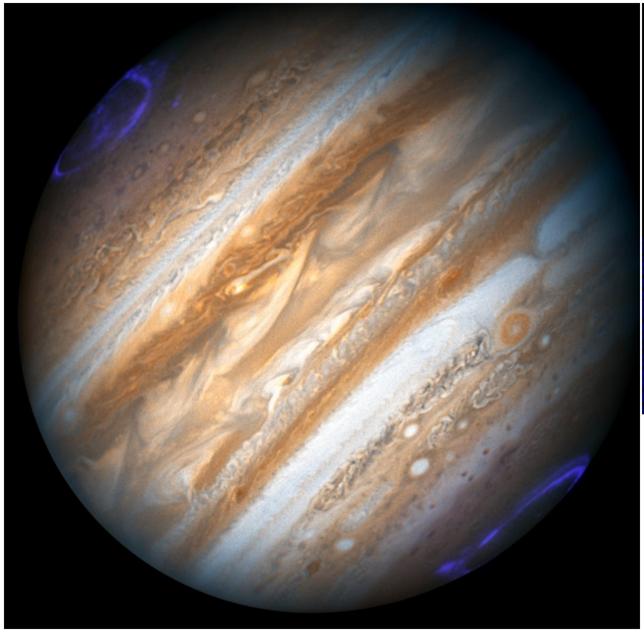
Mars aurora

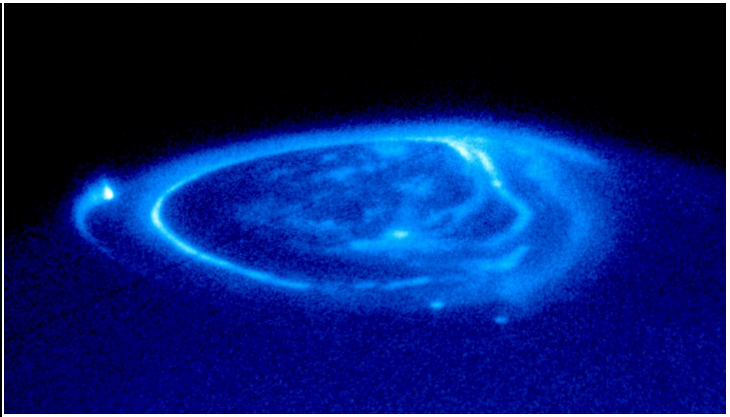
Even in the planets like Mars, which do not have significant magnetic field, we observe aurora, formed as a result of interaction of particles-here mostly protons- from the solar wind shock where the planet moves through the wind. It is most visible at the sunny side of the planet.



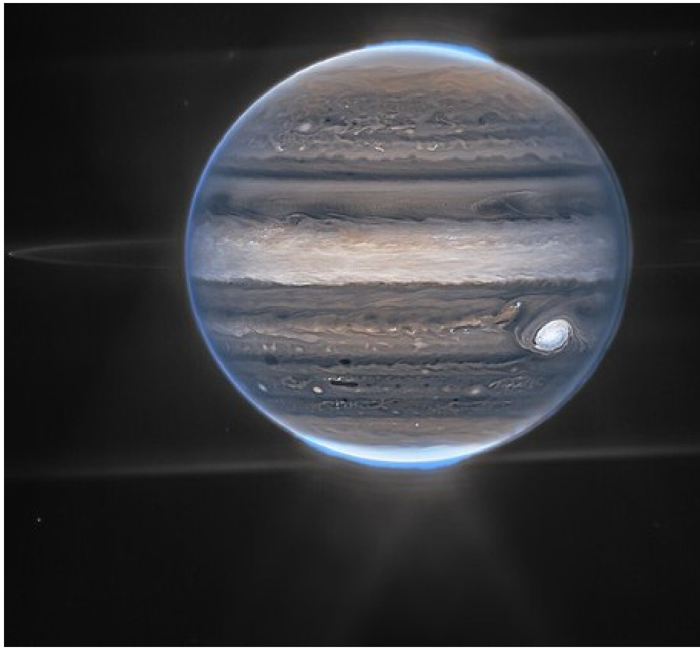
Auroras on large gaseous planets

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.

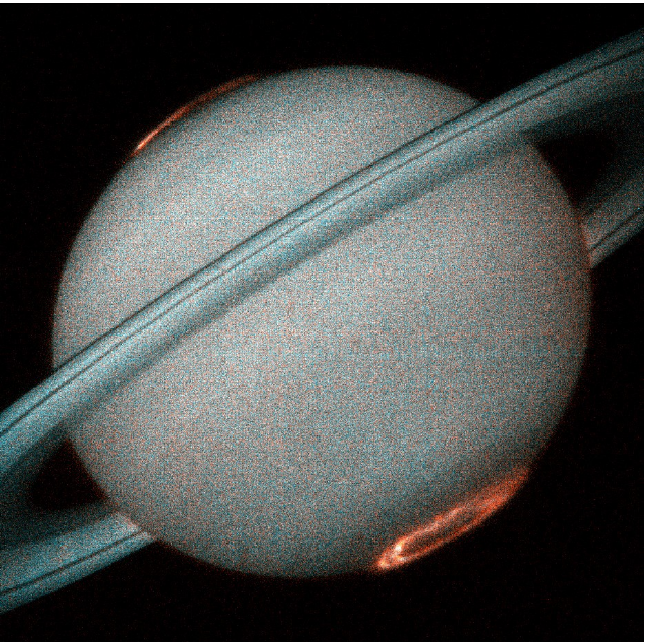




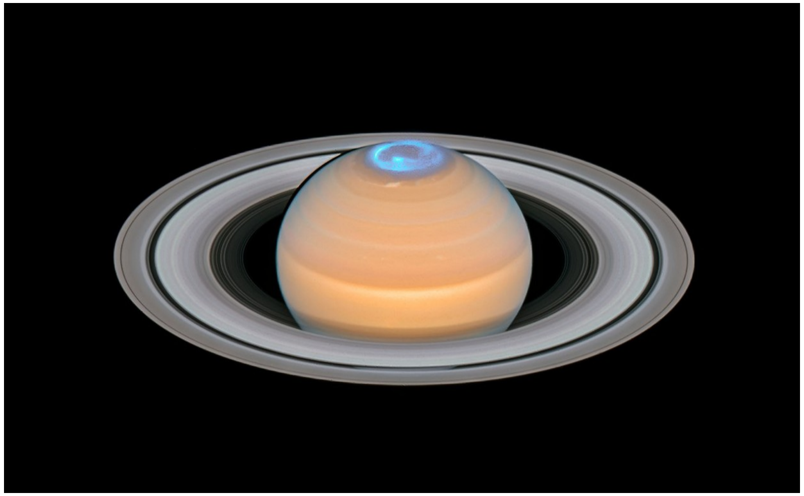
Spots in aurora on Jupiter are magnetically connected with satelites: the spot on the left side is connected with Io, bottom two with Ganymede and Europe.

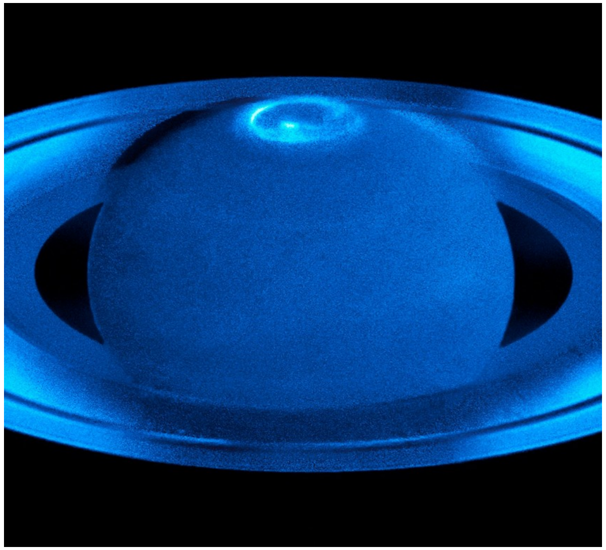


JWST’s capture of aurora on Jupiter



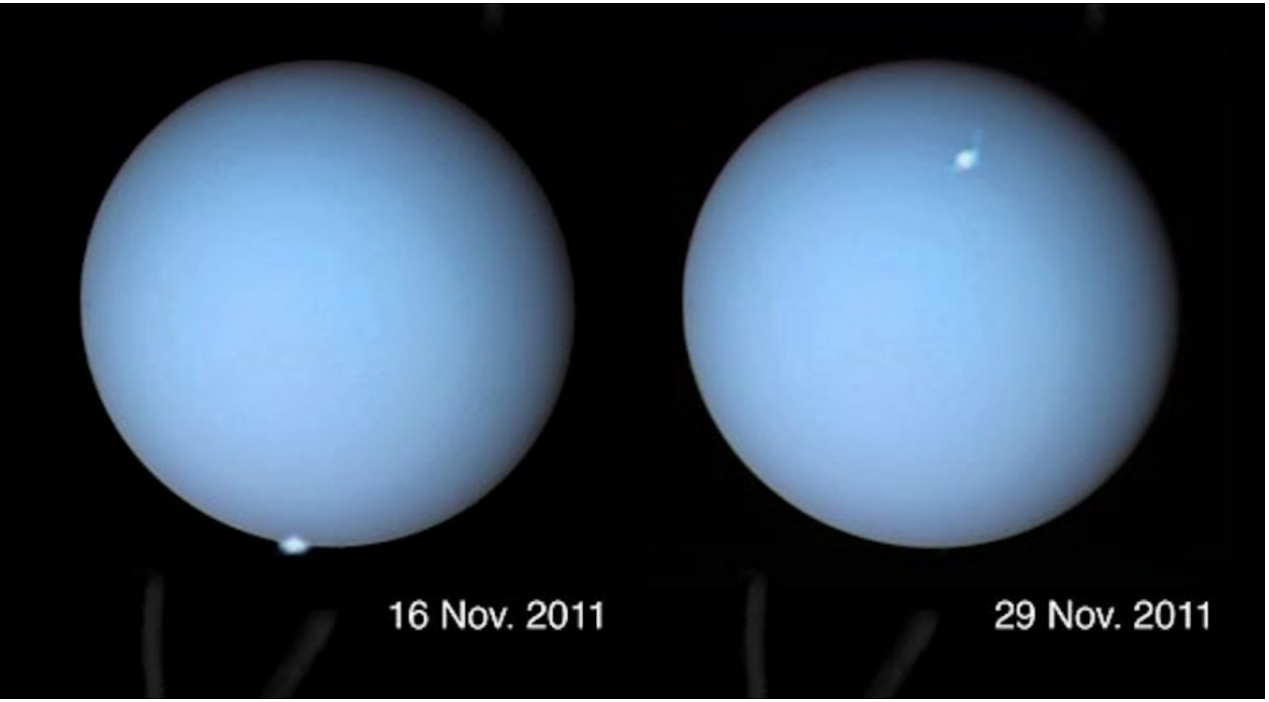
Saturn also features polar aurora.

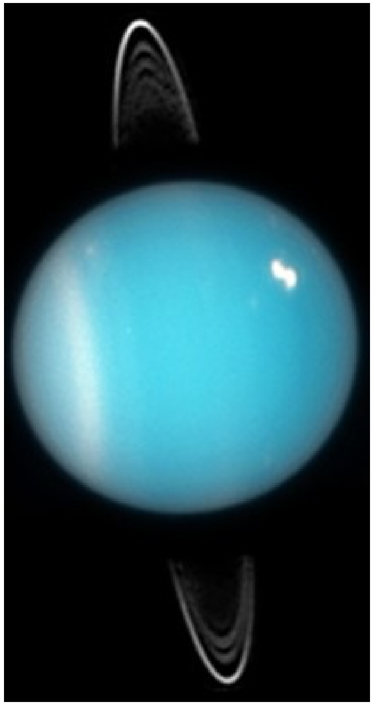




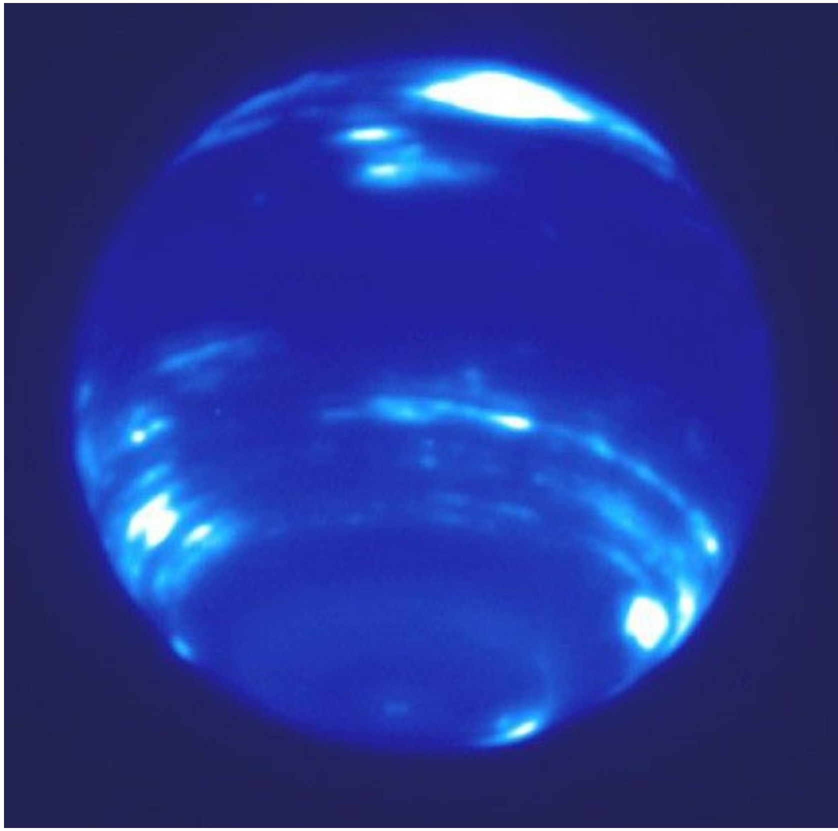
Aurora on Uranus

HST observed auroras on Uranus:





And Keck on Neptune:

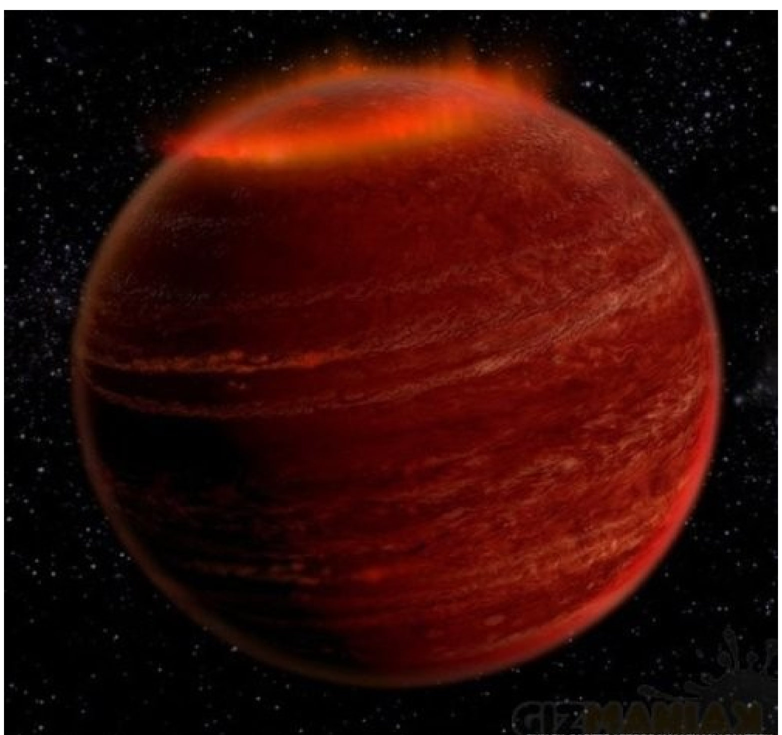


Extrasolar and exoplanet auroras

•As for now, we have an observation of extrasolar aurora on a brown dwarf LSR J1835+3259, 18 lyrs from us, in Lyra. There are more of similar objects which show characteristic spectral features which point to aurora. Shown is an artist impression, not the real observation. It is reddish aurora, from more hydrogen in the atmosphere, and about million times more intense, because of larger magnetic field.

•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 replenished body of plasma within the magnetosphere. This mass-loading can be achieved in multiple ways, including interaction with the interstellar medium, a volcanically active orbiting planet or magnetic reconnection at the photosphere. Alternatively, an orbiting planetary body embedded within the magnetosphere could provide magnetospheric interaction.



In the cases of **exoplanets**, we also expect auroras, and we can use the same simulations and make the predictions for different kinds of planets.

In the cases of **planets around pulsars**, which were actually the first observed exoplanets, we can expect similar effects. Because of much larger field involved, they could behave different from usual planet aurora.

Here we try to make the first such model, by introducing necessary modifications in our star-planet interaction setup.

Numerical simulations of star-planet interaction

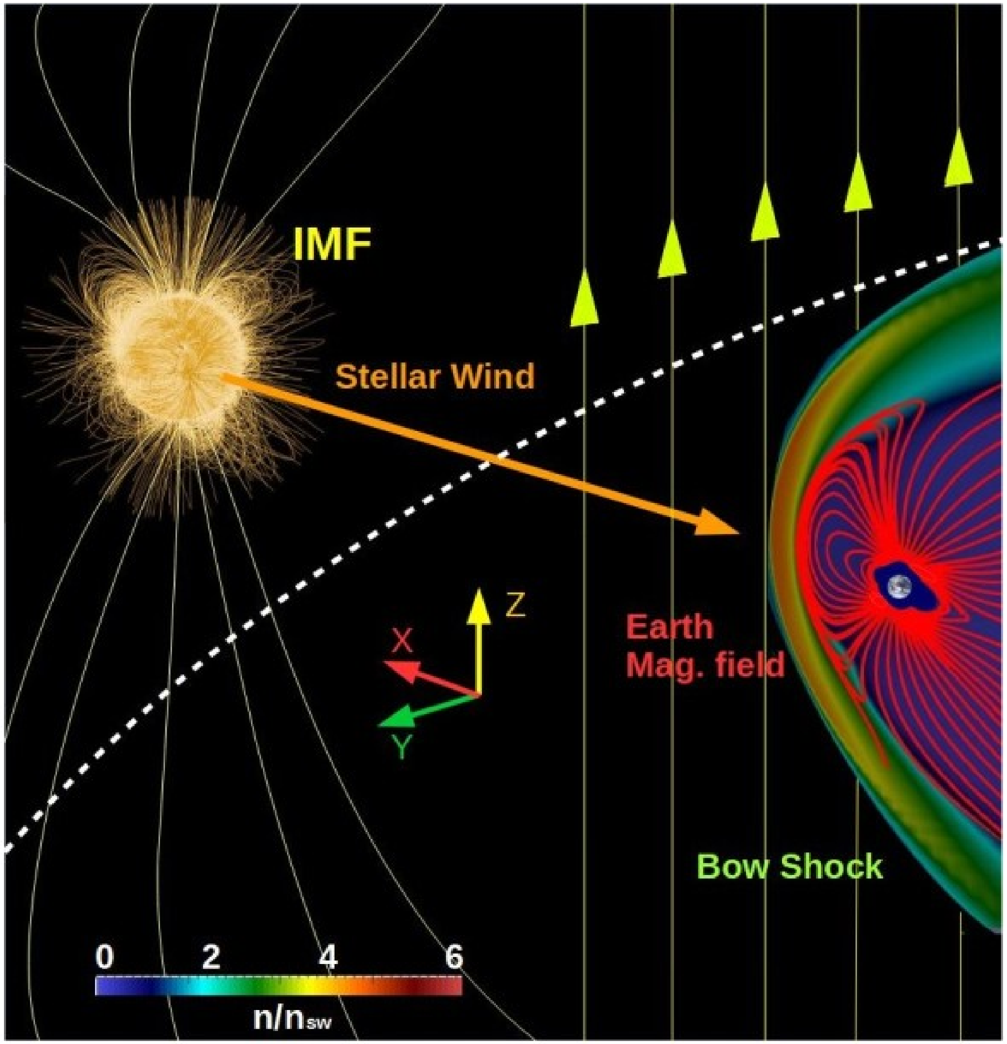


Fig. 1. 3D view of a typical simulation setup. We show the density distribution (color scale), Earth magnetic field lines (red lines), and IMF (yellow lines). The yellow arrows indicate the orientation of the IMF (northward orientation). The dashed white line shows the beginning of the simulation domain (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.

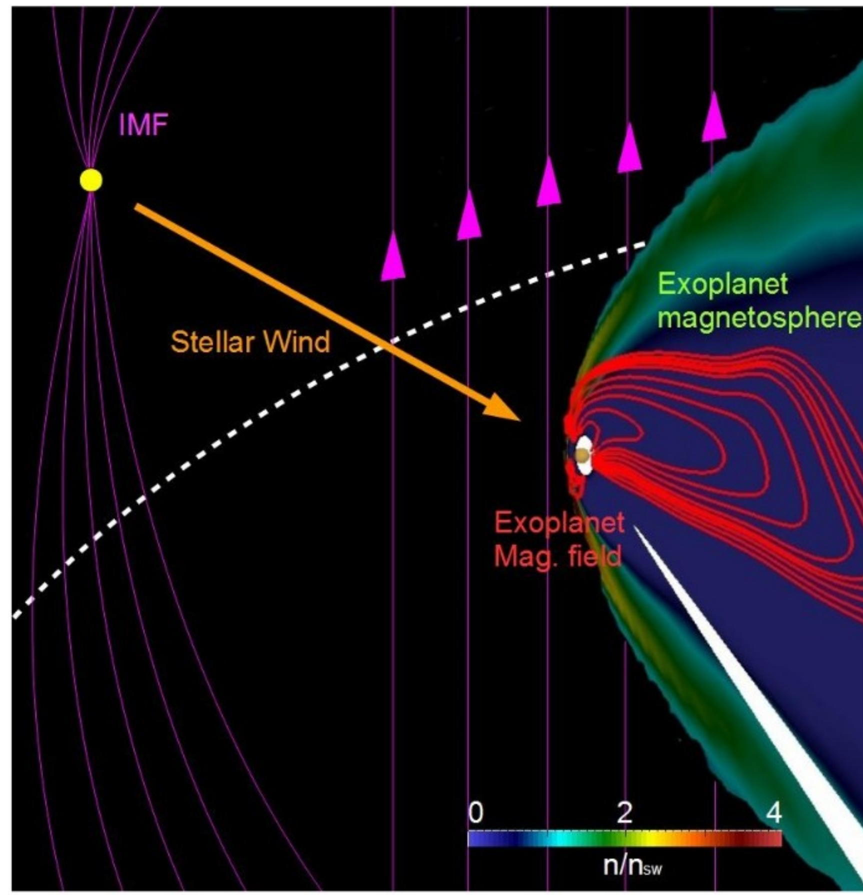


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the exoplanet magnetic field (red lines) and IMF (pink lines). The arrows indicate the orientation of the IMF (Northward orientation). Dashed white line shows the beginning of the simulation domain.

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.

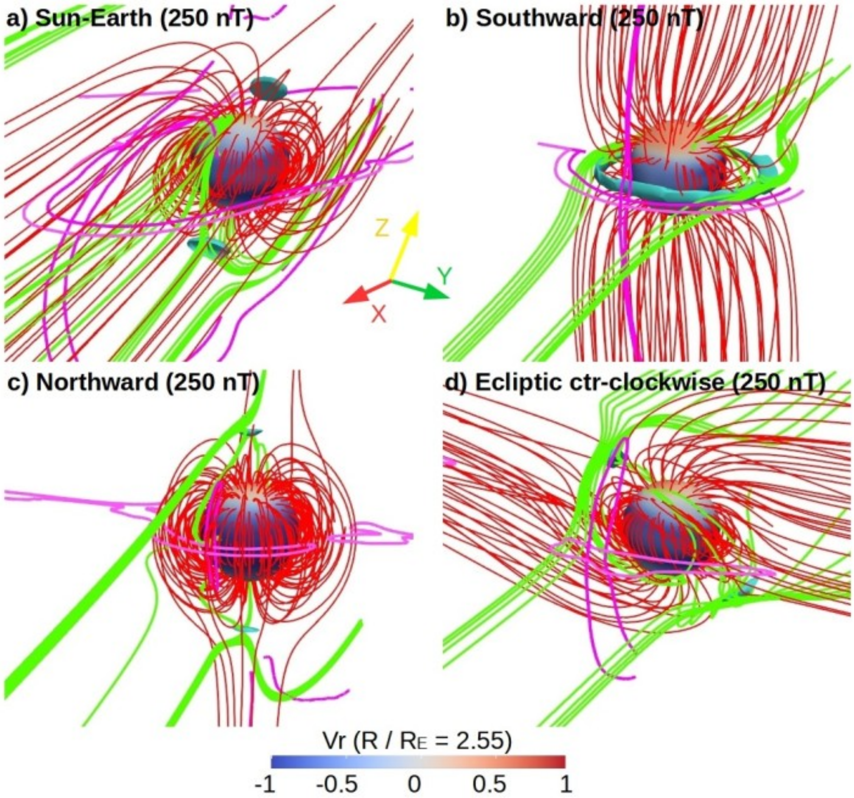


Fig. 3. 3D view of the Earth magnetosphere topology if $|B|_{IMF} = 250$ nT for (*a*) a Sun–Earth, (*b*) southward, (*c*) northward, and (*d*) ecliptic ctr-clockwise IMF orientations. We show the Earth magnetic field (red lines), SW stream functions (green lines), and isocontours of the plasma density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

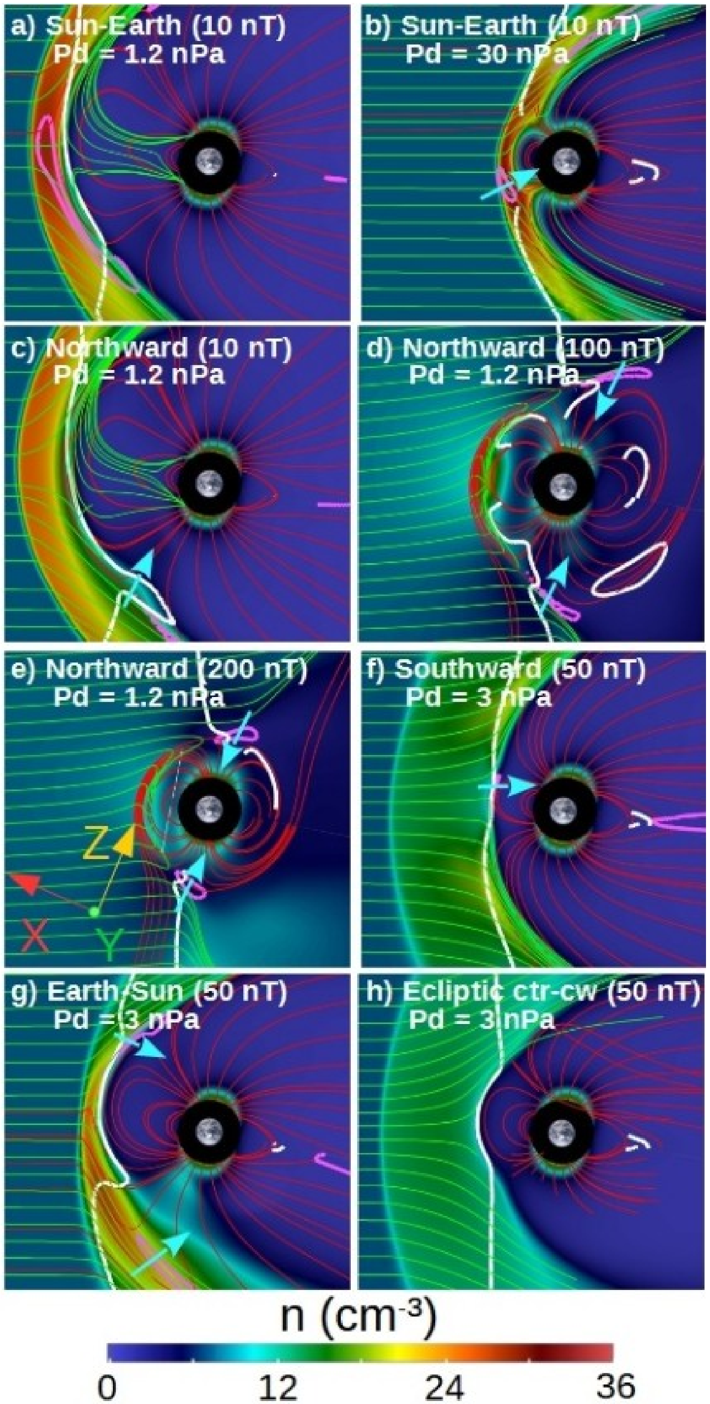


Fig. 2. Polar cut (*XY* plane) of the plasma density in simulations with (*a*) Sun–Earth IMF orientation $|B_{IMF}| = 10$ nT $P_d = 1.2$ nPa, (*b*) Sun–Earth IMF orientation $|B_{IMF}| = 10$ nT $P_d = 30$ nPa, (*c*) northward IMF orientation $|B_{IMF}| = 10$ nT $P_d = 1.2$ nPa, (*d*) northward IMF orientation $|B_{IMF}| = 100$ nT $P_d = 1.2$ nPa, (*e*) northward IMF orientation $|B_{IMF}| = 200$ nT $P_d = 1.2$ nPa, (*f*) southward IMF orientation $|B_{IMF}| = 50$ nT $P_d = 3$ nPa, (*g*) Earth–Sun IMF orientation $|B_{IMF}| = 50$ nT $P_d = 3$ nPa, and (*h*) ecliptic ctr-cw IMF orientation $|B_{IMF}| = 50$ 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.

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.

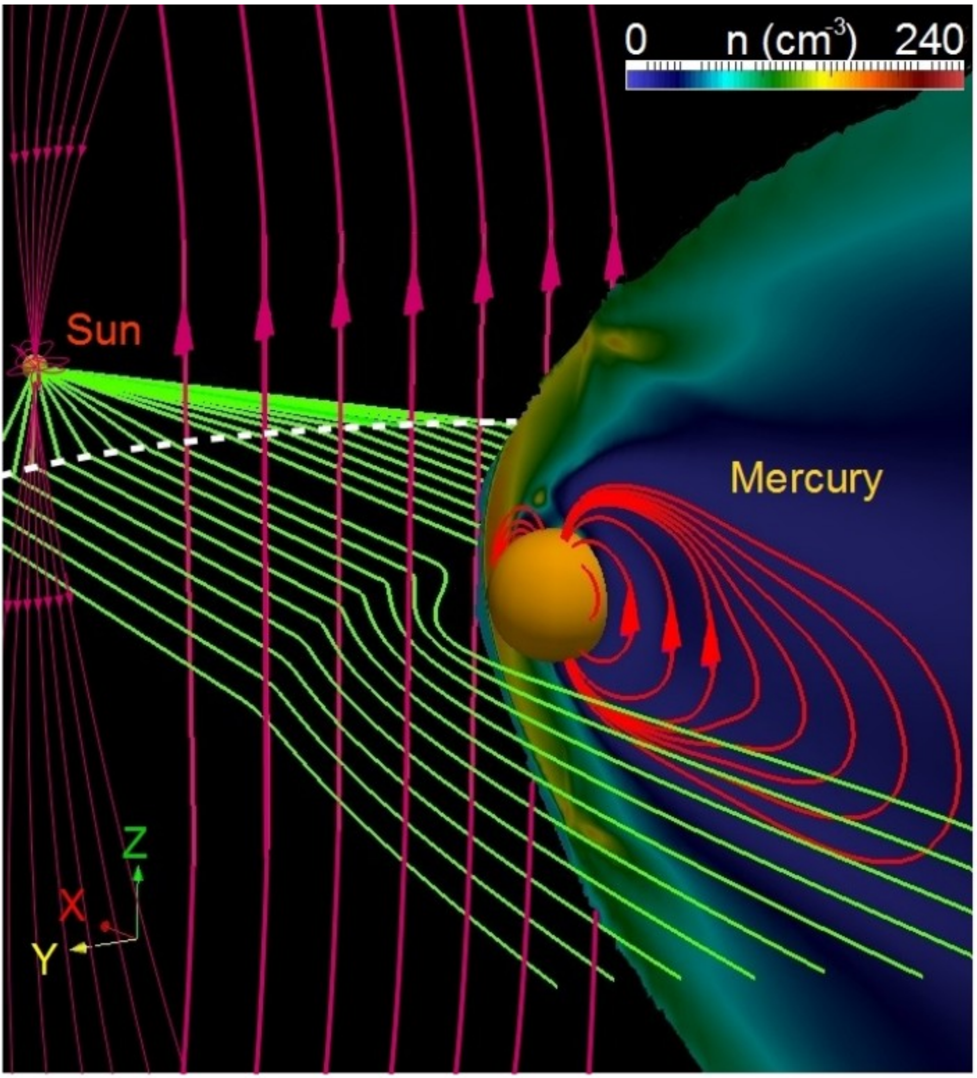


Fig. 1. 3D view of the system. Density distribution (color scale), field lines of the Hermean magnetic field (red lines), IMF (pink lines) and solar wind stream lines (green lines). The arrows indicate the orientation of the Hermean and interplanetary magnetic fields (case Bz). Dashed white line shows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

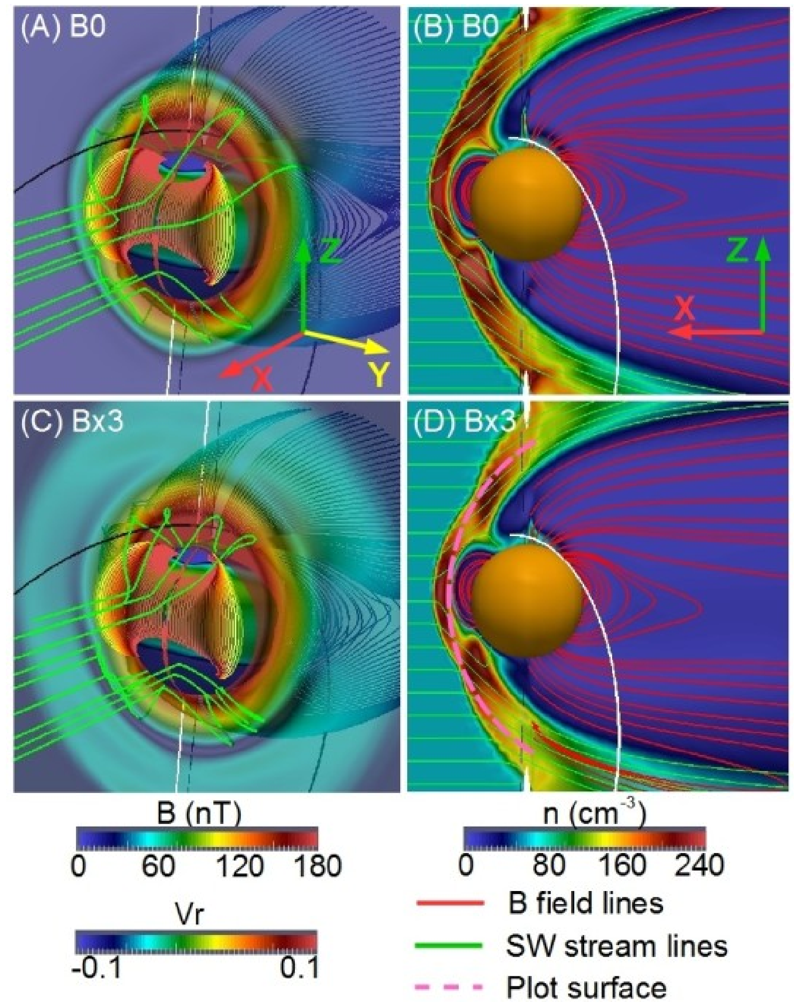


Fig. 2. Hermean magnetic field lines with the intensity imprinted on the field lines by a color scale for the reference case (A) and simulation Bx3 (C). Magnetic field intensity at the frontal plane $X = 0.3R_M$. SW stream lines (green). Inflow/outflow regions on the planet surface (blue/red). Polar 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.

Planets around pulsars

•First exoplanets were found in orbit around a Galactic disk 6.2-ms pulsar PSR1257+12 (Wolszczan & Frail, 1992). PSR stands for "Pulsating Source of Radio" followed by the pulsar's right ascension and degrees of declination, B is added nowadays in the official name, to mark that coordinates are for the 1950.0 epoch, so official name is PSR B1257+12, or PSR J1300+1240 in epoch 2000, assigned with "J". Usually pulsars older than 1993 retain this epoch names, but since the newer epoch includes position precisely to minutes in the name, all pulsars have their J epoch names.

•The precise timing of millisecond pulsars was instrumental for the discovery.

•This pulsar rotates about 161 times per second, 9650 rpm, 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 this gives a dipole magnetic field of $B = 3 \times 10^{19} (P\dot{P})^{1/2}$ 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. It is 2300 ly (710 pc) from us, in the constellation Virgo.

•The detected planets (B and C today) were reported to have masses of at least 4.3 and 3.9 Earth masses. Their respective distances from the pulsar are 0.36 AU and 0.46 AU, and they move in almost circular orbits with periods of 66.6 and 98 days. The third planet of 0.02 Earth masses (=double Moon mass), which is a planet A today, with period of 25 days, positioned closer, at 0.19 AU, was identified after additional analysis of the data (Wolszczan 1994) [Scherer et al. (1997) pointed out that its 25.3 day orbital period is close to the solar rotation period at the 17deg solar latitude of PSR 1257+12, and suggested that the modulation might actually be due to modulation in the electron density 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 (Wolszczan et al. 2000b), which would follow for a plasma effect. So, it is rather still a planet]. Orbits for A, B and C are similarly inclined 50, 53, 47 degrees, respectively.

•The fourth possible planet in this system (Wolszczan 1996) was later dismissed (Wolszczan et al. 2000a).

•This were the first exoplanets, which was long anticipated, but nobody expected it around a pulsar! The first planet around a "normal" star was found only in 1995. It was the first "hot Jupiter", a large gaseous planet with a surprising period of 4.2 days, orbiting very closely the star 51 Pegasi.

•In 2015 naming of exoplanets was given to the public in NameExoWorlds campaign, and 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 increasing distance), 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

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, 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 .

•A special feature because it *revived the field*: Interesting inconclusive one: (1982, 1994?) PSR B1937+21 close (few degrees) by the 1st discovered pulsar PSR B1919+21 (by Jocelyn Bell), this is the 1st discovered ms pulsar, 1.5ms (624 rotations in a second!), a companion of 0.001 M_Earth, like Ceres, at 2.7 AU, asteroid belt? More observations needed. Also points to a large precision of the method, when long observations available.

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.

-(1979 planets rejected, 2017 disputed) PSR B0329+54, 3 460 ly away in Camelopardalis, period 0.71452 s, 5 million yrs old. Remains the possibility of a long period planet.

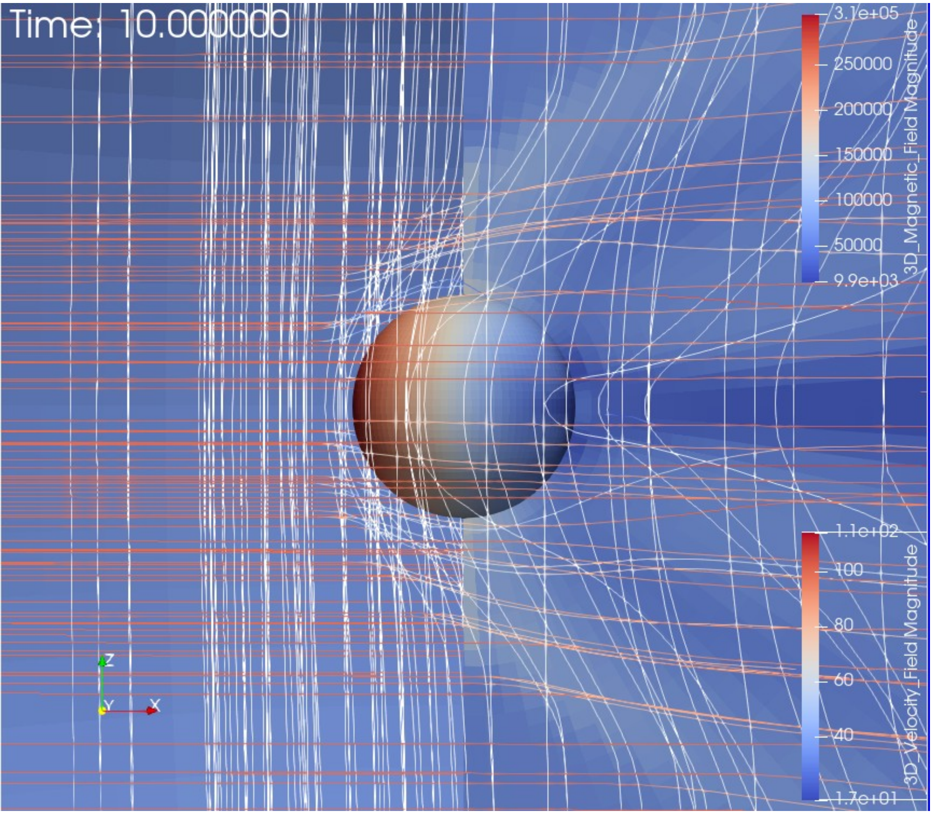
-(1968 Puschino pulsar, 2014 planets) PSR B0943+10 is an 5mln years old pulsar in Leo, 2 000 ly away, with period 1.1s. Two gas giant planets,masses 2.8 and 2.6M_Jup with 730 and 1460 days orbital period, 1/8 and 2.9 AU radius orbits, respectively. There are more tentative objects with planets of Jupiter 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.

Numerical simulations with the NS-planet interaction

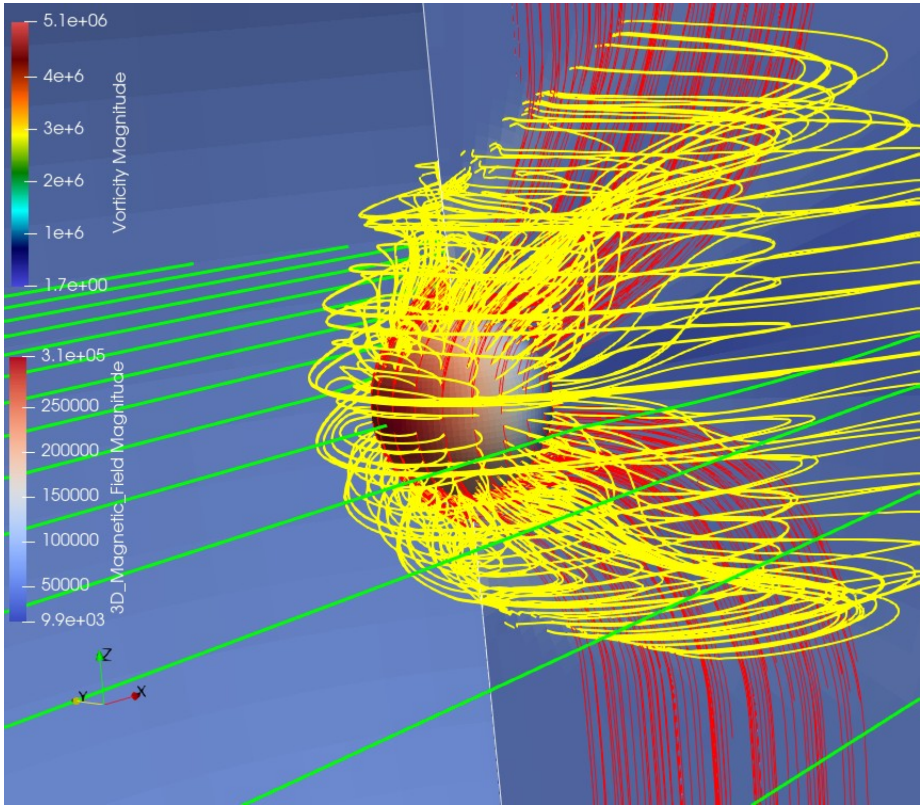
I show preliminary results in our simulations with NS parameters. We are increasing the stellar magnetic field in the simulations-to accommodate for the large field we increase the density of the interplanetary medium, local magnetic field strength near the planet and stellar wind velocity. We probe for the different planetary surface boundary conditions (conducting, ferromagnetic) - this is potentially interesting for the planetary study: planets around NS could have some extreme physical properties.

Conducting planet (B_planet=0):

Bsw=3.0, Vsw=1.e9



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

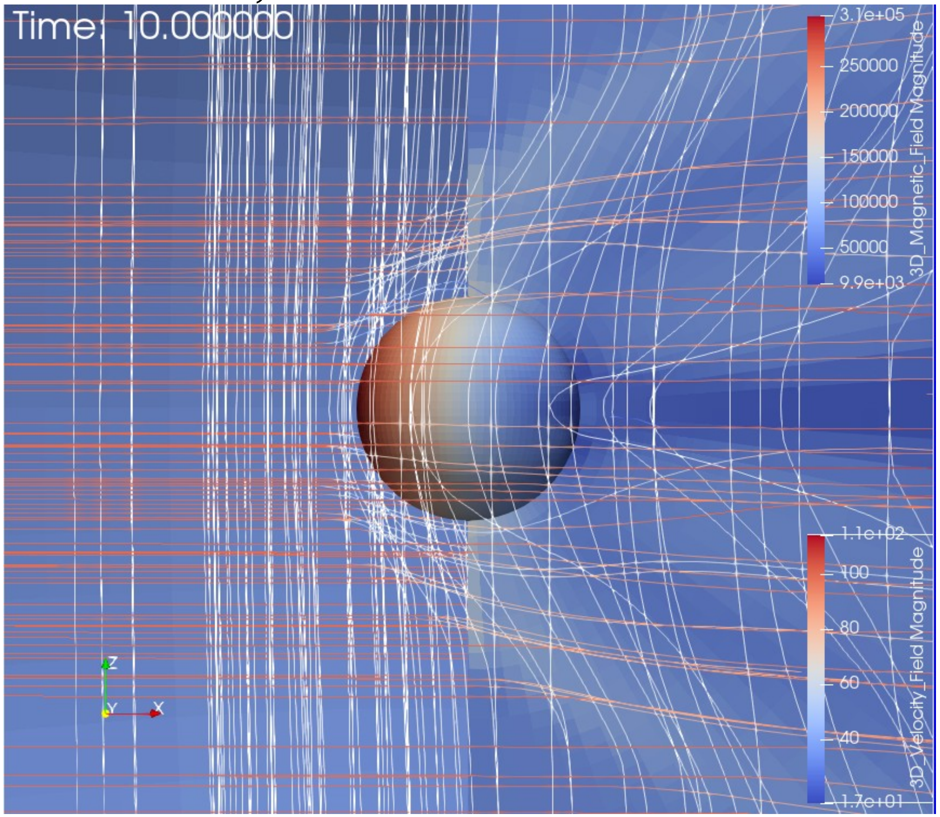


For the conducting planet atmosphere case, electric current loops remain close to the planet surface.

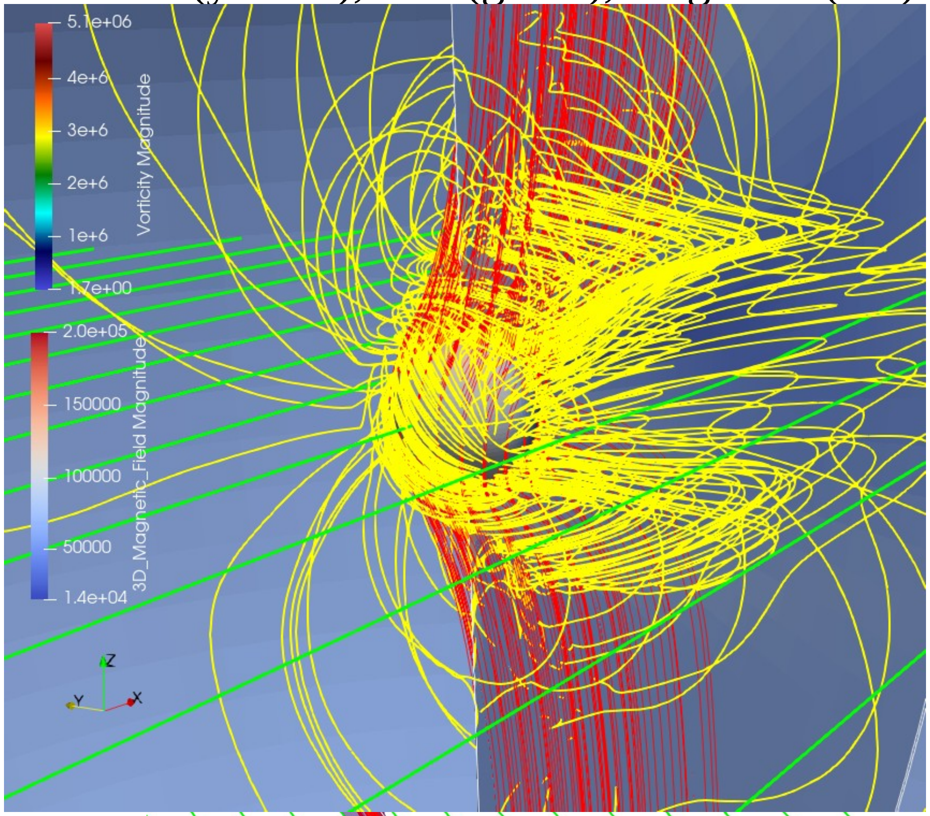
Numerical simulations with the NS-planet interaction

In the case of feromagnetic planet surface, results are different, currents point to an extended dipolar *electric field* structure. Work is in progress to understand the possible auroral effects.

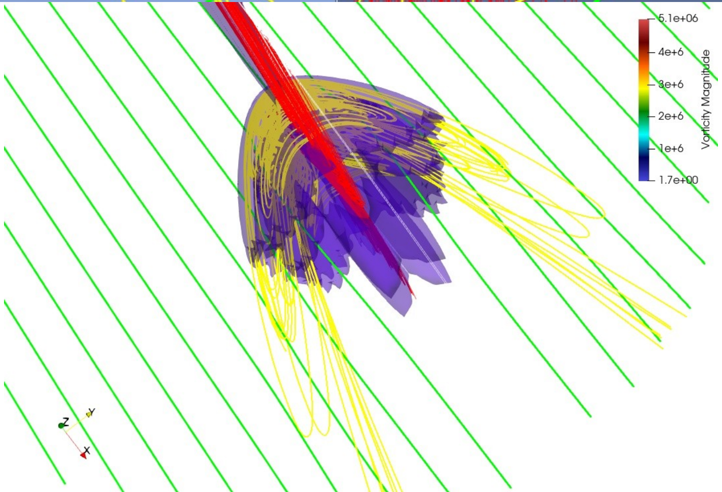
Bsw=3.0, Vsw=1.e9



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



Equatorial view-Alfven "wings":



Summary

- Aurorae are present in almost all planets in the Solar system.
- We have a tool to model 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.