Modeling the interaction of the stellar wind with planetary magnetospheres: radio-emission and exoplanet habitability

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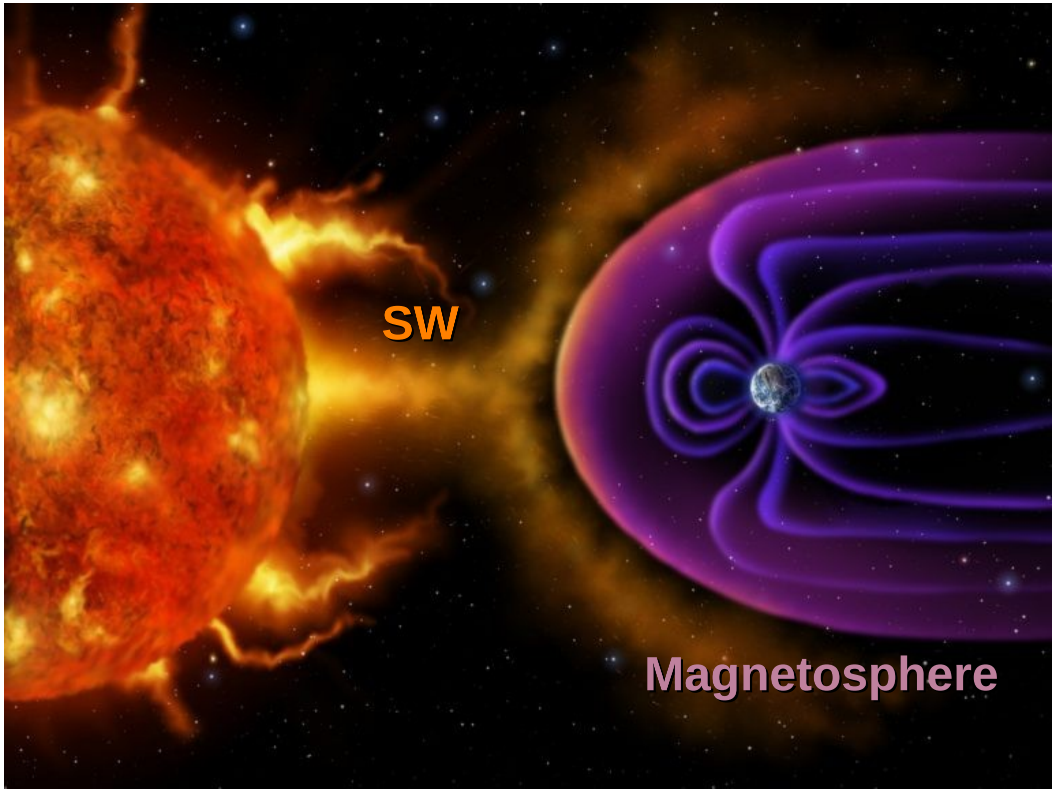
MOTIVATION



The stars expel hot plasma called stellar wind (SW).

Planetary magnetic field bends due to the SW flow.

The planetary magnetosphere deflects the SW.

The magnetosphere avoids the direct precipitation of the SW on the planet surface, condition required for the planet habitability.

The stellar wind and the interplanetary magnetic field modify the topology of planetary magnetosphere: exoplanet habitability depends on the space weather conditions around the host star !!

MOTIVATION

There is a large power dissipation during the SW interaction with the planetary magnetosphere.

Magnetosphere electrons are accelerated along the magnetic field lines.

Cyclotron maser radiation is generated.

Radio-emission from planetary magnetospheres are measured by ground-based radio telescopes.

The radio-emission contains information of the space weather conditions around the host star and the exoplanet intrinsic magnetic field.

MOTIVATION

Target:

1) Analyze the interaction of the stellar wind with planetary magnetospheres.

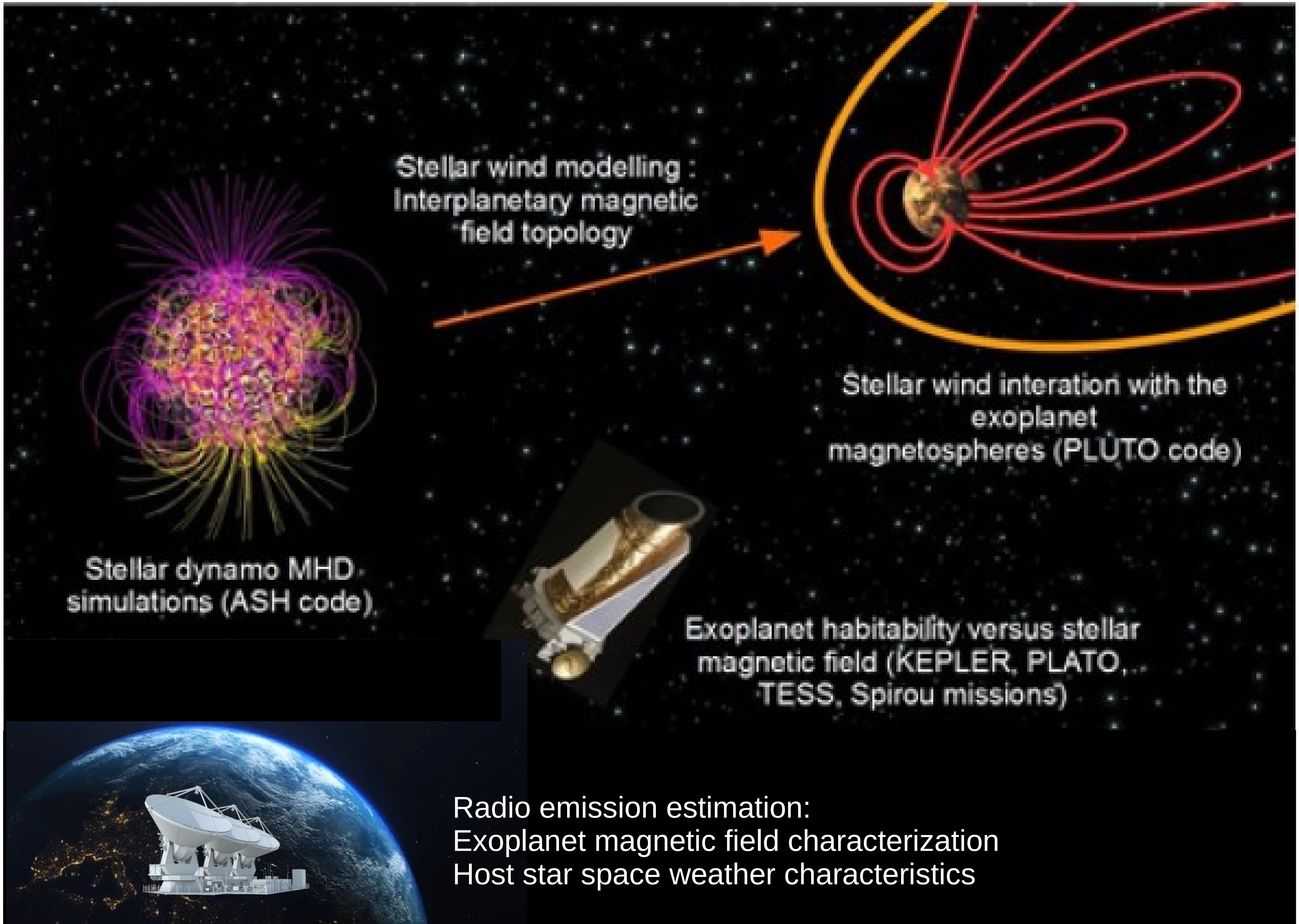
2) Identify the effect of the space weather conditions and intrinsic magnetic field topology on the exoplanet habitability and radio-emision from exoplanets.

Method:

1) Performing parametric studies using a single fluid MHD model with respect to:
- The dynamic pressure of the stellar wind.
- Interplanetary magnetic field intensity and orientation.
- Exoplanet magnetic field intensity and topology.

2) Calculate the radio emission applying the radio-magnetic Bode's law.

MOTIVATION: GLOBAL PICTURE



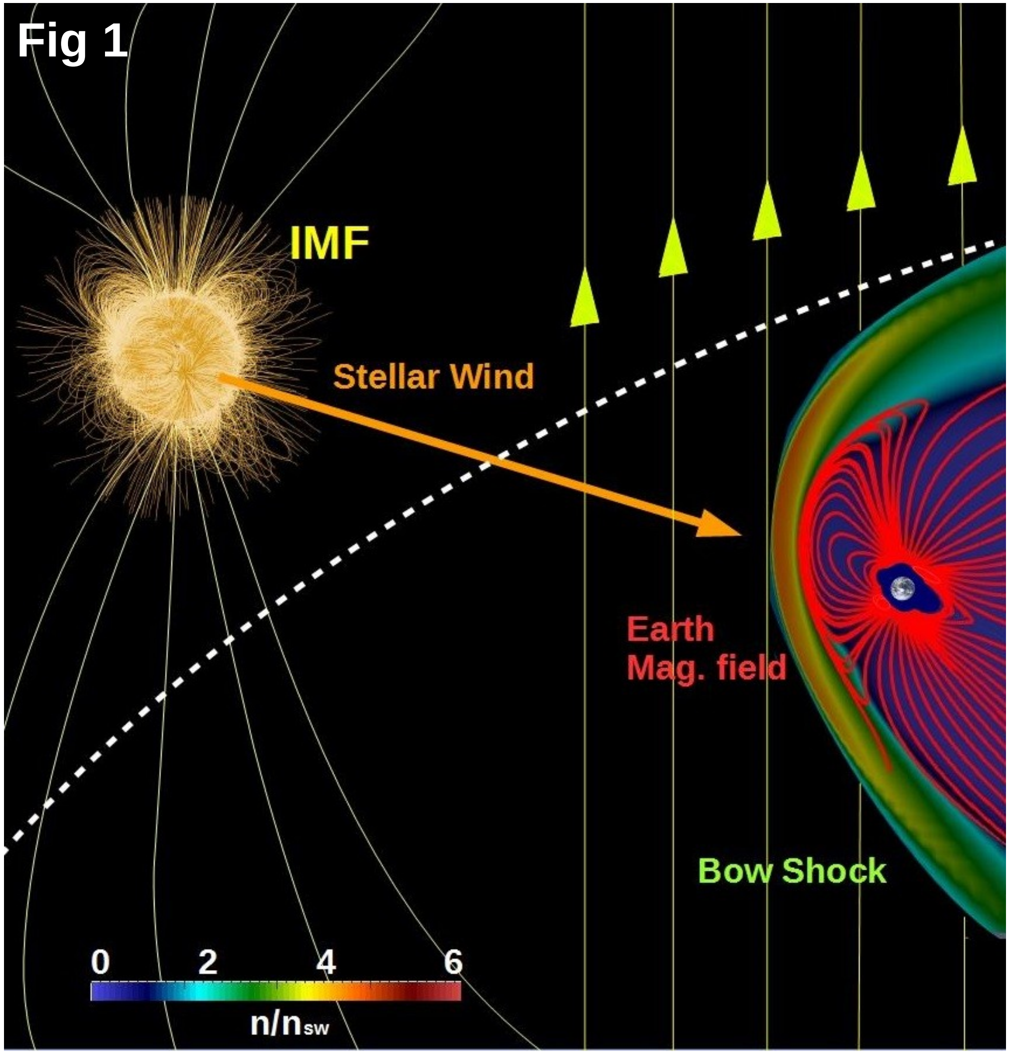
NUMERICAL MODEL

Ideal MHD version of the open source code PLUTO in spherical coordinates.

The model solves the time evolution of a single fluid polytropic plasma in the non resistive and inviscid limit.

3D view of the system for a Northward IMF orientation (**fig 1**).

SW and IMF fixed in the inflow boundary (the star is not included in the model).



NUMERICAL MODEL: EXTREME SPACE WEATHER EXAMPLES

3D view of the Earth magnetosphere for a Northward IMF orientation, IMF intensity of 250 nT and a SW dynamic pressure of 1.2 nPa, **fig 2:**

Earth magnetic field lines (red lines).

SW stream lines (green lines).

Reconnection regions between the Earth magnetic field and the IMF (cyan isocontour).

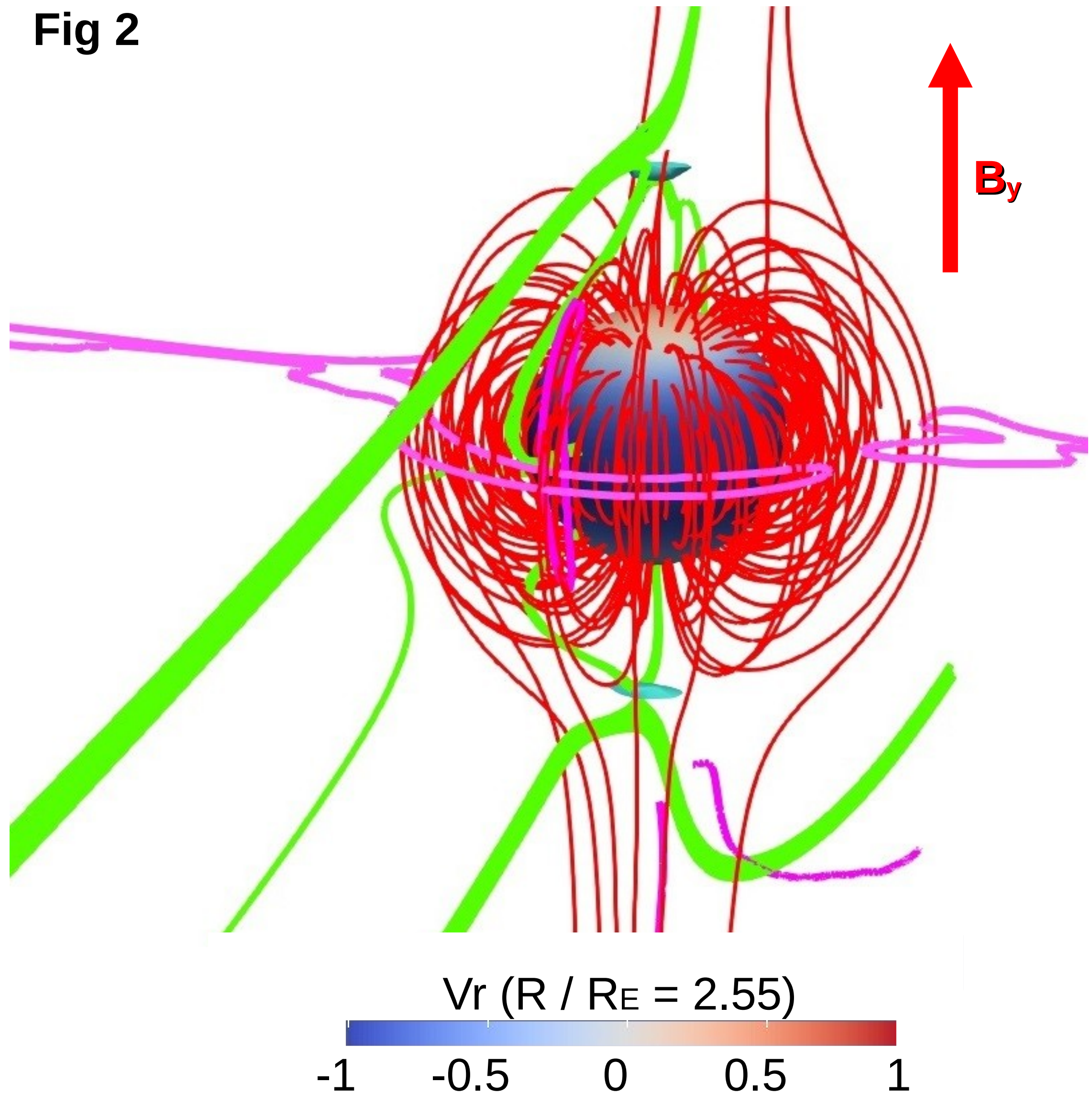
Bow Shock (pink lines).

Plasma flows towards the Earth surface at $R/R_E = 2.55$ (isosurface)

1) The SW is injected inside the inner magnetosphere through the reconnection regions.

2) The IMF modifies the Earth magnetosphere topology.

Fig 2

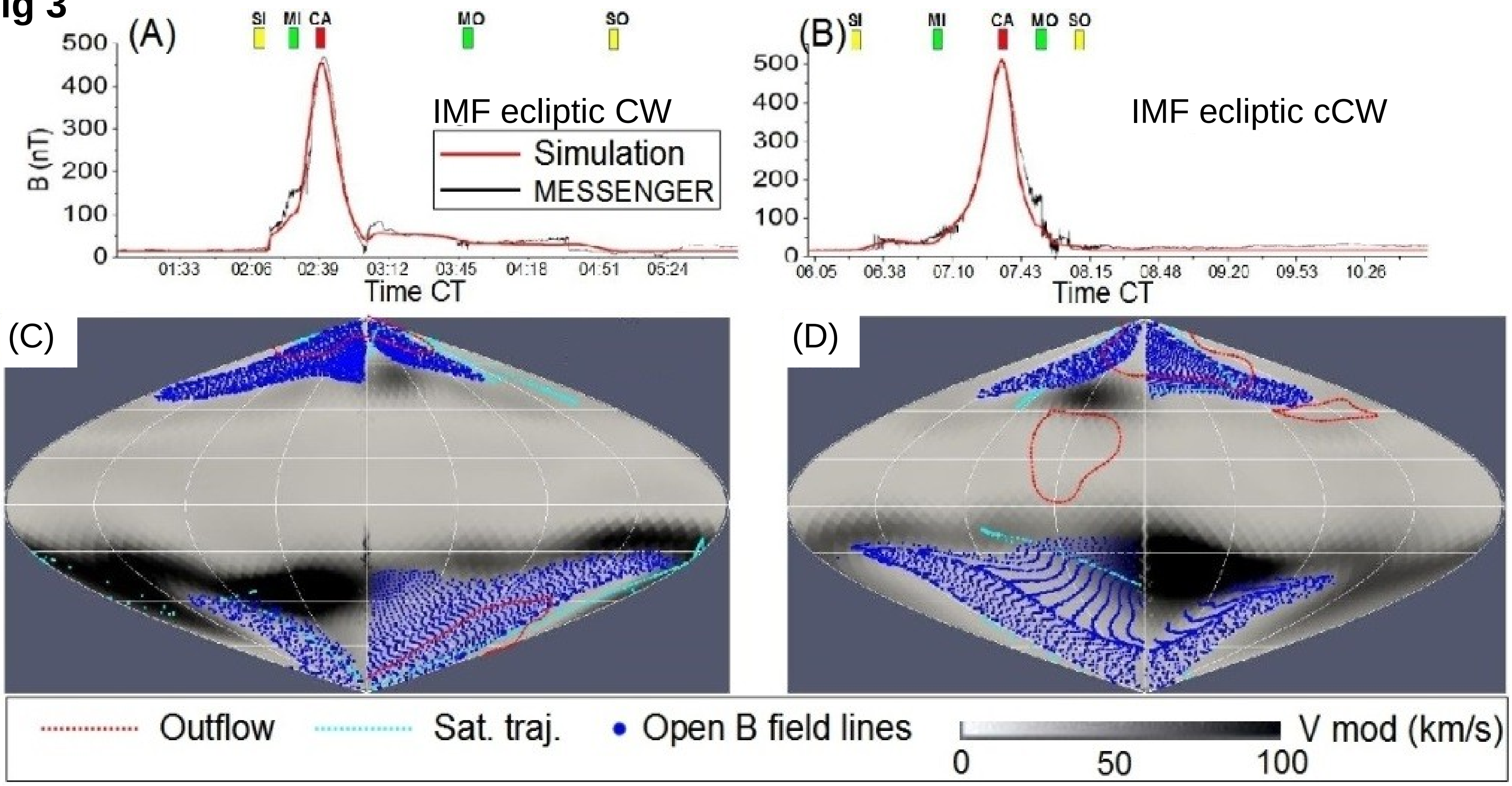


APPLICATIONS

Hermean magnetosphere

Model validation: simulation results versus MESSENGER magnetometer data:

Fig 3



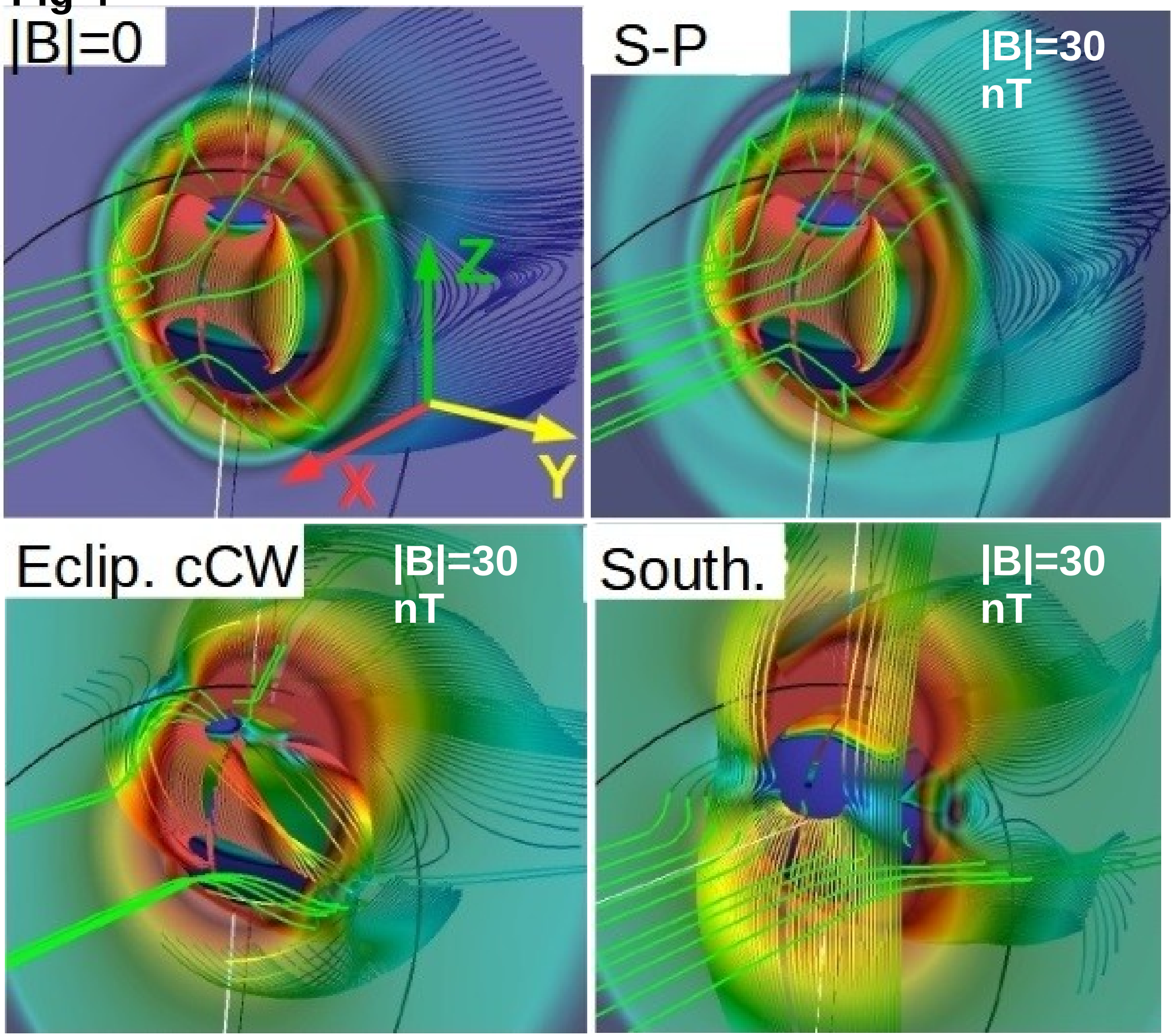
- The simulations reproduce the same global magnetospheric structures with respect to MESSENGER magnetometer data (Fig 3).

- The distortion of the Hermean magnetosphere by the IMF orientation modifies the plasma flows toward the planet surface and the open/close magnetic field lines distribution.

Hermean magnetosphere

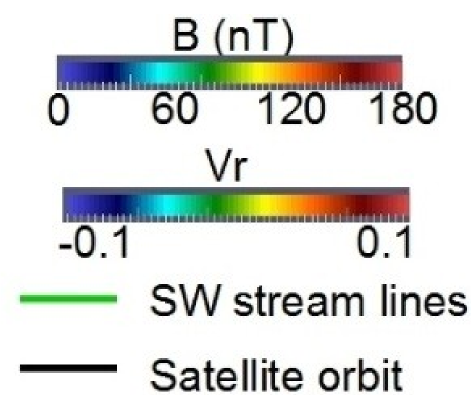
Effect of the IMF orientation and intensity on the Hermean magnetosphere topology:

Fig 4



- The topology of the Hermean magnetosphere depends on the IMF intensity and orientation (fig 4).

- The locations of the IMF / Hermean magnetic field re-connection region is the key !!

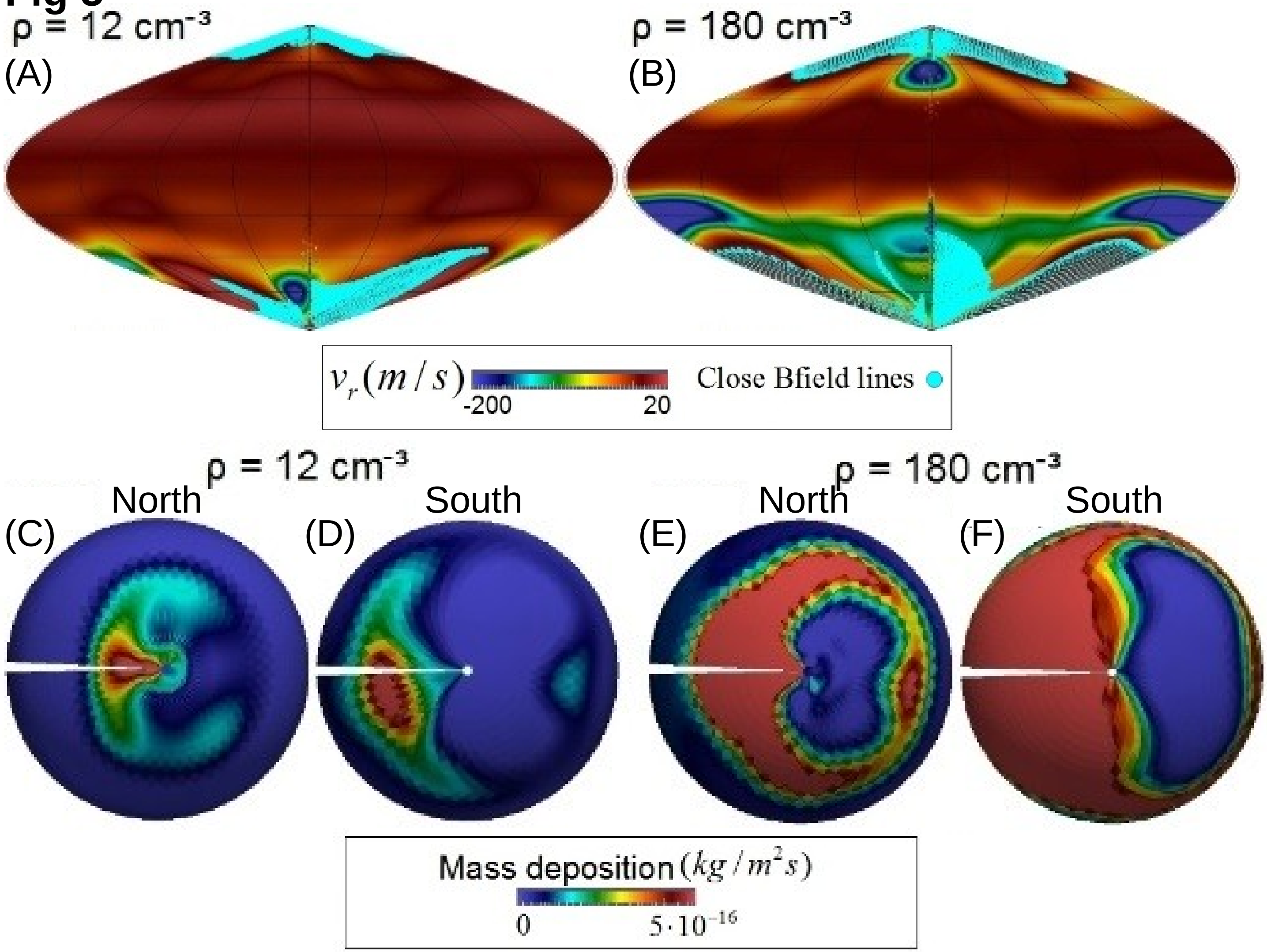


J. Varela et al *"Effect of interplanetary magnetic field orientation and strength on the Hermean magnetosphere"*, Planetary and Space Science, 129, 74, 2016.

Hermean magnetosphere

Effect of the SW dynamic pressure and temperature on the Hermean magnetosphere:

Fig 5



- SW dynamic pressure modifies the stand of distance and the bow shock shape.

- SW temperature changes the bow shock width.

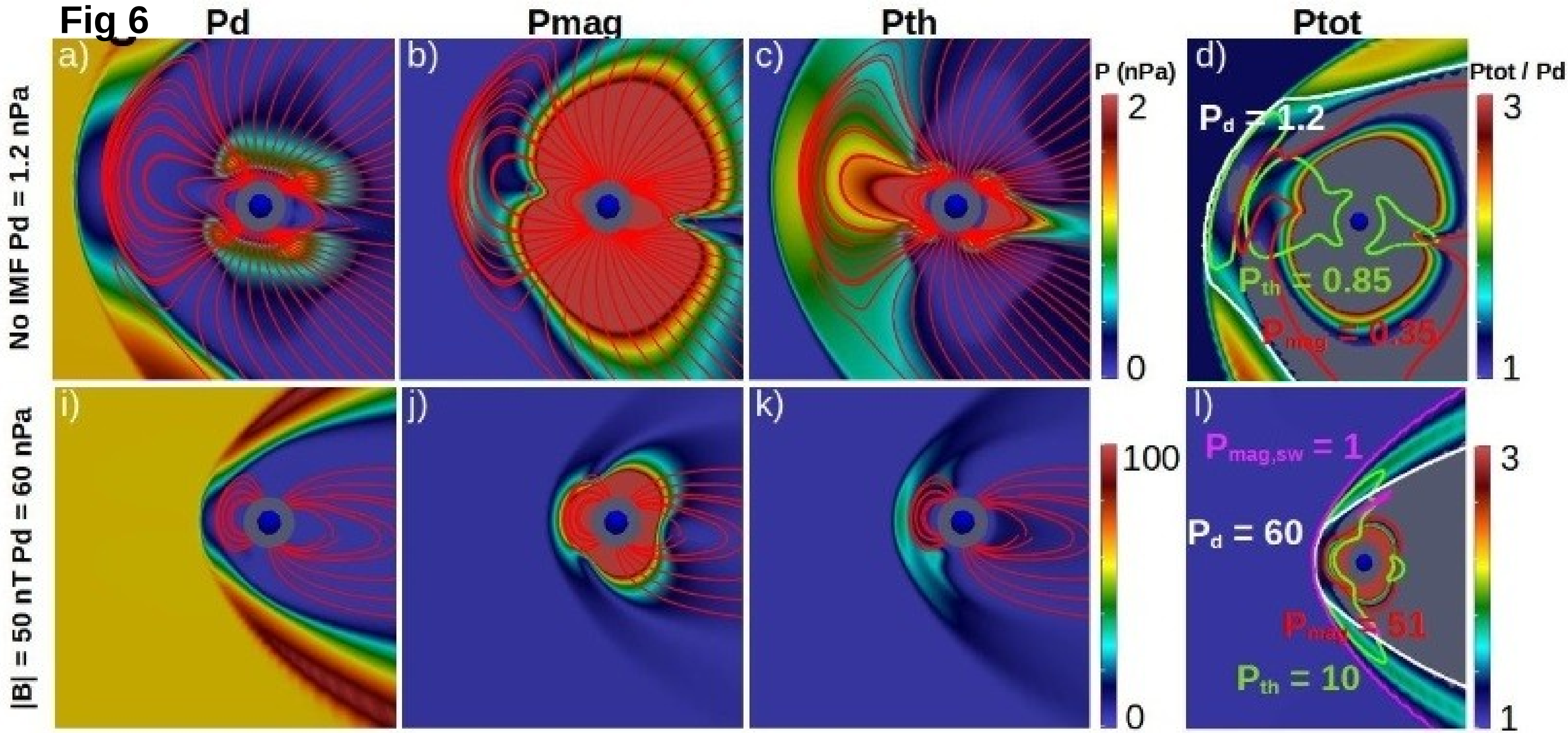
- SW dynamic pressure affects (fig 5):
1) Mass deposition.
2) Plasma flows.
3) Open/close B field line distribution.
4) Magnetosheath depletion
…

J. Varela et al *"Parametric study of the solar wind interaction with the Hermean magnetosphere for a weak interplanetary magnetic field"*, Planetary and Space Science, 120, 78, 2016.

Extreme space weather conditions on the Earth magnetosphere

Pressure balance and magnetosphere stand off distance (R_{SD}) change regarding the space weather conditions, **fig 6**:

Fig 6



- The magneto-pause stand off distance can be calculated as a pressure balance:

SW Dynamic pressure (P_d) SW Thermal pressure ($P_{th,sw}$) IMF Magnetic pressure ($P_{mag,sw}$)

Earth magnetosphere magnetic pressure ($P_{mag,E}$) Earth magnetosphere thermal pressure ($P_{th,BS}$)

Extreme space weather conditions on the Earth magnetosphere

R_{SD} changes with respect to the IMF orientation and module $|B_{IMF}|$ = 50 to 250 nT and the SW dynamic pressure P_d = 1.2 – 100 nPa, **fig 7**:

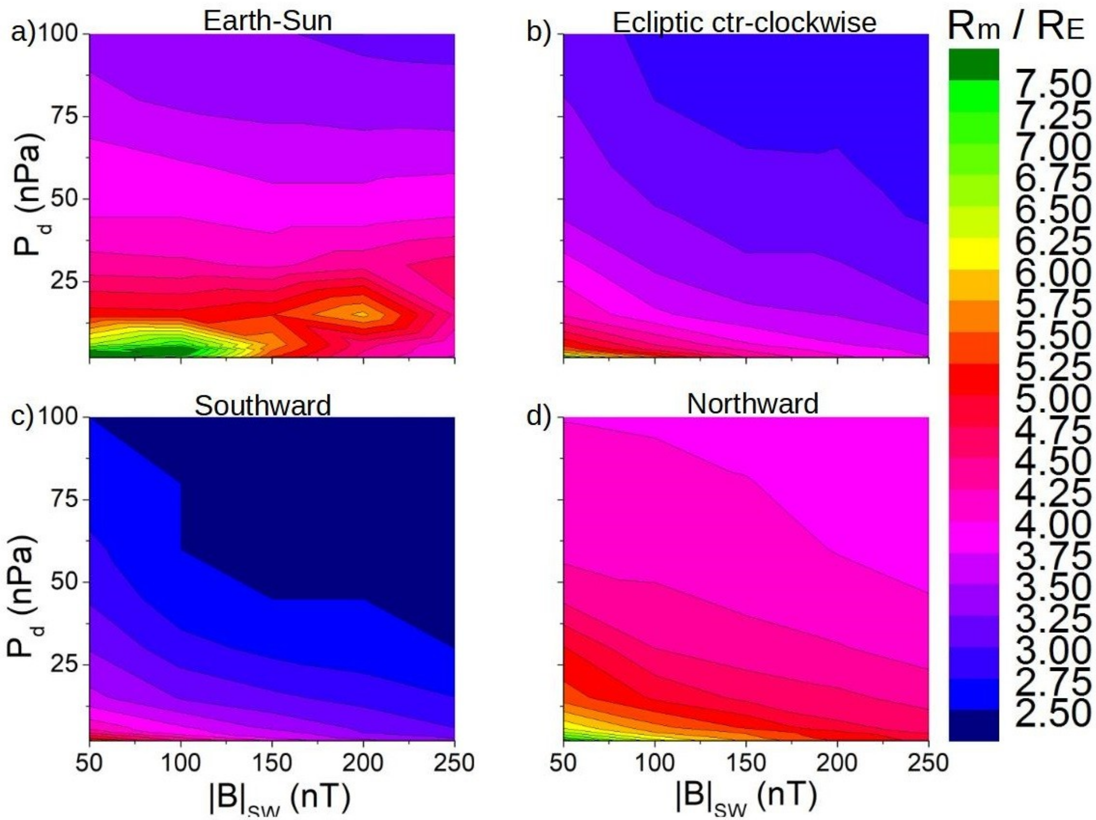
The smallest R_{SD} is observed for Southward IMF orientations.

Fit parameters of the regression:

$$R_{SD}/R_E = A|B|_{IMF}^{\alpha} P_d^{\beta}$$

IMF	A	α	β
Earth-Sun	40	−0.35	−0.16
	±8	±0.04	±0.02
Northward	17.2	−0.196	−0.122
	±1.3	±0.016	±0.007
Southward	20.2	−0.286	−0.175
	±1.6	±0.016	±0.008
Ecliptic	19.2	−0.260	−0.143
	±1.8	±0.019	±0.008

Fig 7



Clear deviations with respect to the theoretical exponents (assuming a dipolar field α = -0.33 , β = -0.17) caused by the Earth magnetic field reconnection with the IMF and the pressure generated by the particles inside the BS.

Extreme space weather conditions on the Earth magnetosphere

The longitude and latitude of the OCB line is affected by the IMF orientation and intensity, **fig 8**:

Northward IMF: OCB line latitude increases with $|B_{IMF}|$.

Southward, Sun-Earth. Earth-Sun and Ecliptic IMF: OCB line latitude decreases with $|B_{IMF}|$.

Kp index indicates the global geomagnetic activity: 0 - 3 (quiet), 4 active, 5 – 9 minor to extreme geomagnetic storm.

Southward IMF can cause severe geomagnetic storms if $|B_{IMF}|$ is large even for low SW P_d.

OCB lines in the Earth surface for different IMF orientation if $|B_{IMF}|$ = 250 nT (extreme space weather conditions), **Fig 9**.

Southward IMF with $|B_{IMF}|$ = 250 nT causes a decrease of the OCB line latitude below 50^0, jeopardizing the electric grid of Canada, North Europe and Russia.

Fig 8

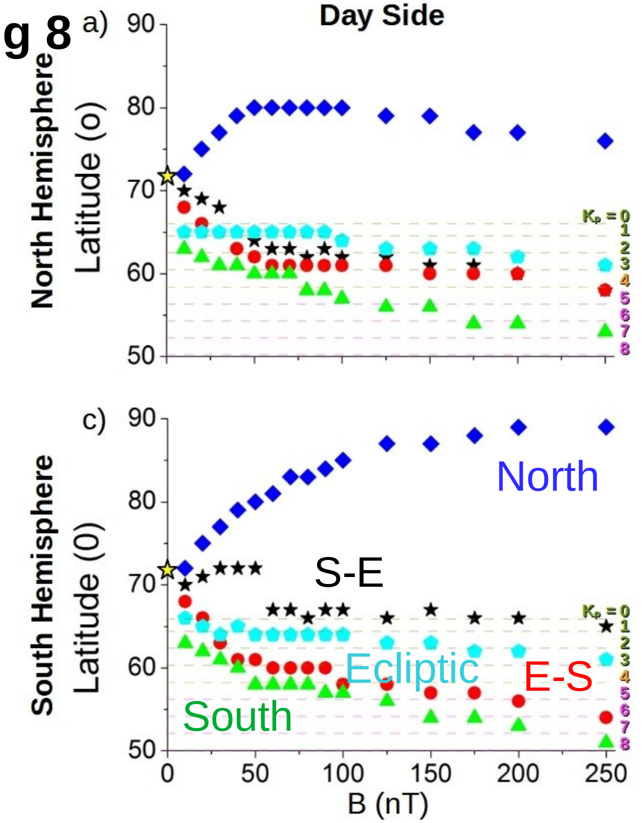
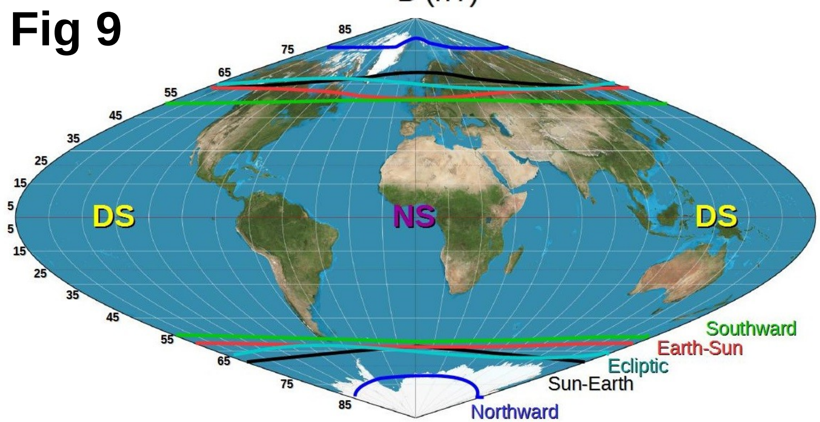


Fig 9



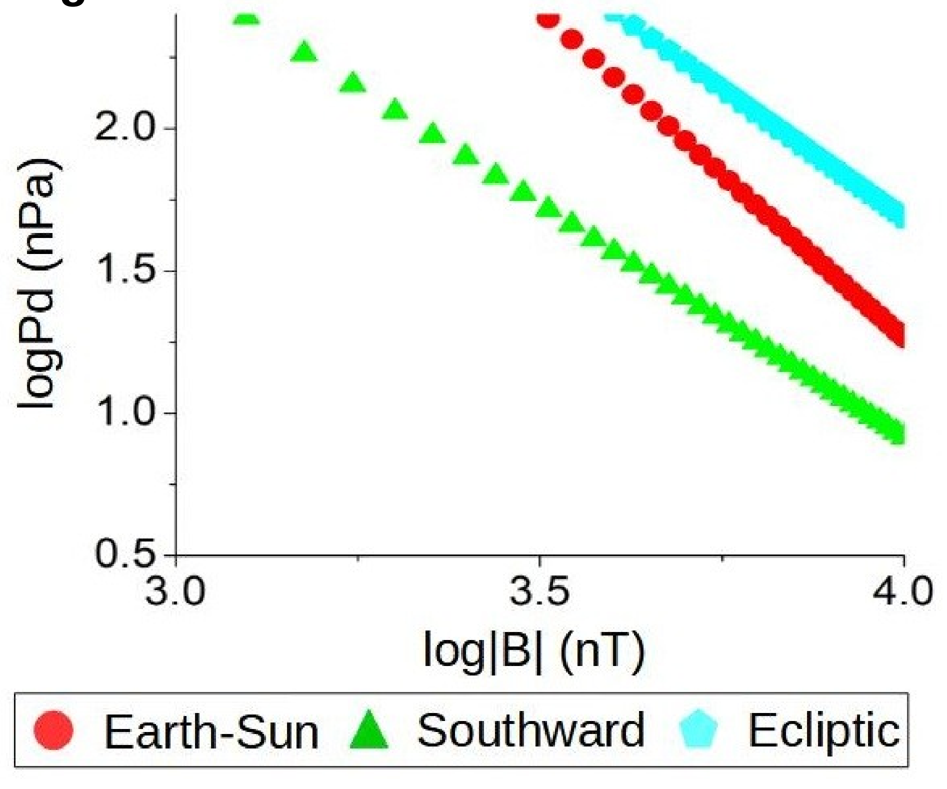
Extreme space weather conditions on the Earth magnetosphere

Critical $|B|_{IMF}$ required for the direct precipitation of the SW towards the Earth surface with respect to P_d and the IMF orientation, **fig 10:**

The direct precipitation of the SW requires the combination of extreme P_d and $|B|_{IMF}$ values well above the space weather conditions at the Earth, even during super-ICME.

For example, a Southward IMF orientation with |B|IMF = 1000 nT requires Pd > 355 nPa.

Fig 10



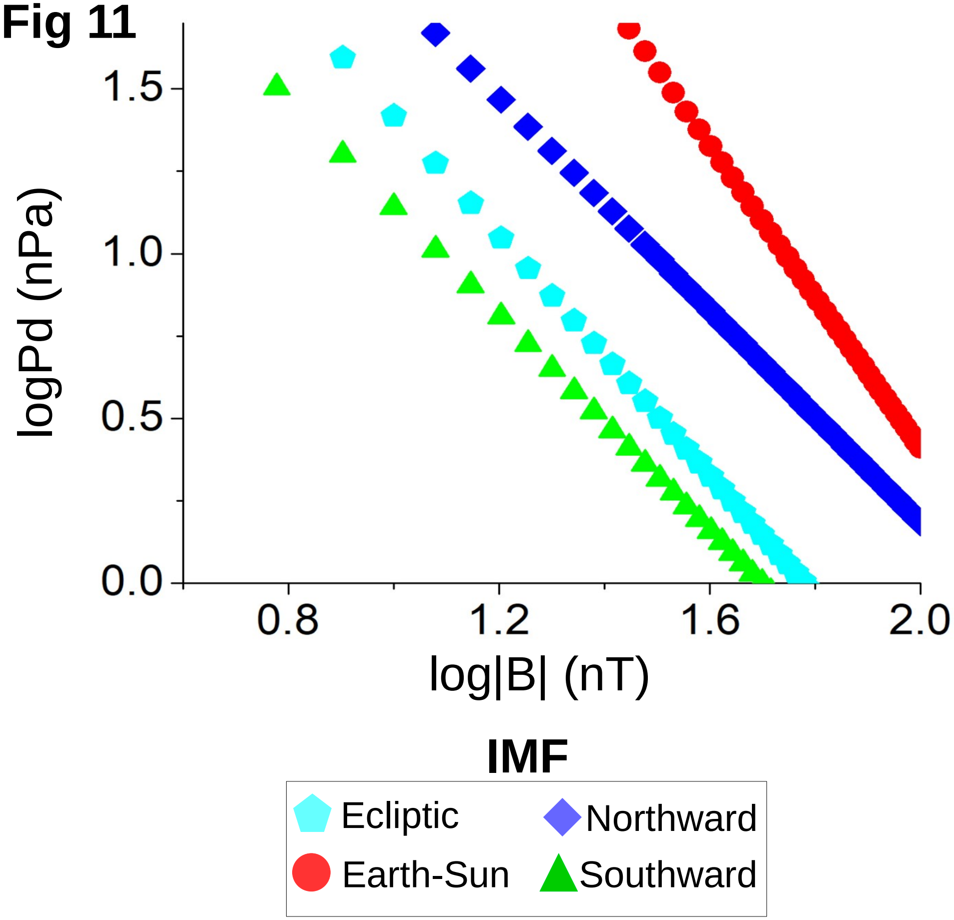
Extreme space weather conditions on the Earth magnetosphere

Critical P_d for different IMF intensities and orientations to reduce R_{SD} below the Geostationary orbit R_{go}, **fig 11**:

Southward and Ecliptic IMF orientations are particularly adverse for Geosynchronous satellites.

Geosynchronous satellites are partially exposed to the SW if the SW dynamic pressure is 14-26 nPa and the IMF intensity 10 nT.

Fig 11



J. Varela et al *“MHD study of the planetary magnetospheric response during extreme solar wind conditions: Earth and exoplanet magnetospheres applications”*, A&A, 659, A10, 2022.

Radio-emission from planetary magnetospheres

The radio emission generated in planetary magnetospheres can be analyzed as a flow facing a magnetized object, leading to the partial dissipation of the flow energy.

The dissipated energy is transformed to radiation and the radiation power is proportional to the intercepted flux of the magnetic and kinetic energy (radio emission Bode's law).

The incident magnetized flow power and the obstacle magnetic field intensity can be used to approximate the radio emission.

$$P_k = \frac{1}{2}\rho \mathbf{v}|\mathbf{v}^2|$$

$$P_B = \frac{\boldsymbol{E} \wedge \boldsymbol{B}}{\mu_0} = \frac{(\eta \boldsymbol{J} - \mathbf{v} \wedge \boldsymbol{B}) \wedge \boldsymbol{B}}{\mu_0}$$

Kinetic (P_k) and magnetic (P_B) energy fluxes

$$\Rightarrow$$

$$[P_k] = \int_V \nabla \cdot \left(\frac{\rho \mathbf{v}|\mathbf{v}^2|}{2}\right) dV$$

$$[P_B] = \int_V \nabla \cdot \frac{\boldsymbol{E} \wedge \boldsymbol{B}}{\mu_0} dV$$

Net kinetic $[P_k]$ and magnetic $[P_B]$ dissipated power.

Bole radio emission law: [P] = α [Pk] + β [PB].

Expected radio emission from Mercury is 10^6 W, but how the SW hydro parameters and the IMF orientation / intensity affect the radio emission ?

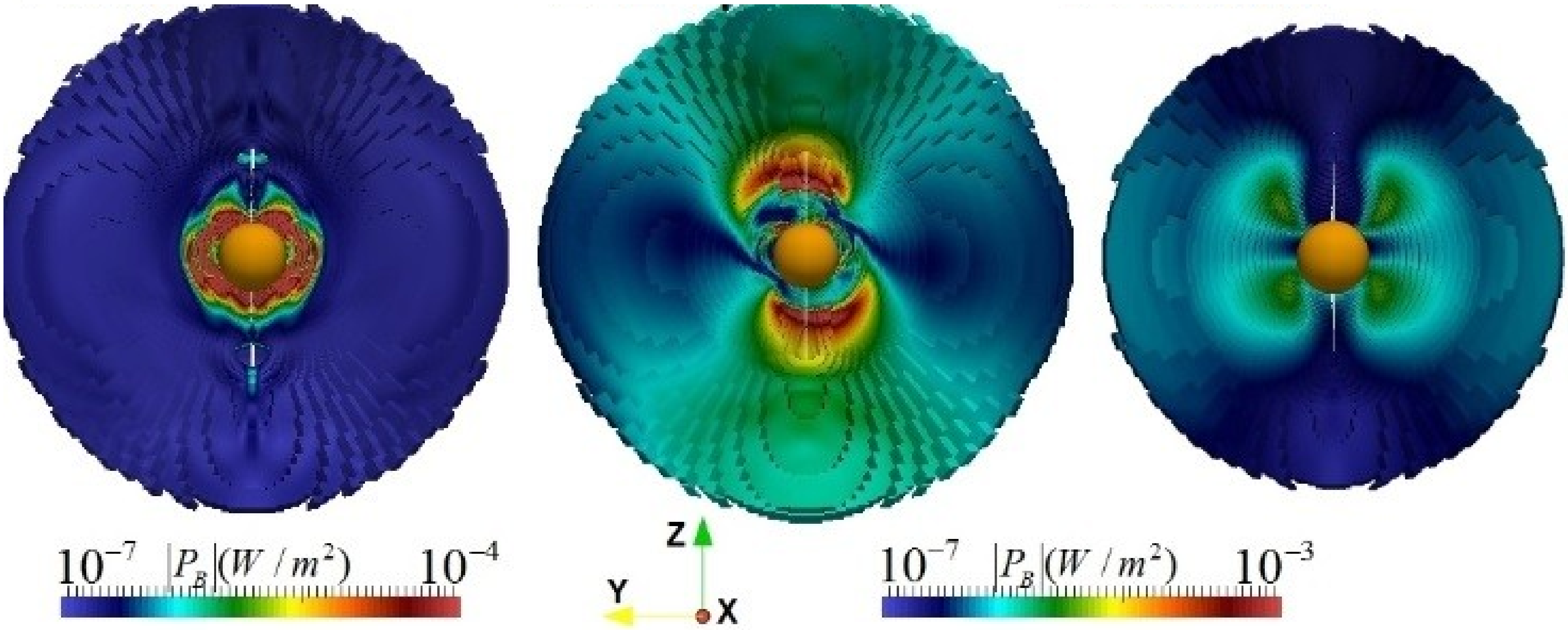
Radio-emission from the Hermean magnetosphere

Radio emission pattern, hot spot distribution, changes regarding the IMF orientation (Fig 12).

Fig 12

|B|=30 nT

S-P Eclip. cCW South.

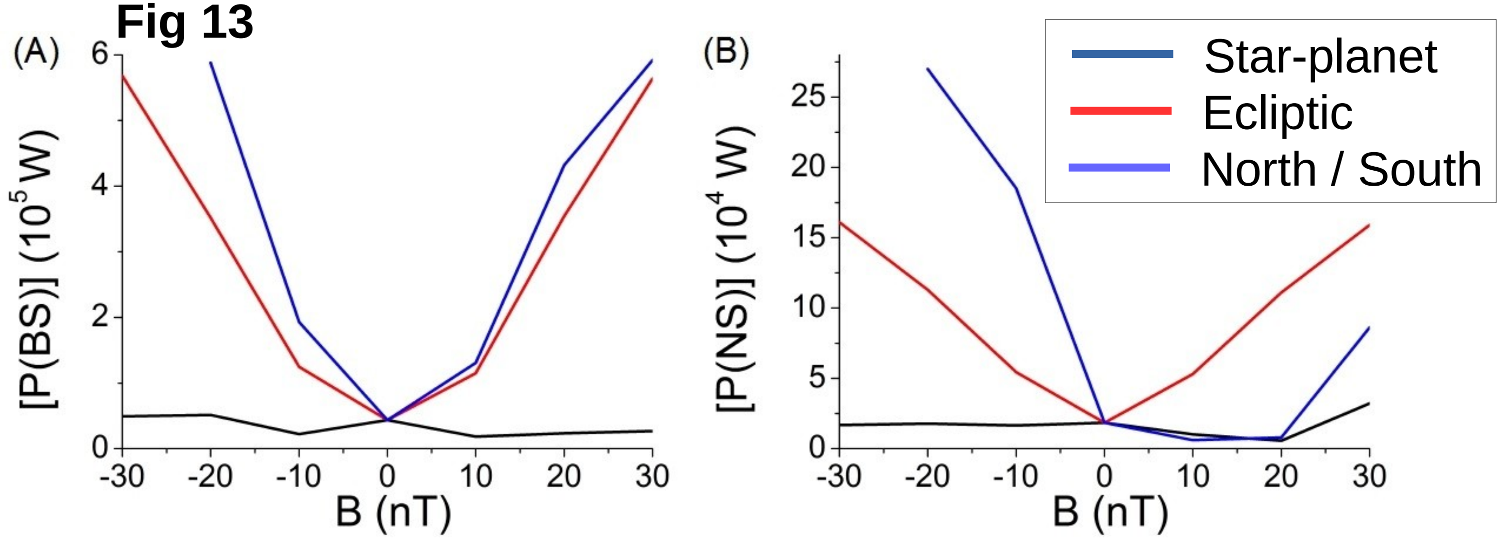


The radio-emission depends on the topology of the Hermean magnetosphere, modified by the interaction with the IMF !!

Radio-emission from the Hermean magnetosphere

The radio emission power changes regarding the IMF orientation and intensity (Fig 13).

Fig 13



|B|=30 nT

Model	$[P(NS)]$ (10^5 W)	$[P(DS)]$ (10^5 W)
Star-planet	0.32	0.28
Planet-star	0.17	0.48
Ecliptic CW	1.59	5.64
Ecliptic cCW	1.61	5.68
Northward	0.86	5.92
Southward	2.70	5.88

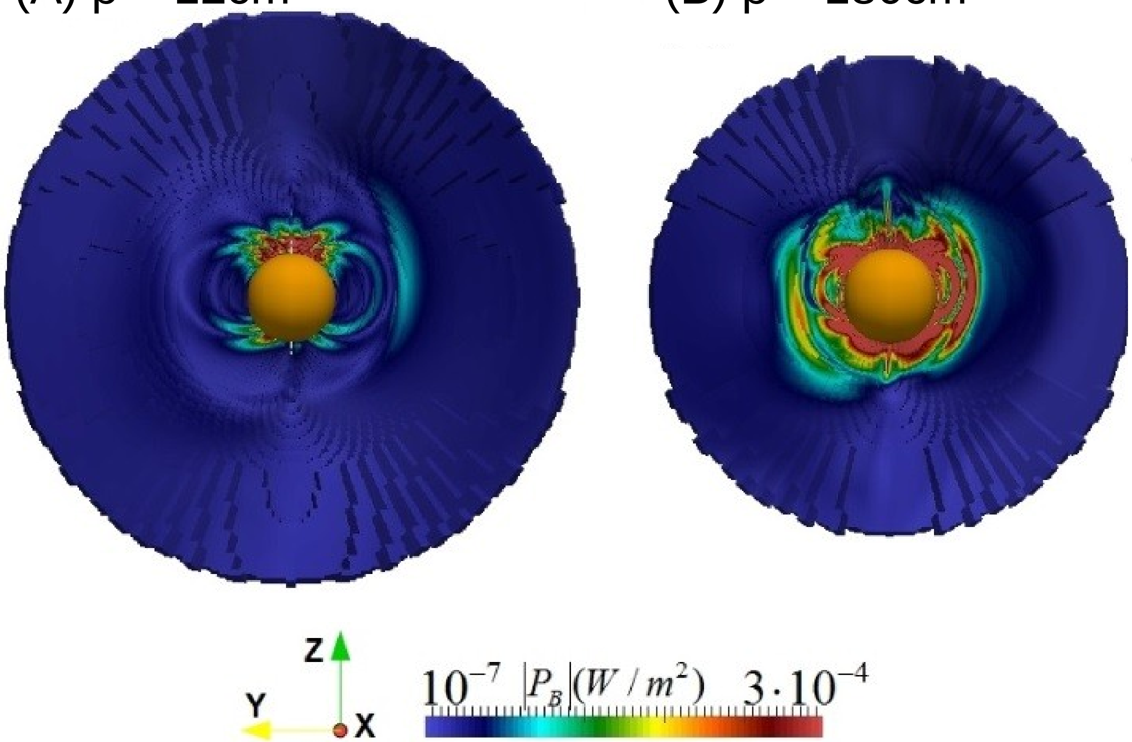
The radio-emission can be up to one order of magnitude higher depending on the IMF orientation and intensity !!

Radio-emission from the Hermean magnetosphere

Radio emission pattern does not change regarding the SW dynamic pressure and temperature (Fig 14).

Fig 14

(A) ρ = 12cm^{-3} (B) ρ = 180cm^{-3} |B|=10 nT (P-S)



Model	Mod. Parameter	$[P]$ (10^6 W)
ρ_{min}	n = 12 cm^{-3}	0.10
ρ_{max}	n = 180 cm^{-3}	2.06
v_{min}	v = 200 km/s	0.14
v_{max}	v = 500 km/s	1.80
T_{min}	$T = 2 \cdot 10^4$ K	0.14
T_{max}	$T = 18 \cdot 10^4$ K	0.20

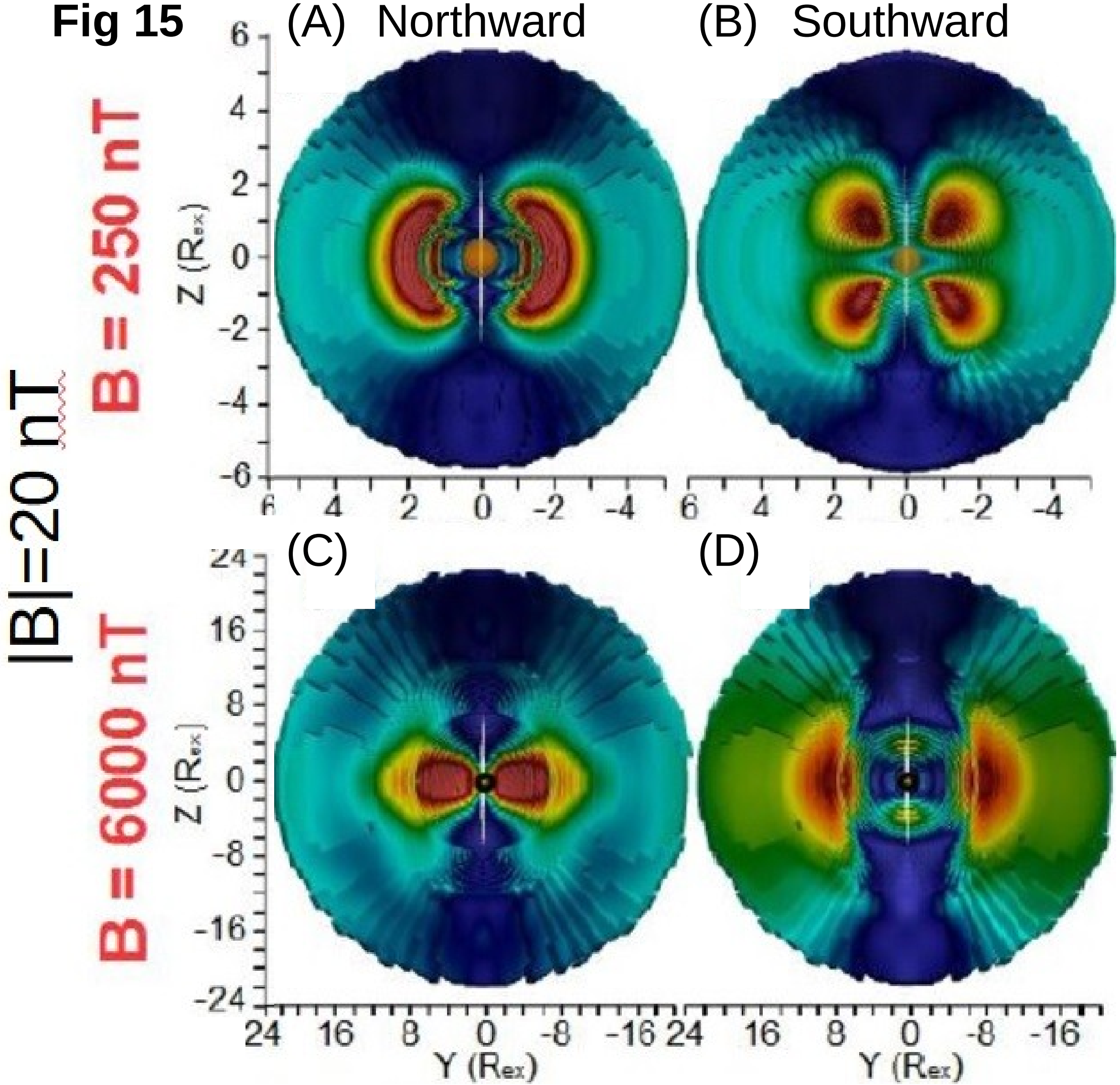
The radio-emission increases as the SW dynamic pressure increases !!

J. Varela et al *"Radio emission in Mercury magnetosphere"*, A&A, 595, A69, 2016.

Radio-emission from exoplanets: the role of the exoplanet magnetic field

The radio emission generated in the exoplanet magnetosphere depends on the intensity of the exoplanet magnetic field (fig 15):

Fig 15



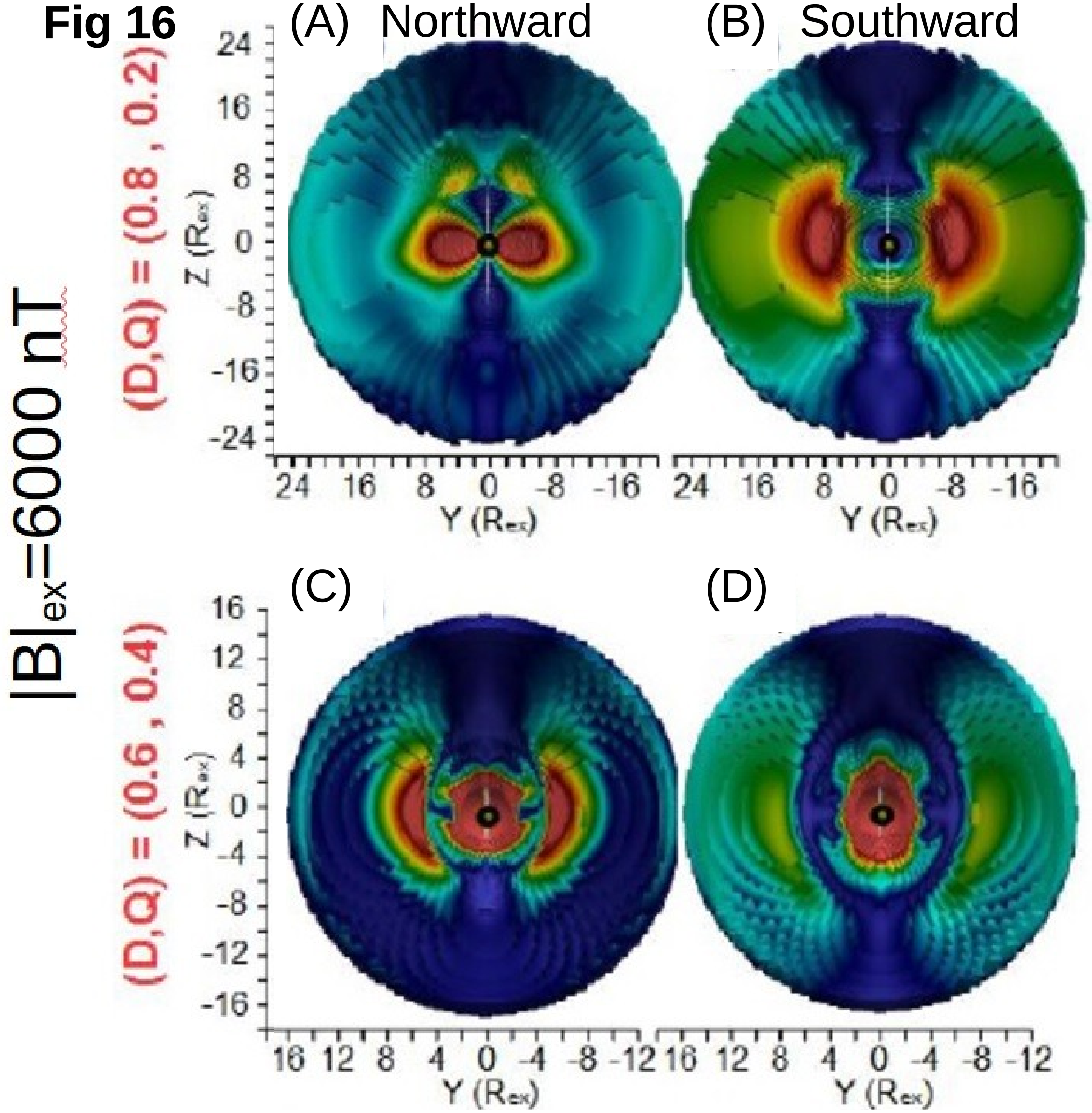
A stronger exoplanet magnetic field leads to a larger magneto-pause stand of distance, modifying the radio emission pattern.

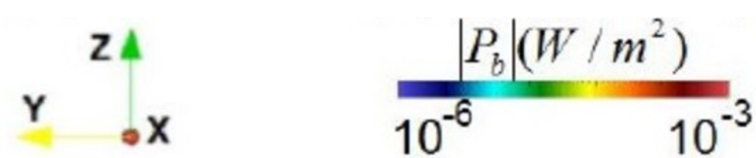
The radio emission encrypt information of the exoplanet magnetic field intensity !!

Radio-emission from exoplanets: the role of the exoplanet magnetic field

The radio emission generated in exoplanet magnetosphere depends on the exoplanet magnetic field topology (fig 16):

Fig 16





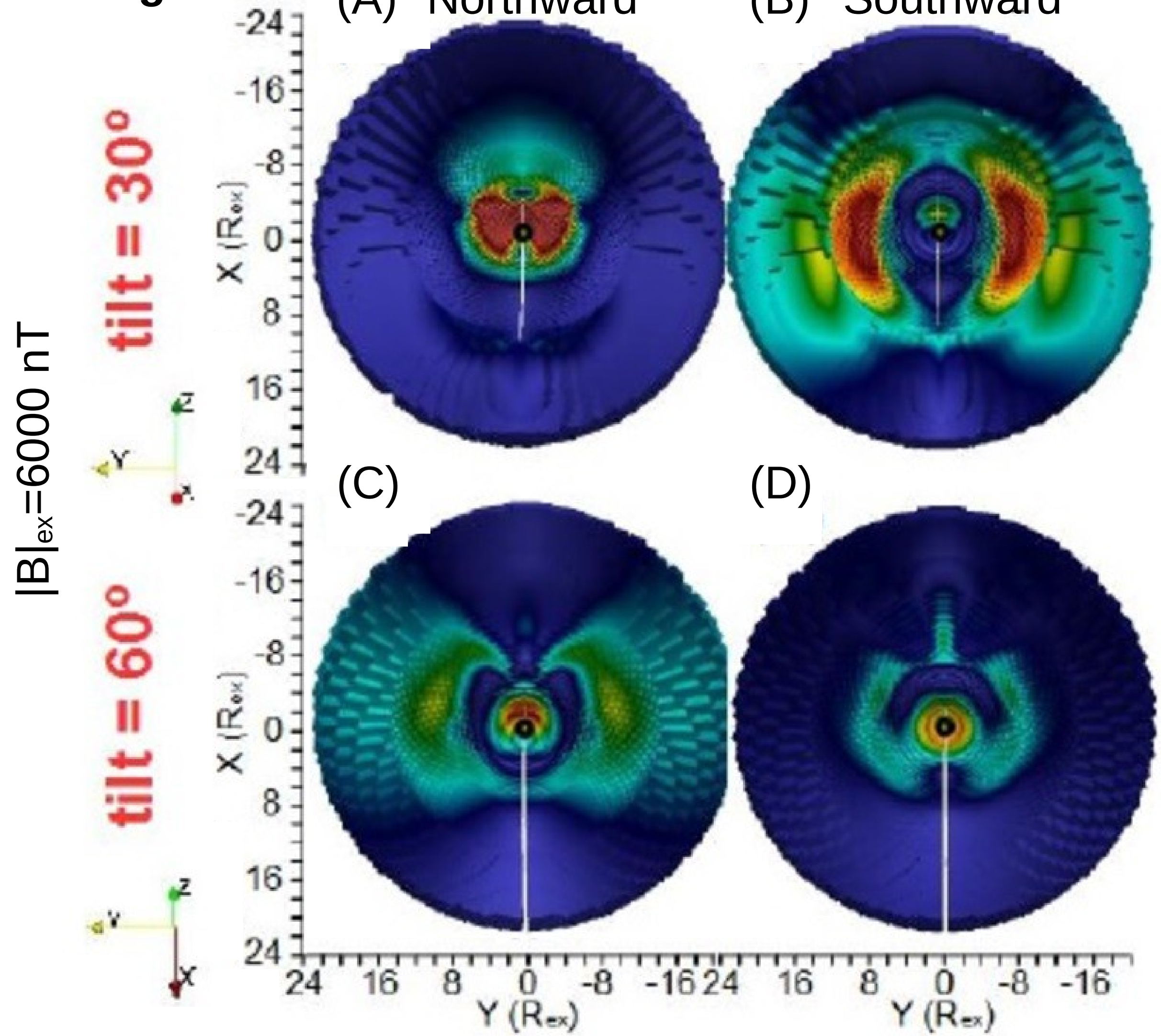
A larger quadrupolar component leads to a Southward displacement of the exoplanet magnetic field.

The radio emission encrypt information of the exoplanet magnetic field topology !!

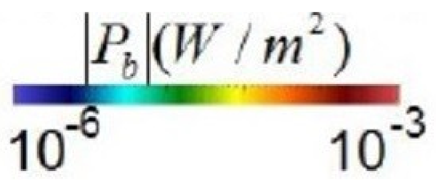
Radio-emission from exoplanets: the role of the exoplanet magnetic field

The radio emission generated in exoplanet magnetosphere depends on the exoplanet magnetic field tilt (fig 17):

Fig 17



The radio emission encrypt information of the exoplanet magnetic field tilt !!



Radio-emission from exoplanets: the role of the exoplanet magnetic field

The analysis of the radio emission versus the exoplanet magnetic field intensity is extrapolated to KOI:

KOI	B (nT)	R (km)	P[DS] (W)
Hot Jupiters	$5 \cdot 10^5$	$7 \cdot 10^4$	$1.5 \cdot 10^{18}$
Super Earth	$6 \cdot 10^4$	$1.3 \cdot 10^4$	$5 \cdot 10^8$

Detectability (LOFAR Φ > 0.1 mJy):

$$\Phi = P / \Omega d^2 \omega$$

Planets at 20 pc = 65 light years

Hot Jupiters Φ = 0.1 – 1 mJy → Detectable !!

Super Earth Φ < 0.0001 mJy → No detectable

The radio emission from Hot Jupiter could be detected by present radio telescopes (recently radio emission detected from the Hot Jupiter Boo b (Turner, J. D. et al. 2021).) !!

Radio-emission from exoplanets: the role of the exoplanet magnetic field

The analysis of the radio emission versus the exoplanet magnetic field intensity is extrapolated to analyze the exoplanet habitability:

Habitability requirement: Exoplanet magnetic field must be strong enough to shelter the exoplanet surface from the stellar wind !!!

$$\frac{R_{MP}}{R} = \left(\frac{B^2}{mn\mu_0 v^2} \right)^{1/6} > 1 \Rightarrow B_{min} = 120nT$$
$$\Rightarrow P_{min} = 10^6 W$$

Extrem space weather: R_{MP} / R > 5, the exoplanet is shielded from standard Coronary Mass Ejections (CMEs) in a star younger (more active) than the Sun:

$$B_{min} = 1.5 \cdot 10^4 nT \qquad \Rightarrow P_{min} = 10^8 W$$

- For a star similar to the Sun and a exoplanet at a distance similar to the Earth:

$$\Rightarrow P_{min} = 10^7 W$$

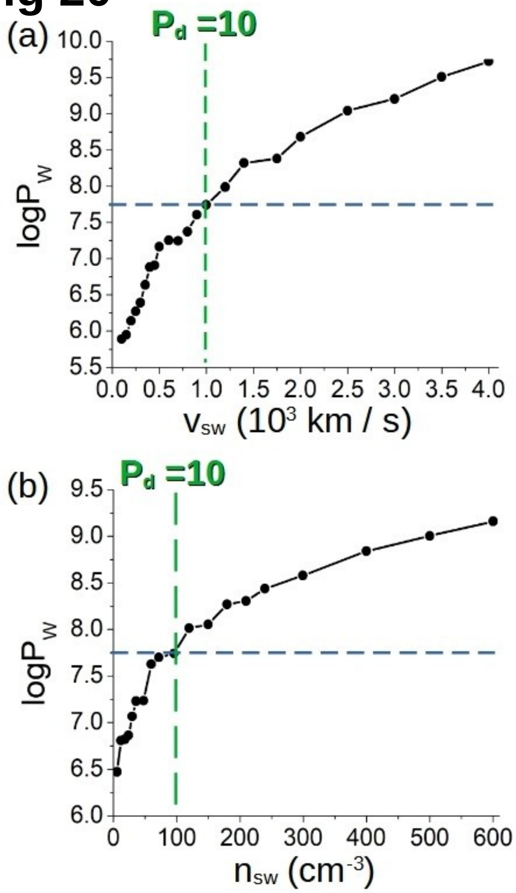
Optimistic scaling of the radio emission minima required for the exoplanet habitability with respect to the magnetic field intensity is obtained !!

J. Varela et al *“Effect of the exoplanet magnetic field topology on its magnetospheric radio emission”*, A&A, 616, A182, 2018.

Radio-emission from exoplanets: the role of the space weather

Effect of the dynamic pressure on the radio emission (from quite to extreme space weather conditions, fig. 20):

Fig 20



Radio emission range versus space weather conditions:

- Quite space weather (P_d < 15 nPa): 10^7 - 10^8 W
- Common CME (15 < P_d < 40 nPa): 10^8 - $6 \cdot 10^8$ W
- Strong CME (40 < P_d < 100 nPa): Up to 10^9 W
- Super CME (P_d > 100 nPa): Above to $2 \cdot 10^9$ W

Scaling: $P_w = \Gamma(n_{sw})^\alpha$ and $P_w = \Gamma(v^2_{sw})^\alpha$

	$P_d \leq 10$ (nPa)	
Regression	Γ	α
Velocity	$(2 \pm 3) \cdot 10^5$	1.2 ± 0.1
Density	$(2 \pm 1) \cdot 10^5$	1.3 ± 0.2
	$P_d > 10$ (nPa)	
Velocity	$(3 \pm 4) \cdot 10^{-4}$	1.84 ± 0.08
Density	$(1.2 \pm 0.3) \cdot 10^4$	1.82 ± 0.04

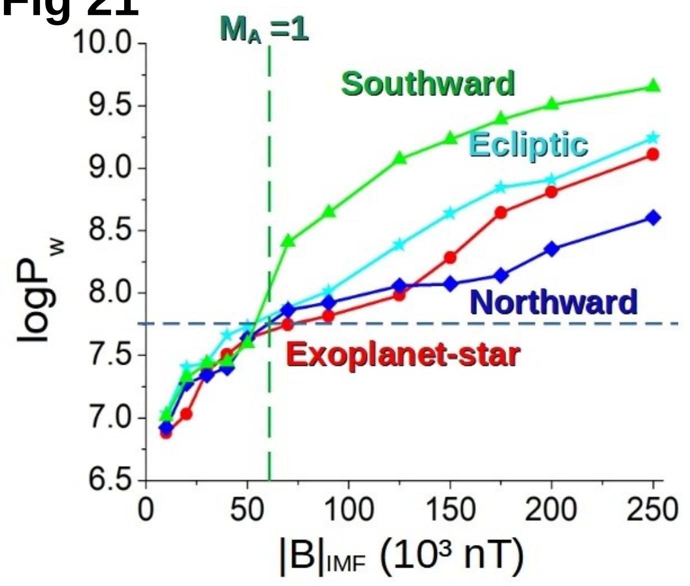
Similar scaling proportional to the SW dynamic pressure !!

A larger magnetosphere compression leads to a larger radio emission !!

Radio-emission from exoplanets: the role of the space weather

Effect of the IMF intensity on the radio emission (from quite to extreme space weather conditions, fig. 21):

Fig 21



IMF	Γ	α
	$M_A > 1$	
Southward	$(7 \pm 6) \cdot 10^5$	1.0 ± 0.3
Northward	$(2.1 \pm 0.9) \cdot 10^6$	0.74 ± 0.12
Exo-star	$(1.6 \pm 0.6) \cdot 10^6$	0.98 ± 0.14
Ecliptic	$(3 \pm 1) \cdot 10^5$	1.29 ± 0.12
	$M_A < 1$	
Southward	$(5 \pm 9) \cdot 10^3$	2.0 ± 0.3
Northward	$(1.0 \pm 0.6) \cdot 10^5$	1.94 ± 0.11
Exo-star	$(3 \pm 3) \cdot 10^2$	2.8 ± 0.12
Ecliptic	$(2 \pm 2) \cdot 10$	3.3 ± 0.2

Simulations with $|B|_{IMF} < 70$ nT leads to $M_A > 1$, that is to say, the bow shock (BS) exist.

The effect of the IMF orientation in the radio emission is larger if the BS does not exist ($|B|_{IMF} \geq 70$ nT).

Radio-telescopes may measure a large radio-emission variability from exoplanets hosted by star with strong magnetic field and relative weak SW dynamic pressure !!

Scaling: $P_w = \Gamma(|B|_{IMF})^{\alpha}$

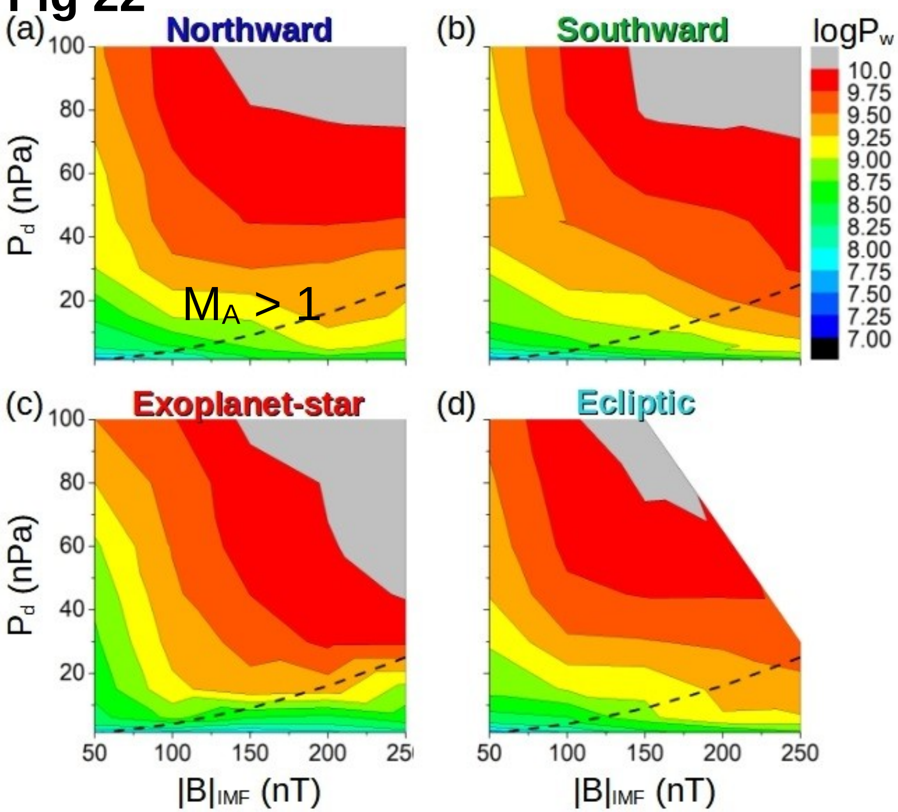
The trend is stronger, 2-3 times larger, in the simulations with $M_A < 1$.

Radio emission increases as the IMF intensity increases !!

Radio-emission from exoplanets: the role of the space weather

Combined effect of the dynamic pressure and IMF intensity on the radio emission (fig. 22):

Fig 22



Radio emission ranges from 10^8 W (common CME) to above 10^{10} W (super CME).

The radio emission enhances as the SW dynamic pressure and IMF intensity increases.

Scaling: $P_w = Z\,(|B|_{IMF})^M\,(P_d)^N$

The trend of the IMF intensity is similar to the SW dynamic pressure if the bow shock exist and it is strongly compressed.

The IMF orientation causes a variability of the radio emission trends around a 25 %.

IMF	Z	M	N
Southward	5.45 ± 0.15	1.22 ± 0.07	0.95 ± 0.03
Northward	5.68 ± 0.17	1.09 ± 0.08	0.97 ± 0.03
Exoplanet-star	5.8 ± 0.3	0.90 ± 0.12	1.15 ± 0.05
Ecliptic	5.7 ± 0.2	1.13 ± 0.07	0.99 ± 0.03

Part of the radio emission variability could be caused by variations of the IMF orientation !!

J. Varela et al *“MHD Study of Extreme Space Weather Conditions for Exoplanets With Earth-Like Magnetospheres: On Habitability Conditions and Radio-Emission”*, Space weather, 20, 11, e2022SW003164, (2022).

CONCLUSIONS AND DISCUSSION

- MHD models are fast and reliable tools to study the global structures of planetary magnetospheres. Validated in plenty of applications !!

- MHD models can be used to study the effect of the space weather conditions in planetary magnetospheres. First order approximation of exoplanets habitability with respect to the space weather conditions around the host star !!

- Radio emission Bode´s law approximates the radio emission “order of magnitude” generated in exoplanet magnetospheres. Reasonable results for the radio-emission generated in the Earth and Hermean magnetospheres !!

- The radio emission is affected by the intensity and topology of the exoplanet magnetic field. The radio emission from exoplanets encrypts information of the exoplanet magnetosphere !!

- A threshold of the exoplanet magnetic field intensity could be obtained from the analysis of the exoplanet radio emission. The exoplanet habitability regarding the SW shielding by the magnetosphere can be derivated from the radio emission !!

- The radio emission is also affect by the space weather conditions around the host star. The dominant pressure component, SW dynamic pressure or IMF magnetic pressure, could be deduced from the radio emission variability, larger if $M_A < 1$!!

FUTURE STUDIES

- Earth habitability with respect to the space weather conditions and intrinsic magnetic field evolution during the main sequence of the Sun. Paper submited (MNRAS) !!

- Space weather and exoplanet habitability: intrinsic magnetic field intensity required for an efficient magnetic shielding of exoplanets detected in stars´ habitable zone: talk EAS 2023: Simulating the habitability conditions of an Earth-like magnetosphere in Proxima b.

- Neutron star winds interaction with host exoplanets. MNRAS article in preparation: Pulsar-exoplanet magnetosphere interaction.

- Characterization of exoplanet magnetospheres using radio-emission telescopes data: observations + simulations + Bayesian analysis.

- Simulation of dynamic events in the Hermean magnetosphere: BepiColombo mission.

- Numerical modeling support to SMILE space mission: the Earth magnetosphere, GOES satellites and open flux in the polar cap.

- Interaction of the SW with the Earth magnetosphere during geomagnetic reversals.

- Effect of the magnetic axis drift on the Earth magnetosphere protection of critical infrastructures.

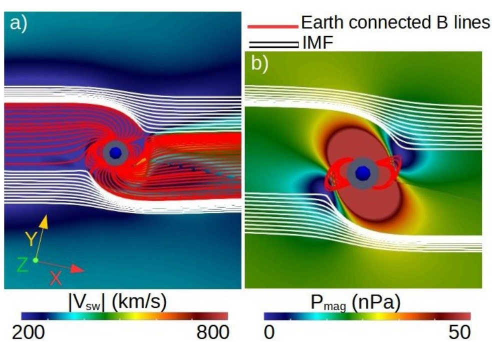
EXTRA SLICES

Extreme space weather conditions on the Earth magnetosphere

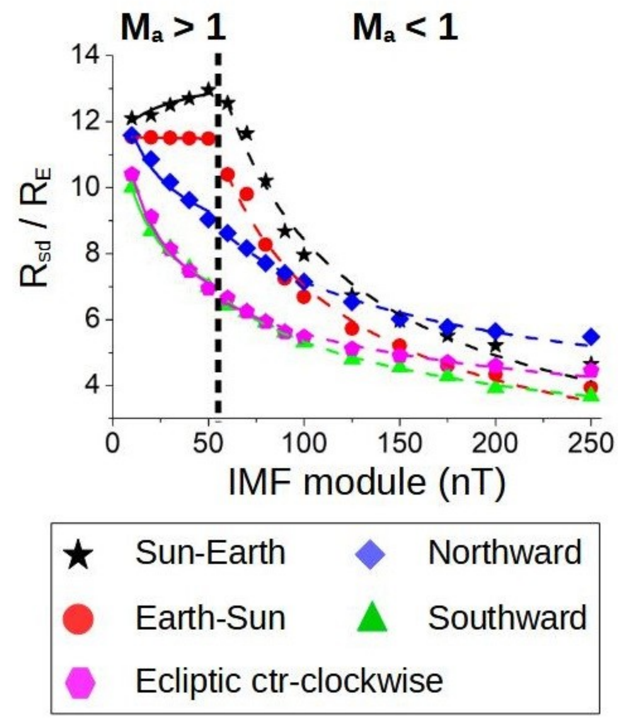
R_{SD} is modified by the IMF orientation and intensity. SW parameters are fixed to $T_{sw} = 1.8 \cdot 10^5$ K and P_d = 1.2 nPa:

Two different trends with respect to the Alfvènic Mach number ($M_A = v_{sw} / v_A$):

a) **Sub-Afvenic shock, $M_A < 1$:**
- The bow shock is not formed.
- R_{BS} depends on the balance between P_d + $P_{mag,sw}$ and $P_{mag,E}$.
- No $P_{th,BS}$, fit parameters close to theory (except Sun-Earth / Earth-Sun IMF: Alfven Wings formation).



b) **Super-Afvenic shock, $M_A > 1$:**
- The bow shock is formed.
- R_{BS} depends on the balance between P_d + $P_{mag,sw}$ and $P_{th,BS}$ + $P_{mag,E}$.
- Fit parameters deviate from theory due to the IMF orientation and $P_{th,BS}$.



IMF	No BS ($M_a < 1$)		BS ($M_a > 1$)	
	A	α	A	α
Sun-Earth	220	−0.71	10.9	0.043
	±40	±0.04	±0.3	±0.008
Earth-Sun	210	−0.73	11.608	−0.0028
	±30	±0.03	±0.014	±0.0004
Northward	35.1	−0.345	16.5	−0.146
	±0.9	±0.005	±0.9	±0.017
Southward	33.9	−0.402	16.3	−0.209
	±1.4	±0.009	±0.7	±0.014
Ecliptic	22.2	−0.300	18.5	−0.244
	±1.3	±0.013	±0.9	±0.016

Extreme space weather conditions on the Earth magnetosphere

R_{SD} is also modified by the SW velocity (v_{sw}) and density (n_{sw}). IMF parameters are fixed to Sun-Earth IMF orientation with $|B|_{sw}$ = 10 nT:

R_{SD} decreases as v_{sw} and density n_{sw} increase (P_d is larger) and the BS is more compressed.

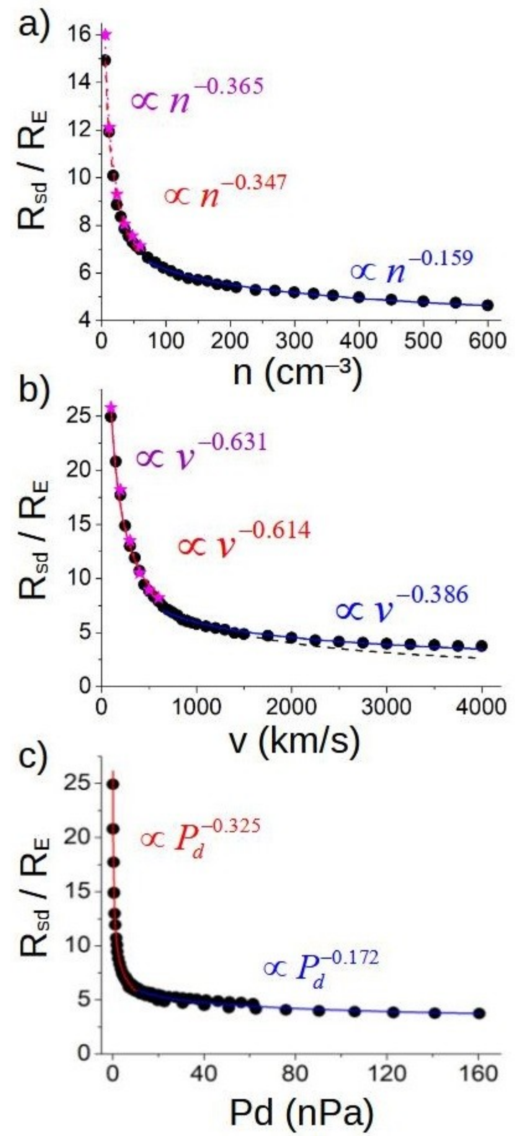
If P_d increases up to 160 nPa, extreme space weather conditions comparable to a super-ICME, R_{sd} > 4.5, thus direct SW deposition towards the Earth surface also requires a large distortion of the magnetosphere by the IMF.

Two different trends with respect to P_d:

a) Large P_d**:**
- Balance between P_d and $P_{mag,E}$.
- Fit exponents close to theory.

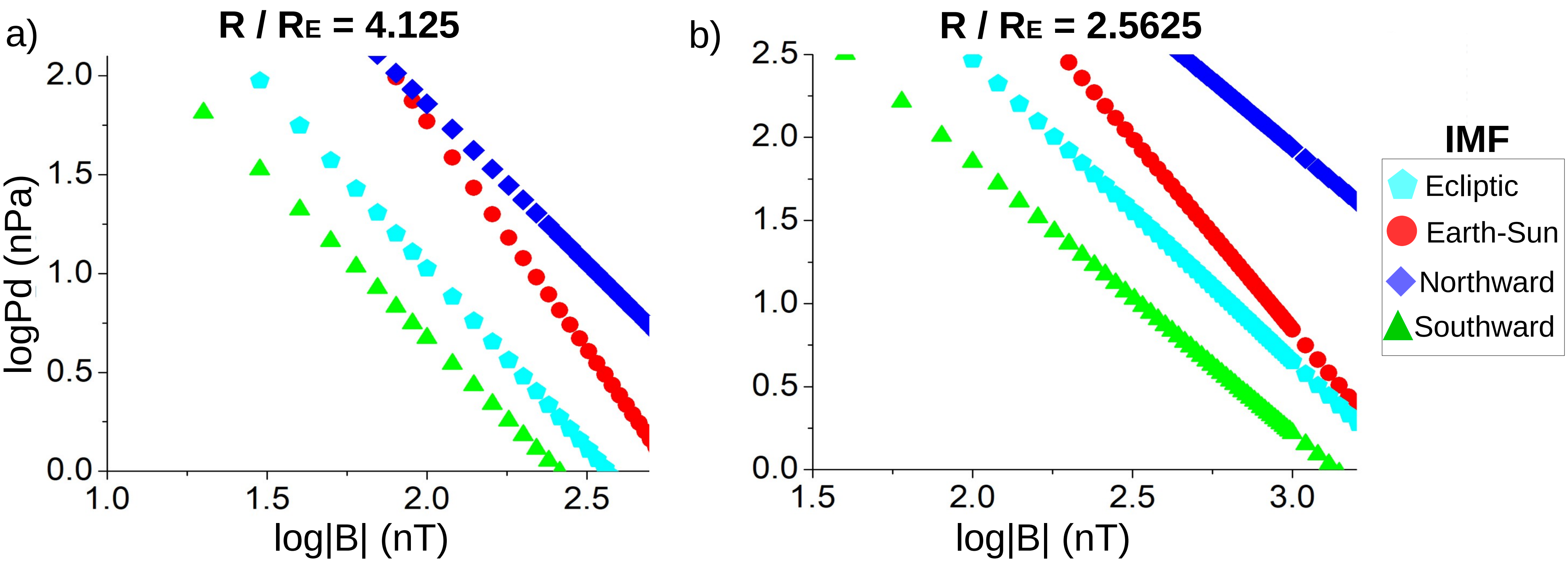
a) Low P_d**:**
- Important role of $P_{th,BS}$ in the pressure balance.
- Fit exponents deviate from theory.

SW parameter	low P_d A	α	High P_d A	α
Density	27.7	−0.35	12.8	−0.159
	±0.7	±0.01	0.3	0.004
Velocity	490	−0.63	85	−0.386
	±60	±0.02	7	0.014
Dynamic pressure	12.37	−0.325	9.0	−0.172
	±0.08	±0.005	0.3	0.011



Extreme space weather conditions on the Earth magnetosphere

Critical P_d for different IMF intensities and orientations to reduce R_{SD} below Medium orbits at R / R_E = 4.1 (20000 km, graph a) and 2.6 (10000 km, graph b):



Satellites at 20000 km are directly exposed to the SW during Common ICME if the IMF orientation is Southward and during Strong ICME if the IMF orientation is Earth-Sun or Ecliptic

Satellites at 10000 km are directly exposed to the SW if a Super ICME with Southward IMF orientation impacts the Earth.